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ESSENTIALS OF GEOLOGY

FOURTH EDITION

Stephen Marshak

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FOURTH EDITION





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FOURTH EDITION

Stephen Marshak
UNIVERSITY OF ILLINOIS

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To Kathy, David, Emma, and Michelle

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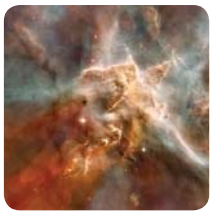
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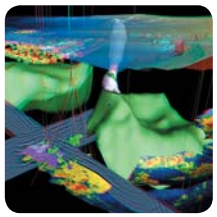
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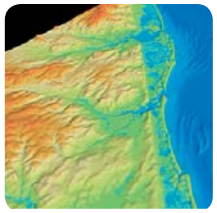
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Preface

Narrative Themes

Why do earthquakes, volcanoes, floods, and landslides happen? What causes mountains to rise? How do beautiful landscapes develop? Do climate and life change through time? When did the Earth form and by what process? Where do we dig to find valuable metals and where do we drill to find oil? Does sea level change? Can continents move? The study of geology addresses these important questions and many more. But from the birth of the discipline in the late 18th century until the mid-20th century, geologists considered each question largely in isolation, without pondering its relation to the others. This approach changed, beginning in the 1960s, in response to the formulation of two "paradigm-shifting" ideas that have unified thinking about the Earth and its features. The first idea, called the *theory of plate tectonics*, states that the Earth's outer shell consists of discrete plates that slowly move relative to each other so that the map of our planet continuously changes. Plate interactions cause earthquakes and volcanoes, build mountains, provide gases that make up the atmosphere, and affect the distribution of life on Earth. The second idea, called the *Earth System concept*, emphasizes that our planet's water, land, atmosphere, and living inhabitants are dynamically interconnected. In the Earth System, materials constantly cycle among various living and nonliving reservoirs on, above, and within the planet. Thus, we have come to realize that the history of life is intimately linked to the history of the physical Earth.

Essentials of Geology, Fourth Edition, is an introduction to the study of our planet that employs the theory of plate tectonics and the concept of the Earth System throughout to weave together a number of narrative themes, including the following:

1. The solid Earth, the oceans, the atmosphere, and life interact in complex ways, yielding a planet that is unique in the Solar System.
2. Most geologic processes reflect the interactions among plates.
3. The Earth is a planet, formed like other planets from dust and gas. But, in contrast to other planets, the Earth is a dynamic place on which new geologic features continue to form and old ones continue to be destroyed.
4. The Earth is very old—about 4.57 billion years have passed since its birth. During this time, the surface, subsurface, and atmosphere of the planet have changed, and life has evolved.
5. Internal processes (driven by Earth's internal heat) and external processes (driven by heat from the Sun) interact at the Earth's surface to produce complex landscapes.
6. Geologic knowledge can help society understand natural hazards such as earthquakes, volcanoes, landslides, and floods, and in some cases can reduce the danger that these hazards pose.
7. Energy and mineral resources come from the Earth and are formed by geologic phenomena. Geologic study can help locate these resources and mitigate the consequences of their use.
8. Physical features of the Earth are linked to life processes, and vice versa.
9. Science comes from observation; people make scientific discoveries.
10. Geology utilizes ideas from physics, chemistry, and biology, so the study of geology provides an excellent means to improve science literacy.

These narrative themes serve as the *take-home message* of this book, a message that students should remember long after they finish their introductory geology course. In effect, they provide a mental framework on which students can organize and connect ideas, and develop a modern, coherent image of our planet.

Pedagogical Approach

Students learn best from textbooks when they can actively engage with a combination of narrative text and narrative art. Some students respond more to the words, which help them to organize information, provide answers to questions, fill in the essential steps that link ideas together, and develop a personal context for understanding information. Some students respond more to narrative art—art designed to tell a story—for visual images help students comprehend and remember processes. And some respond to question-and-answer-based

active learning, an approach where students can in effect "practice" their knowledge in real time. *Essentials of Geology*, Fourth Edition provides all three of these learning tools. The text has been crafted to be engaging and to carry students forward in a narrative form, the art has been configured to tell a story, the chapters are laid out to help students internalize key principles, and the online activities have been designed to both engage students and provide active feedback. For example, *Did You Ever Wonder* panels prompt students to connect new information to their existing knowledge base by asking geology-related questions that they have probably already thought about. *Take-Home Message* panels at the end of each section help students solidify key themes before proceeding to the next section. Questions at the end of each chapter not only test basic knowledge, but also stimulate critical thinking. New SmartWork online homework helps students prepare with automatic feedback, visual drag-and-drop labeling, and "hot spot" reviews. Finally, the *See for Yourself* and *Geotour* features guide students on virtual field trips, via *Google Earth*™, to locales around the globe where they can apply their newly acquired knowledge to the interpretation of real-world geologic features.

Organization

The topics covered in this book have been arranged so that students can build their knowledge of geology on a foundation of overarching principles. Thus, the book starts by considering how the Earth formed, and how it is structured, overall, from its surface to its center. With this basic background, students can delve into plate tectonics, the grand unifying theory of geology. Plate tectonics appears early in the book, so that students can use the theory as a foundation from which they can interpret and link ideas presented in subsequent chapters. Knowledge of plate tectonics, for example, helps students understand the suite of chapters on minerals, rocks, and the rock cycle. Knowledge of plate tectonics and rocks together, in turn, provides a basis for studying volcanoes, earthquakes, and mountains. And with this background, students are prepared to see how the map of the Earth has changed through the vast expanse of geologic time, and how energy and mineral resources have developed. The book's final chapters address processes and problems occurring at or near the Earth's surface, from the unstable slopes of hills, down the course of rivers, to the shores of the sea and beyond. This section concludes with a topic of growing concern in society—global change, particularly climate change.

Although the sequence of chapters was chosen for a reason, this book is designed to be flexible so that instructors can choose their own strategies for teaching geology. Thus, each chapter is self-contained, and we reiterate relevant material where necessary.

Special and Updated Features of This Edition

Narrative Art and *What a Geologist Sees*

To help students visualize topics, this book is lavishly illustrated, with figures designed to provide a realistic context for interpreting geologic features without overwhelming students with extraneous detail. In this edition, many drawings and photographs have been integrated into *narrative art* that has been laid out, labeled, and annotated to tell a story—the figures are drawn to teach! Subcaptions are positioned adjacent to the relevant parts of a figure, labels point out key features, and balloons provide important detail. Subparts have been arranged to convey time progression, where relevant. Color schemes in drawings have been tied to those of relevant photos, so that students can easily visualize the relationships between drawings and photos. In some examples, photographs are accompanied by annotated sketches labeled *What a Geologist Sees*, which help students to be certain that they actually see the specific features that the photo was intended to show.

Featured Paintings: *Geology at a Glance*

In addition to individual figures, renowned British artist Gary Hincks has created spectacular two-page annotated paintings, called *Geology at a Glance*. These paintings integrate key concepts introduced in the chapters and visually emphasize the relationships among components of the Earth System. And, they provide students with a way to review a subject . . . at a glance.

New Coverage of Current Topics

To ensure that *Essentials of Geology*, Fourth Edition, reflects the latest research discoveries and helps students understand the geologic events that have been featured in news headlines, we have updated many topics throughout the book. For example, this edition provides insightful treatment of catastrophic earthquakes in Haiti, Japan, and New Zealand; illustrates recent massive tornado outbreaks; explains the significance of the nonconventional gas reserves of the Marcellus Shale; and characterizes the critical sustainability issues related to our increasing reliance on rare earth elements.

See for Yourself — Using *Google Earth*™

Visiting Field Sites Identified in the Text

There's no better way to appreciate geology than to see it first-hand in the field. The challenge is that the great variety of geologic features that we discuss in this book can't be visited from any one locality. So even if your class can take geology field trips during the semester, you'll at most see examples of just a few geologic settings. Fortunately, *Google Earth*™ makes it possible for you to fly to spectacular geologic field sites anywhere in the world in a matter of seconds—you can take a virtual field trip electronically. At the end of each chapter in this book, you will find a *See For Yourself* section identifying geologic sites that you can explore on your own personal computer (Mac or PC) using *Google Earth*™ software, or on your Apple/Android smartphone or tablet with the appropriate *Google Earth*™ app.

To get started, follow these three simple steps:

1. Check to see whether *Google Earth*™ is installed on your personal computer, smartphone, or tablet. If not, please download the software from **earth.google.com** or the app from the Apple or Android app store.
2. In the *See For Yourself* section at the end of a chapter, find a site that you're interested in visiting. In addition to a thumbnail photo and very brief description of the site (highlighting what you will see at the site), we provide the latitude and longitude of the site.
3. Open *Google Earth*™, and enter the coordinates of the site in the search window. As an example, let's find Mt. Fuji, a beautiful volcano in Japan. We specify the coordinates in the book as follows:

Latitude	35°21′41.78″N,
Longitude	138°43′50.74″E

Type these coordinates into the search window as:

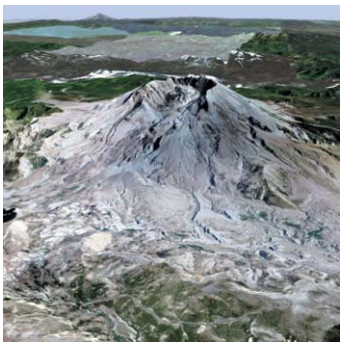
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Note that the degree (°), minute (′), and second (″) symbols are simply left as blank spaces.

When you click Enter or Return, your device will bring you to the viewpoint right above Mt. Fuji illustrated by the thumbnail on the left. Note that you can use the tools built into *Google Earth*™ to vary the elevation, tilt, orientation, and position of your viewpoint. The thumbnail on the right shows the view you'll see of the same location if you tilt your viewing direction and look north.



View looking down.



View looking north.

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We also offer a separate book—the *Geotours Workbook* (ISBN 978-0-393-91891-5)—that identifies even more interesting geologic sites to visit, provides active-learning exercises linked to the sites, and explains how you can create your own virtual field trips.

New SmartWork online Tutorial and Assessment System for Geology

The SmartWork online tutorial and assessment system available to users of *Essentials of Geology*, Fourth Edition features visual assignments that provide students with answer-specific feedback. Students get the coaching they need to work through the assignments, while instructors get real-time assessment of student progress with automatic grading and item analysis. Image-based drag-and-drop and hot-spot questions make use of carefully developed images, and additional *What a Geologist Sees* figures have been created exclusively for SmartWork. Additional video, animation, and conceptual questions challenge students to apply their understanding of important concepts identified by the author in each chapter's *Take-Home Message*. SmartWork also provides Reading Quizzes, *Geotour*-guided inquiry activities using *Google Earth*™, and approximately 1,000 basic content questions.

Features Designed to Help Students Prepare and Review

Each chapter begins with chapter objectives that frame the major concepts for students, and every section ends with a *Take-Home Message*, a brief summary that helps students identify and remember the highlight of the section before moving on to the next. *Did You Ever Wonder* questions are sprinkled within the chapter to both engage students and answer common questions about geology. Each chapter now concludes with a integrated two-page *Chapter Review*, designed to pull together summary points, key terms, basic review questions, *On Further Thought* critical-thinking questions, and *See for Yourself* sites into a single, visually compact, feature. The *See for Yourself* sites introduce students to field examples of geology accessible by using *Google Earth*™.

Interludes

The book contains several Interludes. These "mini-chapters" focus on key topics that are self-contained but are not broad enough to require an entire chapter. Placing some content in the Interludes not only keeps chapters reasonable in length, but also provides additional flexibility in sequencing topics within a course.

Societal Issues

We address geology's practical applications in several chapters, providing students with an opportunity to learn about energy resources, mineral resources, global change, and natural disasters. *Science and Society* features, provided for free on the open student website and in Norton's LMS coursepacks, challenge students to apply material that they learn in *Essentials of Geology*, Fourth Edition to the interpretation of news articles and publicly available geologic data.

Supplementary Materials



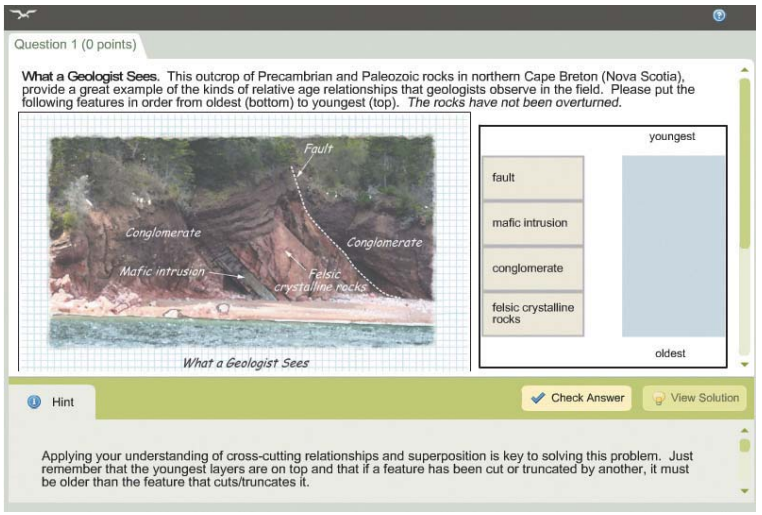
New SmartWork Online Tutorial and Assessment System. The new SmartWork online assessment available for use with *Essentials of Geology*, Fourth Edition features visual assignments with focused feedback. Because students learn best when they can interact with art as well as with text, SmartWork includes drag-and-drop figure-based questions, animation- and video-based questions, and *What a Geologist Sees* photo interpretations. SmartWork also provides questions based on real field examples, via the *Geotours Workbook*, and helps students check their knowledge as they go by working with reading-based questions. Designed to be intuitive and easy to use (for both students and instructors), SmartWork makes it a snap to assign, assess, and report on student performance, and keep the class on track.

Student Access Codes. If students need to purchase an access code for SmartWork, they can order through their college bookstore using ISBN 978–0–393–91939–4 for SmartWork with e-book. Immediate online access can also be purchased at smartwork.wwnorton.com—select the option to buy a registration code before you create your account. Instructors can request their own SmartWork course at wwnorton.com/instructors.

Art Files and PowerPoints

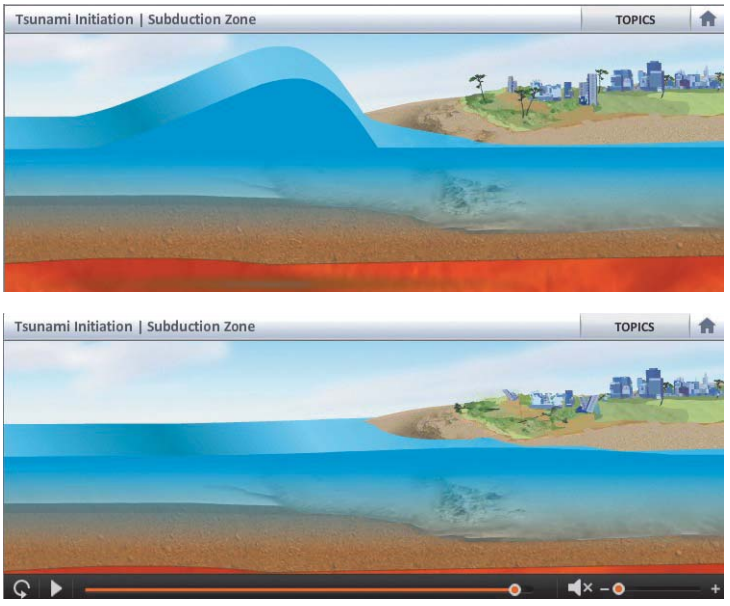
- *Enhanced Art PowerPoints*—Designed for instant classroom use, these slides utilize photographs and line art from the book in a form that has been optimized for use in the PowerPoint environment. The art has been relabeled and resized for projection formats. *Enhanced Art PowerPoints* also include supplemental photographs.
- *Lecture Bullet PowerPoints*—These slides include both art and bulleted text for direct use either in lectures or as student handouts.
- *Labeled and Unlabeled Art PowerPoints*—These include all art from the book formatted as JPEGs that have been prepasted into PowerPoints. We offer one set in which all labeling has been stripped and one set in which labeling remains.
- *Art JPEGs*—We provide a complete file of individual JPEGs for art and photographs used in the book.
- *Monthly Update PowerPoints*—W. W. Norton & Company offers a monthly update service that provides new PowerPoint slides, with instructor support, covering recent geologic events. Starting in December 2012, these updates will help instructors keep their classes current.

New Animations and Videos. The book's accompanying Instructor Resource DVD provides a rich collection of animations to illustrate geologic processes. The set includes



SmartWork

The new SmartWork online assessment system available for use with Essentials of Geology features highly visual questions with immediate, answer-specific feedback.



Animations

New interactive animations help instructors to demonstrate concepts and then allow students to explore those concepts on their own. New topics include Tsunami Initiation, Faults, and Metamorphic Change.



Videos

A new real-world video collection makes clips easily available in a reliable and convenient format. In SmartWork, questions with answer-specific feedback help students connect the videos to what they've learned in class.

10 new animations, developed by Alex Glass of Duke University, that allow you to control variables. In addition, working with Melissa Hudley of the University of North Carolina, Chapel Hill, Heather Lehto of Angelo State University, and Meghan Lindsey of the University of South Florida, our DVD, coursepacks and instructor support website contain over 50 streaming videos of geologic processes including content developed by IRIS. All animations and videos are ready to go and perfect for classroom or online use.

Norton Media Library Instructor's DVD-ROM. The Instructor's DVD offers a wealth of easy-to-use multimedia resources all structured around the text. Resources include all of the PowerPoints art files, animations, and videos described earlier in the preface, and electronic versions of the Instructor's Manual, Test Bank, and Exam View test generation software. Further resources include GeoQuiz clicker questions, and supporting files for using *Google Earth*™.

Instructor's Manual and Test Bank. The Instructor's Manual and Test Bank, prepared by John Werner of Seminole State College of Florida; Jacalyn Gorczynski of Texas A&M, Corpus Christi; Haley Wasson of Texas A&M, College Station; and Daniel Wynne of Sacramento Community College, are designed to help instructors prepare lectures and exams. The Instructor's Manual contains detailed Learning Objectives, Chapter Summaries, and complete answers to end-of-chapter review and *On Further Thought* questions. The Test Bank has been developed using the Norton Assessment Guidelines, and each chapter of the Test Bank consists of three types of questions, classified according to Norton's taxonomy of knowledge types and by section and difficulty, making it easy to construct tests and quizzes that are meaningful and diagnostic. Test questions were also reviewed by instructors (we would like to thank Judy McIlrath of the University of South Florida, Marek Cichanski of DeAnza College, and Karen Koy of Missouri Western State University for their feedback). These supplements are available in print paperback and on DVD, and are also downloadable from wwnorton.com/instructors.

Instructor's Website—wwnorton.com/instructors. Online access is available to a rich array of resources: Test Bank, Instructor's Manual, PowerPoints, JPEGs, *Google Earth*™ file of sites from the text, art from the text, and WebCT- and Blackboard-ready content.

***Coursepacks*.** Available at no cost to professors or students, Norton *Coursepacks* bring high-quality Norton digital media into a new or existing online course. For *Essentials of Geology*, Fourth Edition, content includes Test Bank, Reading Quizzes, Quiz+ questions, *Geotour* questions, Guides to Reading, animations, streaming video, and links to the e-book.

The *Google Earth™ Geotours Workbook*. Created by Scott Wilkerson, Beth Wilkerson, and Stephen Marshak, *Geotours* are active-learning opportunities that take students on virtual field trips to see outstanding examples of geology at localities around the world. Arranged by topic, questions for the *Geotours* have been designed for auto-grading, and are available as Worksheets both in print format (these come free with the book and include complete user instructions and advanced instruction) and electronically with auto-grading through SmartWork or your campus LMS. Request a sample copy to preview each worksheet.

***See for Yourself Google Earth*™ Sample Site File.** Users who simply want access to sample field sites for classroom presentations or distribution to students can download the sites from the book's *See for Yourself* review sections. This single download is available at the Norton instructor download site as well as from wwnorton.com/studyspace.



***Ebook*.** *Essentials of Geology*, Fourth Edition is available in an ebook format at norton**ebooks**.com that replicates actual book pages and provides links to the animations on StudySpace. Students will also have the ability to highlight text and use sticky notes. An iPad-specific format is available through www.coursesmart.com.



***StudySpace*—wwnorton.com/studyspace.** Free and open for students, StudySpace offers students assignment-driven study plans for each chapter. Materials include Quiz+ diagnostic quizzes, *Science and Society* features that challenge students to use course concepts in analyzing news articles and real-time geologic data, reading guides, vocabulary flashcards, a *Geology in the News* feed, and information on how to best utilize the *Google Earth*™ materials provided for this book. StudySpace includes a video designed to help with start-up, all the *See For Yourself* sites in one downloadable file, instructions to enter latitude and longitude coordinates for each site, and links to *Google Earth*™ tutorials and information on updates.

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I am very grateful for the assistance of many people in bringing this book from the concept stage to the shelf in the first place, and for helping to provide the momentum needed to make this revision take shape.

First and foremost, I wish to thank my wife, Kathy, who served as coauthor and in-home project manager for this book. Kathy helped to construct the manuscript by incorporating

changes added to this book's parent, *Earth: Portrait of a Planet*, managed the manuscript traffic between our household and the publisher, cross-checked proofs, maintained the in-home art list and style sheet, and served as an invaluable extra set of eyes for catching errors. This book would not have happened without Kathy. I also wish to thank my daughter, Emma, and son, David, for their willingness to adopt "the book" as a member of the household when they were growing up, and to endure the overabundance of geo-photo stops on family trips. Emma also helped develop the concept of narrative art used in the book, and provided feedback about how the book works from a student's perspective.

I am very grateful to all the staff of W. W. Norton & Company for their incredible efforts during the development of my books over the past two decades. It has been a privilege to work with a company that is willing to work so closely with its authors. In particular, I would like to thank Thom Foley, the project manager for the book, who did a Herculean job of overseeing what proved to be an unexpectedly complicated process of managing the chapter proofs and the figures, all while remaining incredibly calm. Thom invested untold hours in sorting out composition and design issues—it's thanks to Thom that this edition made it to the shelf on schedule. Many thanks to the senior editor, Eric Svendsen, who injected new enthusiasm and ideas into the project. Eric's experience and skill have guided the book in new directions and have connected the project to new trends in science pedagogy and book design. I also greatly appreciate the efforts of Rob Bellinger for his innovative approach to ancillary development and for overseeing the development of the SmartWork supplements; Trish Marx for her expert and thoughtful editing of the photo collection and permissions; Ben Reynolds for coordinating the back-and-forth between the publisher and various suppliers; Stacy Loyal, who has so ably assumed the mantle of sales manager for the book; Callinda Taylor for capably handling the ancillaries; Paula Iborra for assisting Rob with everything emedia; and Jennifer Harris for her excellent copyediting work. *Essentials of Geology* would not have reached a fourth edition without the inspiration and support of Jack Repcheck, the editor of the previous three editions. Jack proposed several of the features that attracted readers to the book in the first place, and continues to provide guidance and support. I also wish to thank Susan Gaustad, the outstanding developmental editor of the first edition, who helped refine the prose style of the book.

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It has been great fun to interact with Gary Hincks, who painted the incredible two-page spreads, in part using his own designs and geologic insights. Some of Gary's paintings originally appeared in *Earth Story* (BBC Worldwide, 1998) and were based on illustrations conceived with Simon Lamb and Felicity Maxwell. Others were developed specifically for *Earth: Portrait of a Planet* and *Essentials of Geology*. Some of the chapter-opening quotes were found in *Language of the Earth*, compiled by F. T. Rhodes and R. O. Stone (Pergamon, 1981).

The four editions of this book and of its parent, *Earth: Portrait of a Planet*, have benefited greatly from input by expert reviewers for specific chapters, by general reviewers of the entire book, and by comments from faculty and students who have used the book and were kind enough to contact me or the publisher. In particular, in this edition I would like to thank Michael Rygel of SUNY Potsdam, who proofed every chapter as we created the initial book pages. Judy McIlrath of the University of South Florida, Marek Cichanski of DeAnza College, and Karen Koy of Missouri Western State University provided valuable feedback on the Test Bank questions and Kurt Wilkie of Washington State University has offered extremely helpful input on both the book and the coursepack. Other reviewers who have provided helpful feedback for this and previous editions include:

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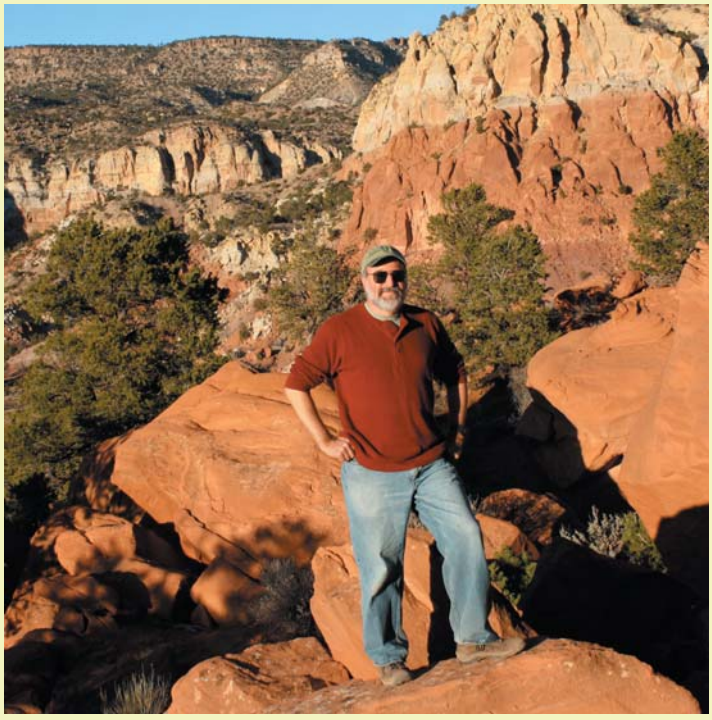
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Lorraine Wolf, *Auburn University*
Christopher J. Woltemade, *Shippensburg University*

I apologize if I inadvertently left anyone off this list.

About the Author

Stephen Marshak is a professor of geology at the University of Illinois, Urbana-Champaign, where he is also the director of the School of Earth, Society, and Environment. He holds an A.B. from Cornell University, an M.S. from the University of Arizona, and a Ph.D. from Columbia University. Steve's research interests in structural geology and tectonics have taken him into the field on several continents. He loves teaching and has won his college's and university's highest teaching awards, as well as the Neil Miner Award of the National Association of Geoscience Teachers "for exceptional contributions to the stimulation of interest in the earth sciences." In addition to *Essentials of Geology*, Steve has authored *Earth: Portrait of a Planet* and has co-authored *Laboratory Manual for Introductory Geology*; *Earth Structure: An Introduction to Structural Geology and Tectonics*; and *Basic Methods of Structural Geology*.



Thanks!

I am very grateful to the students who engaged so energetically with earlier editions of this book, and to the instructors who have selected this book for their classes. I welcome your comments and corrections and can be reached at smarshak@illinois.edu.

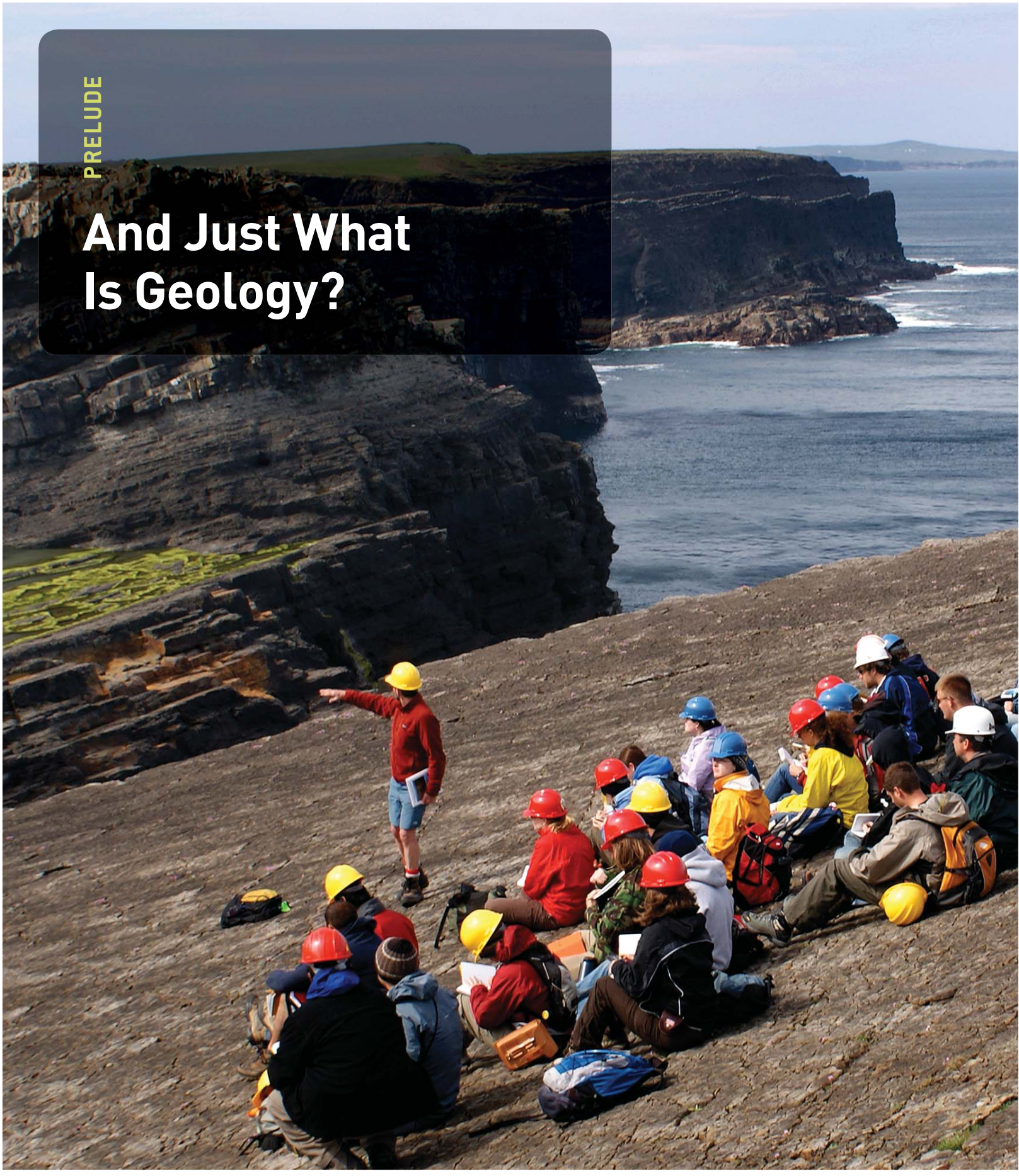
Stephen Marshak

Geology, perhaps more than any other department of natural philosophy, is a science of contemplation. It demands only an enquiring mind and senses alive to the facts almost everywhere presented in nature.

—Sir Humphry Davy (British scientist, 1778–1829)

PRELUDE

And Just What Is Geology?





Students can see the Earth System at a glance on a sea cliff along the coast of Ireland. Here, sunlight, air, water, rock, and life all interact to produce a complex and fascinating landscape.

Prelude Objectives

By the end of this Prelude you should know . . .

- the scope and applications of geology.
- the foundational themes of modern geologic study.
- how geologists employ the scientific mathod.

Civilization exists by geological consent, subject to change without notice.

—Will Durant (1885–1981)

P.1 In Search of Ideas

Our C-130 Hercules transport plane rose from a smooth ice runway on the frozen sea surface at McMurdo Station, Antarctica, and headed south to spend a month studying unusual rocks exposed on a cliff about 250 km away. We climbed past the smoking summit of Mt. Erebus, Earth's southernmost volcano, and for the next hour flew along the Transantarctic Mountains, a ridge of rock that divides the continent into two parts, East Antarctica and West Antarctica (**Fig. P.1**). Glaciers—sheets or rivers of ice that last all year—cover almost all of Antarctica. To the right of the plane we could see a continental glacier, a vast sheet of ice thousands of kilometers across and up to 4.7 km (15,000 ft) thick, that covers East Antarctica. The surface of this ice sheet forms a frigid high plain called the Polar Plateau. To the left we could see numerous valley glaciers, rivers of ice, that slowly carry ice from the Polar Plateau through gaps in the Transantarctic Mountains down to the frozen Ross Sea.

Suddenly, we heard the engines slow. As the plane descended, it lowered its ski-equipped landing gear. The loadmaster shouted an abbreviated reminder of the emergency alarm code: "If you hear three short blasts of the siren, hold on for dear life!" The plane touched the surface of our first choice for a landing spot, the ice at the base of the rock cliff we wanted to study. *Wham, wham, wham, wham!!!!* As the skis slammed into frozen snowdrifts on the ice surface at about 180 km an hour, it seemed as though a fairy-tale giant was shaking the plane. Seconds later, the landing aborted, we were airborne again, looking for a softer runway above the cliff. Finally, we landed in a field of deep snow, unloaded, and bade farewell to the plane. When the plane passed beyond the horizon, the silence of Antarctica hit us—no trees rustled, no dogs barked, and no traffic rumbled in this stark land of black rock and white

ice. It would take us a day and a half to haul our sleds of food and equipment down to our study site (see Fig. P.1). All this to look at a few dumb rocks?

Geologists—scientists who study the Earth—explore remote regions like Antarctica almost routinely. Such efforts often strike people in other professions as a strange way to make a living, as implied by Scottish poet Walter Scott's (1771–1832) classic description of geologists at work: "Some rin uphill and down dale, knappin' the chucky stones to pieces like sa' many roadmakers run daft. They say it is to see how the warld was made!"

Indeed—to see how the world was made, to see how it continues to evolve, to find its valuable resources, to prevent contamination of its waters and soils, and to predict its dangerous movements. That is why geologists spend months at sea drilling holes in the ocean floor, why they scale mountains, camp in rain-drenched jungles, and trudge through scorching desert winds (**Fig. P.2**). That is why geologists use electron microscopes to examine the atomic structure of minerals, use mass spectrometers to measure the composition of rock and water, and use supercomputers to model the paths of earthquake waves. For over two centuries, geologists have pored over the Earth in search of ideas to explain the processes that form and change our planet.

P.2 The Nature of Geology

Geology, or geoscience, is the study of the Earth. Not only do geologists address academic questions such as the formation and composition of our planet, the causes of earthquakes and ice ages, and the evolution of life, but they also address practical problems such as how to keep pollution out of groundwater, how to find oil and minerals, and how to avoid landslides. And in recent years, geologists have made significant contributions to the study of global climate change. When news reports begin with "Scientists say . . . " and then continue with "an earthquake occurred today off Japan," or "landslides will threaten the city," or "chemicals from the proposed toxic waste dump will ruin the town's water supply," or "there's only a limited supply of oil left," the scientists referred to are geologists.

The fascination of geology attracts many to careers in this science. Tens of thousands of geologists work for oil, mining, water, engineering, and environmental companies, while a smaller number work in universities, government geological surveys, and research laboratories. Nevertheless, since most of the students reading this book will not become professional geologists, it's fair to ask the question, "Why should people, in general, study geology?"

FIGURE P.1 Geologic fieldwork in Antarctica unlocks the mysteries of an icebound continent. A map of Antarctica emphasizes that the Transantarctic Mountains separate West Antarctica from East Antarctica.



FIGURE P.2 Geologists in the field. Exploring an outcrop hidden in the woods of Ontario, Canada.



First, geology may be one of the most practical subjects you can learn. Ask yourself the following questions, and you'll realize that geologic processes, phenomena, and materials play major roles in daily life:

- Do you live in a region threatened by landslides, volcanoes, earthquakes, or floods (**Fig. P.3**)?
- Are you worried about the price of energy or about whether there will be a war in an oil-supplying country?
- Do you ever wonder about where the copper in your home's wires comes from?
- Have you seen fields of green crops surrounded by desert and wondered where the irrigation water comes from?
- Would you like to buy a dream house on a beach or near a river?

FIGURE P.3 Human-made cities cannot withstand the vibrations of a large earthquake. These apartment buildings collapsed during an earthquake in Turkey.



- Are you following news stories about how toxic waste can migrate underground into your town's well water?

Clearly, all citizens of the 21st century, not just professional geologists, need to make decisions and understand news reports addressing Earth-related issues. A basic understanding of geology will help you do so.

Second, the study of geology gives you a holistic context for interpreting your surroundings. As you will see, the Earth is a complicated entity, where living organisms, oceans, atmosphere, and solid rock interact with one another in a great variety of ways. Geologic study reveals Earth's antiquity and demonstrates how the planet has changed profoundly during its existence. What our ancestors considered to be the center of the Universe has become, with the development of geologic perspective, our "island in space" today. And what was believed to be an unchanging orb originating at the same time as humanity has become a dynamic planet that existed long before people did and continues to evolve.

Third, the study of geology puts the accomplishments and consequences of human civilization in a broader context. View the aftermath of a large earthquake, flood, or hurricane, and it's clear that the might of natural geologic phenomena greatly exceeds the strength of human-made structures. But watch a bulldozer clear a swath of forest, a dynamite explosion remove the top of a hill, or a prairie field evolve into a housing development, and it's clear that people can change the face of the Earth at rates often exceeding those of natural geologic processes.

Finally, when you finish reading this book, your view of the world may be forever colored by geologic curiosity. If you walk in the mountains, you will think of the many forces that shape and reshape the Earth's surface. If you hear about a natural disaster, you will have insight into the processes that brought it about. And if you go on a road trip, the rock exposures along the highway will no longer be gray, faceless cliffs, but will present complex puzzles of texture and color telling a story of Earth's history.

P.3 Themes of This Book

A number of narrative themes appear (and reappear) throughout this text. These themes, listed below, can be viewed as this book's overall take-home message.

- *The Earth is a unique, evolving system.* Geologists increasingly recognize that the Earth is a complex system; its interior, solid surface, oceans, atmosphere, and life forms interact in many ways to yield the landscapes and environment in which we live. Within this **Earth System**, chemical elements cycle between different types of rock, between rock and sea, between sea and air, and between all of these entities and life.

BOX P.1

CONSIDER THIS . . .

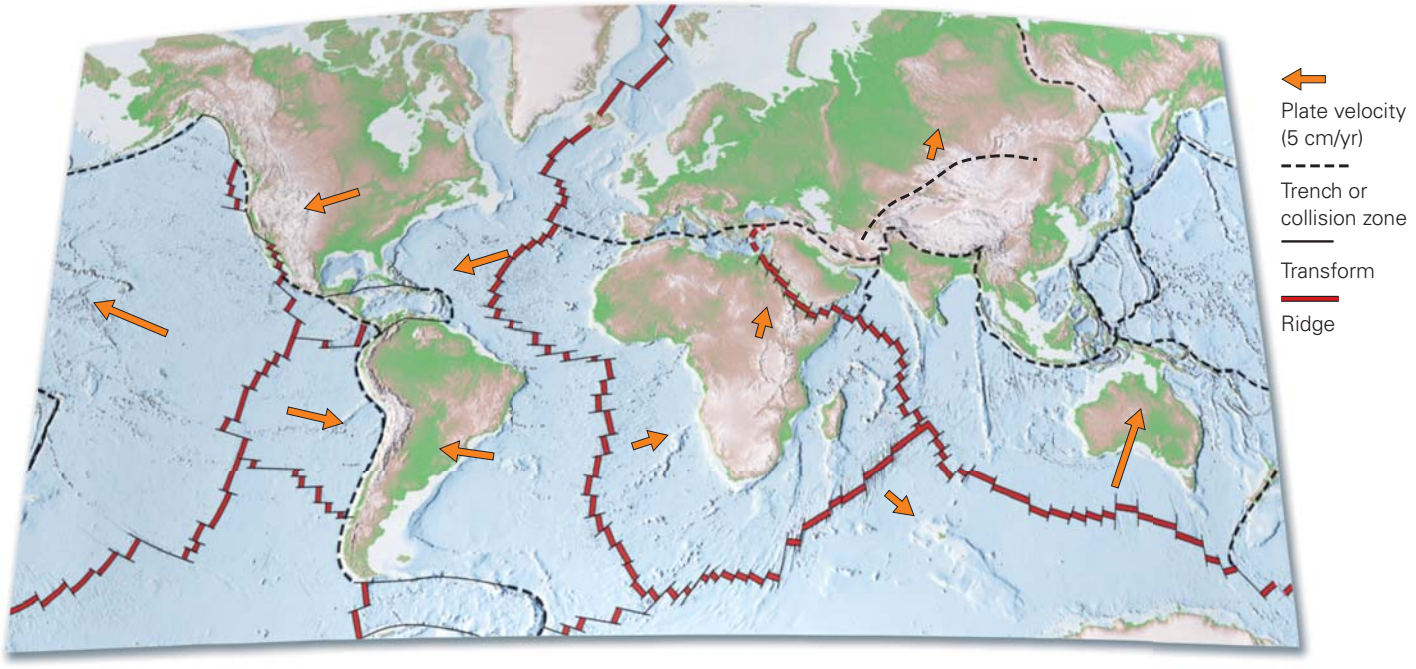
Heat and Heat Transfer

The atoms and molecules that make up matter are not motionless, but rather jiggle in place and/or move with respect to one another. This activity produces **thermal energy**—the faster the atoms vibrate or move, the greater the thermal energy. Put another way, thermal energy in a substance represents the *sum* of the kinetic energy (energy of motion) of all the substance's atoms.

When we say that one object is hotter or colder than another, we are describing its **temperature**, a measure of warmth relative to some standard. Temperature represents the *average* kinetic energy of atoms in the material. We use the freezing and boiling points of water at sea level as a standard for defining temperatures. In the Celsius (centigrade) scale, the freezing point of water is 0°C and the boiling point is 100°C, whereas in the Fahrenheit scale, the freezing point is 32°F and the boiling point is 212°F. The coldest a substance can be is the temperature at which its atoms or molecules stand still. We call this temperature absolute zero, or 0K, where K stands for Kelvin, another unit of temperature. Degrees in the Kelvin scale have the same increment as degrees in the Celsius scale; absolute zero equates to −273.15°C. The term **heat** refers to the thermal energy *transferred* from one object to another. Heat can transfer from one place to another by four distinct means:

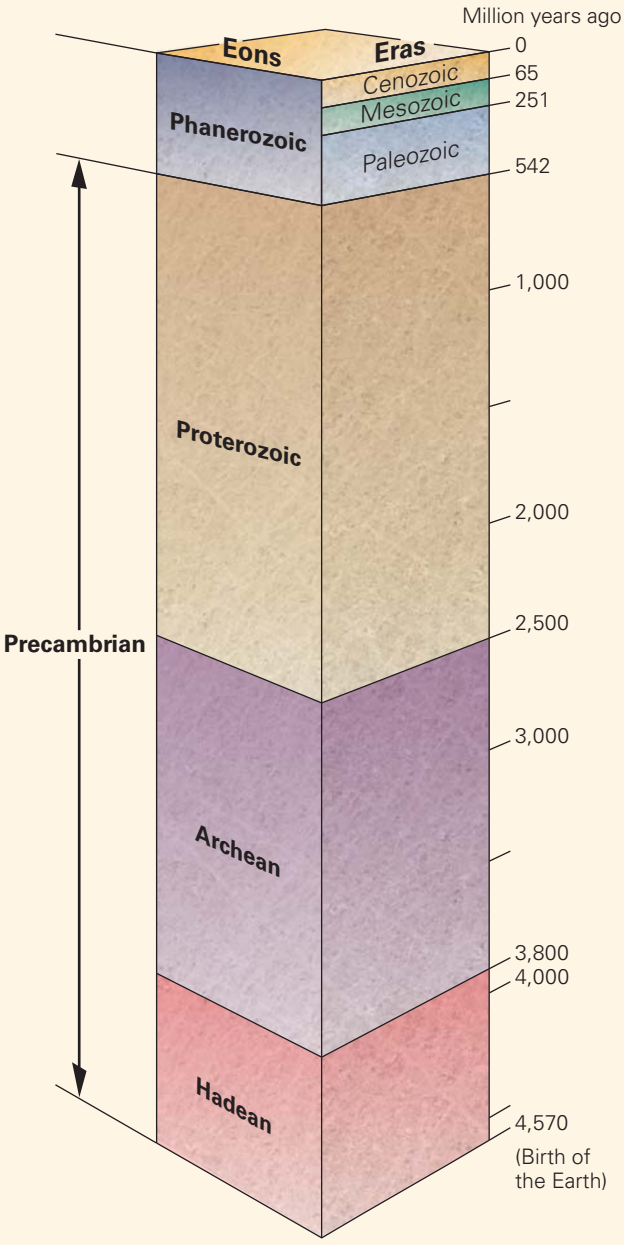
- Electromagnetic waves transport heat to a body as **radiation**. Radiation traveling from the Sun is responsible for heating the Earth's surface.
- If you stick the end of an iron bar in a fire, **conduction** takes place and heat moves up the bar. This happens because atoms in the bar at the hot end start to vibrate more energetically, and this motion incites atoms farther up the bar to start jiggling. Though heat flows along the bar, the atoms do not actually move from one locality to another.
- When you place a pot on a stove and heat it, water at the base of the pot gets hotter and expands, so its density decreases. The hot, less-dense water becomes buoyant relative to the colder, denser water, above it. In a gravitational field, buoyant material rises if the material above it is weak enough to flow out of the way. Since liquid water flows easily, the hot water can rise. When this happens, cold water sinks to take its place. The resulting circulation, during which flow of the material itself carries heat, is called **convection**, the path of flow defines **convective cells**.
- **Advection** happens when a hot fluid flows into cracks and pores within a solid, and heats up the solid. The hottness of a metal water pipe's surface, for example, comes from the hot water through the pipe. In the Earth, advection occurs where molten rock rises into the crust.

FIGURE P.4 A simplified map of the Earth's plates. The arrows indicate the direction each plate is moving, and the length of the arrow indicates plate velocity (the longer the arrow, the faster the motion). We discuss the types of plate boundaries in Chapter 2.



- *Geology helps you understand physical science.* Geology incorporates many of the basic concepts of physics and chemistry because Earth materials are a form of matter, and energy drives geologic processes (**Box P.1**). Thus, studying geology can help you develop a better grasp of key ideas in physical science.
- *Plate tectonics explains many Earth processes.* Earth is not a homogeneous ball, but rather consists of concentric layers—from center to surface, Earth has a core, mantle, and crust. We live on the surface of the crust, where it meets the atmosphere and the oceans. In the 1960s, geologists recognized that the crust, together with the uppermost part of the underlying mantle, forms a 100- to 150-km-thick semi-rigid shell. Large cracks separate this shell into discrete pieces, called **plates**, which move very slowly relative to one another (**Fig. P.4**). The model that describes this movement and its consequences is called the **theory of plate tectonics**, and it is the foundation for understanding most geologic phenomena. Although plates move very slowly—generally less than 10 cm a year—their movements yield earthquakes, volcanoes, and mountain ranges, and cause the map of Earth's surface to change over time.
- *The Earth is a planet.* Despite its uniqueness, the Earth can be viewed as a planet, formed like the other planets of the Solar System from dust and gas that encircled the newborn Sun.
- *The Earth is very old.* Geologic data indicate that the Earth formed 4.57 billion years ago—plenty of time for life to evolve, and for the map of the planet to change. Plate-movement rates of only a few centimeters per year can move a continent thousands of kilometers. There is time enough to build mountains and time enough to grind them down, many times over. To define intervals of this time, geologists developed the **geologic time scale**. **Figure P.5** depicts major subdivisions of the geologic time scale. Chapter 10 discusses these in greater detail.
- *Internal and external processes drive geologic phenomena.* Internal processes are those phenomena driven by heat from inside the Earth. Plate movement is an example. Because plate movements cause mountain building, earthquakes, and volcanoes, we call all of these phenomena internal processes as well. External processes are those phenomena driven by heat supplied by radiation that comes to the Earth from the Sun. This heat drives the movement of air and of water, which grinds and sculpts the Earth's surface and transports the debris to new locations, where it accumulates. The interaction between internal and external processes forms the landscapes of our planet. As we'll see, gravity—the pull that one mass exerts on another—plays an important role in both internal and external processes.
- *Geologic phenomena affect our environment.* Volcanoes, earthquakes, landslides, floods, groundwater, energy sources, and mineral reserves are of vital interest to every inhabitant of this planet. Therefore, throughout this book we emphasize the linkages between geology, the environment, and society.
- *Physical aspects of the Earth System are linked to life processes.* All life on this planet depends on such physical features as the minerals in soil; the temperature, humidity, and composition of the atmosphere; and the flow of surface and subsurface water. And life in turn affects and alters physical features. For example, the oxygen in Earth's atmosphere comes primarily from plant photosynthesis, a life activity.

FIGURE P.5 The geologic time scale.



(a) The scale has been divided into eons and eras.

One thousand years ago = 1 **Ka**
(Ka stands for kilo-annum)

One million years ago = 1 **Ma**
(Ma stands for mega-annum)

One billion years ago = 1 **Ga**
(Ga stands for giga-annum)

(b) Abbreviations for time units.

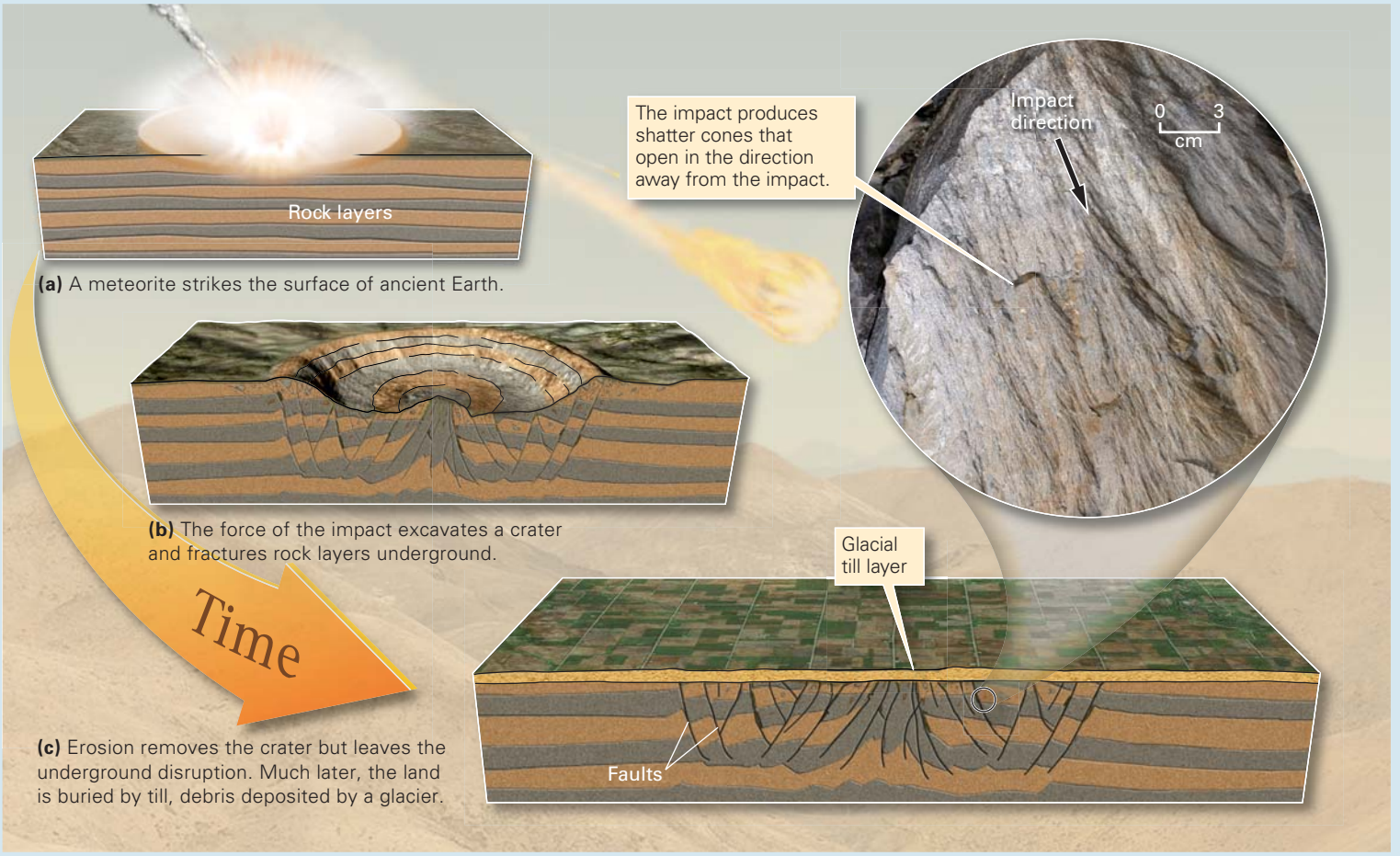
The Scientific Method

Sometime during the past 200 million years, a large block of rock or metal, which had been orbiting the Sun, slammed into our planet. It made contact at a site in what is now the central United States, a landscape of flat cornfields. The impact of this block, a meteorite, released more energy than a nuclear bomb—a cloud of shattered rock and dust blasted skyward, and once-horizontal layers of rock from deep below the ground sprang upward and tilted steeply beneath the gaping hole left by the impact. When the dust had settled, a huge crater surrounded by debris marked the surface of the Earth at the impact site. Later in Earth history, running water and blowing wind wore down this jagged scar. Some 15,000 years ago, sand, gravel, and mud carried by a vast glacier buried what remained, hiding it entirely from view (**Fig. BxP.1a–c**). Wow! So much history beneath a cornfield. How do we know this? It takes scientific investigation.

The movies often portray science as a dangerous tool, capable of creating Frankenstein's monster, and scientists as warped or nerdy characters with thick glasses and poor taste in clothes. In reality, science is simply the use of observation, experiment, and calculation to explain how nature operates, and scientists are people who study and try to understand natural phenomena. Scientists carry out their work in the context of the **scientific method**, a sequence of steps for systematically analyzing scientific problems in a way that leads to verifiable results. Let's see how geologists employed the steps of the scientific method to come up with the meteorite-impact story.

1. *Recognizing the problem.* Any scientific project, like any detective story, begins by identifying a mystery. The cornfield mystery came to light when water drillers discovered limestone, a rock typically made of shell fragments, just below the 15,000-year-old glacial sediment. In surrounding regions, the rock beneath the glacial sediment consists of sandstone, a rock made of cemented-together sand grains. Since limestone can be used to build roads, make cement, and produce the agricultural lime used in treating soil, workers stripped off the glacial sediment and dug a quarry to excavate the limestone. They were amazed to find that rock layers exposed in the quarry were tilted steeply and had

FIGURE BxP.1 An ancient meteorite impact excavates a crater and permanently changes rock beneath the surface.



been shattered by large cracks. In the surrounding regions, all rock layers are horizontal like the layers in a birthday cake, and the rocks contain relatively few cracks. Curious geologists came to investigate and soon realized that the geologic features of the land just beneath the cornfield presented a problem to be explained: What phenomena had brought limestone up close to the Earth's surface, had tilted the layering in the rocks, and had shattered the rocks?

2. *Collecting data*. The scientific method proceeds with the collection of observations or clues that point to an answer. Geologists studied the quarry and determined the age of its rocks, measured the orientation of the rock layers, and documented (made a written or photographic record of) the fractures that broke up the rocks.
3. *Proposing hypotheses*. A scientific **hypothesis** is merely a possible explanation, involving only natural processes, that can explain a set of observations. Scientists propose hypotheses during or after their initial data collection. In this example, the geologists working in the quarry came up with two alternative hypotheses. First, the features in this region could result from a volcanic explosion; and second, they could result from a meteorite impact.
4. *Testing hypotheses*. Since a hypothesis is no more than an idea that can be either right or wrong, scientists must put hypotheses through a series of tests to see if they work. The geologists at the quarry compared their field observations with published observations made at other sites of volcanic explosions and meteorite impacts, and they studied the results of experiments designed to simulate such events. If the geologic features visible in the quarry were the result of volcanism, the quarry should contain rocks formed by solidification of molten rock erupted by a volcano. But no such rocks were found. If, however, the features were the result of an impact, the rocks should contain **shatter cones**, small, cone-shaped cracks (see Fig. Bx P.1c). Shatter cones can be overlooked, so the geologists returned to the quarry specifically to search for them, and found them in abundance. The impact hypothesis passed the test!

Theories are scientific ideas supported by abundant evidence; they have passed many tests and have failed none. Scientists are much more confident in the correctness of a theory than of a hypothesis. Continued study in the quarry eventually yielded so much evidence for impact that the impact hypothesis came to be viewed as a theory. Scientists continue to test theories over a long time. Successful theories withstand these tests and are supported by so many observations that they become part of a discipline's foundation. However, some theories may be disproven and replaced by better ones.

In a few cases, scientists have been able to devise concise statements that completely describe a specific relationship or phenomenon. Such statements are called **scientific laws**. Note that the *law* of gravity does not explain why gravity exists, but the *theory* of evolution does provide an explanation of why evolution occurs.

- *Science comes from observation, and people make scientific discoveries*. Science does not consist of subjective guesses or arbitrary dogmas, but rather of a consistent set of objective statements resulting from the application of the **scientific method** (**Box P.2**). Every scientific idea must be tested thoroughly, and should be used only when supported by documented observations. Further, scientific ideas do not appear out of nowhere, but are the result of human efforts. Wherever possible, this book shows where geologic ideas came from, and tries to answer the question, "How do we know that?"

As you read this book, please keep these themes in mind. Don't view geology as a list of words to memorize, but rather as an interconnected set of concepts to digest. Most of all, enjoy yourself as you learn about what may be the most fascinating planet in the Universe. To help illustrate the geology of our amazing world, we have created "See for Yourself" features. Using *Google Earth*™, you'll be able to find examples of localities that illustrate geologic features and phenomena.

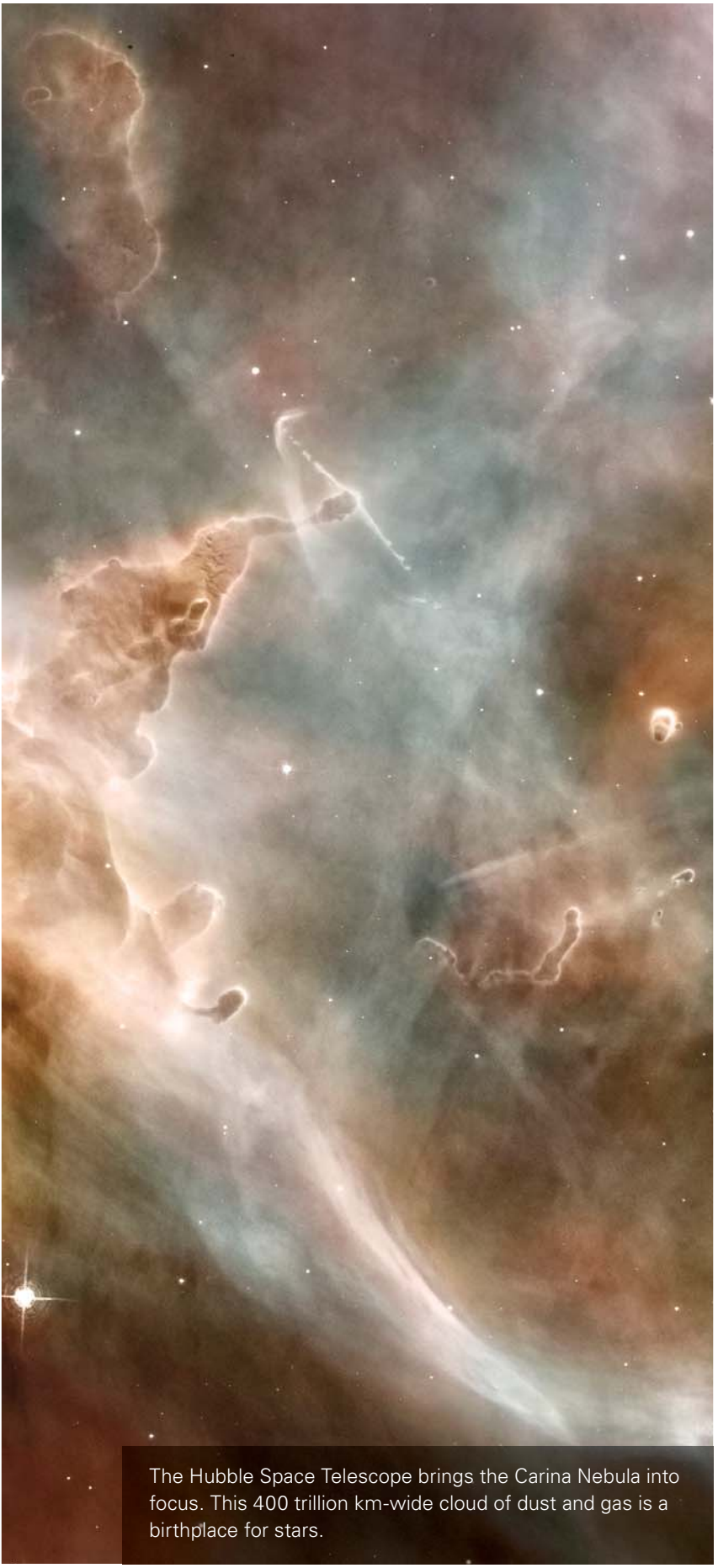
Key Terms

advection (p. 4)
conduction (p. 4)
convection (p. 4)
convection cells (p. 4)
Earth System (p. 3)
geologic time scale (p. 5)
geologist (p. 2)
geology (p. 2)
heat (p. 4)
hypothesis (p. 7)
plate (p. 5)
radiation (p. 4)
scientific laws (p. 7)
scientific method (p. 6)
shatter cones (p. 7)
temperature (p. 4)
theory (p. 7)
theory of plate tectonics (p. 5)
thermal energy (p. 4)



CHAPTER 1

The Earth in Context



The Hubble Space Telescope brings the Carina Nebula into focus. This 400 trillion km-wide cloud of dust and gas is a birthplace for stars.

Chapter Objectives

By the end of this chapter you should know . . .

- modern concepts concerning the basic architecture of our Universe and its components.
- the character of our own Solar System.
- scientific explanations for the formation of the Universe and the Earth.
- the overall character of the Earth's magnetic field, atmosphere, and surface.
- the variety and composition of materials that make up our planet.
- the nature of Earth's internal layering.

This truth within thy mind rehearse,
That in a boundless Universe
Is boundless better, boundless worse.

—Alfred, Lord Tennyson (British poet, 1809–1892)

1.1 Introduction

Sometime in the distant past, humans developed the capacity for complex, conscious thought. This amazing ability, which distinguishes our species from all others, brought with it the gift of curiosity, an innate desire to understand and explain the workings of ourselves and of all that surrounds us—our Universe. Astronomers define the **Universe** as all of space and all the matter and energy within it. Questions that we ask about the Universe differ little from questions a child asks of a playmate: Where do you come from? How old are you? Such musings first spawned legends in which heroes, gods, and goddesses used supernatural powers to mold the planets and sculpt the landscape. Eventually, researchers began to apply scientific principles to **cosmology**, the study of the overall structure and history of the Universe.

In this chapter, we begin with a brief introduction to the principles of scientific cosmology—we characterize the basic architecture of the Universe, introduce the Big Bang theory for the formation of the Universe, and discuss scientific ideas concerning the birth of the Earth. Then we outline the basic characteristics of our home planet by building an image of its surroundings, surface, and interior. Our high-speed tour of the Earth provides a reference frame for the remainder of this book.

1.2 An Image of Our Universe

What Is the Structure of the Universe?

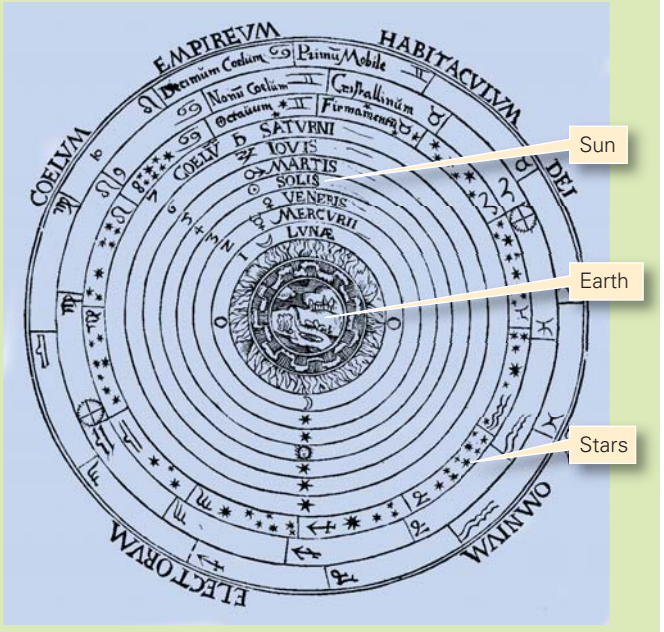
Think about the mysterious spectacle of a clear night sky. What objects are up there? How big are they? How far away are they? How do they move? How are they arranged? In addressing such questions, ancient philosophers first distinguished between stars (points of light whose locations relative to each other are fixed) and planets (tiny spots of light that move relative to the backdrop of stars). Over the centuries, two schools of thought developed concerning how to explain the configuration of stars and planets, and their relationships to the Earth, Sun, and Moon. The first school advocated a **geocentric model** (Fig. 1.1a), in which the Earth sat without moving at the center of the Universe, while the Moon and the planets whirled around it within a revolving globe of stars. The second school advocated a **heliocentric model** (Fig. 1.1b), in which the Sun lay at the center of the Universe, with the Earth and other planets orbiting around it.

The geocentric image eventually gained the most followers, due to the influence of an Egyptian mathematician, Ptolemy (100–170 C.E.), for he developed equations that appeared to predict the wanderings of the planets in the context of the geocentric model. During the Middle Ages (ca. 476–1400 C.E.), church leaders in Europe adopted Ptolemy's geocentric model as dogma, because it justified the comforting thought that humanity's home occupies the most important place in the Universe. Anyone who disagreed with this view risked charges of heresy.

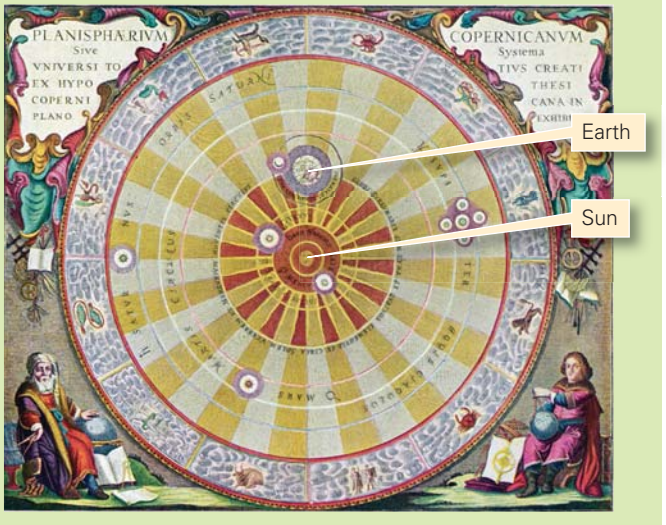
Then came the Renaissance. In 15th-century Europe, bold thinkers spawned a new age of exploration and scientific discovery. Thanks to the efforts of Nicolaus Copernicus (1473–1543) and Galileo Galilei (1564–1642), people gradually came to realize that the Earth and planets did indeed orbit the Sun and could not be at the center of the Universe. And when Isaac Newton (1643–1727) explained **gravity**, the attractive force that one object exerts on another, it finally became possible to understand why these objects follow the orbits that they do.

In the centuries following Newton, scientists gradually adopted modern terminology for discussing the Universe. In this language, the Universe contains two related entities: matter and energy. *Matter* is the substance of the Universe—it takes up space and you can feel it. We refer to the amount of matter in an object as its *mass*, so an object with greater mass contains more matter. *Density* refers to the amount of mass occupying a given volume of space. The mass of an object determines its *weight*, the force that acts on an object due to gravity. An object always has the same mass, but its weight varies depending on where it is. For example, on the Moon, you weigh much less than on the Earth. The matter in the Universe does not sit still. Components vibrate and spin, they move from one place to another, they pull on or push against each other, and they break apart or combine. In a general sense, we consider such changes to be kinds of "work." Physicists refer

FIGURE 1.1 Contrasting views of the Universe, as drawn by artists hundreds of years ago.

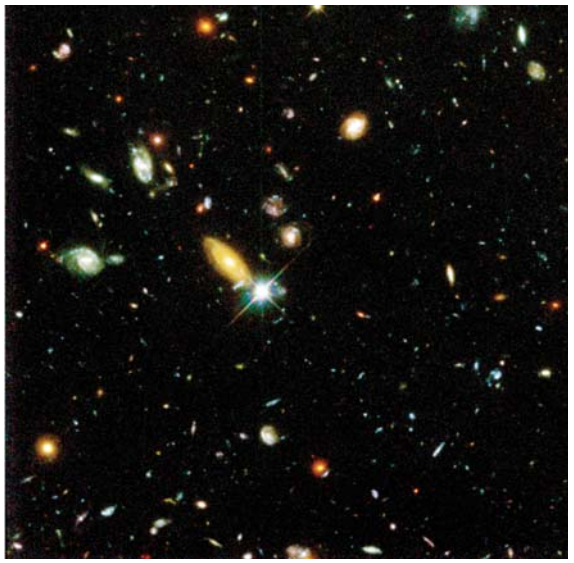


(a) The *geocentric* image of the Universe shows the Earth at the center, surrounded by air, fire, and the other planets, all contained within the globe of the stars.



(b) The *heliocentric* image of the Universe shows the Sun at the center, as envisioned by Copernicus.

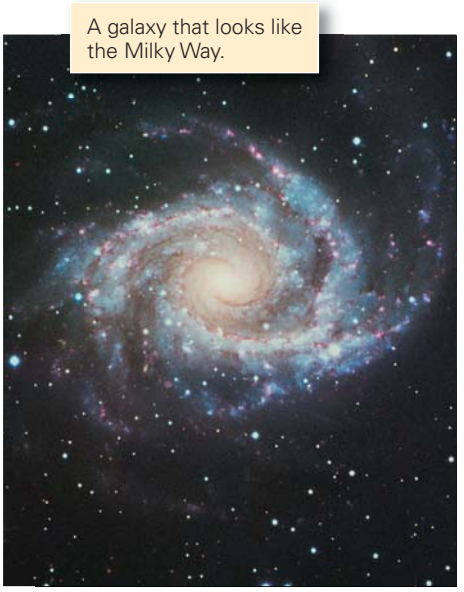
FIGURE 1.2 A galaxy may contain about 300 billion stars.



(a) A Hubble image reveals many galaxies in what looks like empty space to our naked eyes.



(b) As seen from the Earth, the Milky Way looks like a hazy cloud.



(c) From space, it would look like a giant spiral.

to the ability to do work as **energy**. One piece of matter can do work directly on another by striking it. Heat, light, magnetism, and gravity all provide energy that can cause change at a distance.

As the understanding of matter and energy improved, and telescopes became refined so that astronomers could see and measure features progressively farther into space, the interpretation of stars evolved. Though it looks like a point of light, a **star** is actually an immense ball of incandescent gas that emits intense heat and light. Stars are not randomly scattered through the Universe; gravity holds them together in immense groups called **galaxies**. The Sun and over 300 billion stars together form the Milky Way galaxy. More than 100 billion galaxies constitute the visible Universe (**Fig. 1.2a**).

From our vantage point on Earth, the Milky Way looks like a hazy band (**Fig. 1.2b**), but if we could view the Milky Way from a great distance, it would look like a flattened spiral with great curving arms slowly swirling around a glowing, disk-like center (**Fig. 1.2c**). Presently, our Sun lies near the outer edge of one of these arms and rotates around the center of the galaxy about once every 250 million years. So, we hurtle through space, relative to an observer standing outside the galaxy, at about 200 km per second.

Did you ever wonder . . .
how fast you are traveling through space?

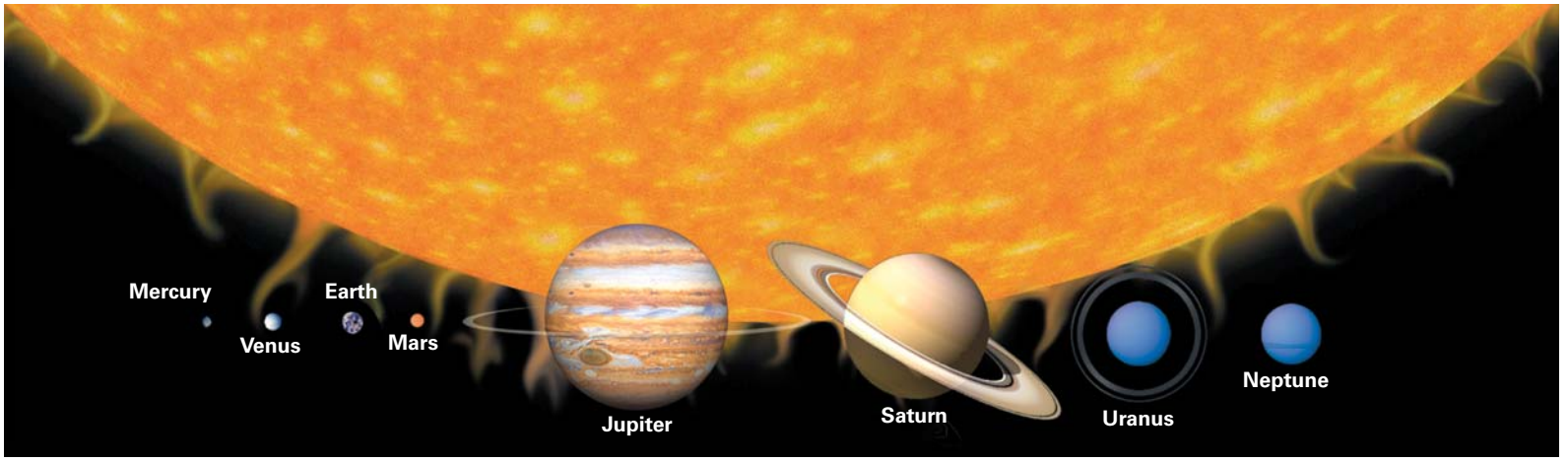
Clearly, human understanding of Earth's place in the Universe has evolved radically over the past few centuries. Neither the Earth, nor the Sun, nor even the Milky Way occupy the center of the Universe—and everything is in motion.

The Nature of Our Solar System

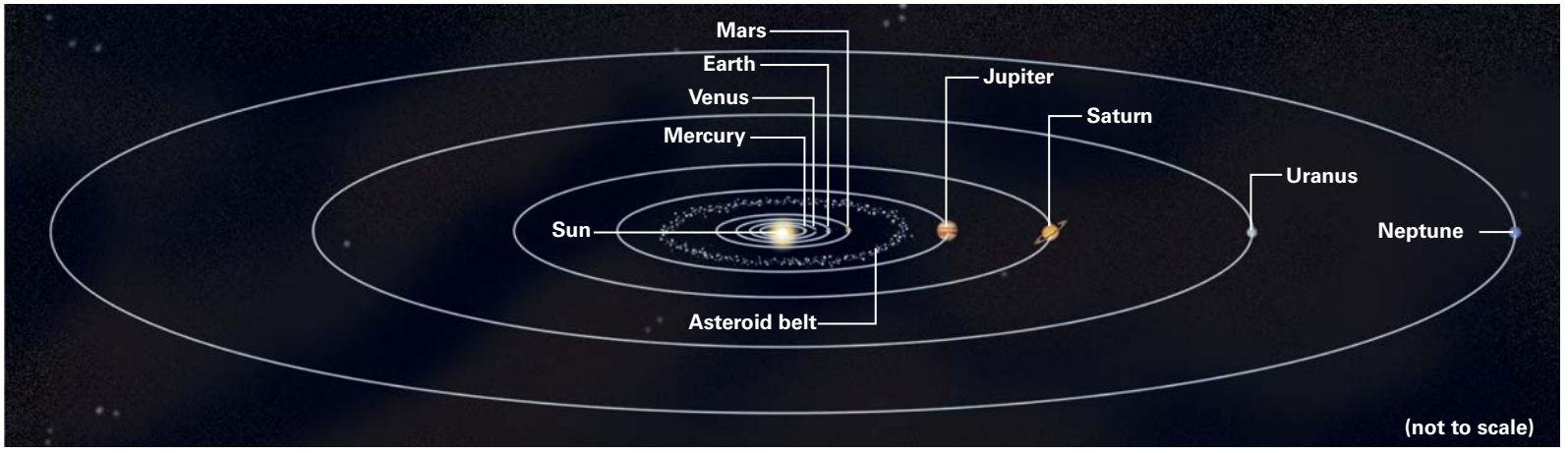
Eventually, astronomical study demonstrated that our Sun is a rather ordinary, medium-sized star. It looks like a sphere, instead of a point of light, because it is much closer to the Earth than are the stars. The Sun is "only" 150 million km (93 million miles) from the Earth. Stars are so far away that we measure their distance in light years, where 1 light year is the distance traveled by light in one year, about 10 trillion km, or 6 trillion miles—the nearest star beyond the Sun is over 4 light years away. How can we picture distances? If we imagined that the Sun were the size of a golf ball (about 4.3 cm), then the Earth would be a grain of sand about one meter away, and the nearest star would be 270 km (168 miles) away. (Note that the distance between stars is tiny by galactic standards—the Milky Way galaxy is 120,000 light years across!)

Our Sun is not alone as it journeys through the heavens. Its gravitational pull holds on to many other objects which, together with the Sun, comprise the **Solar System** (**Fig. 1.3a, b**). The Sun accounts for 99.8% of the mass in the Solar System. The remaining 0.2% includes a great variety of objects, the largest of which are planets. Astronomers define a **planet** as an object that orbits a star, is roughly spherical, and has "cleared its neighborhood of other objects." The last phrase in this definition sounds a bit strange at first, but merely implies that a planet's gravity has pulled in all particles of matter in its orbit.

FIGURE 1.3 The relative sizes and positions of planets in the Solar System.



(a) Relative sizes of the planets. All are much smaller than the Sun, but the gas-giant planets are much larger than the terrestrial planets. Jupiter's diameter is about 11.2 times greater than that of Earth.



(b) Relative positions of the planets. This figure is not to scale. If the Sun in this figure was the size of a large orange, the Earth would be the size of a sesame seed 15 meters (49 feet) away. Note that all planetary orbits lie roughly in the same plane.

According to this definition, which was formalized in 2005, our Solar System includes eight planets—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. In 1930, astronomers discovered Pluto, a 2,390-km-diameter sphere of ice, whose orbit generally lies outside that of Neptune's. Until 2005, astronomers considered Pluto to be a planet. But since it does not fit the modern definition, it has been dropped from the roster. Our Solar System is not alone in hosting planets; in recent years, astronomers have found planets orbiting stars in many other systems. As of 2012, over 760 of these "exoplanets" have been found.

Planets in our Solar System differ radically from one another both in size and composition. The inner planets (Mercury, Venus, Earth, and Mars), the ones closer to the Sun, are relatively small. Astronomers commonly refer to these as **terrestrial planets** because, like Earth, they consist of a shell of rock surrounding a ball of metallic iron alloy. The outer planets (Jupiter, Saturn, Uranus, and Neptune) are known as the **giant planets**, or Jovian planets. The adjective *giant* certainly seems appropriate, for these planets are huge—Jupiter, for example, has a mass 318 times larger than that of Earth and accounts for about 71% of the non-solar mass in the Solar System. The overall composition of the giant planets is very different from that of the terrestrial planets. Specifically, most of the mass of Neptune and Uranus contain solid forms of water, ammonia, and methane, so these planets are known as the *ice giants*. Most of the mass of Jupiter and Saturn consists of hydrogen and helium gas or liquefied gas, so these planets are known as the *gas giants*.

In addition to the planets, the Solar System contains a great many smaller objects. Of these, the largest are moons. A **moon** is a sizable body locked in orbit around a planet. All but two planets (Mercury and Venus) have moons in varying numbers—Earth has one, Mars has two, and Jupiter has at least 63. Some moons, such as Earth's Moon, are large and spherical, but most are small and have irregular shapes. In addition to moons, millions of asteroids (chunks of rock and/or metal) comprise a belt between the orbits of Mars and Jupiter. Asteroids range in size from less than a centimeter to about 930 km in diameter. And about a trillion bodies of ice lie in belts or clouds beyond the orbit of Neptune. Most of these icy objects are tiny, but a few (including Pluto) have diameters of over 2,000 km and may be thought of as "dwarf planets." The gravitational pull of the main planets has sent some of the icy objects on paths that take them into the inner part of the Solar System, where they begin to evaporate and form long tails of gas—we call such objects comets.

Take-Home Message

The Earth is one of eight planets (four terrestrial and four gas or ice giants) orbiting our Sun, which is one of 300 billion stars of the revolving, spiral-shaped Milky Way galaxy. Hundreds of billions of galaxies speckle the visible Universe.

1.3 Forming the Universe

We stand on a planet, in orbit around a star, speeding through space on the arm of a galaxy. Beyond our galaxy lie hundreds of billions of other galaxies. Where did all this "stuff"—the matter of the Universe—come from, and when did it first form? For most of human history, a scientific solution to these questions seemed intractable. But in the 1920s, unexpected observations about the nature of light from distant galaxies set astronomers on a path of discovery that ultimately led to a model of Universe formation known as the Big Bang theory. To explain these observations, we must first introduce an important phenomenon called the Doppler effect. We then show how this understanding leads to the recognition that the Universe is expanding, and finally, to the conclusion that this expansion began during the Big Bang, 13.7 billion years ago.

Waves and the Doppler Effect

When a train whistle screams, the sound you hear moved through the air from the whistle to your ear in the form of sound waves. **Waves** are disturbances that transmit energy from one point to another in the form of periodic motions. As each sound wave passes, air alternately compresses, then expands. We refer to the distance between successive waves as the **wavelength**, and the number of waves that pass a point in a given time interval as the **frequency**. If the wavelength decreases, more waves pass a point in a given time interval, so the frequency increases. The pitch of a sound, meaning its note on the musical scale, depends on the frequency of the sound waves.

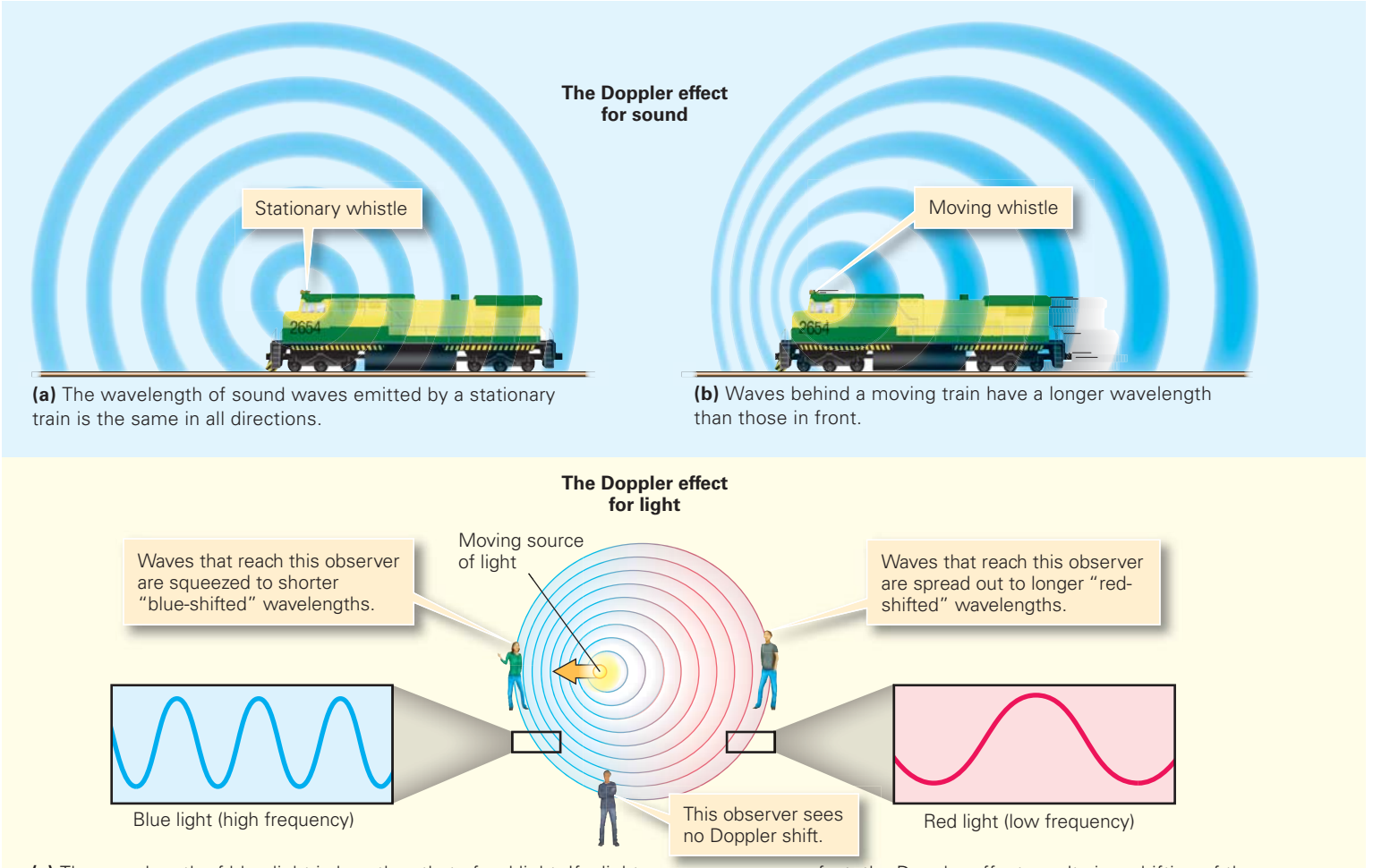
Imagine that you are standing on a station platform while a train moves toward you. The train whistle's sound gets louder as the train approaches, but its pitch remains the same. The instant the train passes, the pitch abruptly changes—it sounds like a lower note in the musical scale. Why? When the train moves toward you, the sound has a higher frequency (the waves are closer together so the wavelength is smaller) because the sound source, the whistle, has moved slightly closer to you between the instant that it emits one wave and the instant that it emits the next (**Fig. 1.4a, b**). When the train moves away from you, the sound has a lower frequency (the waves are farther apart), because the whistle has moved slightly farther from you between the instant it emits one wave and the instant it emits the next. An Austrian physicist, C. J. Doppler (1803–1853), first interpreted this phenomenon, and thus the change in frequency that happens when a wave source moves is now known as the **Doppler effect**.

Light energy also moves in the form of waves. We can represent light waves symbolically by a periodic succession of crests and troughs (**Fig. 1.4c**). Visible light comes in many colors—the colors of the rainbow. The color you see depends on the frequency of the light waves, just as the pitch of a sound you hear depends on the frequency of sound waves. Red light has a longer wavelength (lower frequency) than does blue light. The Doppler effect also applies to light but can be noticed only if the light source moves very fast, at least a few percent of the speed of light. If a light source moves away from you, the light you see becomes redder, as the light shifts to longer wavelength or lower frequency. If the source moves toward you, the light you see becomes bluer, as the light shifts to higher frequency. We call these changes the **red shift** and the blue shift, respectively.

Does the Size of the Universe Change?

In the 1920s, astronomers such as Edwin Hubble, after whom the Hubble Space Telescope was named, braved many a frosty night beneath the open dome of a mountaintop observatory in order to aim telescopes into deep space. These researchers were searching for distant galaxies. At first, they documented

FIGURE 1.4 Manifestations of the Doppler effect for sound and for light.



(a) The wavelength of sound waves emitted by a stationary train is the same in all directions.

(b) Waves behind a moving train have a longer wavelength than those in front.

(c) The wavelength of blue light is less than that of red light. If a light source moves very fast, the Doppler effect results in a shifting of the wavelengths. The observed shift depends on the position of the observer.

(d) The atoms in a star absorb certain specific wavelengths of light. We see these wavelengths as dark lines on a light spectrum. Note that the lines from a galaxy a billion light years away are shifted toward the red end of the spectrum (i.e., to the right), in comparison to the lines from our own Sun.

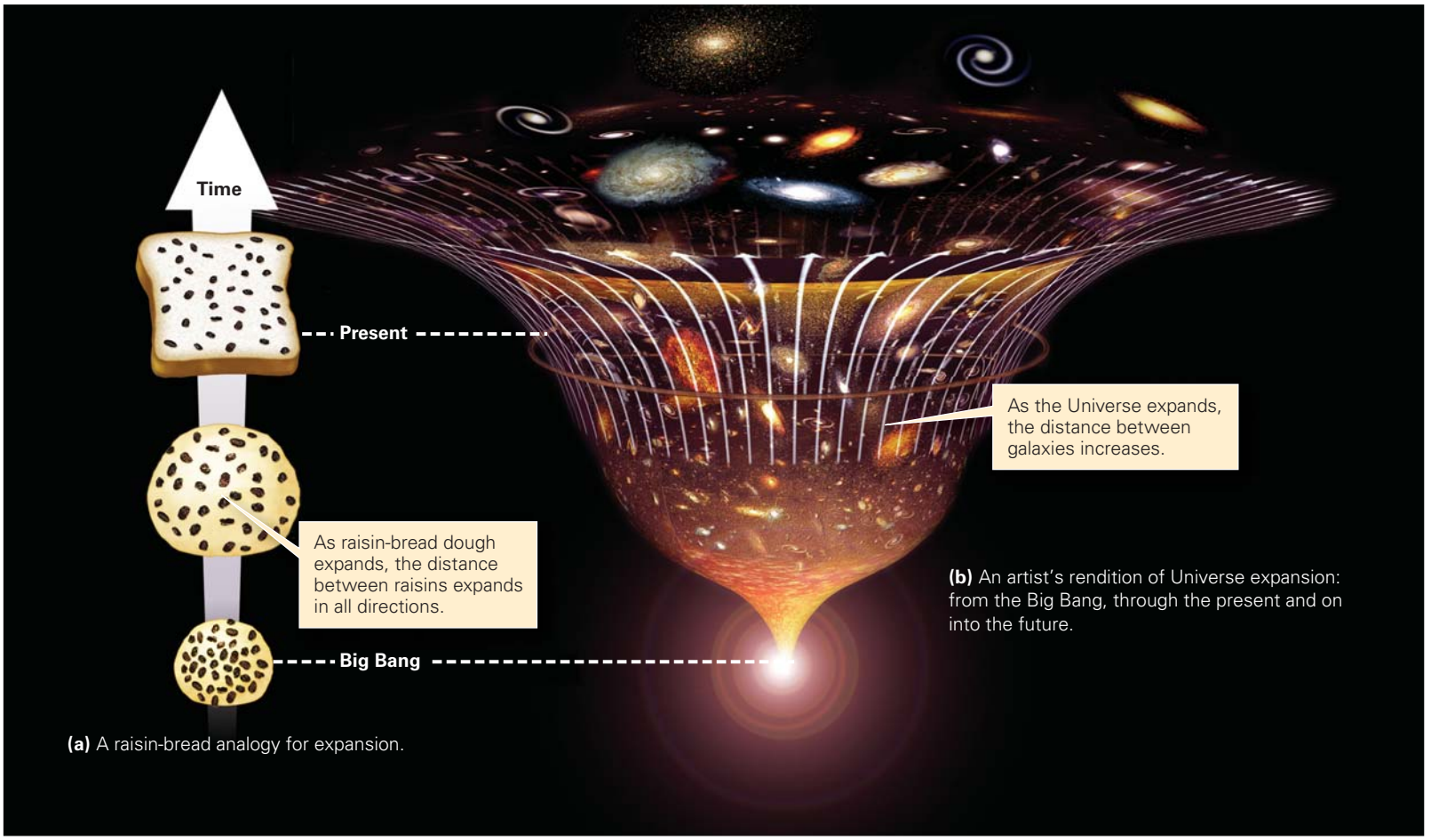
only the location and shape of newly discovered galaxies, but eventually they also began to study the wavelength of light produced by the distant galaxies. The results yielded a surprise that would forever change humanity's perception of the Universe. To their amazement, the astronomers found that the light of distant galaxies *display a red shift* relative to the light of a nearby star (Fig. 1.4d).

Hubble pondered this mystery and, around 1929, attributed the red shift to the Doppler effect, and concluded that the distant galaxies must be moving away from Earth at an immense velocity. At the time, astronomers thought the Universe had a fixed size, so Hubble initially assumed that if some galaxies were moving away from Earth, others must be moving toward Earth. But this was not the case. On further examination, Hubble concluded that the light from all distant galaxies, regardless of their direction from Earth, exhibits a red shift. In other words, *all* distant galaxies are moving rapidly away from us.

Did you ever wonder . . .
do galaxies move?

How can all galaxies be moving away from us, regardless of which direction we look? Hubble puzzled over this question and finally recognized the solution: the whole Universe must be expanding! To picture the expanding Universe, imagine a ball of bread dough with raisins scattered throughout. As the

FIGURE 1.5 The concept of the expanding Universe and the Big Bang.



(a) A raisin-bread analogy for expansion.

(b) An artist's rendition of Universe expansion: from the Big Bang, through the present and on into the future.

dough bakes and expands into a loaf, each raisin moves away from its neighbors, in every direction; **Fig. 1.5a**. This idea came to be known as the **expanding Universe theory**.

The Big Bang

Hubble's ideas marked a revolution in cosmological thinking. Now we picture the Universe as an expanding bubble, in which galaxies race away from each other at incredible speeds. This image immediately triggers the key question of cosmology: did the expansion begin at some specific time in the past? If it did, then that instant would mark the physical beginning of the Universe.

Most astronomers have concluded that expansion did indeed begin at a specific time, with a cataclysmic explosion called the Big Bang. According to the **Big Bang theory**, all matter and energy—everything that now constitutes the Universe—was initially packed into an infinitesimally small point. The point "exploded" and the Universe began, according to current estimates, 13.7 (±1%) billion years ago.

Of course, no one was present at the instant of the Big Bang, so no one actually saw it happen. But by combining clever calculations with careful observations, researchers have developed a consistent model of how the Universe evolved, beginning an instant after the explosion (**Fig. 1.5b**). According to this model of the Big Bang, profound change happened at a fast and furious rate at the outset. During the first instant of existence, the Universe was so small, so dense, and so hot that it consisted entirely of energy—atoms, or even the smallest subatomic particles that make up atoms, could not even exist. (See **Box 1.1** for a review of atomic structure.) Within a few seconds, however, hydrogen atoms could begin to form. And by the time the Universe reached an age of 3 minutes, when its temperature had fallen below 1 billion degrees, and its diameter had grown to about 53 million km (35 million miles), hydrogen atoms could fuse together to form helium atoms. Formation of new nuclei in the first few minutes of time is called *Big Bang nucleosynthesis* because it happened *before* any stars existed. This process could produce only light atoms, meaning ones containing a small number of protons (an atomic number less than 5), and

The Nature of Matter

What does matter consist of? A Greek philosopher named Democritus (ca. 460–370 B.C.E.) argued that if you kept dividing matter into progressively smaller pieces, you would eventually end up with nothing; but since it's not possible to make something out of nothing, there must be a smallest piece of matter that can't be subdivided further. He proposed the name "atom" for these smallest pieces, based on the Greek word *atomos*, which means indivisible.

Our modern understanding of matter developed in the 17th century, when chemists recognized that certain substances (such as hydrogen and oxygen) *cannot* break down into other substances, whereas others (such as water and salt) *can* break down. The former came to be known as *elements*, and the latter came to be known as *compounds*. John Dalton (1766–1844) adopted the word *atom* for the smallest piece of an element that has the property of the element; the smallest piece of a compound that has the properties of the compound is a *molecule*. Separate atoms are held together to form molecules by *chemical bonds*, which we discuss more fully later in the book. As an example, chemical bonds hold two hydrogen atoms to form an H_2 molecule.

Chemists in the 17th and 18th centuries identified 92 naturally occurring elements on Earth; modern physicists have created more than a dozen new ones. Each element has a name and a symbol (e.g., N = nitrogen; H = hydrogen; Fe = iron; Ag = silver).

Atoms are so small that over five trillion (5,000,000,000,000) can fit on the head of a pin. Nevertheless, in 1910, Ernest Rutherford, a British physicist, proved that, contrary to the view of Democritus, atoms actually can be divided into smaller pieces. Most of the mass in an atom clusters in a dense ball, called the *nucleus*, at the atom's center. The nucleus contains two types of subatomic particles: *neutrons*, which have a neutral electrical charge, and *protons*, which have a positive charge. A cloud of electrons surrounds the nucleus (**Fig. Bx1.1a**); an *electron* has a negative charge and contains only 1/1,836 as much mass as a proton. ("Charge," simplistically, refers to the way in which a particle responds to a magnet or an electric current.) Roughly speaking, the diameter of an electron cloud is 10,000 times greater than that of the nucleus, yet the cloud contains only 0.05% of an atom's mass—thus, atoms are mostly empty space!

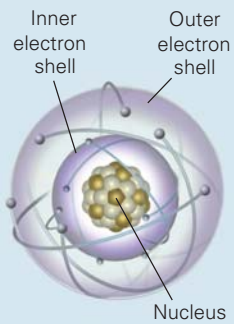
We distinguish atoms of different elements from one another by their *atomic number*, the number of protons in their nucleus. Smaller atoms have smaller atomic numbers, and larger ones have larger atomic numbers. The lightest atom, hydrogen, has an atomic number of 1, and the heaviest naturally occurring atom, uranium, has an atomic number of 92. Except for hydrogen nuclei, all nuclei also contain neutrons. In smaller atoms, the number of neutrons roughly equals the number of protons, but in larger atoms the number of neutrons exceeds the number of protons. The *atomic mass* of an atom is roughly the sum of the number of neutrons and the number of protons. For example, an oxygen nucleus contains 8 protons and 8 neutrons, and thus has an atomic mass of 16.

In 1869, a Russian chemist named Dmitri Mendelév (1834–1907) recognized that groups of elements share similar characteristics, and he organized the elements into a chart that we now call the periodic table of the elements. With modern understanding of the periodic table, it became clear that the ordering of the elements reflects their atomic number and the stream of the electron cloud.

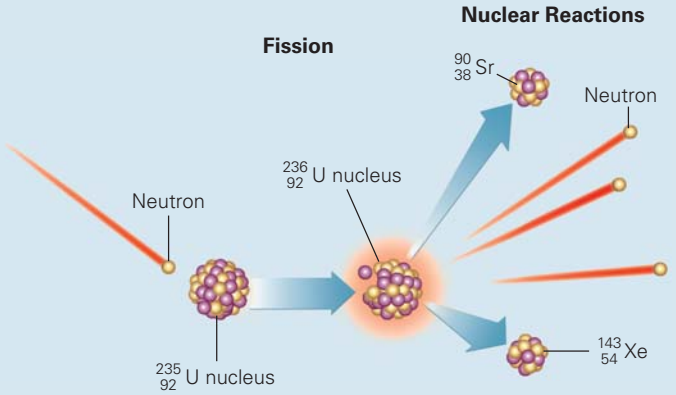
Nuclear bonds serve as the "glue" that holds together subatomic particles in a nucleus. Atoms can change only during nuclear reactions, when nuclear bonds break or form. Physicists recognize several types of nuclear reactions. For example, during "radioactive decay" reactions, a nucleus either emits a subatomic particle or undergoes fission. As a result of **fission**, a large nucleus breaks apart to form two smaller atoms (**Fig. Bx1.1b**). Radioactive decay transforms an atom of one element into an atom of another and produces energy. For example, fission reactions provide the energy of atomic bombs and nuclear power plants. Atoms that spontaneously undergo the process are known as **radioactive elements**.

During **fusion**, smaller atoms collide and stick together to form a larger atom. For example, successive fusion reactions produce a helium atom out of four hydrogen atoms. Fusion reactions power the Sun and occur during the explosion of a hydrogen bomb (**Fig. Bx1.1c**).

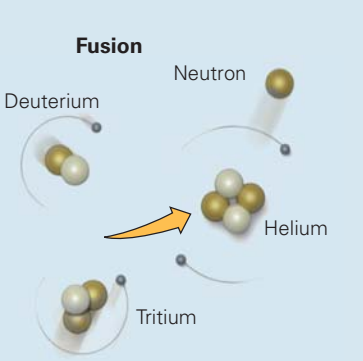
FIGURE Bx1.1 The nature of atoms and nuclear reactions.



(a) An image of an atom with a nucleus orbited by electrons.



(b) A uranium atom splits during nuclear fission.



(c) Two atoms (versions of hydrogen) stick together to form one atom of helium during nuclear fusion in a hydrogen bomb.

it happened very rapidly. In fact, virtually all of the new atomic nuclei that would form by Big Bang nucleosynthesis existed by the end of the first 5 minutes.

Eventually, the Universe became cool enough for chemical bonds to bind atoms of certain elements together in molecules. Most notably, two hydrogen atoms could join to form molecules of H_2. As the Universe continued to expand and cool further, atoms and molecules slowed down and accumulated into patchy clouds called **nebulae**. The earliest nebulae of the Universe consisted almost entirely of hydrogen (74%, by volume) and helium (24%) gas.

Birth of the First Stars

When the Universe reached its 200 millionth birthday, it contained immense, slowly swirling, dark nebulae separated by vast voids of empty space. The Universe could not remain this way forever, though, because of the invisible but persistent pull of gravity. Eventually, gravity began to remold the Universe pervasively and permanently.

All matter exerts gravitational pull—a type of force—on its surroundings, and as Isaac Newton first pointed out, the amount of pull depends on the amount of mass; the larger the mass, the greater its pull. Somewhere in the young Universe, the gravitational pull of an initially more massive region of a nebula began to suck in surrounding gas and, in a grand example of the rich getting richer, grew in mass and, therefore, density. As this denser region attracted progressively more gas, the gas compacted into a smaller region, and the initial swirling movement of gas transformed into a rotation around an axis. As gas continued to move inward, cramming into a progressively smaller volume, the rotation rate became faster and faster. (A similar phenomenon happens when a spinning ice skater pulls her arms inward.) Because of its increased rotation, the nebula evolved into a disk shape (see **Geology at a Glance**, pp. 22–23). As more and more matter rained down onto the disk, it continued to grow, until eventually, gravity collapsed the inner portion of the disk into a dense ball. As the gas squeezed into a smaller and smaller space, its temperature increased dramatically. Eventually, the central ball of the disk became hot enough to glow, and at this point it became a **protostar**. The remaining mass of the disk, as we will see, eventually clumped into smaller spheres, the planets.

A protostar continues to grow, by pulling in successively more mass, until its core becomes extremely dense and its temperature reaches about 10 million degrees. Under such conditions, hydrogen nuclei slam together so forcefully that they join or "fuse," in a series of steps, to form helium nuclei (see Box 1.1). Such fusion reactions produce huge amounts of energy, and the mass becomes a fearsome furnace. When the first nuclear fusion reactions began in the first protostar, the body "ignited" and the first true star formed. When this happened, perhaps 800 million years after the Big Bang, the first starlight pierced the newborn Universe. This process would soon happen again and again, and many first-generation stars came into existence (see Chapter 1 opener photo).

First-generation stars tended to be very massive, perhaps 100 times the mass of the Sun. Astronomers have shown that the larger the star, the hotter it burns and the faster it runs out of fuel and dies. A huge star may survive only a few million years to a few tens of millions of years before it becomes a **supernova**, a giant explosion that blasts much of the star's matter back into space. Thus, not long after the first generation of stars formed, the Universe began to be peppered with the first generation of supernovas.

Take-Home Message

According to the Big Bang theory, a cataclysmic explosion at 13.7 Ga formed the Universe, which has been expanding ever since. Atoms formed during the Big Bang collected into nebulae which, due to gravity, collapsed into dense balls, the first stars.

1.4 We Are All Made of Stardust

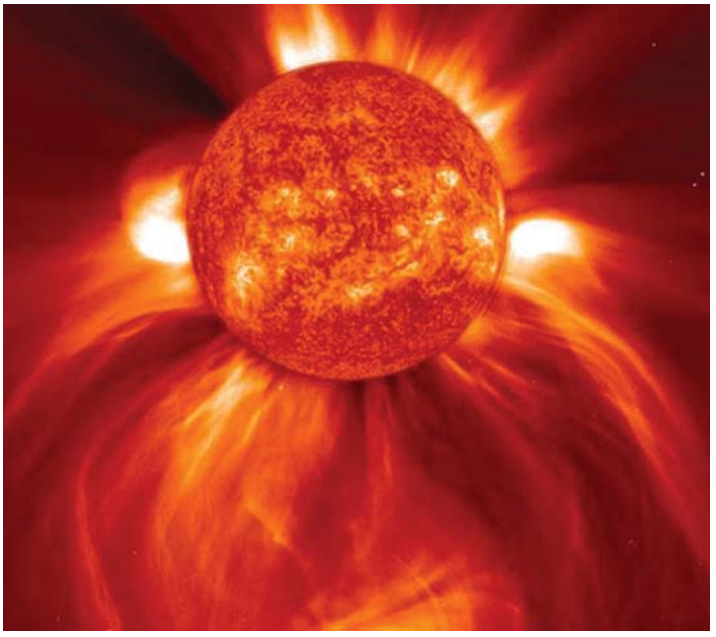
Where Do Elements Come From?

Nebulae from which the first-generation stars formed consisted entirely of the lightest atoms, because only these atoms were generated by Big Bang nucleosynthesis. In contrast, the Universe of today contains 92 naturally occurring elements. Where did the other 87 elements come from? In other words, how did elements with larger atomic numbers (such as carbon, sulfur, silicon, iron, gold, and uranium), which are common on Earth, form? Physicists have shown that these elements form during the life cycle of stars, by the process of **stellar nucleosynthesis**. Because of stellar nucleosynthesis, we can consider stars to be "element factories," constantly fashioning larger atoms out of smaller atoms.

Did you ever wonder . . .
where the atoms in your body first formed?

What happens to the atoms formed in stars? Some escape into space during the star's lifetime, simply by moving fast enough to overcome the star's gravitational pull. The stream of atoms emitted from a star during its lifetime is a **stellar wind** (**Fig. 1.6a**). Some escape only when a star dies. A small or medium star (like our Sun) releases a large shell of gas as it dies, ballooning into a "red giant" during the process, whereas a large star blasts matter into space during a supernova explosion (**Fig. 1.6b**). Most very heavy atoms (those with atomic

FIGURE 1.6 Element factories in space.



(a) The solar wind ejects matter from the Sun into space.



(b) This expanding cloud of gas, ejected into space from an explosion whose light reached the Earth in 1054 C.E., is called the Crab Nebula.

numbers greater than that of iron) require even more violent circumstances to form than generally occurs within a star. In fact, most very heavy atoms form *during* a supernova explosion. Once ejected into space, atoms from stars and supernova explosions form new nebulae or mix back into existing nebulae.

When the first generation of stars died, they left a legacy of new, heavier elements that mixed with residual gas from the Big Bang. A second generation of stars and associated planets formed out of these compositionally more diverse nebulae. Second-generation stars lived and died, and contributed heavier elements to third-generation stars. Succeeding generations contain a greater proportion of heavier elements. Because not all stars live for the same duration of time, at any given moment the Universe contains many different generations of stars. Our Sun may be a third-, fourth-, or fifth-generation star. Thus, the mix of elements we find on Earth includes relicts of primordial gas from the Big Bang as well as the disgorged guts of dead stars. Think of it—the elements that make up your body once resided inside a star!

The Nebular Theory for Forming the Solar System

Earlier in this chapter, we introduced scientific concepts of how stars form from nebulae. But we delayed our discussion of how the planets and other objects in our Solar System originated until we had discussed the production of heavier atoms such as carbon, silicon, iron, and uranium, because planets consist predominantly of these elements. Now that we've discussed stars as element factories, we return to the early history of the Solar System and introduce the **nebular theory**, an explanation for the origin of planets, moons, asteroids, and comets. According to the nebular theory, these objects formed from the material in the flattened outer part of the disk, the material that did not become part of the star. This outer part is called the **protoplanetary disk**.

What did the protoplanetary disk consist of? The disk from which our Solar System formed contained all 92 elements, some as isolated atoms, and some bonded to others in molecules. Geologists divide the material formed from these atoms and molecules into two classes. **Volatile** materials—such as hydrogen, helium, methane, ammonia, water, and carbon dioxide—are materials that can exist as gas at the Earth's surface. In the pressure and temperature conditions of space, all volatile materials remain in a gaseous state closer to the Sun. But beyond a distance called the "frost line," some volatiles condense into ice. (Note that we do not limit use of the word "ice" to water alone.) **Refractory** materials are those that melt only at high temperatures, and they condense to form solid soot-sized particles of "dust" in the coldness of space. As the proto-Sun began to form, the inner part of the disk became hotter, causing volatile elements to evaporate and drift to the outer portions of the disk. Thus, the inner part of the disk ended up consisting predominantly of refractory dust, whereas the outer portions accumulated large quantities of volatile materials and ice. As this was happening, the protoplanetary disk evolved into a series of concentric rings in response to gravity.

How did the dusty, icy, and gassy rings transform into planets? Even before the proto-Sun ignited, the material of the surrounding rings began to clump and bind together, due to gravity and electrical attraction. First, soot-sized particles merged to form sand- to marble-sized grains that resembled "dust bunnies." Then, these grains stuck together to form grainy basketball-sized blocks (**Fig. 1.7**), which in turn collided. If the collision was slow, blocks stuck together or simply bounced apart. If the collision was fast, one or both of the blocks shattered, producing smaller fragments that recombined later. Eventually, enough blocks coalesced to form **planetesimals**, bodies whose diameter exceeded about 1 km. Because of their mass, the planetesimals exerted enough gravity to attract and pull in other objects that were nearby (see Geology at a Glance, pp. 22–23). Figuratively, planetesimals acted like vacuum cleaners, sucking in small pieces of dust and ice as well as smaller planetesimals that lay in their orbit, and in the process they grew progressively larger. Eventually, victors in the competition to attract mass grew into **protoplanets**, bodies approaching the size of today's planets. Once a protoplanet succeeded in incorporating virtually all the debris within its orbit, it became a full-fledged planet.

Early stages in Earth's planet-forming process probably occurred very quickly—some computer models suggest that it may have taken less than a million years to go from the dust and gas stage to the large planetesimal stage. Planets may have grown from planetesimals in 10 to 200 million years. In the inner orbits, where the protoplanetary disk consisted mostly of dust, small terrestrial planets composed of rock and metal formed. In the outer part of the Solar System, where significant amounts of ice existed, protoplanets latched on to vast amounts of ice and gas and evolved into the giant planets. Fragments of materials that were not incorporated in planets remain today as asteroids and comets.

When did the planets form? Using techniques introduced in Chapter 10, geologists have found that special types of meteorites thought to be leftover planetesimals formed at 4.57 Ga, and thus consider that date to be the birth date of the Solar System. If this date is correct, it means that the Solar System formed about 9 billion years after the Big Bang, and thus is only about a third as old as the Universe.

Differentiation of the Earth and Formation of the Moon

When planetesimals started to form, they had a fairly homogeneous distribution of material throughout, because the smaller pieces from which they formed all had much the same composition and collected together in no particular order. But large planetesimals did not stay homogeneous for long, because they began to heat up. The heat came primarily from three sources: the heat produced during collisions (similar to the phenomenon that happens when you bang on a nail with a hammer and they both get warm), the heat produced when matter is squeezed into a smaller volume, and the heat produced from the decay of radioactive elements. In bodies whose temperature rose sufficiently to cause internal melting, denser iron alloy separated out and sank to the center of the body, whereas lighter rocky materials remained in a shell surrounding the center. By this process, called **differentiation**, protoplanets and large planetesimals developed internal layering early in their history. As we will see later, the central ball of iron alloy constitutes the body's core and the outer shell constitutes its mantle.

Did you ever wonder . . .
is the Moon as old as the Earth?

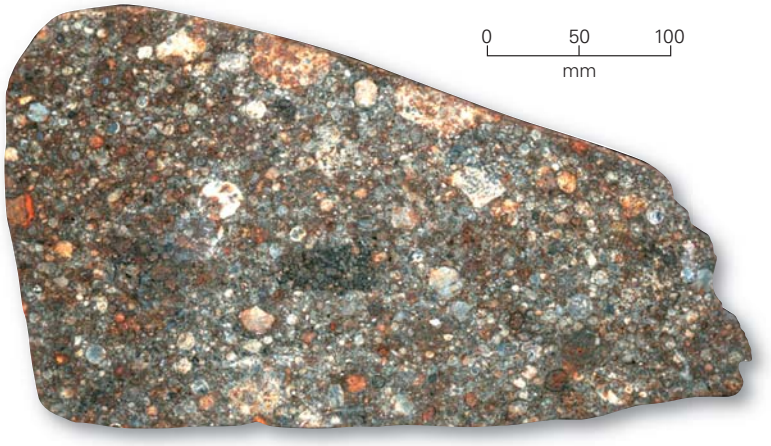
In the early days of the Solar System, planets continued to be bombarded by **meteorites** (solid objects, such as fragments of planetesimals, falling from space that land on a planet) even after the Sun had ignited and differentiation had occurred (**Box 1.2**). Heavy bombardment in the early days of the Solar System pulverized the surfaces of planets and eventually left huge numbers of craters (**See for Yourself A**). Bombardment also contributed to heating the planets.

Based on analysis and the dating of Moon rocks, most geologists have concluded that at about 4.53 Ga, a Mars-sized protoplanet slammed into the newborn Earth. In the process, the colliding body disintegrated and melted, along with a large part of the Earth's mantle. A ring of debris formed around the remaining, now-molten Earth, and quickly coalesced to form the Moon. Not all moons in the Solar System necessarily formed in this manner. Some may have been independent protoplanets or comets that were captured by a larger planet's gravity.

Why Are Planets Round?

Small planetesimals were jagged or irregular in shape, and asteroids today have irregular shapes. Planets, on the other hand, are more or less spherical. Why? Simply put, when a

FIGURE 1.7 The grainy interior of this meteorite may resemble the texture of a small planetesimal.



Meteors and Meteorites

During the early days of the Solar System, the Earth collided with and incorporated countless planetesimals and smaller fragments of solid material lying in its path. Intense bombardment ceased about 3.9 Ga, but even today collisions with space objects continue, and over 1,000 tons of material (rock, metal, dust, and ice) fall to Earth, on average, every year. The vast majority of this material consists of fragments derived from comets and asteroids sent careening into the path of the Earth after billiard-ball-like collisions with each other out in space, or because of the gravitational pull of a passing planet deflected their orbit. Some of the material, however, consists of chips of the Moon or Mars, ejected into space when large objects collided with those bodies.

Astronomers refer to any object from space that enters the Earth's atmosphere as a meteoroid. Meteoroids move at speeds of 20 to 75 km/s (over 45,000 mph), so fast that when they reach an altitude of about 150 km, friction with the atmosphere causes them to heat up and vaporize, leaving a streak of bright, glowing gas. The glowing streak, an atmospheric phenomenon, is a **meteor** (also known colloquially, though incorrectly, as a "falling star") (**Fig. Bx1.2a**). Most visible meteors completely vaporize by an altitude of about 30 km. But dust-sized ones may slow down sufficiently to float to Earth, and larger ones (fist-sized or bigger) can survive the heat of entry to reach the surface of the planet. In some cases, meteoroids explode in brilliant fireballs.

Objects that strike the Earth are called **meteorites**. Although almost all meteorites are small and have not caused notable damage on Earth during human history, a very few have smashed through houses, dented cars, and bruised people. During the longer term of Earth history, however, there have been some catastrophic collisions that left huge craters (**Fig. Bx1.2b**).

Most meteorites are asteroidal or planetary fragments, for icy material is too fragile to survive the fall. Researchers recognize three basic classes of meteorites: iron (made of iron-nickel alloy), stony (made of rock), and stony iron (rock embedded in a matrix of metal). Of all known meteorites, about 93% are stony and 6% are iron (**Fig. Bx1.2c**). Researchers have concluded that some meteors (a special subcategory of stony meteorites called carbonaceous chondrites, because they contain carbon and small spherical nodules called chondrules) are asteroids derived from planetesimals that never underwent differentiation into a core and mantle. Other stony meteorites and all iron meteorites are asteroids derived from planetesimals that had differentiated into a metallic core and a rocky mantle early in Solar System history but later shattered into fragments during collisions with other planetesimals. Most meteorites appear to be about 4.54 Ga, but carbonaceous chondrites are as old as 4.57 Ga and are the oldest solar system materials ever measured.

Since meteorites represent fragments of undifferentiated and differentiated planetesimals, geologists consider the *average* composition of meteorites to be representative of the *average* composition of the whole Earth. In other words, the estimates that geologists use for the proportions of different elements in the Earth are based largely on studying meteorites. Stony meteorites are probably similar in composition to the mantle, and iron meteorites are probably similar in composition to the core.

FIGURE Bx1.2 Meteors and meteorites.



(a) A shower of meteors over Hong Kong in 2001.



The meteorite forming the crater was 50 m across.

(b) The Barringer meteor crater in Arizona. It formed about 50,000 years ago and is 1.1 km in diameter.



(c) Examples of stony meteorites (left) and iron meteorites (right).

protoplanet gets big enough, gravity can change its shape. To picture how, imagine a block of cheese sitting outside on a hot summer day. As the cheese gets softer and softer, gravity causes it to spread out in a pancake-like blob. This model shows that gravitational force alone can cause material to change shape if the material is soft enough. Now let's apply this model to planetary growth.

The rock composing a small planetesimal is cool and strong enough so that the force of gravity is not sufficient to cause the rock to flow. But once a planetesimal grows beyond a certain critical size (about 1,000 km in diameter), its interior becomes warm and soft enough to flow in response to gravity. As a consequence, protrusions are pulled inward toward the center, and the planetesimal re-forms into a special shape that permits the force of gravity to be nearly the same at all points on its surface. This special shape is spherical because in a sphere mass is evenly distributed around the center (see Geology at a Glance, pp. 22–23).

Take-Home Message

Heavier elements formed in stars and supernovas added to gases in nebulae from which new generations of stars formed. Planets formed from rings of dust and ice orbiting the stars. As they formed, planets differentiated, with denser materials sinking to the center.

1.5 Welcome to the Neighborhood

Introducing the Earth System

So far in this chapter, we've described scientific ideas about how the Universe, and then the Solar System, formed. Now, let's focus on our home planet and develop an image of the Earth's overall architecture. We will see that our planet consists of several components—the atmosphere (Earth's gaseous envelope), the hydrosphere (Earth's surface and near-surface water), the biosphere (Earth's great variety of life forms), the lithosphere (the outer shell of the Earth), and the interior (material inside the Earth). These components, and the complex interactions among them, comprise the **Earth System**. Our planet remains a dynamic place. Heat retained inside from the planet's formation, as well as from continuing radioactive decay, provides the energy to move the lithosphere. And heat from the Sun keeps the atmosphere and hydrosphere in motion.

To get an initial sense of what the Earth System looks like, imagine that we are explorers from space rocketing toward the Earth for a first visit. After we pass the Moon, we begin to detect the Earth's magnetic field. Then we enter its atmosphere and orbit its surface.

A First Glance at the Magnetic Field

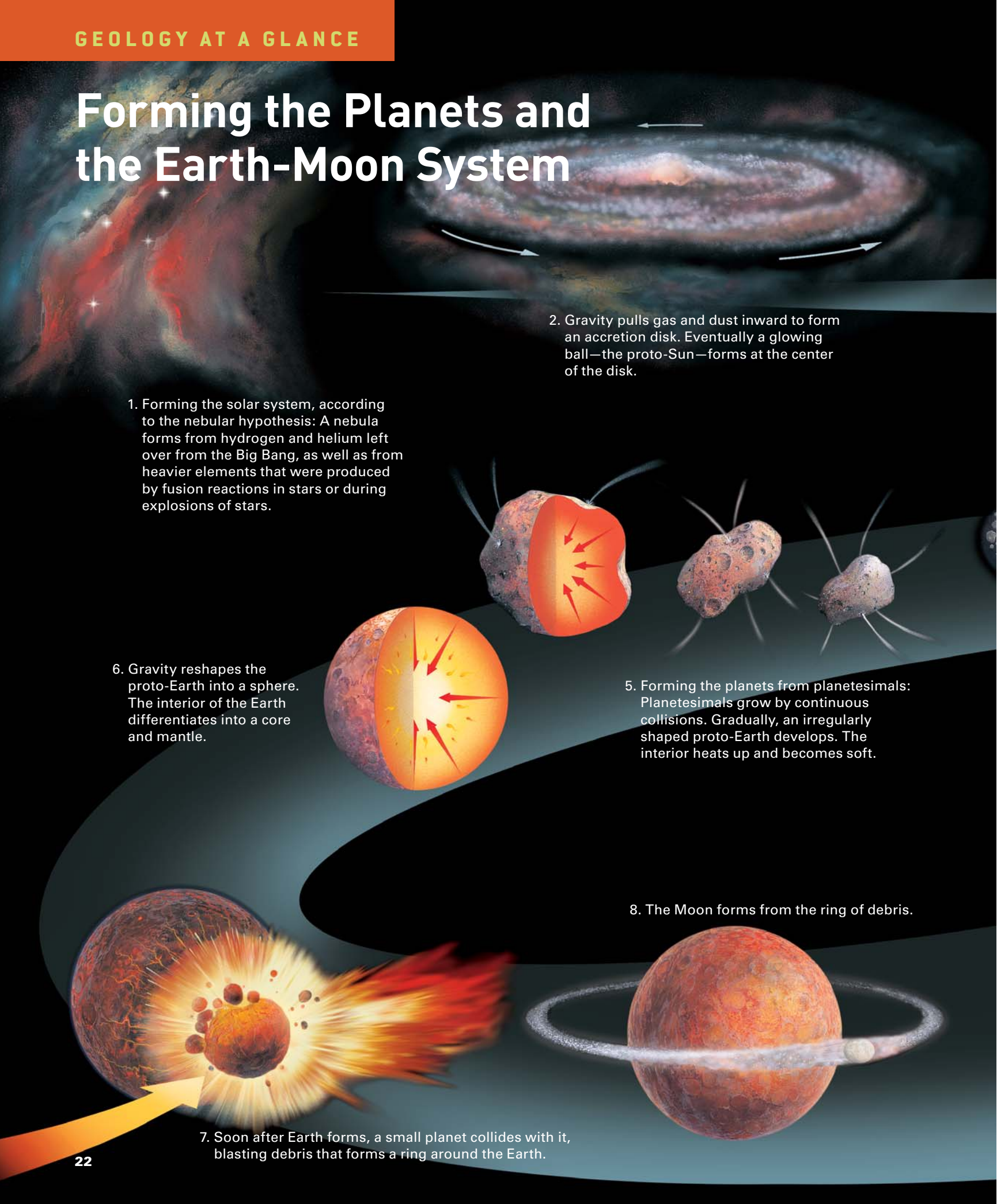
As our rocket approaches the Earth, and we see its beautiful bluish glow (**Fig. 1.8**), our instruments detect the planet's magnetic field, like a signpost shouting, "Approaching Earth!" A **magnetic field**, in a general sense, is the region affected by the force emanating from a magnet. In the context of physics, a force is a push or pull that can cause the velocity or shape of an object to change. Magnetic force, which grows progressively stronger as you approach the magnet, can attract or repel another magnet and can cause charged particles to move. Earth's magnetic field, like the familiar magnetic field around a bar magnet, is largely a **dipole**, meaning that it has two poles—a north pole and a south pole (**Fig. 1.9a, b**). When you bring two bar magnets close to one another, opposite poles attract and like poles repel. By convention, we represent the orientation of a magnetic dipole by an arrow that points from the south pole to the north pole, and we represent the magnetic field of a magnet by a set of invisible magnetic field lines that curve through the space around the magnet and enter the magnet at its poles. Arrowheads along these lines point in a direction to complete a loop. Magnetized needles, such as iron filings or compass needles, when placed in a field align with the magnetic field lines.

If we represent the Earth's magnetic field as emanating from an imaginary bar magnet in the planet's interior, the north pole of this bar lies near the south geographic pole of the Earth, whereas the south pole of the bar lies near the north geographic pole. (The *geographic poles* are the places where the spin axis of the Earth intersects the planet's surface.)

FIGURE 1.8 A view of the Earth as seen from space.



Forming the Planets and the Earth-Moon System



2. Gravity pulls gas and dust inward to form an accretion disk. Eventually a glowing ball—the proto-Sun—forms at the center of the disk.

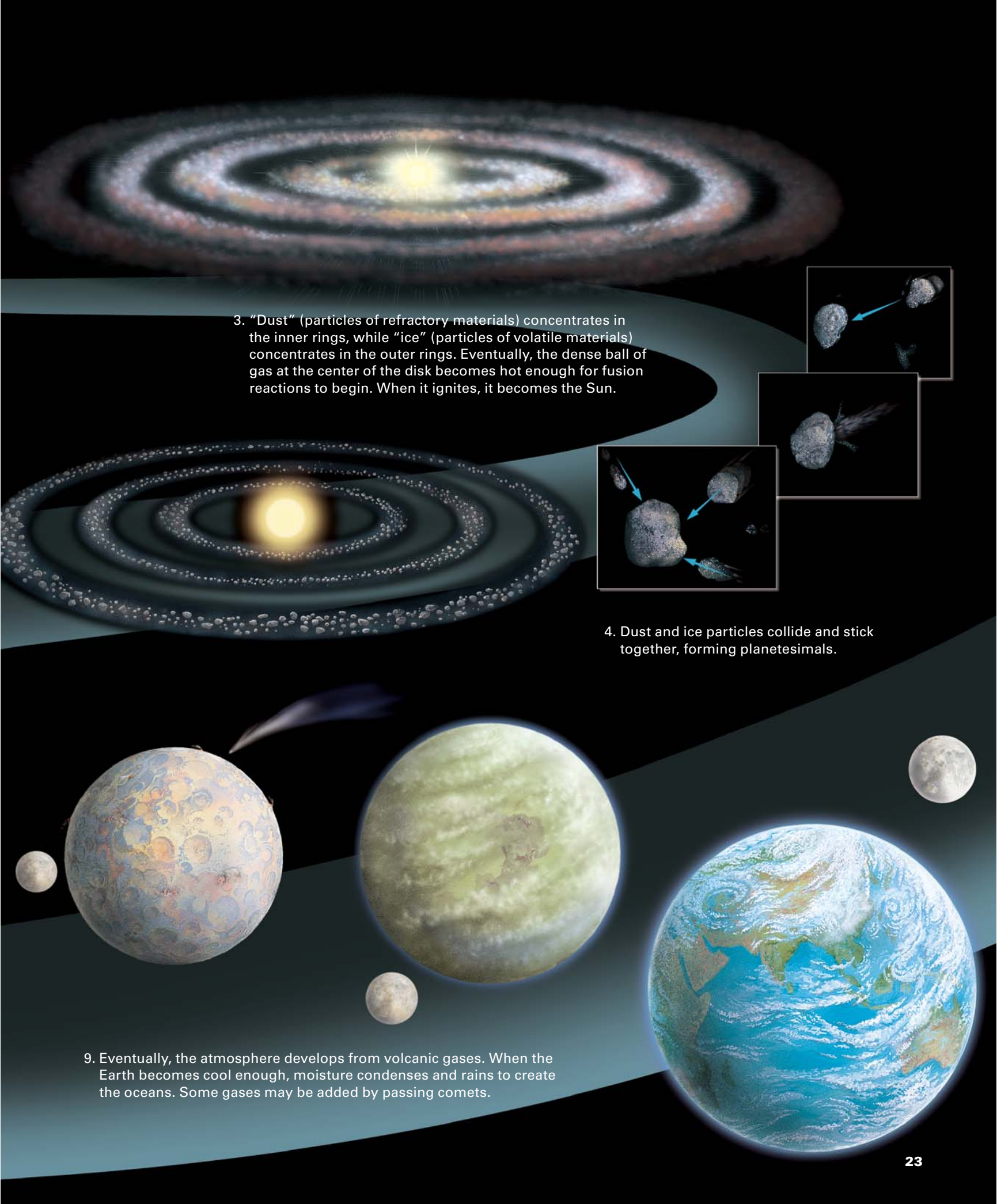
1. Forming the solar system, according to the nebular hypothesis: A nebula forms from hydrogen and helium left over from the Big Bang, as well as from heavier elements that were produced by fusion reactions in stars or during explosions of stars.

6. Gravity reshapes the proto-Earth into a sphere. The interior of the Earth differentiates into a core and mantle.

5. Forming the planets from planetesimals: Planetesimals grow by continuous collisions. Gradually, an irregularly shaped proto-Earth develops. The interior heats up and becomes soft.

8. The Moon forms from the ring of debris.

7. Soon after Earth forms, a small planet collides with it, blasting debris that forms a ring around the Earth.

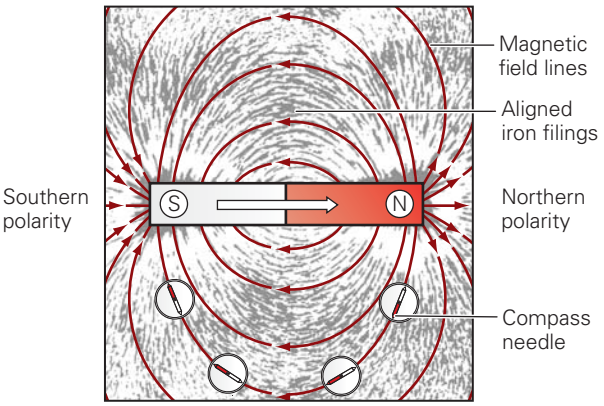


3. "Dust" (particles of refractory materials) concentrates in the inner rings, while "ice" (particles of volatile materials) concentrates in the outer rings. Eventually, the dense ball of gas at the center of the disk becomes hot enough for fusion reactions to begin. When it ignites, it becomes the Sun.

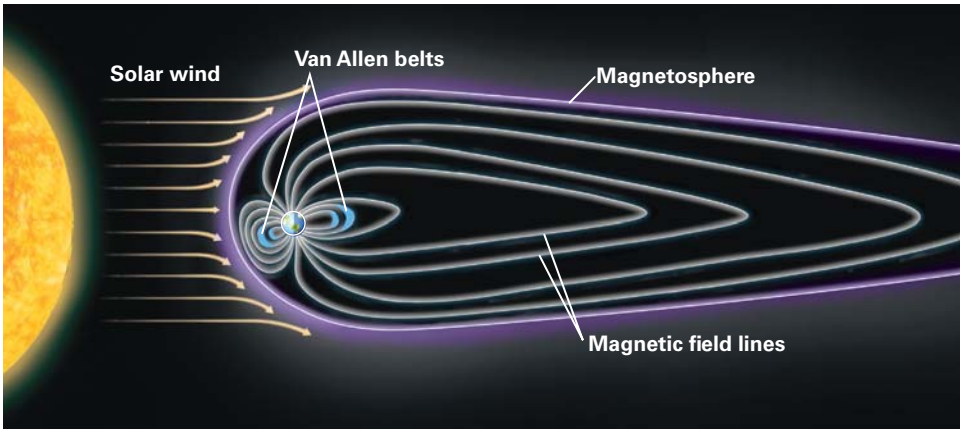
4. Dust and ice particles collide and stick together, forming planetesimals.

9. Eventually, the atmosphere develops from volcanic gases. When the Earth becomes cool enough, moisture condenses and rains to create the oceans. Some gases may be added by passing comets.

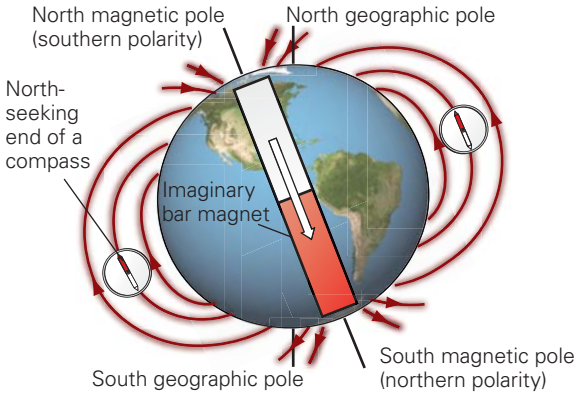
FIGURE 1.9 A magnetic field permeates the space around the Earth. It can be symbolized by a bar magnet.



(a) A bar magnet produces a magnetic field. Magnetic field lines point into the "south pole" and out from the "north pole."



(c) Earth behaves like a magnetic dipole, but the field lines are distorted by the solar wind. The Van Allen radiation belts trap charged particles.



(b) We can represent the Earth's field by an imaginary bar magnet inside.





(d) Charged particles flow toward Earth's magnetic poles and cause gases in the atmosphere to glow, forming colorful aurorae in polar skies.

Nevertheless, geologists and geographers by convention refer to the magnetic pole closer to the north geographic pole as the north magnetic pole, and the magnetic pole closer to the south geographic pole as the south magnetic pole. This way, the north-seeking end of a compass points toward the north geographic pole, since opposite ends of a magnet attract.

Our Sun's stellar wind, known as the "solar wind," interacts with Earth's magnetic field, distorting it into a huge teardrop pointing away from the Sun. The solar wind consists of dangerous, high-velocity charged particles. Fortunately, the magnetic field deflects most (but not all) of the particles, so that they do not reach Earth's surface. In this way, the magnetic field acts like a shield against the solar wind; the region inside this magnetic shield is called the magnetosphere (**Fig. 1.9c**).

Though it protects the Earth from most of the solar wind, the magnetic field does not stop our spaceship, and we continue to speed toward the planet. At distances of about 3,000 km and 10,500 km out from the Earth, we encounter the Van Allen radiation belts, named for the physicist who first recognized them in 1959. These belts trap solar wind particles as well as cosmic rays (nuclei of atoms emitted from supernova explosions) that were moving so fast they were able to penetrate the weaker outer part of the magnetic field. Some charged particles make it past the Van Allen belts and are channeled along magnetic field lines to the polar regions of Earth. When these particles interact with gas atoms in the upper atmosphere, they cause the gases to glow, like the gases in neon signs, creating spectacular aurorae (**Fig. 1.9d**).

Introducing the Atmosphere

As our spaceship descends further, we enter Earth's **atmosphere**, an envelope of gas consisting of 78% nitrogen (N_2) and 21% oxygen (O_2), with minor amounts (1% total) of argon, carbon dioxide (CO_2), neon, methane, ozone, carbon monoxide, and sulfur dioxide (**Fig. 1.10a, b**). Other terrestrial planets have atmospheres, but they are not like Earth's.

The weight of overlying air squeezes down on the air below, pushing gas molecules closer together. Thus, both the density of air and the air pressure (the amount of push that the air exerts on material beneath it) increases closer to the surface (Fig. 1.10c). Technically, we specify pressure in units of force per unit area. Such units include atmospheres (abbreviated atm) and bars, where 1 atm = 1.04 kilograms per square centimeter, or 14.7 pounds per square inch. An atmosphere and a bar are almost the same: 1 atm = 1.01 bars. At sea level, average air pressure is 1 atm. Air pressure (and, therefore, density) decreases by half for every 5.6 km that you rise above sea level. Thus, at the peak of Mt. Everest, the highest point of the planet (8.85 km above sea level), air pressure is only 0.3 atm. People can't survive for long at elevations above about 5.5 km. Because of the decrease in density with elevation, 99% of atmospheric gas lies at elevations below 50 km, and the atmosphere is barely detectable at elevations above 120 km. The vacuum (lack of matter) characterizing interplanetary space lies above an elevation of about 600 km.

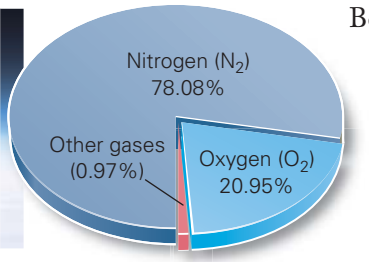
Did you ever wonder . . .
how thick is our atmosphere?

The nature of the atmosphere changes with increasing distance from the Earth's surface. Because of these changes, atmospheric scientists divide the atmosphere into layers. Most winds and clouds develop only in the lowest layer, the troposphere. The layers of the atmosphere that lie above the troposphere are named, in sequence from base to top: the stratosphere, the mesosphere, and the thermosphere (Fig. 1.10d). Boundaries between layers are defined as elevations at which temperature stops decreasing and starts increasing, or vice versa. Boundaries are named for the underlying layer. For example, the boundary between the troposphere and the overlying stratosphere is the tropopause.

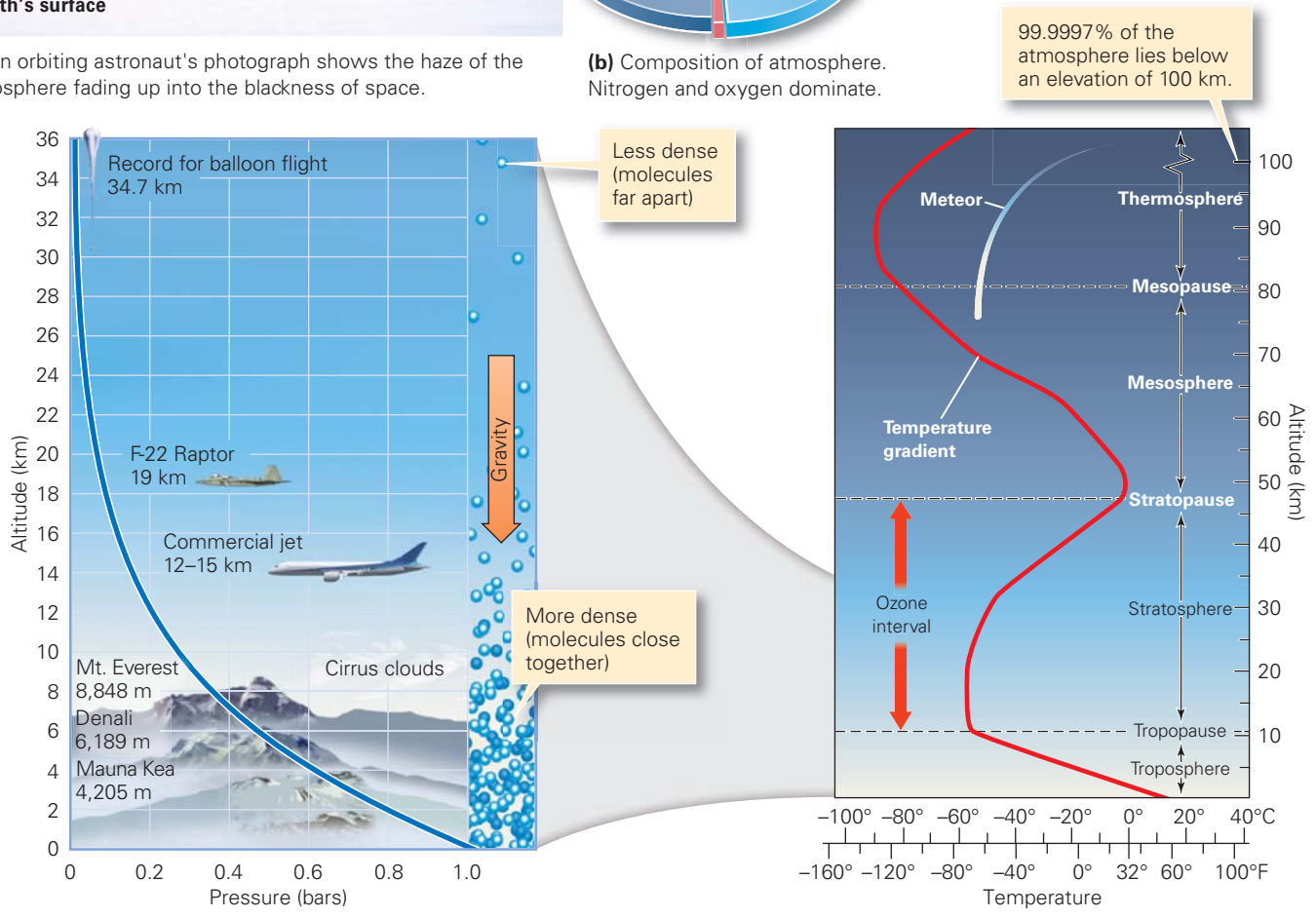
FIGURE 1.10 Characteristics of the atmosphere that envelops the Earth.



(a) An orbiting astronaut's photograph shows the haze of the atmosphere fading up into the blackness of space.



(b) Composition of atmosphere. Nitrogen and oxygen dominate.



(c) Molecules pack together more tightly at the base of the atmosphere, so atmospheric pressure changes with elevation.

(d) The atmosphere can be divided into several distinct layers. We live in the troposphere.

Land and Oceans

Imagine that we now guide our spaceship into orbit around the Earth. Our first task is to make a map of the planet. What features should go on this map? Starting with the most obvious, we note that land (continents and islands) covers about 30% of the surface (**Fig. 1.11**). Some of the land surface consists of solid rock, whereas some has a covering of **sediment** (materials such as sand and gravel, in which the grains are not stuck together). The amount of cover by vegetation varies widely (See For Yourself A). Surface water covers the remaining 70% of the Earth. Most surface water is salty and in oceans, but some is fresh and fills lakes and rivers. Our instruments also detect groundwater, the water that fills cracks and holes (pores) within rock and sediment under the land surface. Finally, we find that ice covers significant areas of land and sea in polar regions and at high elevations, and that living organisms populate the land, sea, air, and even the upper few kilometers of the subsurface.

To finish off our map of the Earth's surface, we note that the surface is not flat. Topography, the variation in elevation of the land surface, defines plains, mountains, and valleys (See for Yourself A). Similarly, **bathymetry**, the variation in elevation of the ocean floor, defines mid-ocean ridges, abyssal plains, and deep-ocean trenches (see Fig. 1.11). The deepest point on the ocean floor is 10.9 km below sea level, and the highest point on land is almost 8.9 km above—the total difference in elevation (19.8 km) is only 0.3% of Earth's radius (6,371 km).

Take-Home Message

The Earth produces a magnetic field that deflects solar wind. An atmosphere of N_2 and O_2 gas surrounds the planet. Oceans cover 70% of the surface, and land the remainder. The difference between the highest and the lowest points is only 0.3% of the radius.

1.6 Looking Inward—Introducing the Earth's Interior

What Is the Earth Made Of?

At this point, we leave our fantasy space voyage and turn our attention inward to the materials that make up the solid Earth, because we need to be aware of these before we can discuss the architecture of the Earth's interior. Let's begin by reiterating that the Earth consists mostly of elements produced by fusion reactions in stars and by supernova explosions. Only four elements (iron, oxygen, silicon, and magnesium) make up 91.2% of the Earth's mass; the remaining 8.8% consists of the other 88 elements (**Fig. 1.12**). The elements of the Earth comprise a great variety of materials. For reference in this chapter and the next, we introduce the basic categories of materials. All of these will be discussed in more detail later in the book.

› *Organic chemicals*. Carbon-containing compounds that either

FIGURE 1.11 This map of the Earth shows variations in elevation on both the land surface and the sea floor. Darker blues are deeper water in the ocean. Greens are lower elevation on land.

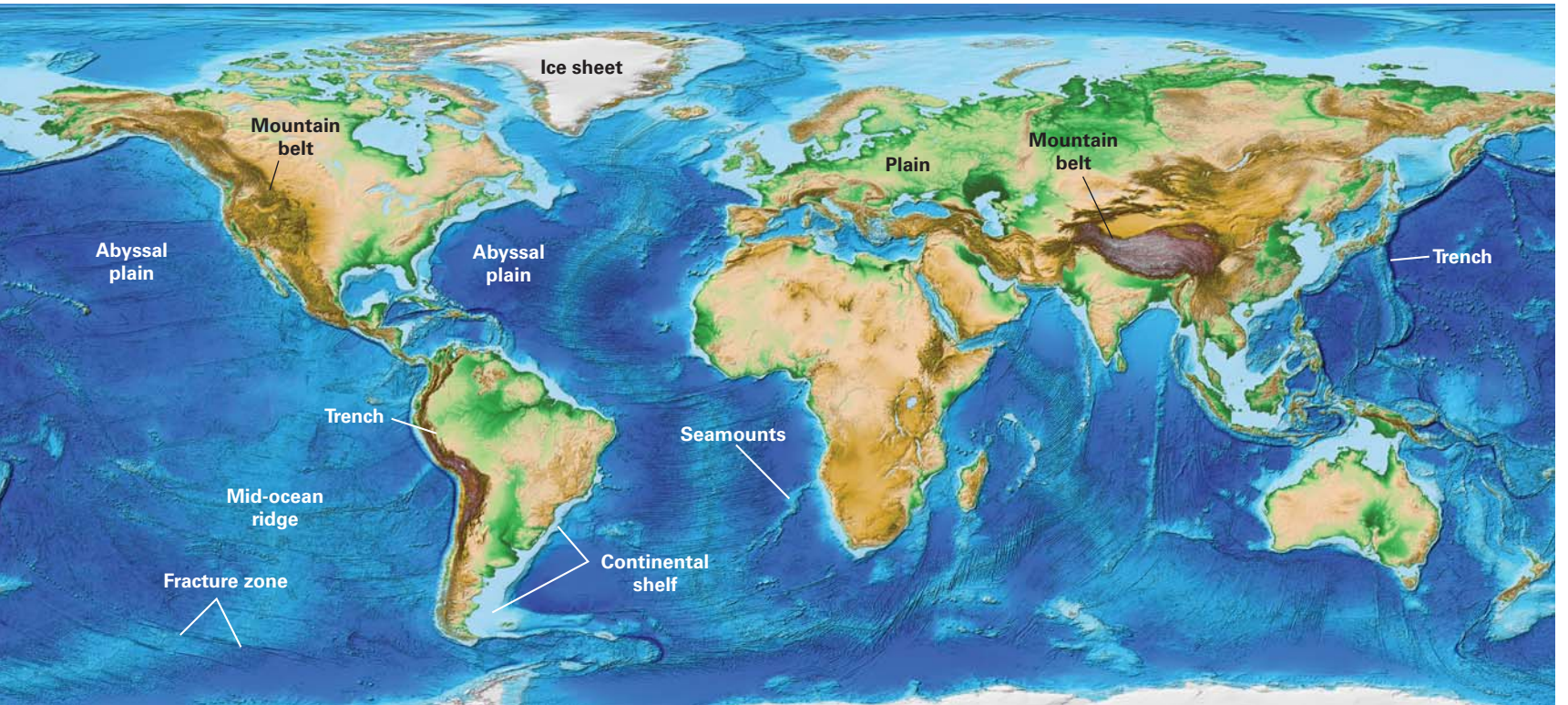
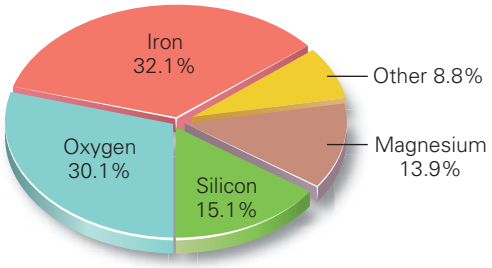


FIGURE 1.12 The proportions of major elements making up the mass of the whole Earth.



occur in living organisms or have characteristics that resemble compounds in living organisms are called *organic chemicals*.

- *Minerals*. A solid, natural substance in which atoms are arranged in an orderly pattern is a **mineral**. A single coherent sample of a mineral that grew to its present shape is a crystal, whereas an irregularly shaped sample, or a fragment derived from a once-larger crystal or cluster of crystals, is a grain.
- *Glasses*. A solid in which atoms are not arranged in an orderly pattern is called *glass*.
- *Rocks*. Aggregates of mineral crystals or grains, or masses of natural glass, are called *rocks*. Geologists recognize three main groups of rocks. (1) *Igneous* rocks develop when hot molten (liquid) rock cools and freezes solid. (2) *Sedimentary* rocks form from grains that break off preexisting rock and become cemented together, or from minerals that precipitate out of a water solution. (3) *Metamorphic* rocks form when preexisting rocks change in response to heat and pressure.
- *Sediment*. An accumulation of loose mineral grains (grains that have not stuck together) is called *sediment*.
- *Metals*. A solid composed of metal atoms (such as iron, aluminum, copper, and tin) is called a **metal**. An **alloy** is a mixture containing more than one type of metal atom.
- *Melts*. A **melt** forms when solid materials become hot and transform into liquid. Molten rock is a type of melt—geologists distinguish between *magma*, which is molten rock beneath the Earth's surface, and *lava*, molten rock that has flowed out onto the Earth's surface.
- *Volatiles*. Materials that easily transform into gas at the relatively low temperatures found at the Earth's surface are called **volatiles**.

The most common minerals in the Earth contain **silica** (a compound of silicon and oxygen) mixed in varying proportions with other elements. These minerals are called silicate minerals. Not surprisingly, rocks composed of silicate minerals are *silicate rocks*. Geologists distinguish four classes of igneous silicate rocks based, in essence, on the proportion of silica to iron and magnesium. In order, from greatest to least proportion of silica to iron and magnesium, these classes are *felsic* (or silicic), *intermediate*, *mafic*, and *ultramafic*. As the proportion of silica in a rock increases, the density (mass per unit volume) decreases. Thus, felsic rocks are less dense than mafic rocks. Many different rock types occur in each class, as will be discussed in detail in Chapters 4 through 7. For now, we introduce the four rock types whose names we need to know for our discussion of the Earth's layers that follows. These are (1) *granite*, a felsic rock with large grains; (2) *gabbro*, a mafic rock with large grains; (3) *basalt*, a mafic rock with small grains; and (4) *peridotite*, an ultramafic rock with large grains.

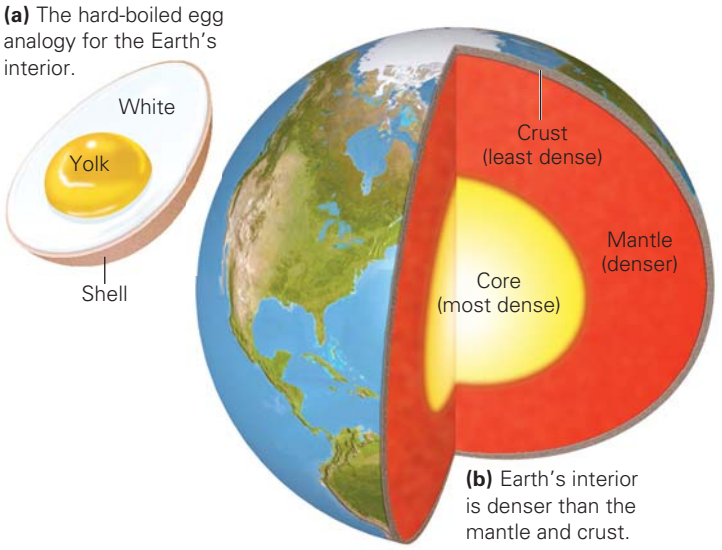
Discovering the Earth's Internal Layers

People have speculated about what's inside our planet since ancient times. What is the source of incandescent lavas that spew from volcanoes, of precious gems and metals found in mines, of sparkling mineral waters that bubble from springs, and of the mysterious forces that shake the ground and topple buildings? In ancient Greece and Rome, the subsurface was the underworld, Hades, home of the dead, a region of fire and sulfurous fumes. Perhaps this image was inspired by the molten rock and smoke emitted by the volcanoes of the Mediterranean region. In the 18th and 19th centuries, European writers thought the Earth's interior resembled a sponge, containing open caverns variously filled with molten rock, water, or air. In fact, in the popular 1864 novel *Journey to the Center of the Earth*, by the French author Jules Verne, three explorers hike through interconnected caverns down to the Earth's center.

How can we explore the interior for real? We can't dig or drill down very far. Indeed, the deepest mine penetrates only about 3.5 km beneath the surface of South Africa. And the deepest drill hole probes only 12 km below the surface of northern Russia—compared with the 6,371 km radius of the Earth, this hole makes it less than 0.2% of the way to the center and is nothing more than a pinprick. Our modern image of the Earth's interior, one made up of distinct layers, is the end product of many discoveries made during the past 200 years.

The first clue that led away from Jules Verne's sponge image came when researchers successfully measured the mass of the whole Earth, and from this information derived its *average* density. They found that the average density of our planet far exceeds the density of common rocks found on the surface. Thus, the interior of the Earth must contain denser material than its outermost layer and can't possibly be full of holes. In fact, the mass of the Earth overall is so great that the planet must contain a large amount of metal. Since the Earth is close to being a sphere, the metal must be concentrated near the center. Otherwise, centrifugal force due to the spin of the Earth on its axis would pull the equator out, and the

FIGURE 1.13 An early image of Earth's internal layers.



(a) The hard-boiled egg analogy for the Earth's interior.

(b) Earth's interior is denser than the mantle and crust.

planet would become a disk. (To picture why, consider that when you swing a hammer, your hand feels more force if you hold the end of the light wooden shaft, rather than the heavy metal head.) Finally, researchers realized that, though molten rock occasionally oozes out of the interior at volcanoes, the interior must be mostly solid, because if it weren't, the land surface would rise and fall due to tidal forces much more than it does.

Eventually, researchers concluded that the Earth resembled a hard-boiled egg, in that it had three principal layers: a not-so-dense **crust** (like an eggshell, composed of rocks such as granite, basalt, and gabbro), a denser solid **mantle** in the middle (the "white," composed of a then-unknown material), and a very dense **core** (the "yolk," composed of an unknown metal) (**Fig. 1.13a, b**). Clearly, many questions remained. How thick are the layers? Are the boundaries between layers sharp or gradational? And what exactly are the layers composed of?

Clues from the Study of Earthquakes: Refining the Image

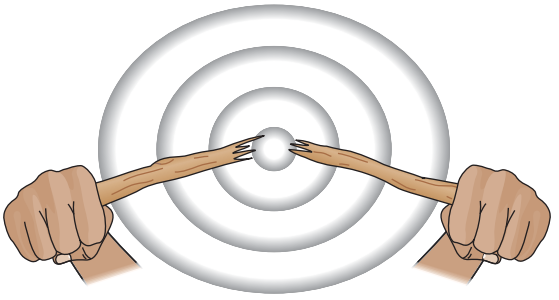
When rock within the outer portion of the Earth suddenly breaks and slips along a fracture called a *fault*, it generates shock waves (abrupt vibrations), called seismic waves, that travel through the surrounding rock outward from the break. Where these waves cause the surface of the Earth to vibrate, people feel an **earthquake**, an episode of ground shaking. You can simulate this process, at a small scale, when you break a stick between your hands and feel the snap with your hands (**Fig. 1.14a, b**).

In the late 19th century, geologists learned that earthquake energy could travel, in the form of waves, all the way through the Earth's interior from one side to the other. Geologists immediately realized that the study of earthquake waves traveling through the Earth might provide a tool for exploring the Earth's insides, much as ultrasound today helps doctors study a patient's insides. Specifically, laboratory measurements demonstrated that earthquake waves travel at different velocities (speeds) through different materials. Thus, by detecting depths at which velocities suddenly change, geoscientists pinpointed the boundaries between layers and even recognized subtler boundaries within layers. For example, such studies led geoscientists to subdivide the mantle into the upper mantle and lower mantle, and subdivide the core into the inner core and outer core. (Chapter 8 provides further details about earthquakes, and Interlude D shows how the study of earthquake waves defines the Earth's layers.)

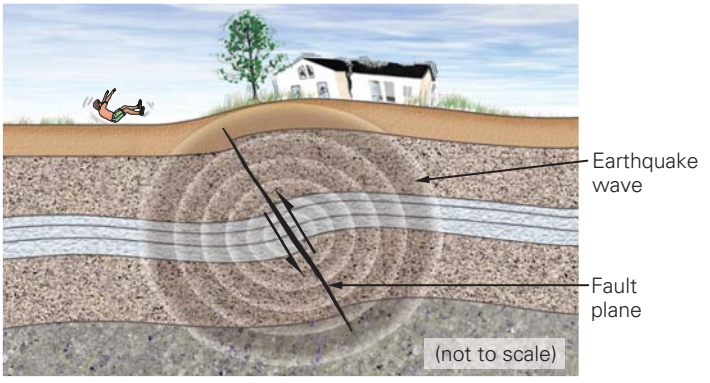
Pressure and Temperature Inside the Earth

In order to keep underground tunnels from collapsing under the pressure created by the weight of overlying rock, mining engineers must design sturdy support structures. It is no surprise

FIGURE 1.14 Faulting and earthquakes.



(a) Snapping a stick generates vibrations that pass through the stick to your hands.



(b) Similarly, when the rock inside the Earth suddenly breaks and slips, forming a fracture called a fault, it generates shock waves that pass through the Earth and shake the surface.

that deeper tunnels require stronger supports: the downward push from the weight of overlying rock increases with depth, simply because the mass of the overlying rock layer increases with depth. In solid rock, the pressure at a depth of 1 km is about 300 atm. At the Earth's center, pressure probably reaches about 3,600,000 atm.

Temperature also increases with depth in the Earth. Even on a cool winter's day, miners who chisel away at gold veins exposed in tunnels 3.5 km below the surface swelter in temperatures of about 53°C (127°F). We refer to the rate of change in temperature with depth as the **geothermal gradient**. In the upper part of the crust, the geothermal gradient averages between 20°C and 30°C per km. At greater depths, the rate decreases to 10°C per km or less. Thus, 35 km below the surface of a continent, the temperature reaches 400°C to 700°C, and the mantle-core boundary is about 3,500°C. No one has ever directly measured the temperature at the Earth's center, but calculations suggest it may exceed 4,700°C, close to the Sun's surface temperature of 5,500°C.

Did you ever wonder . . .
how hot it gets at the center of this planet ?

Take-Home Message

The Earth consists of many materials, the most common of which is silicate rock. Studies, including analysis of earthquake waves, show that the Earth can be divided into three layers—the crust, the mantle, and the core. Temperature and pressure increase with depth.

1.7 What Are the Layers Made Of?

As a result of studies during the past century, geologists have a pretty clear sense of what the layers inside the Earth are made of. Let's now look at the properties of individual layers in more detail (**Fig. 1.15a, b**).

The Crust

When you stand on the surface of the Earth, you are standing on top of its outermost layer, the crust. The crust is our home and the source of all our resources. How thick is this all-important layer? Or, in other words, what is the depth to the crust-mantle boundary? An answer came from the studies of Andrija Mohorovičić, a researcher working in Zagreb, Croatia. In 1909, he discovered that the velocity of earthquake waves suddenly increased at a depth of tens of kilometers beneath the Earth's surface, and he suggested that this increase was caused by an abrupt change in the properties of rock (see Interlude D for further details). Later studies showed that this change can be found most everywhere around our planet, though it occurs at different depths in different locations. Specifically, it's deeper beneath continents than beneath oceans. Geologists now consider the change to define the base of the crust, and they refer to it as the **Moho** in Mohorovičić's honor. The relatively shallow depth of the Moho (7 to 70 km, depending on location) as compared to the radius of the Earth (6,371 km) emphasizes that the crust is very thin indeed. In fact, the crust is only about 0.1% to 1.0% of the Earth's radius, so if the Earth were the size of a balloon, the crust would be about the thickness of the balloon's skin.

The crust is not simply cooled mantle, like the skin on chocolate pudding, but rather consists of a variety of rocks that differ in composition (chemical makeup) from mantle rock. Geologists distinguish between two fundamentally different types of crust—oceanic crust, which underlies the sea floor, and continental crust, which underlies continents.

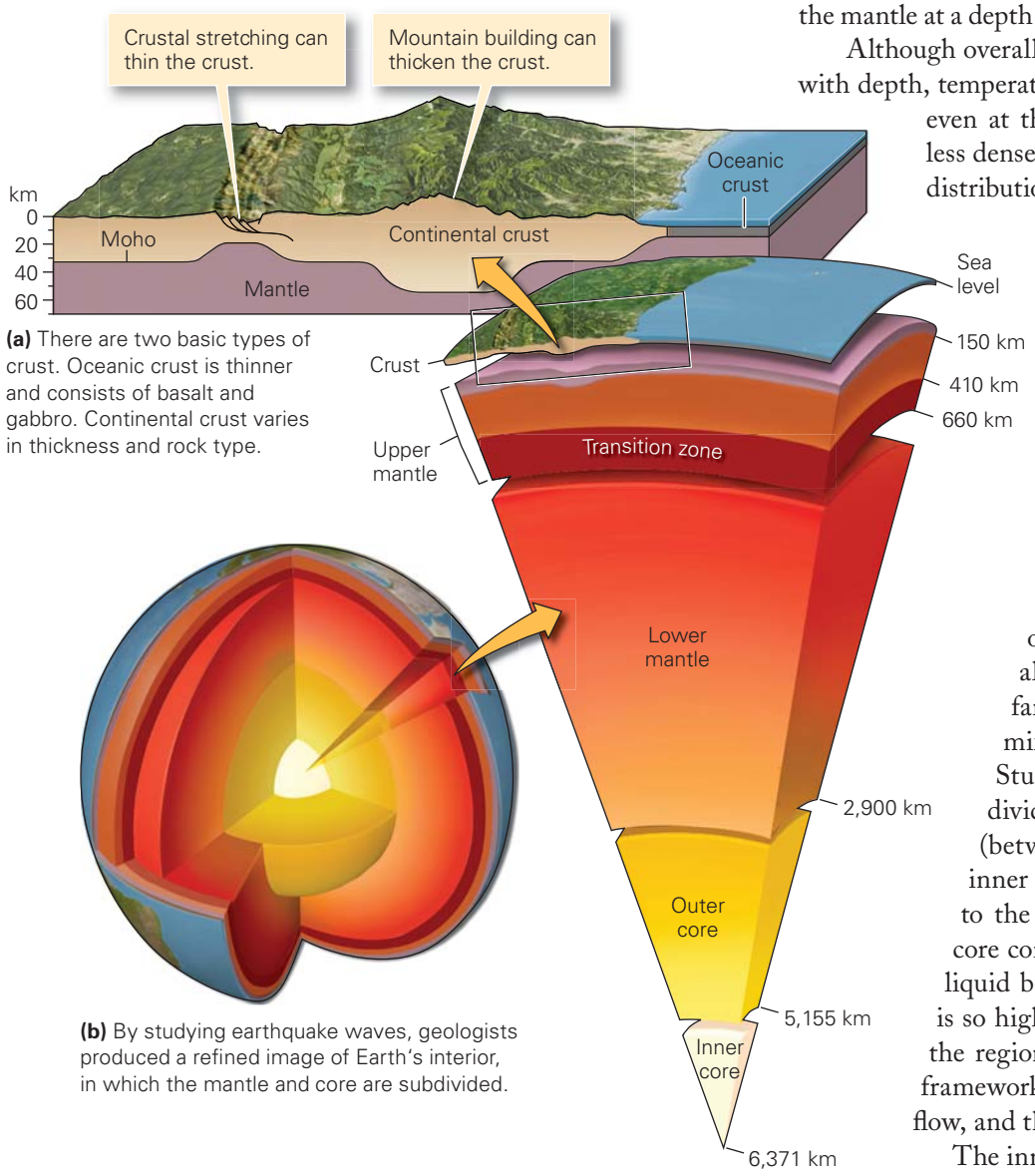
Oceanic crust is only 7 to 10 km thick. At highway speeds (100 km per hour), you could drive a distance equal to the thickness of the oceanic crust in about five minutes. At the top, we find a blanket of sediment, generally less than 1 km thick, composed of clay and tiny shells that settled like snow out of the sea. Beneath this blanket, the oceanic crust consists of a layer of basalt and, below that, a layer of gabbro.

Most continental crust is about 35 to 40 km thick—about four to five times the thickness of oceanic crust—but its thickness varies significantly. In some places, continental crust has been stretched and thinned so it's only 25 km from the surface to the Moho, and in some places, the crust has been crumpled and thickened to become up to 70 km thick. In contrast to oceanic crust, continental crust contains a great variety of rock types, ranging from mafic to felsic in composition. On average, upper continental crust is less mafic than oceanic crust—it has a felsic (granite-like) to intermediate composition—so continental crust overall is less dense than oceanic crust. Notably, oxygen is the most abundant element in the crust (**Fig. 1.16**).

The Mantle

The mantle of the Earth forms a 2,885-km-thick layer surrounding the core. In terms of volume, it is the largest part of the Earth. In contrast to the crust, the mantle consists entirely of an ultramafic (dark and dense) rock called peridotite. This means that peridotite, though rare at the Earth's surface, is actually the most abundant rock in our planet! Researchers have found that earthquake-wave velocity changes at a depth

FIGURE 1.15 A modern view of Earth's interior layers.



(a) There are two basic types of crust. Oceanic crust is thinner and consists of basalt and gabbro. Continental crust varies in thickness and rock type.

(b) By studying earthquake waves, geologists produced a refined image of Earth's interior, in which the mantle and core are subdivided.

of 400 km and again at a depth of 660 km in the mantle. Based on this observation, they divide the mantle into two sublayers: the **upper mantle**, down to a depth of 660 km, and the **lower mantle**, from 660 km down to 2,900 km. The **transition zone** is the interval between 400 km and 660 km deep.

Almost all of the mantle is solid rock. But even though it's solid, mantle rock below a depth of 100 to 150 km is so hot that it's soft enough to flow. This flow, however, takes place extremely slowly—at a rate of less than 15 cm a year. *Soft* here does not mean liquid; it simply means that over long periods of time mantle rock can change shape without breaking. We stated earlier that *almost* all of the mantle is solid. We used the word "almost" because up to a few percent of the mantle has melted. This melt occurs in films or bubbles between grains in the mantle at a depth of 100 to 200 km beneath the ocean floor.

Although overall, the temperature of the mantle increases with depth, temperature also varies significantly with location even at the same depth. The warmer regions are less dense, while the cooler regions are denser. The distribution of warmer and cooler mantle indicates that the mantle convects like water in a simmering pot; warmer mantle is relatively buoyant and gradually flows upward, while cooler, denser mantle sinks.

The Core

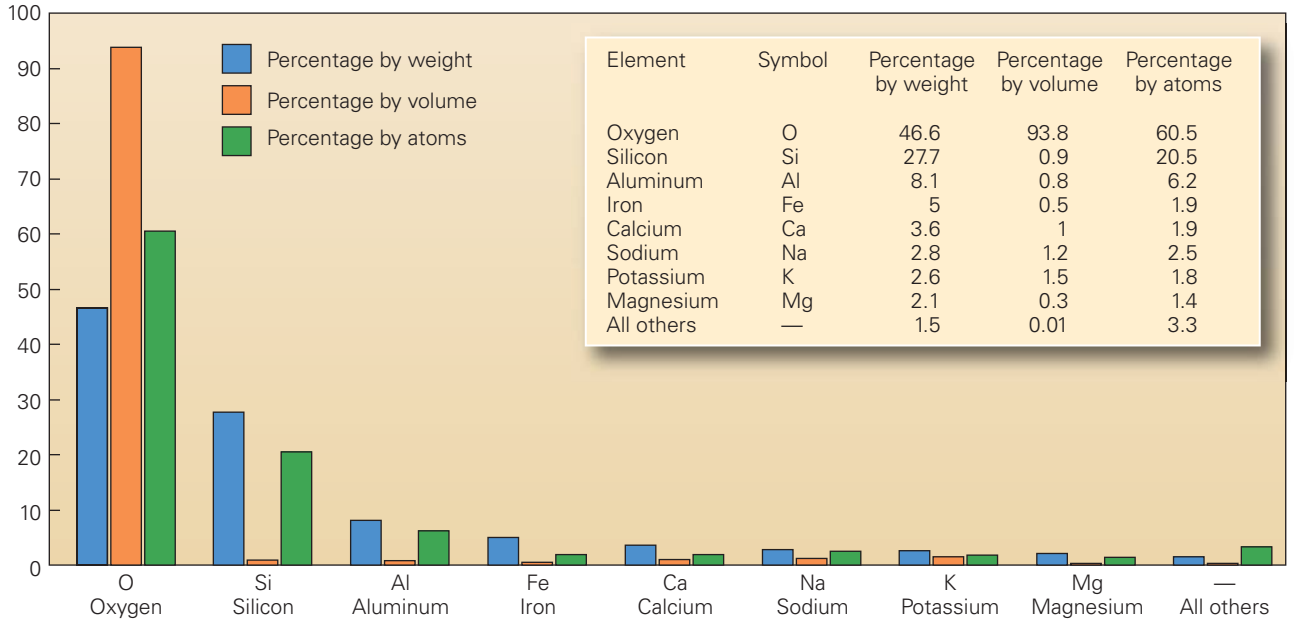
Early calculations suggested that the core had the same density as gold, so for many years people held the fanciful hope that vast riches lay at the heart of our planet. Alas, geologists eventually concluded that the core consists of a far less glamorous material, iron alloy (iron mixed with tiny amounts of other elements). Studies of seismic waves led geoscientists to divide the core into two parts, the outer core (between 2,900 and 5,155 km deep) and the inner core (from a depth of 5,155 km down to the Earth's center at 6,371 km). The outer core consists of *liquid* iron alloy. It can exist as a liquid because the temperature in the outer core is so high that even the great pressures squeezing the region cannot keep atoms locked into a solid framework. The iron alloy of the outer core can flow, and this flow generates Earth's magnetic field.

The inner core, with a radius of about 1,220 km, is a *solid* iron alloy that may reach a temperature of over 4,700°C. Even though it is hotter than the outer core, the inner core is a solid because it is deeper and is subjected to even greater pressure. The pressure keeps atoms locked together tightly in very dense materials.

The Lithosphere and the Asthenosphere

So far, we have identified three major layers (crust, mantle, and core) inside the Earth that differ compositionally from each other. Earthquake waves travel at different velocities through these layers. An alternative way of thinking about Earth layers comes from studying the degree to which the material making up a layer can flow. In this context, we distinguish between *rigid* materials, which can bend or break but cannot flow, and *plastic* materials, which are relatively soft and can flow without breaking.

FIGURE 1.16 A table and a graph illustrating the abundance of elements in the Earth's crust.



Element	Symbol	Percentage by weight	Percentage by volume	Percentage by atoms
Oxygen	O	46.6	93.8	60.5
Silicon	Si	27.7	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5	0.5	1.9
Calcium	Ca	3.6	1	1.9
Sodium	Na	2.8	1.2	2.5
Potassium	K	2.6	1.5	1.8
Magnesium	Mg	2.1	0.3	1.4
All others	—	1.5	0.01	3.3

Geologists have determined that the outer 100 to 150 km of the Earth is relatively rigid. In other words, the Earth has an outer shell composed of rock that cannot flow easily. This outer layer is called the **lithosphere**, and it consists of the crust plus the uppermost, cooler part of the mantle. We refer to the portion of the mantle within the lithosphere as the lithospheric mantle. Note that the terms lithosphere and crust are not synonymous—the crust is just the upper part of the lithosphere. The lithosphere lies on top of the **asthenosphere**, which is the portion of the mantle in which rock can flow. The boundary between the lithosphere and asthenosphere occurs where the temperature reaches about 1280°C, for at temperatures higher than this value mantle rock becomes soft enough to flow.

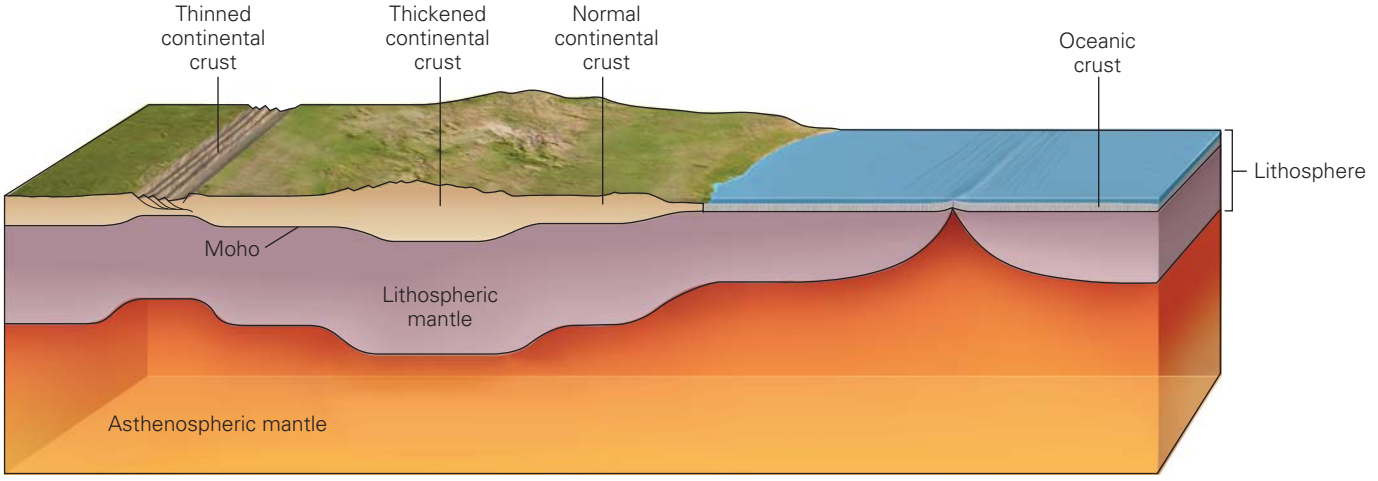
Geologists distinguish between two types of lithosphere (**Fig. 1.17**). Oceanic lithosphere, topped by oceanic crust, generally has a thickness of about 100 km. In contrast, continental lithosphere, topped by continental crust, generally has a thickness of about 150 km. Notice that the asthenosphere is entirely in the mantle and generally lies below a depth of 100 to 150 km. We can't assign a specific depth to the base of the asthenosphere because all of the mantle below 150 km can flow, but for convenience, some geologists consider the base of the asthenosphere to be the top of the transition zone.

Now, with an understanding of Earth's overall architecture at hand, we can discuss geology's grand unifying theory—plate tectonics. The next chapter introduces this key topic.

Take-Home Message

Earth's outermost layer, the crust, is very thin; oceanic and continental crust differ in composition. Most of Earth's mass lies in the mantle. A metallic core lies at this planet's center. The crust and the outermost mantle together comprise the rigid lithosphere.

FIGURE 1.17 A block diagram of the lithosphere, emphasizing the difference between continental and oceanic lithosphere.



Chapter Summary

- The geocentric model of the Universe placed the Earth at the center of the Universe. The heliocentric model placed the Sun at the center.
- The Earth is one of eight planets orbiting the Sun. This Solar System lies on the outer edge of the Milky Way galaxy. The Universe contains hundreds of billions of galaxies.
- The red shift of light from distant galaxies led to the expanding Universe theory. Most astronomers agree that expansion began after the Big Bang, 13.7 billion years ago.
- The first atoms (hydrogen and helium) of the Universe developed within minutes of the Big Bang. These atoms formed vast gas clouds, called nebulae.
- Gravity caused clumps of gas in the nebulae to coalesce into flattened disks with bulbous centers. The center of each disk became so dense and hot that fusion reactions began and they became true stars.
- The Earth, and the life forms on it, contains elements that could have been produced only during the life cycle of stars. Thus, we are all made of stardust.
- Planets developed from the rings of gas and dust surrounding protostars. These condensed into planetesimals that then clumped together to form protoplanets, and finally true planets. Inner rings became the terrestrial planets. Outer rings grew into gas-giant planets.
- The Moon formed from debris ejected when a protoplanet collided with the Earth in the young Solar System.
- A planet assumes a near-spherical shape when it becomes so soft that gravity can smooth out irregularities.
- The Earth has a magnetic field that shields it from solar wind and cosmic rays.
- A layer of gas surrounds the Earth. This atmosphere (78% N_2, 21% O_2, and 1% other gases) can be subdivided into layers. Air pressure decreases with increasing elevation.
- The surface of the Earth can be divided into land (30%) and ocean (70%).
- The Earth consists of organic chemicals, minerals, glasses, rocks, metals, melts, and volatiles. Most rocks on Earth contain silica (SiO_2). We distinguish among various major rock types based on the proportion of silica.
- The Earth's interior can be divided into three distinct layers: the very thin crust, the rocky mantle, and the metallic core.
- Pressure and temperature both increase with depth in the Earth. The rate at which temperature increases as depth increases is the geothermal gradient.
- The crust is a thin skin that varies in thickness from 7–10 km (beneath the oceans) to 25–70 km (beneath the continents). Oceanic crust is mafic in composition, whereas average upper continental crust is felsic to intermediate. The mantle is composed of ultramafic rock. The core is made of iron alloy.
- Studies of earthquake waves reveal that the mantle can be subdivided into an upper mantle (including the transition zone) and a lower mantle. The core can be subdivided into the liquid outer core and a solid inner core. Circulation of the outer core produces the Earth's magnetic field.
- The crust plus the upper part of the mantle constitute the lithosphere, a rigid shell. The lithosphere lies over the asthenosphere, mantle that can flow.

Key Terms

alloy (p. 27)
asthenosphere (p. 31)
atmosphere (p. 24)
bathymetry (p. 26)
Big Bang theory (p. 15)
core (p. 28)
cosmology (p. 9)
crust (p. 28)
differentiation (p. 19)
dipole (p. 21)
Doppler effect (p. 13)
earthquake (p. 28)
Earth System (p. 21)
energy (p. 11)
expanding Universe theory (p. 15)
fission (p. 16)
frequency (p. 13)
fusion (p. 16)
galaxy (p. 11)
geocentric model (p. 10)
geothermal gradient (p. 29)
giant planet (p. 12)
gravity (p. 10)
heliocentric model (p. 10)
lithosphere (p. 31)
lower mantle (p. 30)
magnetic field (p. 21)
mantle (p. 28)
melt (p. 27)
metal (p. 27)
meteor (p. 20)
meteorite (pp. 19, 20)
mineral (p. 27)
Moho (p. 29)
moon (p. 13)
nebula (p. 17)
nebular theory (p. 18)
planet (p. 11)
planetesimal (p. 19)
protoplanetary disk (p. 18)
protoplanet (p. 19)
protostar (p. 17)
radioactive element (p. 16)
red shift (p. 13)
refractory (p. 18)
sediment (p. 26)
silica (p. 27)
Solar System (p. 11)
star (p. 11)
stellar nucleosynthesis (p. 17)
stellar wind (p. 17)
supernova (p. 17)
terrestrial planet (p. 12)
transition zone (p. 30)
Universe (p. 9)
upper mantle (p. 30)
volatile (pp. 18, 27)
wave (p. 13)
wavelength (p. 13)

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This particular chapter also features:

- Labeling problems that help students understand Earth's atmospheric layers.
- An animation-based exercise demonstrating planetary movement.
- A video exercise on the formation of the Moon.

Review Questions

1. Contrast the geocentric and heliocentric Universe concepts.
2. Describe how the Doppler effect works.
3. What does the red shift of the galaxies tell us about their motion with respect to the Earth?
4. What is the Big Bang, and when did it occur?
5. Describe the steps in the formation of the Solar System according to the nebular theory.
6. Why isn't the Earth homogeneous?
7. Describe how the Moon was formed.
8. Why is the Earth round?
9. What is the Earth's magnetic field? Draw a representation of the field on a piece of paper. What causes aurorae?
10. What is the Earth's atmosphere composed of? Why would you die of suffocation if you were to eject from a fighter plane at an elevation of 12 km without an oxygen tank?
11. What is the proportion of land area to sea area on Earth?
12. Describe the major categories of materials constituting the Earth. On what basis do geologists distinguish among different kinds of silicate rock?
13. What are the principal layers of the Earth?
14. How do temperature and pressure change with increasing depth in the Earth?
15. What is the Moho? Describe the differences between continental crust and oceanic crust.
16. What is the mantle composed of? Is there any melt in it?
17. What is the core composed of? How do the inner and outer cores differ? Which produces the magnetic field?
18. What is the difference between the lithosphere and asthenosphere? At what depth does the lithosphere-asthenosphere boundary occur? Is this above or below the Moho? In the asthenosphere entirely liquid?

On Further Thought

19. The further a galaxy lies from Earth, the greater its red shift. Why? (*Hint:* Draw two points that are initially 1 cm apart, and two points that are initially 2 cm apart. Imagine doubling the distance between the points in each pair in a given time.)
20. Did all first-generation stars form at the same time?
21. Why are the giant planets, which contain abundant gas and ice, further from the Sun?
22. Recent observations suggest that the Moon has a very small, solid core that is less than 3% of its mass. In comparison, Earth's core is about 33% of its mass. Explain why this difference might exist.
23. The Moon has virtually no magnetosphere. Why?
24. Popular media sometimes imply that the crust floats on a "sea of magma." Is this a correct image of the mantle just below the Moho? Explain your answer.

SEE FOR YOURSELF A. . . Earth and Sky

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet A of our **Geotours Workbook**.



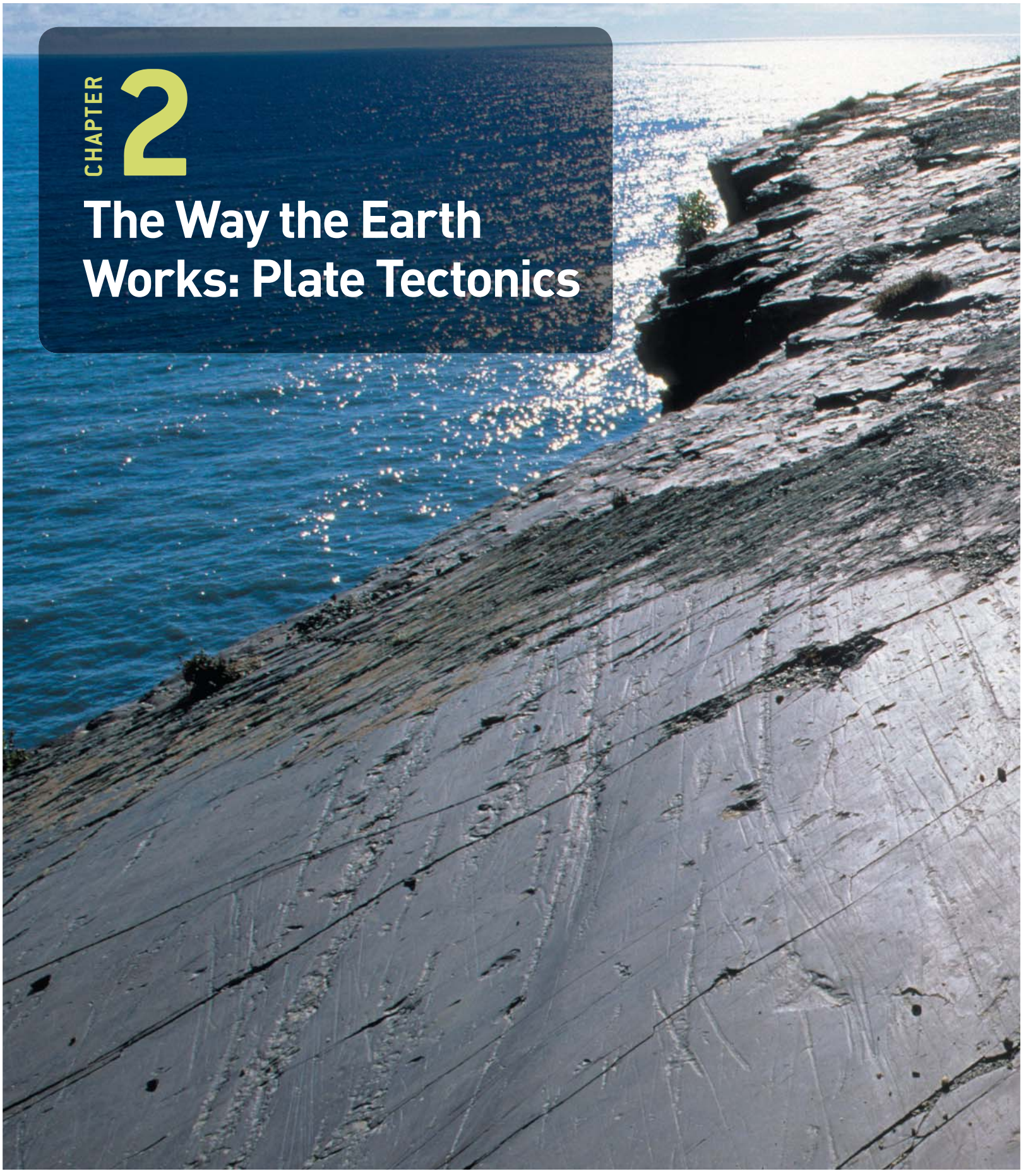
Barringer Crater, Arizona
Latitude 35°1′35.23″N,
Longitude 111°1′22.23″W

This structure, also known as Meteor Crater, is 1.2 km in diameter and formed from the impact of an iron meteorite about 50,000 years ago. Viewed from an elevation of 5 km, you can see the raised rim of the crater.



View of the Whole Earth
Latitude 05°56′59.21″N,
Longitude 143°6′23.83″E

An astronaut looking down on the western Pacific region from 14,000 km out in space can distinguish land from sea and can see the variation in amount of vegetation. Instruments reveal the shape of the sea-floor.



CHAPTER 2

The Way the Earth Works: Plate Tectonics



Bedrock exposed at Hallett Cove, along the south coast of Australia, an area that lies in a warm climate now, was scratched by glaciers 300 million years ago.

Chapter Objectives

By the end of this chapter you should know . . .

- Wegener's evidence for continental drift.
- how study of paleomagnetism proves that continents move.
- how sea-floor spreading works, and how geologists can prove that it takes place.
- that the Earth's lithosphere is divided into about 20 plates that move relative to one another.
- the three kinds of plate boundaries and the basis for recognizing them.
- how fast plates move, and how we can measure the rate of movement.

We are like a judge confronted by a defendant who declines to answer, and we must determine the truth from the circumstantial evidence.

—Alfred Wegener (German scientist, 1880–1930; on the challenge of studying the Earth)

2.1 Introduction

In September 1930, fifteen explorers led by a German meteorologist, Alfred Wegener, set out across the endless snowfields of Greenland to resupply two weather observers stranded at a remote camp. The observers had been planning to spend the long polar night recording wind speeds and temperatures on Greenland's polar plateau. At the time, Wegener was well known, not only to researchers studying climate but also to geologists. Some fifteen years earlier, he had published a small book, *The Origin of the Continents and Oceans*, in which he had dared to challenge geologists' long-held assumption that the continents had remained fixed in position through all of Earth history. Wegener thought, instead, that the continents once fit together like pieces of a giant jigsaw puzzle, to make one vast supercontinent. He suggested that this supercontinent, which he named **Pangaea** (pronounced pan-Jee-ah; Greek for all land), later fragmented into separate continents that drifted apart, moving slowly to their present positions (**Fig. 2.1a, b**). This model came to be known as **continental drift**.

Wegener presented many observations in favor of continental drift, but he met with strong resistance. At a widely publicized 1926 geology conference in New York City, a crowd of celebrated American professors scoffed, "What force could

possibly be great enough to move the immense mass of a continent?" Wegener's writings didn't provide a good answer, so despite all the supporting observations he had provided, most of the meeting's participants rejected continental drift.

Now, four years later, Wegener faced his greatest challenge. On October 30, 1930, Wegener reached the observers and dropped off enough supplies to last the winter. Wegener and one companion set out on the return trip the next day, but they never made it home.

Had Wegener survived to old age, he would have seen his hypothesis become the foundation of a scientific revolution. Today, geologists accept many aspects of Wegener's ideas and take for granted that the map of the Earth constantly changes; continents waltz around this planet's surface, variously combining and breaking apart through geologic time. The revolution began in 1960, when an American geologist, Harry Hess, proposed that as continents drift apart, new ocean floor forms between them by a process that his contemporary, Robert Dietz, also had described and named **sea-floor spreading**. Hess and others suggested that continents move toward each other when the old ocean floor between them sinks back down into the Earth's interior, a process now called **subduction**. By 1968, geologists had developed a fairly complete model encompassing continental drift, sea-floor spreading, and subduction. In this model, Earth's lithosphere, its outer, relatively rigid shell, consists of about twenty distinct pieces, or plates, that slowly move relative to each other. Because we can confirm this model using many observations, it has gained the status of a theory, which we now call the theory of plate tectonics, or simply **plate tectonics**, from the Greek word *tekton*, which means builder; plate movements "build" regional geologic features. Geologists view plate tectonics as the grand unifying theory of geology, because it can successfully explain a great many geologic phenomena.

In this chapter, we introduce the observations that led Wegener to propose continental drift. Then we look at paleomagnetism, the record of Earth's magnetic field in the past, because it provides a key proof of continental drift. Next, we learn how observations about the sea floor, made by geologists during the mid-twentieth century, led Harry Hess to propose the concept of sea-floor spreading. We conclude by describing the many facets of modern plate tectonics theory.

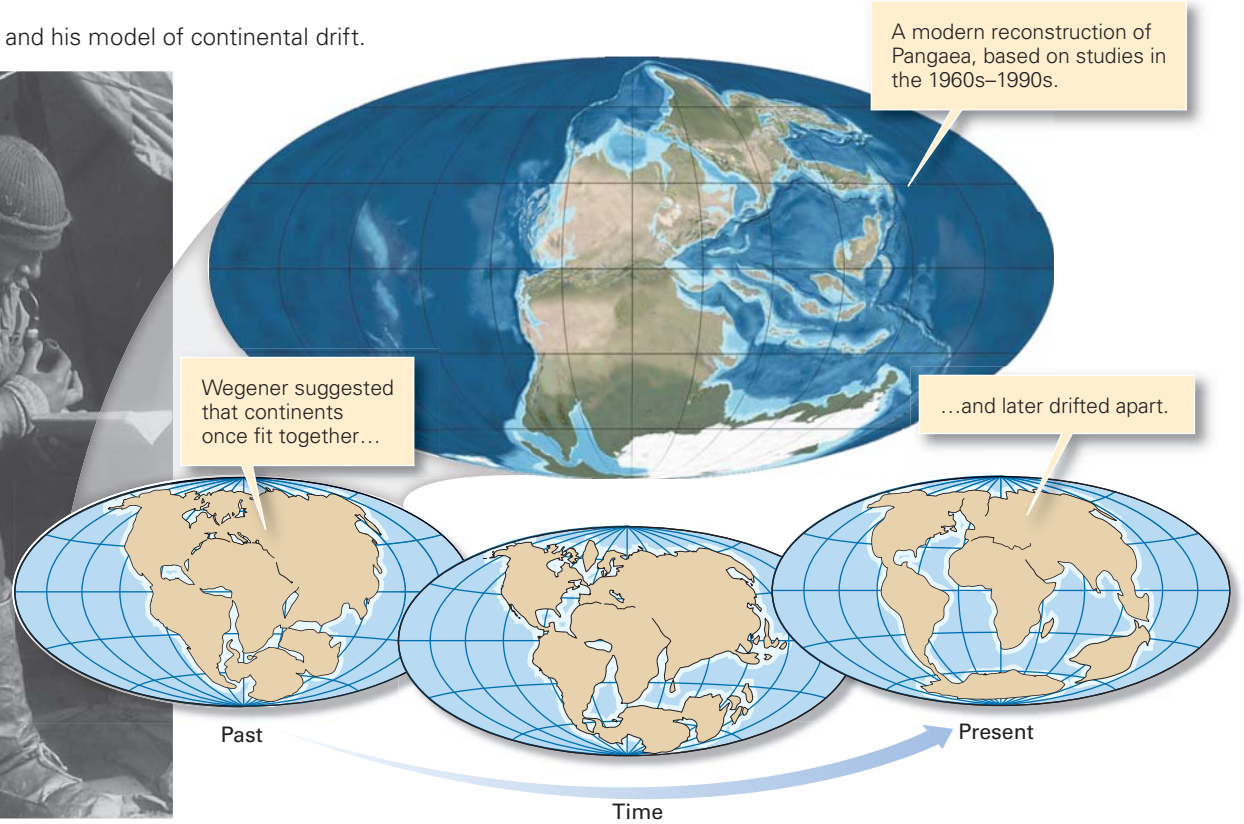
2.2 Wegener's Evidence for Continental Drift

Wegener suggested that a vast supercontinent, Pangaea, existed until near the end of the Mesozoic Era (the interval of geologic time that lasted from 251 to 65 million years ago). He

FIGURE 2.1 Alfred Wegener and his model of continental drift.



(a) Wegener in Greenland



(b) Wegener's maps illustrating continental drift as he drew them about 1915. Many details of the reconstruction have changed since, as illustrated by the inset.

suggested that Pangaea then broke apart, and the landmasses moved away from each other to form the continents we see today. Let's look at some of Wegener's arguments and see what led him to formulate this hypothesis of continental drift.

The Fit of the Continents

Almost as soon as maps of the Atlantic coastlines became available in the 1500s, scholars noticed the fit of the continents. The northwestern coast of Africa could tuck in against the eastern coast of North America, and the bulge of eastern South America could nestle cozily into the indentation of southwestern Africa. Australia, Antarctica, and India could all connect to the southeast of Africa, while Greenland, Europe, and Asia could pack against the northeastern margin of North America. In fact, all the continents could be joined, with remarkably few overlaps or gaps, to create Pangaea. Wegener concluded that the fit was too good to be coincidence and thus that the continents once *did* fit together.

Did you ever wonder . . .
why opposite coasts of the Atlantic look like they fit together?

Locations of Past Glaciations

Glaciers are rivers or sheets of ice that flow across the land surface. As a glacier flows, it carries sediment grains of all sizes (clay, silt, sand, pebbles, and boulders). Grains protruding from the base of the moving ice carve scratches, called striations, into the substrate. When the ice melts, it leaves the sediment in a deposit called till, that buries striations. Thus, the occurrence of till and striations at a location serve as evidence that the region was covered by a glacier in the past (see chapter opening photo). By studying the age of glacial till deposits, geologists have determined that large areas of the land were covered by glaciers during time intervals of Earth history called ice ages. One of these ice ages occurred from about 326 to 267 Ma, near the end of the Paleozoic Era.

Wegener was an Arctic climate scientist by training, so it's no surprise that he had a strong interest in glaciers. He knew that glaciers form mostly at high latitudes today. So he suspected that if he plotted a map of the locations of late Paleozoic glacial till and striations, he might gain insight into the locations of continents during the Paleozoic. When he plotted these locations, he found that glaciers of this time interval occurred in southern South America, southern Africa, southern India, Antarctica, and southern Australia. These places are now widely separated and, with the exception of Antarctica, do not currently lie in cold polar regions (**Fig. 2.2a**). To Wegener's amazement, all late Paleozoic glaciated areas lie *adjacent* to each other on his map of Pangaea. Furthermore, when he plotted the orientation of glacial striations, they all pointed roughly outward from a location in southeastern Africa. In other words, Wegener determined that the distribution of glaciations at the end of the Paleozoic Era could easily be explained if the continents had been united in Pangaea, with the southern part of Pangaea lying beneath the center of a huge ice cap. This distribution of glaciation could not be explained if the continents had always been in their present positions.

The Distribution of Climatic Belts

If the southern part of Pangaea had straddled the South Pole at the end of the Paleozoic Era, then during this same time interval, southern North America, southern Europe, and northwestern Africa would have straddled the equator and would have had tropical or subtropical climates. Wegener searched for evidence that this was so by studying sedimentary rocks that were formed at this time, for the material making up these rocks can reveal clues to the past climate. For example, in the swamps and jungles of tropical regions, thick deposits of plant material accumulate, and when deeply buried, this material transforms into coal. And in the clear, shallow seas of tropical regions, large reefs develop. Finally, subtropical regions, on either side of the tropical belt, contain deserts, an environment in which sand dunes form and salt from evaporating seawater or salt lakes accumulates. Wegener speculated that the distribution of late Paleozoic coal, reef, sand-dune, and salt deposits could define climate belts on Pangaea.

Sure enough, in the belt of Pangaea that Wegener expected to be equatorial, late Paleozoic sedimentary rock layers include abundant coal and the relicts of reefs. And in the portions of Pangaea that Wegener predicted would be subtropical, late Paleozoic sedimentary rock layers include relicts of desert dunes and deposits of salt (**Fig. 2.2b**). On a present-day map of our planet, exposures of these ancient rock layers scatter around the globe at a variety of latitudes. On Wegener's Pangaea, the exposures align in continuous bands that occupy appropriate latitudes.

The Distribution of Fossils

Today, different continents provide homes for different species. Kangaroos, for example, live only in Australia. Similarly, many kinds of plants grow only on one continent and not on others. Why? Because land-dwelling species of animals and plants cannot swim across vast oceans, and thus evolved independently on different continents. During a period of Earth history when all continents were in contact, however,

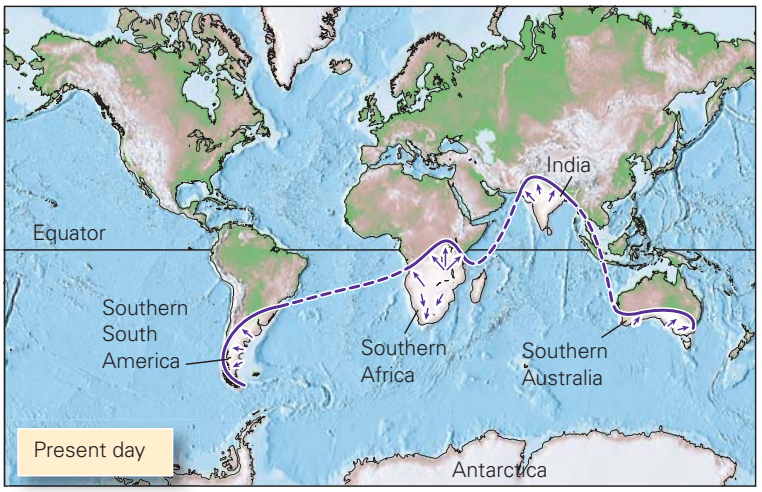
land animals and plants could have migrated among many continents.

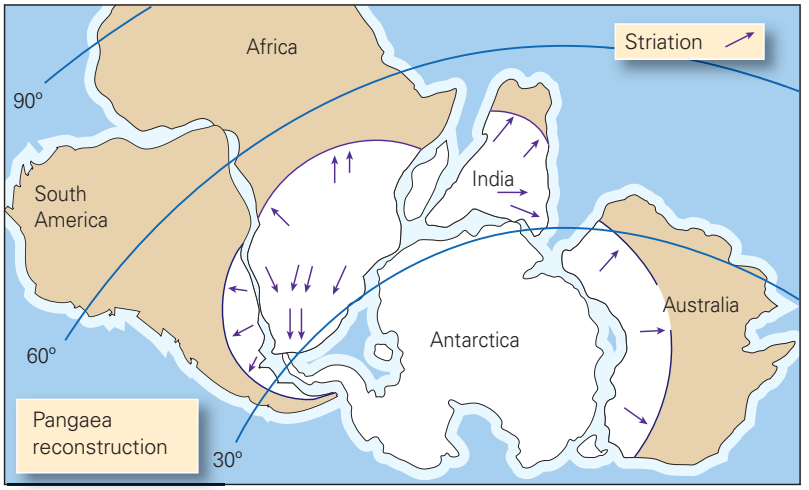
With this concept in mind, Wegener plotted fossil occurrences of land-dwelling species that existed during the late Paleozoic and early Mesozoic Eras (between about 300 and 210 million years ago) and found that these species had indeed existed on several continents (**Fig. 2.2c**). Wegener argued that the distribution of fossil species required the continents to have been adjacent to one another in the late Paleozoic and early Mesozoic Eras.

Matching Geologic Units

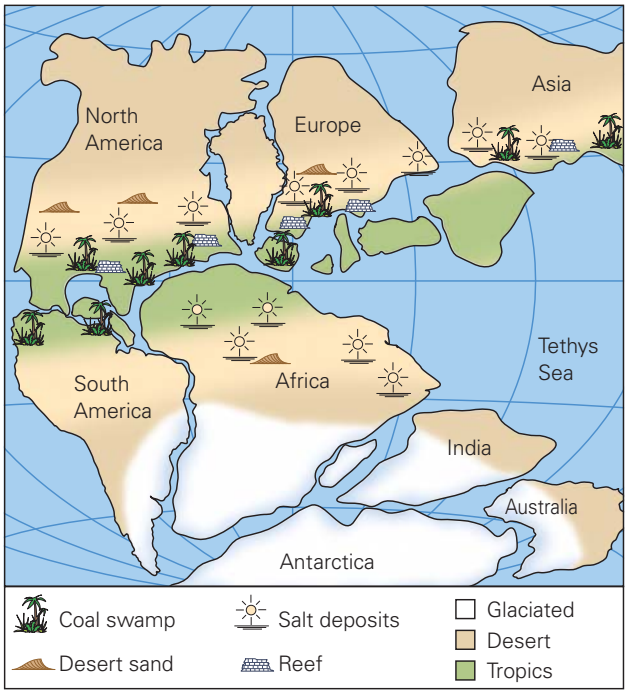
An art historian can recognize a Picasso painting, an architect knows what makes a building look "Victorian," and a geoscientist can identify a distinctive assemblage of rocks. Wegener found that the same distinctive Precambrian rock assemblages occurred on the eastern coast of South America and the western coast of Africa, regions now separated by an ocean (**Fig. 2.3a**). If the continents had been joined to create Pangaea in the past, then these matching rock groups would have been adjacent to each other, and thus could have composed

FIGURE 2.2 Wegener's evidence for continental drift came from analyzing the geologic record.

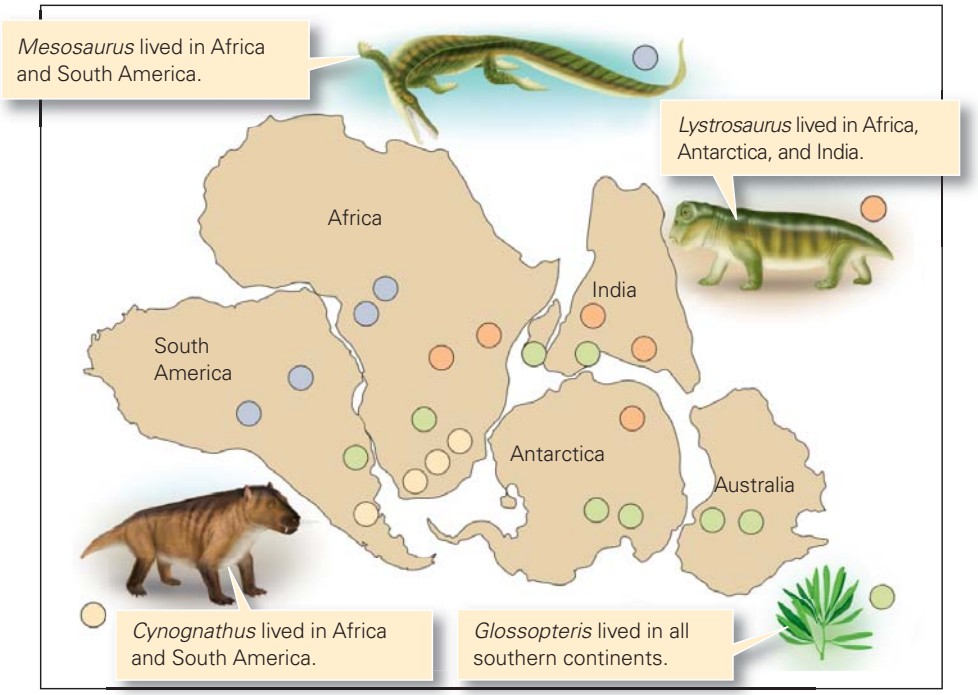




(a) The distribution of late Paleozoic glacial deposits and striations on present-day Earth are hard to explain. But on Pangaea, areas with glacial deposits fit together in a southern polar cap.



(b) The distribution of late Paleozoic rock types plots sensibly in the climate belts of Pangaea.



(c) A plot of fossil localities shows that Mesozoic land-dwelling organisms occur on multiple continents. This would be hard to explain if continents were separated.

continuous blocks or belts. Wegener also noted that features of the Appalachian Mountains of the United States and Canada closely resemble mountain belts in southern Greenland, Great Britain, Scandinavia, and northwestern Africa (Fig. 2.3b, c), regions that would have lain adjacent to each other in Pangaea. Wegener thus demonstrated that not only did the coastlines of continents match, so too did the rocks adjacent to the coastlines.

Take-Home Message

Wegener argued that the continents were once merged into a supercontinent called Pangaea that later broke up to produce smaller continents that "drifted" apart. The matching shapes of coastlines, as well as the distribution of ancient climate belts, fossils, and rock units all make better sense if Pangaea existed.

Criticism of Wegener's Ideas

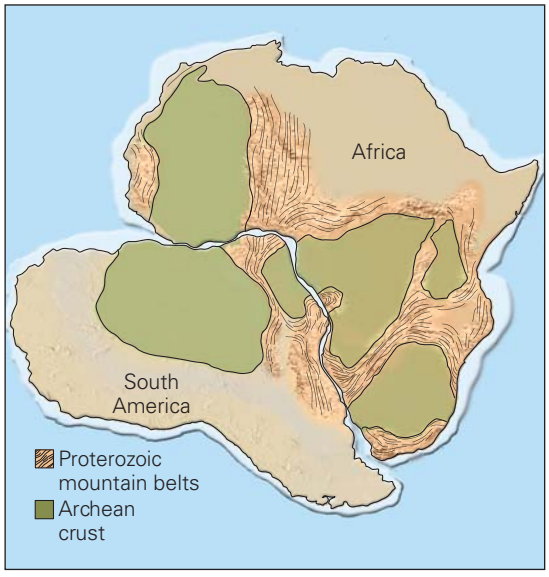
Wegener's model of a supercontinent that later broke apart explained the distribution of ancient glaciers, coal, sand dunes, rock assemblages, and fossils. Clearly, he had compiled a strong *circumstantial* case for continental drift. But as noted earlier, he could not adequately explain how or why continents drifted. He left on his final expedition to Greenland having failed to convince his peers, and he died without knowing that his ideas, after lying dormant for decades, would be reborn as the basis of the broader theory of plate tectonics.

In effect, Wegener was ahead of his time. It would take three more decades of research before geologists obtained sufficient data to test his hypotheses properly. Collecting this data required instruments and techniques that did not exist in Wegener's day. Of the many geologic discoveries that ultimately opened the door to plate tectonics, perhaps the most important came from the discovery of a phenomenon called paleomagnetism, so we discuss it next.

2.3 Paleomagnetism and the Proof of Continental Drift

More than 1,500 years ago, Chinese sailors discovered that a piece of lodestone, when suspended from a thread, points in a northerly direction and can help guide a voyage. Lodestone exhibits this behavior because it consists of magnetite, an iron-rich mineral that, like a compass needle, aligns with Earth's magnetic field lines. While not as magnetic as lodestone, several other rock types contain tiny crystals of magnetite, or other magnetic minerals, and thus behave overall like weak magnets. In this section, we explain how the study of such magnetic behavior led to the realization that rocks preserve paleomagnetism, a record of Earth's magnetic field in the past. An understanding of paleomagnetism provided proof of continental drift and, as we'll see later in this chapter, contributed

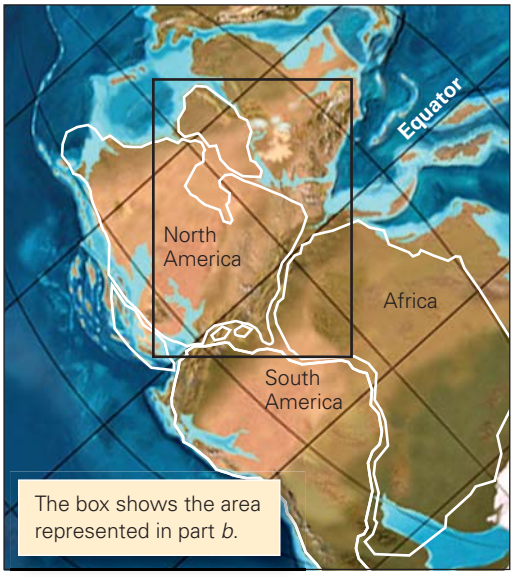
FIGURE 2.3 Further evidence of drift: rocks on different sides of the ocean match.



(a) Distinctive belts of rock in South America would align with similar ones in Africa, without the Atlantic.



(b) If the Atlantic didn't exist, Paleozoic mountain belts on both coasts would be adjacent.



(c) A modern reconstruction showing the positions of mountain belts in Pangaea. Modern continents are outlined in white.

to the development of plate tectonics theory. As a foundation for introducing paleomagnetism, we first provide additional detail about the basic nature of the Earth's magnetic field.

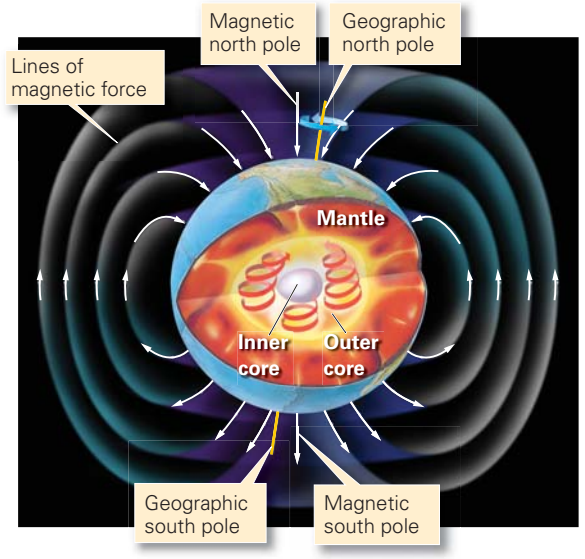
Earth's Magnetic Field

As we mentioned in Chapter 1, circulation of liquid iron alloy in the outer core of the Earth generates a magnetic field. (A similar phenomenon happens in an electrical dynamo at a power plant.) Earth's magnetic field resembles the field produced by a bar magnet, in that it has two ends of opposite polarity. Thus, we can represent Earth's field by a **magnetic dipole**, an imaginary arrow (Fig. 2.4a). Earth's dipole intersects the surface of the planet at two points, known as the **magnetic poles**. By convention, the north *magnetic* pole is at the end of the Earth nearest the north *geographic* pole (the point where the northern end of the spin axis intersects the surface). The north-seeking (red) end of a compass needle points to the north magnetic pole.

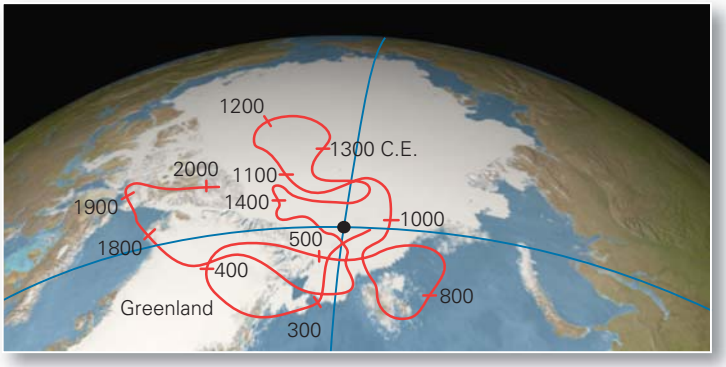
Did you ever wonder . . .
why compasses always point to the north?

Earth's magnetic poles move constantly, but don't seem to stray further than about 1,500 km from the geographic poles, and averaged over thousands of years, they roughly coincide with Earth's geographic poles (Fig. 2.4b). That's because the rotation of the Earth causes the flow to organize into patterns resembling spring-like spirals, and these are roughly aligned with the spin axis. At present, the magnetic poles lie hundreds of kilometers away from the geographic poles, so the magnetic dipole tilts at about 11° relative to the Earth's spin axis. Because of this difference, a compass today does not point exactly to geographic north. The angle between the direction that a compass needle points and a line of longitude at a given location is the **magnetic declination** (Fig. 2.4c).

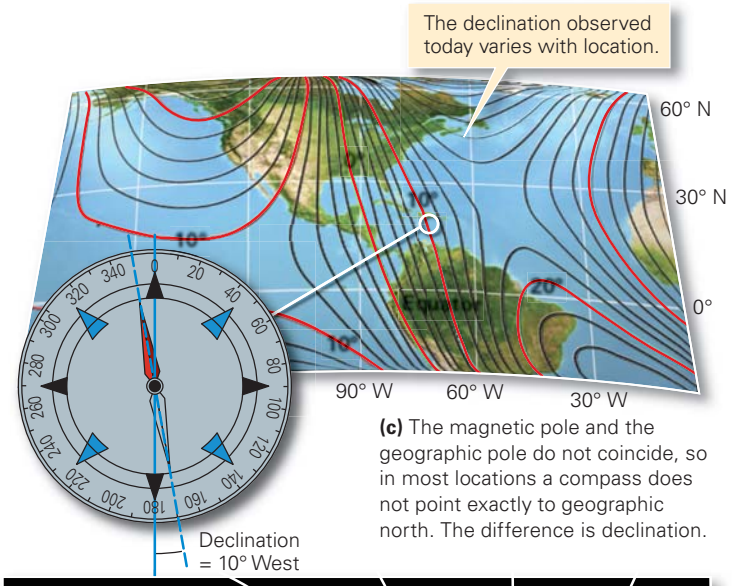
FIGURE 2.4 Features of Earth's magnetic field.



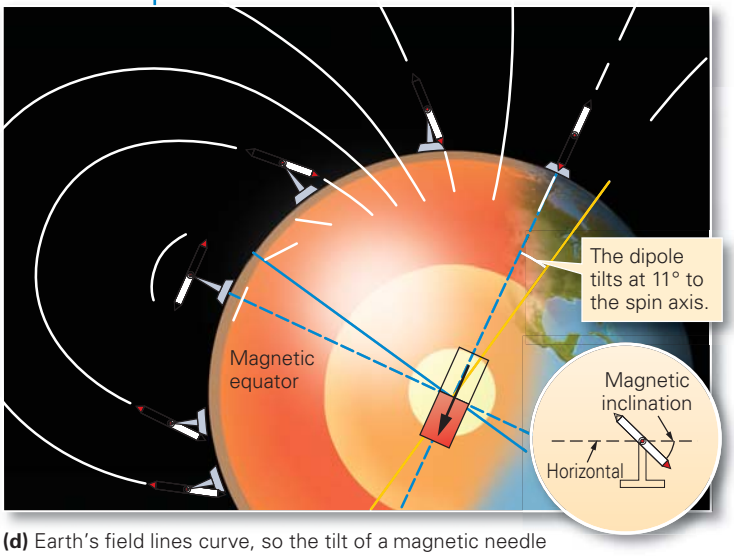
(a) The magnetic axis is not parallel to the spin axis. In 3-D, the Earth's magnetic field can be visualized as invisible curtains of energy, generated by flow to the outer core.



(b) A map of the magnetic pole position during the past 1,800 years shows that the pole moves, but stays within high latitudes.



(c) The magnetic pole and the geographic pole do not coincide, so in most locations a compass does not point exactly to geographic north. The difference is declination.



(d) Earth's field lines curve, so the tilt of a magnetic needle changes with latitude. This tilt is the magnetic inclination.

Invisible field lines curve through space between the magnetic poles. In a cross-sectional view, these lines lie parallel to the surface of the Earth (that is, are horizontal) at the equator, tilt at an angle to the surface in midlatitudes, and plunge perpendicular to the surface at the magnetic poles (Fig. 2.4d). The angle between a magnetic field line and the surface of the Earth, at a given location, is called the **magnetic inclination**. If you place a magnetic needle on a horizontal axis so that it can pivot up and down, and then carry it from the magnetic equator to the magnetic pole, you'll see that the inclination varies with latitude—it is 0° at the magnetic equator and 90° at the magnetic poles. (Note that the compass you may carry with you on a hike does not show inclination because it has been balanced to remain horizontal.)

What Is Paleomagnetism?

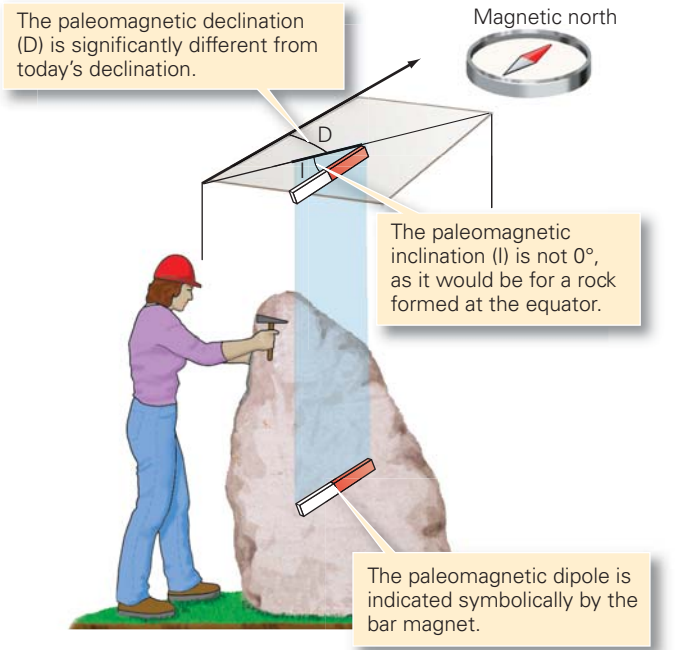
In the early 20th century, researchers developed instruments that could measure the weak magnetic field produced by rocks and made a surprising discovery. In a rock that formed millions of years ago, the orientation of the dipole representing the magnetic field of the rock *is not the same* as that of present-day Earth (Fig. 2.5a). To understand this statement, consider an example. Imagine traveling to a location near the coast on the equator in South America where the inclination and declination are presently 0°. If you measure the weak magnetic field produced by, say, a 90-million-year-old rock, and represent the orientation of this field by an imaginary bar magnet, you'll find that this imaginary bar magnet does *not* point to the present-day north magnetic pole, and you'll find that its inclination is not 0°. The reason for this difference is that the magnetic fields of ancient rocks indicate the orientation of the magnetic field, relative to the rock, at the time the rock formed. This record, preserved in rock, is **paleomagnetism**.

Paleomagnetism can develop in many different ways. For example, when lava, molten rock containing no crystals, starts to cool and solidify into rock, tiny magnetite crystals begin to grow (Fig. 2.5b). At first, thermal energy causes the tiny magnetic dipole associated with each crystal to wobble and tumble chaotically. Thus, at any given instant, the dipoles of the magnetite specks are randomly oriented and the magnetic forces they produce cancel each other out. Eventually, however, the rock cools sufficiently that the dipoles slow down and, like tiny compass needles, align with the Earth's magnetic field. As the rock cools still more, these tiny compass needles lock into permanent parallelism with the Earth's magnetic field at the time the cooling takes place. Since the magnetic dipoles of all the grains point in the same direction, they add together and produce a measurable field.

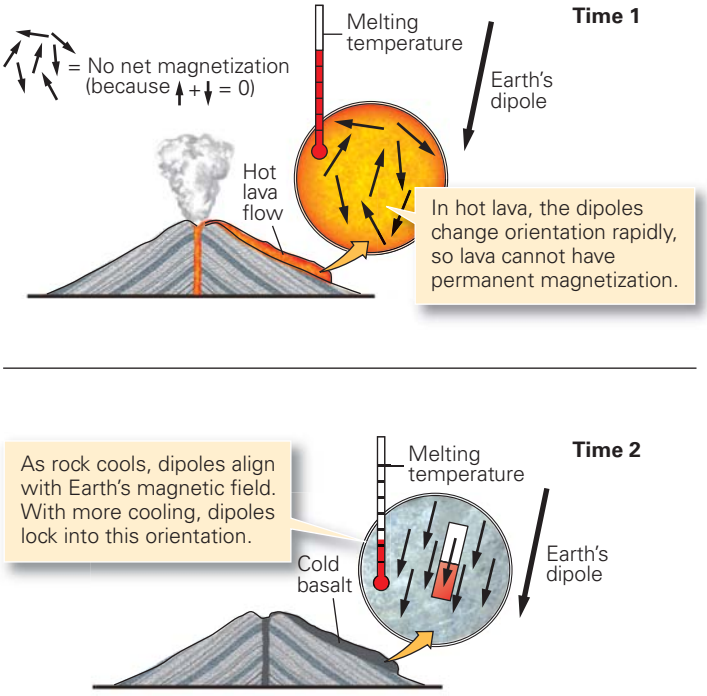
Apparent Polar Wander—A Proof That Continents Move

Why doesn't the paleomagnetic dipole in ancient rocks point to the present-day magnetic field? When geologists first

FIGURE 2.5 Paleomagnetism and how it can form during the solidification and cooling of lava.



(a) A geologist finds an ancient rock sample at a location on the equator, where declination today is 0°. The orientation of the rock's paleomagnetism is different from that of today's field.



(b) Paleomagnetism can form when lava cools and becomes solid rock.

attempted to answer this question, they *assumed* that continents were fixed in position and thus concluded that the positions of Earth's magnetic poles in the past were different than they are today. They introduced the term **paleopole** to refer to the supposed position of the Earth's magnetic north pole in the past. With this concept in mind, they set out to track what they thought was the change in position of the paleopole over time. To do this, they measured the paleomagnetism in a succession of rocks of different ages from the same general location on a continent, and they plotted the position of the associated succession of paleopole positions on a map (Fig. 2.6a). The successive positions of dated paleopoles trace out a curving line that came to be known as an **apparent polar-wander path.**

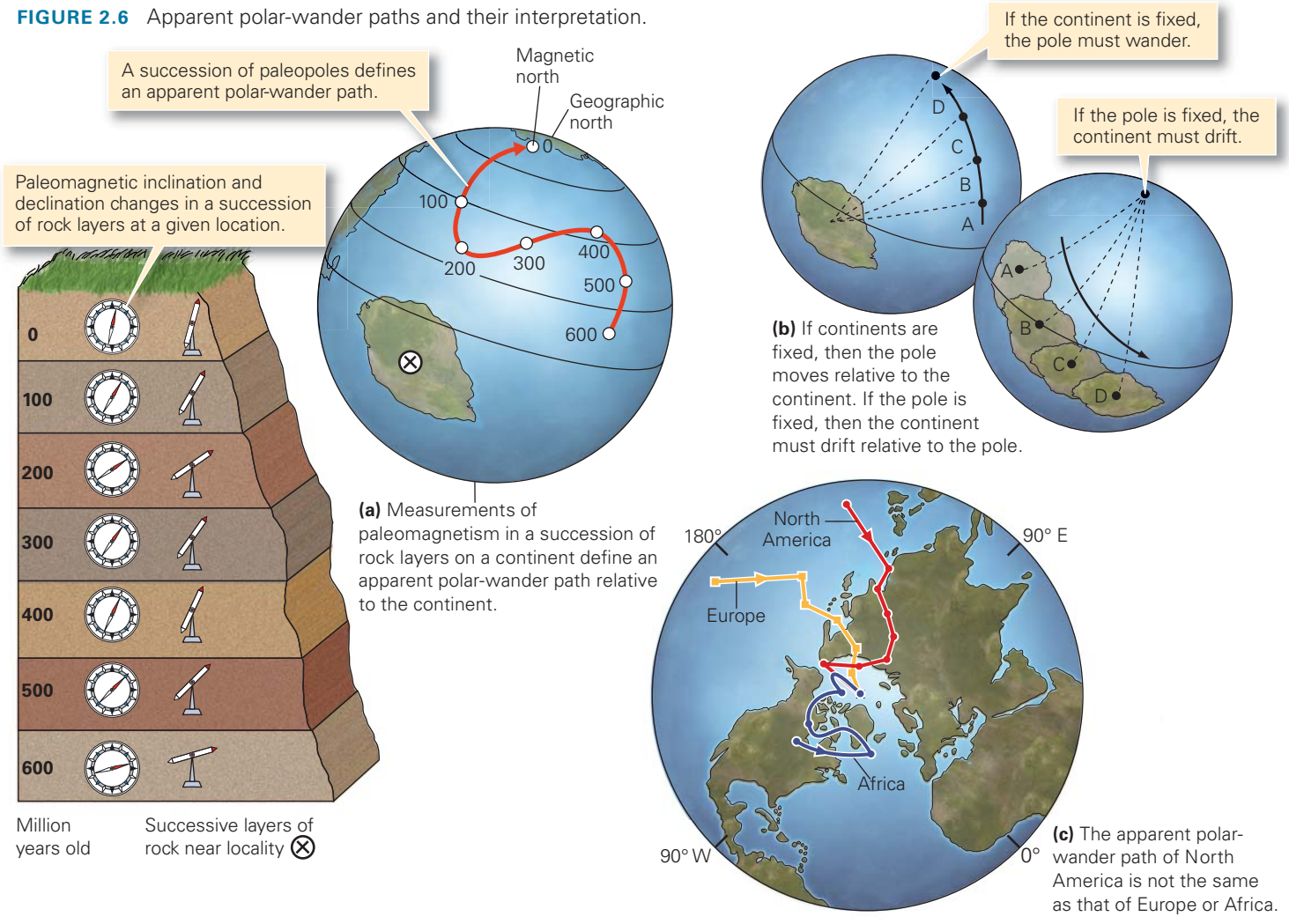
At first, geologists assumed that the apparent polar-wander path actually represented how the position of Earth's magnetic pole migrated through time. But were they in for a surprise! When they obtained polar-wander paths from many different continents, they found that *each continent has a different apparent polar-wander path.* The hypothesis that continents are fixed in position cannot explain this observation, for if the magnetic pole moved while all the continents stayed fixed, measurements from all continents should produce the same apparent polar-wander paths.

Geologists suddenly realized that they were looking at apparent polar-wander paths in the wrong way. It's not the pole that moves relative to fixed continents, but rather the continents that move relative to a fixed pole (Fig. 2.6b). Since each continent has its own unique polar-wander path (Fig. 2.6c), *the continents must move with respect to each other.* The discovery proved that Wegener was essentially right all along—continents do move!

Take-Home Message

Study of paleomagnetism indicates that the continents have moved relative to the Earth's magnetic poles. Each continent has a different apparent polar-wander path, which is only possible if the continents move ("drift") relative to each other.

FIGURE 2.6 Apparent polar-wander paths and their interpretation.



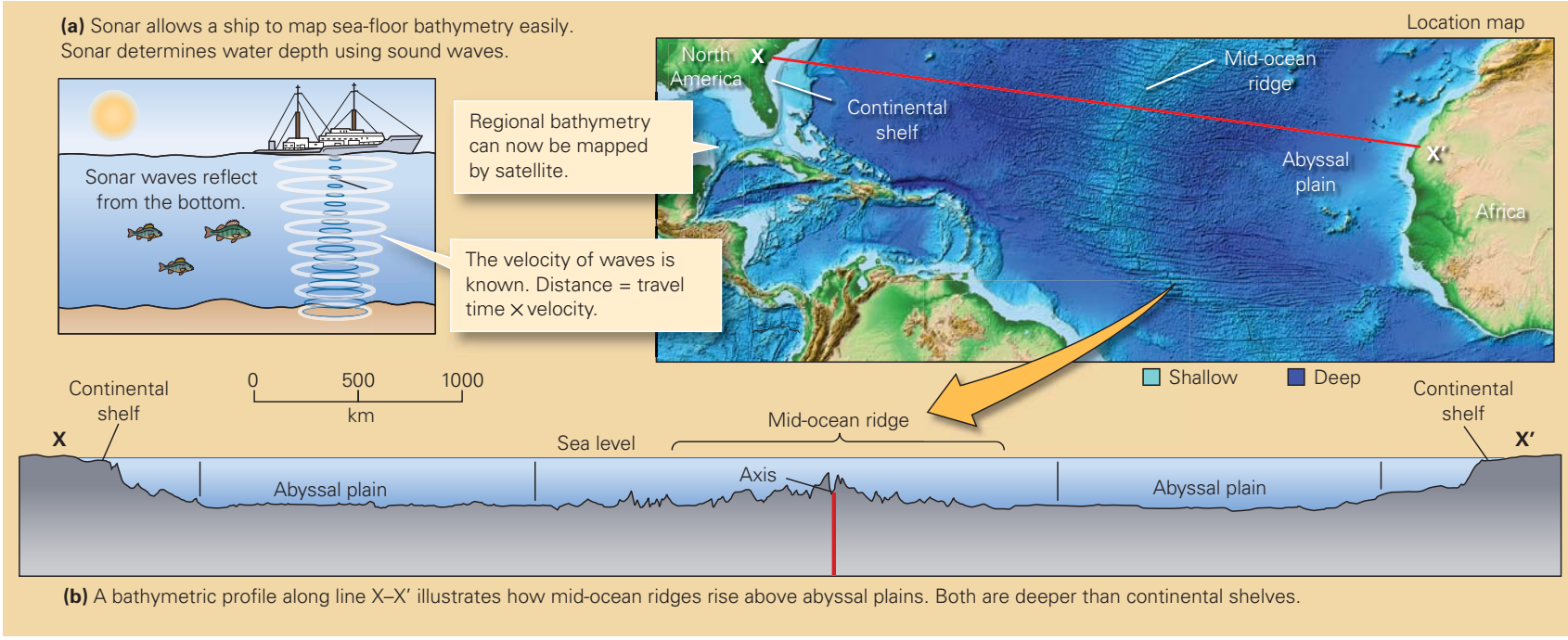
2.4 The Discovery of Sea-Floor Spreading

New Images of Sea-Floor Bathymetry

Military needs during World War II gave a boost to sea-floor exploration, for as submarine fleets grew, navies required detailed information about **bathymetry**, or depth variations. The invention of echo sounding (sonar) permitted such information to be gathered quickly. Echo sounding works on the same principle that a bat uses to navigate and find insects. A sound pulse emitted from a ship travels down through the water, bounces off the sea floor, and returns up as an echo through the water to a receiver on the ship. Since sound waves travel at a known velocity, the time between the sound emission and the echo detection indicates the distance between the ship and the sea floor. (Recall that velocity = distance/time, so distance = velocity × time.) As the ship travels, observers can obtain a continuous record of the depth of the sea floor. The resulting cross section showing depth plotted against location is called a bathymetric profile (Fig. 2.7a, b). By cruising back and forth across the ocean many times, investigators obtained a series of bathymetric profiles and from these constructed maps of the sea floor. (Geologists can now produce such maps much more rapidly using satellite data.) Bathymetric maps reveal several important features.

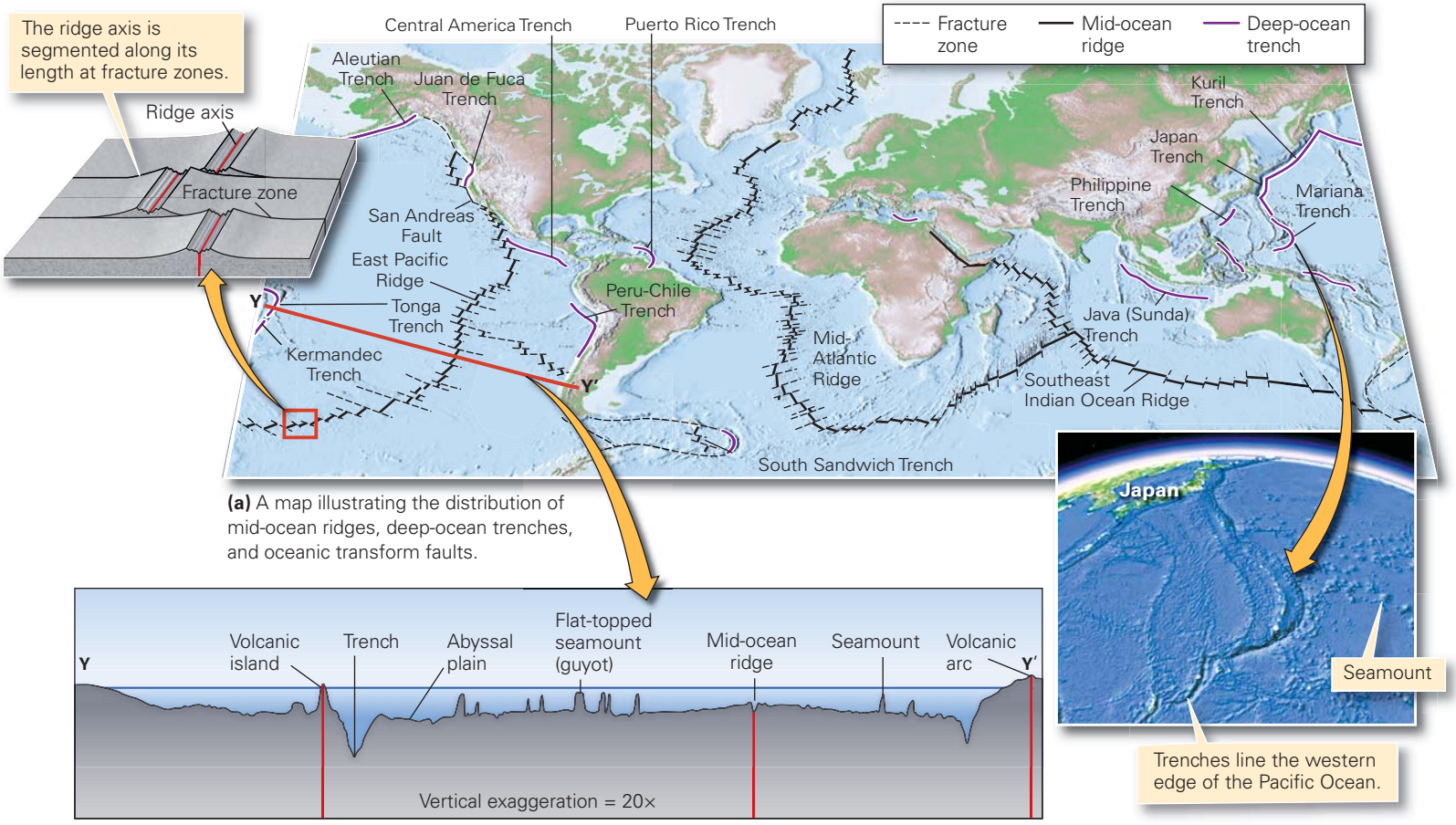
- *Mid-ocean ridges*: The floor beneath all major oceans includes **abyssal plains**, which are broad, relatively flat regions of the ocean that lie at a depth of about 4 to 5 km below sea level; and **mid-ocean ridges**, submarine mountain ranges whose peaks lie only about 2 to 2.5 km below sea level (Fig. 2.8a). Geologists call the crest of the mid-ocean ridge the ridge axis. All mid-ocean ridges are roughly symmetrical—bathymetry on one side of the axis is nearly a mirror image of bathymetry on the other side.
- *Deep-ocean trenches*: Along much of the perimeter of the Pacific Ocean, and in a few other localities as well, the ocean floor reaches depths of 8 to 12 km—deep enough to swallow Mt. Everest. These deep areas occur in elongate troughs that are now referred to as **trenches** (Fig. 2.8b). Trenches border **volcanic arcs**, curving chains of active volcanoes.
- *Seamount chains*: Numerous volcanic islands poke up from the ocean floor: for example, the Hawaiian Islands lie in the middle of the Pacific. In addition to islands that rise above sea level, sonar has detected many **seamounts** (isolated submarine mountains), which were once volcanoes but no longer erupt. Volcanic islands and seamounts typically occur in chains, but in contrast to the volcanic arcs that border deep-ocean trenches, only one island at the end of a seamount and island chain remains capable of erupting volcanically today.
- *Fracture zones*: Surveys reveal that the ocean floor is diced up by narrow bands of vertical cracks and broken-up rock. These **fracture zones** lie roughly at right angles to mid-ocean ridges. The ridge axis typically steps sideways when it intersects with a fracture zone.

FIGURE 2.7 Bathymetry of mid-ocean ridges and abyssal plains.



(b) A bathymetric profile along line X–X′ illustrates how mid-ocean ridges rise above abyssal plains. Both are deeper than continental shelves.

FIGURE 2.8 Other bathymetric features of the ocean floor.



(a) A map illustrating the distribution of mid-ocean ridges, deep-ocean trenches, and oceanic transform faults.

(b) In addition to mid-ocean ridges, the sea floor displays other bathymetric features such as deep-sea trenches, oceanic islands, guyots, and seamounts, as shown in this vertically exaggerated profile.

New Observations on the Nature of Oceanic Crust

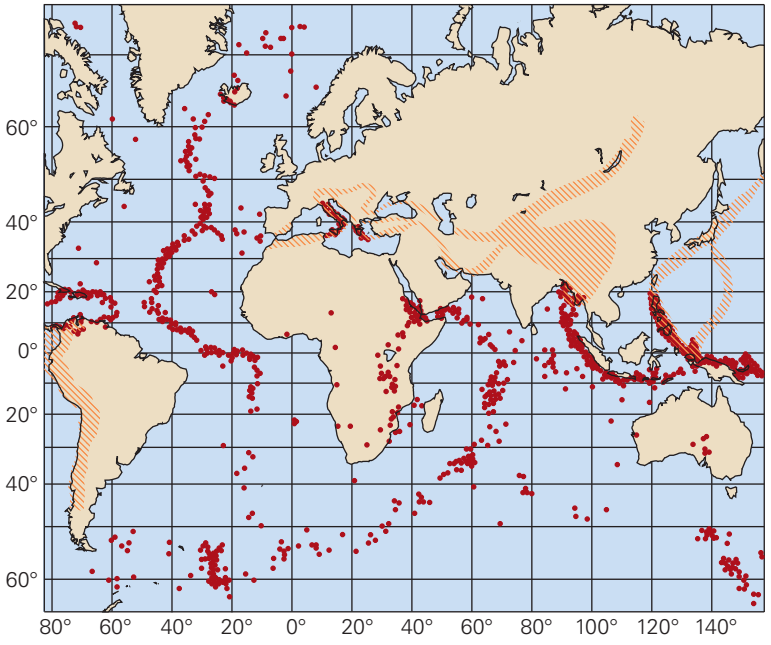
By the mid-20th century, geologists had discovered many important characteristics of the sea-floor crust. These discoveries led them to realize that oceanic crust differs from continental crust, and that bathymetric features of the ocean floor provide clues to the origin of the crust. Specifically:

- A layer of sediment composed of clay and the tiny shells of dead plankton covers much of the ocean floor. This layer becomes progressively thicker away from the mid-ocean ridge axis. But even at its thickest, the sediment layer is too thin to have been accumulating for the entirety of Earth history.
- By dredging up samples, geologists learned that oceanic crust is fundamentally different in composition from continental crust. Beneath its sediment cover, oceanic crust bedrock consists primarily of basalt—it does not display the great variety of rock types found on continents.
- Heat flow, the rate at which heat rises from the Earth's interior up through the crust, is not the same everywhere in the oceans. Rather, more heat rises beneath mid-ocean ridges than elsewhere. This observation led researchers to speculate that hot magma might be rising into the crust just below the mid-ocean ridge axis.
- When maps showing the distribution of earthquakes in oceanic regions became available in the years after World War II, it became clear that earthquakes do not occur randomly, but rather define distinct belts (**Fig. 2.9**). Some belts follow trenches, some follow mid-ocean ridge axes, and others lie along portions of fracture zones. Since earthquakes define locations where rocks break and move, geologists realized that these bathymetric features are places where motion is taking place.

Harry Hess and His "Essay in Geopoetry"

In the late 1950s, Harry Hess, after studying the observations described above, realized that because the sediment layer on the ocean floor was thin overall, the ocean floor might be much younger than the continents. Also, because the sediment thickened progressively away from mid-ocean ridges, the ridges themselves likely were younger than the deeper parts of the

FIGURE 2.9 A 1953 map showing the distribution of earthquake locations in the ocean basins. Note that earthquakes occur in belts.



ocean floor. If this was so, then somehow *new ocean floor must be forming at the ridges*, and thus an ocean basin could be getting wider with time. But how? The association of earthquakes with mid-ocean ridges suggested to him that the sea floor was cracking and splitting apart at the ridge. The discovery of high heat flow along mid-ocean ridge axes provided the final piece of the puzzle, for it suggested the presence of very hot molten rock beneath the ridges. In 1960, Hess suggested that indeed molten rock (basaltic magma) rose upward beneath mid-ocean ridges and that this material solidified to form oceanic crust basalt (Fig. 2.10). The new sea floor then moved away from the ridge, a process we now call **sea-floor spreading**. Hess realized that old ocean floor must be consumed somewhere, or the Earth would have to be expanding, so he suggested that deep-ocean trenches might be places where the sea floor sank back into the mantle. Hess suggested that earthquakes at trenches were evidence of this movement, but he didn't understand how the movement took place. Other geologists, such as Robert Dietz, were coming to similar conclusions at about the same time.

Did you ever wonder . . .
if the distance between New York and Paris changes?

Hess and his contemporaries realized that the sea-floor-spreading hypothesis instantly provided the long-sought explanation of how continental "drift" occurs. Continents passively move apart as the sea floor between them spreads at mid-ocean ridges, and they passively move together as the sea floor between them sinks back into the mantle at trenches. (As we will see later, geologists now realize that it is the lithosphere that moves, not just the crust.) Thus, sea-floor spreading proved to be an important step on the route to plate tectonics—the idea seemed so good that Hess referred to his description of it as "an essay in geopoetry." But first, the idea needed to be tested, and other key discoveries would have to take place before the whole theory of plate tectonics could come together.

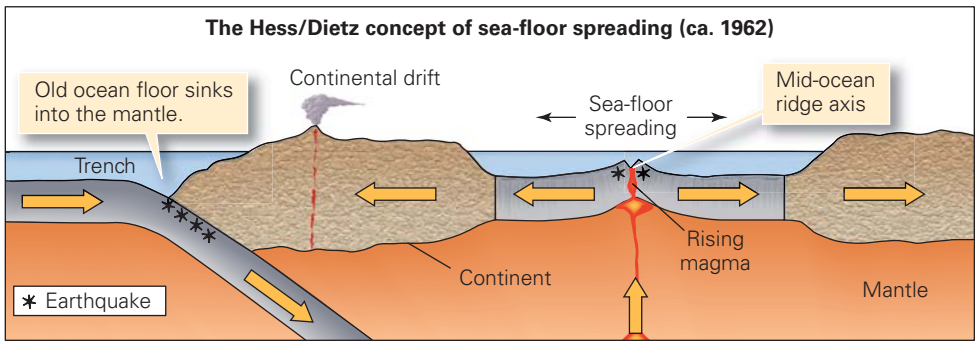
Take-Home Message

New studies of the sea floor led to the proposal of sea-floor spreading. New sea floor forms at mid-ocean ridges and then moves away from the axis, so ocean basins can get wider with time. Old ocean floor sinks back into the mantle by subduction. As ocean basins grow or shrink, continents drift.

2.5 Evidence for Sea-Floor Spreading

For a hypothesis to become a theory (see Box P.1), researchers must demonstrate that the idea really works. During the 1960s, geologists found that the sea-floor spreading hypothesis successfully explains several previously baffling observations. Here we discuss two: (1) the existence of orderly variations in the strength of the measured magnetic field over the sea floor, producing a pattern of stripes called marine magnetic anomalies; and (2) the variation in sediment thickness on the ocean crust, as measured by drilling.

FIGURE 2.10 Harry Hess's basic concept of sea-floor spreading. Hess implied, incorrectly, that only the crust moved. We will see that this sketch is an oversimplification.



Marine Magnetic Anomalies

Recognizing anomalies. Geologists can measure the strength of Earth's magnetic field with an instrument called a magnetometer. At any given location on the surface of the Earth, the magnetic field that you measure includes two parts: one produced by the main dipole of the Earth generated by circulation of molten iron in the outer core, and another produced by the magnetism of near-surface rock. A **magnetic anomaly** is the difference between the *expected* strength of the Earth's main dipole field at a certain location and the *actual* measured strength of the magnetic field at that location. Places where the field strength is stronger than expected are *positive* anomalies, and places where the field strength is weaker than expected are *negative* anomalies.

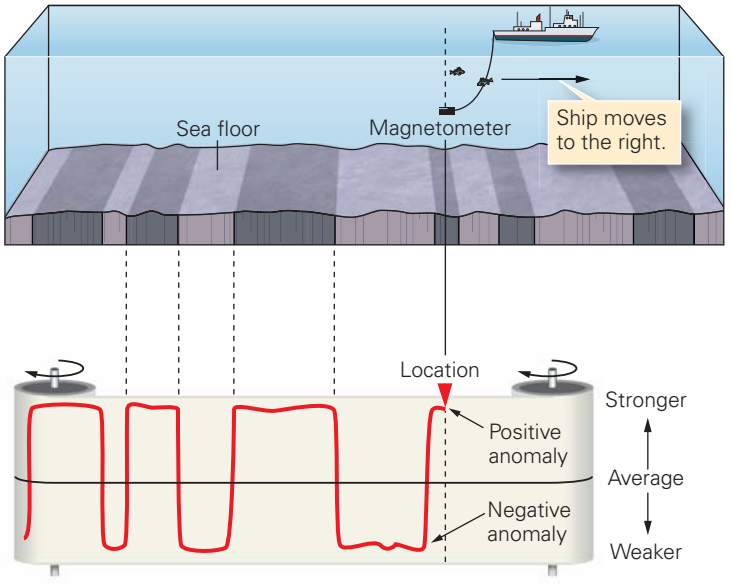
Geologists towed magnetometers back and forth across the ocean to map variations in magnetic field strength (**Fig. 2.11a**). As a ship cruised along its course, the magnetometer's gauge might first detect an interval of strong signal (a positive anomaly) and then an interval of weak signal (a negative anomaly). A graph of signal strength versus distance along the traverse, therefore, has a sawtooth shape (**Fig. 2.11b**). When geologists compiled data from many cruises on a map, these **marine magnetic anomalies** defined distinctive, alternating bands. If we color positive anomalies dark and negative anomalies light, the pattern made by the anomalies resembles the stripes on a candy cane (**Fig. 2.11c**). The mystery of this marine magnetic anomaly pattern, however, remained unsolved until geologists recognized the existence of magnetic reversals.

Magnetic reversals. Recall that Earth's magnetic field can be represented by an arrow, representing the dipole, that presently points from the north magnetic pole to the south magnetic pole. When researchers measured the paleomagnetism of a succession of rock layers that had accumulated over a long period of time, they found that the polarity (which end of a magnet points north and which end points south) of the paleomagnetic field preserved in some layers was the same as that of Earth's present magnetic field, whereas in other layers it was the opposite (**Fig. 2. 12a, b**).

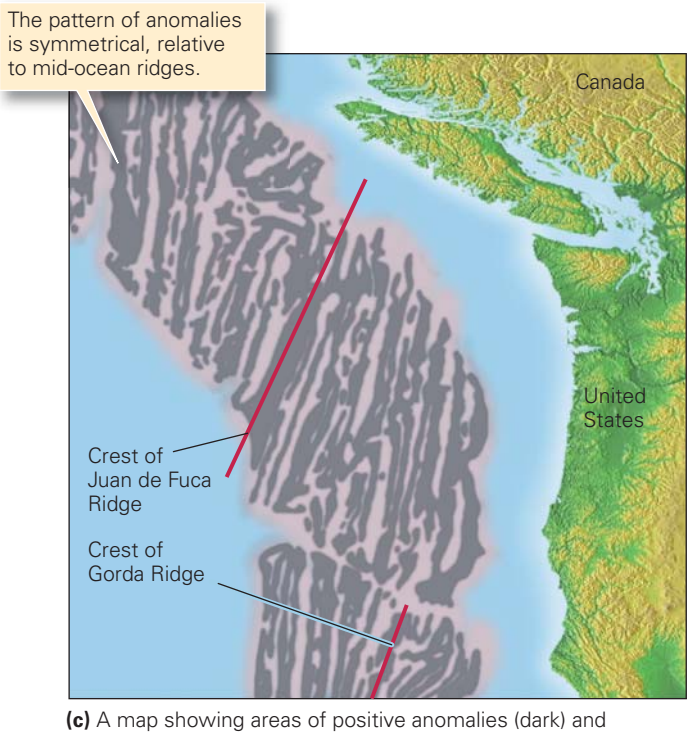
At first, observations of reversed polarity were largely ignored, thought to be the result of lightning strikes or of local chemical reactions between rock and water. But when repeated measurements from around the world revealed a systematic pattern of alternating normal and reversed polarity in rock layers, geologists realized that reversals were a worldwide, not a local, phenomenon. They reached the unavoidable conclusion that, at various times during Earth history, *the polarity of Earth's magnetic field has suddenly reversed*! In other words, sometimes the Earth has normal polarity, as it does today, and sometimes it has reversed polarity (**Fig. 2.12c**). A time when the Earth's field flips from normal to reversed polarity, or vice versa, is called a **magnetic reversal**. When the Earth has reversed polarity, the south magnetic pole lies near the north geographic pole, and the north magnetic pole lies near the south geographic pole. Thus, if you were to use a compass during periods when the Earth's magnetic field was reversed, the north-seeking end of the needle would point to the south

FIGURE 2.11 The discovery of marine magnetic anomalies.

(a) A ship towing a magnetometer detects changes in the strength of the magnetic field.



(b) On a paper record, intervals of stronger magnetism (positive anomalies) alternate with intervals of weaker magnetism (negative anomalies).



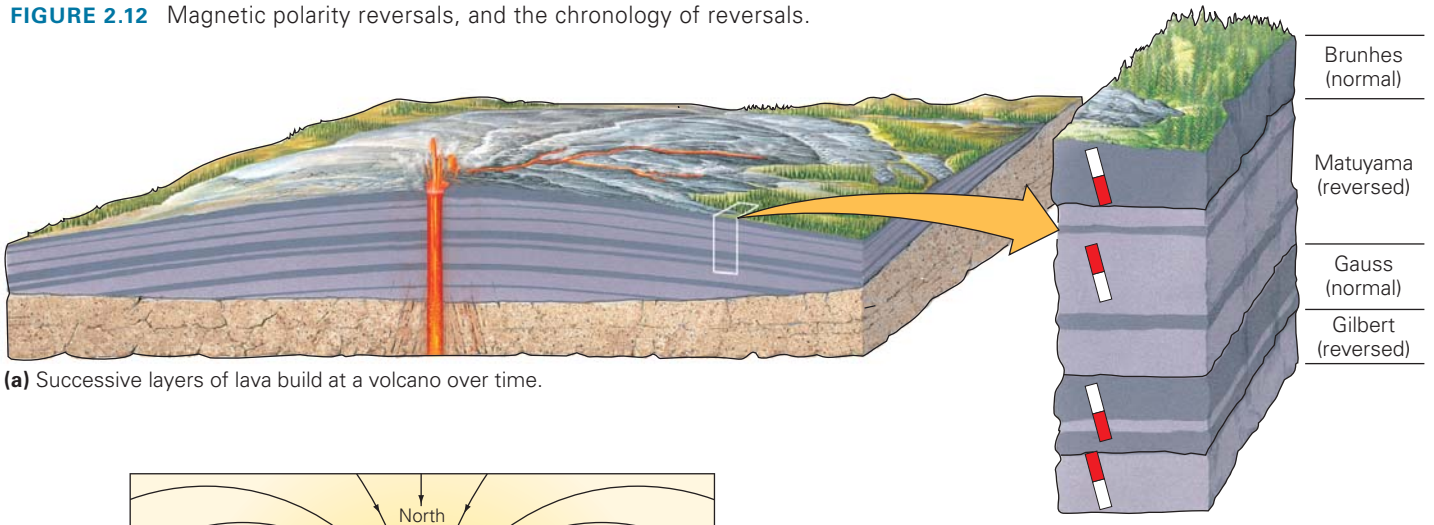
(c) A map showing areas of positive anomalies (dark) and negative anomalies (light) off the west coast of North America. The pattern of anomalies resembles candy-cane strips.

geographic pole. Note that the Earth itself doesn't turn upside down—it is just the magnetic field that reverses.

In the 1950s, about the same time researchers discovered polarity reversals, they developed a technique that permitted them to measure the age of a rock in years. The technique, called isotopic dating, will be discussed in detail in Chapter 10. Geologists applied the technique to determine the ages of rock layers in which they obtained their paleomagnetic measurements, and thus determined *when* the magnetic field of the Earth reversed. With this information, they constructed a history of magnetic reversals for the past 4.5 million years; this history is now called the magnetic-reversal chronology. The time interval between successive reversals is called a **chron**.

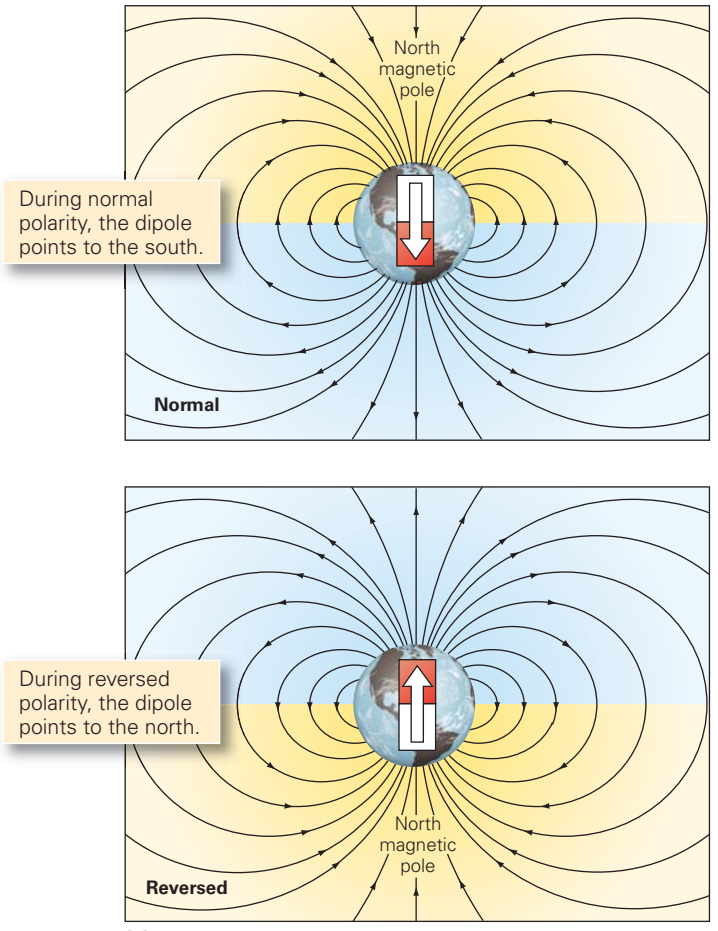
A diagram representing the Earth's magnetic-reversal chronology (**Fig. 2.12d**) shows that reversals do not occur regularly, so the lengths of different polarity chrons are different. For example, we have had a normal-polarity chron for about the last 700,000 years. Before that, a reversed-polarity chron occurred. The youngest four polarity chrons (Brunhes, Matuyama, Gauss, and Gilbert) were named after scientists who had made

FIGURE 2.12 Magnetic polarity reversals, and the chronology of reversals.

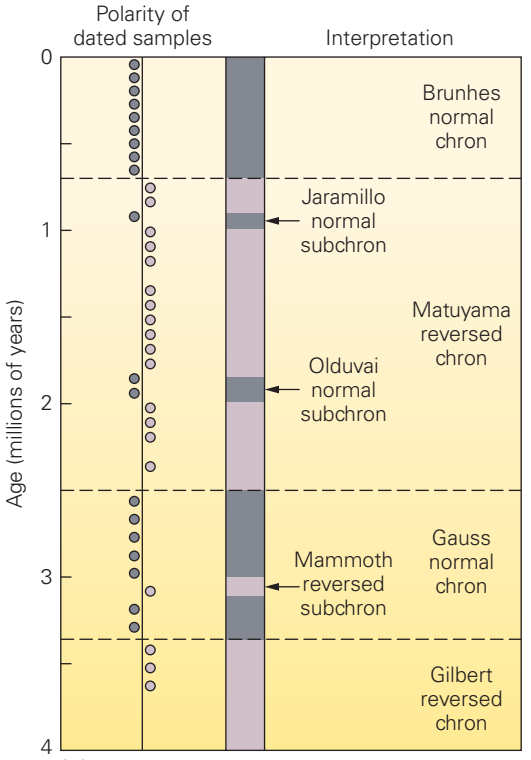


(a) Successive layers of lava build at a volcano over time.

(b) Geologists discovered that some layers have normal polarity, whereas some have reversed polarity.

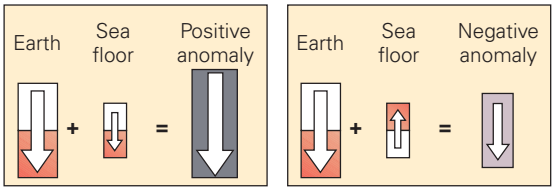


(c) Geologists proposed that the Earth's magnetic field reverses polarity every now and then.

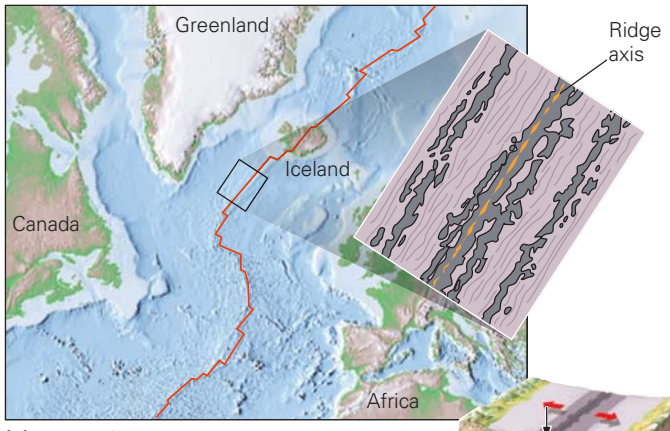


(d) Observations led to the production of a reversal chronology, with named polarity intervals.

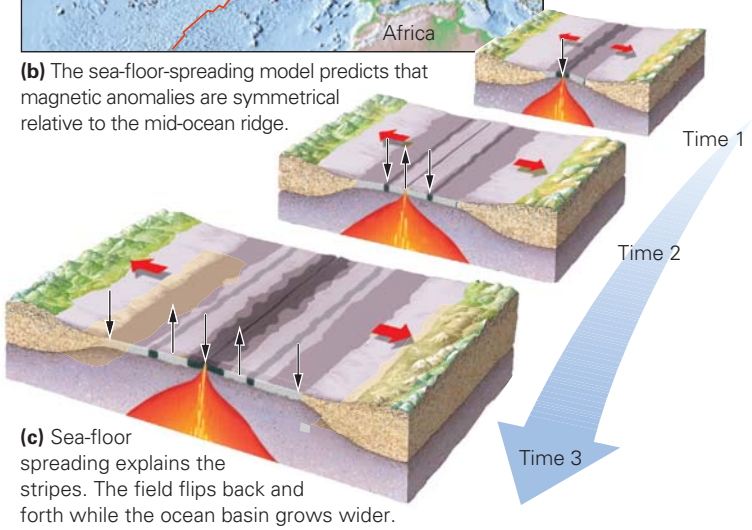
FIGURE 2.13 The progressive development of magnetic anomalies, and the long-term reversal chronology.



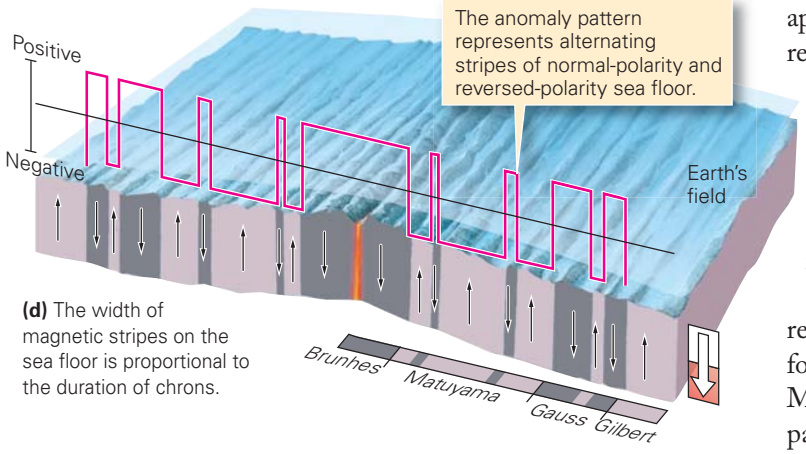
(a) Positive anomalies form when sea-floor rock has the same polarity as the present magnetic field. Negative anomalies form when sea-floor rock has polarity that is opposite to the present field.



(b) The sea-floor-spreading model predicts that magnetic anomalies are symmetrical relative to the mid-ocean ridge.



(c) Sea-floor spreading explains the stripes. The field flips back and forth while the ocean basin grows wider.



(d) The width of magnetic stripes on the sea floor is proportional to the duration of chrons.

important contributions to the study of magnetism. As more measurements became available, investigators realized that some short-duration reversals (less than 200,000 years long) took place within the chrons, and they called these shorter durations "polarity subchrons." Using isotopic dating, it was possible to determine the age of chrons back to 4.5 Ma.

Interpreting marine magnetic anomalies. Why do marine magnetic anomalies exist? In 1963, researchers in Britain and Canada proposed a solution to this riddle. Simply put, a positive anomaly occurs over areas of the sea floor where underlying basalt has normal polarity. In these areas, the magnetic force produced by the magnetite grains in basalt *adds* to the force produced by the Earth's dipole—the sum of these forces yields a stronger magnetic signal than expected due to the dipole alone (**Fig. 2.13a**). A negative anomaly occurs over regions of the sea floor where the underlying basalt has a reversed polarity. In these regions, the magnetic force of the basalt *subtracts* from the force produced by the Earth's dipole, so the measured magnetic signal is weaker than expected.

The sea-floor-spreading model easily explains not only why positive and negative magnetic anomalies exist over the sea floor, but also why they define stripes that trend parallel to the mid-ocean ridge and why the pattern of stripes on one side of the ridge is the mirror image of the pattern on the other side (**Fig. 2.13b**). To see why, let's examine stages in the process of sea-floor spreading (**Fig. 2.13c**). Imagine that at Time 1 in the past, the Earth's magnetic field has normal polarity. As the basalt rising at the mid-ocean ridge during this time interval cools and solidifies, the tiny magnetic grains in basalt align with the Earth's field, and thus the rock as a whole has a normal polarity. Sea floor formed during Time 1 will therefore generate a positive anomaly and appear as a dark stripe on an anomaly map. As it forms, the rock of this stripe moves away from the ridge axis, so half goes to the right and half to the left. Now imagine that later, at Time 2, Earth's field has reversed polarity. Sea-floor basalt formed during Time 2, therefore, has reversed polarity and will appear as a light stripe on an anomaly map. As it forms, this reversed-polarity stripe moves away from the ridge axis, and even younger crust forms along the axis. The basalt in each new stripe of crust preserves the polarity that was present at the time it formed, so as the Earth's magnetic field flips back and forth, alternating positive and negative anomaly stripes form. A positive anomaly exists over the ridge axis today because sea floor is forming during the present chron of normal polarity.

Closer examination of a sea-floor magnetic anomaly map reveals that anomalies are not all the same width. Geologists found that the relative widths of anomaly stripes near the Mid-Atlantic Ridge are the same as the relative durations of paleomagnetic chrons (**Fig. 2.13d**). This relationship between anomaly-stripe width and polarity-chron duration indicates

that the rate of sea-floor spreading has been constant along the Mid-Atlantic Ridge for at least the last 4.5 million years. If you assume that the spreading rate was constant for tens to hundreds of millions of years, then it is possible to estimate the age of stripes right up to the edge of the ocean.

Evidence from Deep-Sea Drilling

In the late 1960s, a research drilling ship called the *Glomar Challenger* set out to sail around the ocean drilling holes into the sea floor. This amazing ship could lower enough drill pipe to drill in 5-km-deep water and could continue to drill until the hole reached a depth of about 1.7 km (1.1 miles) below the sea floor. Drillers brought up cores of rock and sediment that geoscientists then studied on board.

On one of its early cruises, the *Glomar Challenger* drilled a series of holes through sea-floor sediment to the basalt layer. These holes were spaced at progressively greater distances from the axis of the Mid-Atlantic Ridge. If the model of sea-floor spreading was correct, then not only should the sediment layer be progressively thicker away from the axis, but the age of the oldest sediment just above the basalt should be progressively older away from the axis. When the drilling and the analyses were complete, the prediction was confirmed. Thus, studies of both marine magnetic anomalies and the age of the sea floor proved the sea-floor-spreading model.

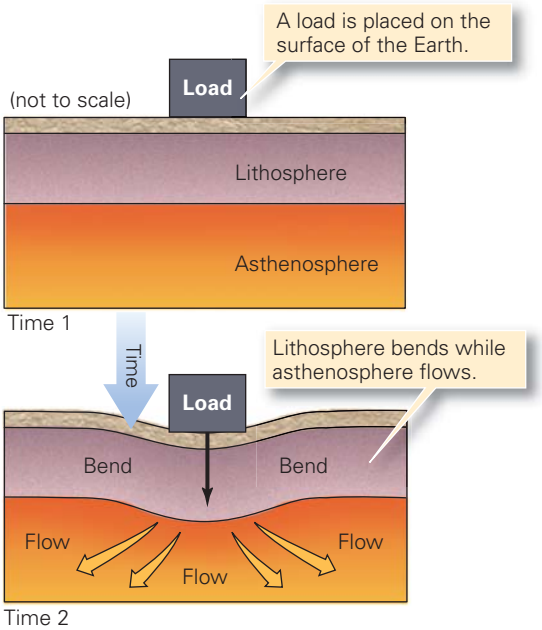
Take-Home Message

Marine magnetic anomalies form because reversals of the Earth's magnetic polarity take place while sea-floor spreading occurs. The discovery of these anomalies, as well as documentation that the sea floor gets older away from the ridge axis, proved that the sea-floor-spreading hypothesis is correct.

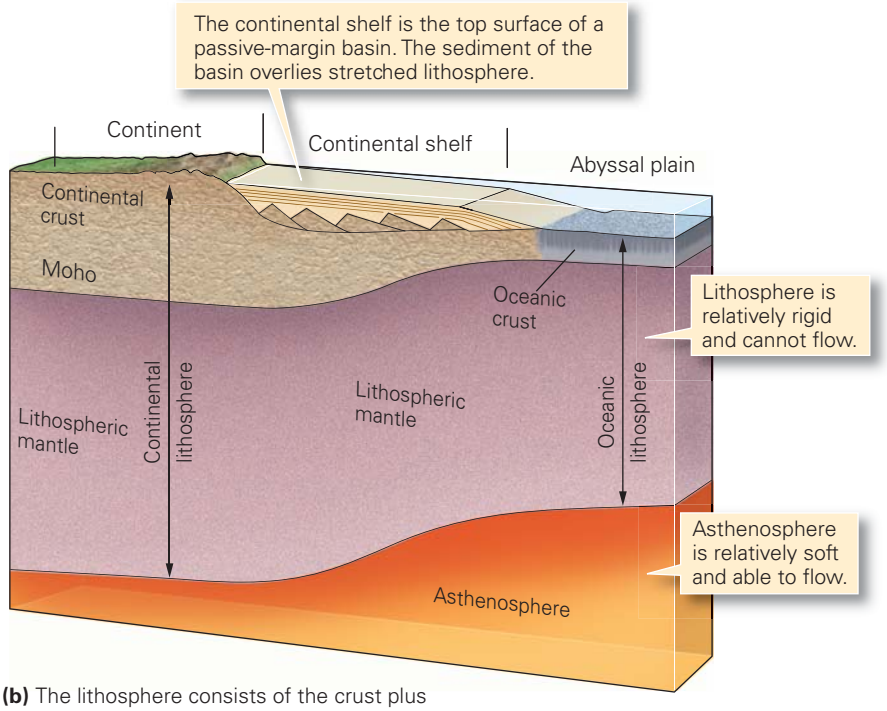
2.6 What Do We Mean by Plate Tectonics?

The paleomagnetic proof of continental drift and the discovery of sea-floor spreading set off a scientific revolution in geology in the 1960s and 1970s. Geologists realized that many of their existing interpretations of global geology, based on the premise that the positions of continents and oceans remain fixed in position through time, were simply wrong! Researchers dropped what they were doing and turned their attention to studying the broader implications of continental drift and sea-floor spreading. It became clear that these phenomena

FIGURE 2.14 Nature of the lithosphere and its behavior.

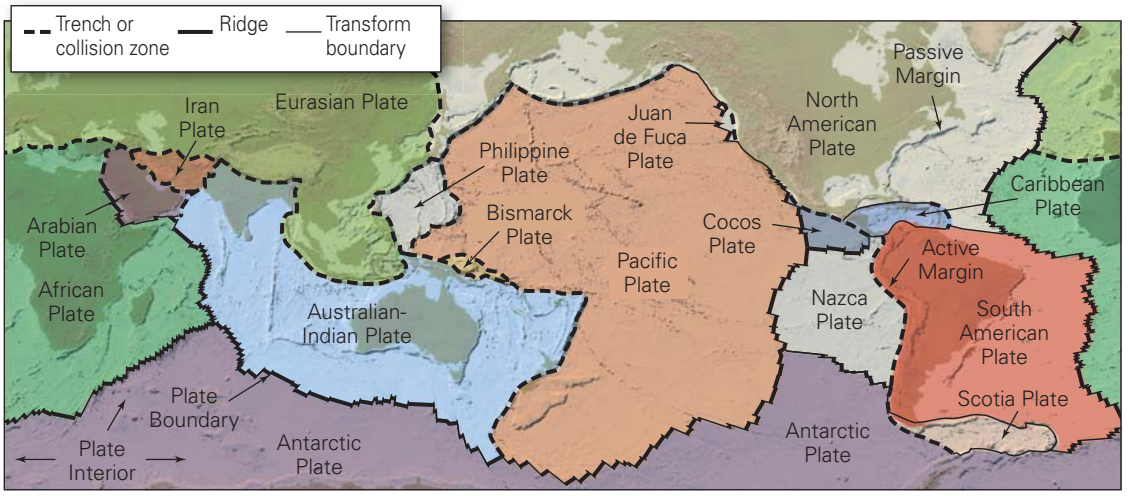


(a) The lithosphere is fairly rigid, but when a heavy load, such as a glacier or volcano, builds on its surface, the surface bends down. This can happen because the underlying "plastic" asthenosphere can flow out of the way.

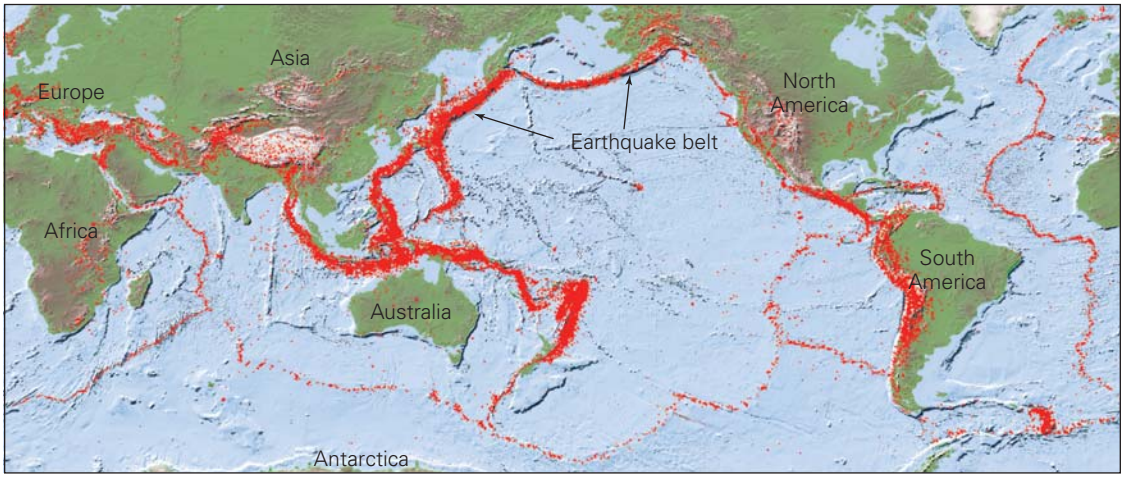


(b) The lithosphere consists of the crust plus the uppermost mantle. It is thicker beneath continents than beneath oceans.

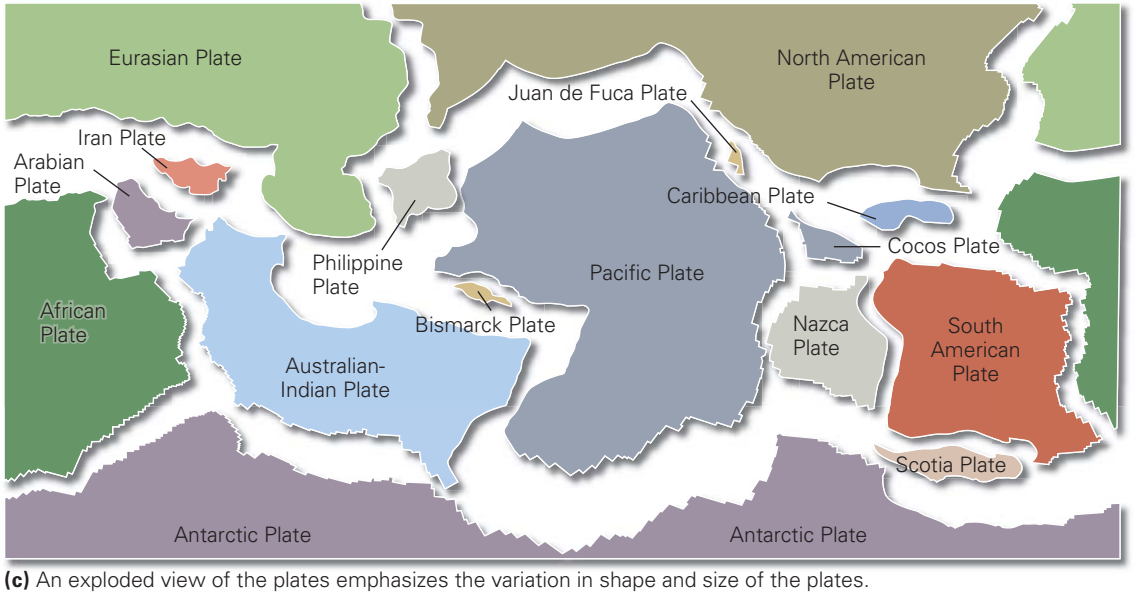
FIGURE 2.15 The locations of plate boundaries and the distribution of earthquakes.



(a) A map of major plates shows that some consist entirely of oceanic lithosphere, whereas some consist of both continental and oceanic lithosphere. Active continental margins lie along plate boundaries; passive margins do not.



(b) The locations of earthquakes (red dots) mostly fall in distinct bands that correspond to plate boundaries. Relatively few earthquakes occur in the stabler plate interiors.



(c) An exploded view of the plates emphasizes the variation in shape and size of the plates.

required that the outer shell of the Earth was divided into rigid plates that moved relative to each other. New studies clarified the meaning of a plate, defined the types of plate boundaries, constrained plate motions, related plate motions to earthquakes and volcanoes, showed how plate interactions can explain mountain belts and seamount chains, and outlined the history of past plate motions. From these, the modern theory of plate tectonics evolved. Below, we first describe lithosphere plates and their boundaries, and then outline the basic principles of plate tectonics theory.

The Concept of a Lithosphere Plate

We learned earlier that geoscientists divide the outer part of the Earth into two layers. The **lithosphere** consists of the crust plus the top (cooler) part of the upper mantle. It behaves relatively rigidly, meaning that when a force pushes or pulls on it, it does not flow but rather bends or breaks (Fig. 2.14a). The lithosphere floats on a relatively soft, or "plastic," layer called the **asthenosphere**, composed of warmer (> 1280°C) mantle that can flow slowly when acted on by a force. As a result, the asthenosphere convects, like water in a pot, though much more slowly.

Continental lithosphere and oceanic lithosphere differ markedly in their thicknesses. On average, continental lithosphere has a thickness of 150 km, whereas old oceanic lithosphere has a thickness of about 100 km (Fig. 2.14b).

(For reasons discussed later in this chapter, new oceanic lithosphere at a mid-ocean ridge is much thinner.) Recall that the crustal part of continental lithosphere ranges from 25 to 70 km thick and consists largely of low-density felsic and intermediate rock (see Chapter 1). In contrast, the crustal part of oceanic lithosphere is only 7 to 10 km thick and consists largely of relatively high-density mafic rock (basalt and gabbro). The mantle part of both continental and oceanic lithosphere consists of very high-density ultramafic rock (peridotite). Because of these differences, the continental lithosphere "floats" at a higher level than does the oceanic lithosphere.

The lithosphere forms the Earth's relatively rigid shell. But unlike the shell of a hen's egg, the lithospheric shell contains a number of major breaks, which separate it into distinct pieces. As noted earlier, we call the pieces **lithosphere plates**, or simply plates. The breaks between plates are known as **plate boundaries** (Fig. 2.15a). Geoscientists distinguish twelve major plates and several microplates.

The Basic Principles of Plate Tectonics

With the background provided above, we can restate plate tectonics theory concisely as follows. The Earth's lithosphere is divided into plates that move relative to each other. As a plate moves, its internal area remains mostly, but not perfectly, rigid and intact. But rock along plate boundaries undergoes intense deformation (cracking, sliding, bending, stretching, and squashing) as the plate grinds or scrapes against its neighbors or pulls away from its neighbors. As plates move, so do the continents that form part of the plates. Because of plate tectonics, the map of Earth's surface constantly changes.

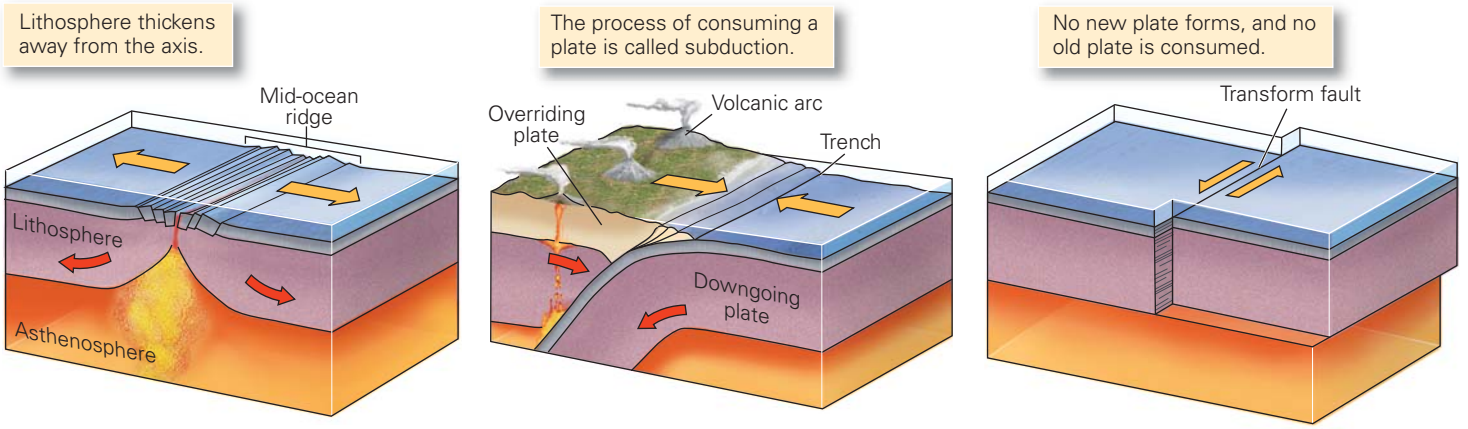
Identifying Plate Boundaries

How do we recognize the location of a plate boundary? The answer becomes clear from looking at a map showing the locations of earthquakes (Fig. 2.15b). Recall from Chapter 1 that earthquakes are vibrations caused by shock waves that are generated where rock breaks and suddenly slips along a fault. The epicenter marks the point on the Earth's surface directly above the earthquake. Earthquake epicenters do not speckle the globe randomly, like buckshot on a target. Rather, the majority occur in relatively narrow, distinct belts. These earthquake belts define the position of plate boundaries because the fracturing and slipping that occurs along plate boundaries generates earthquakes. Plate interiors, regions away from the plate boundaries, remain relatively earthquake-free because they do not accommodate as much movement. While earthquakes serve as the most definitive indicator of a plate boundary, other prominent geologic features also develop along plate boundaries, as you will learn by the end of this chapter.

Note that some plates consist entirely of oceanic lithosphere, whereas some plates consist of both oceanic and continental lithosphere. Also, note that not all plates are the same size (Fig. 2.15c). Some plate boundaries follow continental margins, the boundary between a continent and an ocean, but others do not. For this reason, we distinguish between **active margins**, which are plate boundaries, and **passive margins**, which are not plate boundaries. Earthquakes are common at active margins, but not at passive margins. Along passive margins, continental crust is thinner than in continental interiors. Thick (10 to 15 km) accumulations of sediment cover this thinned crust. The surface of this sediment

Did you ever wonder . . .
why earthquakes don't occur everywhere?

FIGURE 2.16 The three types of plate boundaries differ based on the nature of relative movement.



(a) At a divergent boundary, two plates move away from the axis of a mid-ocean ridge. New oceanic lithosphere forms.

(b) At a convergent boundary, two plates move toward each other; the downgoing plate sinks beneath the overriding plate.

(c) At a transform boundary, two plates slide past each other on a vertical fault surface.

layer is a broad, shallow (less than 500 m deep) region called the **continental shelf**, home to the major fisheries of the world.

Geologists define three types of plate boundaries, based simply on the relative motions of the plates on either side of the boundary (Fig. 2.16a–c). A boundary at which two plates move apart from each other is a **divergent boundary**. A boundary at which two plates move toward each other so that one plate sinks beneath the other is a **convergent boundary**. And a boundary at which two plates slide sideways past each other is a **transform boundary**. Each type of boundary looks and behaves differently from the others, as we will now see.

Take-Home Message

Earth's lithosphere is divided into about twenty plates that move relative to each other. Geologists recognize three different types of plate boundaries (divergent, convergent, and transform) based on relative motion across the boundary. Plate boundaries are defined by seismic belts.

2.7 Divergent Plate Boundaries and Sea-Floor Spreading

At a divergent boundary, or spreading boundary, two oceanic plates move apart by the process of sea-floor spreading. Note that an *open space does not develop* between diverging plates. Rather, as the plates move apart, new oceanic lithosphere forms continually along the divergent boundary (Fig. 2.17a). This process takes place at a submarine mountain range called a mid-ocean ridge that rises 2 km above the adjacent abyssal plains of the ocean. Thus, geologists commonly refer to a divergent boundary as a mid-ocean ridge, or simply a ridge. Water depth above ridges averages about 2.5 km.

To characterize a divergent boundary more completely, let's look at one mid-ocean ridge in more detail (Fig. 2.17b). The Mid-Atlantic Ridge extends from the waters between northern Greenland and northern Scandinavia southward across the equator to the latitude of the southern tip of South America. Geologists have found that the formation of new sea floor takes place *only* along the axis (centerline) of the ridge, which is marked by an elongate valley. The sea floor slopes away, reaching the depth of the abyssal plain (4 to 5 km) at a distance of about 500 to 800 km from the ridge axis (see Fig. 2.7). Roughly speaking, the Mid-Atlantic Ridge is symmetrical—its eastern half looks like a mirror image of its western half. The ridge consists, along its length, of short segments (tens to hundreds of km long) that step over at breaks that, as we noted earlier, are called fracture zones. Later, we will see that these correspond to transform faults.

How Does Oceanic Crust Form at a Mid-Ocean Ridge?

As sea-floor spreading takes place, hot asthenosphere rises beneath the ridge and begins to melt, and molten rock, or magma, forms (Fig. 2.17c). We will explain why this magma forms in Chapter 4. Magma has a lower density than solid rock, so it behaves buoyantly and rises, as oil rises above vinegar in salad dressing. Molten rock eventually accumulates in the crust below the ridge axis, filling a region called a magma chamber. As the magma cools, it turns into a mush of crystals. Some of the magma solidifies completely along the side of the chamber to make the coarse-grained, mafic igneous rock called gabbro. The rest rises still higher to fill vertical cracks, where it solidifies and forms wall-like sheets, or dikes, of basalt. Some magma rises all the way to the surface of the sea floor at the ridge axis and spills out of small submarine volcanoes. The resulting lava cools to form a layer of basalt blobs called pillows. Observers in research submarines have detected chimneys spewing hot, mineralized water rising from cracks in the sea floor along the ridge axis. These chimneys are called **black smokers** because the water they emit looks like a cloud of dark smoke; the color comes from a suspension of tiny mineral grains that precipitate in the water the instant that the water cools (Fig. 2.18).

As soon as it forms, new oceanic crust moves away from the ridge axis, and when this happens, more magma rises from below, so still more crust forms. In other words, like a vast, continuously moving conveyor belt, magma from the mantle rises to the Earth's surface at the ridge, solidifies to form oceanic crust, and then moves laterally away from the ridge. Because all sea floor forms at mid-ocean ridges, the youngest sea floor occurs on either side of the ridge axis, and sea floor becomes progressively older away from the ridge. In the Atlantic Ocean, the oldest sea floor, therefore, lies adjacent to the passive continental margins on either side of the ocean (Fig. 2.19). The oldest ocean floor on our planet underlies the western Pacific Ocean; this crust formed about 200 million years ago.

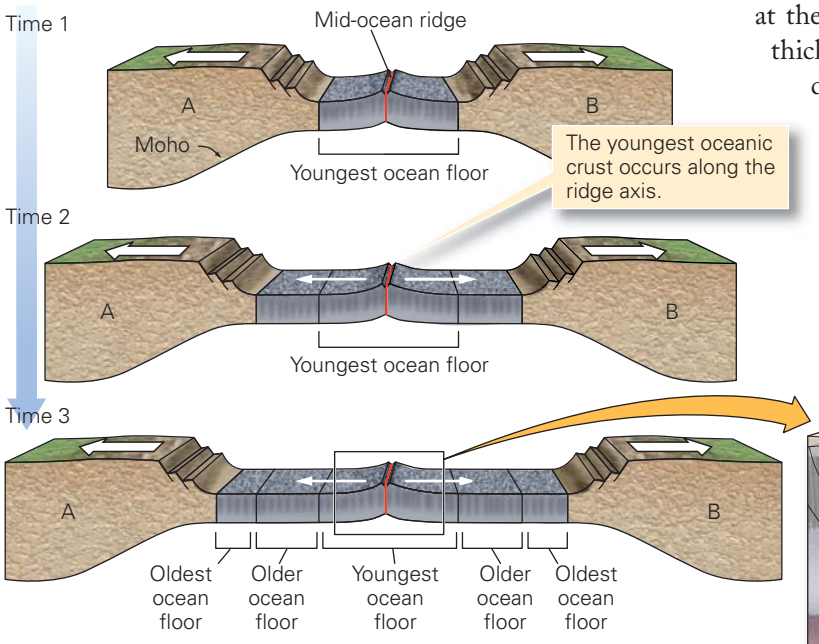
The tension (stretching force) applied to newly formed solid crust as spreading takes place breaks the crust, resulting in the formation of faults. Slip on the faults causes divergent-boundary earthquakes and produces numerous cliffs, or scarps, that lie parallel to the ridge axis.

How Does the Lithospheric Mantle Form at a Mid-Ocean Ridge?

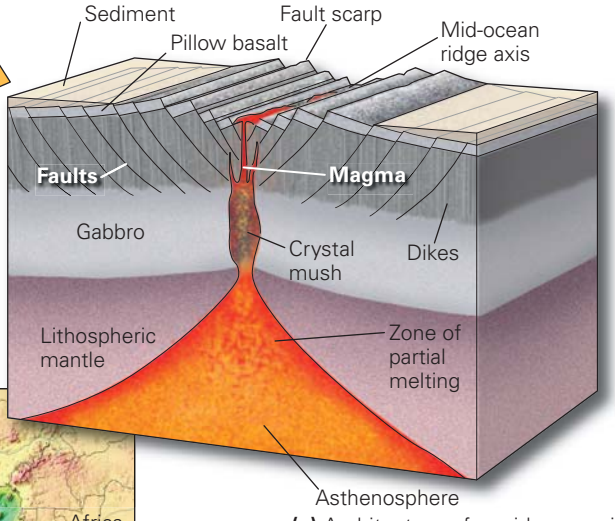
So far, we've seen how oceanic *crust* forms at mid-ocean ridges. How does the *mantle* part of the oceanic lithosphere form? This part consists of the cooler uppermost layer of the mantle, in which temperatures are less than about 1,280°C. At the ridge axis, such temperatures occur almost at the base of the crust, because of the presence of rising hot asthenosphere and hot magma, so lithospheric mantle beneath the ridge axis effectively doesn't exist. But as the newly formed oceanic crust moves away from the ridge axis, the crust and the uppermost mantle directly beneath it gradually cool by losing heat to the ocean above. As soon as mantle rock cools below 1,280°C, it becomes, by definition, part of the lithosphere.

As oceanic lithosphere continues to move away from the ridge axis, it continues to cool, so the lithospheric mantle, and therefore the oceanic lithosphere as a whole, grows progressively thicker (Fig. 2.20a, b). Note that this process doesn't change the thickness of the oceanic crust, for the crust formed entirely at the ridge axis. The rate at which cooling and lithospheric thickening occur decreases progressively with increasing distance from the ridge axis. In fact, by the time the lithosphere is about 80 million years old, it has just about reached its maximum thickness. As lithosphere thickens and gets cooler and denser, it sinks down into the asthenosphere, like a ship taking on ballast. Thus, the ocean is deeper over older ocean floor than over younger ocean floor.

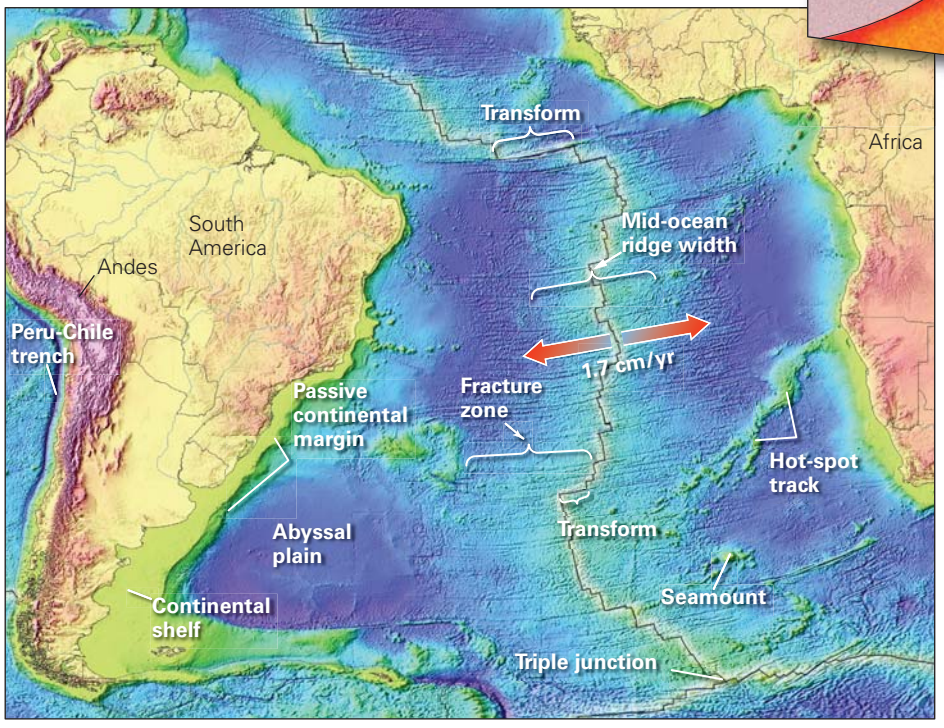
FIGURE 2.17 The process of sea-floor spreading.



(a) As sea-floor spreading progresses, new oceanic lithosphere forms at the mid-ocean ridge axis. For simplicity, only the crust is shown.



(c) Architecture of a mid-ocean ridge, the site of sea-floor spreading. Some magma freezes into new rock within the crust, whereas some spills out onto the surface of the sea floor. Faults break up the crust as it stretches apart.



(b) The bathymetry of the Mid-Atlantic Ridge in the Southern Atlantic Ocean. The lighter shades of blue are shallower depths.

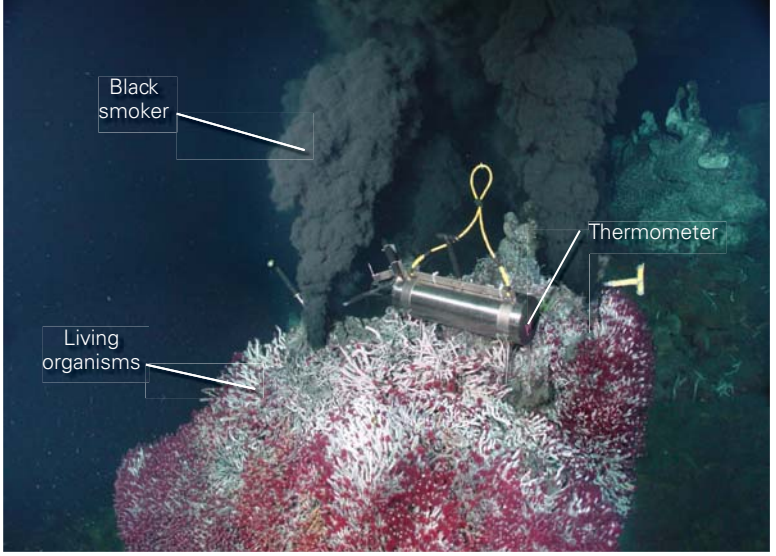


FIGURE 2.18 A column of superhot water gushing from a vent known as a black smoker along the mid-ocean ridge. A local ecosystem of bacteria, shrimp, and worms lives around the vent.

Take-Home Message

Sea-floor spreading occurs at divergent plate boundaries, defined by mid-ocean ridges. New oceanic crust solidifies from basaltic magma along the ridge axis. As plates move away from the axis, they cool, and the lithospheric mantle forms and thickens.

2.8 Convergent Plate Boundaries and Subduction

At convergent plate boundaries, two plates, at least one of which is oceanic, move toward one another. But rather than butting each other like angry rams, one oceanic plate bends and sinks down into the asthenosphere beneath the other plate. Geologists refer to the sinking process as **subduction**, so convergent boundaries are also known as subduction zones. Because subduction at a convergent boundary consumes old ocean lithosphere and thus "consumes" oceanic basins, geologists also refer to convergent boundaries as consuming boundaries, and because they are delineated by deep-ocean trenches, they are sometimes simply called **trenches** (see Fig. 2.8). The amount of oceanic plate consumption worldwide, averaged over time, equals the amount of sea-floor spreading worldwide, so the surface area of the Earth remains constant through time.

Subduction occurs for a simple reason: oceanic lithosphere, once it has aged at least 10 million years, is denser than the underlying asthenosphere and thus can sink through the asthenosphere if given an opportunity. Where it lies flat on the surface of the asthenosphere, oceanic lithosphere can't

FIGURE 2.19 This map of the world shows the age of the sea floor. Note how the sea floor grows older with increasing distance from the ridge axis. (Ma = million years ago.)

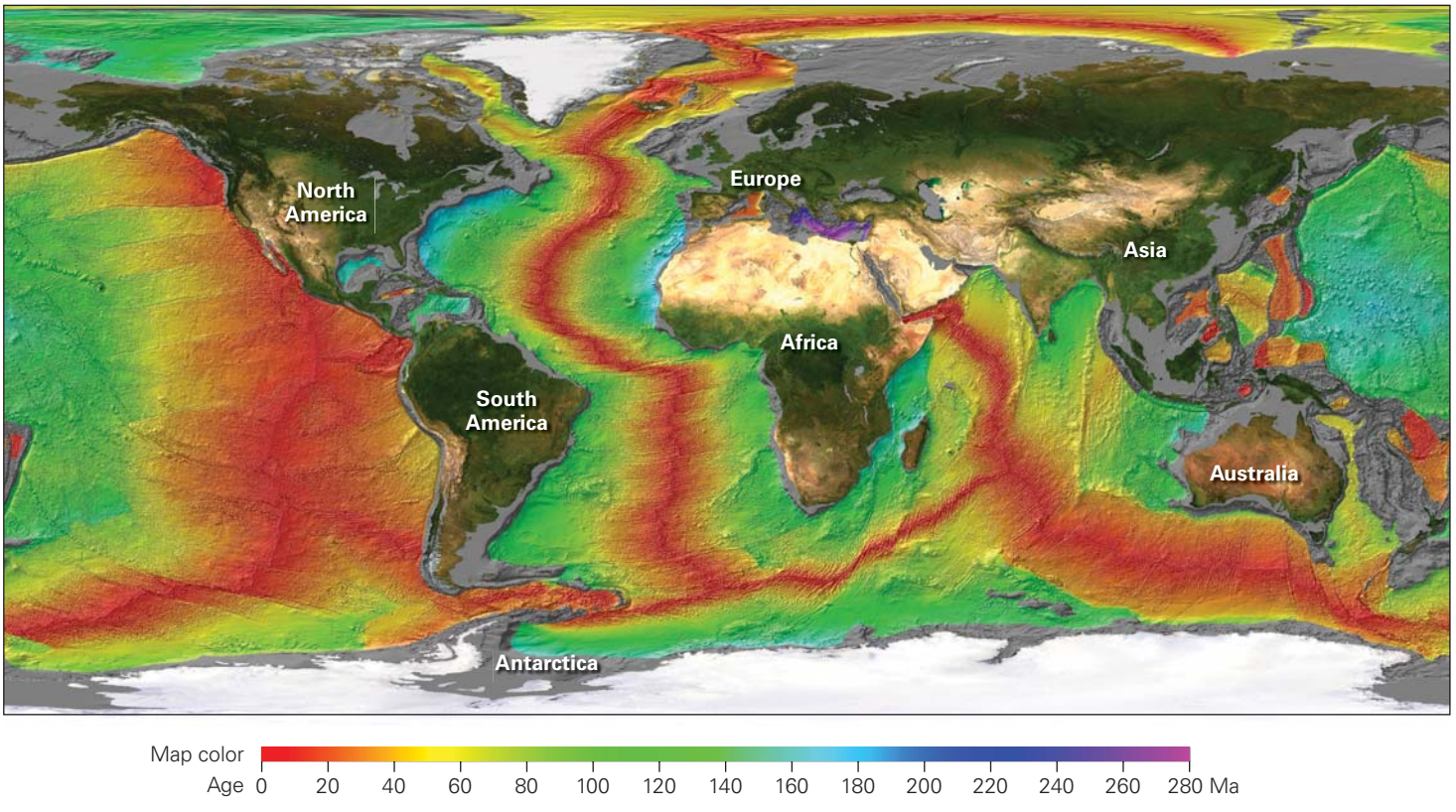
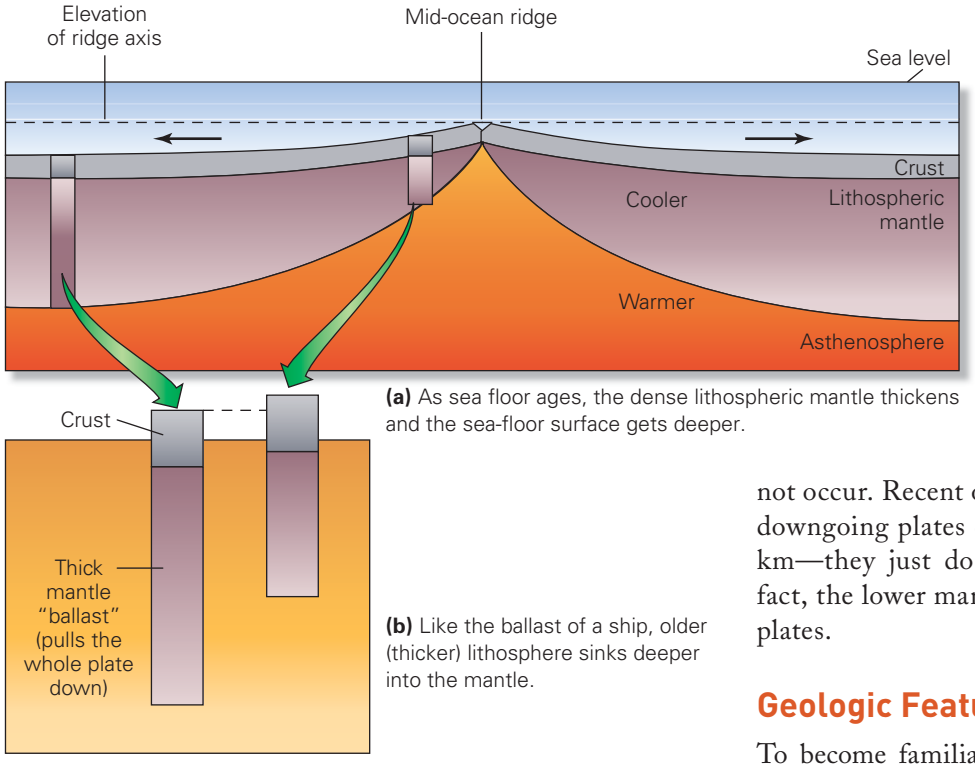


FIGURE 2.20 Changes accompanying the aging of lithosphere.



(a) As sea floor ages, the dense lithospheric mantle thickens and the sea-floor surface gets deeper.

(b) Like the ballast of a ship, older (thicker) lithosphere sinks deeper into the mantle.

sink. However, once the end of the convergent plate bends down and slips into the mantle, it continues downward like an anchor falling to the bottom of a lake (Fig. 2.21a). As the lithosphere sinks, asthenosphere flows out of its way, just as water flows out of the way of a sinking anchor. But unlike water, the asthenosphere can flow only very slowly, so oceanic lithosphere can sink only very slowly, at a rate of less than about 15 cm per year. To visualize the difference, imagine how much faster a coin can sink through water than it can through honey.

Note that the "downgoing plate," the plate that has been subducted, *must* be composed of oceanic lithosphere. The overriding plate, which does not sink, can consist of either oceanic or continental lithosphere. Continental crust cannot be subducted because it is too buoyant; the low-density rocks of continental crust act like a life preserver keeping the continent afloat. If continental crust moves into a convergent margin, subduction eventually stops. Because of subduction, all ocean floor on the planet is less than about 200 million years old. Because continental crust cannot subduct, some continental crust has persisted at the surface of the Earth for over 3.8 billion years.

Earthquakes and the Fate of Subducted Plates

At convergent plate boundaries, the downgoing plate grinds along the base of the overriding plate, a process that generates large earthquakes. These earthquakes occur fairly close to the Earth's surface, so some of them cause massive destruction in coastal cities. But earthquakes also happen in downgoing plates at greater depths. In fact, geologists have detected earthquakes within downgoing plates to a depth of 660 km. The band of earthquakes in a downgoing plate is called a **Wadati-Benioff zone**, after its two discoverers (Fig. 2.21b).

At depths greater than 660 km, conditions leading to earthquakes in subducted lithosphere evidently do not occur. Recent observations, however, indicate that some downgoing plates do continue to sink *below* a depth of 660 km—they just do so without generating earthquakes. In fact, the lower mantle may be a graveyard for old subducted plates.

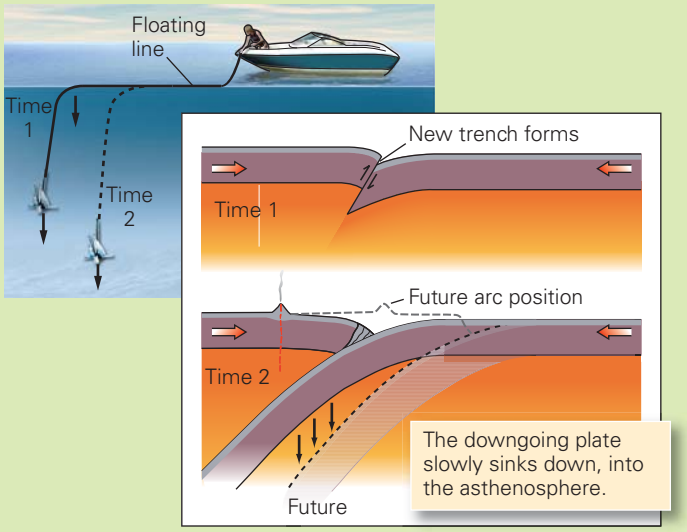
Geologic Features of a Convergent Boundary

To become familiar with the various geologic features that occur along a convergent plate boundary, let's look at an example, the boundary between the western coast of the South American Plate and the eastern edge of the Nazca Plate (a portion of the Pacific Ocean floor). A deep-ocean trench, the Peru-Chile Trench, delineates this boundary (see Fig. 2.17b). Such trenches form where the plate bends as it starts to sink into the asthenosphere.

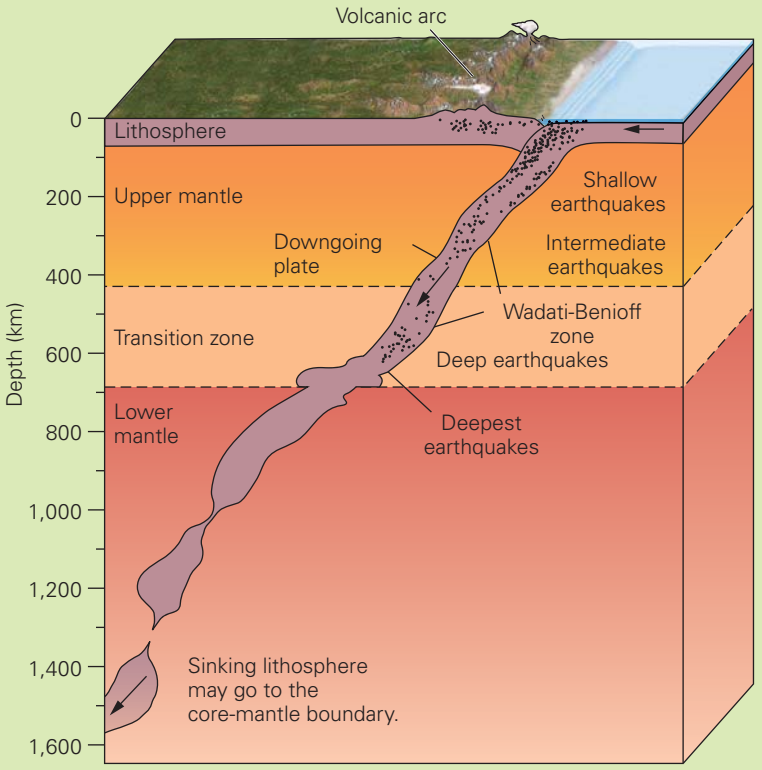
In the Peru-Chile Trench, as the downgoing plate slides under the overriding plate, sediment (clay and plankton) that had settled on the surface of the downgoing plate, as well as sand that fell into the trench from the shores of South America, gets scraped up and incorporated in a wedge-shaped mass known as an **accretionary prism** (Fig. 2.21c). An accretionary prism forms in basically the same way as a pile of snow or sand in front of a plow, and like snow, the sediment tends to be squashed and contorted.

A chain of volcanoes known as a **volcanic arc** develops behind the accretionary prism (See for Yourself B). As we will see in Chapter 4, the magma that feeds these volcanoes forms just above the surface of the downgoing plate where the plate reaches a depth of about 150 km below the Earth's surface. If the volcanic arc forms where an oceanic plate subducts beneath continental lithosphere, the resulting chain of volcanoes grows on the continent and forms a continental volcanic arc. (In some cases, the plates squeeze together across a continental arc, causing a belt of faults to form behind the arc.) If, however, the volcanic arc grows

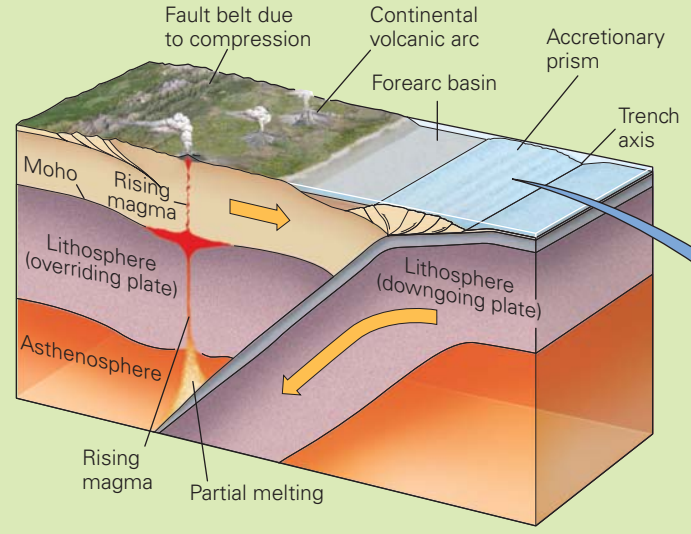
FIGURE 2.21 During the process of subduction, oceanic lithosphere sinks back into the deeper mantle.



(a) Sinking of the downgoing plate resembles the sinking of an anchor attached to a buoyant rope.

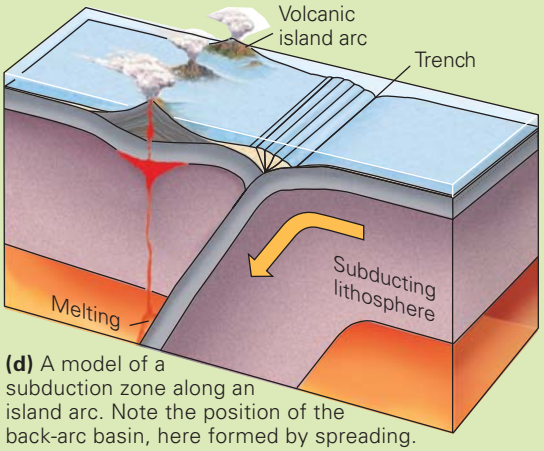


(b) A belt of earthquakes (dots) defines the position of the downgoing plate in the region above a depth of about 660 km.

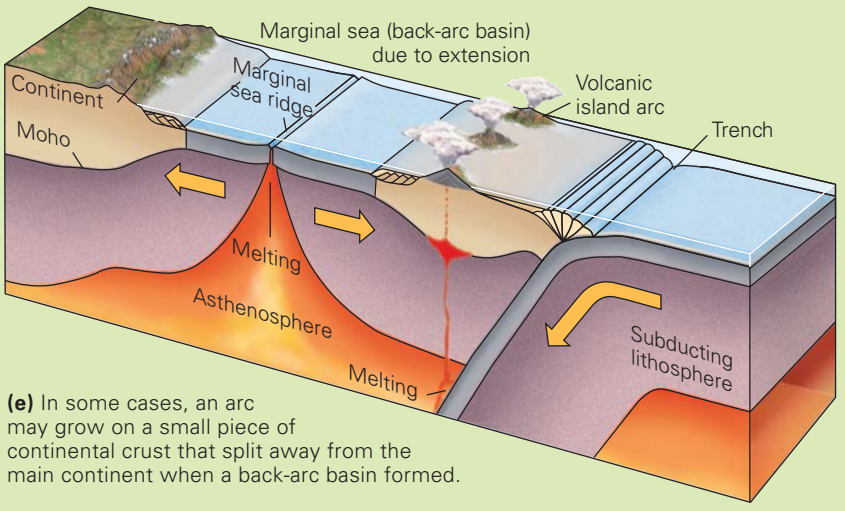




(c) A model of a subduction zone along the edge of a continent. Note the position of the trench, accretionary prism, and volcanic arc.



(d) A model of a subduction zone along an island arc. Note the position of the back-arc basin, here formed by spreading.



(e) In some cases, an arc may grow on a small piece of continental crust that split away from the main continent when a back-arc basin formed.

where one oceanic plate subducts beneath another oceanic plate, the resulting volcanoes form a chain of islands known as a volcanic island arc (Fig. 2.21d). A back-arc basin exists either where subduction happens to begin offshore, trapping ocean lithosphere behind the arc, or where stretching of the lithosphere behind the arc leads to the formation of a small spreading ridge behind the arc (Fig. 2.21e).

Take-Home Message

At a convergent plate boundary, an oceanic plate sinks into the mantle beneath the edge of another plate. A volcanic arc and a trench delineate such plate boundaries, and earthquakes happen along the contact between the two plates as well as in the downgoing slab.

2.9 Transform Plate Boundaries

When researchers began to explore the bathymetry of mid-ocean ridges in detail, they discovered that mid-ocean ridges are not long, uninterrupted lines, but rather consist of short segments that appear to be offset laterally from each other (Fig. 2.22a) by narrow belts of broken and irregular sea floor. These belts, or **fracture zones**, lie roughly at right angles to the ridge segments, intersect the ends of the segments, and extend beyond the ends of the segments. Originally, researchers incorrectly assumed that the entire length of each fracture zone was a fault, and that slip on a fracture zone had displaced segments of the mid-ocean ridge sideways, relative to each other. In other words, they imagined that a mid-ocean ridge initiated as a continuous, fence-like line that only later was broken up by faulting. But when information about the distribution of earthquakes along mid-ocean ridges became available, it was clear that this model could not be correct. Earthquakes, and therefore active fault slip, occur *only* on the segment of a fracture zone that lies between two ridge segments. The portions of fracture zones that extend beyond the edges of ridge segments, out into the abyssal plain, are not seismically active.

The distribution of movement along fracture zones remained a mystery until a Canadian researcher, J. Tuzo Wilson, began to think about fracture zones in the context of the sea-floor-spreading concept. Wilson proposed that fracture zones formed *at the same time* as the ridge axis itself, and thus the ridge consisted of separate segments to start with. These segments were linked (not offset) by fracture zones. With this idea in mind, he drew a sketch map showing two ridge-axis segments linked by a fracture zone, and he drew arrows to indicate the direction that ocean floor was moving, relative to the ridge axis, as a result of sea-floor-spreading (Fig. 2.22b). Look at the arrows in Figure 2.22b. Clearly, the movement direction on the active portion of the fracture zone must be opposite to the movement direction that researchers originally thought occurred on the structure. Further, in Wilson's model, slip occurs only along the segment of the fracture zone between the two ridge segments (Fig. 2.22c). Plates on opposite sides of the inactive part of a fracture zone move together, as one plate.

Wilson introduced the term **transform boundary**, or transform fault, for the actively slipping segment of a fracture zone between two ridge segments, and he pointed out that these are a third type of plate boundary. At a transform boundary, one plate slides sideways past another, but no new plate forms and no old plate is consumed. Transform boundaries are, therefore, defined by a vertical fault on which the slip direction parallels the Earth's surface. The slip breaks up the crust and forms a set of steep fractures.

So far we've discussed only transforms along mid-ocean ridges. Not all transforms link ridge segments. Some, such as the Alpine Fault of New Zealand, link trenches, while others link a trench to a ridge segment. Further, not all transform faults occur in oceanic lithosphere; a few cut across continental lithosphere. The San Andreas Fault, for example, which cuts across California, defines part of the plate boundary between the North American Plate and the Pacific Plate—the portion of California that lies to the west of the fault (including Los Angeles) is part of the Pacific Plate, while the portion that lies to the east of the fault is part of the North American Plate (Fig. 2.22d, e).

Take-Home Message

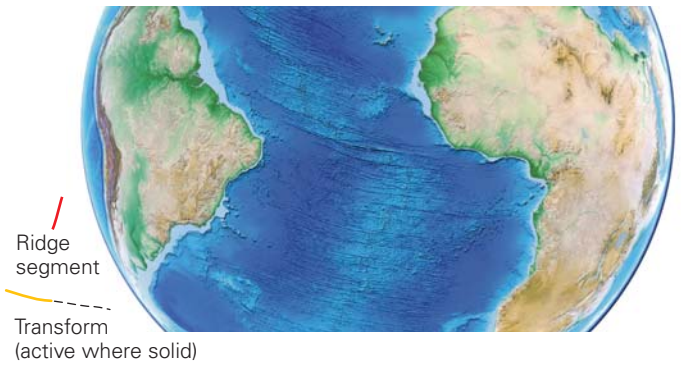
At transform plate boundaries, one plate slips sideways past another. Most transform boundaries link segments of mid-ocean ridges, but some, such as the San Andreas Fault, cut across continental crust.

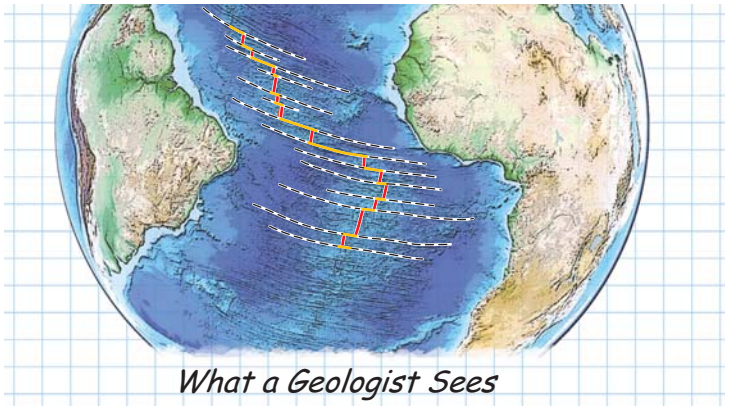
2.10 Special Locations in the Plate Mosaic

Triple Junctions

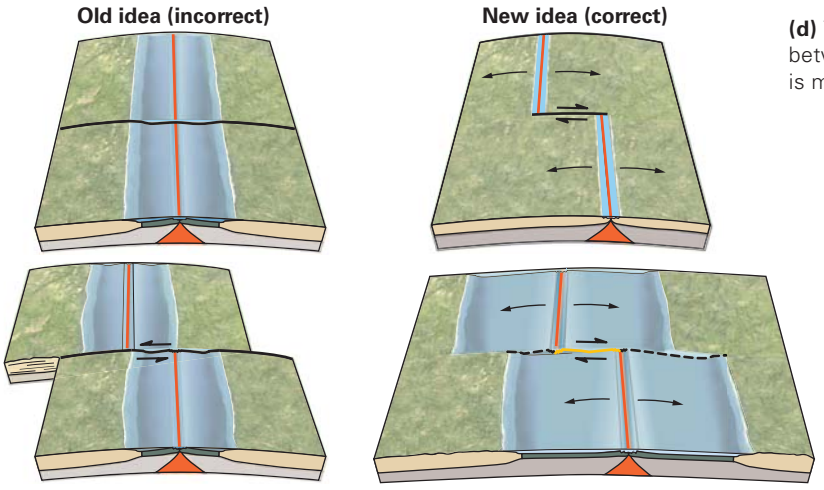
Geologists refer to a place where three plate boundaries intersect as a **triple junction**, and name them after the types of boundaries that intersect. For example, the triple junction formed where the Southwest Indian Ocean Ridge intersects two arms of the Mid–Indian Ocean Ridge (this is the triple

FIGURE 2.22 The concept of transform faulting.

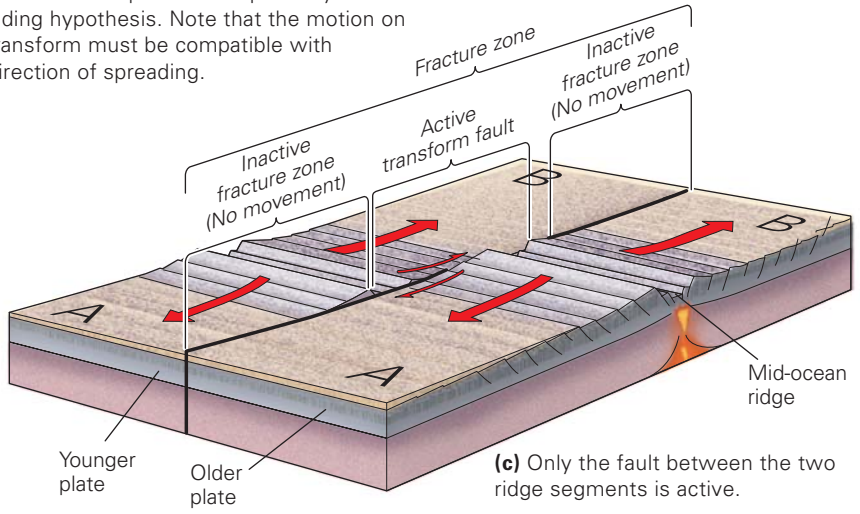




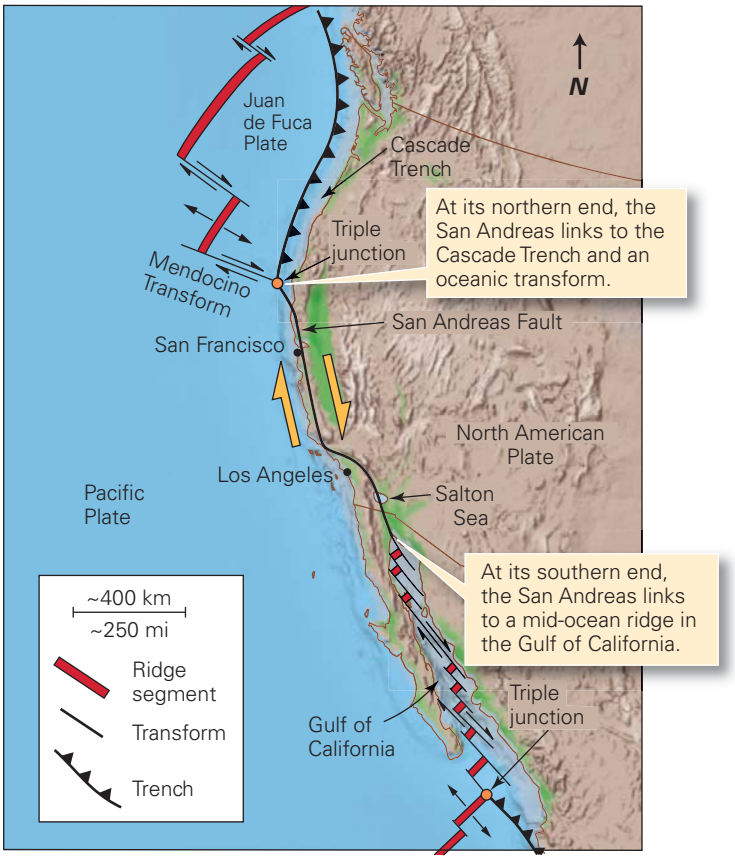
(a) Transform faults segment the Mid-Atlantic Ridge.



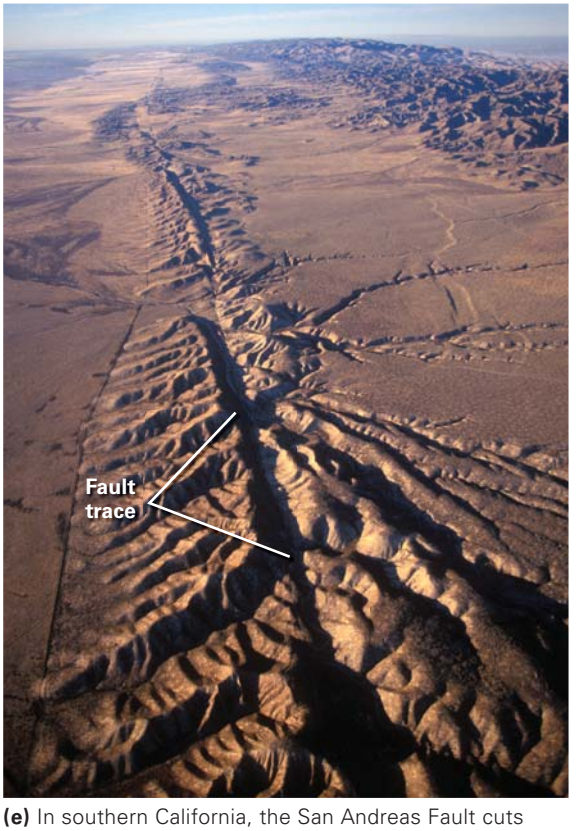
(b) A comparison of the old interpretation of transform faults with the new interpretation required by the sea-floor spreading hypothesis. Note that the motion on the transform must be compatible with the direction of spreading.



(c) Only the fault between the two ridge segments is active.

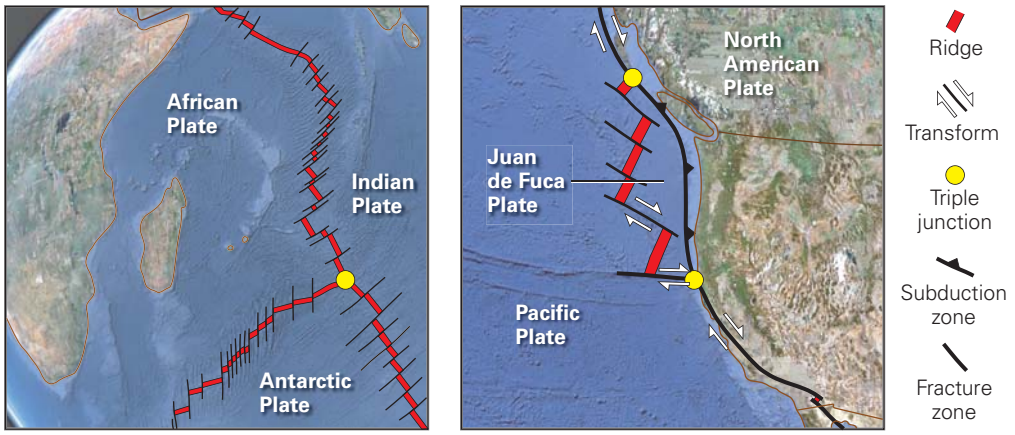


(d) The San Andreas Fault is a transform plate boundary between the North American and Pacific Plates. The Pacific is moving northwest, relative to North America.



(e) In southern California, the San Andreas Fault cuts a dry landscape. The fault trace is in the narrow valley. The land has been pushed up slightly along the fault.

FIGURE 2.23 Examples of triple junctions. The triple junctions are marked by dots.



(a) A ridge-ridge-ridge triple junction occurs in the Indian Ocean.

(b) A trench-transform-transform triple junction occurs at the north end of the San Andreas Fault.

junction of the African, Antarctic, and Australian Plates) is a ridge-ridge-ridge triple junction (Fig. 2.23a). The triple junction north of San Francisco is a trench-transform-transform triple junction (Fig. 2.23b).

Hot Spots

Most subaerial (above sea level) volcanoes are situated in the volcanic arcs that border trenches. Volcanoes also lie along mid-ocean ridges, but ocean water hides most of them. The volcanoes of volcanic arcs and mid-ocean ridges *are plate-boundary volcanoes,* in that they formed as a consequence of movement along the boundary. Not all volcanoes on Earth are plate-boundary volcanoes, however. Worldwide, geoscientists have identified about 100 volcanoes that exist as isolated points and are not a consequence of movement at a plate boundary. These are called hot-spot volcanoes, or simply **hot spots** (Fig. 2.24). Most hot spots are located in the interiors of plates, away from the boundaries, but a few lie along mid-ocean ridges.

What causes hot-spot volcanoes? In the early 1960s, J. Tuzo Wilson noted that *active* hot-spot volcanoes (examples that are erupting or may erupt in the future) occur at the end of a chain of *dead* volcanic islands and seamounts (formerly active volcanoes that will never erupt again). This configuration is different from that of volcanic arcs along convergent plate boundaries—at volcanic arcs, all of the volcanoes are active. With this image in mind, Wilson suggested that the position of the heat source causing a hot-spot volcano is fixed, relative to the moving plate. In Wilson's model, the active volcano represents the present-day location of the heat source, whereas the chain of dead volcanic islands represents locations on the plate that were once over the heat source but progressively moved off.

A few years later, researchers suggested that the heat source for hot spots is a **mantle plume**, a column of very hot rock rising up through the mantle to the base of the lithosphere (Fig. 2.25a–d). In this model, plumes originate deep in the mantle. Rock in the plume, though solid, is soft

FIGURE 2.24 The dots represent the locations of selected hot-spot volcanoes. The red lines represent hot-spot tracks. The most recent volcano (dot) is at one end of this track. Some of these volcanoes are extinct, indicating that the mantle plume no longer exists. Some hot spots are fairly recent and do not have tracks. Dashed tracks were broken by sea-floor spreading.

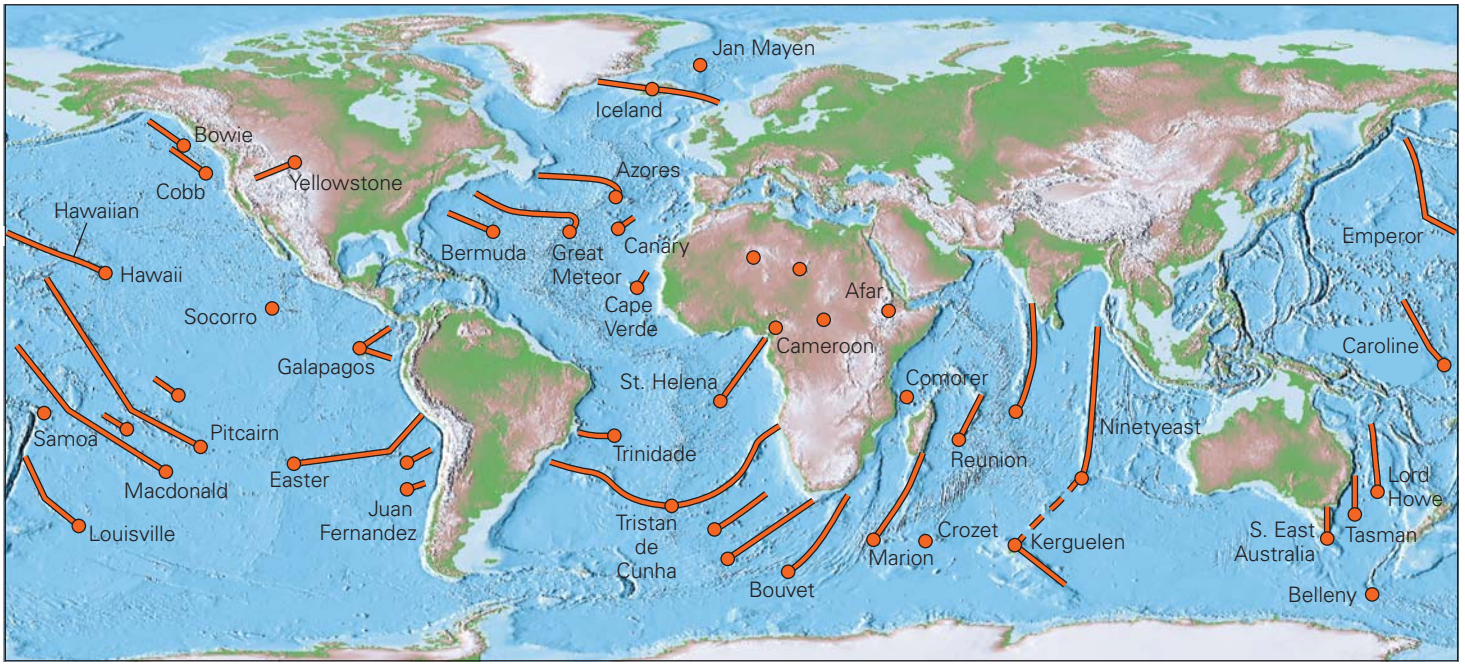
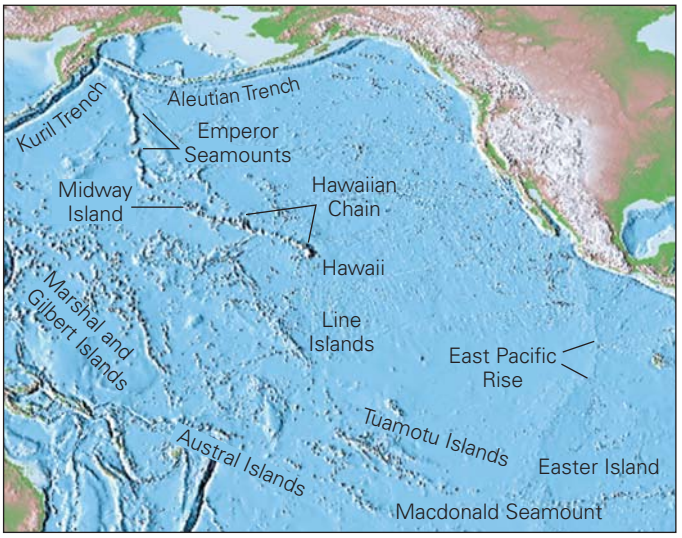
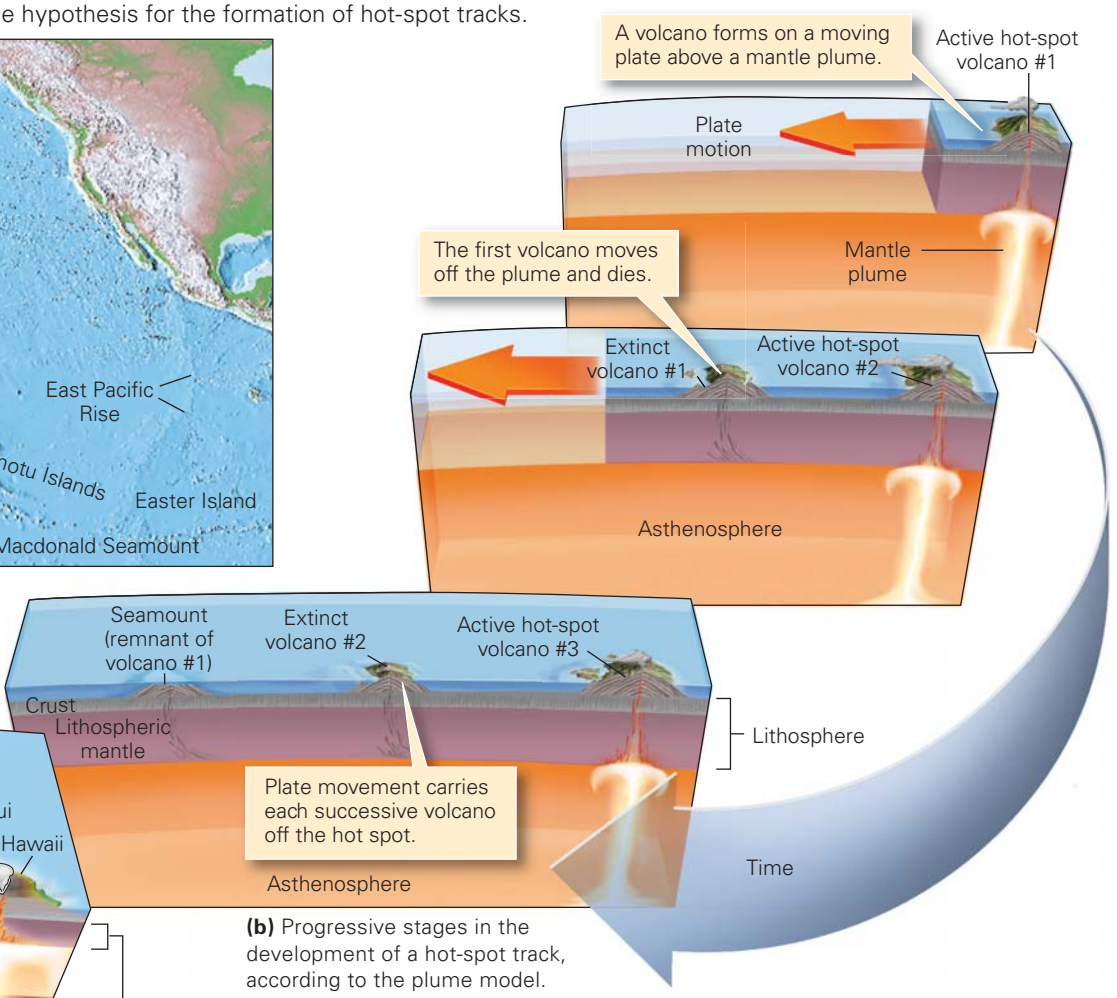


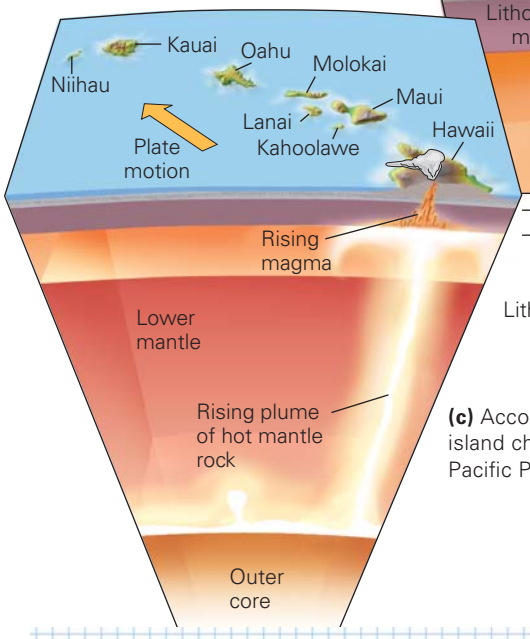
FIGURE 2.25 The deep mantle plume hypothesis for the formation of hot-spot tracks.



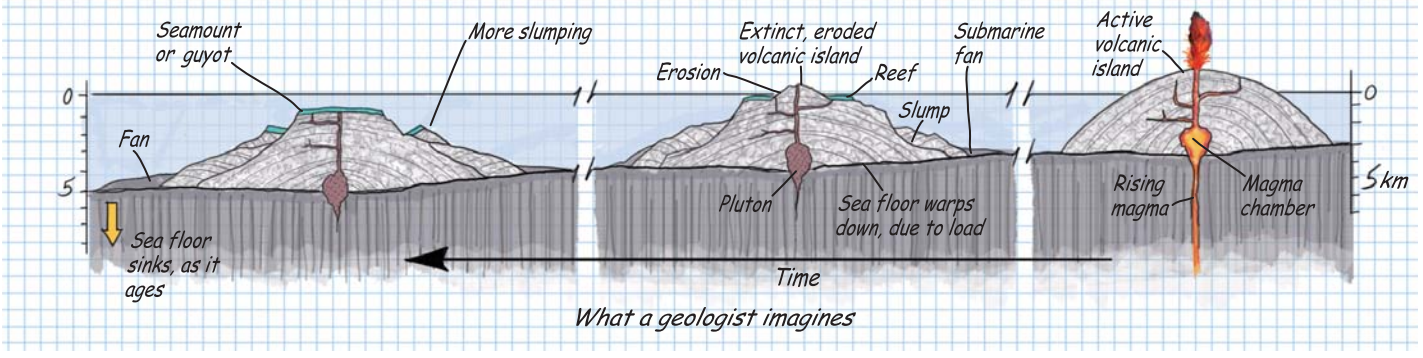
(a) A bathymetric map showing the hot-spot tracks of the Pacific Ocean.



(b) Progressive stages in the development of a hot-spot track, according to the plume model.



(c) According to the plume model, the Hawaiian island chain is a hot-spot track that formed as the Pacific Plate moved northwest relative to a plume.



(d) As a volcano moves off the hot spot, it gradually sinks below sea level, due to sinking of the plate, erosion, and slumping.

enough to flow, and rises buoyantly because it is less dense than surrounding cooler rock. When the hot rock of the plume reaches the base of the lithosphere, it partially melts (for reasons discussed in Chapter 4) and produces magma that seeps up through the lithosphere to the Earth's surface. The chain of extinct volcanoes, or **hot-spot track**, forms when the overlying plate moves over a fixed plume. This movement slowly carries the volcano off the top of the plume, so that it becomes extinct. A new, younger volcano grows over the plume.

The Hawaiian chain provides an example of the volcanism associated with a hot-spot track. Volcanic eruptions occur today only on the big island of Hawaii. Other islands to the northwest are remnants of dead volcanoes, the oldest of which is Kauai. To the northwest of Kauai, still older volcanic remnants are found. About 1,750 km northwest of Midway Island, the track bends in a more northerly direction, and the volcanic remnants no longer poke above sea level; we refer to this northerly trending segment as the Emperor seamount chain. Geologists suggest that the bend is due to a change in the direction of Pacific Plate motion at about 40 Ma.

Some hot spots lie within continents. For example, several have been active in the interior of Africa, and one now underlies Yellowstone National Park. The famous geysers (natural steam and hot-water fountains) of Yellowstone exist because hot magma, formed above the Yellowstone hot spot, lies not far below the surface of the park. While most hot spots, such as Hawaii and Yellowstone, occur in the interior of plates, away from plate boundaries, a few are positioned at points on mid-ocean ridges. The additional magma production associated with such hot spots causes a portion of the ridge to grow into a mound that can rise significantly above normal ridge-axis depths and protrude above the sea surface. Iceland, for example, is the product of hot-spot volcanism on the axis of the Mid-Atlantic Ridge.

Take-Home Message

A triple junction marks the point where three plate boundaries join. A hot spot is a place where volcanism may be due to melting at the top of a mantle plume. As a plate moves over a plume, a hot-spot track develops.

2.11 How Do Plate Boundaries Form and Die?

The configuration of plates and plate boundaries visible on our planet today has not existed for all of geologic history, and will not exist indefinitely into the future. Because of plate motion, oceanic plates form and are later consumed, while continents merge and later split apart. How does a new divergent boundary come into existence, and how does an existing convergent boundary eventually cease to exist? Most new divergent boundaries form when a continent splits and separates into two continents. We call this process **rifting**. A convergent boundary ceases to exist when a piece of buoyant lithosphere, such as a continent or an island arc, moves into the subduction zone and, in effect, jams up the system. We call this process **collision**.

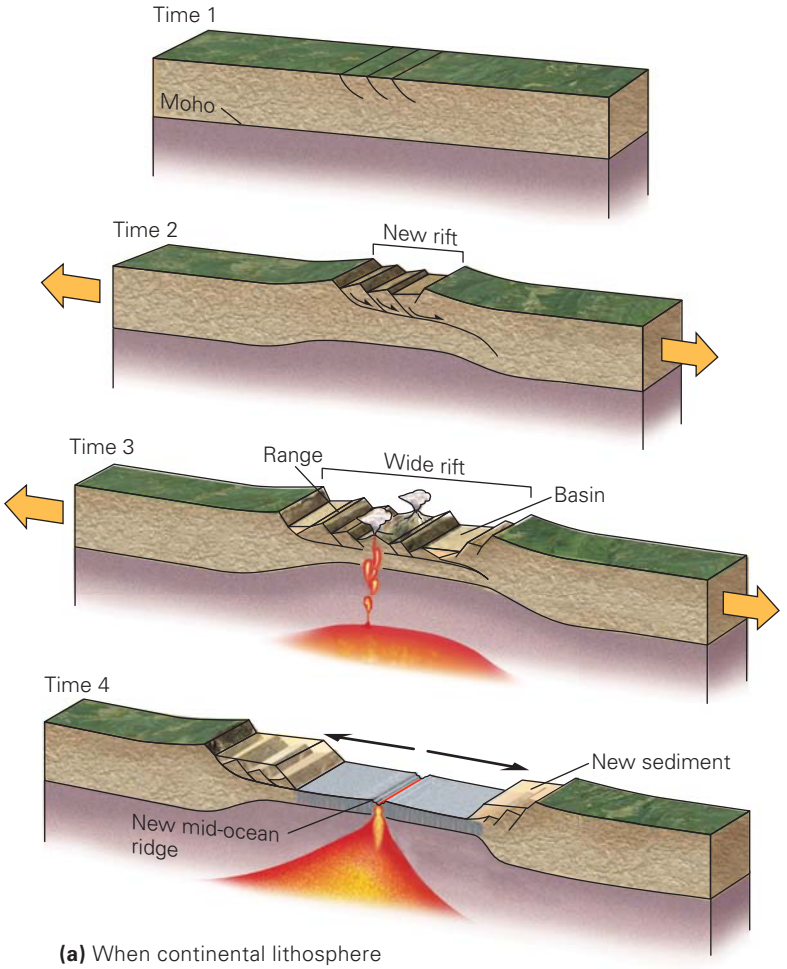
Continental Rifting

A **continental rift** is a linear belt in which continental lithosphere pulls apart (Fig. 2.26a). During the process, the lithosphere stretches horizontally and thins vertically, much like a piece of taffy you pull between your fingers. Nearer the surface of the continent, where the crust is cold and brittle, stretching causes rock to break and faults to develop. Blocks of rock slip down the fault surfaces, leading to the formation of a low area that gradually becomes buried by sediment. Deeper in the crust, and in the underlying lithospheric mantle, rock is warmer and softer, so stretching takes place in a plastic manner without breaking the rock. The whole region that stretches is the rift, and the process of stretching is called rifting.

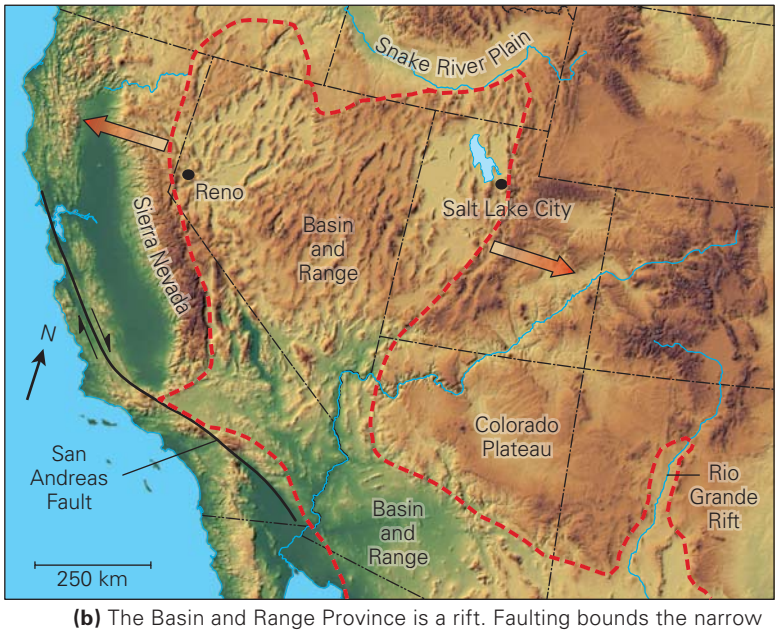
As continental lithosphere thins, hot asthenosphere rises beneath the rift and starts to melt. Eruption of the molten rock produces volcanoes along the rift. If rifting continues for a long enough time, the continent breaks in two, a new mid-ocean ridge forms, and sea-floor spreading begins. The relict of the rift evolves into a passive margin (see Fig. 2.14b). In some cases, however, rifting stops before the continent splits in two; it becomes a low-lying trough that fills with sediment. Then, the rift remains as a permanent scar in the crust, defined by a belt of faults, volcanic rocks, and a thick layer of sediment.

A major rift, known as the Basin and Range Province, breaks up the landscape of the western United States (Fig. 2.26b). Here, movement on numerous faults tilted blocks of crust to form narrow mountain ranges, while sediment that eroded from the blocks filled the adjacent basins (the low areas between the ranges). Another active rift slices through eastern Africa; geoscientists aptly refer to it as the East African Rift (Fig. 2.26c, d). To astronauts in orbit, the rift looks like a giant gash in the crust. On the ground, it consists of a deep trough bordered on both sides by high cliffs formed by faulting. Along the length of the rift, several major volcanoes smoke and fume; these include the snow-crested Mt. Kilimanjaro, towering over 6 km above the savannah. At its north end, the rift joins the Red Sea Ridge and the Gulf of Aden Ridge at a triple junction.

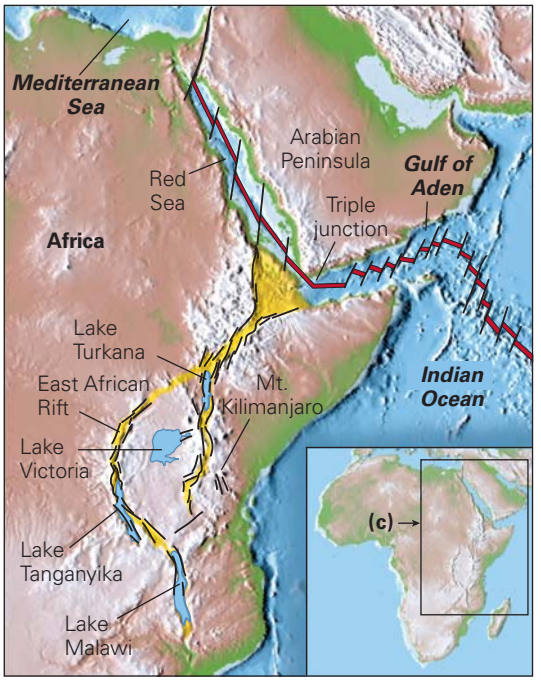
FIGURE 2.26 During the process of rifting, lithosphere stretches.



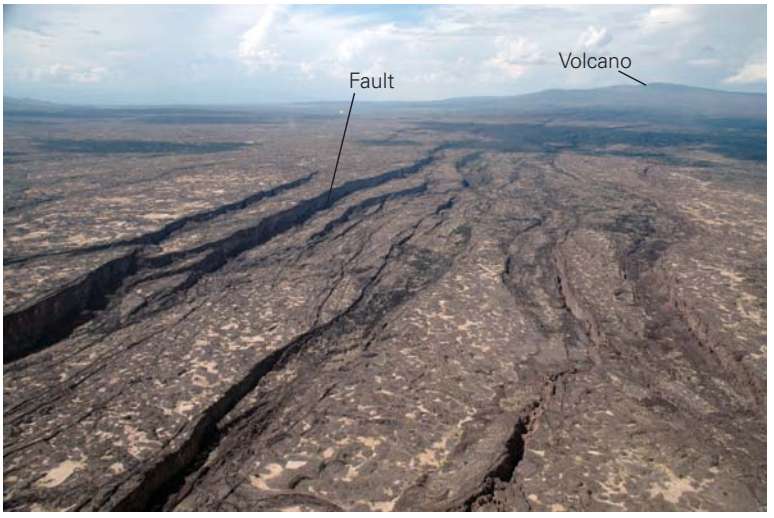
(a) When continental lithosphere stretches and thins, faulting takes place, and volcanoes erupt. Eventually, the continent splits in two and a new ocean basin forms.



(b) The Basin and Range Province is a rift. Faulting bounds the narrow north-south-trending mountains, separated by basins. The arrows indicate the direction of stretching.



(c) The East African Rift is growing today. The Red Sea started as a rift. The inset shows map locations.



(d) An air photo of the northern end of the East African rift, showing faults and volcanoes.

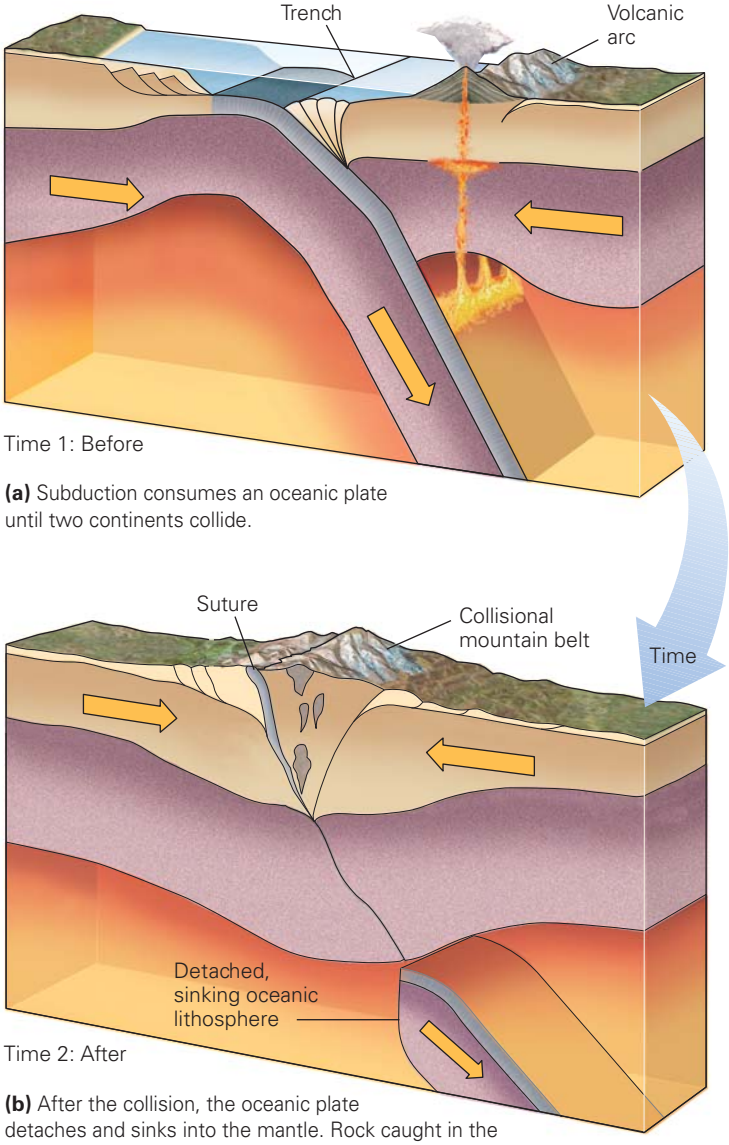
Collision

India was once a small, separate continent that lay far to the south of Asia. But subduction consumed the ocean between India and Asia, and India moved northward, finally slamming into the southern margin of Asia about 40 to 50 million years ago. Continental crust, unlike oceanic crust, is too buoyant to subduct. So when India collided with Asia, the attached oceanic plate broke off and sank down into the deep mantle while India pushed hard into and partly under Asia, squeezing the rocks and sediment that once lay between the two continents into the 8-km-high welt that we now know as the Himalayan Mountains. During this process, not

only did the surface of the Earth rise, but the crust became thicker. The crust beneath a collisional mountain range can be up to 60 to 70 km thick, about twice the thickness of normal continental crust. The boundary between what was once two separate continents is called a suture; slivers of ocean crust may be trapped along a suture.

Geoscientists refer to the process during which two buoyant pieces of lithosphere converge and squeeze together as collision (**Fig. 2.27a, b**). Some collisions involve two continents, whereas some involve continents and an island arc. When a collision is complete, the convergent plate boundary that once existed between the two colliding pieces ceases to exist. Collisions yield some of the most spectacular mountains on the planet, such as the Himalayas and the Alps. They also yielded major mountain ranges in the past, which subsequently eroded away so that today we see only their relicts. For example, the Appalachian Mountains in the eastern United States formed as a consequence of three collisions. After the last one, a collision between Africa and North America around 300 Ma, North America became part of the Pangaea supercontinent.

FIGURE 2.27 Continental collision (not to scale).



(a) Subduction consumes an oceanic plate until two continents collide.

(b) After the collision, the oceanic plate detaches and sinks into the mantle. Rock caught in the collision zone gets broken, bent, and squashed and forms a mountain range.

Take-Home Message

Rifting can split a continent in two and can lead to the formation of a new divergent plate boundary. When two buoyant crustal blocks, such as continents and island arcs, collide, a mountain belt forms and subduction eventually ceases.

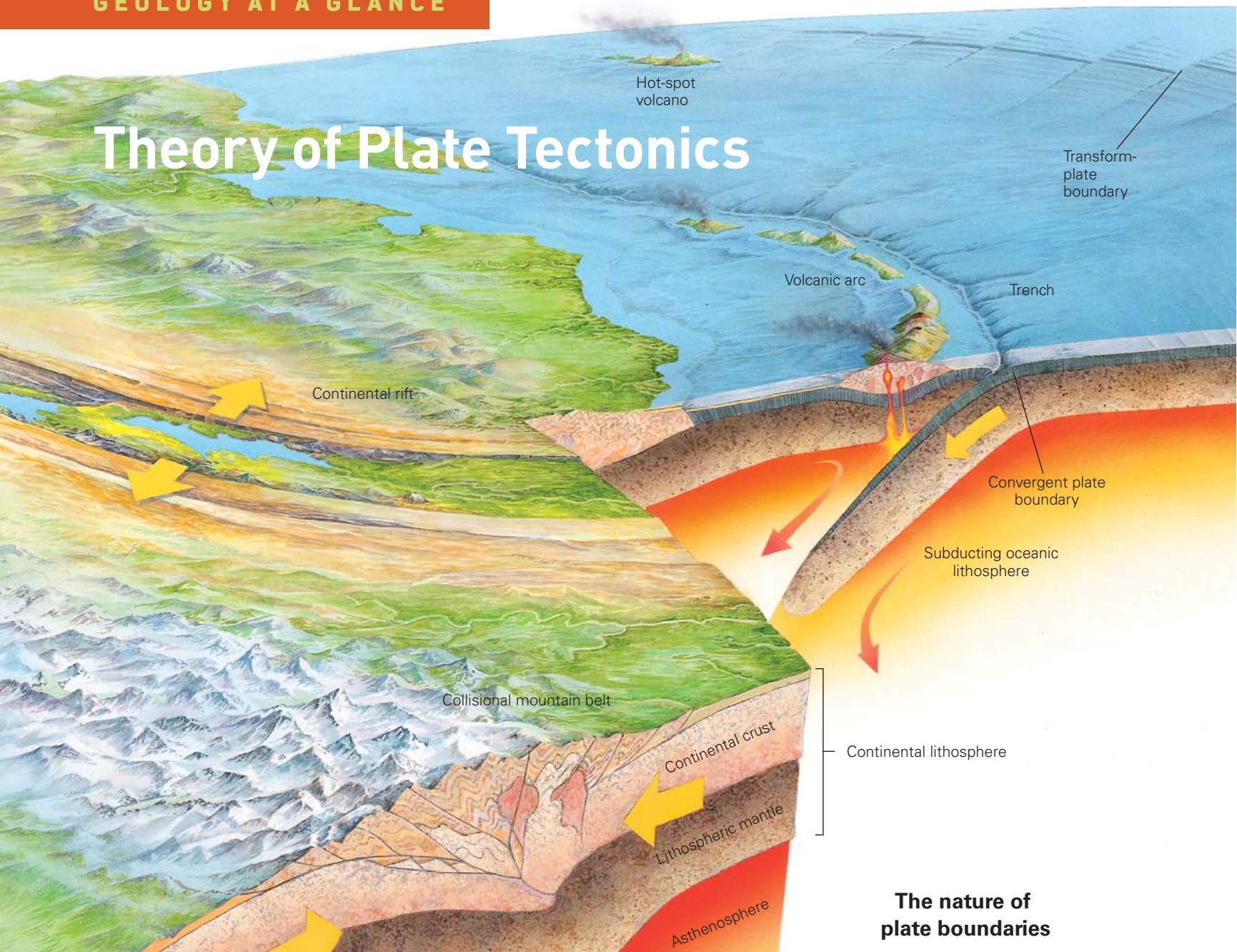
2.12 What Drives Plate Motion, and How Fast Do Plates Move?

Forces Acting on Plates

We've now discussed the many facets of plate tectonics theory (see **Geology at a Glance**, pp. 64–65). But to complete the story, we need to address a major question: "What drives plate motion?" When geoscientists first proposed plate tectonics, they thought the process occurred simply because convective flow in the asthenosphere actively dragged plates along, as if the plates were simply rafts on a flowing river. Thus, early images depicting plate motion showed simple convection cells—elliptical flow paths—in the asthenosphere. At first glance, this hypothesis looked pretty good. But, on closer examination it became clear that a model of simple convection cells carrying plates on their backs can't explain the complex geometry of plate boundaries and the great variety of plate motions that we observe on the Earth. Researchers now prefer a model in which convection, ridge push, and slab pull all contribute to driving plates. Let's look at each of these phenomena in turn.

Convection is involved in plate motions in two ways. Recall that, at a mid-ocean ridge, hot asthenosphere rises and then cools to form oceanic lithosphere which slowly moves away from the ridge until, eventually, it sinks back into the mantle at a trench. Since the material forming the plate starts out hot, cools, and then sinks, we can view the plate itself as the top of a convection cell and plate motion as a form of convection. But in this view, convection is effectively a consequence of plate motion, not the cause. Can convection actually cause plates to move? The answer may come from studies which demonstrate that the interior of the mantle, beneath the plates, is indeed convecting on a very broad scale (see Interlude D). Specifically, geologists have found that there are places where deeper, hotter asthenosphere is rising or *upwelling*, and places where shallower, colder asthenosphere is sinking or *downwelling*. Such

Theory of Plate Tectonics

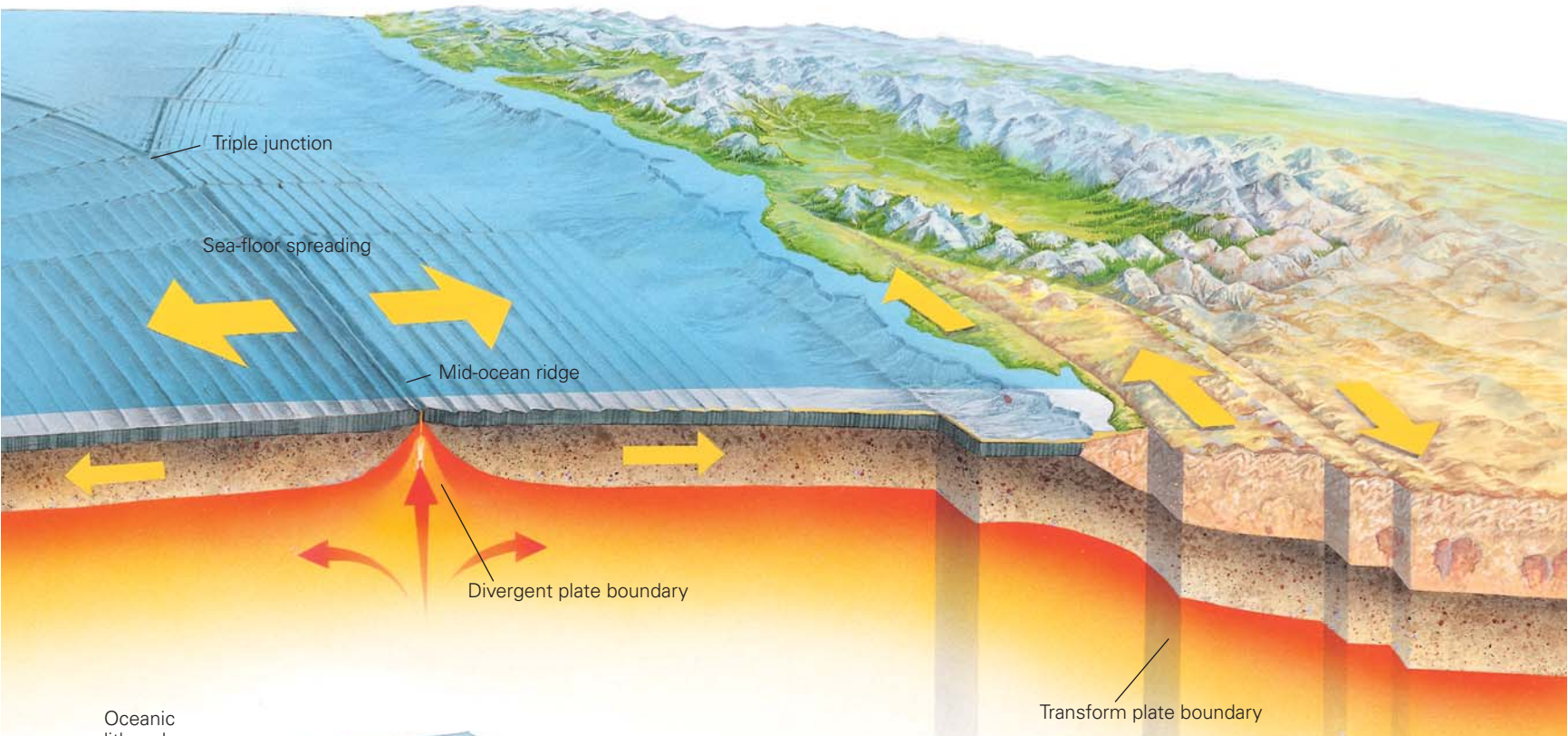


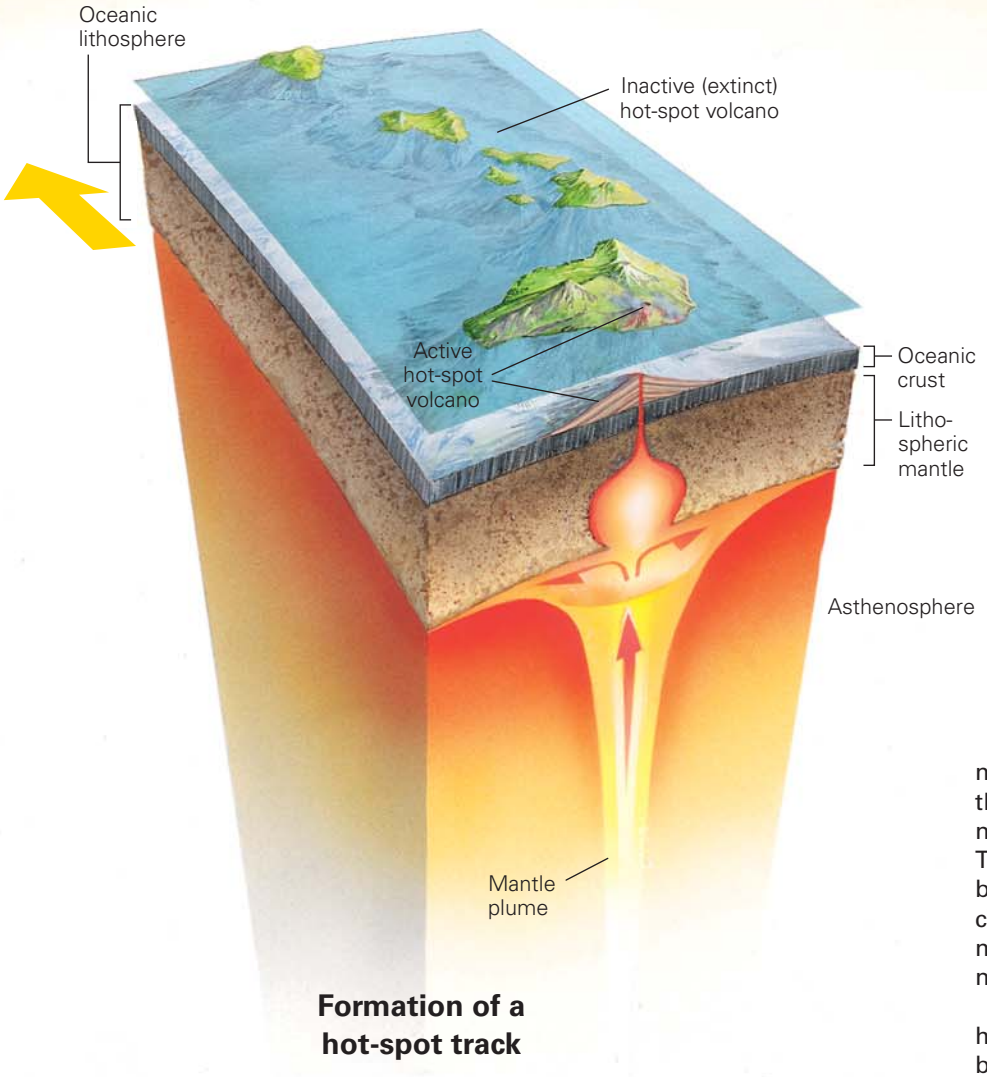
The nature of plate boundaries

The outer portion of the Earth is a relatively rigid layer called the lithosphere. It consists of the crust (oceanic or continental) and the uppermost mantle. The mantle below the lithosphere is relatively plastic (it can flow) and is called the asthenosphere. The difference in behavior (rigid vs. plastic) between lithospheric mantle and asthenospheric mantle is a consequence of temperature—the former is cooler than the latter. Continental lithosphere is typically about 150 km thick, while oceanic lithosphere is about 100 km thick. (*Note*: These are not drawn to scale in this image.)

According to the theory of plate tectonics, the lithosphere is broken into about 20 plates that move relative to each other. Most of the motion takes place by sliding along plate boundaries (the edges of plates); plate interiors stay relatively unaffected by this motion. There are three kinds of plate boundaries.

1. Divergent boundaries: Here, two plates move apart by a process called sea-floor spreading. A mid-ocean ridge delineates a divergent boundary. Asthenospheric mantle rises beneath a





Formation of a hot-spot track

mid-ocean ridge and partially melts, forming magma. The magma rises to create new oceanic crust. The lithospheric mantle thickens progressively away from the ridge axis as the plate cools.

2. Convergent boundaries: Here, two plates move together, and one plate subducts beneath another (it sinks down into the mantle). Only oceanic lithosphere can subduct. At the Earth's surface, the boundary between the two plates is marked by a deep-ocean trench. During subduction, melting above the downgoing plate produces magma that rises to form a volcanic arc.
3. Transform boundaries: Here, one plate slides sideways past another, without the creation of a new plate or the subduction of an old one. The boundary is marked by a large fault, a fracture on which sliding occurs. Transform boundaries link segments of mid-ocean ridges. They may also cut through continental lithosphere.

At a triple junction, three plate boundaries meet. This figure shows a triple junction where three mid-ocean ridges meet. Where two continents collide, a collisional mountain belt forms. This happens because continental crust is too buoyant to be subducted. At a continental rift, a continent stretches and may break in two. Rifts are marked by the existence of many faults. If a continent breaks apart, a new mid-ocean ridge develops.

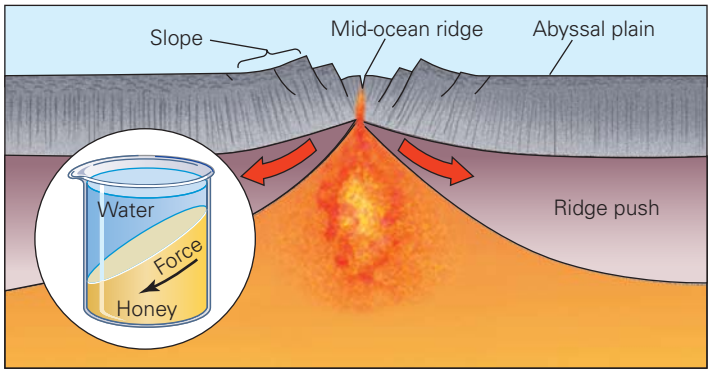
Hot-spot volcanoes may form above plumes of hot mantle rock that rise from near the core-mantle boundary. As a plate drifts over a hot spot, it leaves a chain of extinct volcanoes.

asthenospheric flow probably does exert a force on the base of plates. But the pattern of upwelling and downwelling on a global scale does not match the pattern of plate boundaries exactly. So, conceivably, asthenosphere-flow may either speed up or slow down plates depending on the orientation of the flow direction relative to the movement direction of the overlying plate.

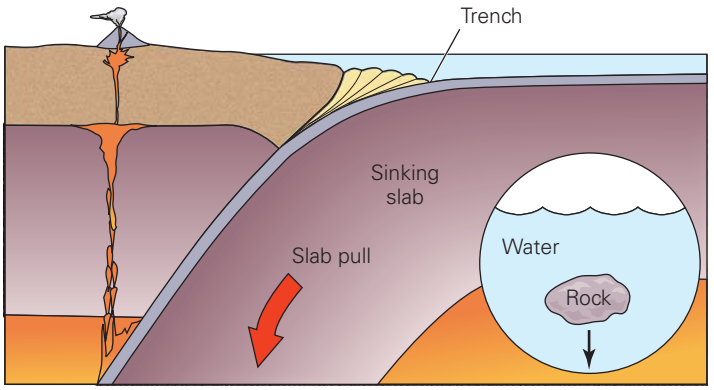
Ridge-push force develops simply because the lithosphere of mid-ocean ridges lies at a higher elevation than that of the adjacent abyssal plains (**Fig. 2.28a**). To understand ridge-push force, imagine you have a glass containing a layer of water over a layer of honey. By tilting the glass momentarily and then returning it to its upright position, you can create a temporary slope in the boundary between these substances. While the boundary has this slope, gravity causes the weight of elevated honey to push against the glass adjacent to the side where the honey surface lies at lower elevation. The geometry of a mid-ocean ridge resembles this situation, for sea floor of a mid-ocean ridge is higher than sea floor of abyssal plains. Gravity causes the elevated lithosphere at the ridge axis to push on the lithosphere that lies farther from the axis, making it move away. As lithosphere moves away from the ridge axis, new hot asthenosphere rises to fill the gap. Note that the local upward movement of asthenosphere beneath a mid-ocean ridge is a *consequence* of sea-floor spreading, not the cause.

Slab-pull force, the force that subducting, downgoing plates apply to oceanic lithosphere at a convergent margin, arises simply because lithosphere that was formed more than 10 million years ago is denser than asthenosphere, so it can sink into the asthenosphere (**Fig. 2.28b**). Thus, once an oceanic plate starts to sink, it gradually pulls the rest of the plate along behind it, like an anchor pulling down the anchor line. This "pull" is the slab-pull force.

FIGURE 2.28 Forces driving plate motions. Both ridge push and slab pull make plates move.



(a) Ridge push develops because the region of a rift is elevated. Like a wedge of honey with a sloping surface, the mass of the ridge pushes sideways.



(b) Slab pull develops because lithosphere is denser than the underlying asthenosphere, and sinks like a stone in water (though much more slowly).

The Velocity of Plate Motions

How fast do plates move? It depends on your frame of reference. To illustrate this concept, imagine two cars speeding in the same direction down the highway. From the viewpoint of a tree along the side of the road, Car A zips by at 100 km an hour, while Car B moves at 80 km an hour. But relative to Car B, Car A moves at only 20 km an hour. Geologists use two different frames of reference for describing plate velocity. If we describe the movement of Plate A with respect to Plate B, then we are speaking about **relative plate velocity**. But if we describe the movement of both plates relative to a fixed location in the mantle below the plates, then we are speaking of **absolute plate velocity** (**Fig. 2.29**).

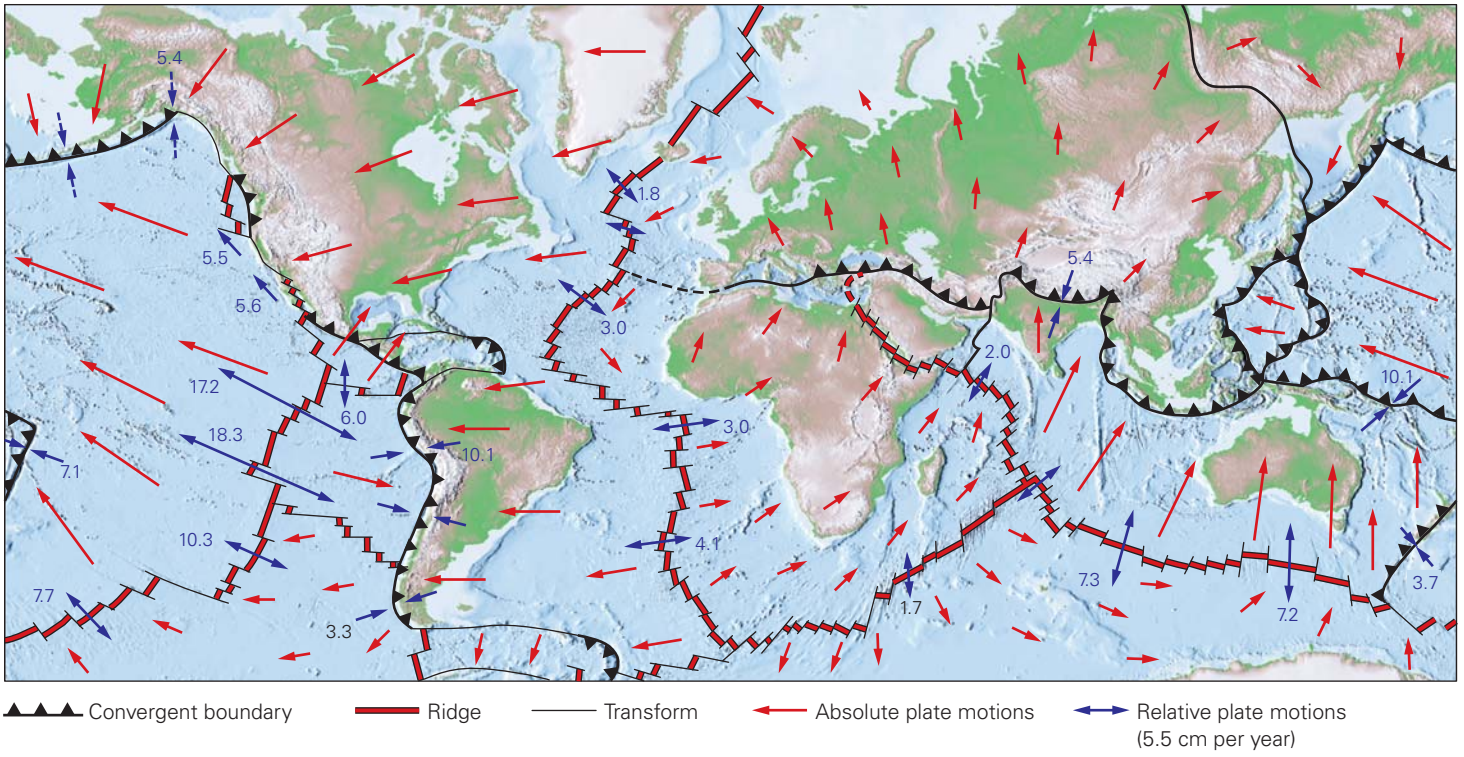
To determine relative plate motions, geoscientists measure the distance of a known magnetic anomaly from the axis of a mid-ocean ridge and then calculate the velocity of a plate relative to the ridge axis by applying this equation: plate velocity = distance from the anomaly to the ridge axis divided by the age of the anomaly (velocity, by definition, is distance ÷ time). The velocity of the plate on one side of the ridge relative to the plate on the other is twice this value.

To estimate absolute plate motions, we can *assume* that the position of a mantle plume does not change much for a long time. If this is so, then the track of hot-spot volcanoes on the plate moving over the plume provides a record of the plate's absolute velocity and indicates the direction of movement. (In reality, plumes are not completely fixed; geologists use other, more complex methods to calculate absolute plate motions.)

Did you ever wonder . . .
whether we can really "see" continents drift?

Working from the calculations described above, geologists have determined that plate motions on Earth today occur at rates of about 1 to 15 cm per year—about the rate that your fingernails grow. But these rates, though small, can yield large displacements given the immensity of geologic time. At a rate of 10 cm per year, a plate can move 100 km in a million years! Can we detect such slow rates? Until the last decade, the

FIGURE 2.29 *Relative plate velocities*: The blue arrows show the rate and direction at which the plate on one side of the boundary is moving with respect to the plate on the other side. The length of an arrow represents the velocity. *Absolute plate velocities*: The red arrows show the velocity of the plates with respect to a fixed point in the mantle.



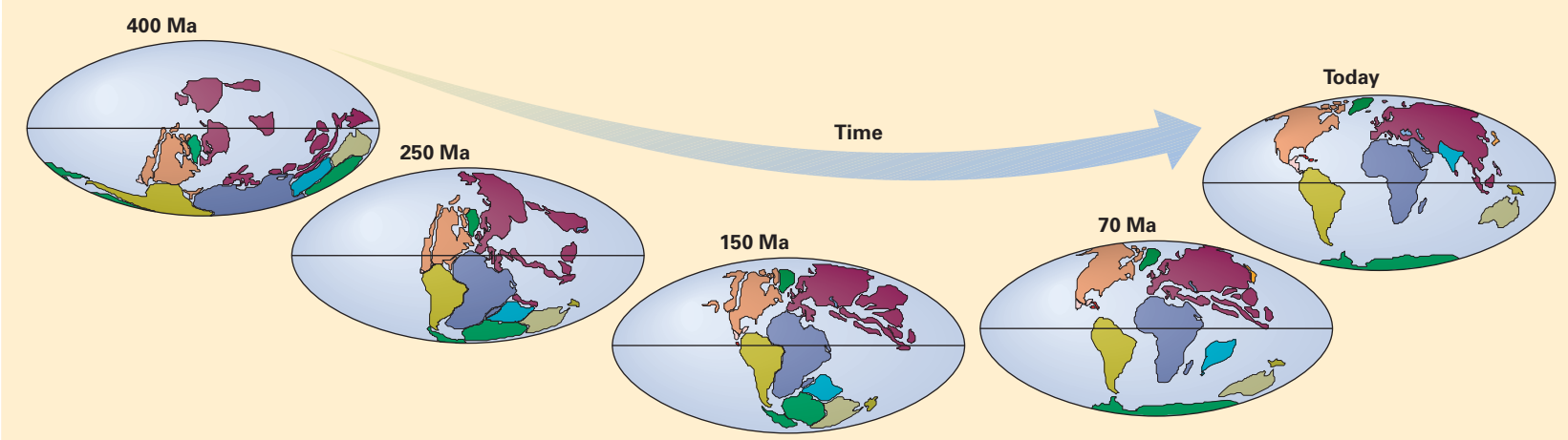
answer was no. Now the answer is yes, because of satellites orbiting the Earth with **global positioning system (GPS)** technology. Automobile drivers use GPS receivers to find their destinations, and geologists use them to monitor plate motions. If we calculate carefully enough, we can detect displacements of millimeters per year. In other words, we can now see the plates move—this observation serves as the ultimate proof of plate tectonics.

Taking into account many data sources that define the motion of plates, geologists have greatly refined the image of continental drift that Wegener tried so hard to prove nearly a century ago. We can now see how the map of our planet's surface has evolved radically during the past 400 million years (Fig. 2.30), and even before.

Take-Home Message

Plates move at 1 to 15 cm/yr. Relative motion specifies the rate that a plate moves relative to its neighbor, whereas absolute motion specifies the rate that a plate moves relative to a fixed point beneath the plate. GPS measurements can detect relative plate motions directly.

FIGURE 2.30 Due to plate tectonics, the map of Earth's surface slowly changes. Here we see the assembly, and later the breakup, of Pangaea during the past 400 million years.



CHAPTER 2 REVIEW

Chapter Summary

- Alfred Wegener proposed that continents had once been joined together to form a single huge supercontinent (Pangaea) and had subsequently drifted apart. This idea is the continental drift hypothesis.
- Wegener drew from several different sources of data to support his hypothesis: (1) the correlation of coastlines; (2) the distribution of late Paleozoic glaciers; (3) the distribution of late Paleozoic climatic belts; (4) the distribution of fossil species; and (5) correlation of distinctive rock assemblages now on opposite sides of the ocean.
- Rocks retain a record of the Earth's magnetic field that existed at the time the rocks formed. This record is called paleomagnetism. By measuring paleomagnetism in successively older rocks, geologists discovered apparent polar-wander paths.
- Apparent polar-wander paths are different for different continents, because continents move with respect to each other, while the Earth's magnetic poles remain roughly fixed.
- Around 1960, Harry Hess proposed the hypothesis of sea-floor spreading. According to this hypothesis, new sea floor forms at mid-ocean ridges, then spreads symmetrically away from the ridge axis. Eventually, the ocean floor sinks back into the mantle at deep-ocean trenches.
- Geologists documented that the Earth's magnetic field reverses polarity every now and then. The record of reversals is called the magnetic-reversal chronology.
- A proof of sea-floor spreading came from the interpretation of marine magnetic anomalies and from drilling studies which proved that sea floor gets progressively older away from a mid-ocean ridge.
- The lithosphere is broken into discrete plates that move relative to each other. Continental drift and sea-floor spreading are manifestations of plate movement.
- Most earthquakes and volcanoes occur along plate boundaries; the interiors of plates remain relatively rigid and intact.
- There are three types of plate boundaries—divergent, convergent, and transform—distinguished from each other by the movement the plate on one side of the boundary makes relative to the plate on the other side.
- Divergent boundaries are marked by mid-ocean ridges. At divergent boundaries, sea-floor spreading produces new oceanic lithosphere.
- Convergent boundaries are marked by deep-ocean trenches and volcanic arcs. At convergent boundaries, oceanic lithosphere subducts beneath an overriding plate.
- Transform boundaries are marked by large faults at which one plate slides sideways past another. No new plate forms and no old plate is consumed at a transform boundary.
- Triple junctions are points where three plate boundaries intersect.
- Hot spots are places where volcanism occurs at an isolated volcano. As a plate moves over the hot spot, the volcano moves off and dies, and a new volcano forms over the hot spot. Hot spots may be caused by mantle plumes.
- A large continent can split into two smaller ones by the process of rifting. During rifting, continental lithosphere stretches and thins. If it finally breaks apart, a new mid-ocean ridge forms and sea-floor spreading begins.
- Convergent plate boundaries cease to exist when a buoyant piece of crust (a continent or an island arc) moves into the subduction zone. When that happens, collision occurs.
- Ridge-push force and slab-pull force contribute to driving plate motions. Plates move at rates of about 1 to 15 cm per year. Modern satellite measurements can detect these motions.

Key Terms

absolute plate velocity (p. 66)
abyssal plain (p. 43)
accretionary prism (p. 55)
active margin (p. 51)
apparent polar-wander path (p. 42)
asthenosphere (p. 50)
bathymetry (p. 43)
black smoker (p. 52)
chron (p. 47)
collision (p. 61)
continental drift (p. 35)
continental rift (p. 61)
continental shelf (p. 52)
convergent boundary (p. 52)
divergent boundary (p. 52)
fracture zone (pp. 43, 57)
global positioning system (GPS) (p. 67)
hot spot (p. 59)
hot-spot track (p. 61)
lithosphere (p. 50)
lithosphere plate (p. 51)
magnetic anomaly (p. 46)
magnetic declination (p. 40)
magnetic dipole (p. 40)
magnetic inclination (p. 41)
magnetic pole (p. 40)
magnetic reversal (p. 46)
mantle plume (p. 59)
marine magnetic anomaly (p. 46)
mid-ocean ridge (p. 43)
paleomagnetism (p. 41)
paleopole (p. 42)
Pangaea (p. 35)
passive margin (p. 51)
plate boundary (p. 51)
plate tectonics (p. 36)
relative plate velocity (p. 66)
ridge-push force (p. 66)
rifting (p. 61)
sea-floor spreading (pp. 36, 45)
seamount (p. 43)
slab-pull force (p. 66)
subduction (pp. 36, 54)
transform boundary (pp. 52, 57)
trench (pp. 43, 54)
triple junction (p. 57)
volcanic arc (pp. 43, 55)
Wadati-Benioff zone (p. 55)

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Animation exercises on plate movements, subduction, and hot spots.
- A video exercise on divergent plate boundaries.
- Problems that help students determine relative plate velocities.

Review Questions

1. What was Wegener's continental drift hypothesis? What was his evidence? Why didn't other geologists agree?
2. How do apparent polar-wander paths show that the continents, rather than the poles, have moved?
3. Describe the hypothesis of sea-floor spreading.
4. Describe the pattern of marine magnetic anomalies across a mid-ocean ridge. How is this pattern explained?
5. How did drilling into the sea floor contribute further proof of sea-floor spreading? How did the sea-floor-spreading hypothesis explain variations in ocean floor heat flow?
6. What are the characteristics of a lithosphere plate? Can a single plate include both continental and oceanic lithosphere?
7. How does oceanic lithosphere differ from continental lithosphere in thickness, composition, and density?
8. How do we identify a plate boundary?
9. Describe the three types of plate boundaries.
10. How does crust form along a mid-ocean ridge?
11. Why is the oldest oceanic lithosphere less than 200 Ma?
12. Describe the major features of a convergent boundary.
13. Why are transform plate boundaries required on an Earth with spreading and subducting plate boundaries?
14. What is a triple junction?
15. How is a hot-spot track produced, and how can hot-spot tracks be used to track the past motions of a plate?
16. Describe the characteristics of a continental rift and give examples of where this process is occurring today.
17. Describe the process of continental collision and give examples of where this process has occurred.
18. Discuss the major forces that move lithosphere plates.
19. Explain the difference between relative plate velocity and absolute plate velocity.

On Further Thought

20. Why are the marine magnetic anomalies bordering the East Pacific Rise in the Pacific Ocean wider than those bordering the Mid-Atlantic Ridge?
21. The North Atlantic Ocean is 3,600 km wide. Sea-floor spreading along the Mid-Atlantic Ridge occurs at 2 cm per year. When did rifting start to open the Atlantic?

SEE FOR YOURSELF B. . . Plate Tectonics

Download the *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet B of our **Geotours Workbook**.



The South Atlantic
Latitude 11°38′14.93″S,
Longitude 14°12′57.84″W

A view of the South Atlantic from 13,500 km emphasizes that South America's coast looks like it could fit tightly against Africa's. If you rotate the Earth, you'll see that the east coast of the United States could fit against Africa's northwest coast.

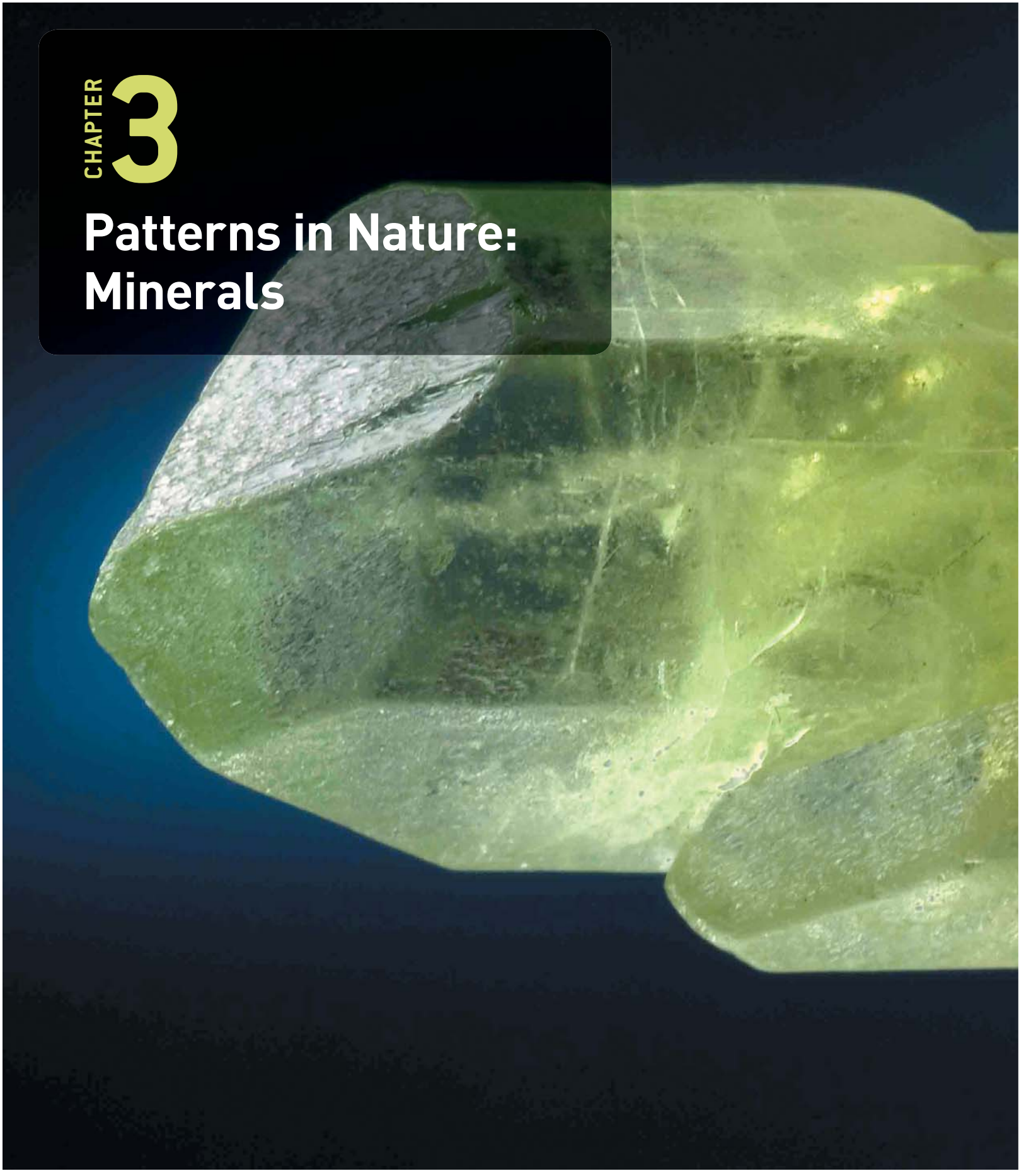


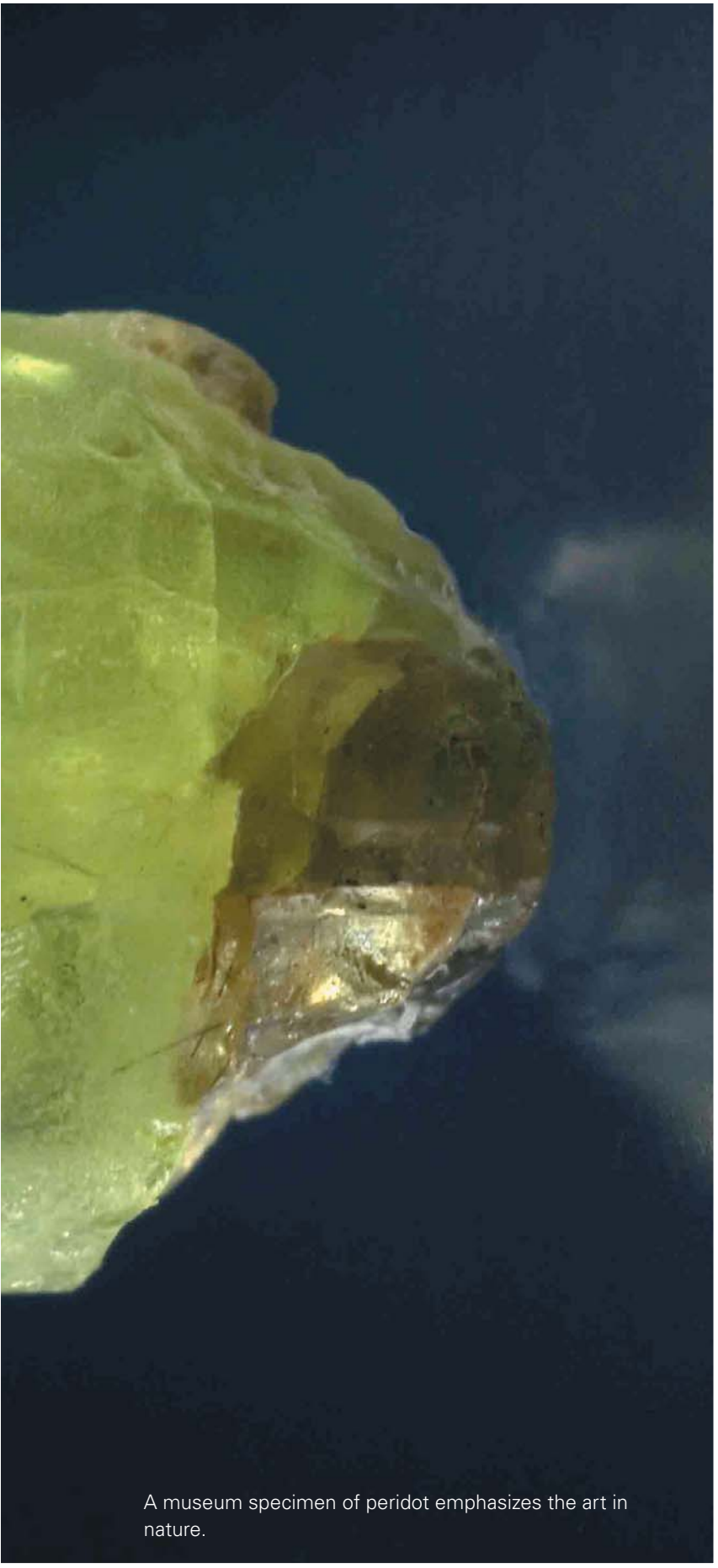
Triple Junction, Japan
Latitude 37°56′27.58″N,
Longitude 140°28′53.87″E

A space view of Japan's coast from 3,250 km shows the presence of deep-sea trenches and a broad accretionary prism. The Pacific is subducting beneath Japan. A triple junction of three trenches lies along the east coast.

CHAPTER 3

Patterns in Nature: Minerals





A museum specimen of peridot emphasizes the art in nature.

Chapter Objectives

By the end of this chapter, you should know . . .

- the special meaning of the word "mineral" when used in a geologic context.
- how to organize the thousands of different minerals into just a few classes based on the chemicals the minerals contain.
- which minerals are the most common ones on Earth, and thus serve as the main building blocks of this planet.
- how to identify common mineral specimens.
- why we consider some minerals to be "gems" and how the shiny facets of gems in jewelry can be produced.

I died a mineral, and became a plant. I died as plant and rose to animal, I died as animal and I was Man. Why should I fear?

—Jalal-Uddin Rumi
(Persian mystic and poet, 1207–1273)

3.1 Introduction

Zabargad Island rises barren and brown above the Red Sea, about 70 km off the coast of southern Egypt. Nothing grows on Zabargad, except for scruffy grass and a few shrubs, so no one lives there now. But in ancient times, many workers toiled on this 5-square-km patch of desert, gradually chipping their way into the side of its highest hill. They were searching for glassy green, pea-sized pieces of peridot, a prized gem. Carefully polished peridots were worn as jewelry by ancient Egyptians. Eventually, some of the gems appeared in Europe, set into crowns and scepters. These peridots now glitter behind glass cases in museums, millennia after first being pried free from the Earth, and perhaps 10 million years after first being formed by the bonding together of still more ancient atoms.

Peridot is the gem version of olivine, one of about 4,000 minerals that have been identified on Earth so far. Mineralogists, people who specialize in the study of minerals, discover 50 to 100 new minerals every year. Each different mineral has a name. Some names come from Latin, Greek, German, or English words describing a certain characteristic; some honor a person; some indicate the place where the mineral was first recognized; and some reflect a particular element in the mineral. Some names (quartz, calcite) may be familiar, whereas others (olivine, biotite) may be less so. Although the vast majority

of mineral types are rare, forming only under special conditions, many are quite common and occur in a variety of rock types at Earth's surface

Why study minerals? Without exaggeration, we can say that *minerals are the building blocks of our planet*. To a geologist, almost any study of Earth materials depends on an understanding of minerals, for minerals make up most of the rocks and sediments comprising the Earth and its landscapes. Minerals are also important from a practical standpoint (see Chapter 12). Industrial minerals serve as the raw materials for manufacturing chemicals, concrete, and wallboard. Ore minerals are the source of valuable metals like copper and gold and provide energy resources like uranium (**Fig. 3.1a, b**). And particularly beautiful forms of minerals—gems—delight the eye in jewelry. Unfortunately, though, some minerals pose environmental hazards. No wonder **mineralogy**, the study of minerals, fascinates professionals and amateurs alike.

In this chapter, we begin by presenting the geologic definition of a mineral, and look at how minerals grow. Then, we discuss the main characteristics that enable us to identify specific samples. Finally, we describe the basic scheme that mineralogists use to classify minerals. This chapter assumes that you understand the fundamental concepts of matter and energy, especially the nature of atoms, molecules, and chemical bonds. If you are rusty on these topics, please study **Box 3.1**.

3.2 What Is a Mineral?

To a geologist, a **mineral** is a naturally occurring solid, formed by geologic processes, that has a crystalline structure and a definable chemical composition. Almost all minerals are inorganic. Let's pull apart this mouthful of a definition and examine its meaning in detail.

- *Naturally occurring*: True minerals are formed in nature, not in factories. We need to emphasize this point because in recent decades, industrial chemists have learned how to synthesize materials that have characteristics virtually identical to those of real minerals. These materials are not minerals in a geologic sense, though they are referred to in the commercial world as synthetic minerals.
- *Formed by geologic processes*: Traditionally, this phrase implied processes, such as solidification of molten rock or direct precipitation from a water solution, that did not involve living organisms. Increasingly, however, geologists recognize that life is an integral part of the Earth System. So, some geologists consider solid, crystalline materials produced by organisms to be minerals too. To avoid confusion, the term "biogenic mineral" may be used when discussing such materials.
- *Solid*: A solid is a state of matter that can maintain its shape indefinitely, and thus will not conform to the shape of its container. Liquids (such as oil or water) and gases (such as air) are not minerals (see Box 3.1).
- *Crystalline structure*: The atoms that make up a mineral are not distributed randomly and cannot move around easily. Rather, they are fixed in a specific, orderly pattern. A material in which atoms are fixed in an orderly pattern is called a crystalline solid.
- *Definable chemical composition*: This simply means that it is possible to write a chemical formula for a mineral (see Box 3.1). Some minerals contain only one element, but most are compounds of two or more elements. For example, diamond and graphite have the formula C, because they consist entirely of carbon. Quartz has the formula SiO_2—it contains the elements silicon and oxygen in the proportion of one silicon atom for every two oxygen atoms. Calcite has the formula $CaCO_3$, meaning it consists of a calcium (Ca^+) ion and a carbonate (CO_3^-) ion. Some formulas are more complicated: for example, the formula for biotite is $K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$.
- *Inorganic*: Organic chemicals are molecules containing some carbon-hydrogen bonds. Sugar ($C_{12}H_{22}O_{11}$), for example,

FIGURE 3.1 Copper ore contains minerals that serve as a source of copper metal.

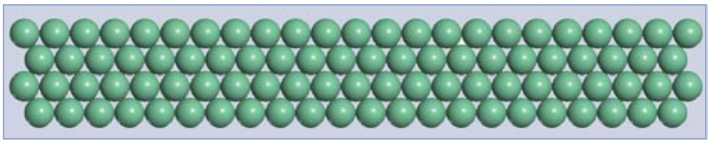


(a) Malachite is a mineral contained in copper ore [$Cu_2(CO_3)(OH)_2$]; it contains copper plus other chemicals.

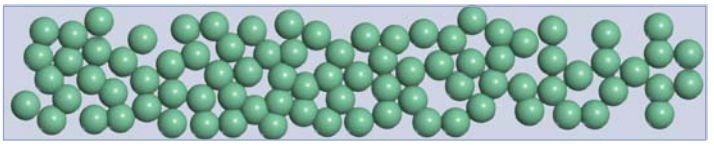


(b) The copper for pots is produced by processing ore minerals.

FIGURE 3.2 The nature of crystalline and noncrystalline materials.



(a) This quartz crystal contains an orderly arrangement of atoms. The arrangement resembles scaffolding.



(b) Atoms in noncrystalline solids, such as glass, are not orderly.

is an organic chemical. *Almost all minerals are inorganic.* Thus, sugar and protein are not minerals. But, we have to add the qualifier "almost all" because mineralogists do consider about 30 organic substances formed by "the action of geologic processes on organic materials" to be minerals. Examples include the crystals that grow in ancient deposits of bat guano.

With these definitions in mind, we can make an important distinction between minerals and **glass**. Both minerals and glass are solids, in that they can retain their shape indefinitely. But a mineral is crystalline, and glass is not. Whereas atoms, ions, or molecules in a mineral are ordered into a crystal lattice, like soldiers standing in formation, those in a glass are arranged in a semi-chaotic way, like people at a party, in small clusters or chains that are neither oriented in the same way nor spaced at regular intervals (**Fig. 3.2a, b**).

If you ever need to figure out whether a substance is a mineral or not, just check it against the criteria listed above. Is motor oil a mineral? No—it's an organic liquid. Is table salt a mineral? Yes—it's a solid crystalline compound with the formula NaCl. Is the hard material making up the shell of an oyster considered to be a mineral? Microscopic examination of an oyster shell reveals that it consists of calcite, so it can be called a biogenic mineral. Is rock candy a mineral? No. Even though it is solid and crystalline, it's made by people and it consists of sugar (an organic chemical).

Did you ever wonder . . .
is rock candy a mineral?

Take-Home Message

Minerals are solids with a crystalline structure (an orderly arrangement of atoms inside) and a definable chemical formula. They form by natural processes in the Earth System.

3.3 Beauty in Patterns: Crystals and Their Structure

What Is a Crystal?

The word crystal brings to mind sparkling chandeliers, elegant wine goblets, and shiny jewels. But, as is the case with the word mineral, geologists have a more precise definition. A **crystal** is a single, continuous (that is, uninterrupted) piece of a crystalline solid, typically bounded by flat surfaces, called **crystal faces**, that grow naturally as the mineral forms. The word comes from the Greek *krystallos*, meaning ice. Many crystals have beautiful shapes that look like they belong in the pages of a geometry book. The angle between two adjacent crystal faces of one specimen is identical to the angle between the corresponding faces of another specimen. For example, a perfectly formed quartz crystal looks like an obelisk (**Fig. 3.3a, b**); the angle between the faces of the columnar part of a quartz crystal is always exactly 120°. This rule, discovered by one of the first geologists, Nicolas Steno (1638–1686) of Denmark, holds regardless of whether the whole crystal is big or small and regardless of whether all of the faces are the same size. Crystals come in a great variety of shapes, including cubes, trapezoids, pyramids, octahedrons, hexagonal columns, blades, needles, columns, and obelisks (**Fig. 3.3c**).

Because crystals have a regular geometric form, people have always considered them to be special, perhaps even a source of magical powers. For example, shamans of some cultures relied on talismans or amulets made of crystals, which supposedly brought power to their wearer or warded off evil spirits. Scientists have concluded, however, that crystals have no effect on health or mood. For millennia, crystals have inspired awe because of the way they sparkle, but such behavior is simply a consequence of how crystal structures interact with light.

Looking Inside Crystals

What makes crystals have regular geometric forms? This problem was the focus of study for centuries. An answer finally came from the work of a German physicist, Max von Laue, in 1912. He showed that an X-ray beam passing through a crystal breaks up into many tiny beams to create a pattern of dots on a screen (**Fig. 3.4a**). Physicists refer to this phenomenon as diffraction; it occurs when waves interact with regularly spaced objects whose spacing is close to the wavelength of the waves—you can see diffraction of ocean waves when they pass through gaps in a seawall. Von Laue concluded that, for a crystal to

BOX 3.1

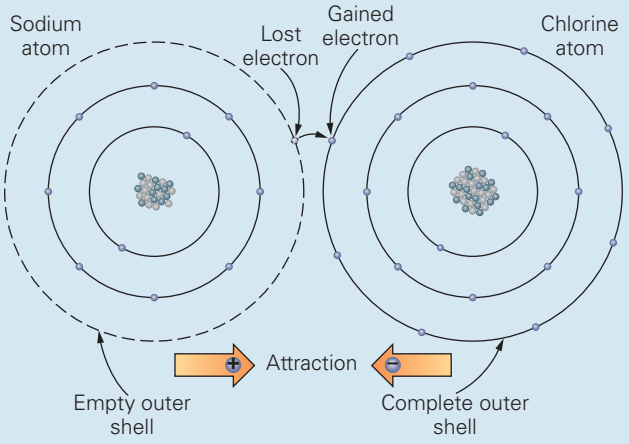
CONSIDER THIS . . .

Some Basic Concepts from Chemistry

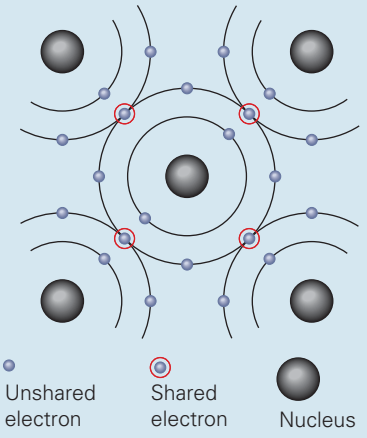
To describe minerals, we need to use several terms from chemistry. To avoid confusion, terms are listed in an order that permits each successive term to utilize previous terms.

- *Element:* A pure substance that cannot be separated into other materials.
- *Atom:* The smallest piece of an element that retains the characteristics of the element. An atom consists of a nucleus surrounded by a cloud of orbiting electrons; the nucleus is made up of protons and neutrons (except in hydrogen, whose nucleus contains only one proton and no neutrons). Electrons have a negative charge, protons have a positive charge, and neutrons have a neutral charge. An atom that has the same number of electrons as protons is said to be neutral, in that it does not have an overall electrical charge.
- *Atomic number:* The number of protons in an atom of an element.
- *Atomic weight:* Approximately the number of protons plus neutrons in an atom of an element.
- *Ion:* An atom that is not neutral. An ion that has an excess negative charge (because it has more electrons than protons) is an *anion*, whereas an ion that has an excess positive charge (because it has more protons than electrons) is a *cation*. We indicate the charge with a superscript. For example, Cl^- has a single excess electron; Fe^{2+} is missing two electrons.
- *Chemical bond:* An attractive force that holds two or more atoms together (**Fig. Bx3.1a–c**). For example, *covalent bonds* form when atoms share electrons. *Ionic bonds* form when a cation and anion (ions with opposite charges) get close together and attract each other. In materials with *metallic bonds*, some of the electrons can move freely.
- *Molecule:* Two or more atoms bonded together. The atoms may be of the same element or of different elements.
- *Compound:* A pure substance that can be subdivided into two or more elements. The smallest piece of a compound that retains the characteristics of the compound is a molecule.

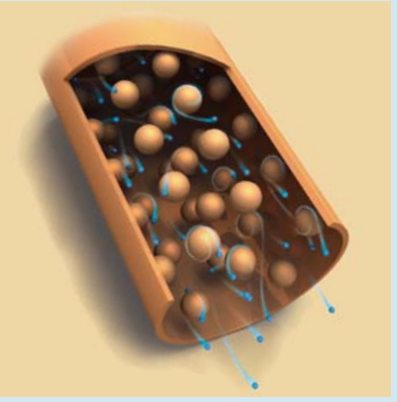
FIGURE Bx3.1 Examples of states of matter and chemical bonds.



(a) An ionic bond forms between a positive ion of sodium (Na^+) and chloride (Cl^-), a negative ion of chlorine produces halite NaCl, when sodium gives up one electron to chloride, so that both have filled shells.



(b) Covalent bonds form when carbon atoms share electrons so that all have filled electron shells.

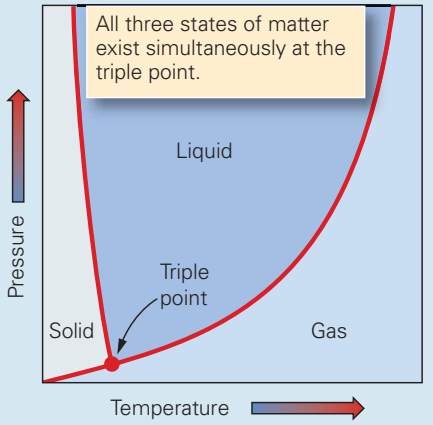


(c) In metallically bonded material, nuclei and their inner shells of electrons float in a "sea" of free electrons. The electrons stream through the metal if there is an electrical current.

cause diffraction, atoms within it must be regularly spaced and the spacing must be comparable to the wavelength of X-rays. Eventually, Von Laue and others learned how to use X-ray diffraction patterns as a basis for defining the specific arrangement of atoms in crystals. This arrangement defines the **crystal structure** of a mineral.

If you've ever examined wallpaper, you've seen an example of a pattern (**Fig. 3.4b**). Crystal structures contain one of nature's most spectacular examples of such a pattern. In crystals, the pattern is defined by the regular spacing of atoms and, if the crystal contains more than one element, by the regular alternation of atoms (**Fig. 3.4c**). (Mineralogists refer to a 3-D geometry of points representing this pattern as a lattice.) The pattern of atoms in a crystal may control the shape of a crystal. For example, if atoms in a crystal pack into the shape of a cube, the crystal may have faces that intersect at 90° angles—galena (PbS) and halite (NaCl) have such a cubic shape. Because of the pattern of atoms in a crystal structure, the structure has

- *State of matter:* The form of a substance, which reflects the degree to which the atoms or molecules comprising the matter are bonded together. **Figure Bx3.1d–f** defines three of the states—solid, liquid, and gas. There are more bonds in a solid than in a liquid, and more in a liquid than in a gas. Which state exists at a given location depends on pressure and temperature, as indicated by a phase diagram (**Fig. Bx3.1g**). A fourth state, plasma, exists only at very high temperatures.
- *Chemical:* A general name used for a pure substance (either an element or a compound).
- *Chemical formula:* A shorthand recipe that itemizes the various elements in a chemical and specifies their relative proportions. For example, the formula for water, H_2O, indicates that water consists of molecules in which two hydrogens bond to one oxygen.
- *Chemical reaction:* A process that involves the breaking or forming of chemical bonds. Chemical reactions can break molecules apart or create new molecules and/or isolated atoms.
- *Mixture:* A combination of two or more elements or compounds that can be separated without a chemical reaction. For example, a cereal composed of bran flakes and raisins is a mixture—you can separate the raisins from the flakes without destroying either.
- *Solution:* A type of material in which one chemical (the solute) dissolves in another (the solvent). In solutions, a solute may separate into ions during the process. For example, when salt (NaCl) dissolves in water, it separates into sodium (Na^+) and chloride (Cl^-) ions. In a solution, atoms or molecules of the solvent surround atoms, ions, or molecules of the solute.
- *Precipitate:* A compound that forms when ions in liquid solution join together to create a solid that settles out of the solution; (verb) the process of forming solid grains by separation and settling from a solution. For example, when saltwater evaporates, solid salt crystals precipitate.



(g) The state of matter depends on pressure and temperature, as depicted in this graph, called a phase diagram.



(d) A solid retains its shape regardless of the size of the container.



(e) A liquid conforms to the shape of the container, so its density does not change when the shape of the container changes.



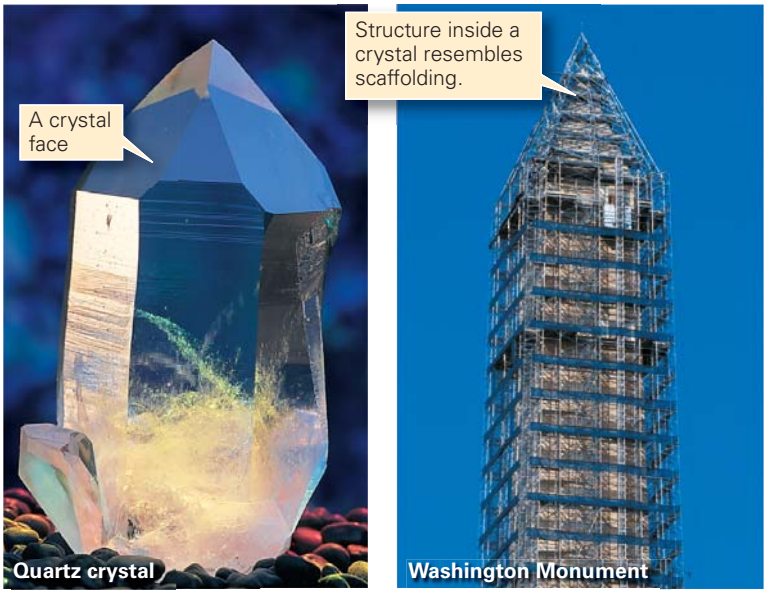
(f) A gas expands to fill whatever volume it occupies, so its density changes if the volume changes.

symmetry, meaning that the shape of one part of the structure is the mirror image of the shape of a neighboring part. For example, if you were to cut a halite crystal or a water crystal (snowflake) in half, and place the half against a mirror, it would look whole again (**Fig. 3.4d**).

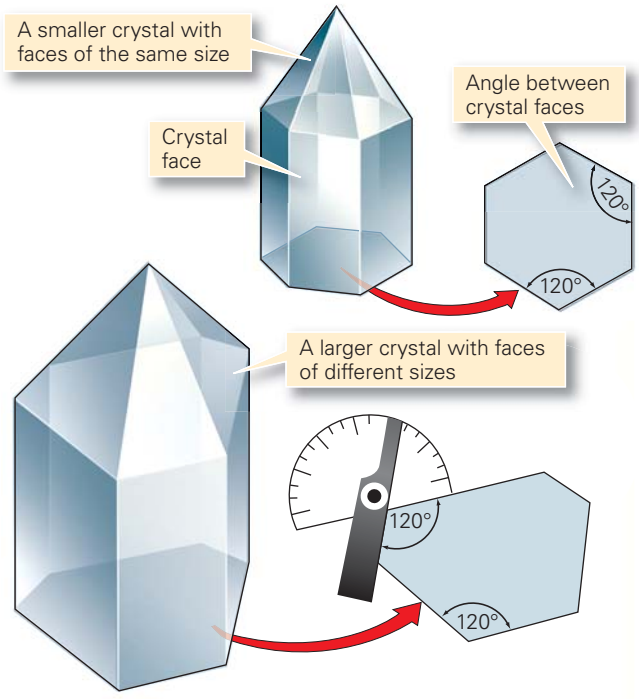
To illustrate crystal structures, we look at a few examples. Halite (rock salt) consists of oppositely charged ions that stick together because opposite charges attract. In halite, six chloride (Cl^-) ions surround each sodium (Na^+) ion, producing an overall arrangement of atoms that defines the shape of a cube (**Fig. 3.5a, b**). Diamond, by contrast, is a mineral made entirely of carbon. In diamond, each atom bonds to four neighbors arranged in the form of a tetrahedron; some naturally formed diamond crystals have the shape of a double tetrahedron (**Fig. 3.5c**). Graphite, another mineral composed entirely of carbon, behaves very differently from diamond. In contrast to diamond, graphite is so soft that we use it as the "lead" in a pencil; when a pencil moves across paper, tiny flakes of

graphite peel off the pencil point and adhere to the paper. This behavior occurs because the carbon atoms in graphite are not arranged in tetrahedra, but rather occur in sheets (Fig. 3.5d). The sheets are bonded to each other by weak bonds and thus can separate from each other easily. Of note, two different minerals (such as diamond and graphite) that have the same composition but different crystal structures are **polymorphs**.

FIGURE 3.3 Some characteristics of crystals.



(a) A quartz crystal can resemble an obelisk. Inside, atoms are arranged in a specific geometric pattern, like the joint points in scaffolding.



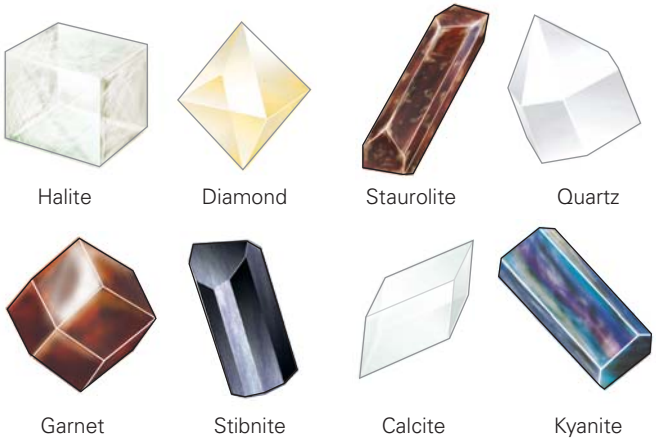
(b) Regardless of specimen size, the angle between two adjacent crystal faces is consistent in a particular mineral.

The Formation and Destruction of Minerals

New mineral crystals can form in five ways. First, they can form by the solidification of a melt, meaning the freezing of a liquid to form a solid. For example, ice crystals, a type of mineral, are made by solidifying water, and many different minerals form by solidifying molten rock. Second, they can form by precipitation from a solution, meaning that atoms, molecules, or ions dissolved in water bond together and separate out of the water. Salt crystals, for example, precipitate when you evaporate salt water (see Box 3.1). Third, they can form by solid-state diffusion, the movement of atoms or ions through a solid to arrange into a new crystal structure, a process that takes place very slowly. For example, garnets grow by diffusion in solid rock. Fourth, minerals can form at interfaces between the physical and biological components of the Earth System by a process called biomineralization. This occurs when living organisms cause minerals to precipitate either within or on their bodies, or immediately adjacent to their bodies. For example, clams and other shelled organisms extract ions from water to produce mineral shells. Fifth, minerals can precipitate directly from a gas. This process typically occurs around volcanic vents or around geysers, for at such locations volcanic gases or steam enter the atmosphere and cool abruptly. Some of the bright yellow sulfur deposits found in volcanic regions form in this way.

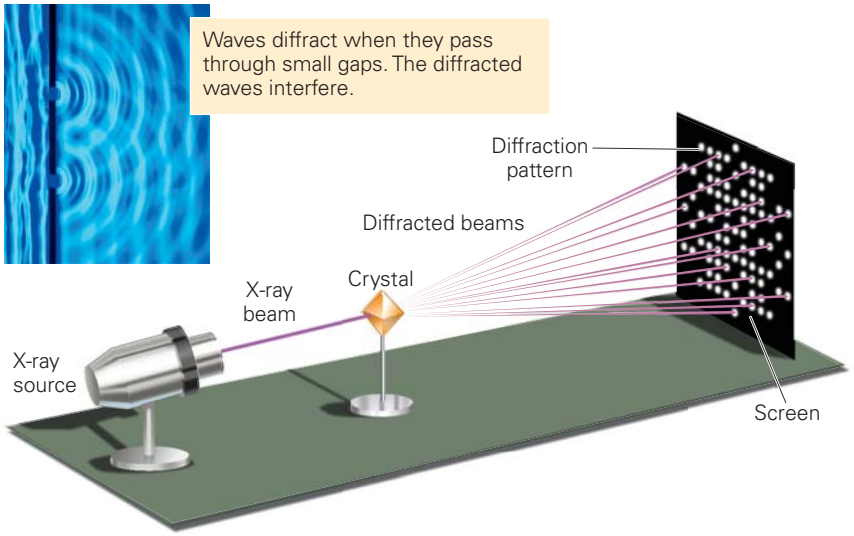
The first step in forming a crystal is the chance formation of a seed, or an extremely small crystal (Fig. 3.6a). Once the seed exists, other atoms in the surrounding material attach themselves to the face of the seed. As the crystal grows, crystal faces move outward but maintain the same orientation (Fig. 3.6b). The youngest part of the crystal is at its outer edge.

In the case of crystals formed by the solidification of a melt, atoms begin to attach to the seed when the melt becomes so cool that thermal vibrations can no longer break apart the



(c) Crystals come in a variety of shapes, including cubes, prisms, blades, and pyramids.

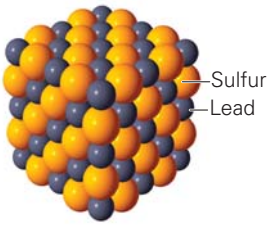
FIGURE 3.4 Patterns and symmetry in minerals.



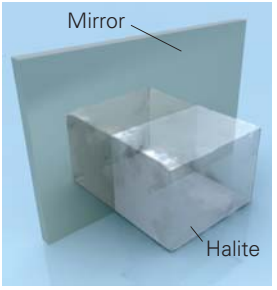
(a) Diffraction of an X-ray beam passing through a crystal produces a pattern of bright spots on a screen. The spots are due to interference of overlapping light waves.

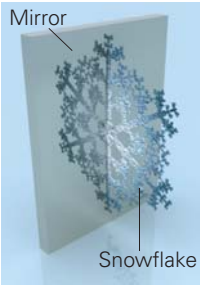


(b) The repetition of a flower motif on wallpaper.



(c) The repetition of alternating sulfur and lead atoms in the mineral galena (PbS).





(d) Minerals display symmetry. One-half of a crystal is a mirror image of the other.

attraction between the seed and the atoms in the melt. Crystals formed by precipitation from a solution develop when the solution becomes saturated, meaning the number of dissolved ions per unit volume of solution becomes so great that they can get close enough to each other to bond together.

As crystals grow, they develop their particular crystal shape, based on the geometry of their internal structure. The shape is defined by the relative dimensions of the crystal (needle-like, sheet-like, etc.) and the angles between crystal faces. Typically, the growth of minerals is restricted in one or more directions, because existing crystals act as obstacles. In such cases, minerals grow to fill the space that is available, and their shape is controlled by the shape of their surroundings. Minerals without well-formed crystal faces are anhedral grains (Fig. 3.6c). If a mineral's growth is unimpeded so that it displays well-formed crystal faces, then it is a euhedral crystal. The surface crystals of a **geode**, a mineral-lined cavity in rock, may be euhedral (Fig. 3.6d).

A mineral can be destroyed by melting, dissolving, or some other chemical reaction. Melting involves heating a mineral to a temperature at which thermal vibration of the atoms or ions in the lattice break the chemical bonds holding them to the lattice. The atoms or ions then separate, either individually or in small groups, to move around again freely. Dissolution occurs when you immerse a mineral in a solvent, such as water. Atoms or ions then separate from the crystal face and are surrounded by solvent molecules. Chemical reactions can destroy a mineral when it comes in contact with reactive materials. For example, iron-bearing minerals react with air and water to form rust. The action of microbes in the environment can also destroy minerals. In effect, some microbes can "eat" certain minerals; the microbes use the energy stored in the chemical bonds that hold the atoms of the mineral together as their source of energy for metabolism.

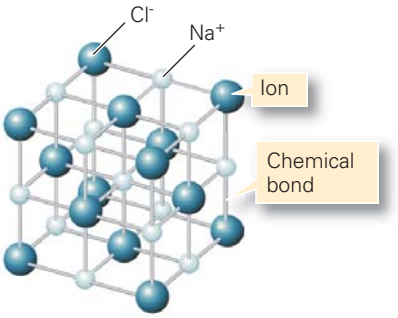
Take-Home Message

The crystal structure of minerals is defined by a regular geometric arrangement of atoms that has symmetry. Minerals can form by solidification of a melt, by precipitation from a water solution or a gas, or by rearrangement of atoms in a solid.

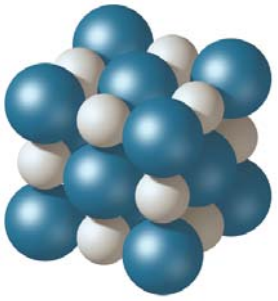
3.4 How Can You Tell One Mineral From Another?

Amateur and professional mineralogists get a kick out of recognizing minerals. They might hover around a display case in a museum and name specimens without bothering to look at the labels. How do they do it? The trick lies in learning to recognize the basic physical properties (visual and material characteristics) that distinguish one mineral from another. Some physical properties, such as shape and color, can be seen from a distance. Others, such as hardness and magnetization, can be determined only by handling the specimen or by performing an identification test on it. Identification tests include scratching the mineral by another object, placing it near a magnet, weighing it, tasting it, or placing a drop of acid on it. Let's examine some of the physical properties most commonly used in basic mineral identification.

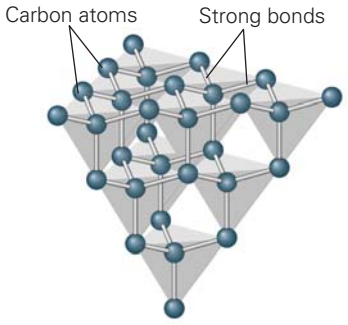
FIGURE 3.5 The nature of crystalline structure in minerals. The arrangement of atoms can be portrayed by a ball-and-stick model, or by a packed-ball model.



(a) In a ball-and-stick model of halite, the balls are ions, and the sticks are chemical bonds.

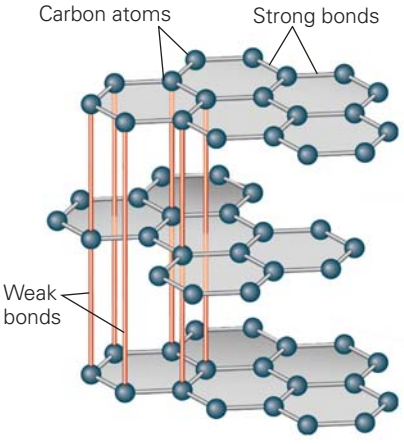


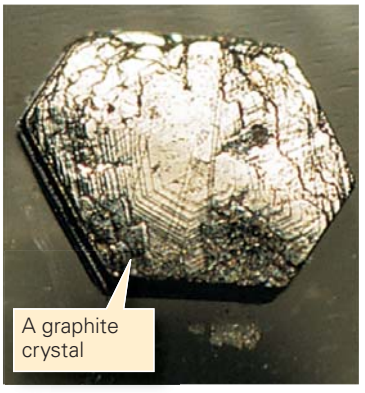
(b) This packed-ball model gives a better sense of how ions fit together in crystal.





(c) In a diamond, carbon atoms are arranged in tetrahedra. All of the bonds are strong.

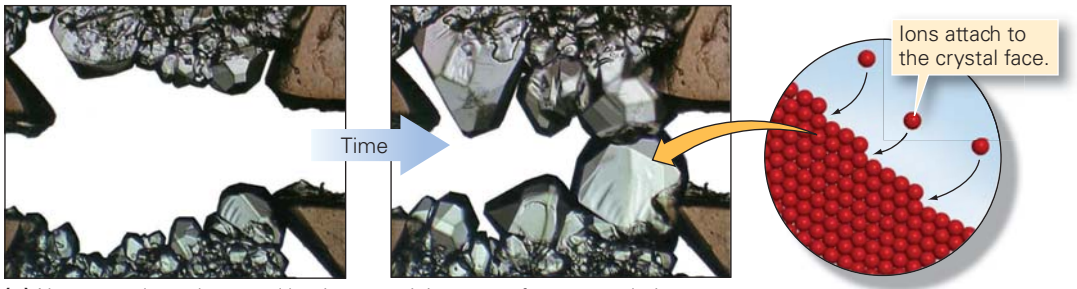




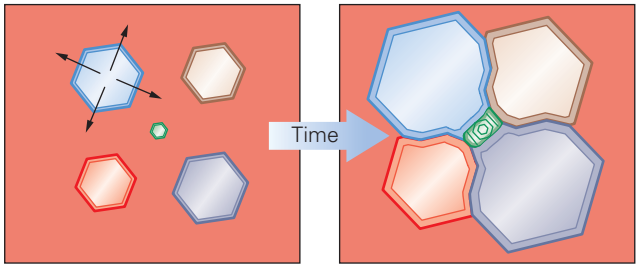
(d) Graphite consists of carbon atoms arranged in hexagonal sheets. The sheets are connected by weak bonds.

- *Color*: **Color** results from the way a mineral interacts with light. Sunlight contains the whole spectrum of colors; each color has a different wavelength. A mineral absorbs certain wavelengths, so the color you see when looking at a specimen represents the wavelengths the mineral does not absorb. Certain minerals always have the same color, but many display a range of colors (Fig. 3.7a). Color variations in a mineral are due to the presence of impurities. For example, trace amounts of iron may give quartz a reddish color.
- *Streak*: The **streak** of a mineral refers to the color of a powder produced by pulverizing the mineral. You can obtain a streak by scraping the mineral against an unglazed ceramic plate (Fig. 3.7b). The color of a mineral powder tends to be less variable than the color of a whole crystal, and thus provides a fairly reliable clue to a mineral's identity. Calcite, for example, always yields a white streak even though pieces of calcite may be white, pink, or clear.
- *Luster*: **Luster** refers to the way a mineral surface scatters light. Geoscientists describe luster by comparing the appearance of the mineral with the appearance of a familiar substance. For example, minerals that look like metal have a metallic luster, whereas those that do not have a nonmetallic luster—the adjectives are self-explanatory (Fig. 3.7c, d). Terms used for types of nonmetallic luster include silky, glassy, satiny, resinous, pearly, or earthy.
- *Hardness*: **Hardness** is a measure of the relative ability of a mineral to resist scratching, and it therefore represents the resistance of bonds in the crystal structure to being broken. The atoms or ions in crystals of a hard mineral are more strongly bonded than those in a soft mineral. Hard minerals can scratch soft minerals, but soft minerals cannot scratch hard ones. Diamond, the hardest mineral known, can scratch most anything, which is why it is used to cut glass. In the early 1800s, a mineralogist named Friedrich Mohs listed some minerals in sequence of relative hardness; a mineral with a hardness of 5 can scratch all minerals with a hardness of 5 or less. This list, the **Mohs hardness scale**, helps in mineral identification. To make the scale easy to use, common items such as your fingernail, a penny, or a glass plate have been added (Table. 3.1).
  - *Specific gravity*: **Specific gravity** represents the density of a mineral, as represented by the ratio between the weight of a volume of the mineral and the weight of an equal volume of water at 4°C. For example, one cubic centimeter of quartz has a weight of 2.65 grams, whereas one cubic centimeter of water has a weight of 1.00 gram. Thus, the specific gravity of quartz is 2.65. In practice, you can develop a "feel" for specific gravity by hefting minerals in your hands. A piece of galena (lead ore) feels heavier than a similar-sized piece of quartz.
- *Crystal habit*: The **crystal habit** of a mineral refers to the shape of a single crystal with well-formed crystal faces, or to the character of an aggregate of many well-formed crystals that grew together as a group (Fig. 3.7e). The habit depends on the internal arrangement of atoms in the crystal. A description of habit generally includes adjectives that

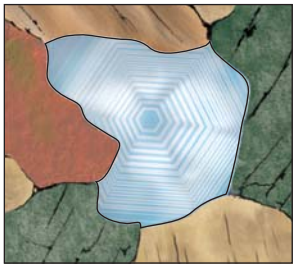
FIGURE 3.6 The growth of crystals.



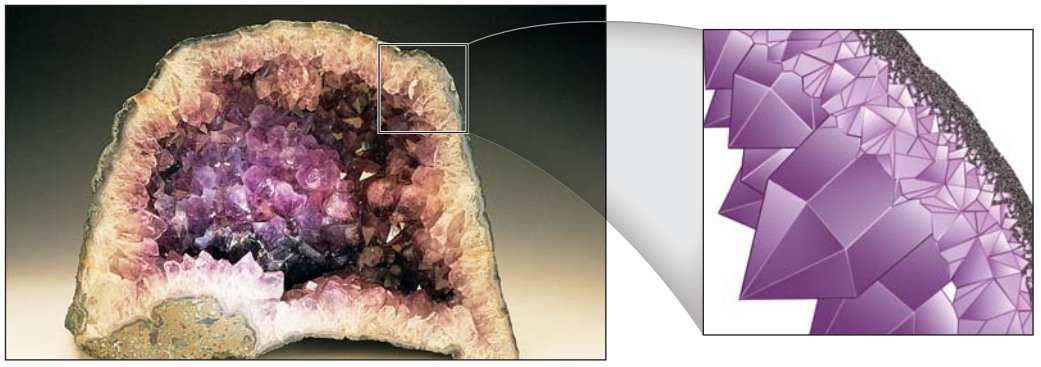
(a) New crystals nucleate and begin to precipitate out of a water solution. As time progresses, they grow into the open space.



(b) New crystals grow outward from the central seed. As time passes, they maintain their shape until they interfere with each other.



(c) A crystal growing in a confined space will be anhedral.



(d) A geode from Brazil consists of purple quartz crystals (amethyst) that grew from the wall into the center. The enlargement sketch indicates that the crystals are euhedral.

highlight the shape of the crystal. For example, crystals that are roughly the same length in all directions are called equant or blocky, those that are much longer in one dimension than in others are columnar or needle-like, those shaped like sheets of paper are platy, and those shaped like knives are bladed.

- *Special properties*: Some minerals have distinctive properties that readily distinguish them from other minerals. For example, calcite ($CaCO_3$) reacts with dilute hydrochloric acid (HCl) to produce carbon dioxide (CO_2) gas (**Fig. 3.7f**). Dolomite ($CaMg[CO_3]_2$) also reacts with acid, but not as strongly. Graphite makes a gray mark on paper, magnetite attracts a magnet (**Fig. 3.7g**), halite tastes salty, and plagioclase has striations (thin parallel corrugations or stripes) on its surface.
- *Fracture and cleavage*: Different minerals fracture (break) in different ways, depending on the internal arrangement of atoms. If a mineral breaks to form distinct planar surfaces that have a specific orientation in relation to the crystal structure, then we say that the mineral has **cleavage** and we refer to each surface as a cleavage plane. Cleavage forms in directions where the bonds holding atoms together in the crystal are the weakest (**Fig. 3.8a–e**). Some minerals have one direction of cleavage. For example, mica has very weak bonds in one direction but strong bonds in the other two directions. Thus, it easily splits into parallel sheets; the surface of each sheet is a cleavage plane. Other minerals have two or three directions of cleavage that intersect at a specific angle. For example, halite has three sets of cleavage planes that intersect at right angles, so halite crystals break into little cubes. Materials that have no cleavage at all (because bonding is equally strong in all directions) break either by forming irregular fractures or by forming conchoidal fractures (**Fig. 3.8f**). **Conchoidal fractures** are smoothly curving, clamshell-shaped surfaces; they typically form in glass. Cleavage planes are sometimes hard to distinguish from crystal faces (**Fig. 3.8g**).

Take-Home Message

The characteristics of minerals (such as color, streak, luster, crystal shape, hardness, specific gravity, cleavage, magnetism, and reaction with acid) are a manifestation of the crystal structure and chemical composition of minerals.

FIGURE 3.7 Physical characteristics of minerals.



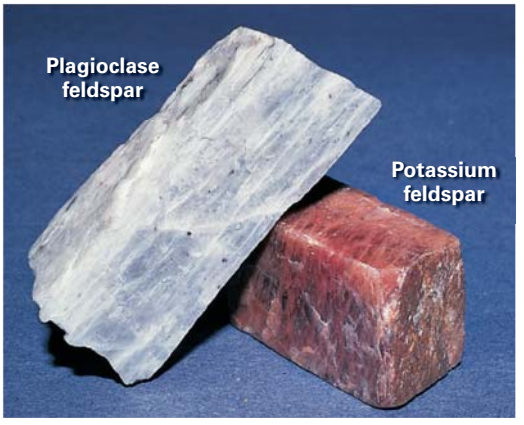
(a) Color is diagnostic of some minerals, but not all. For example, quartz can come in many colors.



(b) To obtain the streak of a mineral, rub it against a porcelain plate. The streak consists of mineral powder.



(c) Pyrite has a metallic luster because it gleams like metal.

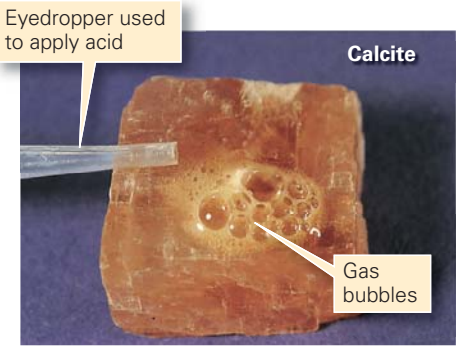


(d) Feldspar has a nonmetallic luster.

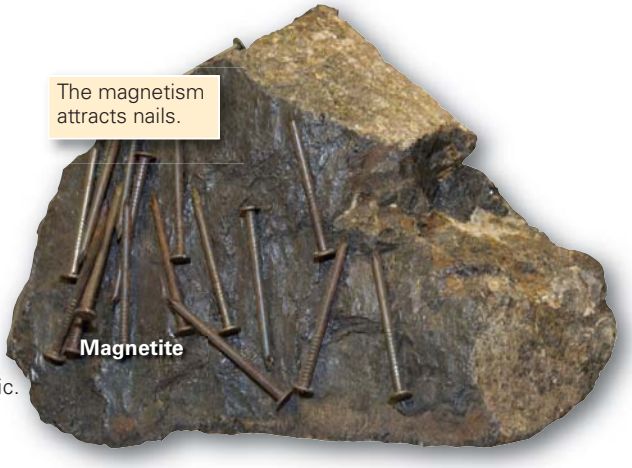




(e) Crystal habit refers to the shape or character of the crystal. The blue kyanite crystals on the left are bladed, and the chrysotile on the right is fibrous.



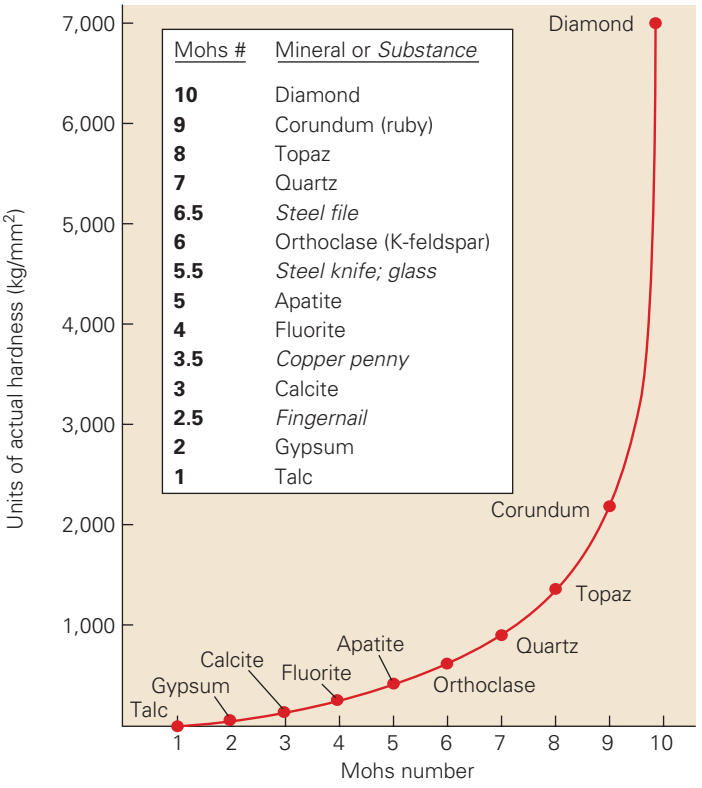
(f) Calcite reacts with hydrochloric acid to produce carbon dioxide gas.



(g) Magnetite is magnetic.

TABLE 3.1 Mohs hardness scale. Mohs' numbers are relative—in reality, diamond is 3.5 times harder than corundum, as the graph shows.

Mohs #	Mineral or *Substance*
10	Diamond
9	Corundum (ruby)
8	Topaz
7	Quartz
6.5	*Steel file*
6	Orthoclase (K-feldspar)
5.5	*Steel knife; glass*
5	Apatite
4	Fluorite
3.5	*Copper penny*
3	Calcite
2.5	*Fingernail*
2	Gypsum
1	Talc



3.5 Organizing Our Knowledge: Mineral Classification

The 4,000 known minerals can be separated into a small number of groups, or mineral classes. You may think, "Why bother?" Classification schemes are useful because they help organize information and streamline discussion. Biologists, for example, classify animals into groups based on how they feed their young and on the architecture of their skeletons, and botanists classify plants according to the way they reproduce and by the shape of their leaves. In the case of minerals, a good means of classification eluded researchers until it became possible to determine the chemical makeup of minerals. A Swedish chemist, Baron Jöns Jacob Berzelius (1779–1848), analyzed minerals and noted chemical similarities among many of them. Berzelius, along with his students, established that most minerals can be classified by specifying the principal anion (negative ion) or anionic group (negative molecule) within the mineral (see Box 3.1). We now take a look at principal mineral classes, focusing especially on silicates, the class that constitutes most of the rock in the Earth.

The Mineral Classes

Mineralogists distinguish several principal classes of minerals. Here are some of the major ones.

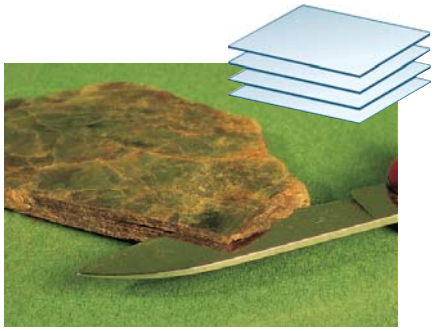
- *Silicates*: The fundamental component of most silicates in the Earth's crust is the SiO_4^{4-} anionic group. A well-known example, quartz (Fig. 3.7a), has the formula SiO_2. We will learn more about silicates in the next section.
- *Oxides*: Oxides consist of metal cations bonded to oxygen anions. Typical oxide minerals include hematite (Fe_2O_3; Fig. 3.7b) and magnetite (Fe_3O_4; Fig. 3.7g).
- *Sulfides*: Sulfides consist of a metal cation bonded to a sulfide anion (S^{2-}). Examples include galena (PbS) and pyrite (FeS_2; Fig. 3.7c).
- *Sulfates*: Sulfates consist of a metal cation bonded to the SO_4^{2-} anionic group. Many sulfates form by precipitation out of water at or near the Earth's surface. An example is gypsum ($CaSO_4 \cdot 2H_2O$).
- *Halides*: The anion in a halide is a halogen ion (such as chloride [Cl^-] or fluoride [F^-]), an element from the second column from the right in the periodic table (see Appendix). Halite, or rock salt (NaCl; Fig. 3.8d), and fluorite (CaF_2), a source of fluoride, are common examples.
- *Carbonates*: In **carbonates**, the molecule CO_3^{2-} serves as the anionic group. Elements such as calcium or magnesium bond to this group. The two most common carbonates are calcite ($CaCO_3$; Fig. 3.8e) and dolomite ($CaMg[CO_3]_2$).
- *Native metals*: Native metals consist of pure masses of a single metal. The metal atoms are bonded by metallic bonds (see Box 3.1). Copper and gold, for example, may occur as native metals.

Silicates: The Major Rock-Forming Minerals

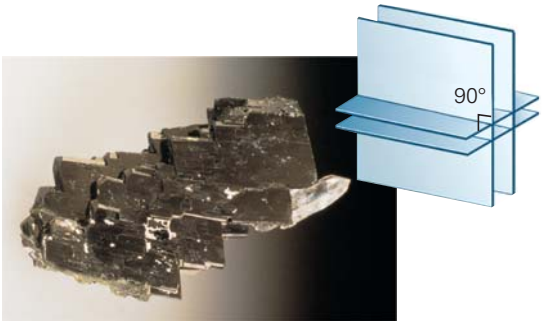
Silicate minerals, or **silicates**, make up over 95% of the continental crust and almost 100% of the oceanic crust and of the Earth's mantle consist almost entirely of silicates. Thus, silicates are the most common minerals on Earth. As we've noted, silicates in the Earth's crust and upper mantle contain the SiO_4^{4-} anionic group. In this group, four oxygen atoms surround a single silicon atom, thereby defining the corners of a tetrahedron, a pyramid-like shape with four triangular faces (**Fig. 3.9a**). We refer to this anionic group as the **silicon-oxygen tetrahedron** (or, informally, as the silica tetrahedron), and it acts, in effect, as the building block of silicate minerals.

Mineralogists distinguish among several groups of silicate minerals based on the way in which silica tetrahedra are arranged (**Fig. 3.9b**). The arrangement, in turn, determines the degree to which tetrahedra share oxygen atoms. Note that the number of shared oxygens determines the ratio of silicon (Si) to oxygen (O) in the mineral. Here are the groups, in

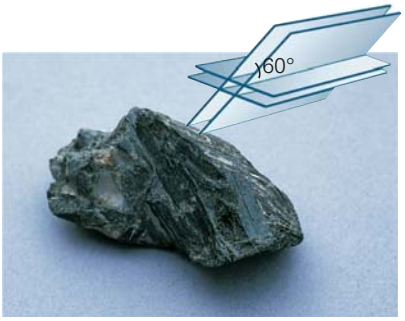
FIGURE 3.8 The nature of mineral cleavage and fracture.



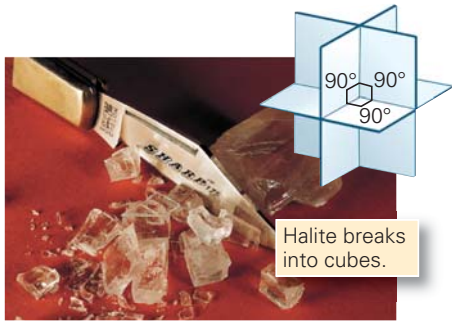
(a) Mica has one strong plane of cleavage and splits into sheets.



(b) Pyroxene has two planes of cleavage that intersect at 90°.



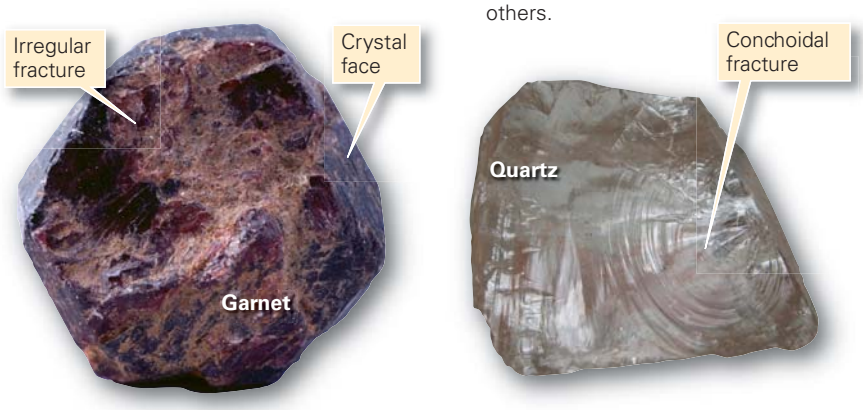
(c) Amphibole has two planes that intersect at 60°.



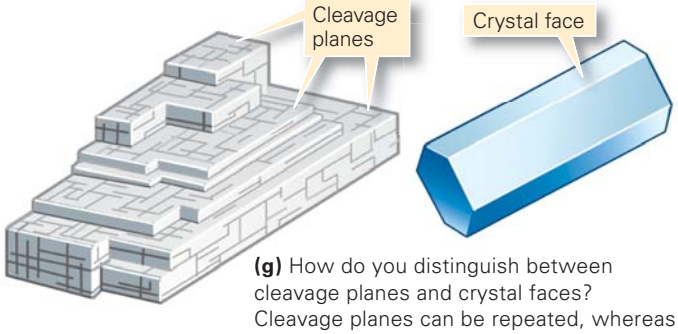
(d) Halite has three mutually perpendicular planes of cleavage.



(e) Calcite has three planes of cleavage, none of which are perpendicular to the others.



(f) Minerals without cleavage can develop irregular or conchoidal fractures.



(g) How do you distinguish between cleavage planes and crystal faces? Cleavage planes can be repeated, whereas a crystal face is a single surface.

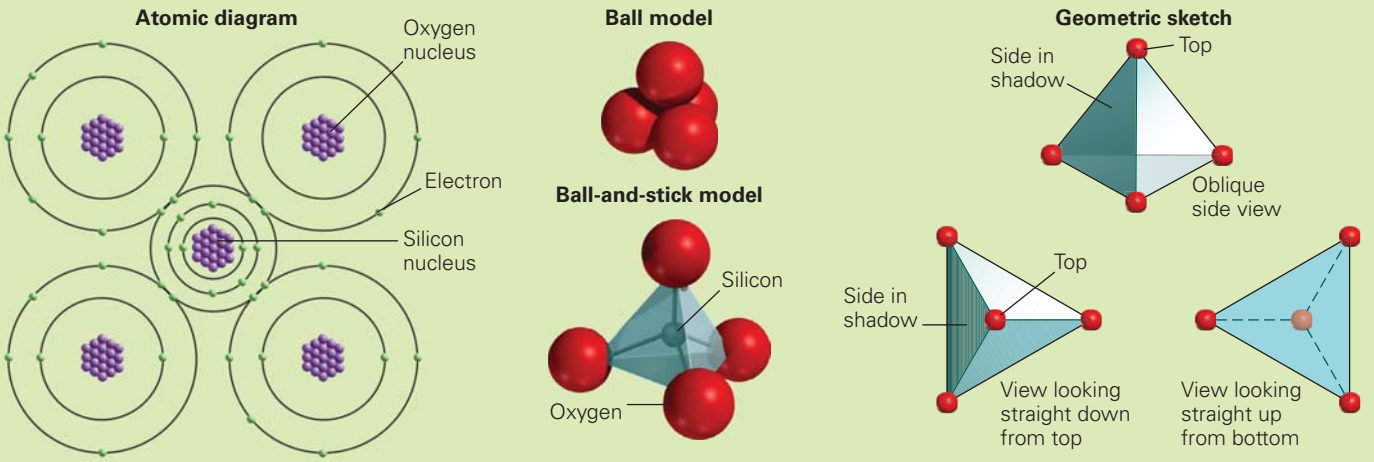
order from fewer shared oxygens to more shared oxygens:

- *Independent tetrahedra*: In this group, the tetrahedra are independent and do not share any oxygen atoms. The attraction between the tetrahedra and positive ions holds such minerals together. This group includes olivine, a glassy green mineral, and garnet (Fig. 3.8f).
- *Single chains*: In a single-chain silicate, the tetrahedra link to form a chain by sharing two oxygen atoms. The most common of the many different types of single-chain silicates are pyroxenes (Fig. 3.8b).
- *Double chains*: In a double-chain silicate, the tetrahedra link to form a double chain by sharing two or three oxygen atoms. Amphiboles are the most common type (Fig. 3.8c).
- *Sheet silicates*: The tetrahedra in this group share three oxygen atoms and therefore link to form two-dimensional sheets. Other ions and, in some cases, water molecules fit between the sheets in some sheet silicates. Because of their structure, sheet silicates have cleavage in one direction, and they occur in books of very thin sheets. In this group, we find micas (Fig. 3.8a) and clays. Clays occur only in extremely tiny flakes.
- *Framework silicates*: In a framework silicate, each tetrahedron shares all four oxygen atoms with its neighbors, forming a three-dimensional structure. Examples include feldspar and quartz. The two most common feldspars are plagioclase, which tends to be white, gray, or blue; and orthoclase (also called potassium feldspar, or K-feldspar), which tends to be pink (Fig. 3.7d).

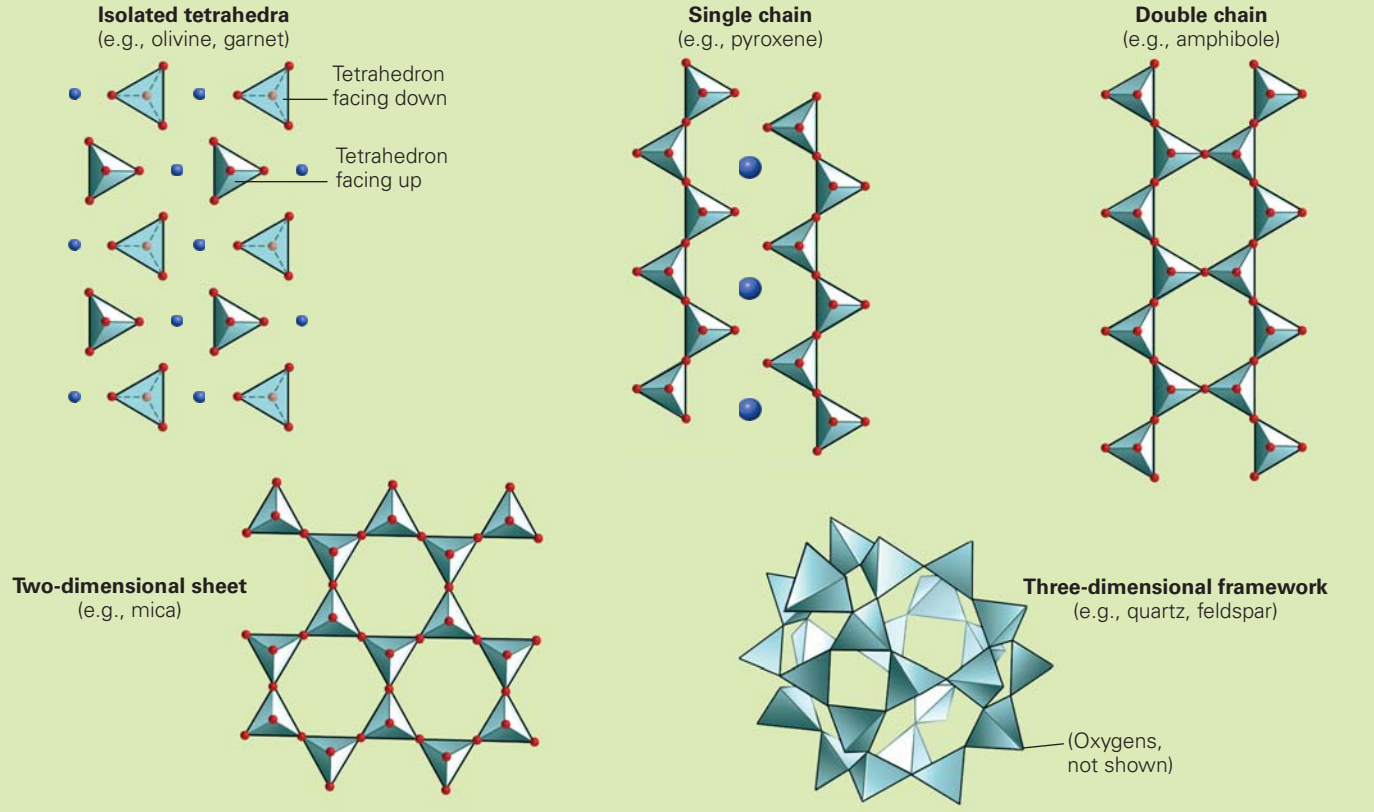
Take-Home Message

The 4,000 known minerals can be organized into a relatively small number of classes based on chemical makeup. Most minerals are silicates, which contain silicon-oxygen tetrahedral arranged in various ways.

FIGURE 3.9 The structure of silicate minerals.



(a) The fundamental building block of a silicate mineral is the silicon-oxygen tetrahedron. Oxygens occupy the corners of the tetrahedron, and silicon lies at the center. Geologists portray the tetrahedron in a number of different ways.



(b) The classes of silicate minerals differ from one another by the way in which the silicon-oxygen tetrahedra are linked. Where the tetrahedra link, they share an oxygen atom. Oxygen atoms are shown in red. Positive ions (not shown) occupy spaces between tetrahedra.

3.6 Something Precious—Gems!

Mystery and romance follow famous gems. Consider the stone now known as the Hope Diamond, recognized by name the world over (**Fig. 3.10**). No one knows who first dug it out of the ground (**Box 3.2**). Was it mined in the 1600s, or was it stolen off an ancient religious monument? What we do know is that in the 1600s, a French trader named Jean Baptiste Tavernier obtained a large (112.5 carats, where 1 carat = 200 milligrams), rare blue diamond in India, perhaps from a Hindu statue, and carried it back to France. King Louis XIV bought the diamond and had it fashioned into a jewel of 68 carats. This jewel vanished in 1762 during a burglary. Perhaps it was lost forever—perhaps not. In 1830, a 44.5-carat blue diamond mysteriously appeared on the jewel market for sale.

Did you ever wonder . . .
where diamonds come from and how they form?

BOX 3.2

CONSIDER THIS . . .

Where Do Diamonds Come From?

Diamonds consist of carbon, which typically accumulates only at or near Earth's surface. Experiments demonstrate that the pressures needed to form diamond are so extreme that, in nature, they generally occur only at depths of around 150 km below the Earth's surface. Nowadays, engineers can duplicate these conditions in the laboratory, so corporations manufacture several tons of synthetic diamonds a year.

How does carbon get down to depths of 150 km? Geologists speculate that subduction or collision carries carbon-containing rocks and sediments down to the depth where it transforms into diamond beneath continents. But if diamonds form at great depth, how do they return to the surface? Some diamonds rise when rifting cracks the continental crust and causes a small part of the underlying mantle to melt. Magma generated during this process rises to the surface, bringing the diamonds with it. Near the surface, the magma solidifies to form an igneous rock called kimberlite, named for Kimberley, South Africa. Diamonds brought up with the magma are embedded as crystals in solid kimberlite (**Fig. Bx3.2**). Much of the world's diamond supply comes from mines in this rock (**See For Yourself C**). But some sources occur in deposits of sediment formed from the breakdown and erosion of kimberlite that had been exposed at the surface. Rivers and glaciers may transport diamond-bearing sediments far from their original bedrock source.

Not all natural diamonds are valuable; the value depends on color and clarity. Diamonds that contain imperfections (cracks, or specks of other material), or are dark gray in color, are not used for jewelry. These stones, called industrial diamonds, are used as abrasives. Gem-quality diamonds come in a range of sizes. Jewelers measure the size of these gems in carats, where one carat equals 200 milligrams (0.2 gram). In English units of measurement, one ounce equals 142 carats. The largest diamond ever found, a stone called the Cullinan Diamond, was discovered in South Africa in 1905, and weighed 3,106 carats (621 grams) before being cut. By comparison, the diamond on a typical engagement ring weighs less than one carat. Gem-quality diamonds are actually more common than you might expect—suppliers stockpile the stones in order to avoid flooding the market and lowering the price.

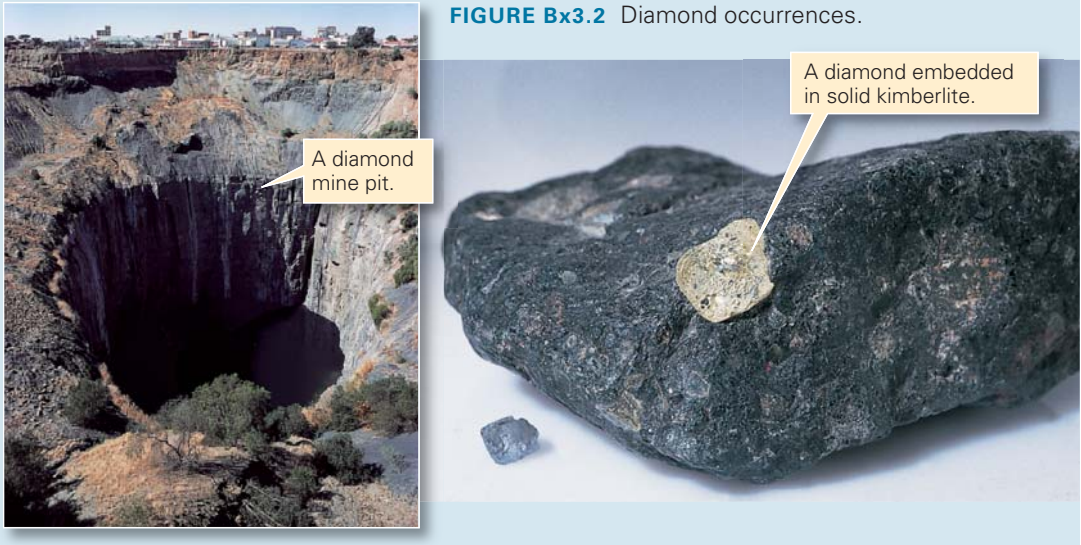


FIGURE Bx3.2 Diamond occurrences.

Henry Hope, a British banker, purchased the stone, which then became known as the Hope Diamond. It changed hands several times until 1958, when a famous New York jeweler named Harry Winston donated it to the Smithsonian Institution in Washington, DC, where it now sits behind bulletproof glass in a heavily guarded display.

What makes stones such as the Hope Diamond so special that people risk life and fortune to obtain them? What is the difference between a gemstone, a gem, and any other mineral? A gemstone is a mineral that has special value because it is rare and people consider it beautiful. A **gem**, or jewel, is a finished stone ready to be set in jewelry. Jewelers distinguish between precious stones (such as diamond, ruby, sapphire, and emerald), which are particularly rare and expensive, and semiprecious stones (such as topaz, tourmaline, aquamarine, and garnet), which are less rare and less expensive. All the stones mentioned so far are transparent crystals, though most have some color. The category of semiprecious stones also includes opaque or translucent minerals such as lapis, malachite (see Fig. 3.1a), and opal.

In everyday language, pearls and amber may also be considered gemstones. Unlike diamonds and garnets, which form inorganically in rocks, pearls form in living oysters when the oyster extracts calcium and carbonate ions from water and precipitates them around an impurity, such as a sand grain, embedded in its body. Thus, pearls are a result of biomineralization. Most pearls used in jewelry today are "cultured" pearls, made by artificially introducing round sand grains into oysters in order to stimulate pearl production. Amber is also formed by organic processes—it consists of fossilized tree sap. But because amber consists of organic compounds that are not arranged in a crystal structure, it does not meet the definition of a mineral.

In some cases, gemstones are merely pretty and rare versions of more common minerals. For example, ruby is a special version of the common mineral corundum, and emerald

is a special version of the common mineral beryl (Fig. 3.11a). As for the beauty of a gemstone, this quality lies basically in its color and, in the case of transparent gems, its "fire"—the way the mineral bends and internally reflects the light passing through it, and disperses the light into a spectrum. Fire makes a diamond sparkle more than a similarly cut piece of glass.

Gemstones form in many ways. Some solidify from a melt, some form by diffusion, some precipitate out of a water solution in cracks, and some are a consequence of the chemical interaction of rock with water near the Earth's surface. Many gems come from pegmatites, particularly coarse-grained rocks formed by the solidification of steamy melt.

Most gems used in jewelry are "cut" stones, meaning that they are not raw crystals right from the ground, but rather have been faceted. The smooth **facets** on a gem are ground and polished surfaces made with a faceting machine (Fig. 3.11b). Facets are not the natural crystal faces of the mineral, nor are they cleavage planes, though gem cutters sometimes make the facets parallel to cleavage directions and will try to break a large gemstone into smaller pieces by splitting it on a cleavage plane. A faceting machine consists of a doping arm, a device that holds a stone in a specific orientation, and a lap, a rotating disk covered with a wet paste of grinding powder and water. The gem cutter fixes a gemstone to the end of the doping arm and positions the arm so that it holds the stone against the moving lap. The movement of the lap grinds a facet. When the facet is complete, the gem cutter rotates the arm by a specific angle, lowers the stone, and grinds another facet. The geometry of the facets defines the cut of the stone. Different cuts have names, such as "brilliant," "French," "star," and "pear." Grinding facets is a lot of work—a typical engagement-ring diamond with a brilliant cut has 57 facets (Fig. 3.11c)!

Did you ever wonder . . .
how jewelers make the facets on a jewel?

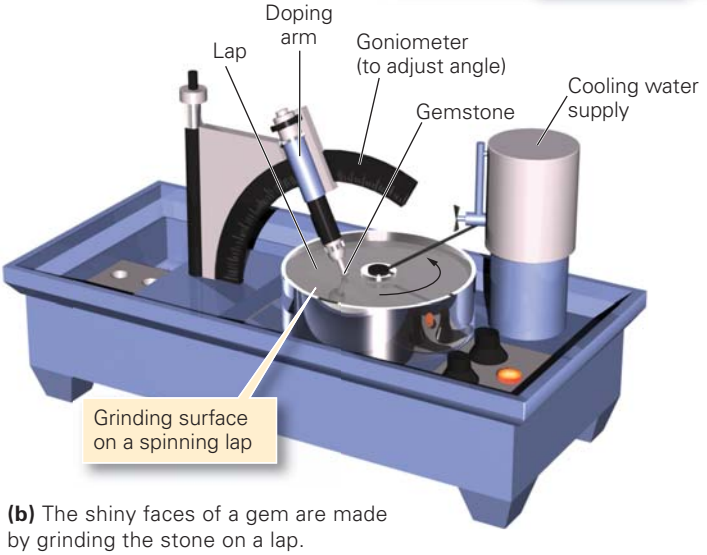
FIGURE 3.10 The Hope Diamond.



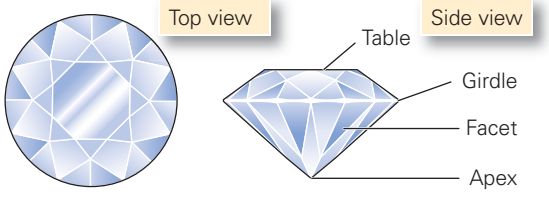
FIGURE 3.11 Cutting gemstones.



(a) Emerald is a green, transparent variety of the mineral beryl.



(b) The shiny faces of a gem are made by grinding the stone on a lap.



(c) There are many different "cuts" for a gem. Here we see the top and side views of a brilliant-cut diamond.

Take-Home Message

Gemstones are particularly rare and beautiful minerals. The gems or jewels found in jewelry have been faceted using a lap—the facets are not natural crystal faces or cleavage surfaces. The fire of a jewel comes from the way it reflects light internally.

Chapter Summary

- Minerals are naturally occurring, solid substances, formed by geologic processes, with a definable chemical composition and an internal structure characterized by an orderly arrangement of atoms, ions, or molecules in a crystalline lattice. Most minerals are inorganic.
- Biogenic minerals are produced by organisms. The minerals in shells are an example of biomineralization.
- In the crystalline lattice of minerals, atoms occur in a specific pattern—one of nature's finest examples of ordering.
- Minerals can form by the solidification of a melt, precipitation from a water solution, diffusion through a solid, the metabolism of organisms, and precipitation from a gas.
- About 4,000 different types of minerals are known, each with a name and distinctive physical properties (such as color, streak, luster, hardness, specific gravity, crystal habit, cleavage, magnetism, and reactivity with acid).
- The unique physical properties of a mineral reflect its chemical composition and crystal structure. By observing these physical properties, you can identify minerals.
- The most convenient way to classify minerals is to group them according to their chemical composition. Mineral classes include silicates, oxides, sulfides, sulfates, halides, carbonates, and native metals.
- Silicate minerals are the most common minerals on Earth. The silicon-oxygen tetrahedron, a silicon atom surrounded by four oxygen atoms, serves as the fundamental building block of silicate minerals.
- Groups of silicate minerals are distinguished from each other by the ways in which the silicon-oxygen tetrahedra that constitute them are linked.
- Gemstones are minerals known for their beauty and rarity. The facets on cut gems used in jewelry are made by grinding and polishing the stones with a faceting machine.

Key Terms

carbonate (p. 81)
cleavage (p. 79)
color (p. 78)
conchoidal fracture (p. 79)
crystal (p. 73)
crystal face (p. 73)
crystal habit (p. 78)
crystal structure (p. 74)
facet (p. 85)
gem (p. 84)
geode (p. 77)
glass (p. 73)
hardness (p. 78)
luster (p. 78)
mineral (p. 72)
mineralogy (p. 72)
Mohs hardness scale (p. 78)
polymorph (p. 76)
silicate (p. 81)
silicon-oxygen tetrahedron (p. 81)
specific gravity (p. 78)
streak (p. 78)

Review Questions

1. What is a mineral, as geologists understand the term? How is this definition different from the everyday usage of the word?
2. Why is glass not a mineral?
3. Salt is a mineral, but the plastic making up an inexpensive pen is not. Why not?
4. Describe several ways that mineral crystals can form.
5. Why do some minerals occur as euhedral crystals, whereas others occur as anhedral grains?
6. List and define the principal physical properties used to identify a mineral. Which minerals react with acid to produce CO_2?
7. How can you determine the hardness of a mineral? What is the Mohs hardness scale?
8. How do you distinguish cleavage surfaces from crystal faces on a mineral? How does each type of surface form?
9. What is the prime characteristic that geologists use to separate minerals into classes?
10. What is a silicon-oxygen tetrahedron? What is the anionic group that occurs in carbonate minerals?
11. On what basis do mineralogists organize silicate minerals into distinct groups?
12. What is the relationship between the way in which silicon-oxygen tetrahedra bond in micas and the characteristic cleavage of micas?
13. Why are some minerals considered gemstones? How do you make the facets on a gem?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- A What a Geologist Sees exercise on identifying mineral properties.
- An Animation exercise on mineral growth.
- Problems that help students with mineral classification.

On Further Thought

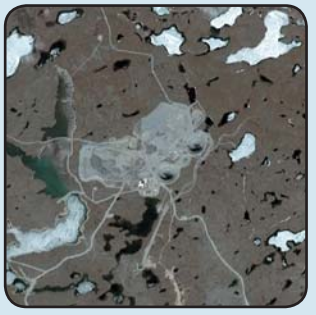
14. Compare the chemical formula of magnetite with that of biotite. Considering that iron is a relatively heavy element, which mineral has the greater specific gravity?
15. Imagine that you are given two milky white crystals, each about 2 cm across. You are told that one of the crystals is composed of plagioclase and the other of quartz. How can you determine which is which?
16. Could you use crushed calcite to grind facets on a diamond? Why or why not?

SEE FOR YOURSELF C. . . Minerals

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet C of our **Geotours Workbook**.



Kimberley Diamond Mine
Latitude 64°43′1.78″N,
Longitude 110°36′22.00″W
The field of view shows part of the town of Kimberley, in South Africa. Looking down from 13 km, you can see an inactive diamond mine, which looks like a circular pit, and the tailings pile of excavated rock debris.



New Diamond Mine, Canada
Latitude 64°43′14.74″N,
Longitude 110°37′32.76″W
In this remote region, the landscape is largely untouched tundra. In the 1990s, prospectors found diamond pipes, and now the area contains small open-pit mines. Mining is difficult on the frozen ground.



Mir Mine, Siberia
Latitude 62°31′40.77″N,
Longitude 113°59′36.16″E
Viewed from 4.2 km, we see an open pit (1.2 km across and 525 m deep) dug into kimberlite. In the 1960s, the mine produced 2,000 kg of diamonds per year. Mining continued underground after the pit closed in 2001.



Diamantina, Brazil
Latitude 18°15′4.35″S,
Longitude 43°34′57.21″W
Independent miners excavated Precambrian sedimentary rocks by hand in this pit, viewed from 2.2 km. Diamonds occur as grains. They weathered out of kimberlite, then mixed in with sand and pebbles carried by rivers. The sediment later cemented into rock.

INTERLUDE A

Rock Groups



The rock traversed by this highway in Utah tells us a story of the Earth's past.

A.1 Introduction

During the 1849 gold rush in the Sierra Nevada of California, only a few lucky individuals actually became rich. The rest of the "forty-niners" either slunk home in debt or took up less glamorous jobs in new towns such as San Francisco. These towns grew rapidly, and soon people from the American west coast were demanding large quantities of manufactured goods from east-coast factories. Making the goods was no problem, but getting them to California meant either a stormy voyage around the southern tip of South America or a trek with stubborn mule teams through the deserts of Nevada and Utah. The time was ripe to build a railroad linking the east and west coasts of North America, and, with much fanfare, the Central Pacific line decided to punch one right across the peaks of the Sierras. In 1863, while the Civil War raged elsewhere in the United States, the company transported six thousand Chinese laborers across the Pacific in the squalor of unventilated cargo holds and set them to work chipping ledges and blasting tunnels. Along the way, untold numbers of laborers died of frostbite, exhaustion, mistimed blasts, landslides, or avalanches.

Through their efforts, the railroad laborers certainly gained an intimate knowledge of how rock feels and behaves—it's solid, heavy, and hard! They also found that some rocks break easily into layers but others do not, and that some rocks are dark-colored while others are light-colored. They realized, like anyone who looks closely at rock exposures, that rocks are not just gray, featureless masses, but rather come in a great variety of colors and textures.

Why are there so many distinct types of rocks? The answer is simple: rocks can form in many different ways and from many different materials. Because of the relationship between rock type and the process of formation, rocks provide a historical record of geologic events and give insight into interactions among components of the Earth System. The next few chapters are devoted to a discussion of rocks and a description of how rocks form. This interlude serves as a general introduction to these chapters. We learn what the term "rock" means to geologists, what rocks are made of, and how to distinguish among the three principal groups of rocks. We also look at how geologists study rocks.

A.2 What Is Rock?

To geologists, **rock** is a coherent, naturally occurring solid, consisting of an aggregate of minerals or, less commonly, of glass. Let's take this definition apart to see what its components mean.

- *Coherent*: A rock holds together, and thus must be broken to be separated into pieces. As a result of its coherence, rock can form cliffs or can be carved into sculptures. A pile of unattached mineral grains does not constitute a rock.
- *Naturally occurring*: Geologists consider only naturally occurring materials to be rocks, so manufactured materials, such as concrete and brick, do not qualify.
- *An aggregate of minerals or a mass of glass*: The vast majority of rocks consist of an aggregate (a collection) of many mineral grains, and/or crystals, stuck or grown together. Some rocks contain only one kind of mineral, whereas others contain several different kinds. A few rock types consist of glass.

What holds rock together? Grains in rock stick together to form a coherent mass either because they are bonded by natural **cement**, mineral material that precipitates from water and fills the space between grains (**Fig. A.1a**), or because they interlock with one another like pieces in a jigsaw puzzle (**Fig. A.1b**). Rocks whose grains are stuck together by cement are called **clastic**, whereas rocks whose crystals interlock with one another are called **crystalline**. Glassy rocks hold together because they originate as a continuous mass (that is, they have no separate grains), because glassy grains were welded together while still hot, or because they were cemented together at a later time.

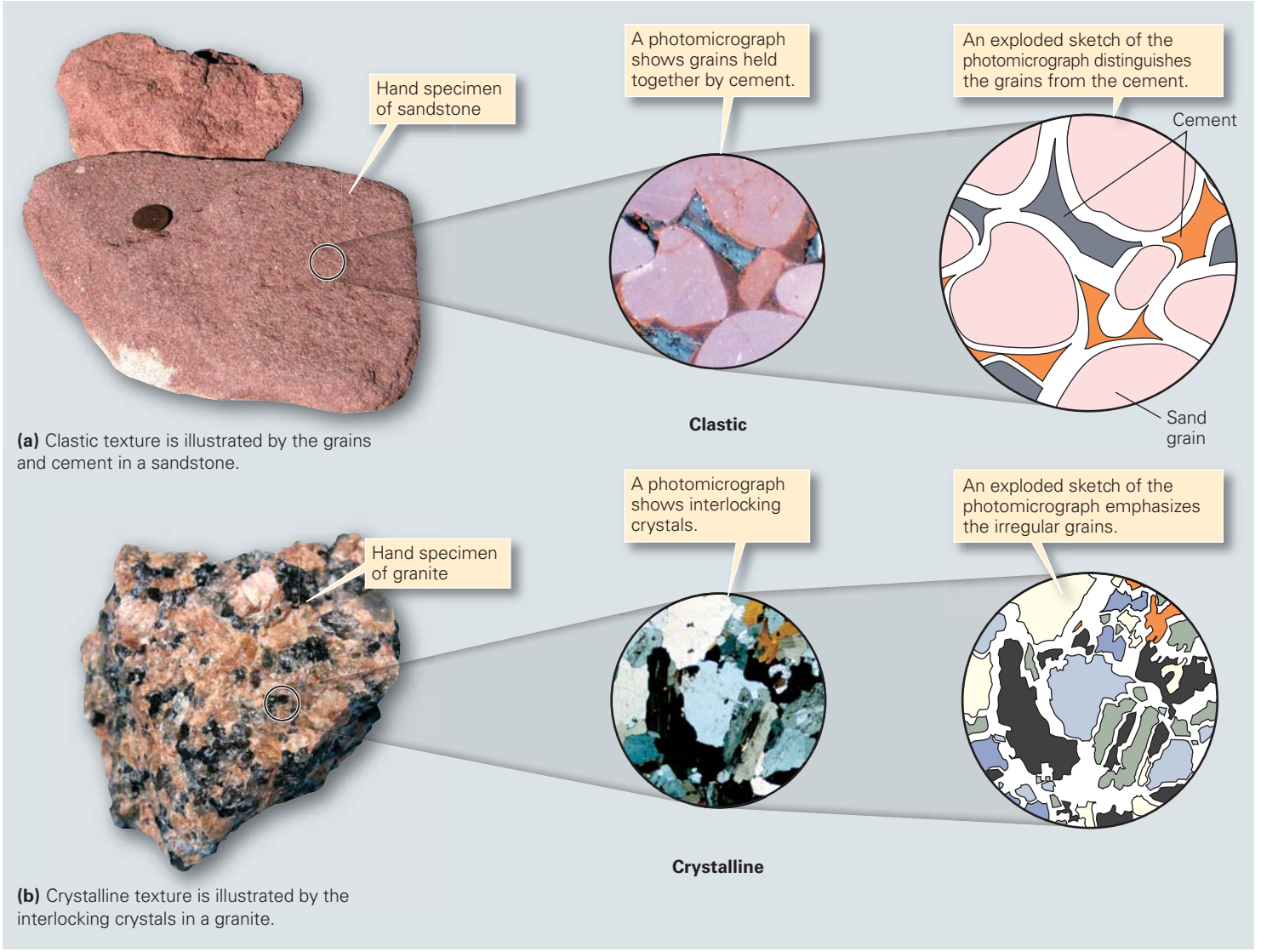
At the surface of the Earth, rock occurs either as broken chunks (pebbles, cobbles, or boulders; see Chapter 6) that have moved by falling down a slope or by being transported in ice, water, or wind, or as **bedrock** that is still attached to the Earth's crust. Geologists refer to an exposure of bedrock as an **outcrop**. An outcrop may appear as a rounded knob out in a field, as a ledge forming a cliff or ridge, on the face of a stream cut (where running water dug down into bedrock), or along human-made roadcuts and excavations (**Fig. A.2a–d**).

To people who live in cities or forests or on farmland, outcrops of bedrock may be unfamiliar, since bedrock may be completely covered by vegetation, sand, mud, gravel, soil, water, asphalt, concrete, or buildings. Outcrops are particularly rare in regions such as the midwestern United States, where, during the past million years, ice-age glaciers melted and buried bedrock under thick deposits of debris (see Chapter 18).

A.3 The Basis of Rock Classification

Beginning in the 18th century, geologists struggled to develop a sensible way to classify rocks, for they realized, as did miners from centuries past, that not all rocks are the same. Classification schemes help us organize information and remember significant details about materials or objects, and they help us recognize similarities and differences among them. By the end of the 18th century, most geologists had accepted the *genetic scheme* for classifying rocks that we continue to use today. This scheme focuses on the origin (genesis) of rocks. Using this

FIGURE A.1 Rocks, aggregates of mineral grains and/or crystals, can be clastic or crystalline.



(a) Clastic texture is illustrated by the grains and cement in a sandstone.

(b) Crystalline texture is illustrated by the interlocking crystals in a granite.

approach, geologists recognize three basic groups: (1) **igneous rocks**, which form by the freezing (solidification) of molten rock (**Fig. A.3a**); (2) **sedimentary rocks**, which form either by the cementing together of fragments (grains) broken off preexisting rocks or by the precipitation of mineral crystals out of water solutions at or near the Earth's surface (**Fig. A.3b**); and (3) **metamorphic rocks**, which form when preexisting rocks change character in response to a change in pressure and temperature conditions (**Fig. A.3c**). Metamorphic change occurs in the solid state, which means that it does not require melting. In the context of modern plate tectonics theory, different rock types form in different geologic settings, as we discuss in succeeding chapters (**Fig. A.4**).

Each of the three groups contains many different individual rock types, distinguished from one another by physical characteristics.

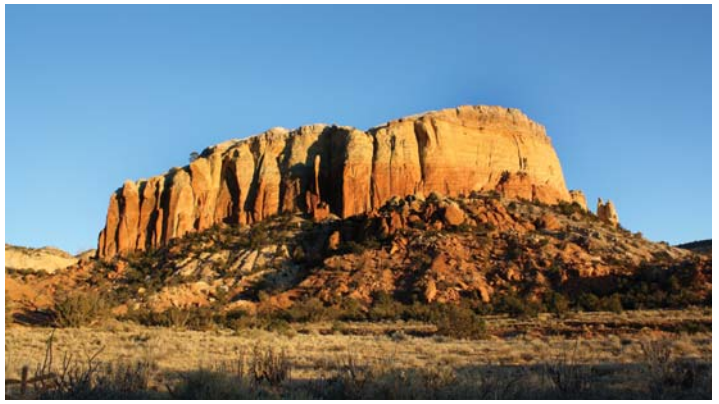
- *Grain size*: The dimensions of individual "grains" (here used in a general sense to mean fragments or crystals) in a rock may be measured in millimeters or centimeters. Some grains are so small that they can't be seen without a microscope, whereas others are as big as a fist or larger. Some grains are **equant**, meaning that they have the same dimensions in all directions; some are **inequant**, meaning that the dimensions are not the same in all directions (**Fig. A.5a, b**). In some rocks, all the grains are the same size, whereas other rocks contain a variety of grain sizes.

- *Composition*: A rock is a mass of chemicals. The term rock composition refers to the proportions of different chemicals making up the rock. The proportion of chemicals, in turn, affects the proportion of different minerals constituting the rock.

FIGURE A.2 Types of rock exposures.



(a) Outcrops are natural rock exposures. These outcrops rise as cliffs above the forest of the Rocky Mountains in Colorado.



(b) In arid (dry) climates, a lack of vegetation leaves outcrops unobscured.



(c) By blasting into the ground to produce a more level grade for roads, highway engineers produce roadcuts.



(d) Stream cuts form where flowing water grinds into the land and strips away soil and vegetation.

- *Texture*: This term refers to the arrangement of grains in a rock, that is, the way grains connect to one another and whether or not inequant grains are aligned parallel to each other. The concept of rock texture will become easier to grasp as we look at different examples of rocks in the following chapters.
- *Layering*: Some rock bodies appear to contain distinct layering, defined either by bands of different compositions or textures, or by the alignment of inequant grains so that they trend parallel to each other. Different types of layering occur in different kinds of rocks. For example, the layering in sedimentary rocks is called **bedding**, whereas the layering in metamorphic rocks is called **metamorphic foliation** (**Fig. A.6a, b**).

Each distinct rock type has a name. Names come from a variety of sources. Some come from the dominant component making up the rock, some from the region where the rock was first discovered or is particularly abundant, some from a root word of Latin origin, and some from a traditional name used by people in an area where the rock is found. All told, there are hundreds of different rock names, though in this book we will introduce only about 30.

A.4 Studying Rock

Outcrop Observations

The study of rocks begins by examining a rock in an outcrop. If the outcrop is big enough, such an examination will reveal relationships between the rock you're interested in and the rocks around it, and will allow you to detect layering. Geologists carefully record observations about an outcrop, then break off a **hand specimen**, a fist-sized piece, that they can examine more closely with a hand lens (magnifying glass). Observation with a hand lens enables geologists to identify sand-sized or

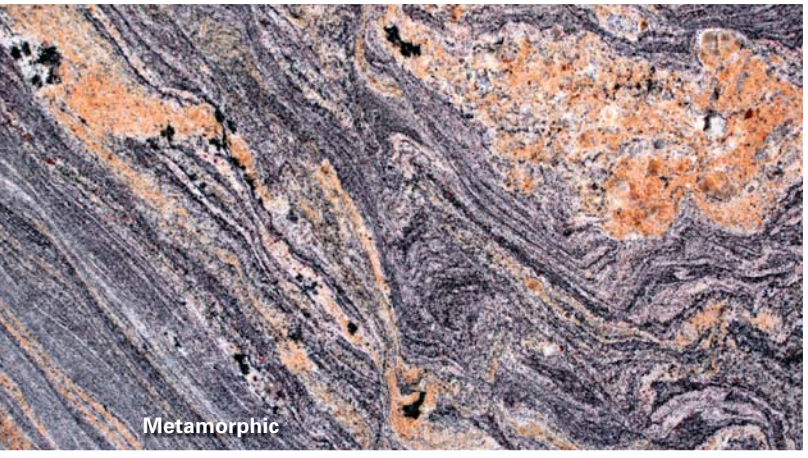
FIGURE A.3 Examples of the three major rock groups.



(a) Lava (molten rock) freezes to form igneous rock. Here, the molten tip of a brand-new flow still glows red. Older flows are already solid.



(b) Sand, formed from grains eroded off the rock cliffs, collects on the beach. If buried and turned to rock, it becomes layers of sandstone, such as those making up cliffs.



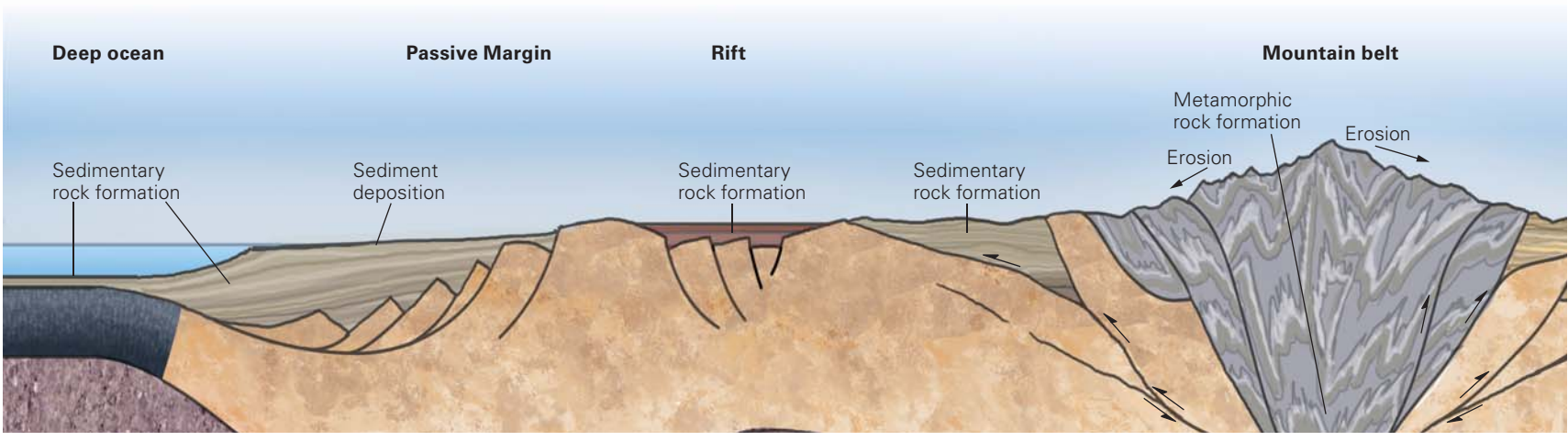
(c) Metamorphic rock forms when preexisting rocks endure changes in temperature and pressure and/or are subjected to shearing, stretching, or shortening. New minerals and textures form.

larger grains, and may enable them to describe the texture of the rock.

Thin-Section Study

Geologists often must examine rock composition and texture in minute detail in order to identify a rock and develop a hypothesis for how it formed. To do this, they take a specimen back to the lab, make a very thin slice (about 0.03 mm thick, the thickness of a human hair) and mount it on a glass slide (**Fig. A.7a–c**). They study the resulting **thin section** with a petrographic microscope (*petro* comes from the Greek word for rock). A petrographic microscope differs from an ordinary microscope in that it illuminates the thin section with transmitted polarized light. This means that the illuminating

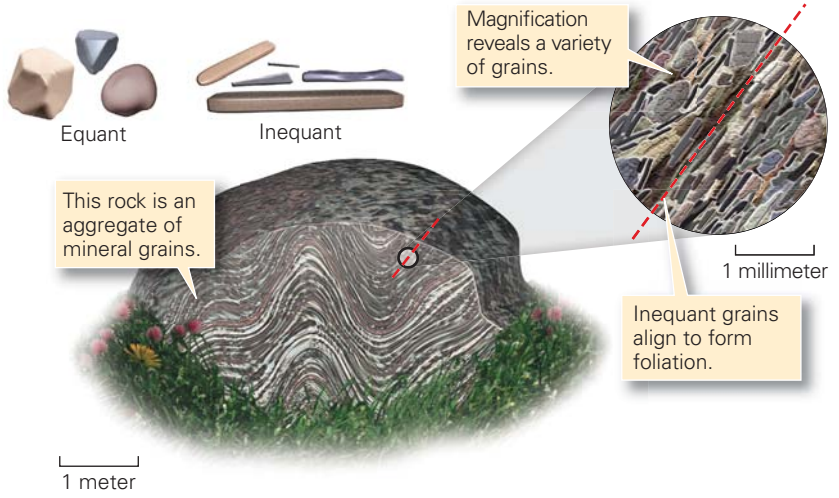
FIGURE A.4 A cross section illustrating various geologic settings in which rocks form.



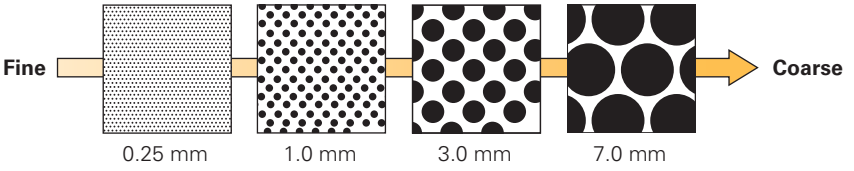
light beam first passes through a special polarity filter that makes all the light waves in the beam vibrate in the same plane, and then the light passes up through the thin section and then up through another polarizing filter. An observer looks through the thin section as if it were a window. When illuminated with transmitted polarized light, and viewed through two polarizing filters, each type of mineral grain displays a unique suite of colors (Fig. A.7d). The specific color the observer sees depends on both the identity of the grain and its orientation with respect to the waves of polarized light.

The brilliant colors and strange shapes in a thin section viewed in polarized light rival the beauty of an abstract painting or stained glass. By examining a thin section with a petrographic microscope, geologists can identify most of the minerals constituting the rock and can describe the way in which the grains connect to each other. They can make a record of the image by using a camera. A photograph taken through a petrographic microscope is called a **photomicrograph**.

FIGURE A.5 Describing grains in rock.



(a) Grains in rock come in a variety of shapes. Some are equant, whereas some are inequant. In this example of metamorphic rock, inequant grains align to define a foliation.



(b) Geologists define grain size by using this comparison chart.

High-Tech Analytical Equipment

Beginning in the 1950s, high-tech electronic instruments became available that enabled geologists to examine rocks on an even finer scale than is possible with a petrographic microscope. Modern research laboratories typically boast instruments such as electron microprobes, which can focus a beam of electrons on a small part of a grain to create a signal that defines the chemical composition of the mineral (Fig. A.8); mass spectrometers, which analyze the proportions of atoms with different atomic weights contained in a rock; and X-ray diffractometers, which identify minerals by measuring how X-ray beams interact with crystals. Such instruments, in conjunction with optical examination, can provide geologists with highly detailed characterizations of rocks, which in turn help them understand how the rocks formed and where the rocks came from. This information enables geologists to use the study of rocks as a basis for deciphering Earth history.

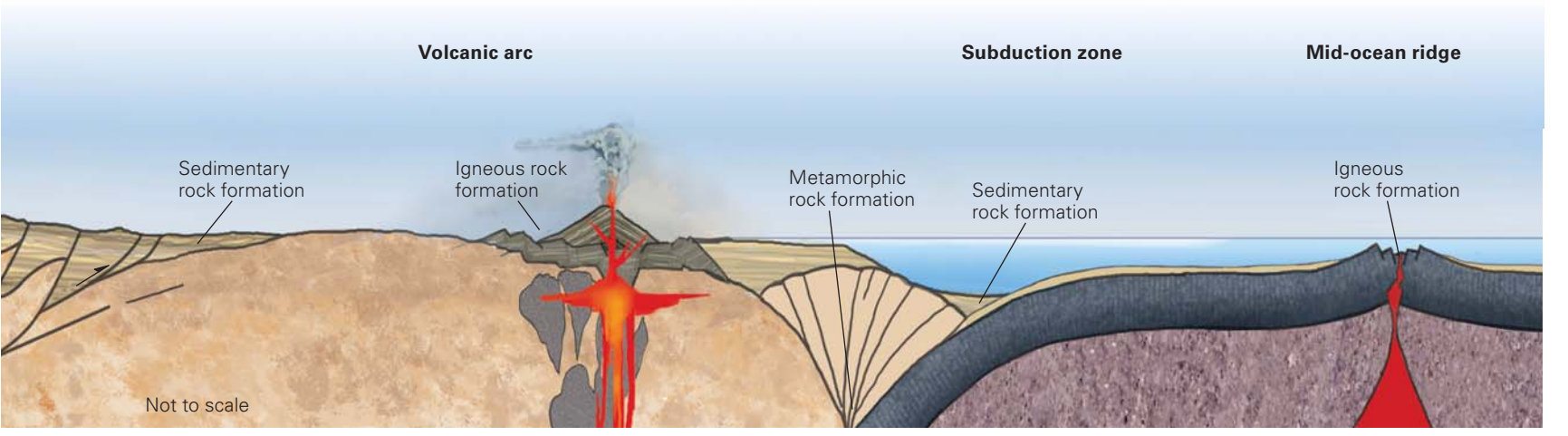


FIGURE A.6 Layering in rock.

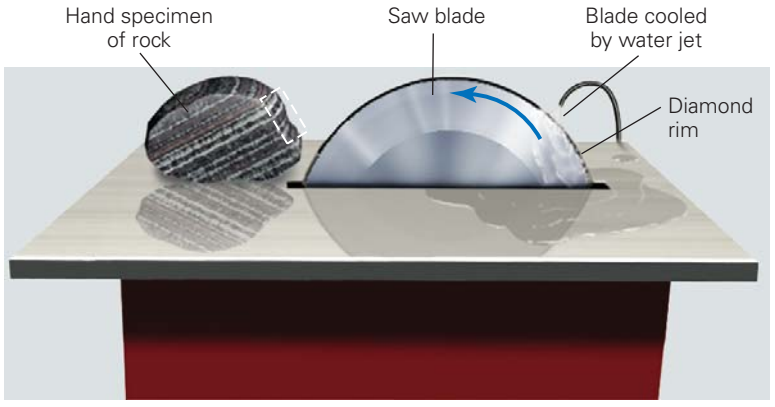


(a) Bedding in a sedimentary rock, here defined by alternating layers of coarser and finer grains, as exposed on a cliff along an Oregon beach. Older beds were tilted before younger ones were deposited.

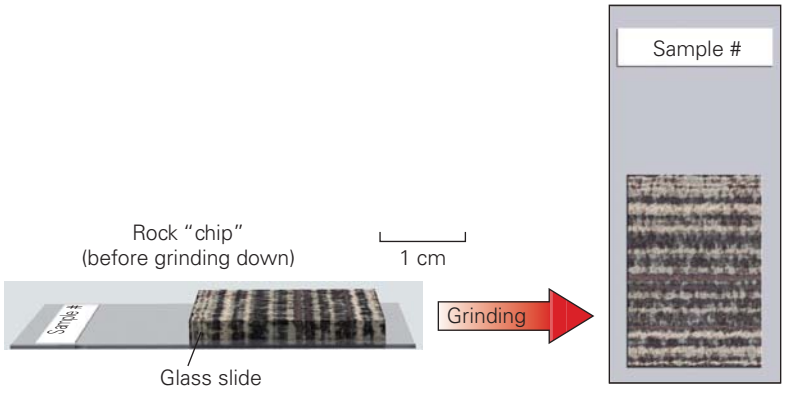


(b) Foliation in this outcrop of metamorphic rock in Ontario, Canada is defined by alternating layers of light and dark minerals.

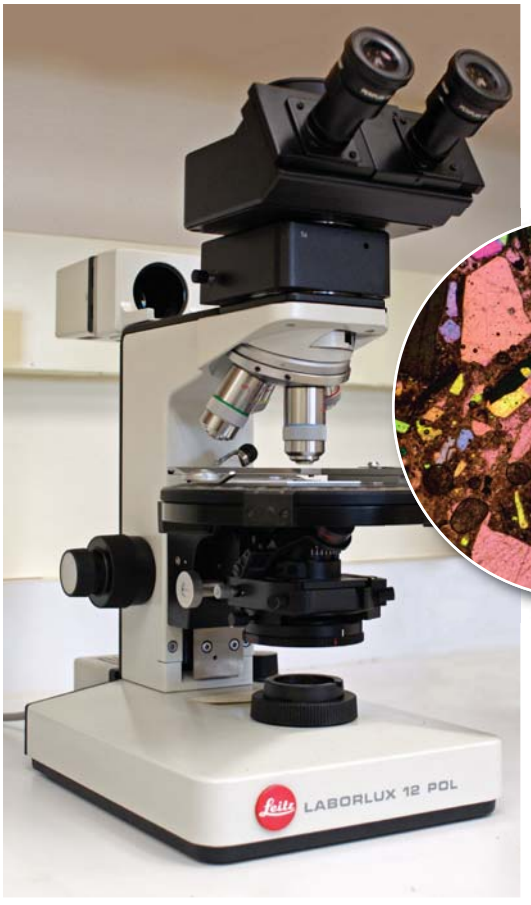
FIGURE A.7 Studying rocks in thin section.



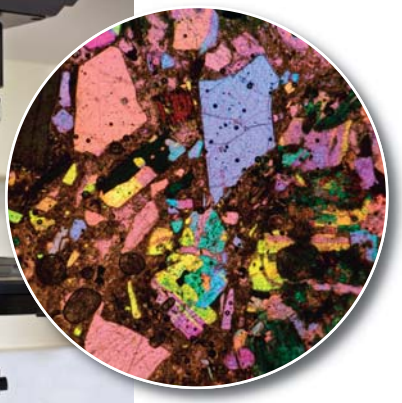
(a) Using a special saw, a geologist cuts a thin chip of a rock specimen.



(b) The geologist glues the chip to a glass slide and grinds it down until it is so thin that light can pass through it.



(c) With a petrographic microscope, it's possible to view thin sections with light that shines through the sample from below.



(d) If the light is polarized, different minerals display different colors when viewed through the microscope.

FIGURE A.8 An electron microprobe uses a beam of electrons to analyze the chemical composition of minerals.



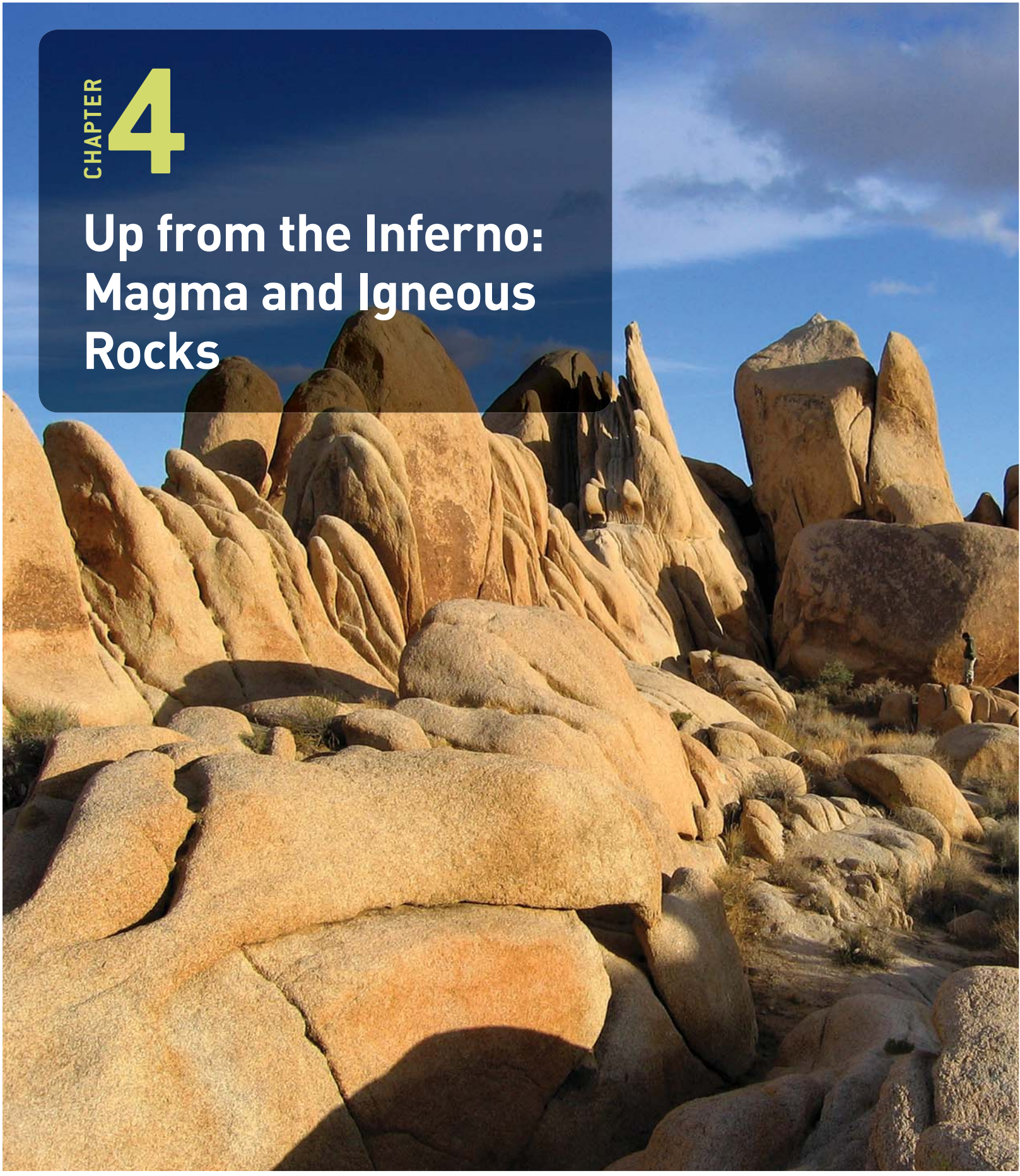
Key Terms

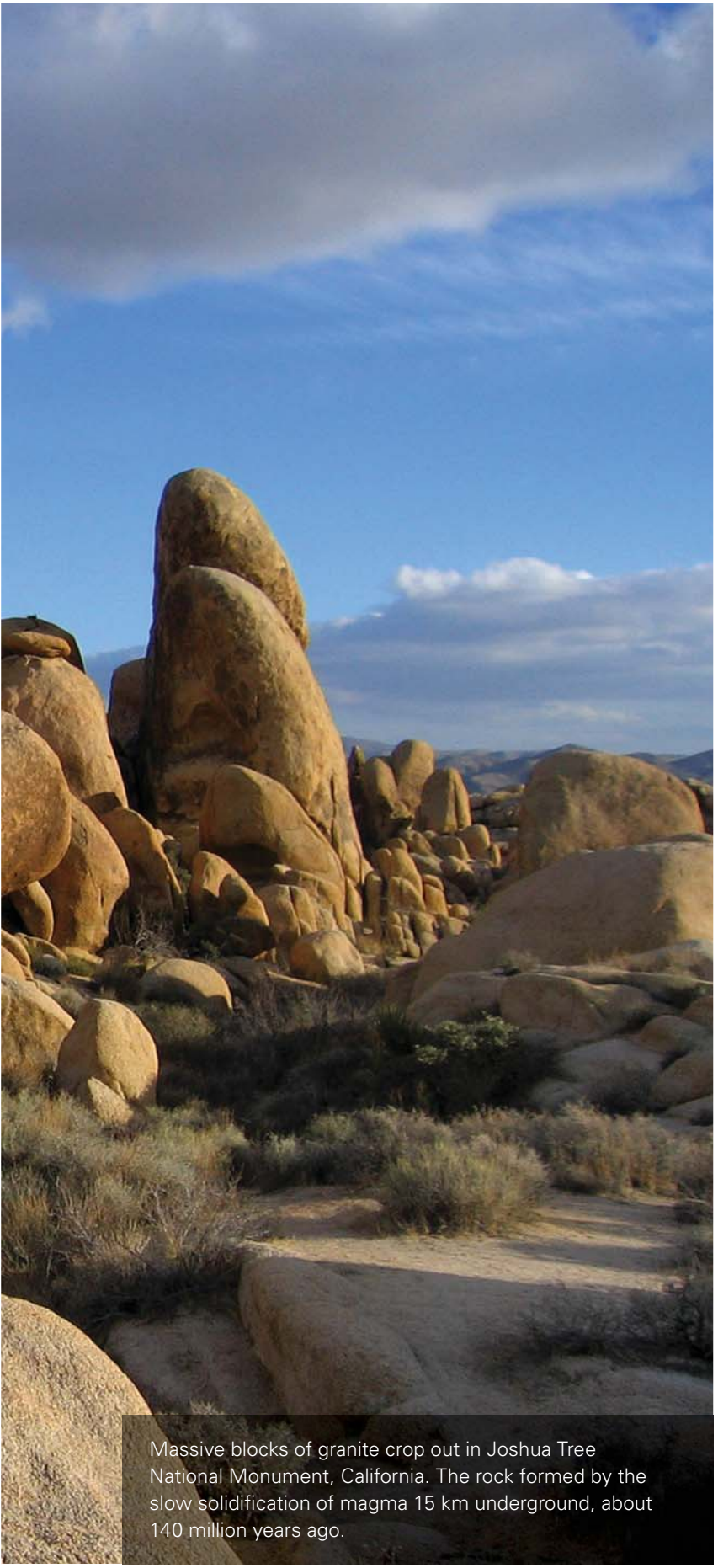
bedding (p. 91)
bedrock (p. 89)
cement (p. 89)
clastic (p. 89)
crystalline (p. 89)
equant (p. 90)
hand specimen (p. 91)
igneous rock (p. 90)
inequant (p. 90)
metamorphic foliation (p. 91)
metamorphic rock (p. 90)
outcrop (p. 89)
photomicrograph (p. 93)
rock (p. 89)
sedimentary rock (p. 90)
thin section (p. 92)

ANOTHER VIEW This quarry, in northwestern Italy, provides blocks of pure white marble, some of which have been carved into beautiful sculptures. It also provides a view into the bedrock that lies beneath rugged peaks.

CHAPTER 4

Up from the Inferno: Magma and Igneous Rocks





Massive blocks of granite crop out in Joshua Tree National Monument, California. The rock formed by the slow solidification of magma 15 km underground, about 140 million years ago.

Chapter Objectives

By the end of this chapter, you should know . . .

- why melting produces molten rock at special places in the Earth.
- why magma moves into intrusive or extrusive settings, where it solidifies.
- why there are different types of igneous rock, and how to classify these rocks.
- where igneous activity takes place, in the context of plate tectonics theory.

To their grey heights they rise,
The basalt crags thus far into blue air…
Archaic columns of fire frozen to stone.

—Kathleen Raine (British poet, 1908–2003)

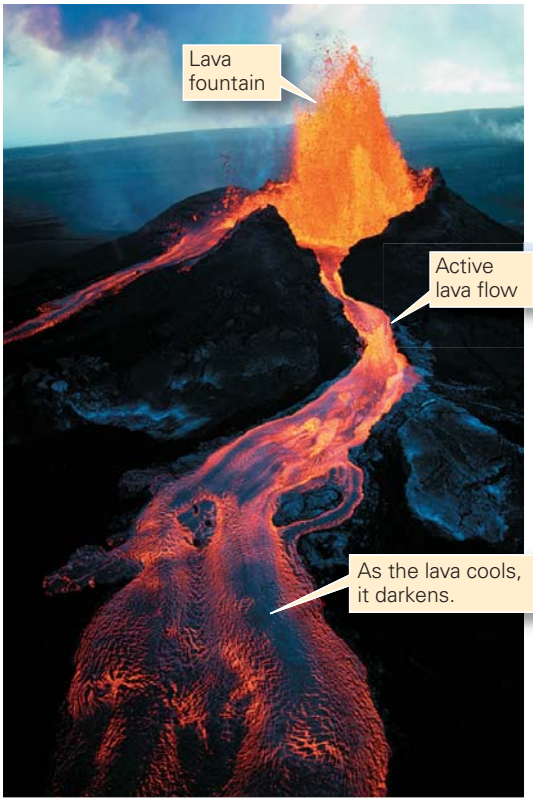
4.1 Introduction

Every now and then, an incandescent liquid—hot molten rock, or "melt"—fountains from a crater or crack on the big island of Hawaii. Hawaii is a **volcano**, a vent at which melt from inside the Earth spews onto the planet's surface, an event called a *volcanic eruption*. Geologists refer to melt that has emerged at the surface as **lava**. Some lava pools around the vent, while some runs down the mountainside as a syrupy red-yellow stream called a **lava flow**. Near its source, lava on Hawaii has a temperature of about 1150°C and moves swiftly, cascading over escarpments at speeds of up to 60 km per hour (**Fig. 4.1a**). At the base of the mountain, the lava flow slows but advances nonetheless, engulfing roads, houses, or vegetation in its path (**Fig. 4.1b**). As the flow cools, its surface darkens and crusts over, occasionally breaking to reveal the hot, sticky mass that continues to ooze within. Finally, the flow stops moving entirely, and within days or weeks the once red-hot melt has become a hard, black solid through and through (**Fig. 4.1c, d**). New **igneous rock**, rock made by the freezing (solidifying) of a melt, has formed. Considering the fiery heat of the melt from which igneous rocks solidify, the name igneous—from the Latin *ignis*, meaning fire—makes sense. Igneous rocks are very common on Earth. They make up all of the oceanic crust and much of the continental crust.

It may seem strange to speak of "freezing" in the context of forming rock, for most people think of freezing as the transformation of liquid water to solid ice when the temperature drops below 0°C (32°F). Nevertheless, the freezing of liquid melt to form solid igneous rock represents the same phenomenon, solidification of a liquid, except that igneous rocks freeze at high temperatures—between 650°C and 1100°C. To put such temperatures in perspective, keep in mind that home ovens attain a maximum temperature of only 260°C (500°F).

Rock that forms by the freezing of lava above ground, after it spills out (extrudes) onto the surface of the Earth and comes into contact with the atmosphere or ocean, is **extrusive igneous rock** (Fig. 4.2a). Extrusive igneous rock includes both solid lava flows, formed when streams or mounds of lava solidify on the surface of the Earth, and deposits of pyroclastic debris (from the Greek word *pyro*, meaning fire). Such debris includes **volcanic ash**, consisting of fine particles of glass that form when a spray of lava erupts into the air and freezes instantly. Some ash billows up several kilometers into the sky above a volcano and eventually drifts down in a snow-like ash fall. But some ash rushes down the side of the volcano in a scalding avalanche called an ash flow. Pyroclastic debris also includes larger fragments formed when clots of

FIGURE 4.1 Formation and evolution of lava flows.



(a) Lava erupts as a fountain from a volcanic vent on Hawaii. A fast-moving river of lava then flows downslope.



(b) At a distance from the vent, the lava has completely crusted over with new rock, but the interior of the flow remains molten.



(c) Eventually, the flow cools completely and becomes a layer of new rock. This flow engulfed a road on Hawaii.

Time



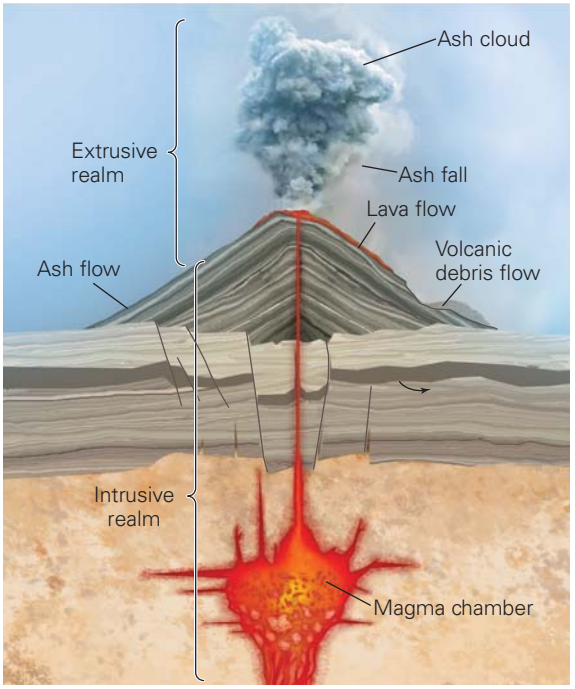
(d) Over time, many lava flows can accumulate one on top of another to build a large volcano. A canyon cut into the volcano exposes dozens of ancient flows.

lava freeze in the air, or when the force of the eruption blasts apart pre-existing rock of a volcano (Fig. 4.2b). We'll provide further detail about pyroclastic debris in Chapter 5.

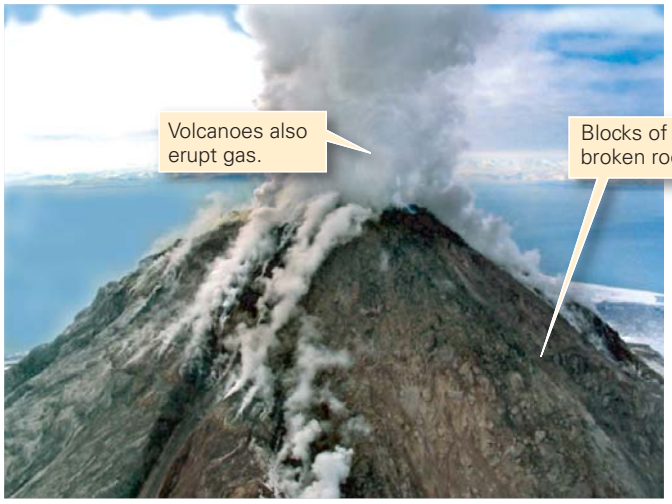
The spectacle of a Hawaiian volcano erupting may give the impression that the formation of igneous rocks happens exclusively at the Earth's surface. But in fact, a vastly greater volume of igneous rock forms by solidification of molten rock underground and out of view. Geologists refer to underground melt as **magma**. Magma pushes its way, or "intrudes," into pre-existing rock (called wall rock), where it may accumulate into an irregularly shaped mass called a **magma chamber**, rise to form a chimney-like column, or inject into cracks to form tabular underground sheets. When magma in such intrusions solidifies underground, it becomes **intrusive igneous rock**.

A great variety of igneous rocks exist on Earth. To understand why and how these rocks form, and why there are so many different kinds, we first discuss why magma forms, why it rises, how it flows, and how it freezes in intrusive and extrusive environments. We then look at the scheme that geologists use to classify igneous rocks.

FIGURE 4.2 The intrusive and extrusive realms.



(a) The intrusive realm lies underground and the extrusive realm lies above ground. Lava flows, as well as various types of ash eruptions, all produce extrusive rocks.



(b) Broken blocks of lava were blasted out of this Alaskan volcano and now litter its slopes.

Take-Home Message

Molten rock underground is called magma, whereas molten rock that has come out of a vent at the Earth's surface is lava. Solidification of magma produces intrusive rocks. Solidification of lava, either in flows on the surface, or as fragments cooled in the air, produces extrusive igneous rock.

4.2 Why Does Magma Form, and What Is It Made of?

It's Hot Inside the Earth

Where does the heat that can cause the production of magma come from? As we discussed in Chapter 1, some of the Earth's internal heat is a relict of the planet's formation. In fact, during the first 700 million years or so of its existence, the Earth was very hot, and at times may even have been largely molten. But our planet has had a long time to cool since then, and probably would have become too cool to melt at all were it not for the presence of radioactive elements. Every time a radioactive element decays, it generates new heat. The Earth produces enough radioactive heat to keep its inside quite hot.

Causes of Melting

Even though the Earth is very hot inside, the popular image that the crust floats on a sea of molten rock is wrong. The crust and the mantle of this planet are almost entirely solid. Magma forms only in special places where pre-existing solid rock undergoes melting. Below, we describe conditions that lead to melting. We'll briefly note the settings, in the context of plate tectonics,

Did you ever wonder . . .
whether Earth's crust floats on a magma sea?

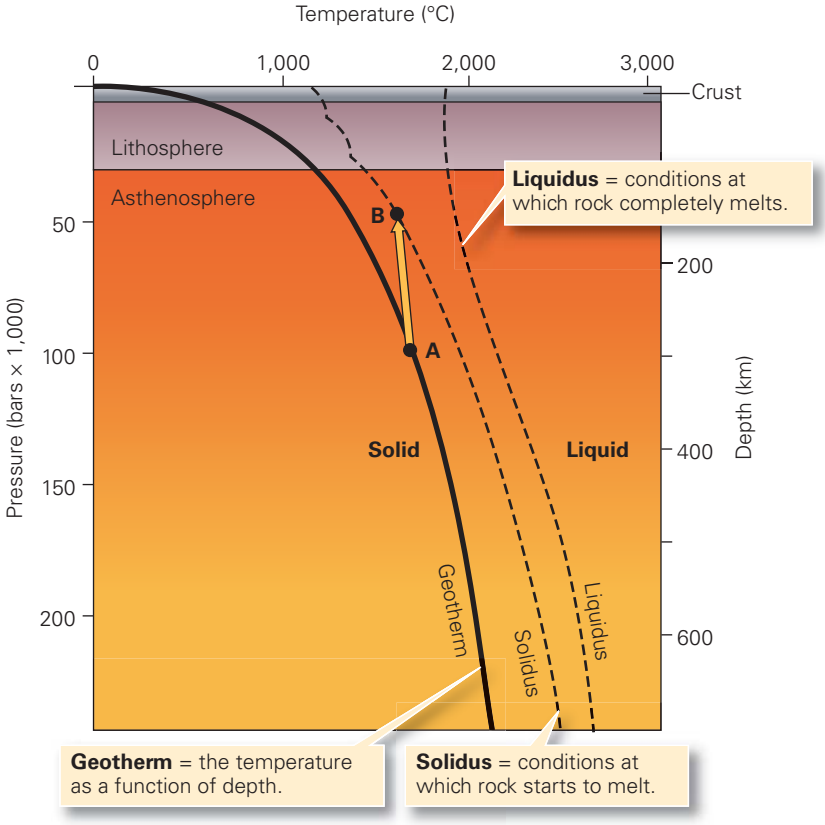
in which melting conditions develop, but will wait until the end of this chapter to characterize specific types of igneous rocks that form at these settings.

Melting due to a decrease in pressure (decompression). Beneath typical oceanic crust, temperatures comparable to those of lava occur in the upper mantle (Fig. 4.3a). But even though the upper mantle is very hot, its rock stays solid because it is also under great pressure from the weight of overlying rock, and pressure prevents atoms from breaking free of solid mineral crystals. Because pressure prevents melting, a decrease in pressure can permit melting. Thus, if the pressure affecting hot mantle rock decreases while the temperature remains unchanged, magma forms. This kind of melting, called *decompression melting*, occurs where hot mantle rock rises to shallower depths in the Earth. Such movement occurs in mantle plumes, beneath rifts, and beneath mid-ocean ridges (Fig. 4.3b).

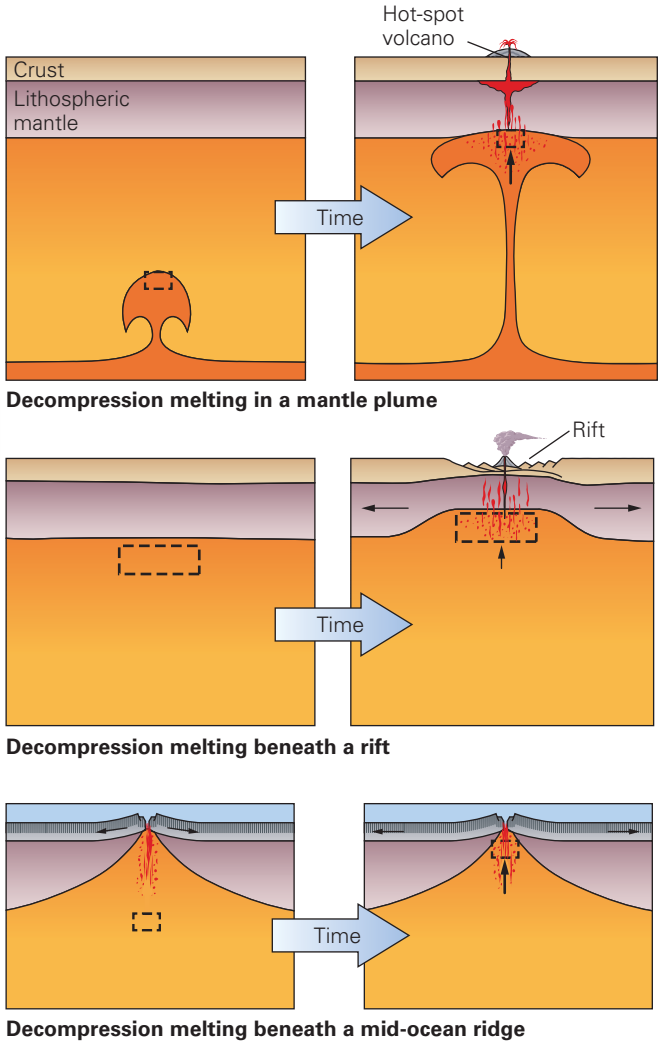
Melting as a result of the addition of volatiles. Magma also forms at locations where chemicals called volatiles mix with hot mantle rock. Volatiles, as noted in Chapter 1, are substances such as water (H_2O) and carbon dioxide (CO_2) that evaporate easily and can exist in gaseous forms at the Earth's surface. When volatiles mix with hot, dry rock, they help break chemical bonds so that the rock begins to melt (Fig. 4.4a). In effect, adding volatiles decreases a rock's melting temperature. Melting due to addition of volatiles is sometimes called *flux melting*.

Melting as a result of heat transfer from rising magma. When magma from the mantle rises up into the crust, it brings heat with it. This heat raises the temperature of the surrounding crustal rock and, in some cases, the rise in temperature may be sufficient for the crustal rock to begin melting. To picture

FIGURE 4.3 The concept of decompression melting.



(a) Decompression melting takes place when the pressure acting on hot rock decreases. As this graph of pressure and temperature conditions in the Earth shows, when rock rises from point A to point B, the pressure decreases a lot, but the rock cools only a little, so the rock begins to melt.



(b) The conditions leading to decompression melting occur in several different geologic environments. In each case, a volume of hot asthenosphere (outlined by dashed lines) rises to a shallower depth, and magma (red dots) forms.

the process, imagine injecting hot fudge into ice cream; the fudge transfers heat to the ice cream, raises its temperature, and causes it to melt (Fig. 4.4b). We call such melting *heat-transfer melting*, because it results from the transfer of heat from a hotter material to a cooler one.

The Major Types of Magma

All magmas contain silica, a compound of silicon and oxygen. But magmas also contain varying proportions of other elements such as aluminum (Al), calcium (Ca), sodium (Na), potassium (K), iron (Fe), and magnesium (Mg); each of these ions also bonds to oxygen to form a metal-oxide compound. Because magma is a liquid, its molecules do not lie in an orderly crystalline lattice but are grouped instead in clusters or short chains, relatively free to move with respect to one another.

Geologists distinguish between "dry" magmas, which contain no volatiles, and "wet" magmas, which do. In fact, wet magmas include up to 15% dissolved volatiles such as water, carbon dioxide, nitrogen (N_2), hydrogen (H_2), and sulfur dioxide (SO_2). These volatiles come out of the Earth at volcanoes in the form of gas. Usually, water constitutes about half of the gas erupting at a volcano. Thus, magma contains not only the molecules that constitute solid minerals in rocks but also the molecules that become water or air.

Magmas differ from one another in terms of the proportions of chemicals that they contain. Geologists distinguish four major compositional types depending, overall, on the proportion of silica (SiO_2) relative to other metal oxides (Table 4.1). **Mafic magma** contains a relatively high proportion of iron oxide (FeO or Fe_2O_3) and magnesium oxide (MgO) relative to silica. The "ma-" in the word stands for magnesium, and the "-fic" comes from the Latin word for iron. **Ultramafic magma** has an even higher proportion of magnesium and iron oxides, relative to silica. *Felsic magmas* have a relatively high proportion of silica, relative to magnesium and iron oxides. (Occasionally, geologists use the term "silicic" interchangeably with felsic.) *Intermediate magma* gets its name because its composition is partway between mafic and felsic.

TABLE 4.1 The Four Categories of Magma

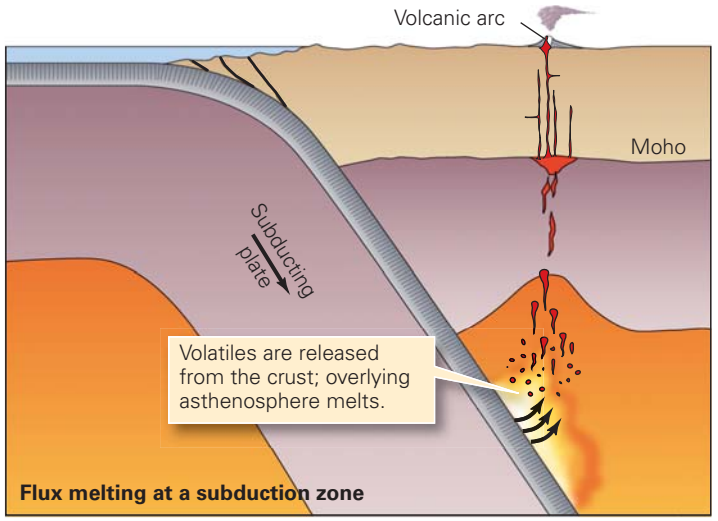
Felsic (or silicic) magma	66–76% silica*
Intermediate magma	52–66% silica
Mafic magma	45–52% silica
Ultramafic magma	38–45% silica

*The numbers provided are "weight percent," meaning the proportion of the magma's weight that consists of silica (SiO_2).

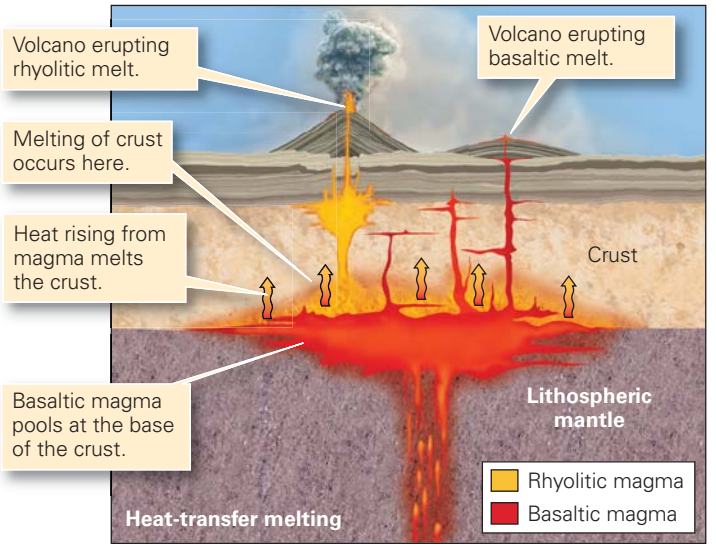
Why are there so many kinds of magma? Several factors control magma composition, including those described below.

- *Source rock composition*: The composition of a melt reflects the composition of the solid from which it was derived. Not all magmas form from the same source rock, so not all magmas have the same composition.
- *Partial melting*: Under the temperature and pressure conditions that occur in the Earth, only about 2% to 30% of an original rock can melt to produce magma at a given location—the temperature at sites of magma production simply never gets high enough to melt the entire original rock before the magma has a chance to migrate away from its source.

FIGURE 4.4 Flux melting and heat-transfer melting.



(a) Flux melting occurs where volatiles enter hot mantle; this happens at subduction zones.



(b) Heat-transfer melting occurs when rising magma brings heat up with it and melts overlying or surrounding rock. (Not to scale.)

Partial melting refers to the process by which only part of an original rock melts to produce magma (Fig. 4.5a). Magmas formed by partial melting are more felsic than the original rock from which they were derived. For example, partial melting of an ultramafic rock produces a mafic magma.

- *Assimilation*: As magma sits in a magma chamber before completely solidifying, it may incorporate chemicals dissolved from the wall rocks of the chamber or from blocks that detached from the wall and sank into the magma (Fig. 4.5b). This process is called contamination or **assimilation**.
- *Magma mixing*: Different magmas formed in different locations from different sources may enter a magma chamber. In some cases, the originally distinct magmas mix to create a new, different magma. Thoroughly mixing a felsic magma with a mafic magma in equal proportions produces an intermediate magma.

Take-Home Message

The Earth is hot inside. Even so, the crust and mantle are solid, except in special places where pre-existing solid rock undergoes melting. Melting can be triggered by a decrease in pressure, addition of volatiles, and/or injection of hot magma from deeper below. Geologists classify magma based on its composition.

4.3 Movement and Solidification of Molten Rock

If magma stayed put once it formed, new igneous rocks would not develop in or on the crust. But it doesn't stay put; magma tends to move upward, away from where it formed. In some cases, it reaches the Earth's surface and erupts at a volcano. This movement is a key component of the Earth System, because it transfers material from deeper parts of the Earth upward and provides the raw material from which new rocks and the atmosphere and ocean form. Eventually, magma freezes and transforms into a new solid rock.

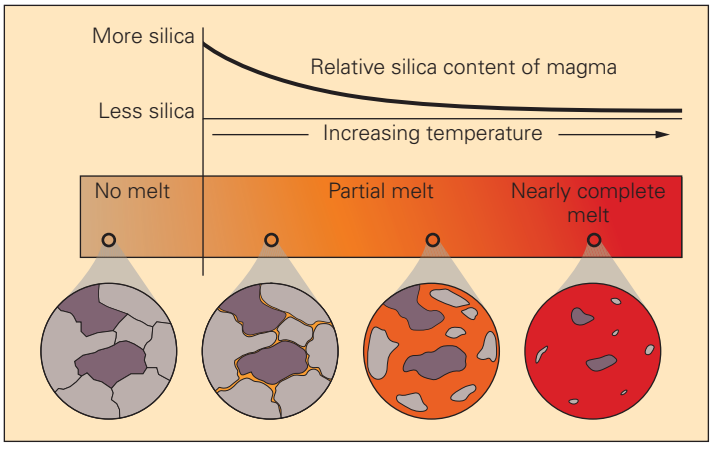
Why Does Magma Rise?

Magma rises for two reasons. First, buoyancy drives magma upward just as it drives a wooden block up through water, because magma is less dense than the surrounding rock. Second, magma rises because the weight of overlying rock creates pressure at depth that literally squeezes magma upward. The same process happens when you step into a puddle barefoot and mud squeezes up between your toes.

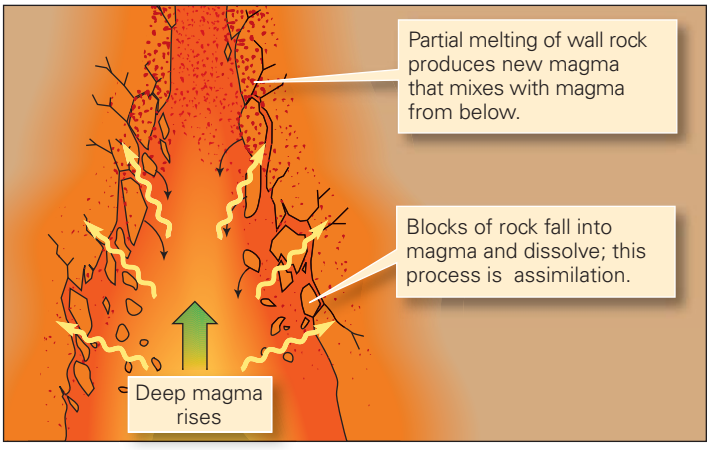
What Controls the Speed of Flow?

Viscosity, or resistance to flow, affects the speed with which magmas or lavas move. Magmas with low viscosity flow more easily than those with high viscosity, just as water flows more easily than molasses. Viscosity depends on temperature, volatile content, and silica content. Hotter magma is less viscous than cooler magma, just as hot tar is less viscous than cool tar, because thermal energy breaks bonds and allows atoms to move more easily. Similarly, magmas or lavas containing more volatiles are less viscous than dry (volatile-free) magmas, because the volatiles also tend to break apart silicate molecules and may also form gas bubbles. Mafic magmas are less viscous than felsic magmas, because silicon-oxygen tetrahedra tend to link together in magma to create long molecular chains that can't move past each

FIGURE 4.5 Phenomena that can affect the composition of magma.



(a) Partial melting: The first-formed melt will be richer in silica than the original rock. As melting continues, magma becomes increasingly mafic.



(b) Mixing and assimilation: Heat provided by deep magma partially melts wall rock; the new magma may then mix with deep magma. Also, blocks of wall rock can dissolve (assimilate) in the deep magma, and the wall rock may chemically react with the magma.

other easily, and there are more of these chains in a felsic magma than in a mafic magma. Thus, hotter mafic lavas have relatively low viscosity and flow in thin sheets over wide regions, but cooler felsic lavas are highly viscous and may clump into a dome-like mound at the volcanic vent (**Fig. 4.6a, b**).

Transforming Melt into Rock

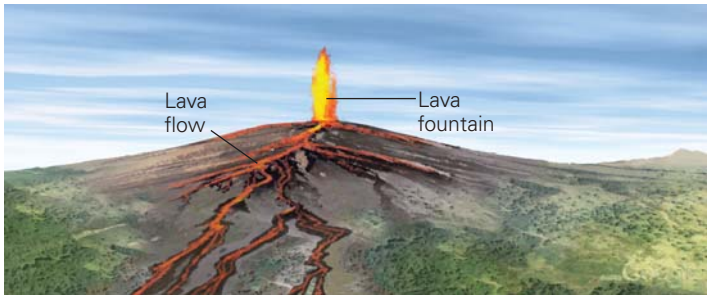
If a melt stayed at its point of origin, and nothing in its surroundings changed, it would stay molten. But melts don't last forever. Rather, they eventually solidify or "freeze." This process happens, in some cases, because volatiles escape from the melt, so that the freezing temperature rises—if the melt's temperature stays the same but its freezing temperature rises, it will solidify. Most often, however, freezing takes place simply when melt cools below its freezing temperature. Temperature decreases upward, toward the Earth's surface, so magma enters a cooler environment automatically as it rises. If it is trapped underground as an intrusion, it slowly loses heat to surrounding wall rock, drops below its freezing temperature, and solidifies. If melt extrudes as lava at the ground surface, it cools in contact with air or water.

The time it takes for a magma to cool depends on how fast it is able to transfer heat into its surroundings. To see why, think about the process of cooling coffee. If you pour hot coffee into a thermos bottle and seal it, the coffee stays hot for hours; because it's insulated, the coffee in the thermos loses heat to the air outside only very slowly. Like the thermos bottle, surrounding wall rock acts as an insulator in that it transports heat away from a magma only very slowly, so magma underground (in an intrusive environment) cools slowly. In contrast, if you spill coffee on a table, it cools quickly because it loses heat to the cold air. Similarly, lava that erupts at the ground surface cools quickly because the air or water surrounding it can conduct heat away quickly.

Three factors control the cooling time of magma that freezes below the surface in the intrusive realm.

- *The depth of intrusion*: Magma intruded deep in the crust, where it is surrounded by warm wall rock, cools more slowly than does magma intruded into cold wall rock near the ground surface.
- *The shape and size of a magma body*: Heat escapes from magma at an intrusion's surface, so the greater the surface area for a given volume of intrusion, the faster it cools. Thus, a body of magma roughly with the shape of a pancake cools faster than one with the shape of a melon. And since the ratio of surface area to volume increases as size decreases, a body of magma the size of a car cools faster than one the size of a ship (**Fig. 4.7a, b**).
- *The presence of circulating groundwater*: Water passing through magma absorbs and carries away heat, much like the coolant that flows around an automobile engine.

FIGURE 4.6 Viscosity affects lava behavior.



(a) Mafic lava has relatively low viscosity. It can erupt in fountains, move long distances, and form thin lava flows.



(b) Felsic to intermediate lava is very viscous. When it erupts, it may form a mound-like lava dome around the volcano's vent.

Changes in Magma during Cooling: Fractional Crystallization

Most people are familiar with the process of forming ice out of liquid water—cool the water to a temperature of 0°C and crystals of ice start to form. Keep the temperature cold enough for long enough and all the water becomes solid, composed entirely of one type of mineral—water ice. The process of freezing magma or lava is much more complex, because molten rock contains many different compounds, not just water, so during freezing of molten rock, many different minerals form. Further, not all of these minerals form at the same time (**Box 4.1**). To get a sense of this complexity, let's look at an example.

When a mafic magma starts to freeze, mafic (iron- and magnesium-rich) minerals such as olivine and pyroxene start to crystallize first. These solid crystals are denser than the remaining magma, so they start to sink (**Fig. 4.7c**). Some react chemically with the remaining magma as they sink, but some reach the floor of the magma chamber and become isolated from the magma. This process of sequential crystal formation and settling is called **fractional crystallization**—it progressively extracts iron and magnesium from the magma, so the remaining magma becomes more felsic. If a magma freezes completely before much fractional crystallization has occurred, the magma becomes mafic igneous rock. But freezing of a magma that has been left over after lots of fractional crystallization has occurred produces felsic igneous rock.

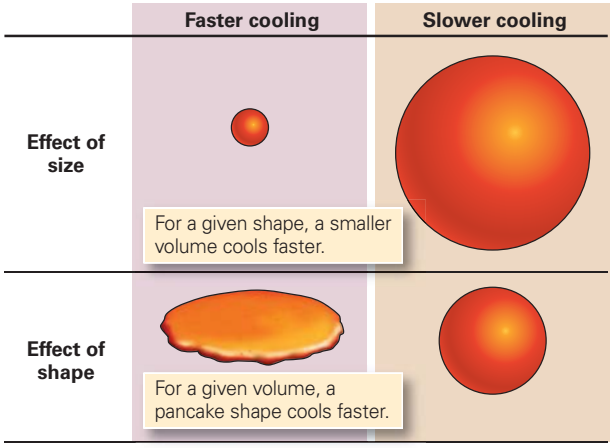
Take-Home Message

Magma rises because it's buoyant and because of pressure due to overlying rocks. The rate of melt movement is affected by viscosity, which depends on composition and temperature. When molten rock enters a cooler environment, it freezes. The rate of cooling depends on the environment and on the shape of the magma body.

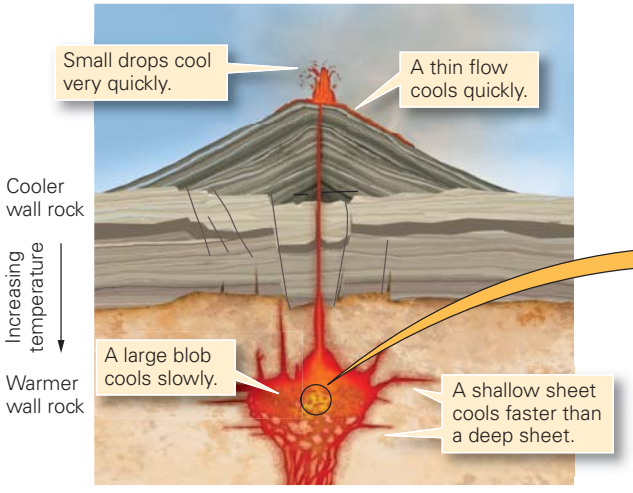
4.4 How Do Extrusive and Intrusive Environments Differ?

With a background on how melts form and freeze, we can now introduce key features of the two settings—intrusive and extrusive—in which igneous rocks form.

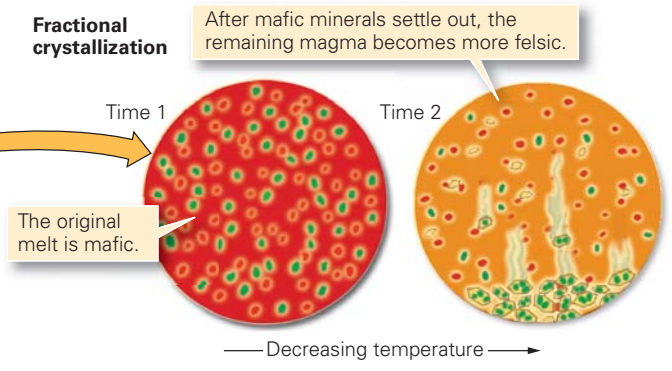
FIGURE 4.7 Factors that affect the freezing of molten rock.



(a) The larger the ratio of its surface area to volume, the faster an intrusion cools. This ratio depends on both size and shape.



(b) The cooling rate of molten rock depends on the size and shape of the magma or lava body, and on its depth.



(c) The process of fractional crystallization results in a progressive change in magma composition during freezing.

Extrusive Igneous Settings

Different volcanoes extrude molten rock in different ways. Some volcanoes erupt streams of low-viscosity lava that flood down the flanks of the volcano and then cover broad swaths of the countryside. When this lava freezes, it forms a relatively thin lava flow. Such flows may cool in days to months. In contrast, some volcanoes erupt viscous masses of lava that pile into rubbly domes. And still others erupt explosively, sending clouds of volcanic ash and debris skyward, and/or avalanches of ash tumbling down the sides of the volcano.

Which type of eruption occurs depends largely on a magma's composition and volatile content. Volatile-rich felsic lavas tend to erupt explosively and form thick ash and debris deposits (**Fig. 4.8a, b**). Mafic lavas tend to have low viscosity and spread in broad, thin flows (**Fig. 4.8c, d**). We discuss the products of extrusive eruptions in more detail in Chapter 5.

Intrusive Igneous Settings

Magma rises and intrudes into pre-existing rock by slowly percolating upward between grains and/or by forcing open cracks. The magma that doesn't make it to the surface freezes solid underground in contact with pre-existing rock and becomes intrusive igneous rock. As we noted, geologists commonly refer to the preexisting rock into which magma intrudes as wall rock. The boundary between wall rock and an intrusive igneous rock is called an intrusive contact.

Geologists distinguish among different types of intrusions on the basis of their shape. Tabular intrusions, or sheet intrusions, are planar and are of roughly uniform thickness. Most are in the range of centimeters to tens of meters thick, and tens of meters to tens of kilometers long. A **dike** is a tabular intrusion that cuts across pre-existing layering (bedding or

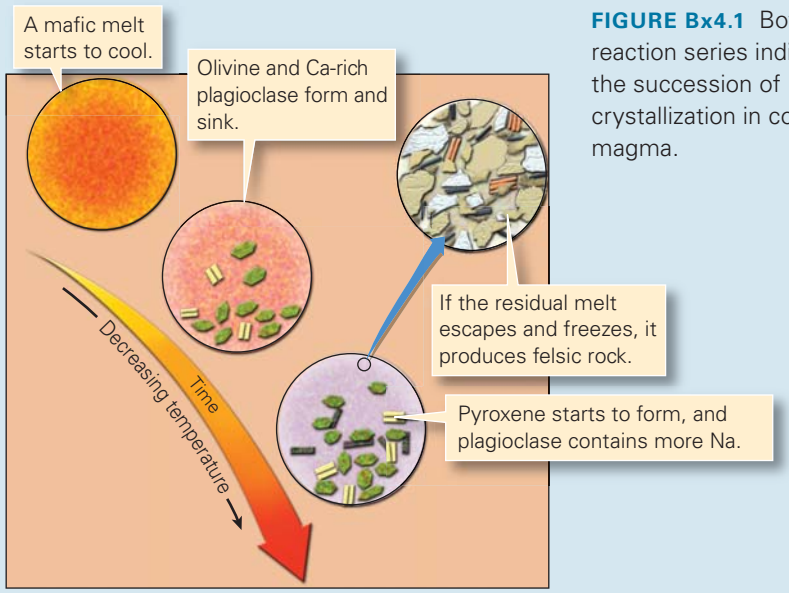
Bowen's Reaction Series

In the 1920s, the Canadian geologist Norman L. Bowen began a series of laboratory experiments designed to determine the sequence in which silicate minerals crystallize from a melt. First, Bowen melted powdered mafic igneous rock by raising its temperature to about 1280°C. Then he cooled the melt just enough to cause part of it to solidify. Finally, he "quenched" the remaining melt by submerging it quickly in cold mercury. Quenching, which means sudden cooling to form a solid, transformed any remaining liquid into glass. The glass trapped the earlier-formed crystals within it. Bowen identified mineral crystals formed before quenching with a microscope, and he analyzed the chemical composition of the remaining glass.

After experiments at different temperatures, Bowen found that, as new crystals form, they extract certain chemicals preferentially from the melt (**Fig. Bx4.1a**). Thus, the chemical composition of the remaining melt progressively changes as the melt cools. Bowen described the specific sequence of mineral-producing reactions that take place in a cooling, initially mafic, magma. This sequence is now called **Bowen's reaction series** in his honor.

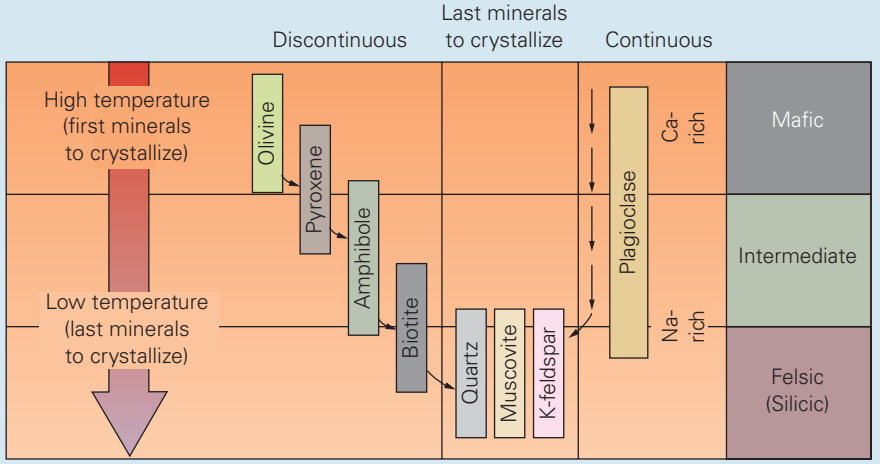
Let's examine the sequence more closely. In a cooling melt, olivine and calcium-rich plagioclase form first. This plagioclase reacts with the melt to form more, but different plagioclase; the plagioclase formed at a later stage contains more sodium (Na). Meanwhile, some olivine crystals react with the remaining melt to produce pyroxene, which may encase early olivine crystals or even replace them. However, some of the early olivine and Caplagioclase crystals settle out of the melt, taking iron, magnesium, and calcium atoms with them. By this process, the remaining melt becomes progressively enriched in silica. As the melt continues to cool, plagioclase continues to form, with later-formed plagioclase having progressively more sodium than earlier-formed plagioclase. Pyroxene crystals react with melt to form amphibole, and then amphibole reacts with the remaining melt to form biotite. All the while, crystals continue to settle out, so the remaining melt continues to become more felsic. At temperatures of between 650°C and 850°C, only about 10% melt remains, and this melt has a high silica content. At this stage, the final melt freezes, yielding quartz, K-feldspar (orthoclase), and muscovite.

On the basis of his observations, Bowen realized that there are two tracks to the reaction series. The "discontinuous" reaction series refers to the sequence olivine, pyroxene, amphibole, biotite, K-feldspar-muscovite-quartz in that each step yields a different class of silicate mineral. The "continuous" reaction series refers to the progressive change from calcium-rich to Na-rich plagioclase: the steps yield different versions of the same mineral (**Fig. Bx4.1b**). It's important to note that not all minerals listed in the series appear in all igneous rock. For example, a mafic magma may completely crystallize before felsic minerals such as quartz or K-feldspar have a chance to form.



(a) With decreasing temperature, fractional crystallization begins and the composition of the remaining magma becomes more felsic.

FIGURE Bx4.1 Bowen's reaction series indicates the succession of crystallization in cooling magma.



(b) This chart displays the discontinuous and continuous reaction series. Rocks formed from minerals at the top of the series are mafic, whereas rocks formed from the bottom of the series are felsic.

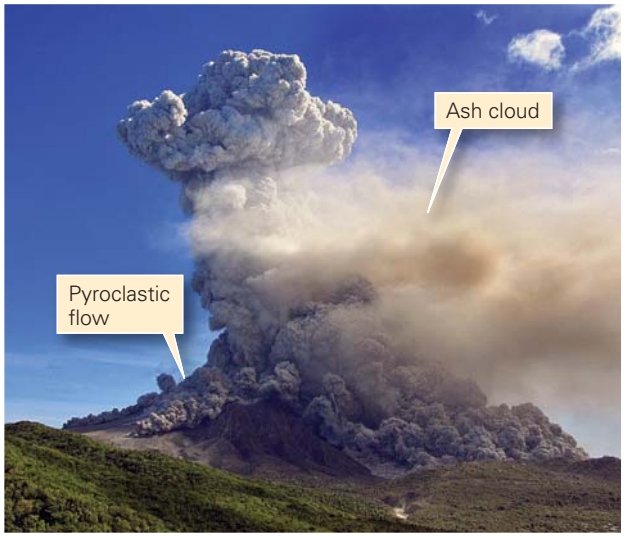
foliation), whereas a **sill** is a tabular intrusion that injects parallel to layering (Fig. 4.9a–d). In places where tabular intrusions cut across rock that does not have layering, a nearly vertical, wall-like tabular intrusion is called a dike, and a nearly horizontal, tabletop-shaped tabular intrusion is called a sill. Some intrusions start to inject between layers but then dome upward, creating a blister-shaped intrusion known as a **laccolith**.

Plutons are blob-shaped intrusions that range in size from tens of meters across to tens of kilometers across (Fig. 4.10a–e). The intrusion of numerous plutons in a region creates a vast composite body that may be several hundred kilometers long and over 100 km wide; such immense masses of igneous rock are called **batholiths**. The rock making up the Sierra Nevada of California is a batholith formed from plutons that intruded between 145 and 80 million years ago.

Where does the space for intrusions come from? Dikes form in regions where the crust is being stretched horizontally, such as in a rift. Thus, as the magma that makes a dike forces its way up into a crack, the crust opens up sideways (Fig. 4.11a). Intrusion of sills occurs near the surface of the Earth, so the pressure of the magma effectively pushes up the rock above the sill, leading to uplift of the Earth's surface (Fig. 4.11b).

How does the space for a pluton develop? Some geologists propose that a pluton is a frozen "diapir," meaning a light-bulb-shaped blob of magma that pierced overlying rock and pushed it aside as it rose (Fig. 4.11c). Another explanation involves **stoping**, a process during which magma assimilates wall rock, and blocks of wall rock break off and sink into the magma (Fig. 4.11d). If a stoped block does not

FIGURE 4.8 Examples of eruptions and extrusive materials.



(a) This volcanic explosion produced two styles of ash eruption.



(b) Thick layers of tuff deposited by explosive eruptions in New Mexico, about 1.14 Ma. Note the highway, for scale.



(c) This volcano is producing lava flows and fountains.



(d) A stack of over 50 thin lava flows, capped by pyroclastic debris, visible from inside Mt. Vesuvius, Italy.

FIGURE 4.9 Igneous sills and dikes, examples of tabular intrusions.

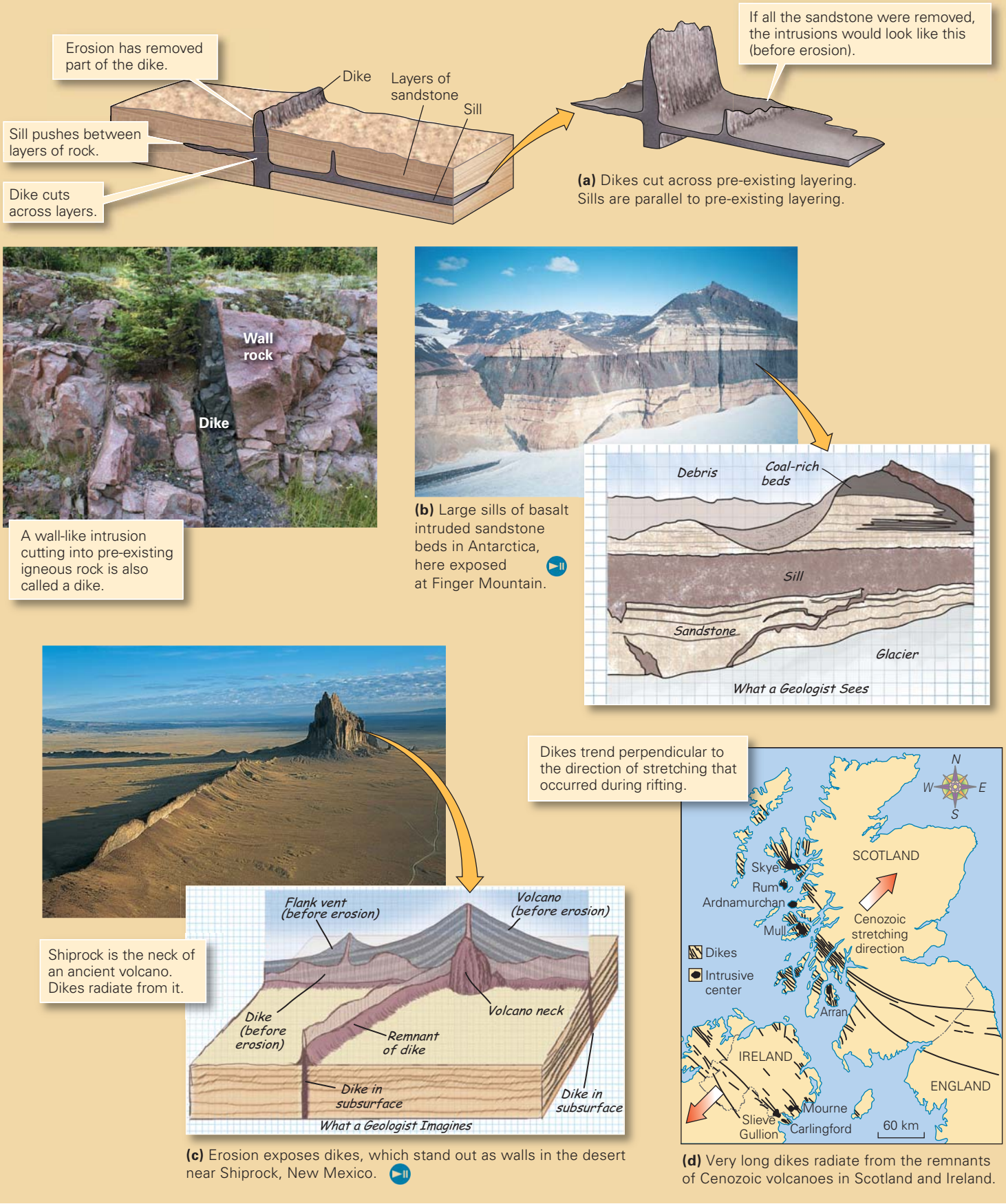
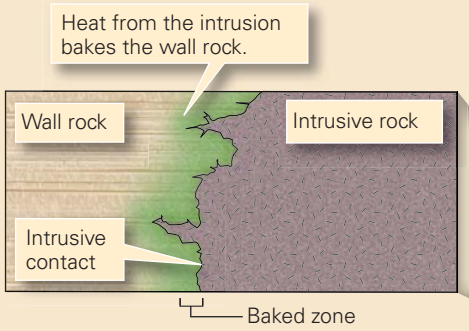
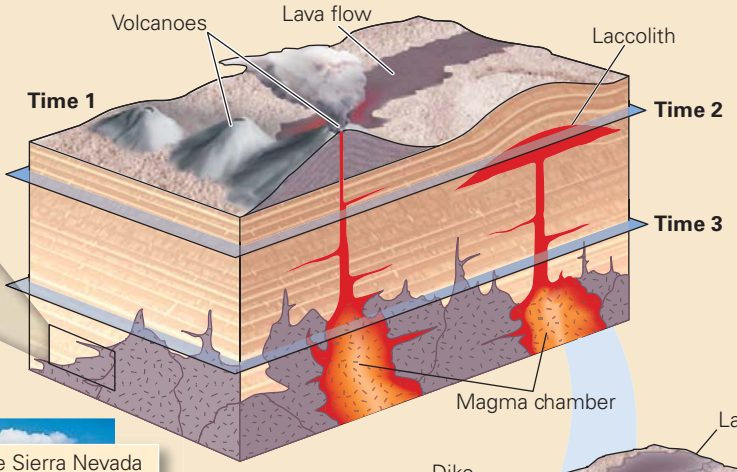
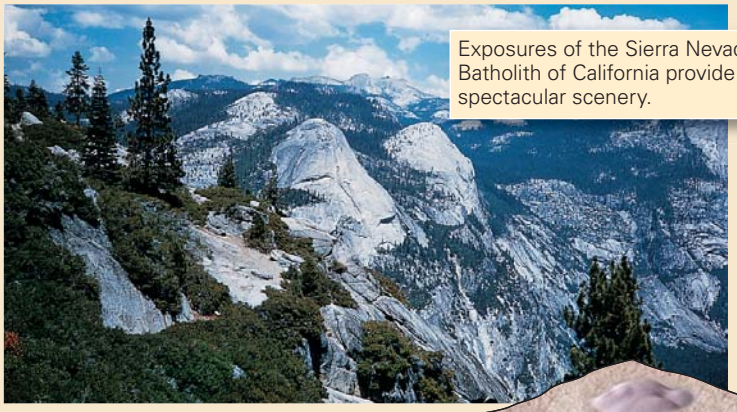


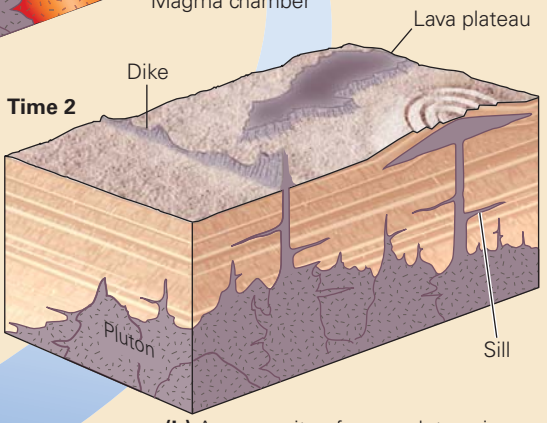
FIGURE 4.10 Igneous plutons, "blob-shaped" intrusions.



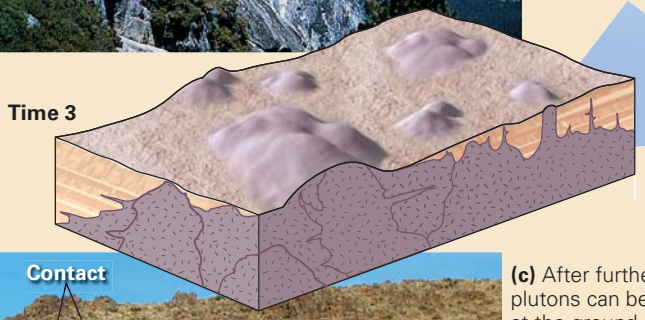
(a) Plutons form when volumes of magma cool slowly at depth. Molten rock that reaches the surface erupts as lava.

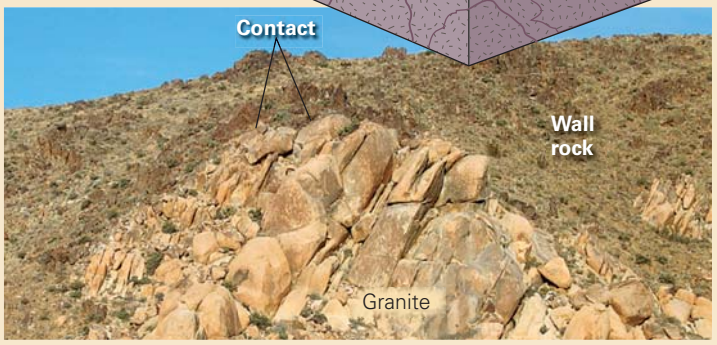




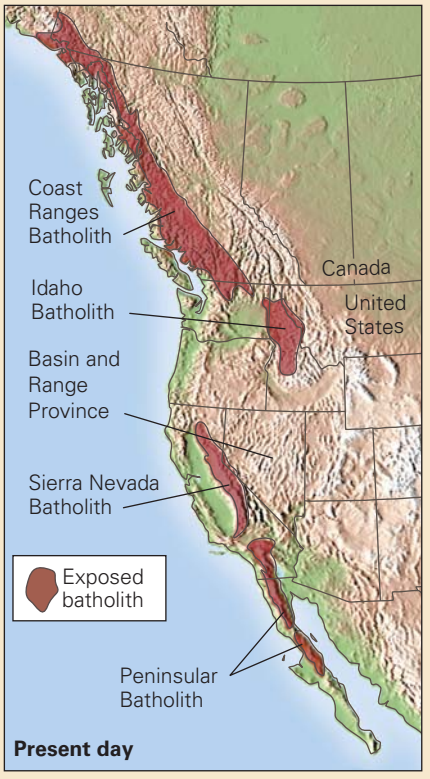


(b) A composite of many plutons is a batholith. As erosion progresses, dikes, sills, and laccoliths are exposed.





(c) After further erosion, plutons can be exposed at the ground surface. This example from the Mojave Desert shows the top of a pluton.

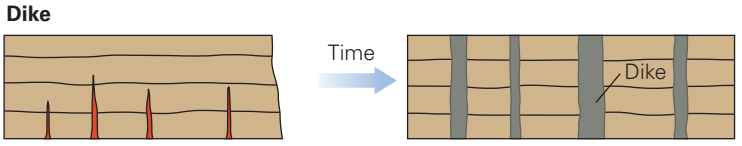


(d) Huge batholiths formed during the Mesozoic Era in western North America.

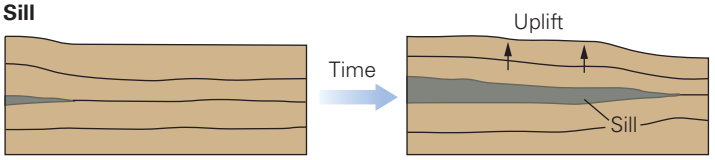


(e) The light-colored rock of the Torres del Paines in Chile is an intrusion of granite. The granite formed when melt froze deep in the crust. It has been exposed due to mountain building and erosion. A remnant of the roof above the pluton still exists.

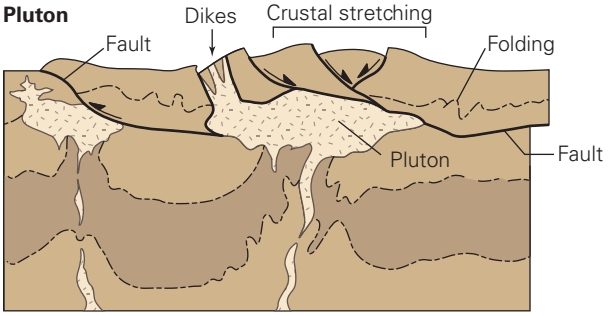
FIGURE 4.11 Making room for an igneous intrusion.



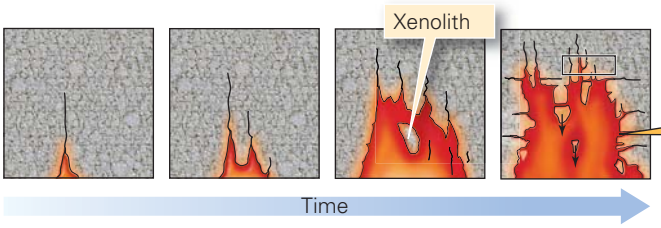
(a) Dikes fill space formed when crust undergoes horizontal stretching.



(b) Sills intrude between layers and may cause the uplift of the land surface.



(c) The magma comprising a pluton may rise as a buoyant blob, filling space produced by crustal stretching.



(d) Plutons may intrude by stoping. When blocks of wall rock fall into the magma, some dissolve but others may remain as xenoliths.



melt entirely, but rather becomes surrounded by new igneous rock, it is a **xenolith**, after the Greek word *xeno*, meaning foreign. More recently, geologists have proposed that plutons form by injection of numerous superimposed dikes or sills, which coalesce and recrystallize to become a single, massive body.

Take-Home Message

Molten rock can extrude either as a lava flow or as pyroclastic debris. Intrusions underground juxtapose igneous rock with wall rock. Tabular intrusions (sills and dikes) are wall-like intrusions. Blob-shaped intrusions are plutons. Huge batholiths consist of many plutons.

4.5 How Do You Describe an Igneous Rock?

Characterizing Color and Texture

If you wander around a city admiring building facades, you'll find that many facades consist of igneous rock, for such rocks tend to be very durable. If you had to describe one of these rocks to a friend, what words might you use? You would probably start by noting the rock's color. Overall, is the rock dark or light? More specifically, is it gray, pink, white, or black? Describing color may not be easy, because some igneous rocks contain many visible mineral grains, each with a different color; but even so, you'll probably be able to characterize the overall hue of the rock. Generally, the color reflects the rock's composition, but it isn't always so simple, because color may also be influenced by grain size and by the presence of trace amounts of impurities. (For example, the presence of a small amount of iron oxide gives rock a reddish tint.) Next, you would probably characterize the rock's texture. A description of igneous texture indicates whether the rock consists of glass, crystals, or fragments. If the rock consists of crystals or fragments, a description of texture also specifies the grain size. Here are the common terms for defining texture:

- *Crystalline texture*: Rocks that consist of minerals that grow when a melt solidifies interlock like pieces of a jigsaw puzzle (Fig. 4.12a). Rocks with such a texture are called **crystalline igneous rocks**. The interlocking of crystals in these rocks occurs because once some grains have developed, they interfere with the growth of later-formed grains. The last grains to form end up filling irregular spaces between already existing grains. Geologists distinguish subcategories of crystalline igneous rocks according to the size of the crystals. Coarse-grained (phaneritic) rocks have crystals large enough to be identified

with the naked eye. Fine-grained (aphanitic) rocks have crystals too small to be identified with the naked eye. Porphyritic rocks have larger crystals surrounded by a mass of fine crystals. In a porphyritic rock, the larger crystals are called phenocrysts, while the mass of finer crystals is called groundmass.

- *Fragmental texture*: Rocks consisting of igneous chunks and/or shards that are packed together, welded together, or cemented together after having solidified are **fragmental igneous rocks** (Fig. 4.12a).
- *Glassy texture*: Rocks made of a solid mass of glass, or of tiny crystals surrounded by glass, are **glassy igneous rocks** (Fig. 4.12a). Glassy rocks fracture conchoidally (Fig. 4.12b).

What factors control the texture of igneous rocks? In the case of nonfragmental rocks, *texture largely reflects cooling rate*. The presence of glass indicates that cooling happened so quickly that the atoms within a lava didn't have time to arrange into crystal lattices. Crystalline rocks form when a melt cools more slowly. In crystalline rocks, grain size depends on cooling time. A melt that cools rapidly, but not rapidly enough to make glass, forms fine-grained rock, because many crystals form but none has time to grow large (Fig. 4.12c). A melt that cools very slowly forms a coarse-grained rock, because a few crystals have time to grow large.

Because of the relationship between cooling rate and texture, lava flows, dikes, and sills tend to be composed of fine-grained igneous rock. In contrast, plutons tend to be composed of coarse-grained rock. Plutons that intrude into hot wall rock at great depth cool very slowly and thus tend to have larger crystals than plutons that intrude into cool country rock at shallow depth, where they cool relatively rapidly. Porphyritic rocks form when a melt cools in two stages. First, the melt cools slowly at depth, so that phenocrysts form. Then, the melt erupts and the remainder cools quickly, so that groundmass crystallizes around the phenocrysts.

There is, however, an exception to the standard cooling rate and grain size relationship. A very coarse-grained igneous rock called **pegmatite** doesn't necessarily cool slowly. Pegmatite contains crystals up to tens of centimeters across and occurs in dikes. Because pegmatite occurs in dikes, which generally cool quickly, the coarseness of the rock may seem surprising. Researchers have shown that pegmatites are coarse because they form from water-rich melts in which atoms can move around so rapidly that large crystals can grow very quickly.

Classifying Igneous Rocks

Because melts can have a variety of compositions and can freeze to form igneous rocks in many different environments above and below the surface of the Earth, we observe a wide spectrum of igneous rock types. We classify these according to their texture and composition. Studying a rock's texture tells us about the rate at which it cooled, as we've seen, and therefore the environment in which it formed (see **Geology at a Glance**, p. 112). Studying its composition tells us about the original source of the magma and the way in which the magma evolved before finally solidifying. Below, we introduce some of the more important igneous rock types.

Crystalline igneous rocks. The scheme for classifying the principal types of crystalline igneous rocks is quite simple. The different compositional classes are distinguished on the basis of silica content—ultramafic, mafic, intermediate, or felsic—whereas the different textural classes are distinguished according to whether the grains are coarse or fine. The chart in **Figure 4.13** gives the texture and composition of the most commonly used crystalline igneous rock names. As a rough guide, the color of an igneous rock reflects its composition: mafic rocks tend to be black or dark gray, intermediate rocks tend to be lighter gray or greenish gray, and felsic rocks tend to be light tan to pink or maroon. Figure 4.12 provides images of some of these rocks.

Note that, according to Figure 4.13, rhyolite and granite have the same chemical composition but differ in grain size. Which of these two rocks develops from a melt of felsic composition depends on the cooling rate. A felsic lava that solidifies quickly at the Earth's surface or in a thin dike or sill turns into fine-grained rhyolite; but the same magma, if solidifying slowly at depth in a pluton, turns into coarse-grained granite. A similar situation holds for mafic lavas—a mafic lava that cools quickly in a lava flow forms basalt, but a mafic magma that cools slowly forms gabbro.

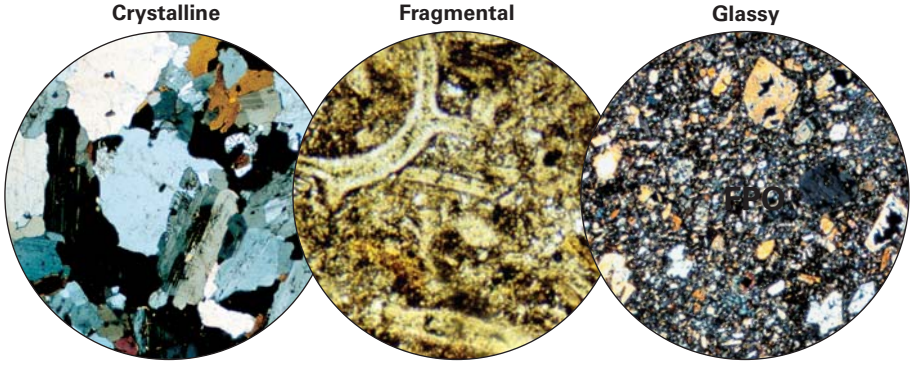
Glassy igneous rocks. Glassy texture develops more commonly in felsic igneous rocks because the high concentration of silica inhibits the easy growth of crystals. But basaltic and intermediate lavas can form glass if they cool rapidly enough. In some cases, a rapidly cooling lava freezes while it still contains a high concentration of gas bubbles—these bubbles remain as open holes known as **vesicles**. Geologists distinguish among several different kinds of glassy rocks.

- **Obsidian** is a mass of solid, felsic glass. It tends to be black or brown (Fig. 4.12b). Because it breaks conchoidally, sharp-edged pieces split off its surface when you hit a sample with a hammer. Preindustrial people worldwide used such pieces for arrowheads, scrapers, and knife blades.

Did you ever wonder . . .
how black glass once used for arrowheads formed?

- **Pumice** is a felsic volcanic rock that contains abundant vesicles, giving it the appearance of a sponge. Pumice forms by the quick cooling of frothy lava that resembles the head of foam in a glass of beer. In some cases, pumice contains so many air-filled pores that it can actually float on water, like styrofoam (Fig. 4.14).

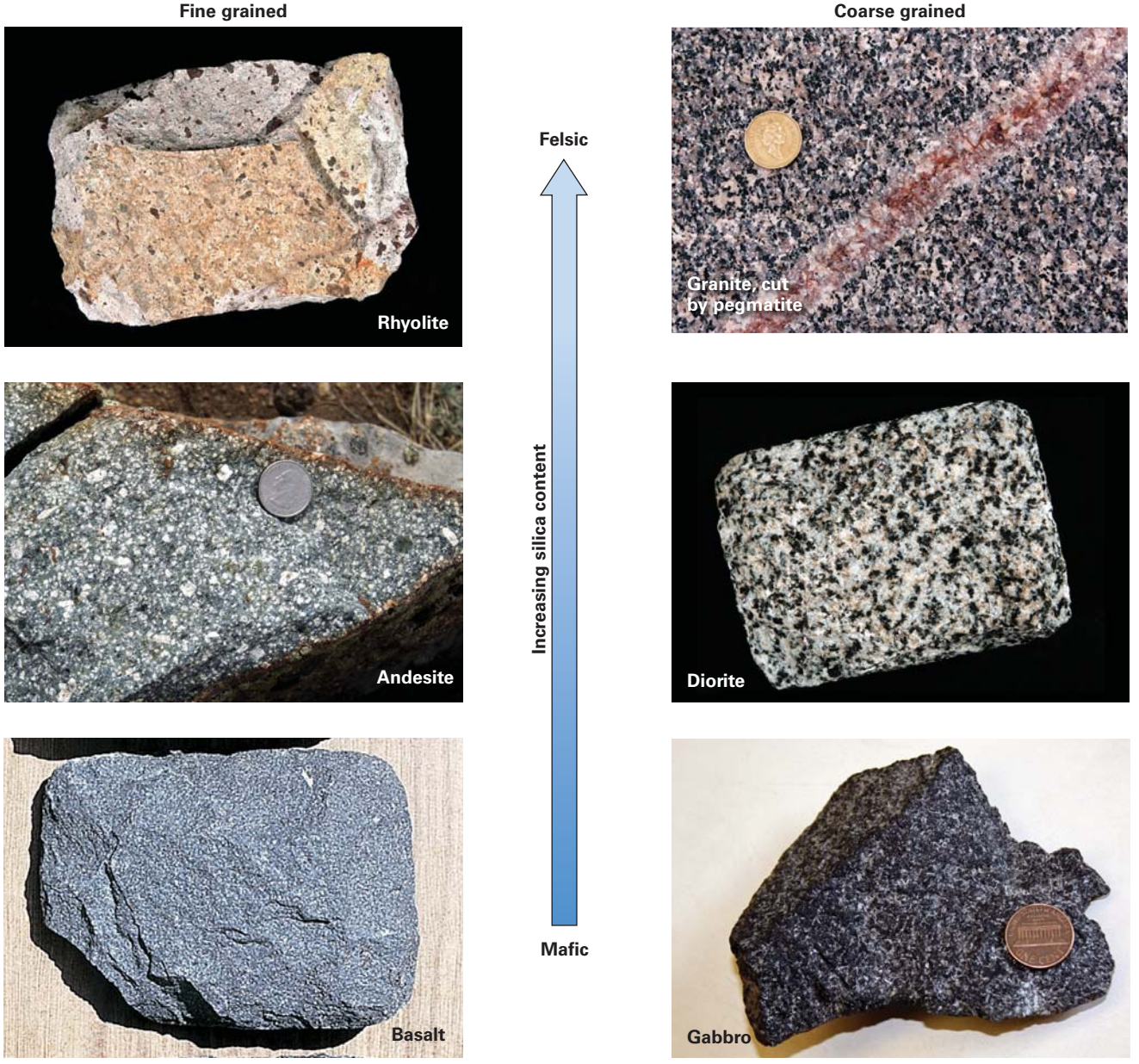
FIGURE 4.12 Textures and types of igneous rocks.



(a) Photomicrographs of thin sections reveal the different textures of igneous rocks.



(b) Obsidian fractures conchoidally.



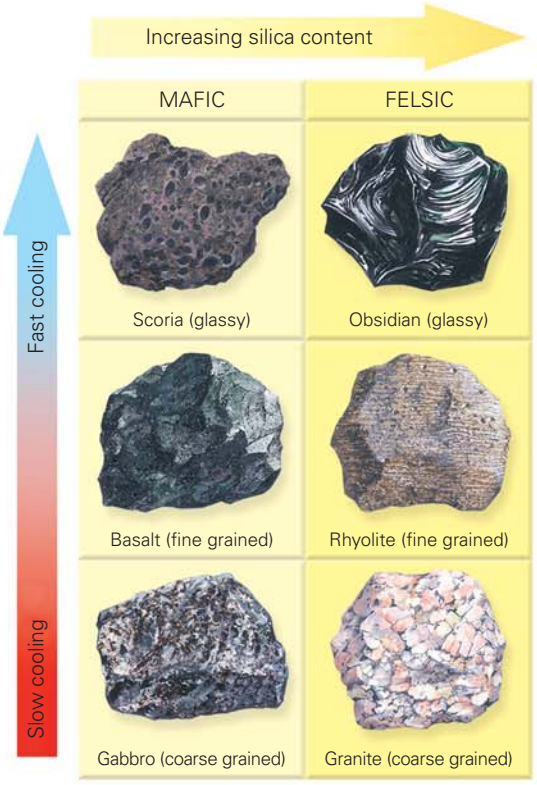
(c) Examples of igneous rocks, arranged by grain size and composition. Different environments yield different rock types.

Formation of Igneous Rocks

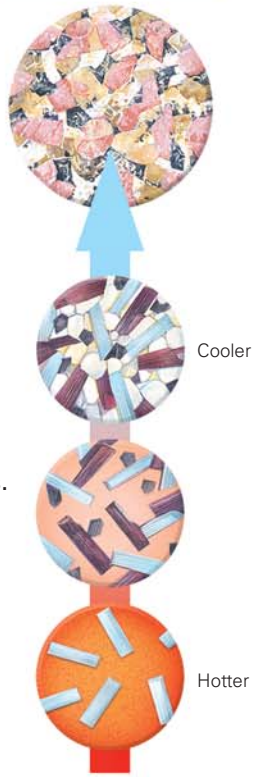
Igneous rock forms by the cooling of magma underground, or of lava at the surface. Igneous rocks that solidify underground are intrusive, whereas those that solidify at the surface are extrusive. The type of igneous rock that forms depends on the composition of the melt and the environment of cooling.

In the extrusive environment, melt may cool quickly and have a glassy texture. Melt that explodes into the air forms ash and other debris with fragmental texture.

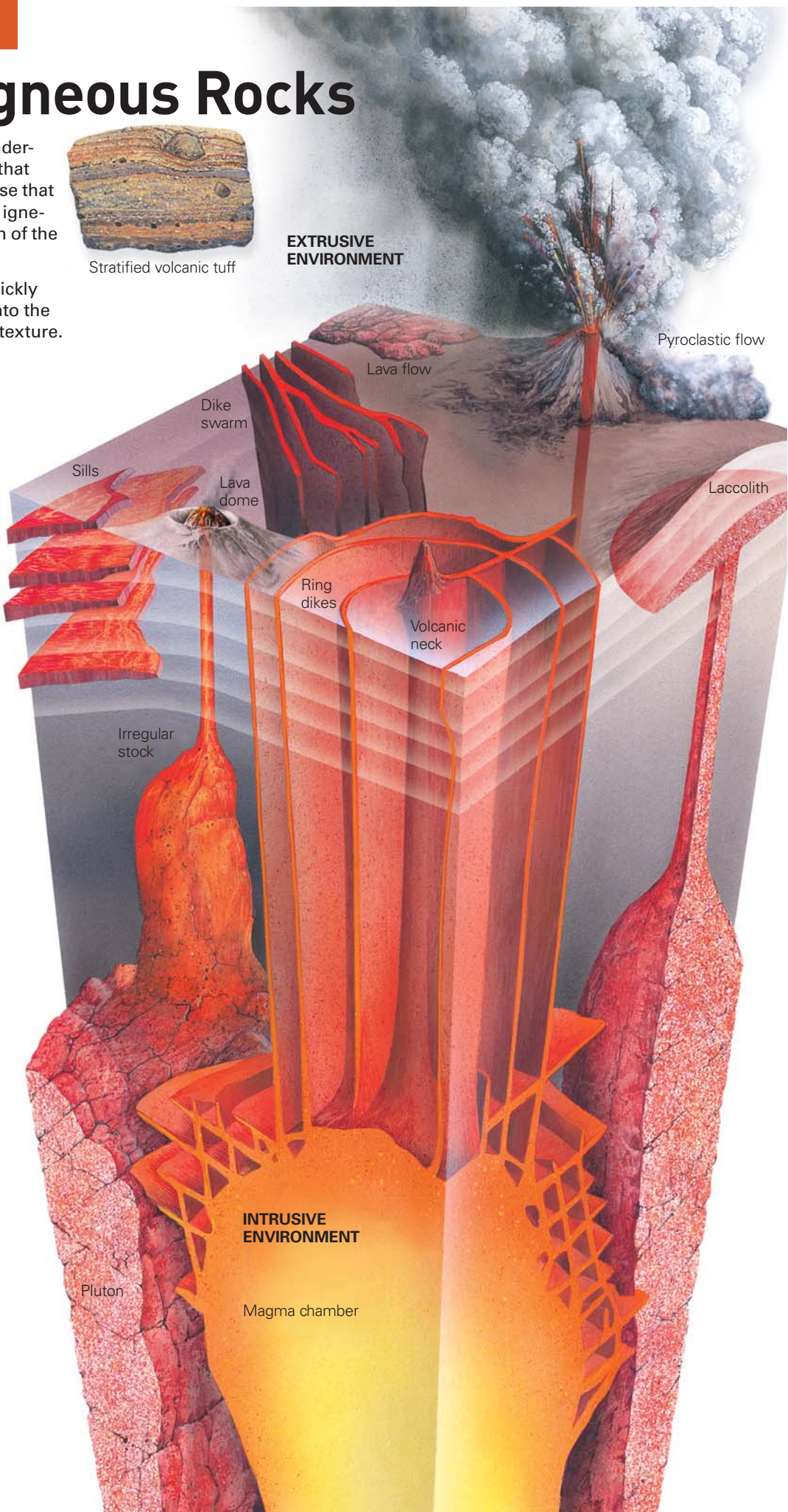
Stratified volcanic tuff



In the intrusive environment, crystals grow together to form an interlocking texture. Slower cooling makes coarser grains.



Minerals in an igneous rock crystallize in succession as the melt cools.



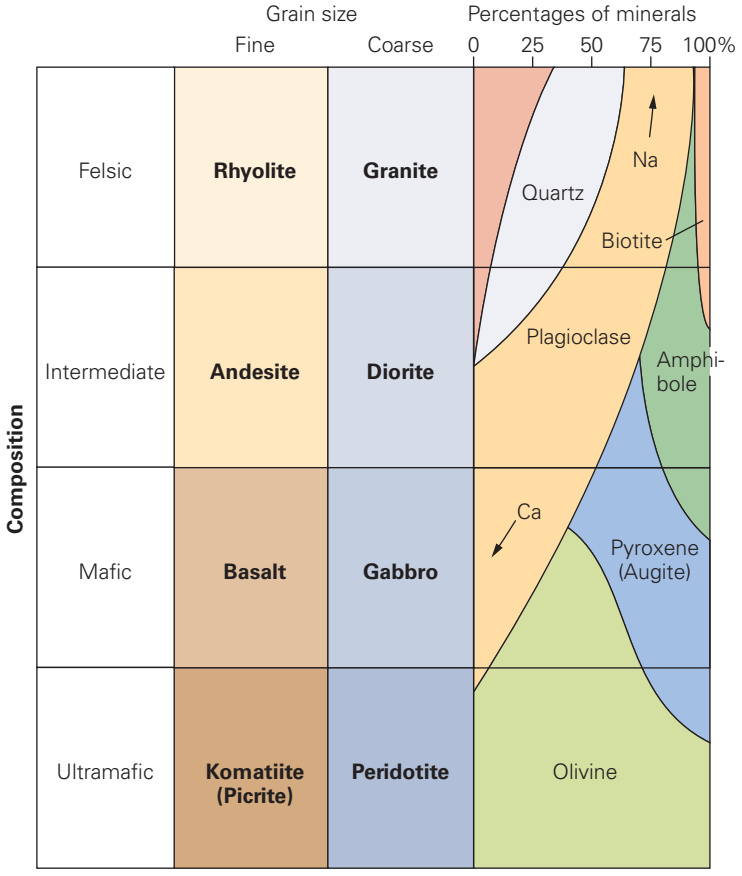


FIGURE 4.13 Igneous rocks are classified based on composition and texture.

FIGURE 4.14 Pumice, a vesicle-filled volcanic rock, is so light that paper can hold it up. The vesicles it contains tend to be small.



- **Scoria** is a mafic volcanic rock that contains abundant vesicles (more than about 30%). Generally, the bubbles in scoria are bigger than those in pumice, and the rock, overall, looks darker.

Pyroclastic igneous rocks. As we have noted, when volcanoes erupt explosively, they spew out fragments of lava. Geologists refer to all such fragments as pyroclasts. Accumulations of fragmental volcanic debris are called pyroclastic deposits, and when the material in these deposits consolidates into a solid mass, due either to welding together of still-hot clasts or to cementation by minerals precipitating from water passing through, it becomes a **pyroclastic rock**. Geologists distinguish among several types of pyroclastic rocks based on grain size. Let's consider two examples.

- **Tuff** is a fine-grained pyroclastic igneous rock composed of volcanic ash. It may contain fragments of pumice.
- **Volcanic breccia** consists of larger fragments of volcanic debris that either fall through the air and accumulate, or form when a lava flow breaks into pieces.

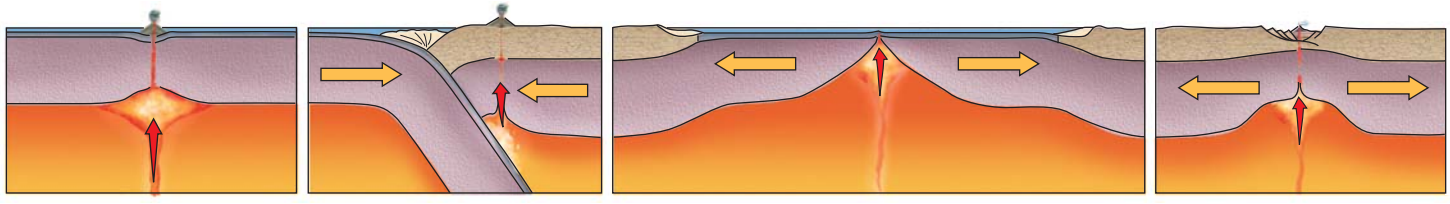
Take-Home Message

Igneous rocks come in a variety of colors; mafic rocks tend to be darker than felsic rocks. Textures of igneous rock vary from glassy, to fine-grained, to coarse-grained. Geologists classify and assign names to igneous rocks based on texture and composition.

4.6 Plate-Tectonic Context of Igneous Activity

Earlier in this chapter, we pointed out that melting occurs only in special locations where conditions lead to decompression, addition of volatiles, and/or heat transfer. The conditions that lead to melting and, therefore, to igneous activity, can develop in four geologic settings (Fig. 4.15): (1) along volcanic arcs bordering oceanic trenches; (2) at hot spots; (3) within continental rifts; (4) along mid-ocean ridges. Let's look more carefully at melting and igneous rock production at these

FIGURE 4.15 The tectonic setting of igneous rocks.



settings, in the context of plate-tectonics theory, with a focus on the types of igneous rocks that may form in each setting. In Chapter 5, we'll add to the story by discussing the types of eruptions associated with different settings.

Products of Subduction

A chain of volcanoes, called a **volcanic arc** (or just an arc), forms on the overriding plate, adjacent to the deep-ocean trenches that mark convergent plate boundaries (see Chapter 2). The word "arc" emphasizes that many of these chains define a curve on a map. *Continental arcs*, such as the Andean arc of South America and the Cascade arc in the northwestern United States, grow along the edge of a continent, where oceanic lithosphere subducts beneath continental lithosphere. *Island arcs*, such as the Aleutian arc of Alaska and the Mariana arc of the western Pacific, protrude from the ocean at localities where one oceanic plate subducts beneath another. Beneath volcanic arcs, a variety of intrusions—plutons, dikes, and sills—develop, to be exposed only later, when erosion has removed the volcanic overburden. In some localities, arc-related igneous activity produces huge batholiths.

How does subduction trigger melting? Some minerals in oceanic crust rocks contain volatile compounds (mostly water). At shallow depths, volatiles are chemically bonded to the minerals. But when subduction carries crust down into the hot asthenosphere, "wet" crustal rocks warm up. At a depth of about 150 km, crust becomes so hot that volatiles separate from crustal minerals and diffuse up into the overlying asthenosphere. Addition of volatiles causes the hot ultramafic rock in the asthenosphere to undergo partial melting, a process that yields mafic magma. This magma either rises directly, to erupt as basaltic lava, or undergoes fractional crystallization before erupting and evolves into intermediate or felsic lava.

In continental volcanic arcs, not all the mantle-derived basaltic magma rises directly to the surface; some gets trapped at the base of the continental crust, and some in magma chambers deep in the crust. When this happens, heat transfers into the continental crust and causes partial melting of this crust. Because much of the continental crust is mafic to intermediate in composition to start with, the resulting magmas are intermediate to felsic in composition. This magma rises, leaving the basalt behind, and either cools higher in the crust to form plutons or rises to the surface and erupts. For this reason, granitic plutons and andesite lavas form at continental arcs.

Products of Hot Spots

As we learned in Chapter 2, most researchers think that **hot-spot volcanoes** form above plumes of hot mantle rock from deep in the mantle, though some studies suggest that some hot spots may originate due to other processes happening at shallower depths. According to the plume hypothesis, a column, or "plume" of very hot rock rises like soft plastic up through the overlying mantle beneath a hot spot. (Note that a plume does *not* consist of magma; it is solid, though relatively soft and able to flow.) When the hot rock of a plume reaches the base of the lithosphere, decompression causes it to undergo partial melting, a process that generates mafic magma. The mafic magma then rises through the lithosphere, pools in a magma chamber in the crust, and eventually erupts at the surface, forming a volcano. In the case of oceanic hot spots, mostly mafic magma erupts. In the case of continental hot spots, some of the mafic magma erupts to form basalt; but some transfers heat to the continental crust, which then partially melts itself, producing felsic magmas that erupt to form rhyolite.

Large Igneous Provinces (LIPs)

In many places on Earth, particularly voluminous quantities of mafic magma have erupted and/or intruded (**Fig. 4.16**). Some of these regions occur along the margins of continents, some in the interior of oceanic plates, and some in the interior of continents. The largest of these, the Ontong Java Oceanic Plateau of the western Pacific, covers an area of about 5,000,000 km^2 of the sea floor and has a volume of about 50,000,000 km^3. Such provinces also occur on land. It's no surprise that these huge volumes of igneous rock are called **large igneous provinces** (**LIPs**). More recently, this term LIP has been applied to huge eruptions of felsic ash too.

Mafic LIPs may form when the bulbous head of a mantle plume first reaches the base of the lithosphere. More partial melting can occur in a plume head than in normal asthenosphere, because temperatures are higher in a plume head. Thus, an unusually large quantity of unusually hot basaltic magma forms in the plume head; when the magma reaches the surface, huge quantities of basaltic lava spew out of the ground. If the plume head lies beneath a rift, added decompression can lead to even more melting (**Fig. 4.17a**). The particularly hot basaltic lava that erupts at such localities has such low viscosity that it can flow tens to hundreds of kilometers across the landscape. Geoscientists refer to such flows as **flood basalts**. Flood basalts make up the bedrock of the Columbia River Plateau in Oregon and Washington (**Fig. 4.17b, c**), the Paraná Plateau in southeastern Brazil, the Karoo region of southern Africa, and the Deccan region of southwestern India.

Igneous Rocks at Rifts

Successful rifting splits a continent in two and gives birth to a new mid-ocean ridge. As the continental lithosphere thins during rifting, the weight of rock overlying the asthenosphere decreases, so pressure in the asthenosphere decreases and decompression melting produces basaltic magma, which rises into the crust. Some of this magma makes it to the surface and erupts as basalt. However, some of the magma gets trapped in the crust and transfers heat to the crust. The resulting partial melting of the crust yields felsic (silicic) magmas that erupt as rhyolite.

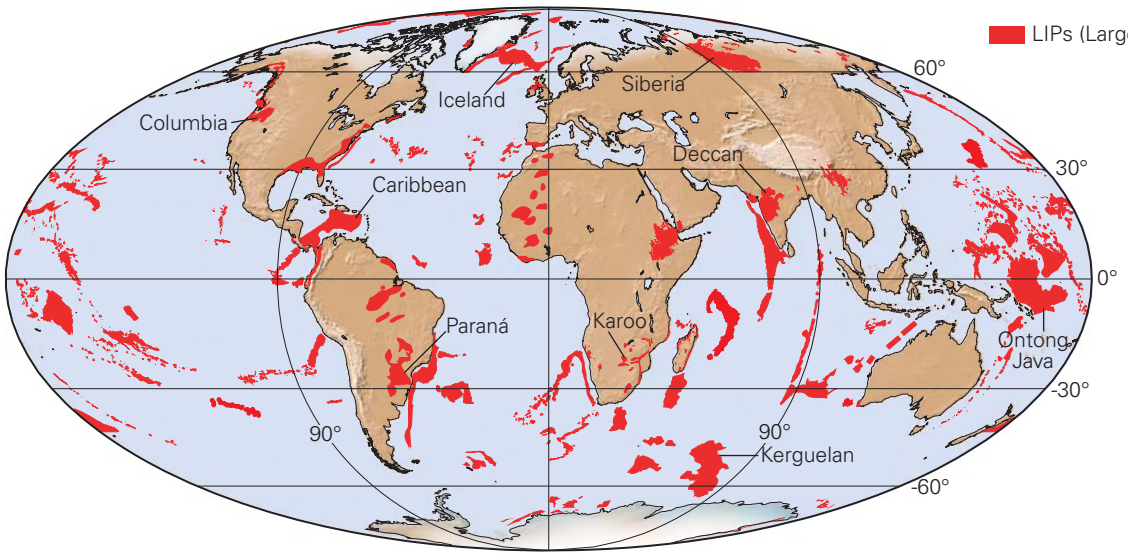


FIGURE 4.16 A map showing the distribution of large igneous provinces (LIPs) on Earth. The red areas are or once were underlain by immense volumes of basalt; not all of this basalt is exposed.

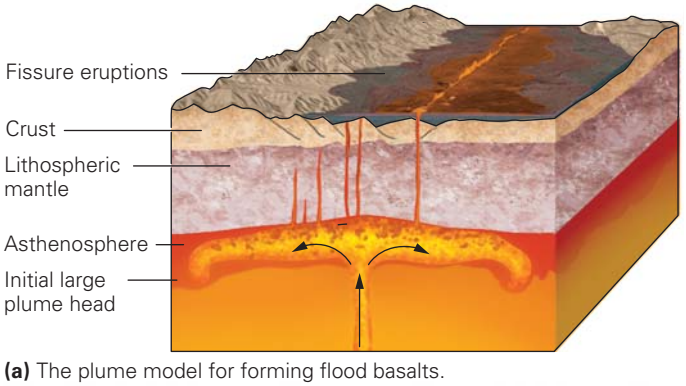
Thus, a sequence of volcanic rocks in a rift generally includes basaltic flows and sheets of rhyolitic lava or ash. Locally, the felsic and mafic magmas mix to form intermediate magma.

Forming Igneous Rocks at Mid-Ocean Ridges

Most igneous rocks at the Earth's surface form at mid-ocean ridges, that is, along divergent plate boundaries. Think about it—the entire oceanic crust, a 7- to 10-km-thick layer of basalt and gabbro that covers 70% of the Earth's surface, forms at mid-ocean ridges. And this entire volume gets subducted and replaced by new crust, over a period of about 200 million years.

Igneous magmas form at mid-ocean ridges for much the same reason they do at hot spots and rifts. As sea-floor spreading occurs and oceanic lithosphere plates drift away from the ridge, hot asthenosphere rises to keep the resulting space filled. As this asthenosphere rises, it undergoes decompression, which leads to partial melting and the generation of basaltic magma. As noted in Chapter 2, this magma rises into the crust and pools in a shallow magma chamber. Some cools slowly along the margins of the magma chamber to form massive gabbro, while some intrudes upward to fill vertical cracks that appear as newly formed crust splits apart (see Fig. 2.17c). Magma that cools in the cracks forms basalt dikes, and magma that makes it to the sea floor and extrudes as lava forms **pillow basalt** flows.

FIGURE 4.17 Flood basalts form when vast quantities of low-viscosity mafic lava "floods" over the landscape and freezes into a thin sheet. Accumulation of successive flows builds a flat-topped plateau.



(a) The plume model for forming flood basalts.



(b) Flood basalts form the layers exposed in Palouse Canyon, Washington.

Take-Home Message

The formation of igneous rocks can be understood in the context of plate-tectonics theory. Flux melting due to release of fluids from subducting slabs produces melts at convergent margins. Melting at hot spots is probably due to decompression at the top of a mantle plume. Decompression of rising asthenosphere also triggers melting beneath rifts and mid-ocean ridges. Injection of hot mantle-derived magma into the crust at rifts and convergent margins causes melting of the crust.



(c) Flood basalts underlie the Columbia River Plateau in Washington and Oregon, the dark area on this map.

Chapter Summary

- Magma is liquid rock (melt) under the Earth's surface. Lava is melt that has erupted from a volcano at the Earth's surface.
- Magma forms when hot rock in the Earth partially melts. This process occurs only under certain circumstances—when the pressure decreases, when volatiles are added to hot rock, and when heat is transferred into the crust by magma rising from the mantle into the crust.
- Magma occurs in a range of compositions: felsic (silicic), intermediate, mafic, and ultramafic. The composition of magma reflects the original composition of the rock from which the magma formed and the way the magma evolves.
- Magma rises from depth because of its buoyancy and because of pressure caused by the weight of overlying rock.
- Magma viscosity depends on composition. Felsic magma is more viscous than mafic magma.
- The rate at which intrusive magma cools depends on the depth at which it intrudes, the size and shape of the magma body, and whether circulating groundwater is present. The cooling time influences the texture of an igneous rock.
- Extrusive igneous rocks form from lava that erupts out of a volcano. Intrusive igneous rocks develop from magma that freezes inside the Earth.
- Lava may solidify to form flows, or it may explode into the air to form ash.
- Intrusive igneous rocks form when magma intrudes into pre-existing rock below Earth's surface. Blob-shaped intrusions are called plutons. Tabular intrusions that cut across layering are dikes, and those that form parallel to layering are sills. Huge intrusions, made up of many plutons, are known as batholiths.
- Igneous rocks are classified according to texture and composition.
- The origin of igneous rocks can readily be understood in the context of plate tectonics. Magma forms at continental or island volcanic arcs along convergent margins, mostly because of the addition of volatiles to the asthenosphere above the subducting slab. Igneous rocks form at hot spots, owing to the decompression melting of a rising mantle plume. Igneous rocks form at rifts as a result of decompression melting of the asthenosphere below the thinning lithosphere or heat transfer from mantle melts into crustal rocks. Igneous rocks form along mid-ocean ridges because of decompression melting of the rising asthenosphere.

Key Terms

assimilation (p. 102)
batholith (p. 106)
Bowen's reaction series (p. 105)
crystalline igneous rock (p. 109)
dike (p. 104)
extrusive igneous rock (p. 98)
flood basalt (p. 114)
fractional crystallization (p. 103)
fragmental igneous rock (p. 110)
geotherm (p. 100)
glassy igneous rock (p. 110)
hot-spot volcano (p. 114)
igneous rock (p. 97)
intrusive igneous rock (p. 99)
laccolith (p. 106)
large igneous province (LIP) (p. 114)
lava (p. 97)
lava flow (p. 97)
liquidus (p. 100)
mafic magma (p. 101)
magma (p. 99)
magma chamber (p. 99)
obsidian (p. 110)
partial melting (p. 102)
pegmatite (p. 110)
pillow basalt (p. 115)
pluton (p. 106)
pumice (p. 110)
pyroclastic rock (p. 113)
scoria (p. 113)
sill (p. 106)
solidus (p. 100)
stoping (p. 106)
tuff (p. 113)
ultramafic magma (p. 101)
vesicle (p. 110)
viscosity (p. 102)
volcanic arc (p. 114)
volcanic ash (p. 98)
volcanic breccia (p. 113)
volcano (p. 97)
xenolith (p. 109)

Review Questions

1. How is the process of freezing magma similar to that of freezing water? How is it different?
2. What is the source of heat in the Earth? How did the first igneous rocks on the planet form?
3. Describe the three processes that are responsible for the formation of magmas.
4. Why are there so many different types of magmas? Does partial melting produce magma with the same composition as the parent rock from which it was derived?
5. Why do magmas rise from depth to the surface of the Earth?
6. What factors control the viscosity of a melt?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Interactive exercises on lava composition.
- A video exercise addressing lava composition.
- A What a Geologist Sees exercise on magma viscosity and mineral formation in igneous rocks.

7. What factors control the cooling time of a magma within the crust?
8. What is the difference between a sill and a dike and how do both differ from a pluton?
9. How does grain size reflect the cooling time of a magma?
10. What does the mixture of grain sizes in a porphyritic igneous rock indicate about its cooling history?
11. Describe the way magmas are produced in subduction zones.
12. What process in the mantle may be responsible for causing hot-spot volcanoes to form?
13. Describe how magmas are produced at continental rifts. Why can you find both basalt and rhyolite in such settings?
14. What is a large igneous province (LIP)? How might the formation of LIPs have affected the Earth System?
15. Why does melting take place beneath the axis of a mid-ocean ridge?

On Further Thought

16. If you look at the Moon, even without a telescope, you see broad areas where its surface appears relatively darker and smoother. These areas are individually called *mare* (plural: *maria*), from the Latin word for sea. The term is misleading, for they are not bodies of water but rather plains of igneous rock formed after huge meteors struck the Moon and formed very deep craters. These impacts occurred early in the history of the Moon, when its interior was warmer. With this background information in mind, propose a cause for the igneous activity, and suggest the type of igneous rock that fills the mare. (*Hint*: Think about how the presence of a deep crater affects pressure in the region below the crater, and think about the viscosity of a magma that could spread over such a broad area.)
17. The Cascade volcanic chain of the northwestern United States is only about 800 km long (from the southernmost volcano in California to the northernmost one in Washington State). The volcanic chain of the Andes is several thousand kilometers long. Look at a map showing the Earth's plate boundaries, and explain why the Andes volcanic chain is so much longer than the Cascade volcanic chain.

SEE FOR YOURSELF D. . . Igneous Rocks

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet D of our **Geotours Workbook**.



Granite of the Sierra Nevada Batholith
Latitude 37°45′18.01″N,
Longitude 119°32′21.00″W
(oblique, looking east)

This view looks at the valley of Yosemite National Park, with the famous climbing peak Half Dome on the right. The bedrock in this view consists of granite, part of a batholith that intruded during the Mesozoic either beneath an island or along a convergent margin.

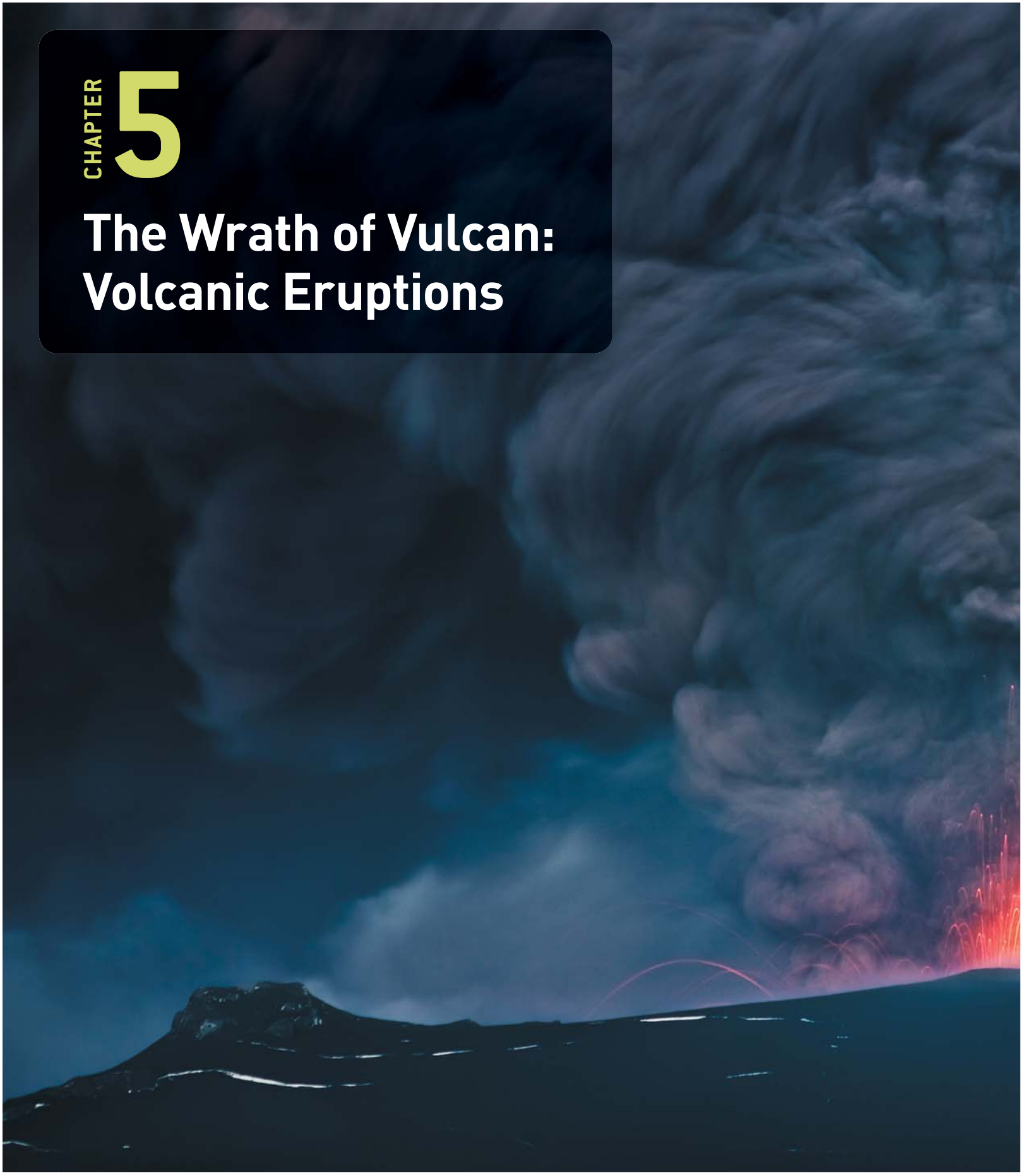


Izalco Volcano, El Salvador
Latitude 13°48′50.40″N,
Longitude 89°37′57.74″W
(oblique, looking east)

This volcano was active almost continuously from 1770 to 1958. Several basalt lava flows spread down the slopes into the green jungle. Younger flows have a darker color. The gray covering near the summit consists of pyroclastic debris.

CHAPTER 5

The Wrath of Vulcan: Volcanic Eruptions





A large ash plume with lava erupting from the Eyjafjallajokull volcano in Iceland, April 2010. The ash cloud from the eruption grounded air traffic around the world.

Chapter Objectives

By the end of this chapter you should know . . .

- the nature of the great variety of materials (such as lava, pyroclastic debris, and gas) that erupt at volcanoes.
- how volcanic eruptions can differ from one another, so that some yield rivers of lava, whereas others produce catastrophic explosions.
- the various hazards to life and environment that can result from volcanic eruptions.
- that, in some cases, impending eruptions can be predicted, allowing people to take precautions.
- how volcanoes may affect climate, evolution, and perhaps the future of civilizations.

Glowing waves rise and flow, burning all life on their way, and freeze into black, crusty rock which adds to the height of the mountain and builds the land, thereby adding another day to the geologic past. . . . I became a geologist forever, by seeing with my own eyes: the Earth is alive!

—Hans Cloos (1886–1951),
on seeing the eruption of Mt. Vesuvius (Italy)

5.1 Introduction

Every few hundred years, one of the hills on Vulcano, an island in the Mediterranean Sea off the western coast of Italy, rumbles and spews out molten rock, glassy cinders, and dense "smoke" (actually a mixture of various gases, fine ash, and very tiny liquid droplets). Ancient Romans thought that such eruptions happened when Vulcan, the god of fire, fueled his forges beneath the island to manufacture weapons for the other gods. Geologic study suggests, instead, that eruptions take place when hot magma, formed by melting inside the Earth, rises through the crust and emerges at the surface. No one believes the Roman myth anymore, but the island's name evolved into the English word **volcano**, which geologists use to designate either an erupting vent through which molten rock reaches the Earth's surface or a mountain built from the products of eruption.

On the main peninsula of Italy, not far from Vulcano, another volcano, Mt. Vesuvius, towers over the Bay of Naples. Two thousand years ago, a prosperous Roman resort and trading town

FIGURE 5.1 The eruption of Vesuvius devastated and buried Pompeii and nearby Herculaneum in 79 C.E.



(a) In this 1817 painting, the British artist J.M.W. Turner depicted the cataclysmic explosion.



(b) Excavations exposed the ruins of Pompeii. Vesuvius towers behind; dashed lines give its profile before eruption.



(c) A plaster cast of a Pompeii resident who was buried in ash.

named Pompeii sprawled at the foot of Vesuvius. One morning in 79 C.E., earthquakes signaled the mountain's awakening. At 1:00 P.M. on August 24, a dark mottled cloud, streaked by lightning, boiled up above Mt. Vesuvius's summit to a height of 27 km. The cloud spread over Pompeii and turned day into night. Blocks and pellets of rock fell like hail, while fine ash and choking fumes filled the air (Fig. 5.1a, b). Frantic people rushed to escape, but for many it was too late. As the growing weight of volcanic debris began to crush buildings, a scalding, turbulent current of ash mixed with pumice fragments surged down the flank of the volcano and swept into Pompeii. By the next day, the town had vanished beneath a 6-m-thick gray-black blanket. This covering protected the ruins of Pompeii so well that when archaeologists excavated the town 1,800 years later, they found an amazingly complete record of Roman daily life. In addition, they discovered open spaces in the debris covering Pompeii. Out of curiosity, they filled the spaces with plaster and then dug away the surrounding ash. The spaces turned out to be fossil casts of Pompeii's unfortunate inhabitants, their bodies forever twisted in agony or huddled in despair (Fig. 5.1c).

Clearly, volcanoes are unpredictable and dangerous. Volcanic activity can build a towering, snow-crested mountain or can blast one apart. It can provide the fertile soil and mineral deposits that enable a civilization to thrive, or a rain of destruction that can snuff one out. Because of the diversity of volcanic activity and its consequences, this chapter sets out ambitious goals. We first look more closely at the products of volcanic eruptions and the basic characteristics of volcanoes. Then we consider the different kinds of volcanic eruptions on Earth and why they occur where they do. Finally, we consider the hazards posed by volcanoes, efforts by geoscientists to predict eruptions and help minimize the damage they cause, and the possible influence of eruptions on climate and civilization.

5.2 The Products of Volcanic Eruptions

The drama of a volcanic eruption transfers materials from inside the Earth to our planet's surface. Products of an eruption come in three forms—lava flows, pyroclastic debris, and gas. Note that we use the name *flow* for both a molten, moving layer of lava and for the solid layer of rock that forms when the lava freezes.

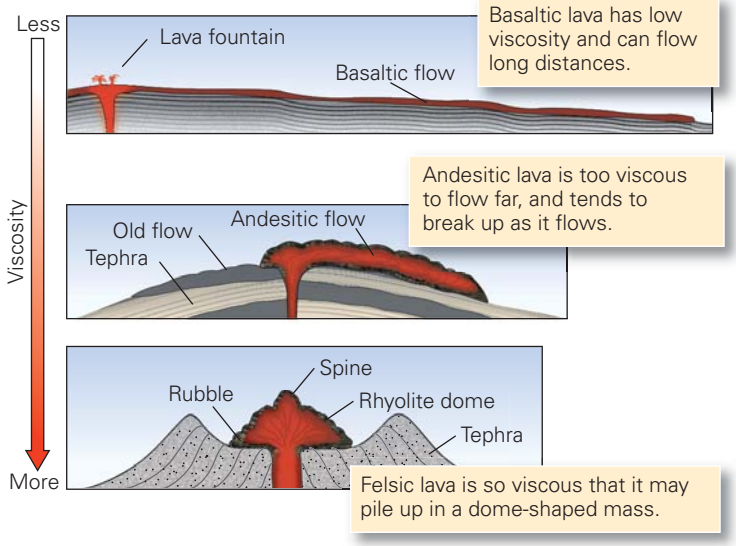
Lava Flows

Sometimes it races down the side of a volcano like a fast-moving, incandescent stream, sometimes it builds into a

rubble-covered mound at a volcano's summit, and sometimes it oozes like a sticky but scalding paste. Clearly, not all lava behaves in the same way when it rises out of a volcano. Therefore, not all lava flows look the same. Why? The character of a lava primarily reflects its *viscosity* (resistance to flow), and not all lavas have the same viscosity. Differences in viscosity depend, in turn, on chemical composition, temperature, gas content, and crystal content. Silica content plays a particularly key role in controlling viscosity. As noted in Chapter 4, silica-poor (basaltic) lava is less viscous, and thus flows farther than does silica-rich (rhyolitic) lava (Fig. 5.2). To illustrate the different ways in which lava behaves, we now examine flows of different compositions.

Basaltic lava flows. Basaltic (mafic) lava has very low viscosity when it first emerges from a volcano because it contains relatively little silica and is very hot. Thus, on the steep slopes near the summit of a volcano, it can flow very quickly, sometimes at speeds of over 30 km per hour (Fig. 5.3a). The lava slows down to less-than-walking pace after it starts to cool (Fig. 5.3b). Most flows measure less than a few km long, but some flows reach as far as 600 km from the source. How can lava travel such distances? Although all the lava in a flow moves when it first emerges, rapid cooling causes the surface of the flow to crust over after the flow has moved a short distance from the source. The solid crust serves as insulation, allowing the hot interior of the flow to remain liquid and continue to move. As time progresses, part of the flow's interior solidifies, so eventually, molten lava moves only through a tunnel-like passageway, or **lava tube**, within the flow—the largest of these may be tens of meters in diameter. In some cases, lava tubes drain and eventually become empty tunnels.

FIGURE 5.2 The character of a lava flow depends on its viscosity.



The surface texture of a basaltic lava flow when it finally freezes reflects the timing of freezing relative to its movement. Basalt flows with warm, pasty surfaces wrinkle into smooth, glassy, rope-like ridges; geologists have adopted the Hawaiian word **pahoehoe** (pronounced "pa-hoy-hoy") for such flows (Fig. 5.3c). If the surface layer of the lava freezes and then breaks up due to the continued movement of lava underneath, it becomes a jumble of sharp, angular fragments, creating a rubbly flow also called by its Hawaiian name, **a'a'** (pronounced "ah-ah") (Fig. 5.3d). Footpaths made by people living in basaltic volcanic regions follow the smooth surface of pahoehoe rather than the foot-slashing surface of a'a'.

During the final stages of cooling, lava flows contract, because rock shrinks as it loses heat, and may fracture into polygonal columns. This type of fracturing is called **columnar jointing** (Fig. 5.3e).

Basaltic flows that erupt underwater look different from those that erupt on land because the lava cools so much more quickly in water. Because of rapid cooling, submarine basaltic lava can travel only a short distance before its surface freezes, producing a glass-encrusted blob, or "pillow" (Fig. 5.3f). The rind of a pillow momentarily stops the flow's advance, but within minutes the pressure of the lava squeezing into the pillow breaks the rind, and a new blob of lava squirts out, freezes, and produces another pillow. In some cases, successive pillows add to the end of previous ones, forming worm-like chains.

Andesitic and rhyolitic lava flows. Because of its higher silica content and thus its greater viscosity, andesitic lava cannot flow as easily as basaltic lava. When erupted, andesitic lava first forms a large mound above the vent. This mound then advances slowly down the volcano's flank at only about 1 to 5 m a day, in a lumpy flow with a bulbous snout. Typically, andesitic flows are less than a few km long. Because the lava moves so slowly, the outside of the flow has time to solidify; so as it moves, the surface breaks up into angular blocks, and the whole flow looks like a jumble of rubble called **blocky lava**.

Rhyolitic lava is the most viscous of all lavas because it is the most silicic and the coolest. Therefore, it tends to accumulate either above the vent in a lava dome (Fig. 5.4), or in short and bulbous flows rarely more than 1 to 2 km long. Sometimes rhyolitic lava freezes while still in the vent and then pushes upward as a column-like spire up to 100 m above the vent. Rhyolitic flows, where they do form, have broken and blocky surfaces.

Volcaniclastic Deposits

On a mild day in February 1943, as Dionisio Pulido prepared to sow the fertile soil of his field 330 km (200 miles) west of Mexico City, an earthquake jolted the ground, as it had dozens of times in the previous days. But this time, to

FIGURE 5.3 Features of basaltic lava flows. They have low viscosity and thus can flow long distances. Their surface and interior can be complex.



(a) A fast-moving flow coming from Mt. Etna, Sicily.



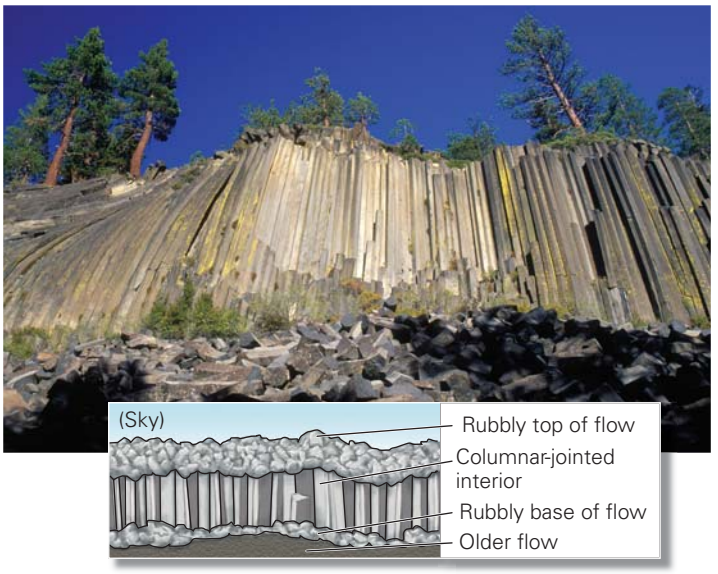
(b) A basaltic lava flow covers a highway in Hawaii.



(c) Pahoehoe from a recent lava flow in Hawaii. Note the coin for scale.



(d) The rubbly surface of an a'a' flow, Sunset Crater, Arizona.



(e) Columnar jointing develops when the interior of a flow cools and cracks. Such jointing develops in dikes and sills. This example is Devils Postpile in California.



(f) Pillow basalt develops when lava erupts underwater. Later uplift may expose pillows above sea level, as in this Oregon outcrop.

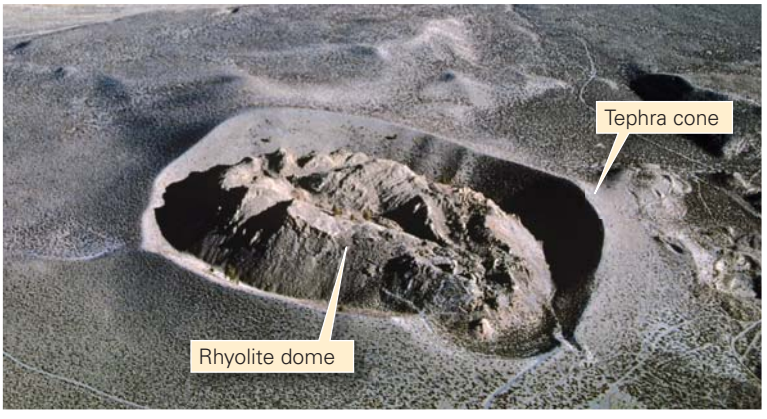
Dionisio's amazement, the surface of his field visibly bulged upward by a few meters and then cracked. Ash and sulfurous fumes filled the air, and Dionisio fled. When he returned the following morning, his field lay buried beneath a 40-m-high mound of gray cinders—Dionisio had witnessed the birth of Paricutín, a new volcano. During the next several months, Paricutín erupted continuously, at times blasting clots of lava into the sky like fireworks. By the following year, it had become a steep-sided cone 330 m high. Nine years later, when the volcano ceased erupting, its lava and debris covered 25 square km.

This description of Paricutín's eruption, and that of Vesuvius at the beginning of this chapter, emphasizes that volcanoes can erupt large quantities of fragmental igneous material. Geologists use the general term **volcaniclastic deposits** for accumulations of this material. Volcaniclastic deposits include **pyroclastic debris** (from the Greek *pyro*, meaning fire), which forms from lava that flies into the air and freezes. They also include the debris formed when an eruption blasts apart preexisting volcanic rock that surrounds the volcano's vent, the debris that accumulates after tumbling down the volcano in landslides or after being transported in water-rich slurries, and the debris formed as lava flows break up or shatter. Let's look at these components in more detail.

Did you ever wonder . . .
has anyone ever seen a brand-new volcano form?

Pyroclastic debris from basaltic eruptions. Basaltic magma rising in a volcano may contain dissolved volatiles (such as water). As such magma approaches the surface, the volatiles form bubbles. When the bubbles reach the surface, they burst and eject clots and drops of molten magma upward to form dramatic fountains (**Fig. 5.5a**). To picture this process, think of the droplets that spray from a newly opened bottle of soda. Solidification of the pea-sized fragments of glassy lava and scoria produces a type of **lapilli** (from the Latin word for little stones). Pieces of this type of lapilli are informally known as cinders. Rarely, flying droplets may trail thin strands of lava, which freeze into filaments of glass known as Pelé's hair, after the Hawaiian goddess of volcanoes, and the droplets themselves freeze into tiny streamlined glassy beads known as Pelé's tears. Apple- to refrigerator-sized fragments called **blocks** (**Fig. 5.5b**) may consist of already-solid volcanic rock, broken up during the eruption—such blocks tend to be angular and chunky. In some cases, however, blocks form when soft lava squirts out of the vent and then solidifies—such blocks, also known as **bombs**, have streaked, polished surfaces.

FIGURE 5.4 This rhyolite dome formed about 650 years ago, in Panum Crater, California. Tephra (cinders) accumulated around the vent.



Pyroclastic debris from andesitic or rhyolitic eruptions. Andesitic or rhyolitic lava is more viscous than basalt, and may be more gas-rich. The lava flows tend to be blocky to start with, and blocks of flows may tumble down the volcano. Eruptions of these lavas also tend to be explosive. Debris ejected from explosive eruptions includes fragments of pumice and ash. **Ash** consists of particles less than 2 mm in diameter, made from both glass shards formed when frothy lava explosively breaks up during an eruption, and from pulverized pre-existing volcanic rock (**Fig. 5.6a**). Two types of lapilli are produced by explosive eruptions: **pumice lapilli** consists of angular pumice fragments formed from frothy lava (**Fig. 5.6b**); **accretionary lapilli** consists of snowball-like lumps of ash formed when ash mixes with water in the air and then sticks together (**Fig. 5.6c**).

Much of the pyroclastic debris erupted from an exploding volcano billows upward in a turbulent cloud that can reach stratospheric heights (**Fig. 5.6d**). Some, however, rushes down the flank of the volcano in an avalanche-like current known as a **pyroclastic flow** (**Fig. 5.6e**). Pyroclastic flows were once known as *nuées ardentes* (French for glowing cloud), because the debris they contain can be quite hot—200°C to 450°C.

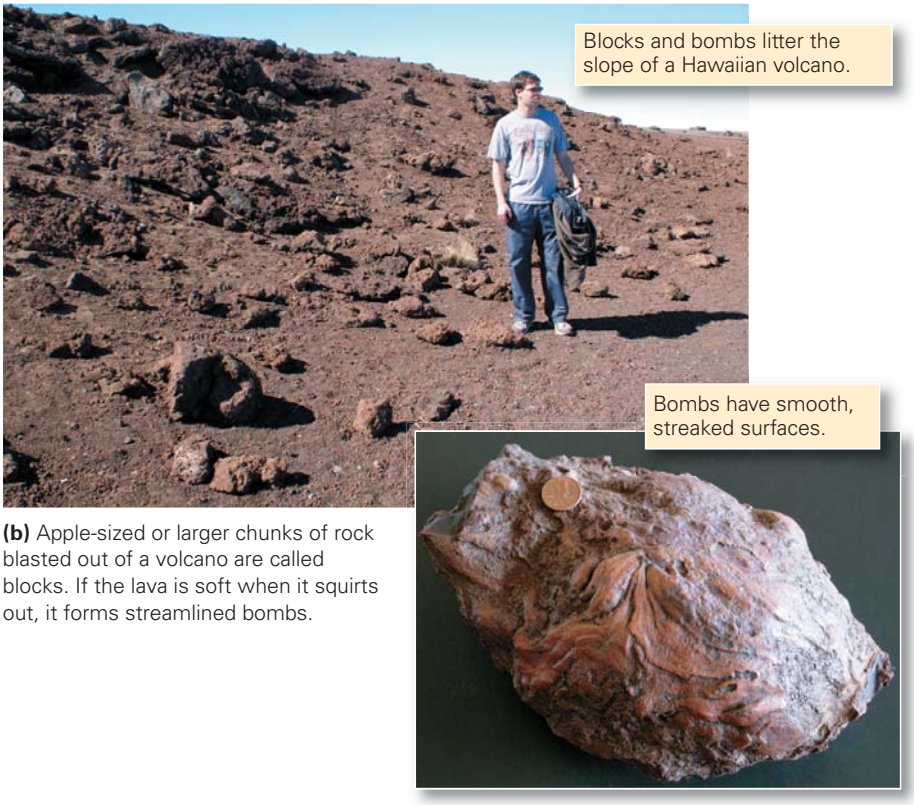
Unconsolidated deposits of pyroclastic grains, regardless of size, constitute **tephra**. Ash, or ash mixed with lapilli, becomes **tuff** when buried and transformed into coherent rock. Tuff that formed from ash and/or pumice lapilli that fell like snow from the sky is called *air-fall tuff,* whereas a sheet of tuff that formed from a pyroclastic flow is an **ignimbrite**. Ash and pumice lapilli in an ignimbrite is sometimes so hot that it welds together to form a hard mass.

Other volcaniclastic deposits. In cases where volcanoes are covered with snow and ice, or are drenched with rain, water mixes with debris to form a **volcanic debris flow** that moves downslope like wet concrete. Very wet, ash-rich debris flows

FIGURE 5.5 Pyroclastic debris from basaltic eruptions.



(a) Fountains of lava may erupt from basaltic volcanoes.



(b) Apple-sized or larger chunks of rock blasted out of a volcano are called blocks. If the lava is soft when it squirts out, it forms streamlined bombs.

become a slurry called a **lahar**, which can reach speeds of 50 km per hour and may travel for tens of kilometers. When debris flows and lahars stop moving, they yield a layer consisting of volcanic debris suspended in ashy mud.

Volcanic Gas

Most magma contains dissolved gases, including water, carbon dioxide, sulfur dioxide, and hydrogen sulfide (H_2O, CO_2, SO_2, and H_2S). In fact, up to 9% of a magma may consist of gaseous components, and generally, lavas with more silica contain a greater proportion of gas. Volcanic gases come out of solution when the magma approaches the Earth's surface and pressure decreases, just as bubbles come out of solution in a soda when you pop the bottle top off.

In low-viscosity magma, gas bubbles can rise faster than the magma moves, and thus most reach the surface of the magma and enter the atmosphere before the lava does. Thus some volcanoes may, for a while, produce large quantities of steam, without much lava (Fig. 5.7a). The last bubbles to form, however, freeze into the lava and become holes called **vesicles** (Fig. 5.7b). In high-viscosity magmas, the gas has trouble escaping because bubbles can't push through the sticky lava. When this happens, explosive pressures build inside or beneath the volcano.

Take-Home Message

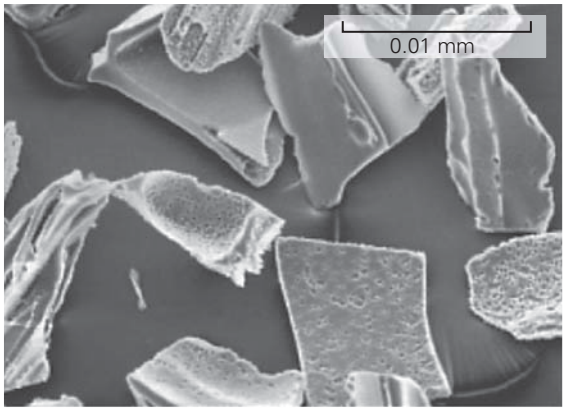
Volcanoes erupt lava, pyroclastic debris, and gas. The character of a lava flow—whether it has low viscosity and spreads over a large area, or has high viscosity and builds a mound over the vent, depends largely on its composition. Pyroclastic debris includes pumice, lapilli, blocks, and bombs. Some may fall over the countryside like snow, but some surges down the flank of a volcano as a pyroclastic flow.

5.3 The Structure and Eruptive Style of Volcanoes

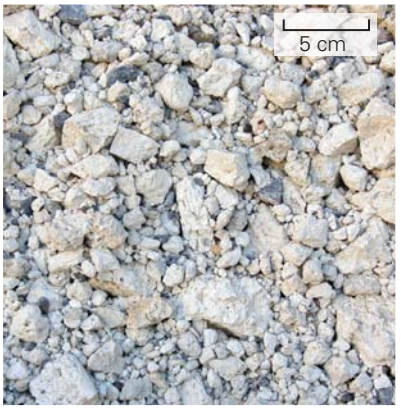
Volcanic Architecture

As we saw in Chapter 4, melting in the upper mantle and lower crust produces magma, which rises into the upper crust.

FIGURE 5.6 The components of an explosive eruption.



(a) Ash flakes



(b) Pumice lapilli, Mexico.



(c) Accretionary lapilli



(d) The 1989–1990 eruption of Redoubt Volcano in Alaska produced a giant cloud of ash that mushroomed up to the stratosphere.



(e) Ash erupts from Mt. Merapi, Indonesia, in 2006. Some of the ash rises into the sky, whereas some rushes down the volcano's flank as a pyroclastic flow.

FIGURE 5.7 The gas component of volcanic eruptions.



(a) A volcano in Alaska erupting large quantities of steam.



(b) Gas bubbles frozen in lava produce vesicles, as in this block from Sunset Crater, Arizona.

Typically, this magma accumulates underground in a **magma chamber**, a zone of open spaces and/or fractured rock that can contain a large quantity of magma. A portion of the magma may solidify in the magma chamber and transform into intrusive igneous rock, whereas the rest rises through an opening, or conduit, to the Earth's surface and erupts from a volcano. The conduit may have the shape of a vertical pipe, or chimney, or may be a crack called a **fissure** (Fig. 5.8a, b). At the top of a volcanic edifice, a circular depression called a **crater** (shaped like a bowl, up to 500 m across and 200 m deep) may develop. Craters form either during eruption as material accumulates around the summit vent, or just after eruption as the summit collapses into the drained conduit.

During major eruptions, the sudden draining of a magma chamber produces a **caldera**, a big circular depression up to thousands of meters across and up to several hundred meters deep. Typically, a caldera has steep walls and a fairly flat floor and may be partially filled with ash (Fig. 5.9a–d).

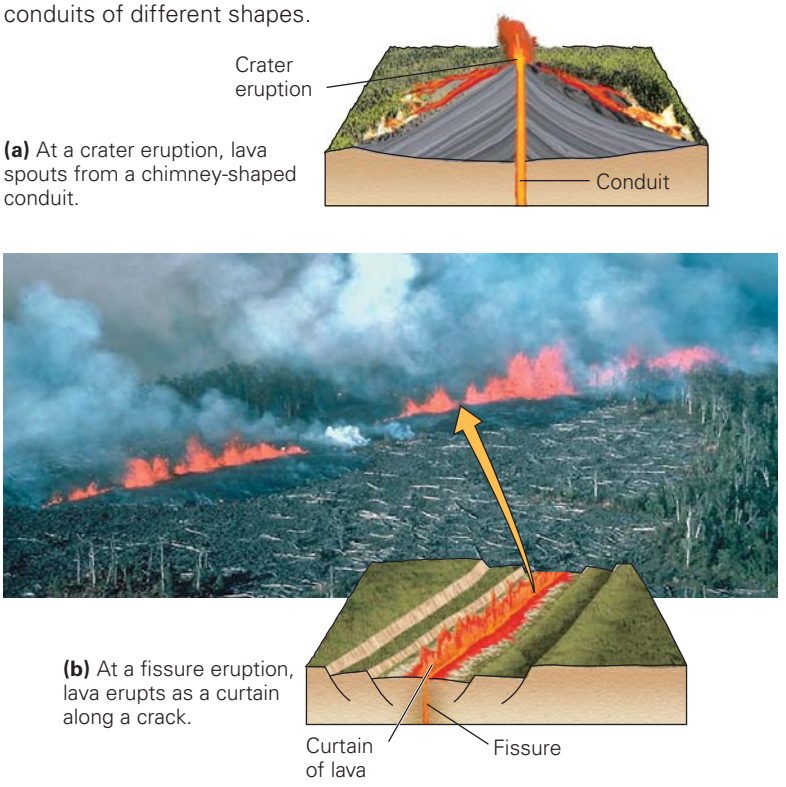
Geologists distinguish among several different shapes of subaerial (above sea level) volcanic edifices. **Shield volcanoes**, broad, gentle domes, are so named because they resemble a soldier's shield lying on the ground (Fig. 5.10a). They form when the products of eruption have low viscosity and thus are weak, so they cannot pile up around the vent but rather spread out over large areas. **Scoria cones** (informally called **cinder cones**) consist of cone-shaped piles of basaltic lapilli and blocks, generally from a single eruption (Fig. 5.10b). **Stratovolcanoes**, also known as composite volcanoes, are large and cone-shaped, generally with steeper slopes near the summit, and consist of interleaved layers of lava, tephra, and volcaniclastic debris (Fig. 5.10c). Their shape, exemplified by Japan's Mt. Fuji, supplies the classic image that most people have of a volcano; the prefix *strato-* emphasizes that they can grow to be kilometers high.

Concept of Eruptive Style: Will It Flow, or Will It Blow?

Kilauea, a volcano on Hawaii, produces rivers of lava that cascade down the volcano's flanks. Mt. St. Helens, a volcano near the Washington–Oregon border, exploded catastrophically in 1980 and blanketed the surrounding countryside with tephra. Clearly, different volcanoes erupt differently and, as we've noted, successive eruptions from the same stratovolcano may differ markedly in character from one another. Geologists refer to the character of an eruption as **eruptive style**. Below, we describe several distinct eruptive styles and explore why the differences occur.

Effusive eruptions. The term *effusive* comes from the Latin word for pour out, and indeed that's what happens during an **effusive eruption**—lava pours out a summit vent or fissure, filling a lava lake around the crater and/or flowing in molten rivers for great distances (Fig. 5.11a). Effusive eruptions occur where the magma feeding the volcano is hot and mafic and, therefore, has low viscosity. Pressure, applied to the magma chamber by the weight of overlying rock, squeezes magma upward and out of the vent; in some cases, the pressure is great enough to drive the magma up into a fountain over the vent.

FIGURE 5.8 Crater eruptions and fissure eruptions come from conduits of different shapes.



(a) At a crater eruption, lava spouts from a chimney-shaped conduit.

(b) At a fissure eruption, lava erupts as a curtain along a crack.

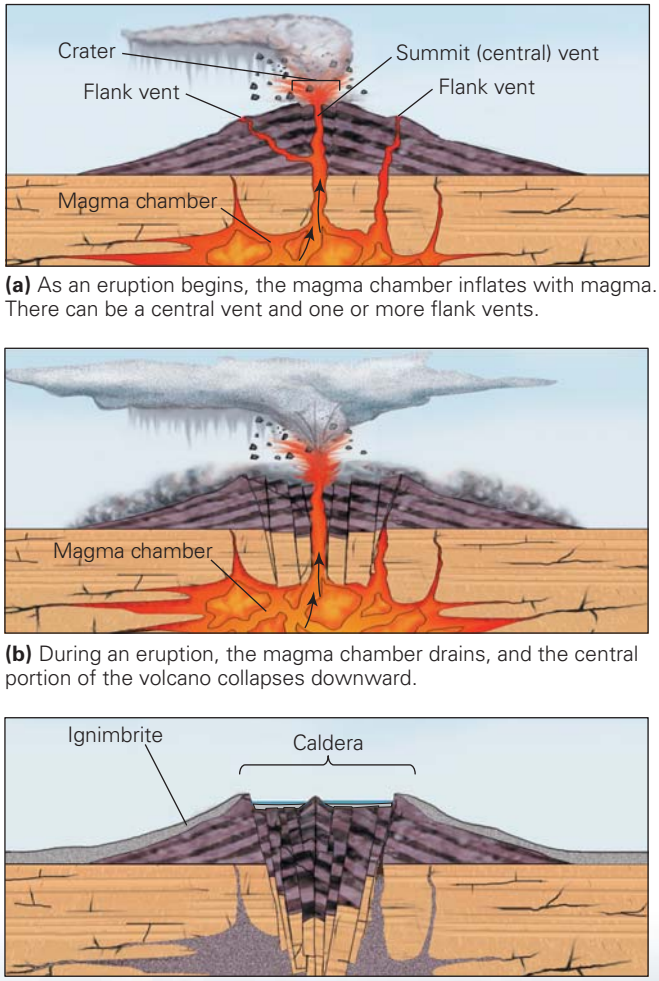
Explosive eruptions. When pressure builds in a volcano, the eruption will likely yield an explosion. Smaller explosions take place during basaltic eruptions, when gas builds up and suddenly escapes, spattering lava drops and blobs upward—these then solidify and fall as tephra. Occasionally, a volcano blows up in a huge explosion. Such catastrophic explosions can be triggered by many causes. For example, if a crack forms in the flank of an island volcano, water will enter the magma chamber and suddenly turn to steam, the expansion of which blasts the volcano apart. Such explosions can also happen in felsic or andesitic volcanoes, if very viscous magma plugs the vent until huge pressure builds inside. If the plug eventually cracks, or the flank of the volcano cracks, the gas inside the volcano suddenly expands, and like a giant shotgun blast, it sprays out the molten contents of the

volcano and may cause the volcano itself to break apart. Such explosions, awesome in their power and catastrophic in their consequences, can eject cubic kilometers of debris outward. In some cases, the sudden draining of the magma chamber, and the ejection of debris, causes the remnants of the volcano to collapse and form a caldera.

During a large explosion, the force of the blast shoots debris skyward in a vertical column (Fig. 5.11b). But the force can only take the material so high. The huge plumes of ash that rise to stratospheric heights above large explosions do so by becoming turbulent, billowing, *convective* clouds. This means that the warm mixture of volcanic ash, gas, and air is less dense than the surrounding, cooler air, so the warm mixture rises buoyantly. The resulting plume resembles a mushroom cloud above a nuclear explosion. Coarser-grained ash and lapilli settle from the cloud close to the volcano, whereas finer ash gets carried farther away. Some ash enters high-elevation winds and will be carried around the globe. The denser components collapse downward once they run out of explosive energy, and gravity pulls them back down. This phenomenon, the "collapse" of the column, produces the pyroclastic flows that surge down a volcano's flanks.

What is a pyroclastic flow like? In 1902, the people of St. Pierre, a town on the Caribbean island of Martinique, sadly found out. St. Pierre was a busy port town, about 7 km south of the peak of Mt. Pelée, a volcano. When the volcano began emitting steam and lapilli, residents of the town became nervous and debated about the need to evacuate. Meanwhile, a rhyolite dome grew and obstructed the throat

FIGURE 5.9 The formation of volcanic calderas.



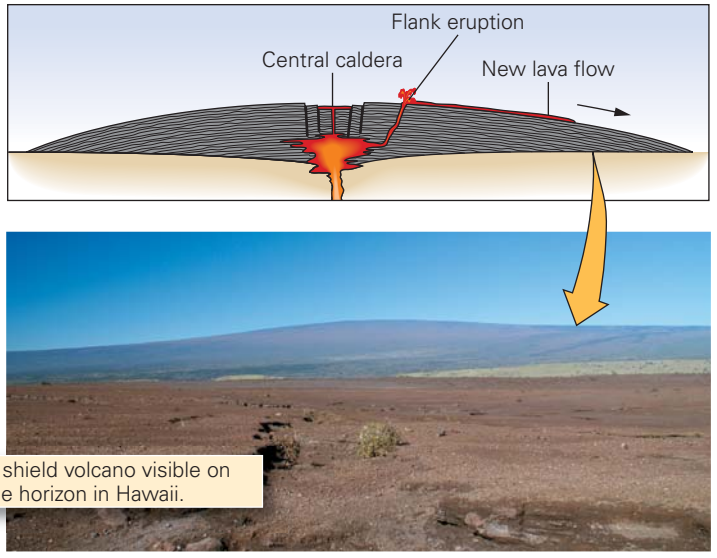
(a) As an eruption begins, the magma chamber inflates with magma. There can be a central vent and one or more flank vents.

(b) During an eruption, the magma chamber drains, and the central portion of the volcano collapses downward.

(c) The collapsed area becomes a caldera. Later, a new volcano may begin to grow within the caldera.

(d) This caldera in Oregon formed about 7,700 years ago. Afterward, it filled with water to become Crater Lake. Wizard Island, protruding from the lake, is a cinder cone that grew on top of the caldera floor.

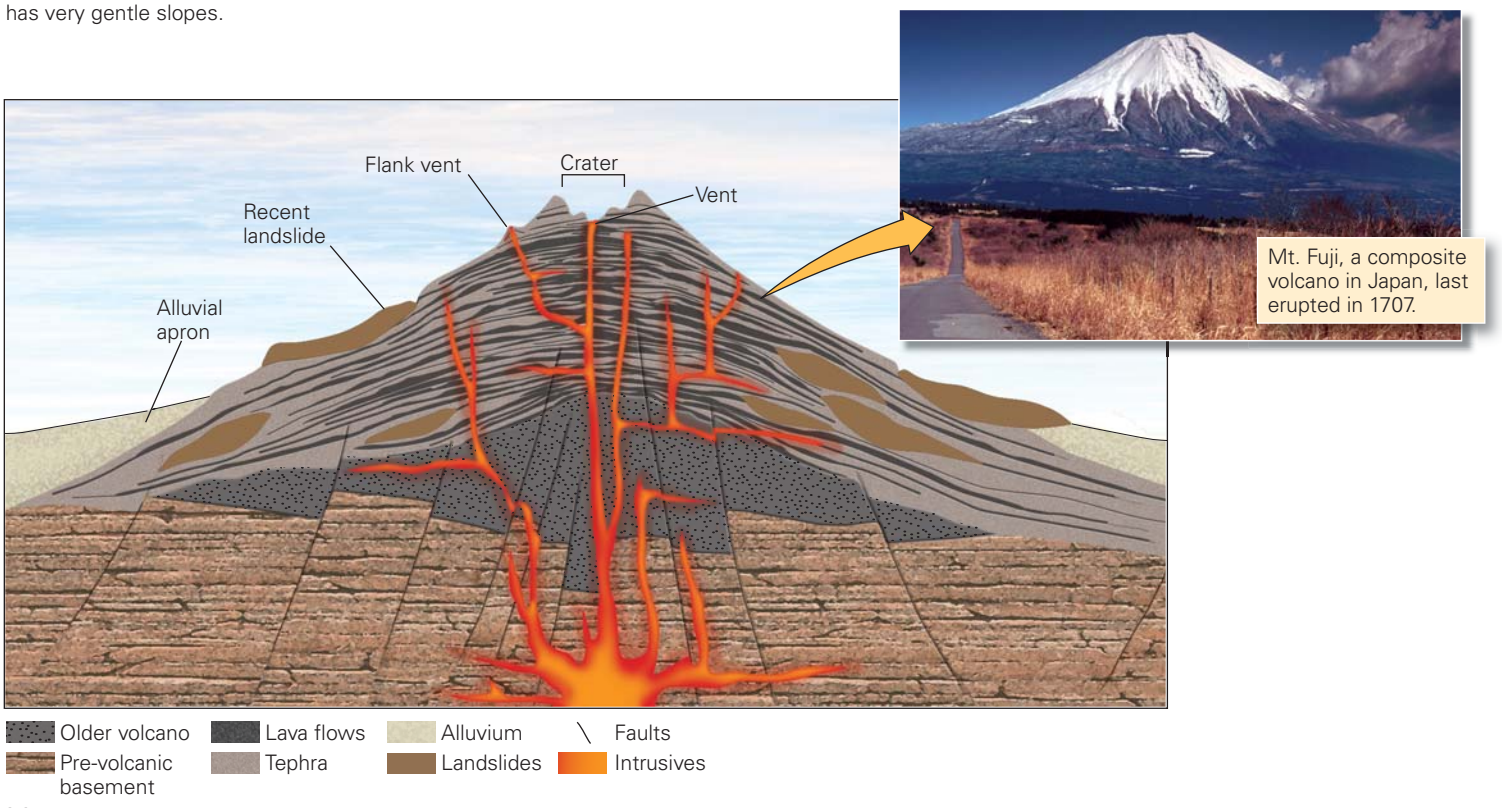
FIGURE 5.10 Different shapes of volcanoes.



(a) A shield volcano, made from successive flows of low-viscosity basalt, has very gentle slopes.



(b) A cinder cone on the flank of a larger volcano in Arizona. The pile of cinders has assumed the angle of repose. A lava flow covers the land surface in the distance.



(c) A stratovolcano (composite volcano) consists of layers of tephra and lava. Volcanic debris flows and ash avalanches modify slopes and contribute to the development of a classic cone-like shape.

of the volcano. On May 8, the dome suddenly cracked, and the immense pressure that had been building beneath the obstruction was released. In the same way that champagne bursts out of a bottle when you pull out the cork, a cloud of hot ash and pumice lapilli spewed out of Mt. Pelée, and a pyroclastic flow swept down Pelée's flank. Partly riding on a cushion of air, this flow reached speeds of 300 km per hour, and slammed into St. Pierre. Within moments, all the town's buildings had been flattened and all but two of its 28,000 inhabitants were dead of incineration or asphyxiation. Similar eruptions have happened more recently on

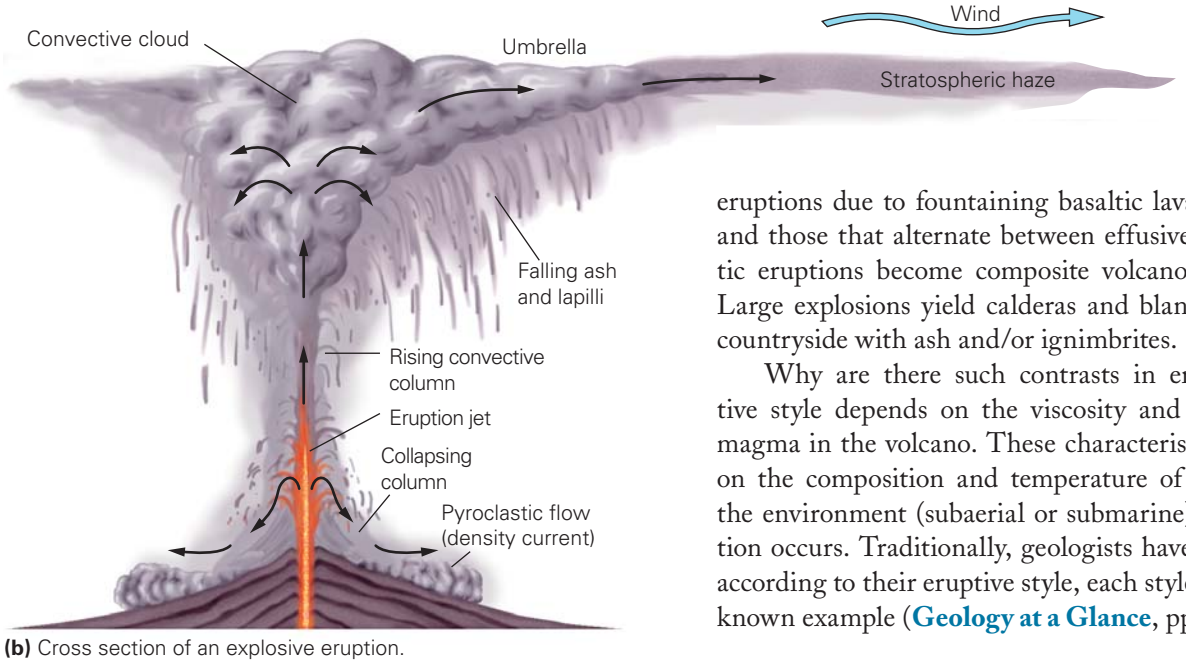
FIGURE 5.11 Contrasting eruptive styles.



(a) Effusive (lava-dominated) eruption of Mount Etna in Sicily, Italy, 1992.



(c) The aftermath of a pyroclastic flow down the flank of the Soufrière Hills Volcano, Montserrat (Caribbean).



(b) Cross section of an explosive eruption.

the nearby island of Montserrat, but with a much smaller death toll because of timely evacuation (**Fig. 5.11c**).

Relation of eruptive style to volcanic type. Note that the type of volcano (shield, cinder cone, or composite) depends on its eruptive style. Volcanoes that have only effusive eruptions become shield volcanoes, those that generate small pyroclastic eruptions due to fountaining basaltic lava yield cinder cones, and those that alternate between effusive and large pyroclastic eruptions become composite volcanoes (stratovolcanoes). Large explosions yield calderas and blanket the surrounding countryside with ash and/or ignimbrites.

Why are there such contrasts in eruptive style? Eruptive style depends on the viscosity and gas contents of the magma in the volcano. These characteristics, in turn, depend on the composition and temperature of the magma and on the environment (subaerial or submarine) in which the eruption occurs. Traditionally, geologists have classified volcanoes according to their eruptive style, each style named after a well-known example (**Geology at a Glance**, pp. 132–133).

Take-Home Message

At a volcano, lava rises from a magma chamber and erupts from chimney-like conduits or from crack-like fissures. Low-viscosity basalt lava flows build shield volcanoes. Fountaining basalt spatters tephra to build cones. Successive eruptions of pyroclastic debris and lava build stratovolcanoes, and explosions produce calderas.

Volcanic Explosions to Remember

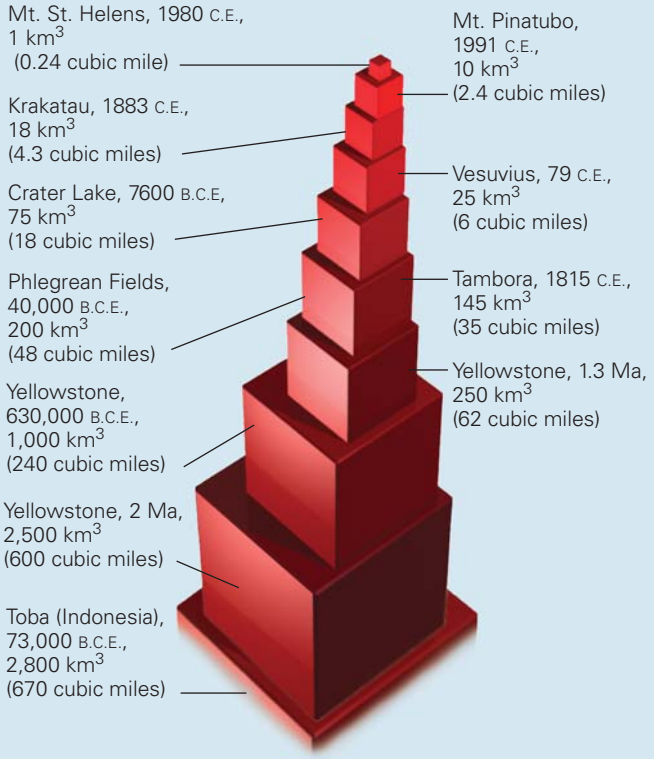
Explosions of volcanoes generate enduring images of destruction. The historical record shows a vast range in the volume of debris erupted, even though the largest *observed* eruption (Tambora in 1815) was small compared to a super-explosion that took place over 600,000 years ago in what is now Yellowstone National Park, Wyoming (**Fig. Bx5.1a**). Let's look at two notable examples of explosions.

Mt. St. Helens, a snow-crested stratovolcano in the Cascades of the northwestern United States, had not erupted since 1857. However, geologic evidence suggested that the mountain had a violent past, punctuated by many explosive eruptions. On March 20, 1980, an earthquake announced that the volcano was awakening once again. A week later, a crater 80 m in diameter burst open at the summit and began emitting gas and pyroclastic debris. Geologists who set up monitoring stations to observe the volcano noted that its north side was beginning to bulge markedly, suggesting that the volcano was filling with magma, making the volcano expand like a balloon. Their concern that an eruption was imminent led local authorities to evacuate people in the area.

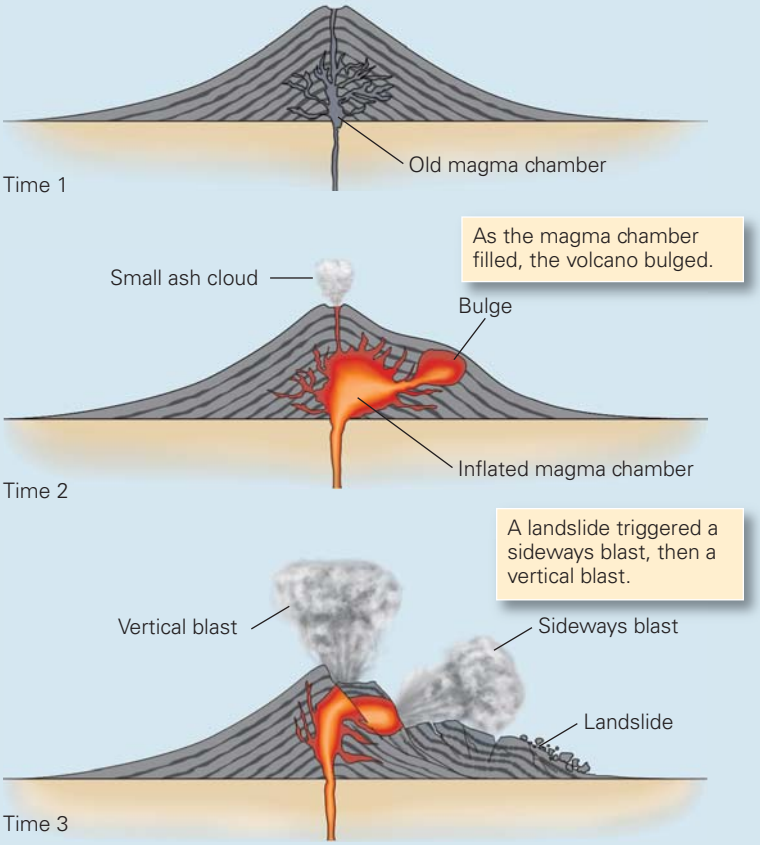
The climactic eruption came suddenly. At 8:32 A.M. on May 18, a geologist, David Johnston, monitoring the volcano from a distance of 10 km, shouted over his two-way radio, "Vancouver, Vancouver, this is it!" An earthquake had triggered a huge landslide that caused 3 cubic km of the volcano's weakened north side to slide away. The sudden landslide released pressure on the magma in the volcano, causing a sudden and violent expansion of gases that blasted through the side of the volcano (**Fig. Bx5.1b**). Rock, steam, and ash screamed north at the speed of sound and flattened a forest and everything in it over an area of 600 square km (**Fig. Bx5.1c**). Tragically, Johnston, along with 60 others, vanished forever.

Seconds after the sideways blast, a vertical column carried about 540 million tons

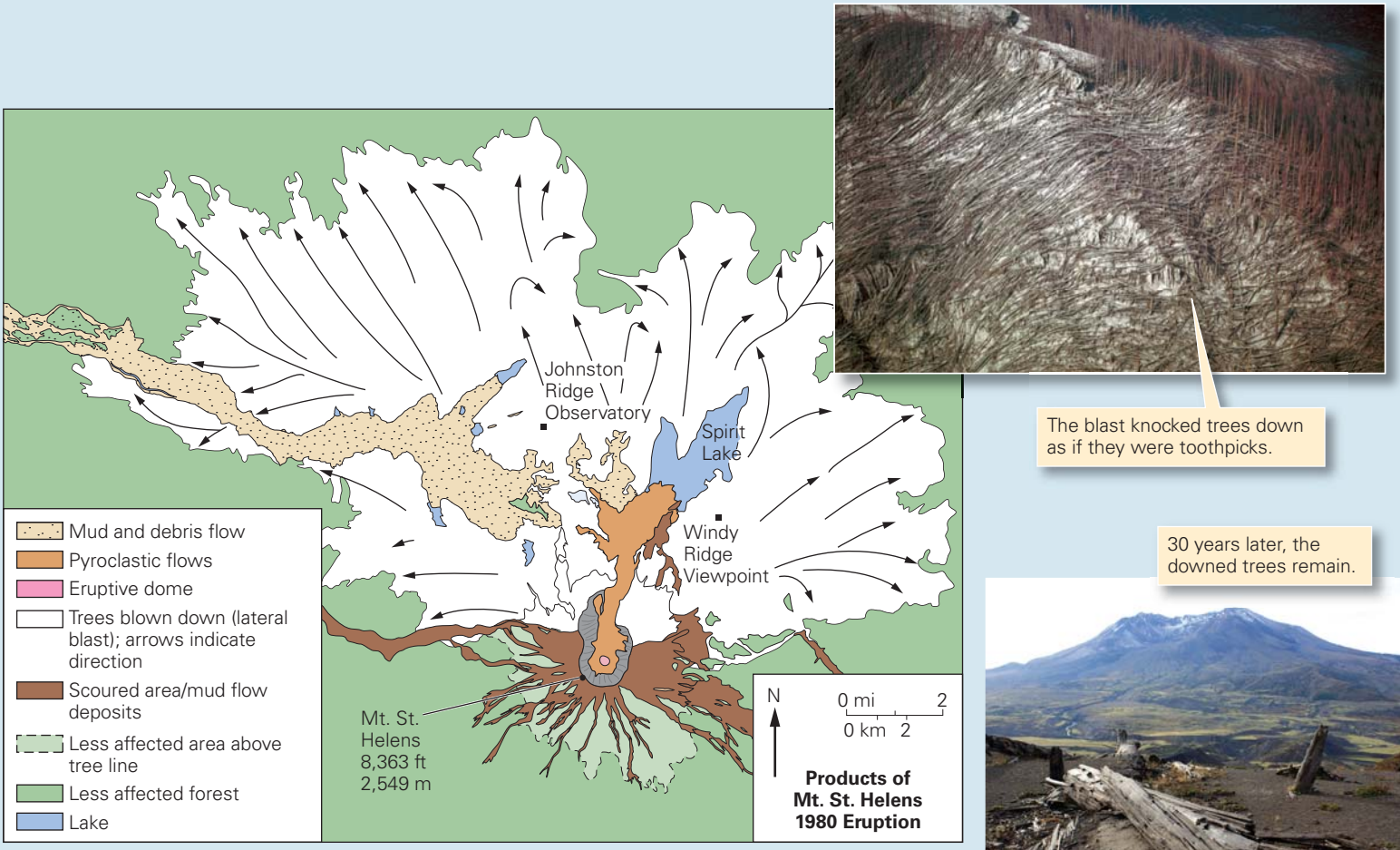
FIGURE Bx5.1 Examples of explosive eruptions.



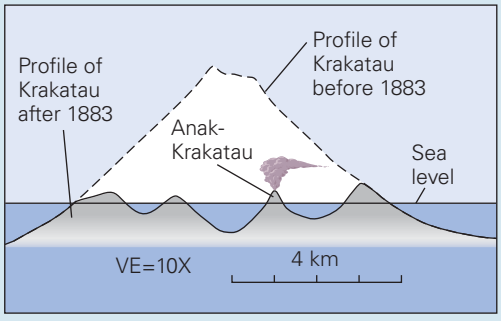
(a) The relative amounts of pyroclastic debris (in cubic km) ejected during major explosive eruptions.



(b) Stages during the eruption of Mt. St. Helens, 1980.



(c) A map shows the dimensions of the region destroyed by the eruption of Mt. St. Helens. The arrows indicate the blast direction. The neighboring forest was flattened by a blast of rock, steam, and ash.



(d) Profile of Krakatau, before and after the eruption. Note that a new volcano (Anak-Krakatau) has formed.

of ash (about 1 cubic km) 25 km into the sky, where the jet stream carried it away so that it was able to circle the globe. In towns near the volcano, a blizzard of ash choked roads and buried fields. Water-saturated ash formed viscous slurries, or lahars, that flooded river valleys, carrying away everything in their path.

When the eruption was finally over, the once cone-like peak of Mt. St. Helens had disappeared—the summit now lay 440 m lower, and the once snow-covered mountain was a gray mound with a large gouge in one side. The volcano came alive again in 2004, but did not explode.

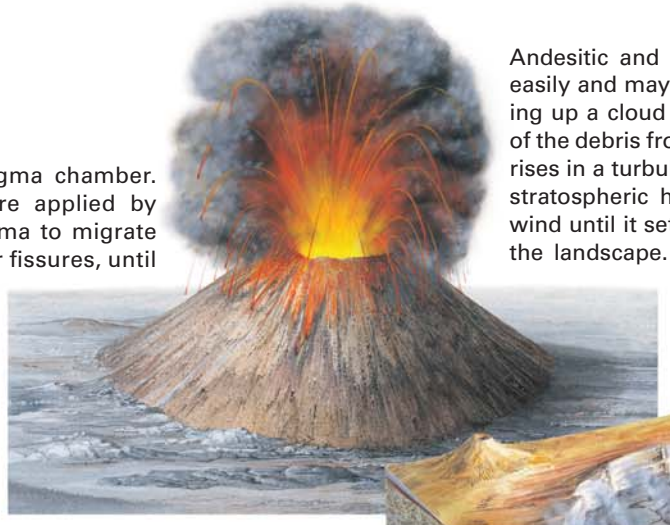
An even greater explosion happened in 1883. Krakatau, a volcano in the sea between Indonesia and Sumatra, where the Indian Ocean floor subducts beneath Southeast Asia, had grown to become a 9-km-long island rising 800 m (2,600 ft) above the sea. On May 20, the island began to erupt with a series of large explosions, yielding ash that settled as far as 500 km away. Smaller explosions continued through June and July, and steam and ash rose from the island, forming a huge black cloud that rained ash into the surrounding straits. Ships sailing by couldn't see where they were going, and their crews had to shovel ash off the decks.

Krakatau's demise came at 10 A.M. on August 27, perhaps when the volcano cracked and the magma chamber suddenly flooded with seawater. The resulting blast, five thousand times greater than the Hiroshima atomic bomb explosion, could be heard as far as 4,800 km away, and subaudible sound waves traveled around the globe seven times. Giant waves pushed out by the explosion slammed into coastal towns, killing over 36,000 people. Near the volcano, a layer of ash up to 40 m thick accumulated. When the air finally cleared, Krakatau was gone, replaced by a submarine caldera some 300 m deep (**Fig. Bx5.1d**). All told, the eruption shot 20 cubic km of rock into the sky. Some ash reached elevations of 27 km. Because of this ash, people around the world could view spectacular sunsets during the next several years.

Volcanoes

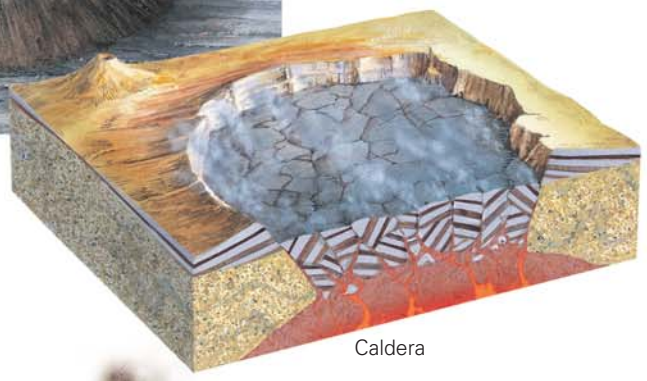
Beneath a volcano, magma rises to fill a magma chamber. Buoyancy of the magma, along with pressure applied by the weight of overlying crust, causes the magma to migrate upward, through either chimney-like conduits or fissures, until it erupts at a surface vent. An eruption is a sight to behold, and often a hazard to fear.

Once molten rock has erupted at the surface, it is called lava. Some lava spills down the side of the volcano in a river of molten rock called lava flows. Lava may also fountain out of a vent. Eruptions may eject larger chunks as blocks or bombs. The nature of eruptions depends on the viscosity of the lava. Basaltic lava tends to flow easily.



Cinder Cone

Andesitic and rhyolitic lava can't flow easily and may erupt explosively, blasting up a cloud of ash and lapilli. Some of the debris from an explosive eruption rises in a turbulent, convecting cloud to stratospheric heights, to be blown by wind until it settles like snow or hail on the landscape. Denser portions of the eruption column collapse and surge down the flanks of the volcano



Caldera



Vulcanian eruptions occur when a buildup of gas and magma explodes.



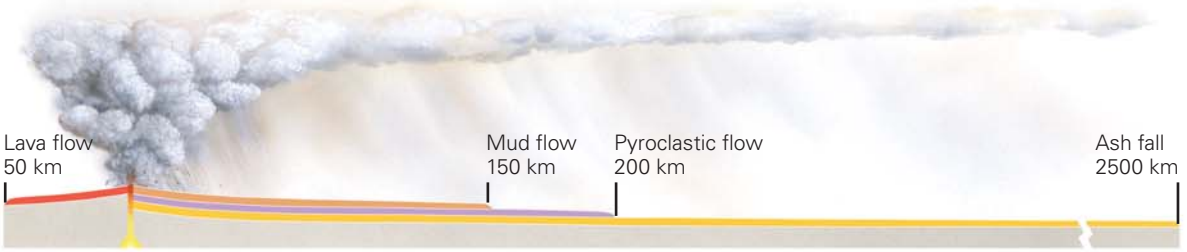
Strombolian crater explosions frequently burst through thinly crusted lava.



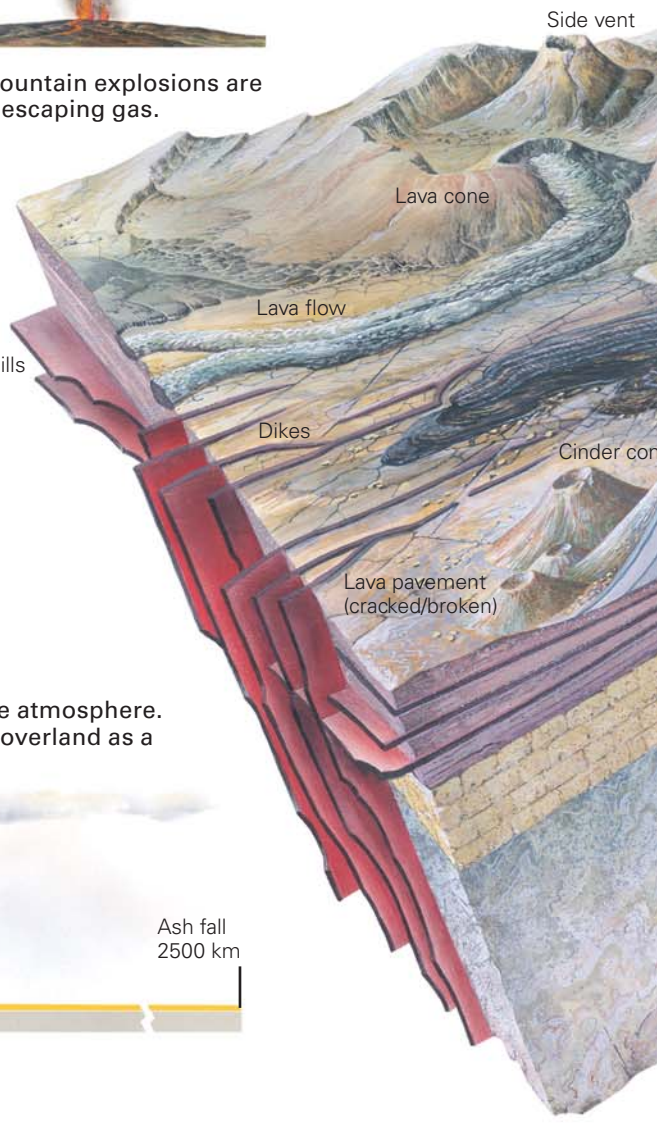
Hawaiian fountain explosions are caused by escaping gas.



Plinean explosions shoot a huge column of pumice fragments up to 50 km into the atmosphere. The ash fall rains down and the column collapses back around the vent, traveling overland as a pyroclastic flow.

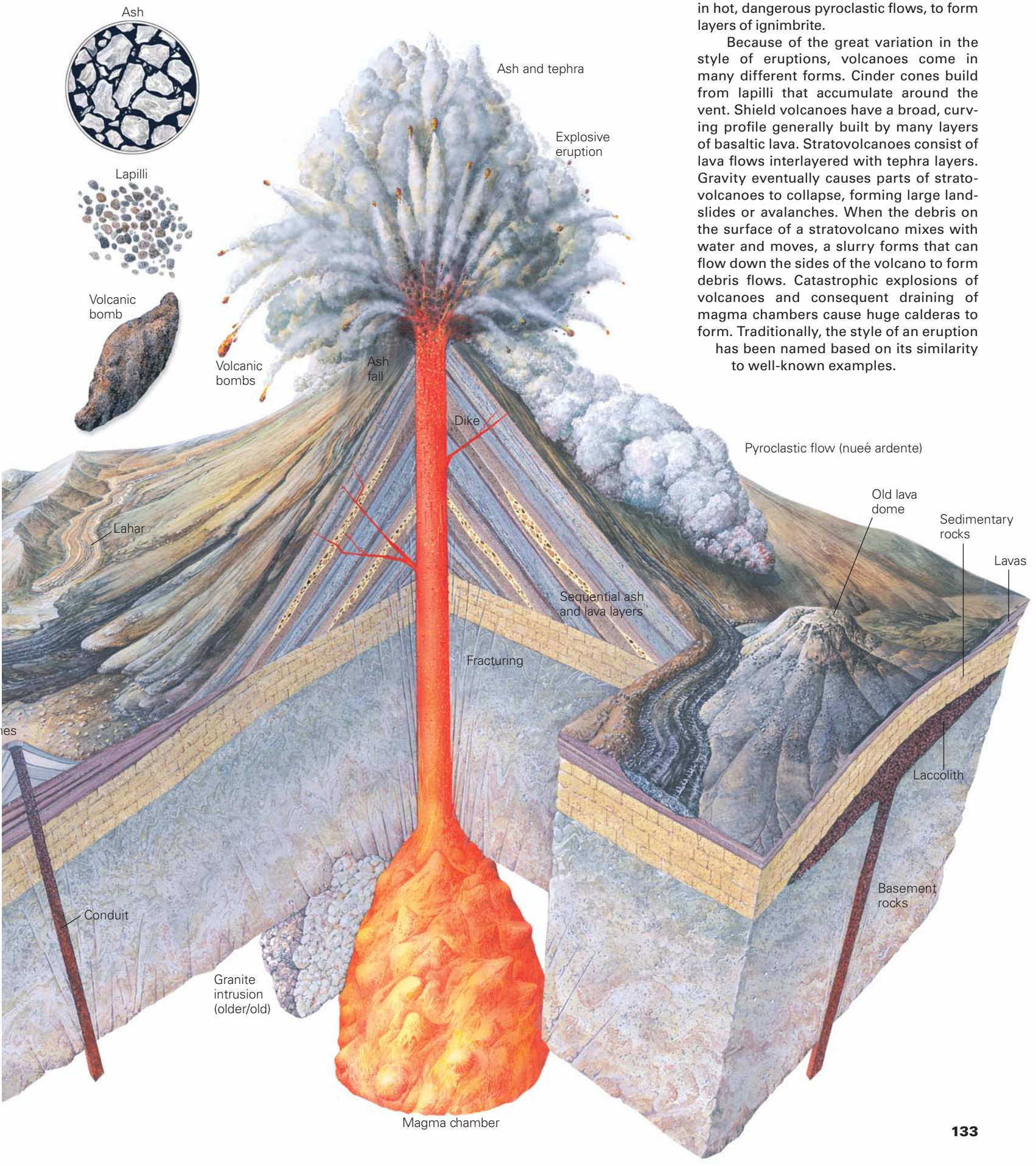


The distance volcanic hazards can travel from an eruption.



in hot, dangerous pyroclastic flows, to form layers of ignimbrite.

Because of the great variation in the style of eruptions, volcanoes come in many different forms. Cinder cones build from lapilli that accumulate around the vent. Shield volcanoes have a broad, curving profile generally built by many layers of basaltic lava. Stratovolcanoes consist of lava flows interlayered with tephra layers. Gravity eventually causes parts of stratovolcanoes to collapse, forming large landslides or avalanches. When the debris on the surface of a stratovolcano mixes with water and moves, a slurry forms that can flow down the sides of the volcano to form debris flows. Catastrophic explosions of volcanoes and consequent draining of magma chambers cause huge calderas to form. Traditionally, the style of an eruption has been named based on its similarity to well-known examples.



5.4 Relation of Volcanism to Plate Tectonics

Different styles of volcanism occur at different locations on Earth. Most eruptions occur along plate boundaries, but major eruptions also occur at hot spots (Fig. 5.12). We'll now look at the settings in which eruptions occur, in the context of plate tectonics theory and see why different kinds of volcanoes form in different settings.

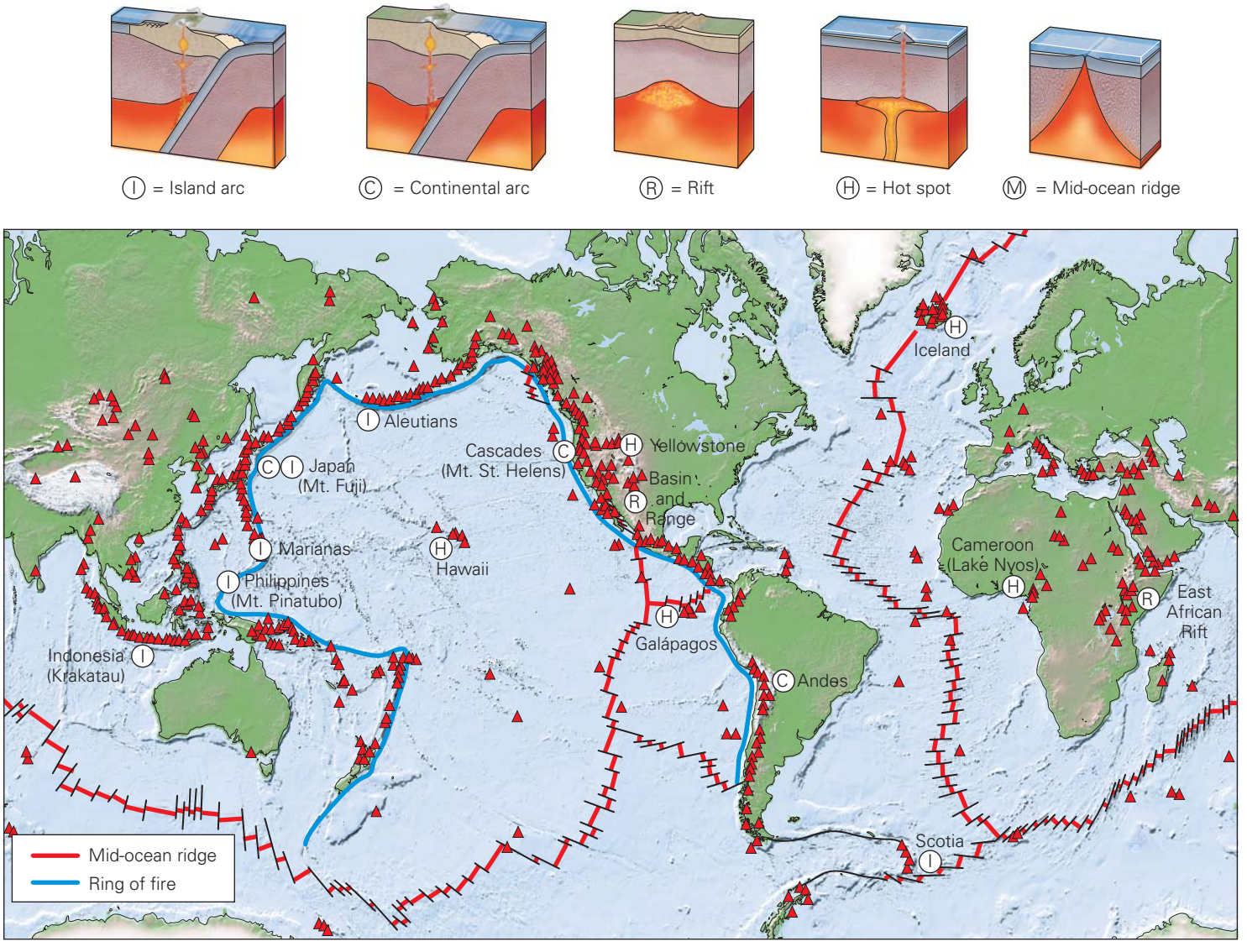
Mid-Ocean Ridges

Products of mid-ocean ridge volcanism cover 70% of our planet's surface. We don't generally see this volcanic activity, however, because the ocean hides most of it beneath a blanket of water. Mid-ocean ridge volcanoes, which develop along fissures parallel to the ridge axis, are not all continuously active. Each one turns on and off in a time scale measured in tens to hundreds of years. They erupt basalt which, because it cools so quickly underwater, forms pillow-lava mounds. Water that heats up as it circulates through the crust near the magma chamber bursts out of hydrothermal (hot-water) vents along these mounds. As mentioned in Chapter 2, these vents are called black smokers.

Convergent Boundaries

Most of the subaerial volcanoes on Earth lie along convergent plate boundaries (subduction zones). Subduction zones border over 60% of the Pacific Ocean, creating a 20,000-km-long chain of volcanoes known as the Ring of Fire. Typically, individual volcanoes in volcanic arcs lie about 50 to 100 km apart.

FIGURE 5.12 A map showing the distribution of volcanoes around the world and the basic geologic settings in which volcanoes form, in the context of plate tectonics theory.



Some of these volcanoes grow on oceanic crust and become volcanic island arcs, such as the Marianas of the western Pacific. Others grow on continental crust, building continental volcanic arcs such as the Cascade volcanic chain of Washington and Oregon or the Andes chain of South America.

Some of the lava that erupts at volcanic arcs consists of basalt derived by partial melting of the asthenosphere. At times when basaltic lava erupts, arc volcanoes display effusive activity. But, as discussed in Chapter 4, some of the lava that erupts at arcs—particularly at continental arcs—is andesitic or rhyolitic. When these viscous lavas are erupting, arc volcanoes display explosive activity. Over the life of a volcano, effusive and explosive activity may alternate. As a result, the volcaniclastic debris erupted at one time may later be cloaked by a shell of hard lava, and thus will be protected from erosion. Eventually, arc volcanism can yield large stratovolcanoes, such as the elegant symmetrical cone of Mt. Fuji (see Fig. 5.10c). Periods of growth, however, may be interrupted by explosions that leave behind a blasted-apart hulk like Mt. St. Helens (see Box 5.1).

Continental Rifts

Due to the diversity of magmas that can form beneath rifts, rifts can host both basaltic fissure eruptions, in which curtains of lava fountain up or linear chains of cinder cones develop, and explosive rhyolitic volcanoes. In some places, they even host stratovolcanoes such as Mt. Kilimanjaro in Africa.

Oceanic Hot-Spot Volcanoes

When a hot-spot volcano first forms on oceanic lithosphere, basaltic magma erupts at the surface of the sea floor. At first, such submarine eruptions yield an irregular mound of pillow lava. With time, the volcano grows up above the sea surface and becomes an island. When the volcano emerges from the sea, the basalt lava that erupts no longer freezes so quickly, and thus flows as a thin sheet over a great distance. Thousands of thin basalt flows pile up, layer upon layer, to build a broad, dome-shaped shield volcano with gentle slopes (**Fig. 5.13**). As the volcano grows, portions of it can't resist the pull of gravity and slip seaward, creating large submarine slumps.

Continental Hot-Spot Volcanoes

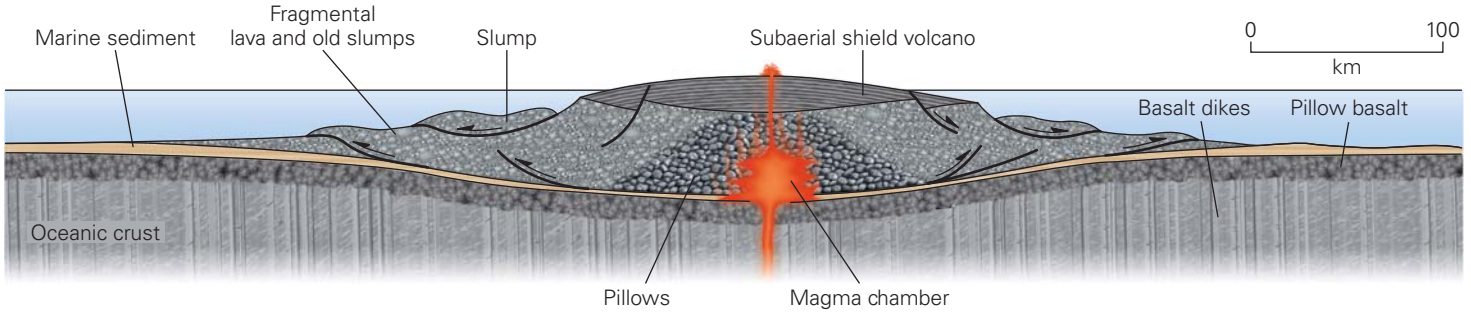
Yellowstone National Park lies at the northeast end of a string of calderas, the oldest of which, at the southwest end of the track, erupted 16 million years ago (**Fig. 5.14a, b**). Recent and ongoing activity beneath Yellowstone has yielded fascinating landforms, volcanic rock deposits, and geysers. Eruptions at the Yellowstone hot spot differ from those in Hawaii in an important way: unlike Hawaii, the Yellowstone hot spot erupts both basaltic lava and rhyolitic pyroclastic debris.

About 630,000 years ago, immense pyroclastic flows, as well as convective clouds of ash and pumice lapilli, blasted out of the Yellowstone region. Close to the eruption, ignimbrites up to tens of meters thick formed, and ash and lapilli from the giant cloud sifted down over the United States as far east as the Mississippi River (**Fig. 5.14c**). The eruption produced an immense caldera, up to 72 km across. When the debris settled, it blanketed an area of 2,500 square km with tuffs that, in the park, reached a thickness of 400 m. The park's name reflects the brilliant color of volcaniclastic debris (**Fig. 5.14d**). Magma remains beneath Yellowstone today, causing geyser activity, which will be discussed in Chapter 16.

Flood-Basalt Eruptions

In several locations around the world, huge sheets of low-viscosity lava erupted out of fissures and spread out in vast sheets. Geologists refer to the lava of these sheets as **flood basalt** (**Fig. 5.15**). Over time, many successive eruptions of

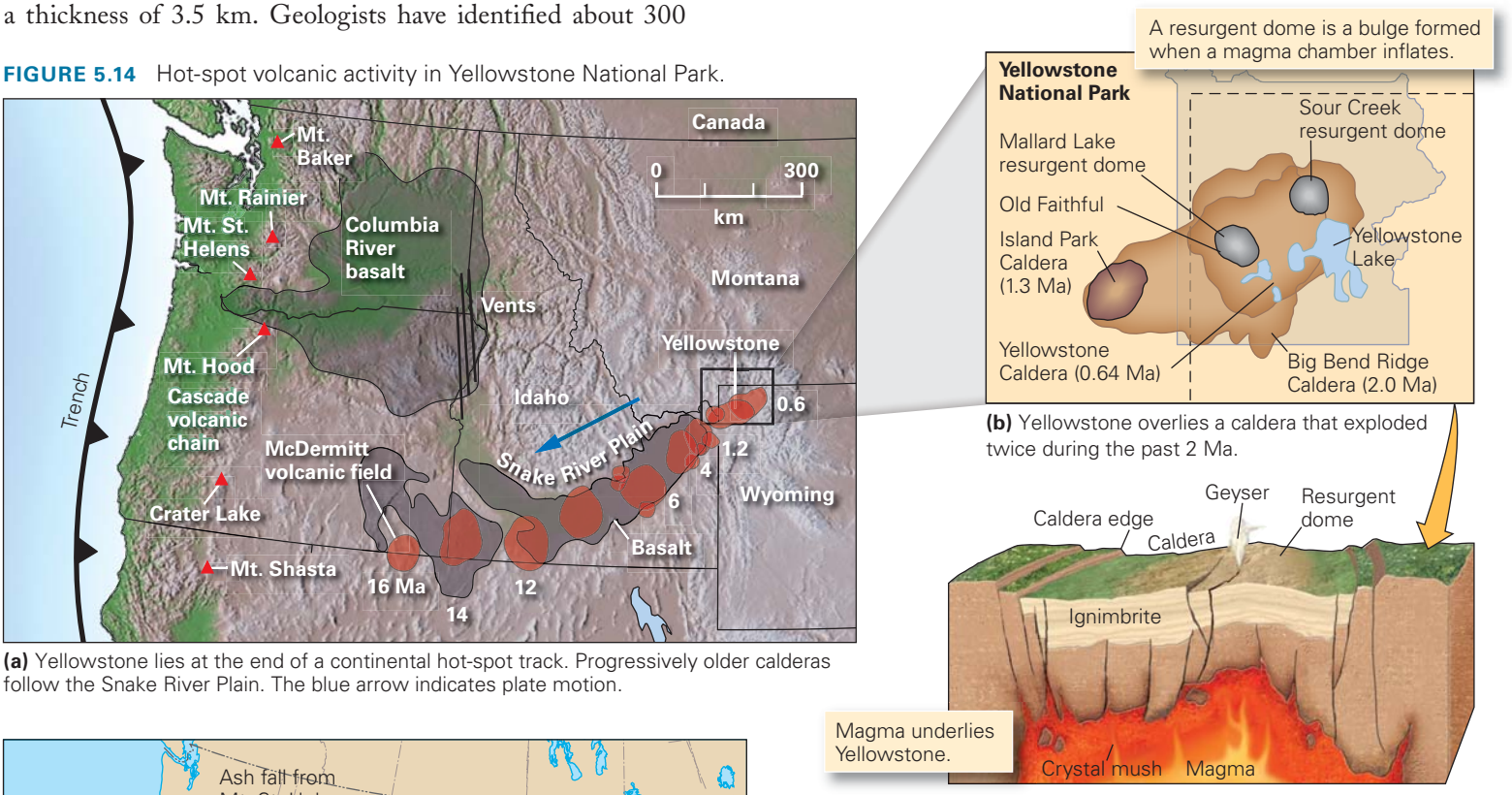
FIGURE 5.13 The interior of an oceanic hot-spot volcano is complicated. Initially, eruption produces pillow basalts. When the volcano emerges above sea level, it becomes a shield volcano. The margins of the island frequently undergo slumping, and the weight of the volcano pushes down the surface of the lithosphere. The Hawaiian islands exemplify this architecture.



flood basalt can build up a broad plateau. The aggregate volume of rock in such a plateau may be so great (over 175,000 km^3), that geologists also refer to the region as a **large igneous province** (**LIP**), as we noted in Chapter 4.

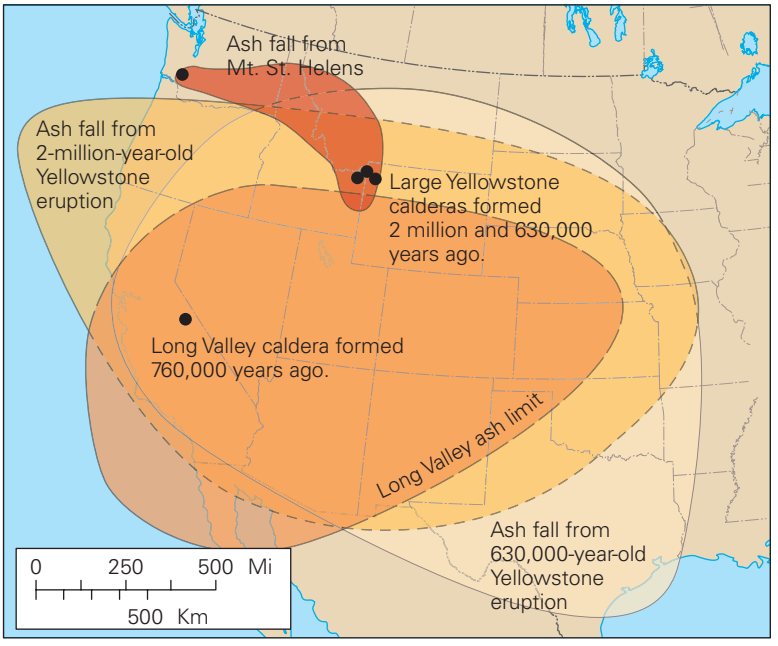
An example of a LIP, the Columbia River Plateau, occurs in Washington and Oregon (see Fig. 4.17). The basalt here, which erupted around 15 million years ago, reaches a thickness of 3.5 km. Geologists have identified about 300 individual flows in the Columbia River Plateau. Lava in some of these flows traveled great distances—up to 600 km—from its source. Eventually, basalt covered an area of 220,000 km. Even larger flood-basalt provinces occur in eastern Siberia (an occurrence known as the Siberian Traps), the Deccan Plateau of India, the Paraná region of Brazil, and the Karroo Plateau of south Africa.

FIGURE 5.14 Hot-spot volcanic activity in Yellowstone National Park.

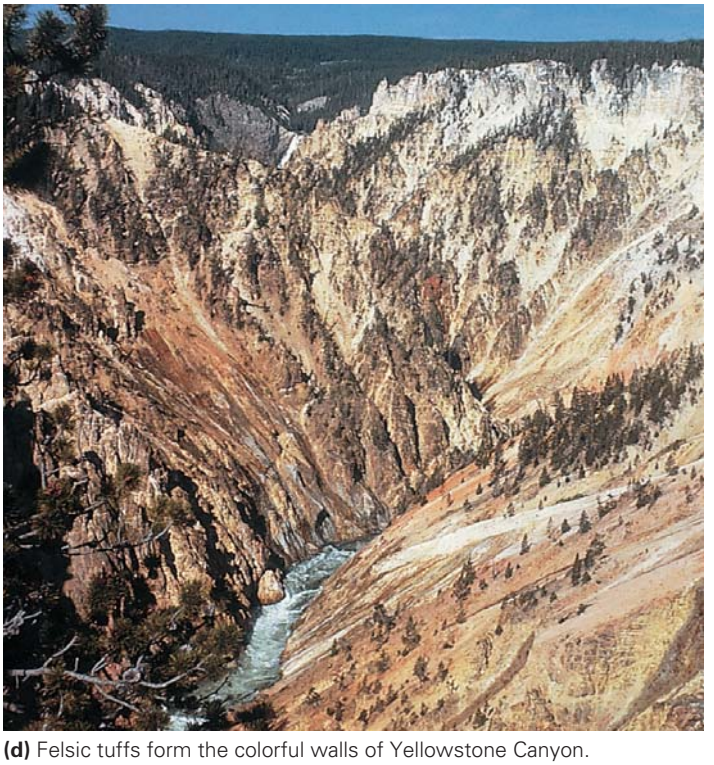


(a) Yellowstone lies at the end of a continental hot-spot track. Progressively older calderas follow the Snake River Plain. The blue arrow indicates plate motion.

(b) Yellowstone overlies a caldera that exploded twice during the past 2 Ma.



(c) The ash produced by explosions of the Yellowstone calderas covered vast areas—much more than Mt. St. Helens.



(d) Felsic tuffs form the colorful walls of Yellowstone Canyon.

FIGURE 5.15 Flood basalt layers exposed on the wall of a canyon in Idaho.



Iceland—a Hot Spot on a Ridge

Iceland is one of the few places on Earth where mid-ocean ridge volcanism has built a mound of basalt that protrudes above the sea. The island formed where a hot spot lies beneath the Mid-Atlantic Ridge—the presence of this hot spot (probably due to an underlying mantle plume) means that far more magma erupted here than beneath other places along the ridge. Because Iceland straddles a divergent plate boundary, it is being stretched apart, with faults forming as a consequence. Indeed, the central part of the island is a narrow rift, in which the youngest volcanic rocks of the island have erupted (Fig. 5.16a, b). This rift *is* the trace of the Mid-Atlantic Ridge. Faulting cracks the crust and so provides a conduit to a magma chamber. Thus, some eruptions on Iceland tend to be fissure eruptions, yielding either curtains of lava that are many kilometers long or linear chains of small cinder cones.

Not all volcanic activity on Iceland occurs subaerially. Some eruptions take place under glaciers and melt large amounts of ice. When the meltwater bursts through the edge of the glacier it becomes a devastating flood called a *jokulhlaup* in Icelandic.

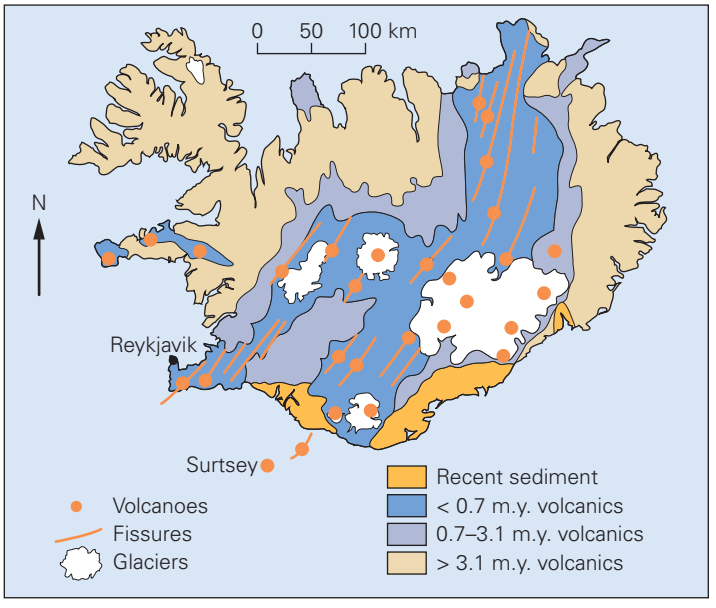
Take-Home Message

Most volcanic activity takes place on plate boundaries, but some occurs at hot spots. The style of eruption depends on the setting. The sea hides divergent-boundary volcanoes, which erupt pillow basalt. Volcanic arcs rise above sea level and may produce stratovolcanoes. Oceanic hot spots produce shield volcanoes. Continental hot spots and rifts produce both effusive and explosive eruptions.

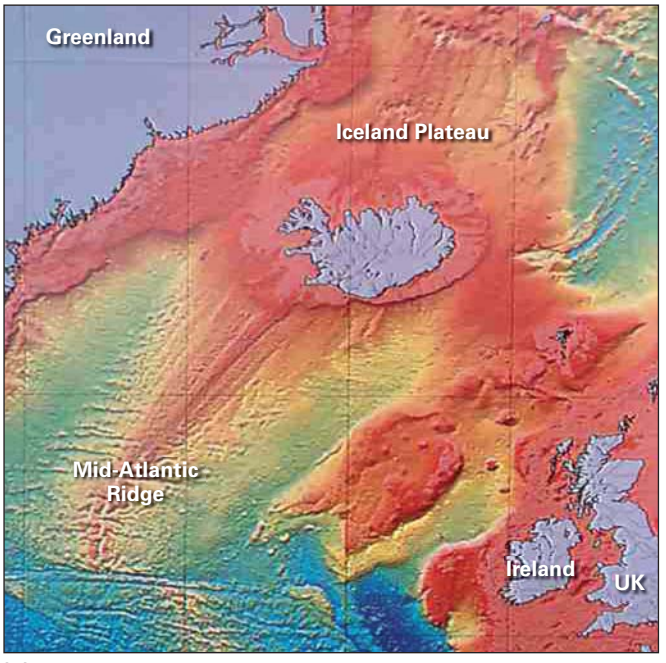
5.5 Beware: Volcanoes Are Hazards!

Like earthquakes, volcanoes are natural hazards that have the potential to cause great destruction to humanity, in both the

FIGURE 5.16 Iceland, a hot spot on the Mid-Atlantic Ridge.



(a) A geologic map of Iceland shows how the youngest volcanics occur in the central rift, effectively the on-land portion of the Mid-Atlantic Ridge.



(b) A bathymetric map shows that Iceland sits atop a huge plateau straddling the Mid-Atlantic Ridge. Red is shallower water; blue is deeper.

short term and the long term. According to one estimate, volcanic eruptions in the last two thousand years have caused about a quarter of a million deaths—much fewer than those caused by earthquakes, but nevertheless a sizable number. Considering the rapid expansion of cities, far more people live in dangerous proximity to volcanoes today than ever before, so if anything, the hazard posed by volcanoes has gotten worse—imagine if a large explosion were to occur next to a major city today! Let's now look at the different kinds of threats posed by volcanic eruptions.

Hazards Due to Eruptive Materials

Threat of flows. Basaltic lava from effusive eruptions can spread over a broad area (**Fig. 5.17a–d**). In Hawaii, recent lava flows have buried roads, housing developments, and vehicles. Although people have time to get out of the way of such flows, they might have to watch helplessly from a distance as an advancing flow engulfs their homes. Before the lava even touches it, the building bursts into flames from the intense heat. The most disastrous lava flow in recent times came from the 2002 eruption of Mt. Nyiragongo in the Congo. Lava flows traveled almost 50 km and flooded the streets in the city of Goma, encasing them under a 2-m-thick layer of basalt. The flows destroyed almost half the city.

Pyroclastic flows can move extremely fast (100 to 300 km/h) and are so hot (500° to 1000°C) that they represent a profound hazard to humans and the environment (**Fig. 5.17e**). They can flatten towns and devastate fields even though they leave only a few centimeters of ash and lapilli behind. People caught in the direct path of such flows are likely to be killed.

Threat of falling ash and lapilli. During a pyroclastic eruption, large quantities of ash and lapilli erupt into the air, later to fall back to Earth (**Fig. 5.17f**). Close to the volcano, pumice and lapilli tumble out of the sky; these materials can accumulate into a blanket up to several meters thick. When rain saturates the ash with water, the sodden mass can cause roofs and power lines to collapse. Winds can carry fine ash over a broad region. In the Philippines, for example, a typhoon spread air-fall ash from the 1991 eruption of Mt. Pinatubo so that it covered a 4,000-square-km area (**Fig. 5.17g**). Ash buries crops, may spread toxic chemicals that poison the soil, and insidiously infiltrates machinery, causing moving parts to wear out.

Threat to aircraft. Fine ash from an eruption can also present a hazard to airplanes. Like a sandblaster, the sharp, angular shards of ash abrade turbine blades, greatly reducing engine efficiency. The ash, along with sulfuric acid formed from the volcanic gas, scores windows and damages the fuselage. Also, when heated inside a jet engine, the ash melts, creating a liquid that coats interior parts of the engine and freezes to glass, coating temperature sensors, which falsely indicate that the engines are overheating so they automatically shut down.

Encounters between airliners and volcanic plumes have led to terrifying incidents. In 1982, a British Airways 747 flew through the ash cloud above a volcano in Java. The windshield turned opaque and all four engines failed. For 13 minutes, the plane silently glided earthward, dropping from 11.5 km (37,000 ft). As the pilots frantically tried to restart at 3.7 km (12,000 ft), the engines cooled sufficiently that they prepared to ditch at sea. Suddenly, the engines roared back to life and the plane headed for a landing in Jakarta. There, without functioning instruments, the pilot squinted out an open side window to see the runway, and brought the plane safely to a halt. A similar event happened between a KLM 747 and the eruptive cloud of Redoubt Volcano in Alaska in 1989.

Because of the lessons learned from such incidents, the 2010 eruption of the Eyjafjallajökull volcano in Iceland had a profound impact on air traffic. All told, the eruption sent about 0.25 cubic km of pyroclastic material up into the air. The jet stream, a high-altitude current of rapidly moving air, was passing over Iceland at the time of the eruption and thus dispersed the ash throughout European air space. Because of concern that this ash could damage planes, officials shut down almost all air traffic across Europe for 6 days. The closure directly cost airlines $200 million/day, disrupted travel plans for countless passengers, and halted shipment of everything from electronic goods to flowers, thus impacting economies worldwide.

Other Hazards Related to Eruptions

Threat of the blast. Most exploding volcanoes direct their fury upward. But some, like Mt. St. Helens, explode sideways. The forcefully ejected gas and ash, like the blast of a bomb, flattens everything in its path. In the case of Mt. St. Helens, the region around the volcano had been a beautiful pine forest; but after the eruption, the once-towering trees were stripped of bark and needles and lay scattered over the hill slopes like matchsticks (see Box 5.1).

Threat of landslides. Eruptions commonly trigger large landslides along a volcano's flanks. The debris, composed of ash and solidified lava that erupted earlier, can move quite fast (250 km per hour) and far. During the eruption of Mt. St. Helens, 8 billion tons of debris took off down the mountainside, careened over a 360-m-high ridge, and tumbled down a river valley, until the last of it finally came to rest over 20 km from the volcano.

Threat of lahars. When volcanic ash and other debris mix with water, the result is a lahar that resembles very wet concrete.

FIGURE 5.17 Hazards due to lava and ash from volcanic eruptions.

Lava Flows



(a) A lava flow reaches a house in Hawaii and sets it on fire.



(b) Lava from Mt. Etna threatens a town and olive grove in Sicily.



(c) Residents rescue household goods after a lava flow filled the streets of Goma, along the East African Rift.



(d) This empty school bus was engulfed by lava in Hawaii.

Pyroclastic Debris



(e) A pyroclastic flow from the 1991 eruption of Mt. Pinatubo chases a fleeing vehicle.



(e) Astronauts in the International Space Station observed the ash cloud erupted by the Sarychev Volcano (Kurile Islands) pushing up through high-altitude clouds in 2009.



(g) A blizzard of ash fell from the cloud erupted by Mt. Pinatubo in the Philippines.

A lahar can move downslope at speeds of over 50 km per hour. Because lahars are denser and more viscous than clear water, they pack more force than clear water and can literally carry away everything in their path. The lahars of Mt. St. Helens traveled along existing drainages for more than 40 km from the volcano. When they had passed, they left a gray and barren wake of mud, boulders, broken bridges, and crumpled houses, as if a giant knife had scraped across the landscape.

Lahars may develop in regions where snow and ice cover an erupting volcano, for the eruption melts the snow and ice, thereby creating a supply of water. Perhaps the most destructive lahar of recent times accompanied the eruption of the snow-crested Nevado del Ruiz in Colombia on the night of November 13, 1985. The lahar surged down a valley like a 40-m-high wave, hitting the sleeping town of Armero, 60 km from the volcano. Ninety percent of the buildings in the town vanished, replaced by a 5-m-thick layer of mud, which now entombs the bodies of 25,000 people (**Fig. 5.18a**).

Threat of earthquakes. Earthquakes accompany almost all major volcanic eruptions, for the movement of magma breaks rocks underground. Such earthquakes may trigger landslides on the volcano's flanks and can cause buildings to collapse and dams to rupture, even before the eruption itself begins.

Threat of tsunamis (giant waves). Where explosive eruptions occur in the sea or along a coast, the blast and the underwater collapse of a caldera or giant landslides from ocean island volcanoes can generate huge sea waves, or tsunamis, tens of meters high. Most of the 36,000 deaths attributed to the 1883 eruption of Krakatau were not due to ash or lava, but rather to tsunamis that slammed into nearby coastal towns.

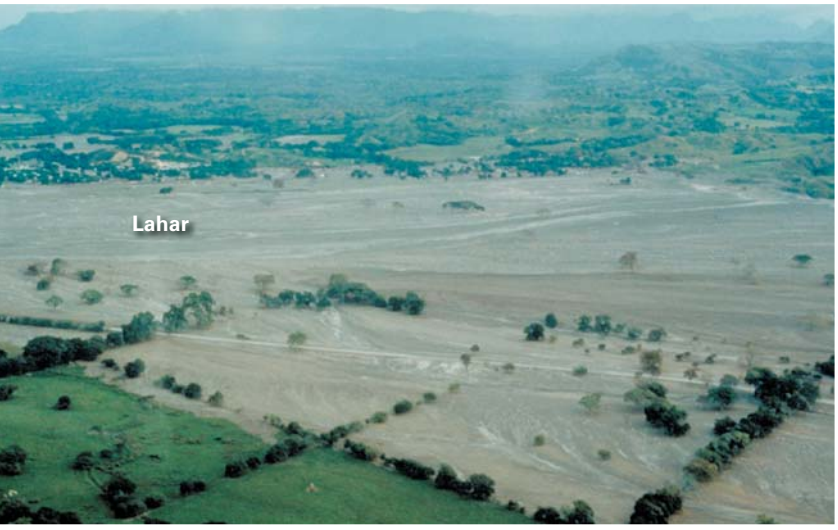
Threat of gas and aerosols. We have already seen that volcanoes erupt not only solid material but also large quantities of gases such as water vapor, carbon dioxide, sulfur dioxide, and hydrogen sulfide. Usually the gas eruption accompanies the lava and ash eruption, with the gas contributing only a minor part of the calamity. But occasionally the gas alone snuffs out life in its path without causing any other damage. Such an event occurred in 1986 near Lake Nyos in western Africa.

Lake Nyos is a small but deep lake filling the crater of an active volcano in Cameroon. Though only 1 km across, the lake reaches a depth of over 200 m. Because of its depth, the cool bottom water of the lake does not mix with warm surface water. Carbon dioxide gas slowly bubbles out of cracks in the floor of the crater and dissolves in the cool bottom water. Apparently, by August 21, 1986, the bottom water had become supersaturated in carbon dioxide. On that day, perhaps because a landslide or wind disturbed the water, the lake "burped" and expelled a forceful froth of CO_2 bubbles. Because it is denser than air, this invisible gas flowed down the flank of the volcano and spread out over the countryside for a distance of about 23 km before dispersing. Although not toxic, carbon dioxide cannot provide oxygen for metabolism or oxidation. When the gas cloud engulfed the village of Nyos, it quietly put out cooking fires and suffocated the sleeping inhabitants. The next morning, the landscape looked exactly as it had the day before, except for the lifeless bodies of 1,742 people and about 6,000 head of cattle (**Fig. 5.18b**).

Take-Home Message

Volcanoes can be dangerous! The lava flows, pyroclastic debris, explosions, mudflows (lahars), landslides, earthquakes, and tsunamis that can be produced during eruptions can destroy cities and farmland. Ash that enters the air can be a hazard for air travel.

FIGURE 5.18 Hazards due to lahars and gas.



(a) A lahar completely buried Armero, Colombia.



(b) Cattle died where they stood, due to CO_2 from Lake Nyos, Cameroon.

5.6 Protection From Vulcan's Wrath

Volcanic eruptions are a natural hazard of extreme danger. Can anything be done to protect lives and property from this danger? The answer is yes. Below, we first examine the evidence that geologists use to determine if a volcano has the potential to erupt and then we consider the suite of observations that may allow geologists to predict the timing of an eruption.

Active, Dormant, and Extinct Volcanoes

Geologists refer to volcanoes that are erupting, have erupted recently, or are likely to erupt soon as **active volcanoes** and distinguish them from **dormant volcanoes**, which have not erupted for hundreds to thousands of years but may erupt again in the future. Volcanoes that were active in the geologic past but have shut off entirely and will not erupt ever again are called **extinct volcanoes**. As examples, geologists consider Hawaii's Kilauea to be active, for it currently is erupting and has erupted frequently during recorded history. In contrast, Mt. Rainier in the Cascades last erupted centuries to millennia ago, but since subduction continues along the western edge of Oregon and Washington, the volcano could erupt in the future, so it is considered dormant. Devils Tower, in eastern Wyoming, is the remnant of a shallow igneous intrusion, formed beneath a volcano and subsequently exposed by erosion (**Fig. 5.19**). Eastern Wyoming was a volcanic region at the time the magma of Devils Tower intruded, tens of millions of years ago. But volcanism could not happen again in this region because the geologic cause for volcanism no longer exists there. Thus, we can say volcanism in the Devils Tower area is extinct.

How do you determine if a volcano is active, dormant, or extinct? One way is to examine the historical record. Another is to determine the age of erupted rocks, and to search for evidence that the volcano still lies within a tectonically active area. Finally, you can examine the landscape character of the volcano. Specifically, the shape (shield, stratovolcano, or cinder cone) of an active volcano depends primarily on the eruptive style, because at an erupting volcano, the process of construction happens faster than the process of erosion. But once a volcano stops erupting, erosion attacks. The rate at which erosion destroys a volcano depends on whether it's composed of pyroclastic debris or lava. Cinder cones and ash piles can wash away quickly. In contrast, composite or shield volcanoes, which have been armor-plated by lava flows, can withstand the attack of water and ice for quite some time. In the end, however, erosion wins out, and you can distinguish a dormant volcano from an active volcano by the extent to which river or glacial valleys have been carved into its flanks (**Fig. 5.20**). In some cases, the softer exterior of a volcano completely erodes away, leaving behind the plug of harder frozen magma that once lay within or beneath the volcano, as well as the network of dikes that radiate from this plug. You can see good examples of such landforms at Shiprock, New Mexico (**See for Yourself E**).

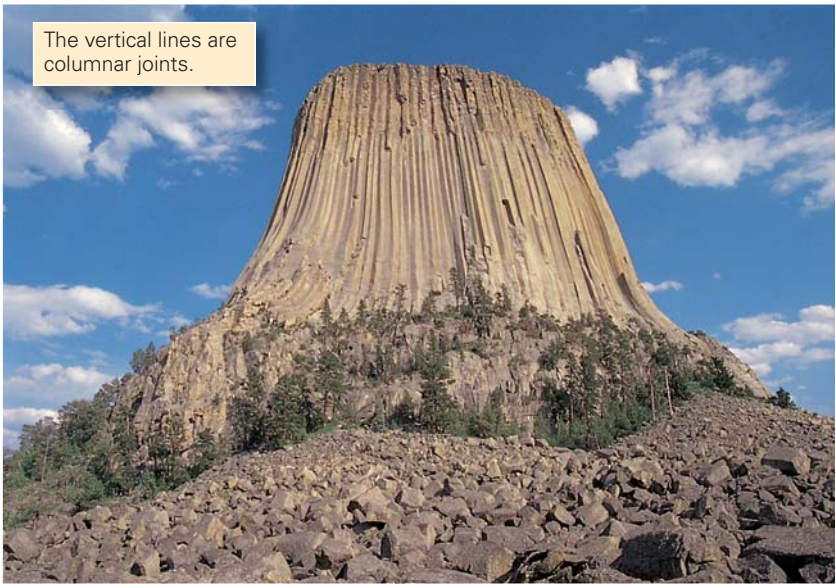


FIGURE 5.19 Devils Tower, Wyoming, is not an eroded volcano but probably an intrusion into sedimentary rocks beneath a volcano. It has been exposed by erosion. Volcanism here is extinct.

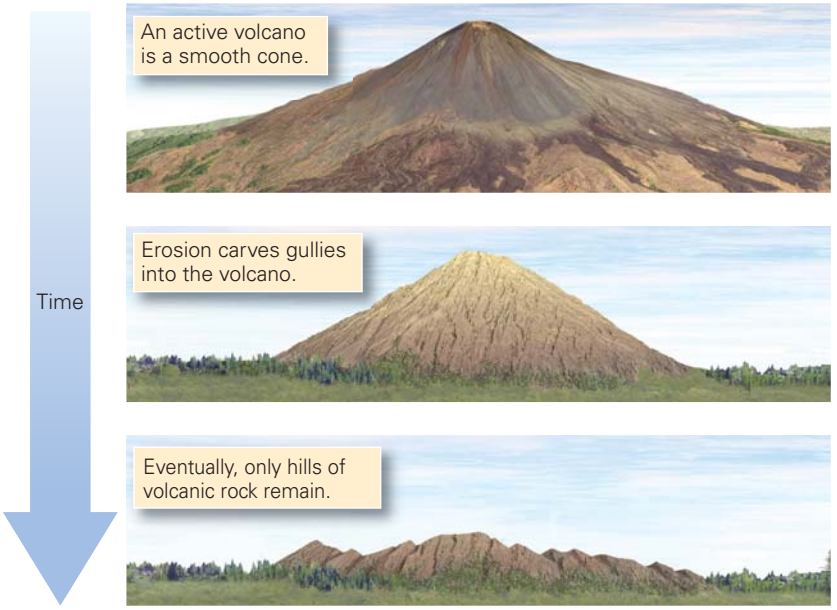
Predicting Eruptions

Predicting the time of an eruption decades or even years in advance is impossible. The only way to constrain a *long-term* prediction is to determine the recurrence interval (the average time between eruptions). If the geologic record indicates that eruptions at a particular volcano happen on average every 10 ± 3 years, then a volcano that hasn't erupted for more than 10 years may well erupt in the next few. If a volcano erupts, on average, every 2,000 ± 600 years, then a volcano that erupted two centuries ago might be reasonably safe. The recurrence interval just gives a sense of the probability, and surprises happen.

Did you ever wonder . . .
could a volcano erupt beneath London?

Short-term (days to weeks to months) predictions of impending volcanic activity, unlike short-term predictions of earthquakes, are actually feasible. Some volcanoes send out distinct warning signals announcing that an eruption may take place very soon, for as magma squeezes into the magma

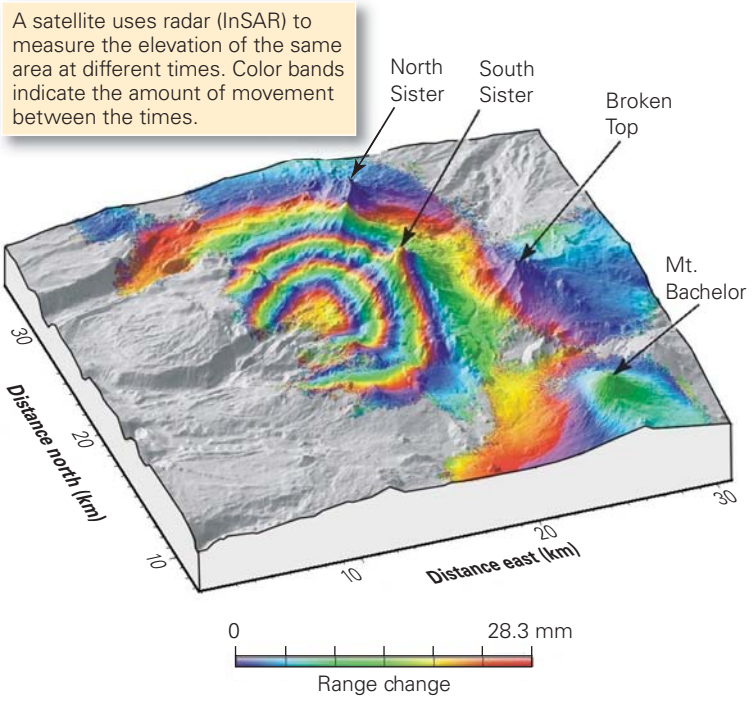
FIGURE 5.20 The shape of a volcano changes as it is eroded.



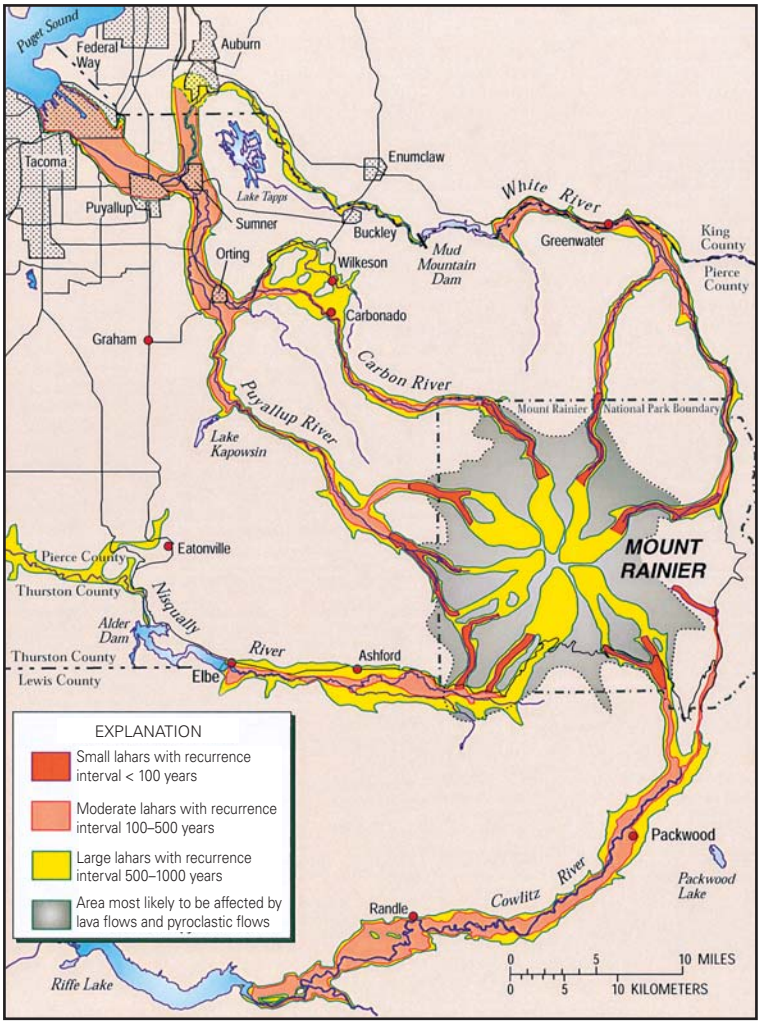
chamber, it causes a number of changes that geologists can detect. These include:

- *Earthquake activity*: Movement of magma generates vibrations in the Earth. When magma flows into a volcano, rocks surrounding the magma chamber crack, and blocks slip with respect to each other. Such cracking and shifting also causes earthquakes. Thus, in the days or weeks preceding an eruption, the region between 1 and 7 km beneath a volcano becomes seismically active.
- *Changes in heat flow*: The presence of hot magma increases the local heat flow, the amount of heat passing up through rock. In some cases, the increase in the heat flow melts snow or ice on the volcano, triggering floods and lahars even before an eruption occurs.
- *Changes in shape*: As magma fills the magma chamber inside a volcano, it pushes outward and can cause the surface of the volcano to bulge; the same effect happens when you blow into a bal-

FIGURE 5.21 Studies designed to mitigate volcanic disasters in the Cascade volcanic chain, western USA.



(a) Satellite radar measurements of the Three Sisters Wilderness in Oregon, indicate that the region centered over the concentric bands is moving up rapidly, due to intrusion of magma below. Each rainbow band (from red to blue) represents ~28 mm of uplift. So the center of the bulls-eye has gone up over 8 cm relative to the edge.



(b) A volcanic hazard assessment map for Mt. Rainier, Washington, showing the regions that might be affected by flows and lahars.

loon. Geologists now use laser sighting, accurate tiltmeters, surveys using the global positioning system (GPS), and a technique called satellite interferometry (InSAR), which uses radar beams emitted by satellites to measure elevation changes, to detect modification of a volcano's shape due to the rise of magma (Fig. 5.21a).

- *Increases in gas and steam emission*: Even though magma remains below the surface, gases bubbling out of the magma, or steam formed by the heating of groundwater by the magma, percolate upward through cracks in the Earth and rise from the volcanic vent. So an increase in the volume of gas emission, or of new hot springs, may indicate that magma has entered the ground below.

Because geologists can determine when magma has moved into the magma chamber of a volcano, government agencies now send monitoring teams to a volcano at the first sign of activity. These teams issue warnings if activity appears to increase.

Mitigating Volcanic Hazards

Danger assessment maps. Let's say that a given active volcano has the potential to erupt in the near future. What can we do to prevent the loss of life and property? Since we can't prevent the eruption, the first and most effective precaution is to define the regions that can be directly affected by the eruption—to compile a volcanic-hazard assessment map (Fig. 5.21b). These maps delineate areas that lie in the path of potential lava flows, lahars, or pyroclastic flows.

Evacuation. Unfortunately, because of the uncertainty of prediction, the decision about whether or not to evacuate is a hard one. In the case of Mt. St. Helens, hundreds of lives were saved in 1980 by timely evacuation, but in the case of Mt. Pelée in 1902, thousands of lives were lost because warning signs were ignored.

Diverting flows. In traditional cultures, people believed that gods or goddesses controlled volcanic eruptions, so when a volcano rumbled, they provided offerings to appease the deity. Sometimes, people have used direct force to change the direction of a flow or even to stop it. For example, during a 1669 eruption of Mt. Etna, an active volcano on the Italian island of Sicily, basaltic lava formed a glowing orange river that began to spill down the side of the mountain. When the flow approached the town of Catania, 16 km from the summit, 50 townspeople protected by wet cowhides boldly hacked through the chilled side of the flow to create an opening through which the lava could exit. They hoped thereby to cut off the supply of lava feeding the end of the flow, near their homes. Their strategy worked, and the flow began to ooze through the new hole in its side. But unfortunately, the diverted flow began to move toward the neighboring town of Paterno. Five hundred men of Paterno then chased away the Catanians so that the hole would not be kept open, and eventually the flow swallowed part of Catania.

Did you ever wonder . . .
can you redirect a lava flow?

More recently, people may use high explosives to blast breaches in the flanks of flows, and use bulldozers to build dams and channels to divert flows. Major efforts to divert flows from a 1983 eruption of Mt. Etna, and again in 1992, were successful. Inhabitants of Iceland used a particularly creative approach in 1973 to stop a flow before it overran a town—they sprayed cold seawater onto the flow to freeze it in its tracks (Fig. 5.22). The flow did stop short of the town, but whether this was a consequence of the cold shower it received remains unknown.

FIGURE 5.22 Firefighters pumping 6 million cubic meters of water on a lava flow in Iceland, in an effort to freeze it and stop it.



Take-Home Message

Volcanoes don't erupt continuously and don't last forever, so we can distinguish among active, dormant, and extinct volcanoes. Once a volcano ceases to erupt, erosion destroys its eruptive shape. Geologists can provide near-term predictions of eruptions so that people can take precautions.

5.7 Effect of Volcanoes on Climate and Civilization

In 1783, Benjamin Franklin was living in Europe, serving as the American ambassador to France. The summer of that year seemed to be unusually cool and hazy. Franklin, who was an

accomplished scientist as well as a statesman, couldn't resist seeking an explanation for this phenomenon, and learned that in June of 1783, a huge volcanic eruption had taken place in Iceland. He wondered if the "smoke" from the eruption had prevented sunlight from reaching the Earth, thus causing the cooler temperatures. Franklin reported this idea at a meeting, and by doing so, may well have been the first scientist ever to suggest a link between eruptions and climate.

Franklin's idea seemed to be confirmed in 1815, when Mt. Tambora in Indonesia exploded. Tambora's explosion ejected over 100 cubic km of ash and pumice into the air. The sky became so hazy that stars dimmed by a full magnitude. Temperatures dipped so low in the northern hemisphere that 1816 became known as "the year without a summer." The unusual weather of that year inspired artists and writers. For example, memories of fabulous sunsets and the hazy glow of the sky inspired the luminous and atmospheric quality that made the landscape paintings of the English artist J.M.W. Turner so famous (see Fig. 5.1a). Mary Shelley, trapped in her house by bad weather, wrote *Frankenstein*, with its numerous scenes of gloom and doom. Geoscientists have witnessed other examples of eruption-triggered coolness more recently. In the months following the 1883 eruption of Krakatau and the 1991 eruption of Pinatubo, global temperatures noticeably dipped.

How can a volcanic eruption create these cooling effects? When a large explosive eruption takes place, fine ash and aerosols (tiny liquid droplets) enter the stratosphere (**Fig. 5.23**). It takes only about two weeks for the ash and aerosols to circle the planet. They stay suspended in the stratosphere for many months to years, because they are above the weather and do not get washed away by rainfall. The resulting haze causes cooler average temperatures, for it keeps energy from reaching the Earth, but unlike greenhouse gases (such as CO_2), it does not prevent heat from escaping.

FIGURE 5.23 The ash cloud from the 2011 eruption of a volcano in the Puyehue-Cordón Caulle chain of Chile. The ash circled the globe within two weeks.



The largest eruption to have happened in the last million years of Earth's history took place at the Toba Volcano in Indonesia about 73,000 years ago. The explosion put out huge quantities of ash, some of which was nearly white, and covered much of southern Asia like a snowfall. In addition, the eruption injected a huge dose of aerosols into the atmosphere. The aerosols and ash diminished the solar radiation reaching the Earth, and the white ash on the ground reflected some of the radiation that did reach the planet back into space. The resulting cooling event may have cooled the atmosphere for a decade, possibly as long as 1,000 years. The duration of the cooling may have been sufficient to cause species of organisms to go extinct. Anthropologists have speculated that the event killed off all but 3,000 to 10,000 humans on Earth. Genetic studies suggest that a bottleneck in evolution occurred about the same time as the Toba eruption, in that all modern humans are descended from a single ancestor who lived about that time. If so, then the Toba eruption could have significantly impacted human evolution.

The observed effect of volcanic eruptions on the climate provides a model with which to predict the consequences of a nuclear war. Researchers have speculated that so much dust and gas would be blown into the sky in the mushroom clouds of nuclear explosions that a "nuclear winter" would ensue.

In more recent millennia, volcanic eruptions may have led to the demise of civilizations. For example, archeological research suggests that the Minoan culture, which thrived in the eastern Mediterranean during the Bronze Age (beginning 3000 B.C.E.), disappeared during the century following explosive eruptions of the Santorini volcano in 1645 B.C.E. All that remains of Santorini today is a huge caldera whose rim projects above sea level as the Greek island of Thera. Ash clouds, tsunamis, and earthquakes generated by Santorini may have so disrupted their daily life that the Minoan people moved elsewhere, leaving behind their elaborately decorated palaces.

Take-Home Message

The ash, gases, and aerosols produced by explosive eruptions can be blown around the globe. This material can cause significant global cooling. Climatic effects, as well as other consequences of eruptions, may have impacted human evolution and civilization.

5.8 Volcanoes on Other Planets

We conclude this chapter by looking beyond the Earth, for our planet is not the only one in the Solar System to have hosted volcanic eruptions. We can see the effects of volcanic activity on our nearest neighbor, the Moon, just by looking up on a

clear night. The broad darker areas of the Moon, the maria (singular *mare*, after the Latin word for sea), consist of flood basalts that erupted more than 3 billion years ago (Fig. 5.24a). Geologists propose that the flood basalts formed when huge meteors collided with the Moon, blasting out giant craters. Crater formation decreased the pressure in the Moon's mantle so that it underwent partial melting, producing basaltic magma that rose to the surface and filled the craters.

On Venus, about 22,000 volcanic edifices have been identified. Some of these even have caldera structures at their crests (Fig. 5.24b). Though no volcanoes currently erupt on Mars, the planet's surface displays a record of a spectacular volcanic past. The largest known mountain in the Solar System, Olympus Mons (Fig. 5.24c), is an extinct shield volcano on Mars. The base of Olympus Mons is 600 km across, and its peak rises 27 km above the surrounding plains.

Did you ever wonder . . .
is Earth the only planet with volcanoes?

Active volcanism currently occurs on Io, one of the many moons of Jupiter. Cameras in the *Galileo* spacecraft have recorded these volcanoes in the act of spraying plumes of sulfur gas into space (Fig. 5.24d) and have tracked immense, moving lava flows. Different colors of erupted material make the surface of this moon resemble a pizza. Researchers have proposed that the volcanic activity is due to tides: the gravitational pull exerted by Jupiter and by other moons alternately stretches and then squeezes Io, generating sufficient friction to keep Io's mantle hot. Geologists have also detected eruptions from moons of Saturn (Fig. 5.24e).

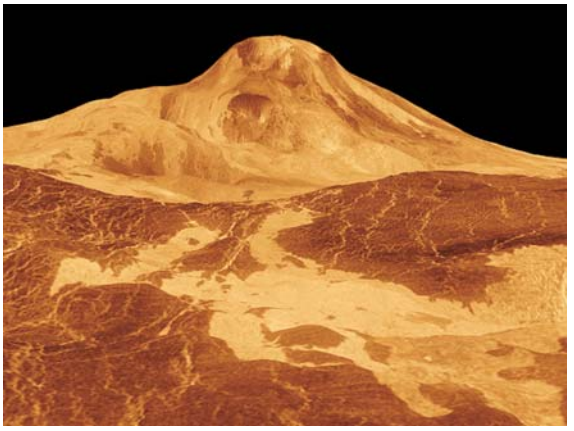
Take-Home Message

Space exploration reveals that volcanism occurs not only on Earth, but has also left its mark on other terrestrial planets and on the moons of giant planets. Satellites have detected active eruptions on moons of Jupiter and Saturn.

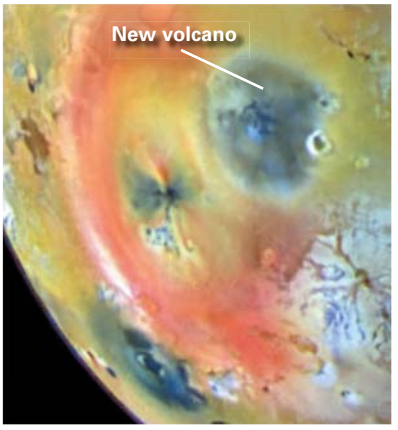
FIGURE 5.24 Volcanism on other planets and moons in the Solar System.



(a) Maria of the Moon were seas of basaltic lava.



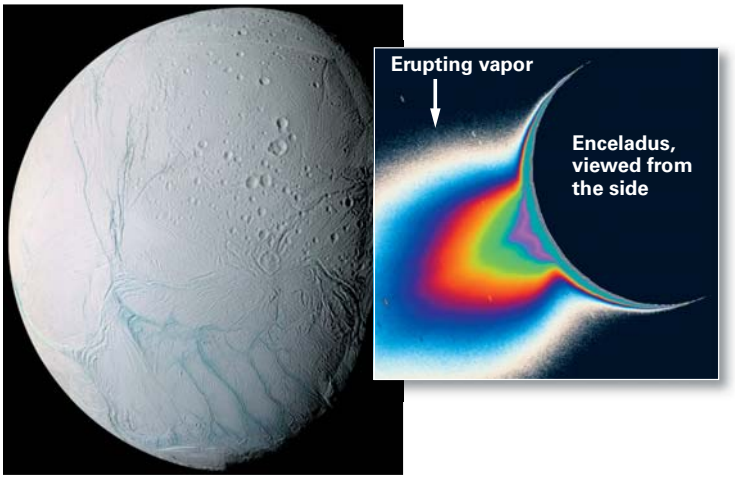
(b) A volcano rises above the plains of Venus.



(d) An active volcano erupts sulfur on Io, a moon of Jupiter.



(c) Olympus Mons rises 27 km above the surface of Mars. It's the largest volcano in our Solar System.



(e) Large cracks at the southern end of Enceladus, a moon of Saturn, erupt water vapor.

Chapter Summary

- Volcanoes are vents at which molten rock (lava), pyroclastic debris, gas, and aerosols erupt at the Earth's surface.
- The characteristics of a lava flow depend on its viscosity, which in turn depends on its temperature and composition.
- Basaltic lava can flow great distances. Pahoehoe flows have smooth, ropy surfaces, whereas a'a' flows have rough, rubbly surfaces. Andesitic and rhyolitic lava flows tend to pile into mounds at the vent.
- Pyroclastic debris includes powder-sized ash, marble-sized lapilli, and apple- to refrigerator-sized blocks and bombs. Some falls from the air, whereas some forms pyroclastic flows.
- Eruptions may occur at a volcano's summit or from fissures on its flanks. The summit of an erupting volcano may collapse to form a bowl-shaped depression called a caldera.
- A volcano's shape depends on the type of eruption. Shield volcanoes are broad, gentle domes. Cinder cones are steep-sided, symmetrical hills. Composite volcanoes (stratovolcanoes) can become quite large and consist of alternating layers of pyroclastic debris and lava.
- The type of eruption depends on the lava's viscosity and gas content. Effusive eruptions produce flows, whereas explosive eruptions produce pyroclastic debris.
- Different kinds of volcanoes form in different geologic settings as defined by plate tectonics theory.
- Volcanic eruptions pose many hazards: lava flows overrun roads and towns, ash falls blanket the landscape, pyroclastic flows incinerate towns and fields, landslides and lahars bury the land surface, earthquakes topple structures and rupture dams, tsunamis wash away coastal towns, and invisible gases suffocate people and animals.
- Eruptions can be predicted by earthquake activity, changes in heat flow, changes in shape of the volcano, and the emission of gas and steam.
- We can minimize the consequences of an eruption by avoiding construction in danger zones.
- Immense flood basalts cover portions of the Moon. The largest known volcano, Olympus Mons, towers over the surface of Mars. Satellites have documented evidence for eruptions on moons of Jupiter and Saturn.

Key Terms

a'a' (p. 121)
accretionary lapilli (p. 123)
active volcano (p. 141)
ash (p. 123)
block (p. 123)
blocky lava (p. 121)
bomb (p. 123)
caldera (p. 126)
cinder cone (p. 126)
columnar jointing (p. 121)
crater (p. 126)
dormant volcano (p. 141)
effusive eruption (p. 126)
eruptive style (p. 126)
extinct volcano (p. 141)
fissure (p. 126)
flood basalt (p. 135)
ignimbrite (p. 123)
lahar (p. 124)
lapilli (p. 123)
large igneous province (LIP) (p. 136)
lava tube (p. 121)
magma chamber (p. 126)
pahoehoe (p. 121)
pumice lapilli (p. 123)
pyroclastic debris (p. 123)
pyroclastic flow (p. 123)
scoria cone (p. 126)
shield volcano (p. 126)
stratovolcano (p. 126)
tephra (p. 123)
tuff (p. 123)
vesicle (p. 124)
volcanic debris flow (p. 123)
volcaniclastic deposit (p. 123)
volcano (p. 119)

Review Questions

1. Describe the three different kinds of material that can erupt from a volcano.
2. Contrast a pyroclastic flow with a lahar.
3. Describe the differences among shield volcanoes, stratovolcanoes, and cinder cones. How are these differences explained by the composition of their lavas and other factors?
4. Why do some volcanic eruptions consist mostly of lava flows, while others are explosive and do not produce flows?
5. What processes may lead to hot-spot eruptions?
6. How do continental-rift eruptions form flood basalts?
7. Contrast an island arc with a continental arc.
8. Identify some of the major volcanic hazards, and explain how they develop.
9. How do geologists predict volcanic eruptions?
10. Explain how steps can be taken to protect people from the effects of eruptions.

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

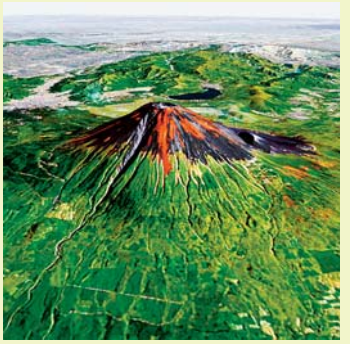
- An animation exercise on the formation of stratovolcanoes.
- A video exercise on propagating fissures.
- What a Geologist Sees exercises on volcano types and eruption products.

On Further Thought

11. The Long Valley Caldera, near the Sierra Nevada mountains, exploded about 700,000 years ago and produced a huge ignimbrite (a lapilli tuff deposited from vast pyroclastic density currents) called the Bishop Tuff. About 30 km to the northwest lies Mono Lake (see photo), with an island in the middle and a string of craters extending south from its south shore. Hot springs and tufa deposits can be found along the lake. You can see the lake on *Google Earth*™ at Latitude 37°59′56.58″N, Longitude 119°2′18.20″W. Explain the origin of Mono Lake. Do you think that it represents a volcanic hazard?



12. Mt. Fuji is a 3.6-km-high stratovolcano in Japan formed as a consequence of subduction (see photo). With *Google Earth*™, you can see the volcano at Latitude 35°21′46.72″N, Longitude 138°43′49.38″E. It contains volcanic rocks with a range of compositions, including some andesitic rocks. Why do andesites erupt at Mt. Fuji? Very little andesite occurs on the Marianas Islands, which are also subduction-related volcanoes. Why?



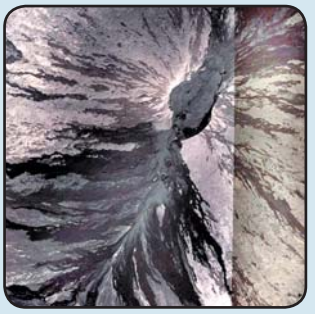
SEE FOR YOURSELF E. . . Volcanoes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet E of our **Geotours Workbook**.



Mt. St. Helens, Washington
Latitude 46°12′1.24″N,
Longitude 122°11′20.73″W

Mt. St. Helens, a stratovolcano of the Cascade volcanic arc, erupted explosively in 1980. This oblique view from 25 km elevation shows that the explosion blew away the north side of the mountain. Lahars incorporating ash from the eruption swept down nearby river valleys. Subsequent to the explosion, a new lava dome has grown in the crater.

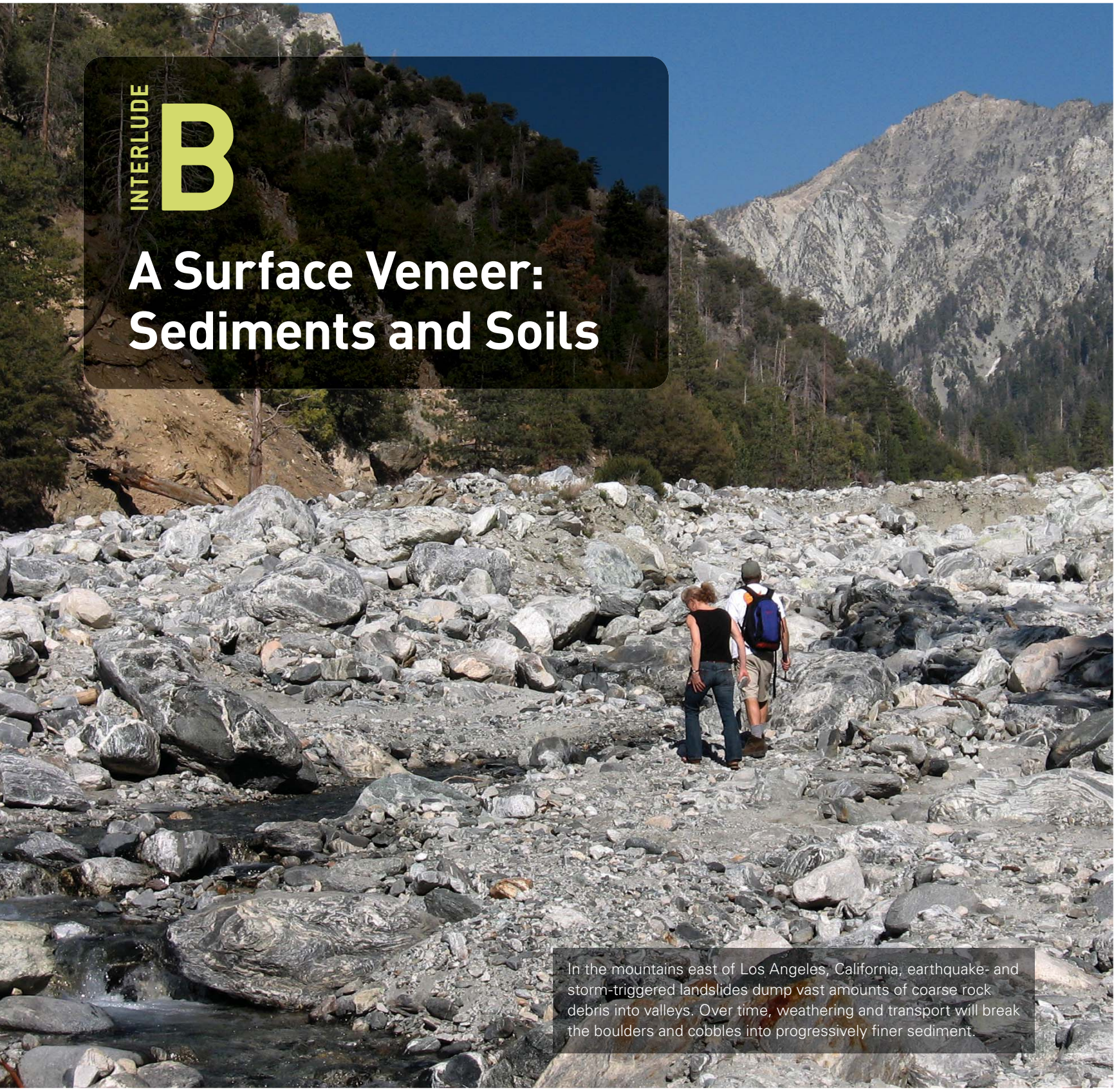


Mauna Loa, Hawaii
Latitude 19°27′0.50″N,
Longitude 155°36′2.94″W

Looking straight down from 25 km, you can see the NNE-trending crest of Mauna Loa, a shield volcano associated with the Hawaiian hot spot. A large, elliptical caldera dominates the view. Basaltic lava flows have spilled down the flank of the volcano.

INTERLUDE B

A Surface Veneer: Sediments and Soils



In the mountains east of Los Angeles, California, earthquake- and storm-triggered landslides dump vast amounts of coarse rock debris into valleys. Over time, weathering and transport will break the boulders and cobbles into progressively finer sediment.

B.1 Introduction

In the 1950s, the government of Egypt decided to build the Aswan High Dam to trap water of the Nile River in a huge reservoir before the water could reach the Mediterranean Sea. In the process of identifying a good site for the dam's foundation, geologists discovered that the present-day Nile River flows on the surface of a 1.5-km-thick layer of gravel, sand, and mud that fills what was once a canyon as large as the Grand Canyon (Fig. B.1). How could the river once have carved a canyon 1.5 km deep, and why did this canyon later fill with debris?

The origin of the pre-Nile canyon remained a mystery until the summer of 1970, when geologists began to study the material that forms the floor of the Mediterranean Sea. They expected to find layers consisting of the shells of plankton (tiny floating organisms) that had settled out of the water, or of clay that rivers had carried to the sea. To their surprise, however, they also found a 2-km-thick layer of halite and gypsum. Such minerals, types of salts, form when seawater dries up. The researchers proposed that to yield a salt layer that is 2 km thick, the entire Mediterranean would have had to dry up completely several times, with the sea refilling after each drying event. They soon realized that this discovery solved the mystery of the pre-Nile canyon. When the Mediterranean Sea dried up, the Nile River could cut downward, and produce a canyon. And when the sea refilled with water, this canyon flooded and filled with sand and gravel.

Why did the Mediterranean Sea dry up? Only 10% of its water comes from rivers, so for the Mediterranean Sea to remain full, water must flow in from the Atlantic Ocean through the Strait of Gibraltar. About 6 million years ago, the northward-drifting African Plate collided with the European Plate, forming a natural dam separating the Mediterranean from the Atlantic. At times when global sea level dropped, water stopped flowing over this dam from the Atlantic and the Mediterranean evaporated. The salt that had been dissolved in its water precipitated to form a solid deposit of halite and gypsum on the floor of the resulting basin, and the pre-Nile canyon formed. At times when sea level rose, water flooded in from the Atlantic into the Mediterranean, filling the basin again. About 5.5 million years ago, the Mediterranean rose to its present level, and gravel, sand, and mud carried by the Nile River filled the Nile canyon to its brim.

Geologists refer to the kinds of deposits just described—sand, mud, gravel, halite and gypsum layers, and shell fragments—as sediment. **Sediment**, broadly defined, consists of loose fragments of rocks or minerals broken off bedrock, mineral crystals that precipitate directly out of water, and shells or shell fragments.

Sediments are produced by the weathering (physical and chemical breakdown) of preexisting rock. They form a surface veneer, or "cover," over bedrock (Fig. B.2). This veneer ranges in thickness from nonexistent, in places where bedrock crops out at the Earth's surface, to several kilometers. Some sediments transform into soil, essential for life. In this interlude, we look at how weathering produces sediment, and how soils form and evolve from sediment or from rock.

FIGURE B.1 The present Nile River flows on sediment that filled a deep canyon, cut when the Mediterranean Basin was dry.

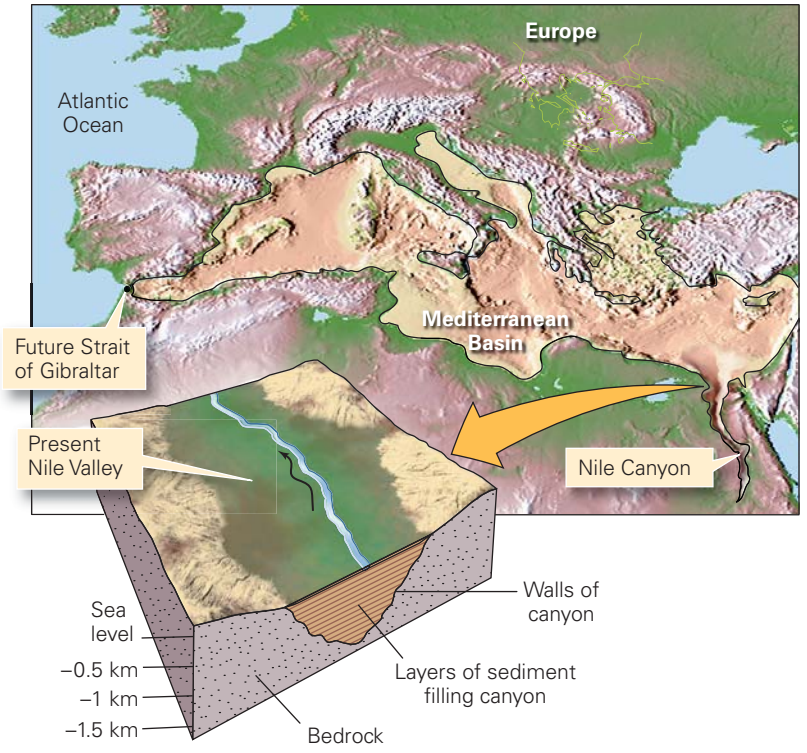


FIGURE B.2 A layer of unconsolidated sediment (sand, clay, and cobbles), topped by dark soil, overlies bedrock in this outcrop along the coast of western Ireland.



B.2 Weathering: Forming Sediment

Weathering refers to the combination of processes that break up and corrode solid rock, eventually transforming it into sediment. Geologists refer to rock that has not undergone weathering as unweathered or "fresh" (Fig. B.3). Rock exposed at the Earth's surface sooner or later crumbles away because of weathering. Just as a plumber can unclog a drain by using physical force (with a plumber's snake) or by causing a chemical reaction (with a dose of liquid drain opener), nature can attack rocks via two types of weathering: physical and chemical.

Physical Weathering

Physical weathering, sometimes referred to as mechanical weathering, breaks intact rock into unconnected *clasts* (grains or chunks), collectively called debris or detritus. Each size range of clasts has a name (Table B.1). Many different phenomena contribute to physical weathering, as described below.

Jointing. Rocks buried deep in the Earth's crust endure enormous pressure due to the weight of overlying rock or overburden. Rocks at depth are also warmer than rocks nearer the surface because of the Earth's geothermal gradient. Over long periods of time, moving water, air, and ice at the Earth's surface grind away and remove overburden, a process called **erosion**, so rock formerly at depth rises closer to the Earth's surface. As a result, the pressure squeezing this rock decreases, and the rock also becomes cooler. A change in pressure and temperature causes rock to change shape slightly. Such changes cause hard rock to break. Natural cracks that form in rocks due to removal of overburden or due to cooling (and for other reasons as well; see Chapter 9) are known as **joints**.

FIGURE B.3 The texture of granite changes as it weathers.



TABLE B.1 Clasts Are Classified by Grain Diameter

Boulders	More than 256 millimeters (mm)
Cobbles	Between 64 mm and 256 mm
Pebbles	Between 2 mm and 64 mm
Sand	Between 1/16 mm and 2 mm
Silt	Between 1/256 mm and 1/16 mm
Clay	Less than 1/256 mm

Almost all rock outcrops contain joints. Some joints are fairly planar, some curving, and some irregular. For example, large granite plutons may split into onion-like sheets along joints that lie parallel to the mountain face; this process is called exfoliation. Sedimentary rock beds, however, may break into rectangular blocks bounded by joints on the sides and bed (layer) surfaces above and below (Fig. B.4a). Regardless of their orientation, the formation of joints turns formerly intact bedrock into separate blocks. Eventually, these blocks topple from the outcrop at which they formed. After a while, they may collect in an apron of *talus*, the rock rubble at the base of a slope (Fig. B.4b).

Frost wedging. Freezing water bursts pipes and shatters bottles because water expands when it freezes and pushes the walls of the container apart. The same phenomenon happens in rock. When the water trapped in a joint freezes, it forces the joint open and may cause the joint to grow. Such frost wedging helps break blocks free from intact bedrock (Fig. B.5a).

Salt wedging. In arid climates, dissolved salt in groundwater precipitates and grows as crystals in open pore spaces in rocks. This process, called salt wedging, pushes apart the surrounding grains and weakens the rock so that when exposed to wind and rain, the rock disintegrates into separate grains. The same phenomenon happens along the coast, where salt spray percolates into rock and then dries (Fig. B.5b).

Root wedging. Have you ever noticed how the roots of an old tree can break up a sidewalk? As roots grow, they apply pressure to their surroundings, and can push joints open in a process known as root wedging (Fig. B.5c).

Thermal expansion. When the heat of an intense forest fire bakes a rock, the outer layer of the rock expands. On cooling, the layer contracts. This change creates forces in the rock sufficient to make the outer part of the rock break off in sheet-like pieces. Recent research suggests that the intense heat of the

Sun's rays sweeping across dark rocks in a desert may cause the rocks to fracture into thin slices.

Animal attack. Animal life also contributes to physical weathering: burrowing creatures, from earthworms to gophers, push open cracks and move rock fragments. And in the past century, humans have become perhaps the most energetic agent of physical weathering on the planet. When we excavate quarries, foundations, mines, or roadbeds by digging and blasting, we shatter and displace rock that might otherwise have remained intact for millions of years more.

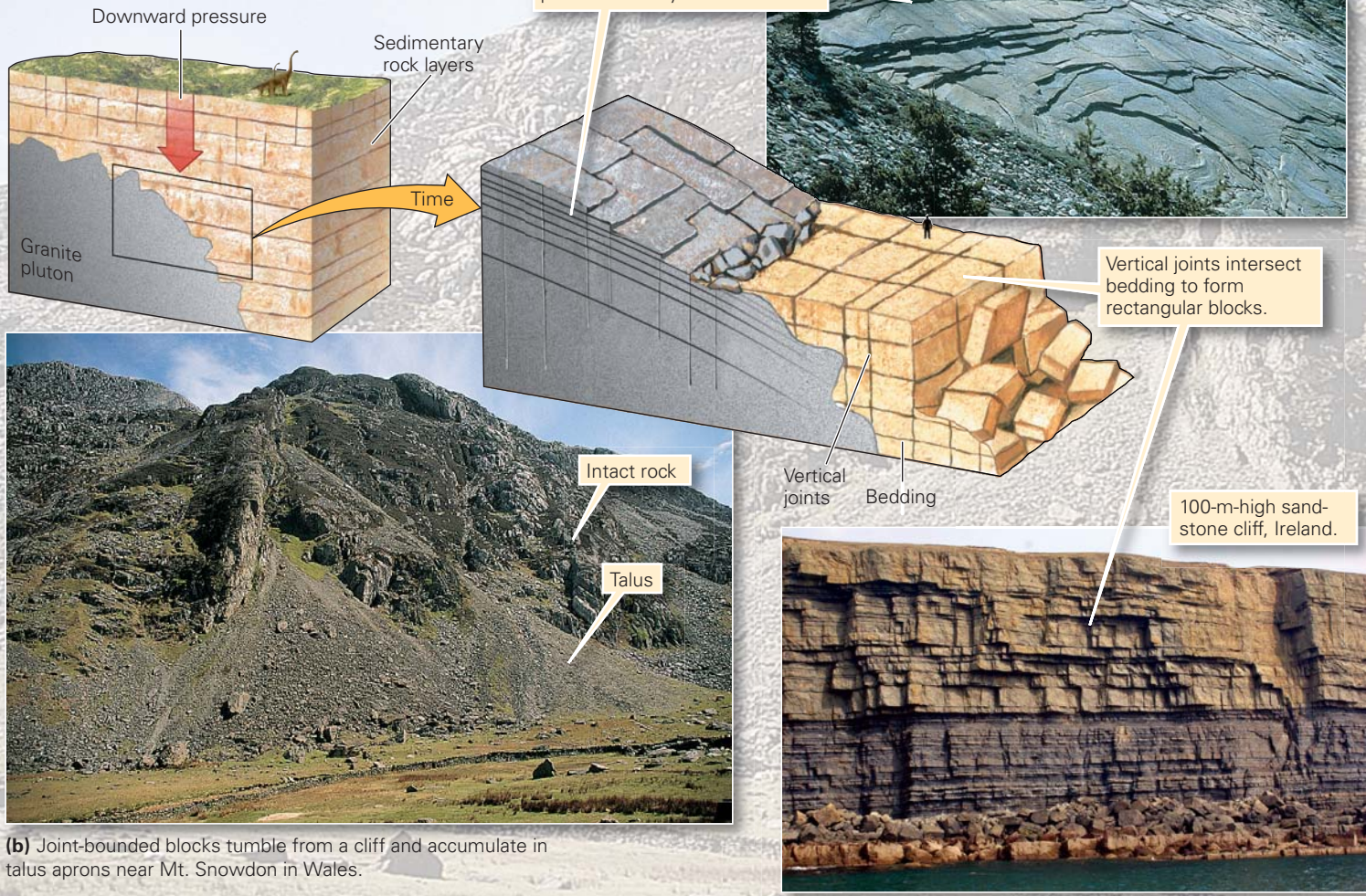
Chemical Weathering

Up to now, we've taken the plumber's-snake approach to breaking up rock. Now let's look at the liquid-drain-opener approach. **Chemical weathering** refers to the many chemical reactions that alter or destroy minerals when rock comes in contact with water solutions and/or air. Common reactions involved in chemical weathering include the following:

- ***Dissolution***. Chemical weathering during which minerals dissolve into water is called dissolution. Dissolution primarily affects salts and carbonate minerals (**Fig. B.6a, b**), but even quartz dissolves slightly.
- ***Hydrolysis***. During hydrolysis, water chemically reacts with minerals and breaks them down (*lysis* means loosen in Greek) to form other minerals. For example, hydrolysis reactions in feldspar produce clay.
- ***Oxidation***. Oxidation reactions in rocks transform iron-bearing minerals (such as biotite and pyrite) into a rusty-brown mixture of various iron-oxide and iron-hydroxide minerals. In effect, iron-bearing rocks can "rust."
- ***Hydration***. Hydration, the absorption of water into the crystal structure of minerals, causes some minerals, such as certain types of clay, to expand. Such expansion weakens rock.

FIGURE B.4 Joints (natural cracks) break bedrock into blocks and sheets, which can tumble down a slope.

(a) When buried deeply, rocks are subjected to a large downward pressure. Later, after erosion removes overburden, rocks expand and crack.



(b) Joint-bounded blocks tumble from a cliff and accumulate in talus aprons near Mt. Snowdon in Wales.

Not all minerals undergo chemical weathering at the same rates. Some weather in a matter of months or years, whereas others remain unweathered for millions of years. For example, when a granite (which contains quartz, mica, and feldspar) undergoes chemical weathering, most of its minerals except quartz transform to clay.

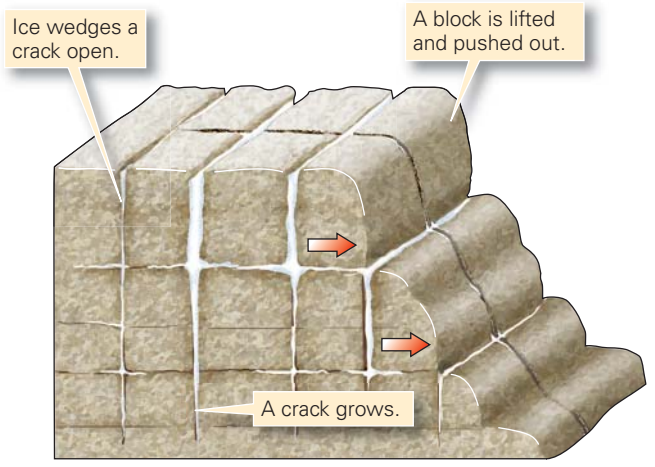
Until fairly recently, geoscientists tended to think of chemical weathering as a strictly inorganic chemical reaction, occurring entirely independently of life forms. But researchers now realize that organisms play a major role in the chemical-weathering process. For example, the roots of plants, fungi, and lichens secrete organic acids that help dissolve minerals in rocks; these organisms extract nutrients from the minerals. Microbes, such as bacteria, are amazing in that they literally eat minerals for lunch. Bacteria pluck off molecules from minerals and use the energy from the molecules' chemical bonds to supply their own life force.

Physical and Chemical Weathering Working Together

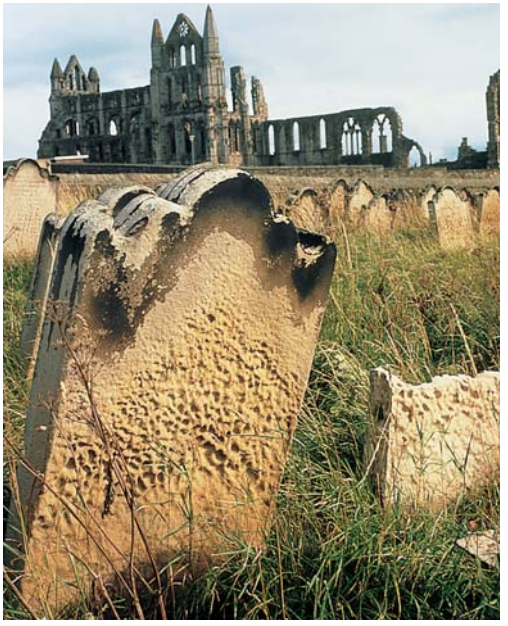
So far we've looked at the processes of chemical and physical weathering separately, but in the real world they happen together, aiding one another in disintegrating rock to form sediment (see **Geology at a Glance**, pp. 154–155).

Physical weathering speeds up chemical weathering. To understand why, keep in mind that chemical-weathering reactions take place at the surface of a material. Thus, the overall rate at which chemical weathering occurs depends on the ratio of surface area to volume—the greater the surface area, the faster the volume as a whole can chemically weather. When jointing (physical weathering) breaks a large block of rock into smaller pieces, the surface area increases, so chemical weathering happens faster (**Fig. B.7a**).

FIGURE B.5 Wedging is one type of physical (mechanical) weathering.



(a) When the water that fills cracks freezes, it expands and wedges the cracks open.

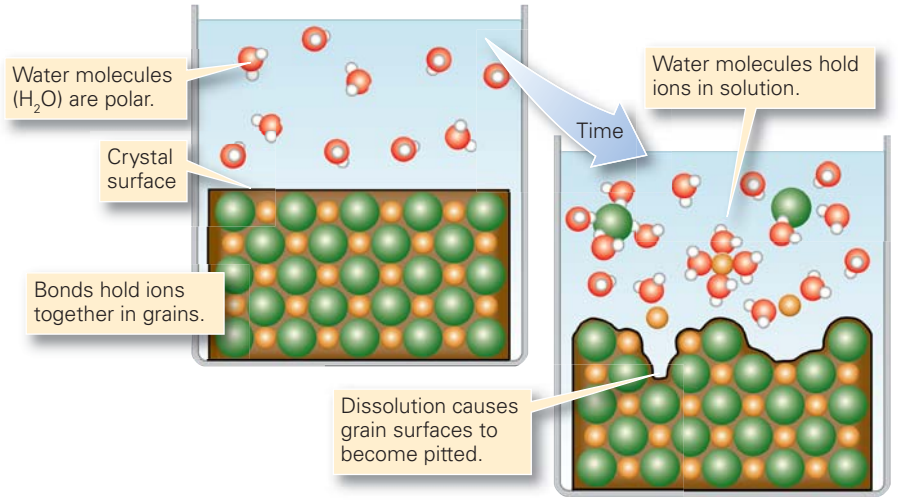


(b) Salt wedging led to disintegration of gravestones in Whitby, England.

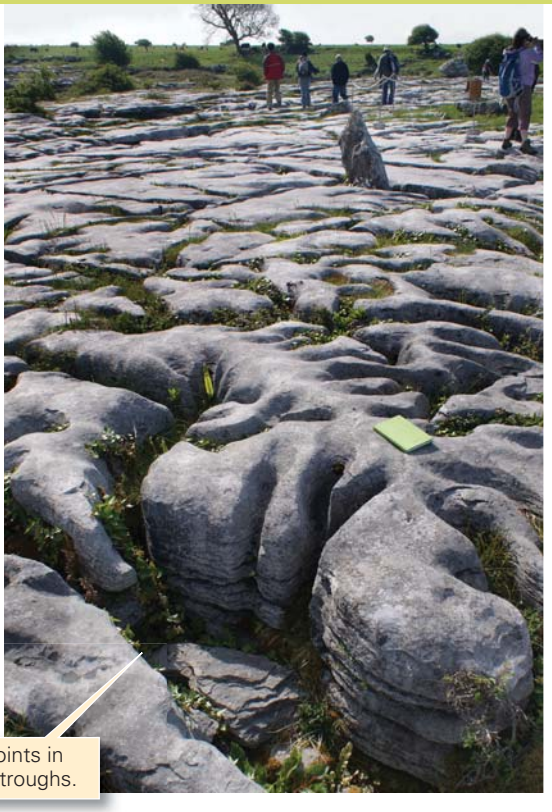


(c) Root wedging pushes open a joint, slowly separating a block from the cliff.

FIGURE B.6 Dissolution is one type of chemical weathering.

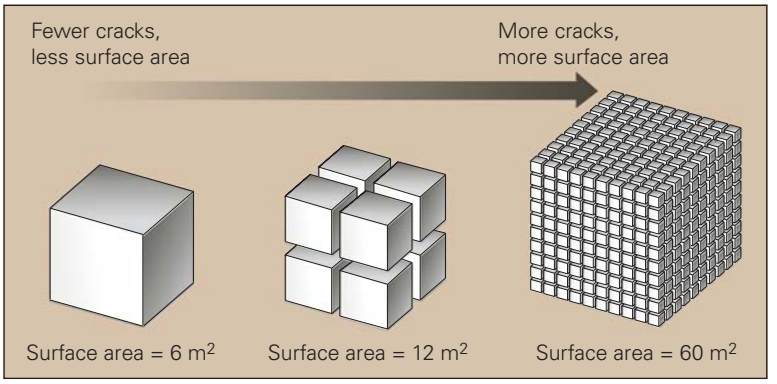


(a) Dissolution occurs when water molecules pluck ions off of grain surfaces.

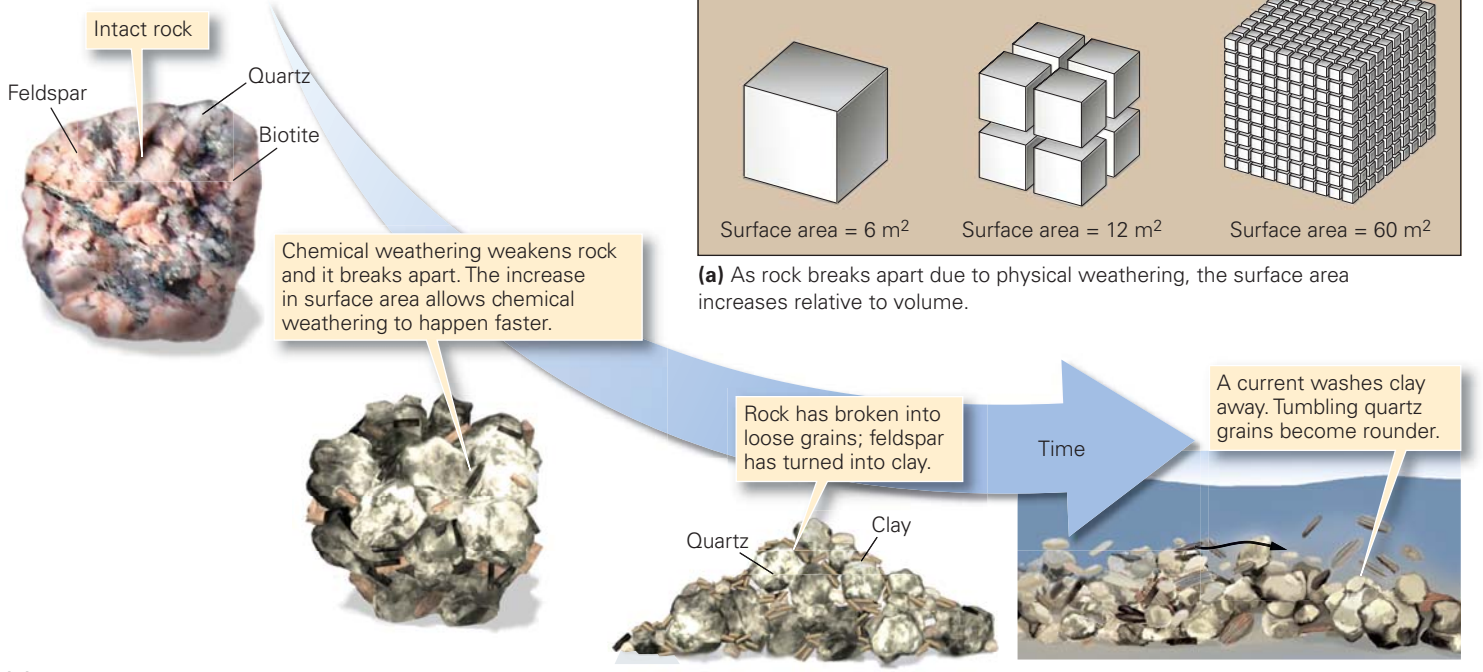


(b) Dissolution along joints in Ireland.

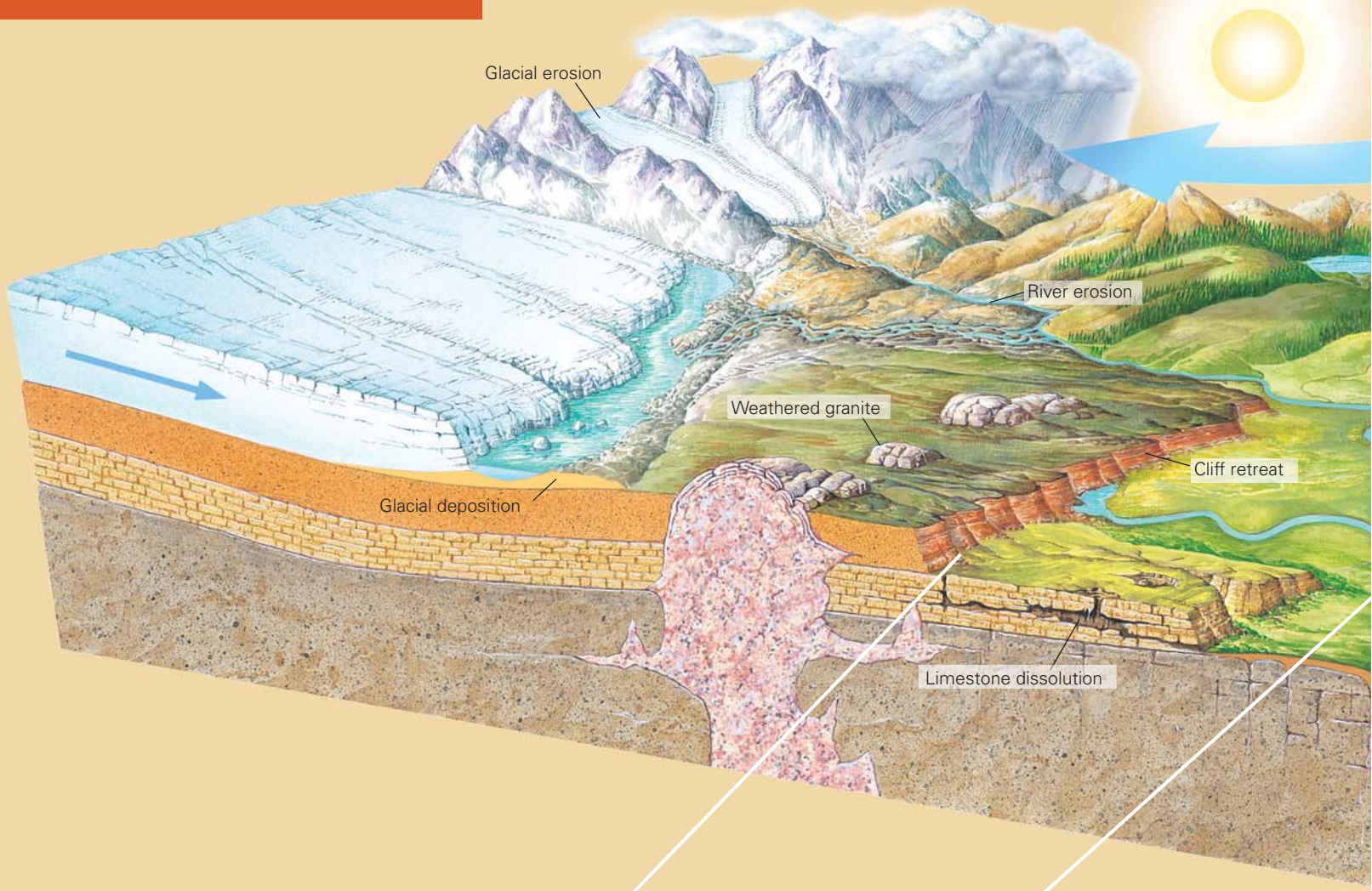
FIGURE B.7 Physical and chemical processes work together during the weathering process.



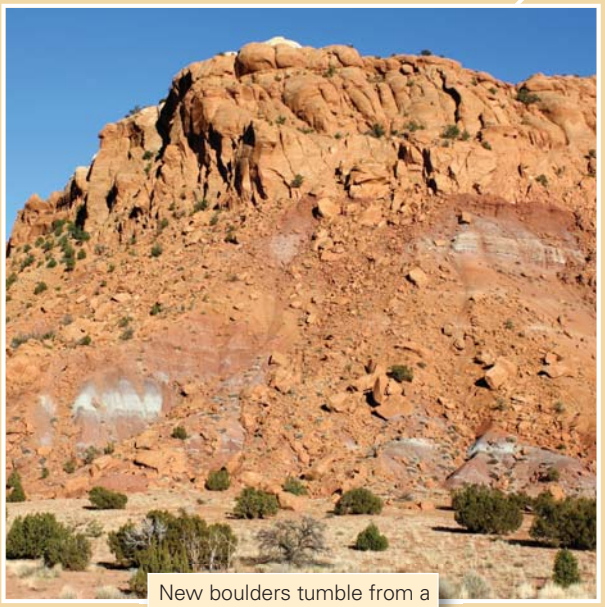
(a) As rock breaks apart due to physical weathering, the surface area increases relative to volume.



(b) Chemical weathering weakens rock so it breaks apart. As this happens, the surface area increases, so chemical weathering happens still faster. Eventually, the rock completely disaggregates to form sediment. Weathering of granite produces quartz sand and clay.



Weathering, Sediment, and Soil Production



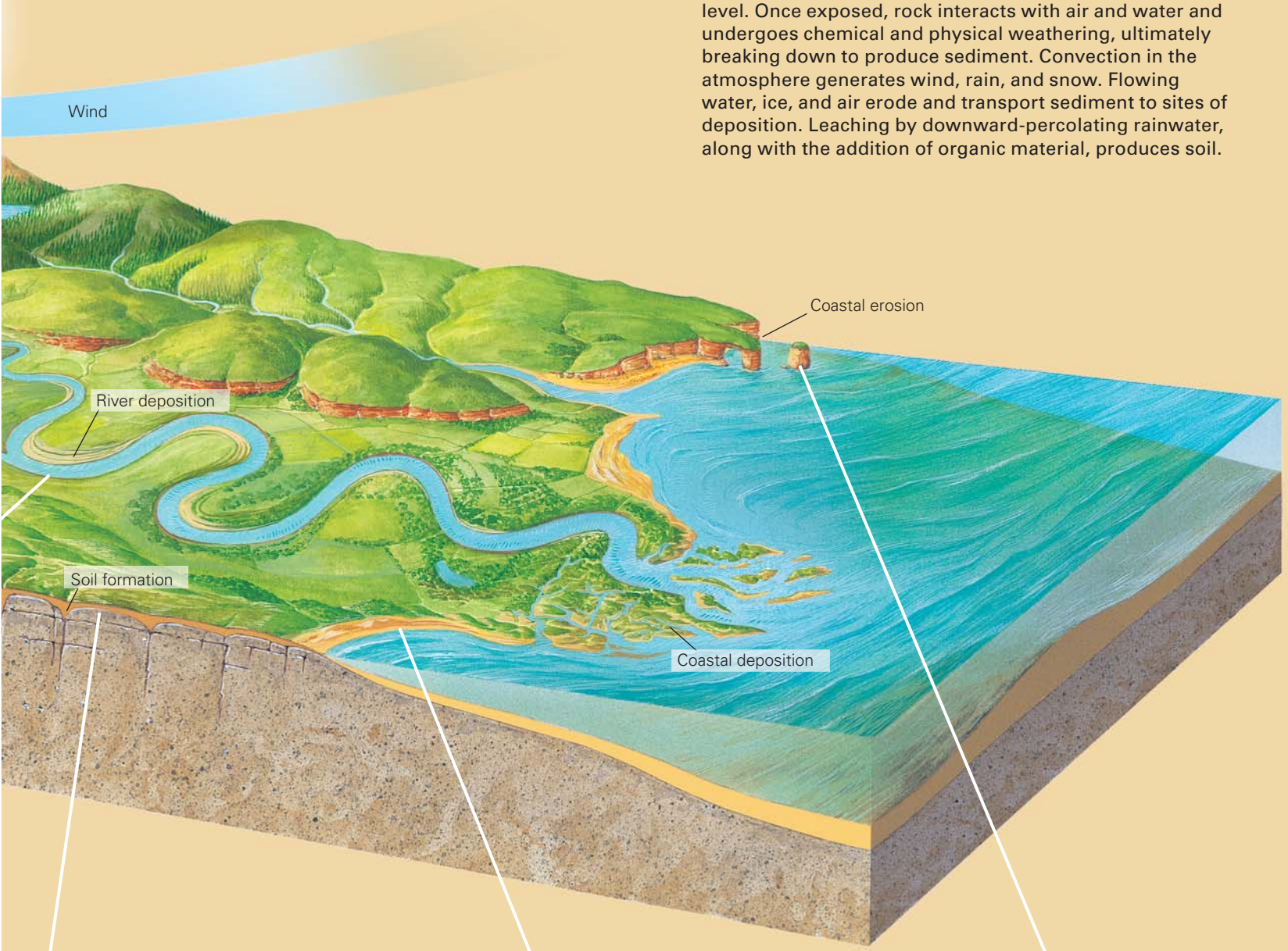
New boulders tumble from a cliff in New Mexico.



Silt collects along a stream in Indiana.

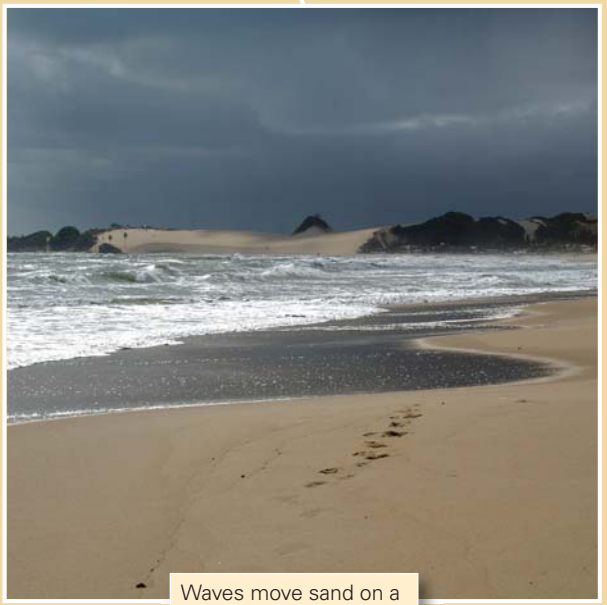


Tectonic processes uplift the land surface above sea level. Once exposed, rock interacts with air and water and undergoes chemical and physical weathering, ultimately breaking down to produce sediment. Convection in the atmosphere generates wind, rain, and snow. Flowing water, ice, and air erode and transport sediment to sites of deposition. Leaching by downward-percolating rainwater, along with the addition of organic material, produces soil.





Soil forms on bedrock of chalk in southern England.



Waves move sand on a beach in Brazil.



Erosion carves the coastal cliffs of Ireland.

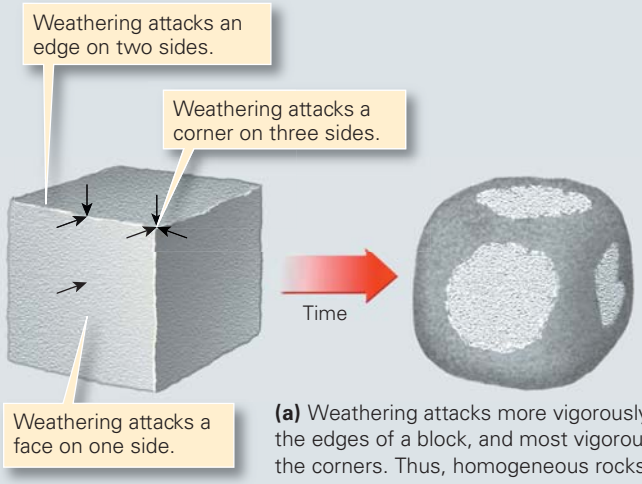
Similarly, chemical weathering speeds up physical weathering by dissolving away grains or cements that hold a rock together, transforming hard minerals (like feldspar) into soft minerals (like clay) and causing minerals to absorb water and expand. These phenomena make rock weaker, so it can disintegrate more easily (**Fig. B.7b**).

Weathering happens faster at edges, and even faster at the corners of broken blocks. This is because weathering attacks a flat face from only one direction, an edge from two directions, and a corner from three directions. Thus, with time, edges of blocks become blunt and corners become rounded (**Fig. B.8a**).

In rocks such as granite, which do not contain layering that can affect weathering rates, rectangular blocks transform into a spheroidal shape (**Fig. B.8b**).

When different rocks in an outcrop undergo weathering at different rates, we say that the outcrop has undergone "differential weathering." As a result of this process, cliffs composed of a variety of rock layers take on a stair-step or sawtooth shape (**Fig. B.8c**). You can easily see the consequences of differential weathering if you walk through a graveyard. The inscriptions on some headstones are sharp and clear, whereas those on other stones have become blunted or have even disappeared

FIGURE B.8 Differential weathering.



(a) Weathering attacks more vigorously at the edges of a block, and most vigorously at the corners. Thus, homogeneous rocks tend to weather into rounded blocks.



(b) Weathering along cracks in granite of the Mojave Desert led to the formation of rounded blocks. This style is called spheroidal weathering.



(c) Sawtooth weathering profiles develop in sequences of alternating strong and weak layers on this exposure in New Mexico. Weak layers are indented, whereas strong layers protrude.



(d) Inscriptions on a granite headstone (left) last for centuries, but those on a marble headstone (right) may weather away in decades. These gravestones are in the same cemetery and are about the same age.

(Fig. B.8d). That's because the minerals in these different stones have different resistances to weathering. Granite, an igneous rock with a high quartz content, retains inscriptions the longest. But marble, a metamorphic rock composed of calcite, dissolves away relatively rapidly in acidic rain.

B.3 Soil

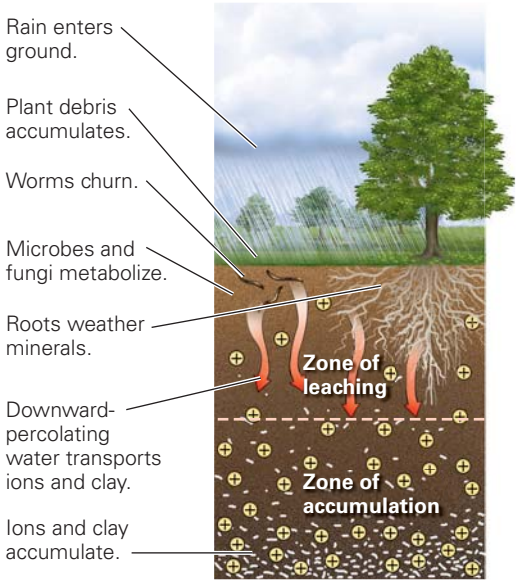
If you've ever had the chance to dig in a garden, you've seen firsthand that the material in which flowers grow looks and feels different from beach sand or potter's clay. We call the material in a garden "dirt" or, more technically, soil. **Soil** consists of rock or sediment that has been modified by physical and chemical interaction with organic material, rainwater, and organisms over time. Soil is one of our planet's most valuable resources, for without it there could be no agriculture, forestry, ranching, or home gardening.

How Does Soil Form?

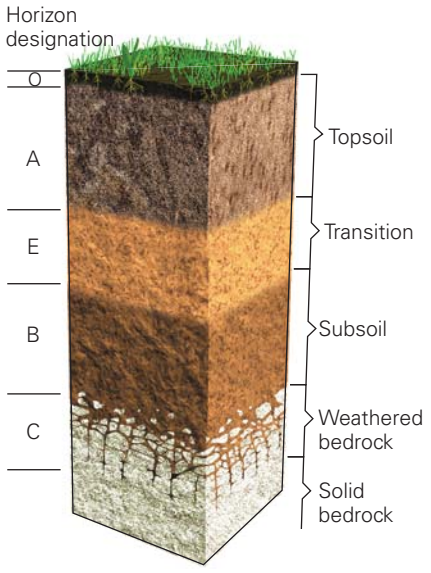
Three processes taking place at or just below the surface of the Earth contribute to soil formation. First, chemical and physical weathering produces loose debris, new minerals (such as clay), and ions in solution. Second, rainwater percolates through the debris and carries dissolved ions and clay flakes downward. The region in which this downward transport takes place is called the **zone of leaching**, because leaching means extracting, absorbing, and removal. Farther down, new mineral crystals precipitate directly out of the water or form by reaction of the water with debris. Also, the water leaves behind its load of fine clay. The region in which new minerals and clay collect is the **zone of accumulation** (Fig. B.9a). Third, microbes, fungi, plants, and animals interact with sediment by producing acids that weather grains, by absorbing nutrient atoms, and by leaving behind organic waste and remains. Plant roots and burrowing animals (insects, worms, and gophers) churn and break up the soil, and microbes metabolize minerals and organic matter and release chemicals.

Because different soil-forming processes operate at different depths, soils typically develop distinct zones, known as **soil horizons**, arranged in a vertical sequence called a **soil profile** (Fig. B.9b, c). Let's look at an idealized soil profile, from top to bottom, using a soil formed in a temperate forest as our example. The highest horizon is the O-horizon (the prefix stands for organic), so called because it consists almost entirely of humas (plant debris) and contains barely any mineral matter. Below the O-horizon, we find the A-horizon, in which humus has decayed further and has mixed with mineral grains (clay, silt, and sand). Water percolating through the A-horizon causes chemical weathering reactions to occur and produces ions in solution and new clay minerals. Downward-moving water eventually carries soluble chemicals and fine clay deeper into the subsurface. The O- and

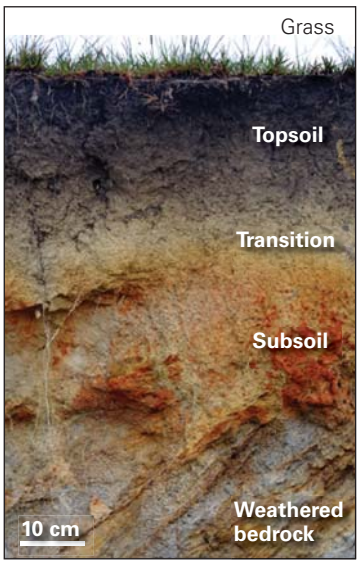
FIGURE B.9 Formation of soil horizons.



(a) Soil character depends on climate, for climate controls rainfall and vegetation.



(b) Distinct soil horizons develop, each with a characteristic composition and texture.



(c) Soil horizons exposed on the wall of a gully in eastern Brazil.

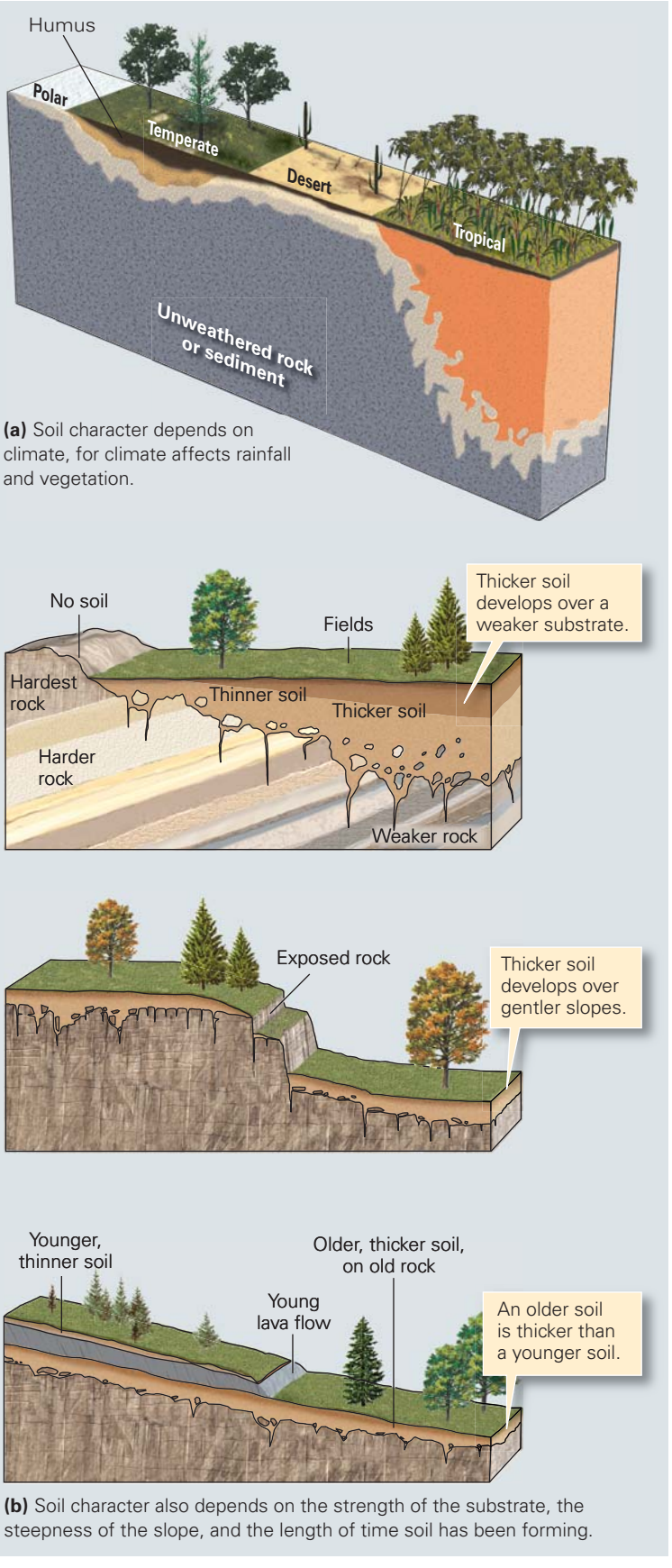
A-horizons constitute dark-gray to blackish-brown *topsoil*, the fertile portion of soil that farmers till for planting crops. (In some places, the A-horizon grades downward into the E-horizon, a soil level that has undergone substantial leaching but has not yet mixed with organic material.) Beneath the A-horizon (or the A- and E-horizons) lies the B-horizon. Ions and clay accumulate in the B-horizon, or subsoil. Note from our description that the O-, A-, and E-horizons make up the zone of leaching, whereas the B-horizon makes up the zone of accumulation.

Finally, at the base of a soil profile we find the C-horizon, which consists of material derived from the substrate that's been chemically weathered and broken apart, but has not yet undergone leaching or accumulation. The C-horizon grades downward into unweathered bedrock, or into unweathered sediment.

As farmers, foresters, and ranchers well know, the soil in one locality can differ greatly from the soil in another, in terms of composition, thickness, and texture. Indeed, crops that grow well in one type of soil may wither and die in another nearby. Such diversity exists because the makeup of a soil depends on several soil-forming factors (**Fig. B.10a, b**).

- *Climate*: Large amounts of rainfall and warm temperatures accelerate chemical weathering and cause most of the soluble elements to be leached. Small amounts of rainfall and cooler temperatures result in slower rates of weathering and leaching, so soils take a long time to develop and can retain unweathered minerals and soluble components. Climate is the single most important factor in determining the nature of soils that develop.
- *Substrate composition*: Some soils form on basalt, some on granite, some on volcanic ash, and some on recently deposited quartz silt. These different substrates consist of different materials, so the soils formed on them end up with different chemical compositions.
- *Slope steepness*: A thick soil can accumulate under land that lies flat. But on a steep slope, weathered rock may wash away before it can evolve into a soil. Thus, all other factors being equal, soil thickness increases as the slope angle decreases.
- *Wetness*: Depending on the details of local topography and on the depth below the surface at which groundwater occurs, some soil is wetter than other soil in the same region. Wet soils tend to contain more organic material than do dry soils.
- *Time*: Because soil formation is an evolutionary process, a young soil tends to be thinner and less developed than an old soil. The rate of soil formation varies greatly with environment.
- *Vegetation type*: Different kinds of plants extract or add different nutrients and quantities of organic matter to a soil. Also, some plants have deeper root systems than others and help prevent soil from washing away.

FIGURE B.10 Factors that control the character of soil.



(a) Soil character depends on climate, for climate affects rainfall and vegetation.

(b) Soil character also depends on the strength of the substrate, the steepness of the slope, and the length of time soil has been forming.

TABLE B.2 Soil Orders: U.S. Comprehensive Soil Classification System (see Fig. B.11)

Alfisol	Gray/brown, has subsurface clay accumulation and abundant plant nutrients. Forms in humid forests.
Andisol	Forms in volcanic ash.
Aridisol	Low in organic matter, has carbonate horizons. Forms in arid environments.
Entisol	Has no horizons. Formed very recently.
Gelisol	Underlain with permanently frozen ground.
Histosol	Very rich in organic debris. Forms in swamps and marshes.
Inceptisol	Moist, has poorly developed horizons. Formed recently.
Mollisol	Soft, black, and rich in nutrients. Forms in subhumid to subarid grasslands.
Oxisol	Very weathered, rich in aluminum oxide and iron oxide, low in plant nutrients. Forms in tropical regions.
Spodosol	Acidic, low in plant nutrients, ashy, has accumulations of iron and aluminum. Forms in humid forests.
Ultisol	Very mature, strongly weathered soils, low in plant nutrients.
Vertisol	Clay-rich soils capable of swelling when wet and shrinking and cracking when dry.

Soil Classification

Soil scientists worldwide have struggled mightily to develop a rational scheme for classifying soils. Not all schemes utilize the same criteria, and even today there is not worldwide agreement on which works best. In the United States, a country that includes many climates at mid-latitudes, many soil scientists use the *U.S. Comprehensive Soil Classification System*, which distinguishes among 12 orders of soil based on the physical characteristics and environment of soil formation (see **Table B.2** and **Fig. B.11**). Canadians use a different scheme focusing only on soils that develop north of the 40th parallel. The Canadian scheme works well for cooler, high-latitude climates.

As we've noted, rainfall and vegetation play a key role in determining the type of soil that forms. For example, in deserts, where there is very little rainfall and sparse vegetation, an aridisol forms (**Fig. B.12a**). (In older classifications, these were known as "pedocal" soils.) Aridisols have no O-horizon (because there is so little organic material), and the A-horizon is thin. Soluble minerals, specifically calcite, that would be washed away entirely if there were more rainfall, instead accumulate in the B-horizon. In fact, capillary action may bring calcite *up* from deeper down as water evaporates at the ground surface. The calcite locally cements clasts together in the B-horizon to form a rock-like mass called caliche or calcrete. In temperate environments, an alfisol forms—this soil has an O-horizon, and because of moderate amounts of rainfall, materials leached from the A-horizon accumulate in the B-horizon (**Fig. B.12b**). (In older classifications, these were known as "pedalfer" soils.) In a tropical climate, oxisols develop. Here, so much rainfall percolates down into the ground that all reactive minerals in the soil undergo chemical weathering, producing ions and clay that flush downward. This process leaves an A-horizon that contains substantial amounts of stable iron-oxide, aluminum-oxide, and aluminum-hydroxide residues (**Fig. B.12c**). The resulting soil tends to be brick-red and is traditionally called laterite.

Soil Erosion

As we have seen, soils take time to form, so soils capable of supporting crops or forests are a natural resource worthy of protection. However, agriculture, overgrazing, and clear-cutting have led to the destruction of soil. Crops rapidly remove nutrients from soil, so if they are not replaced, the soil will not contain sufficient nutrients to maintain plant life. When the natural plant cover disappears, the surface of the soil becomes exposed to wind and water. Actions such as the impact of falling raindrops or the rasping of a plow break up the soil at the surface, with the result that it can wash away in water or blow away as dust. When this happens, **soil erosion**, the removal of soil by running water or by wind, takes place (**Fig. B.13**). In some localities, erosion carries away almost six tons of soil from an acre of land per year. Human activities can increase rates of soil erosion by 10 to 100 times, so that it far exceeds the rate of soil formation. Droughts exacerbate the situation. For example, during the 1930s a succession of droughts killed off so much vegetation in the American plains that wind stripped the land of soil and caused devastating dust

FIGURE B.11 U.S. Department of Agriculture map of soil types around the world.

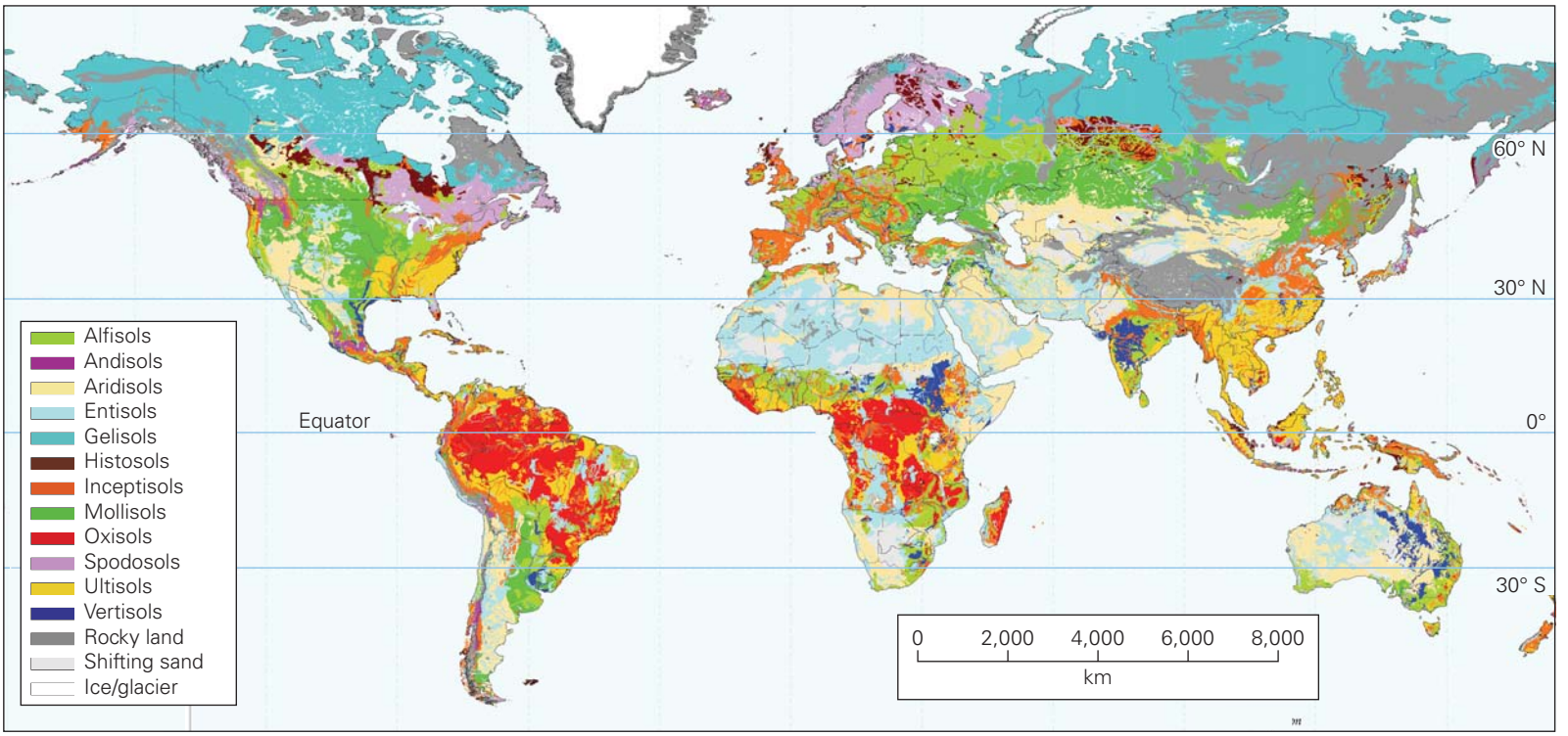
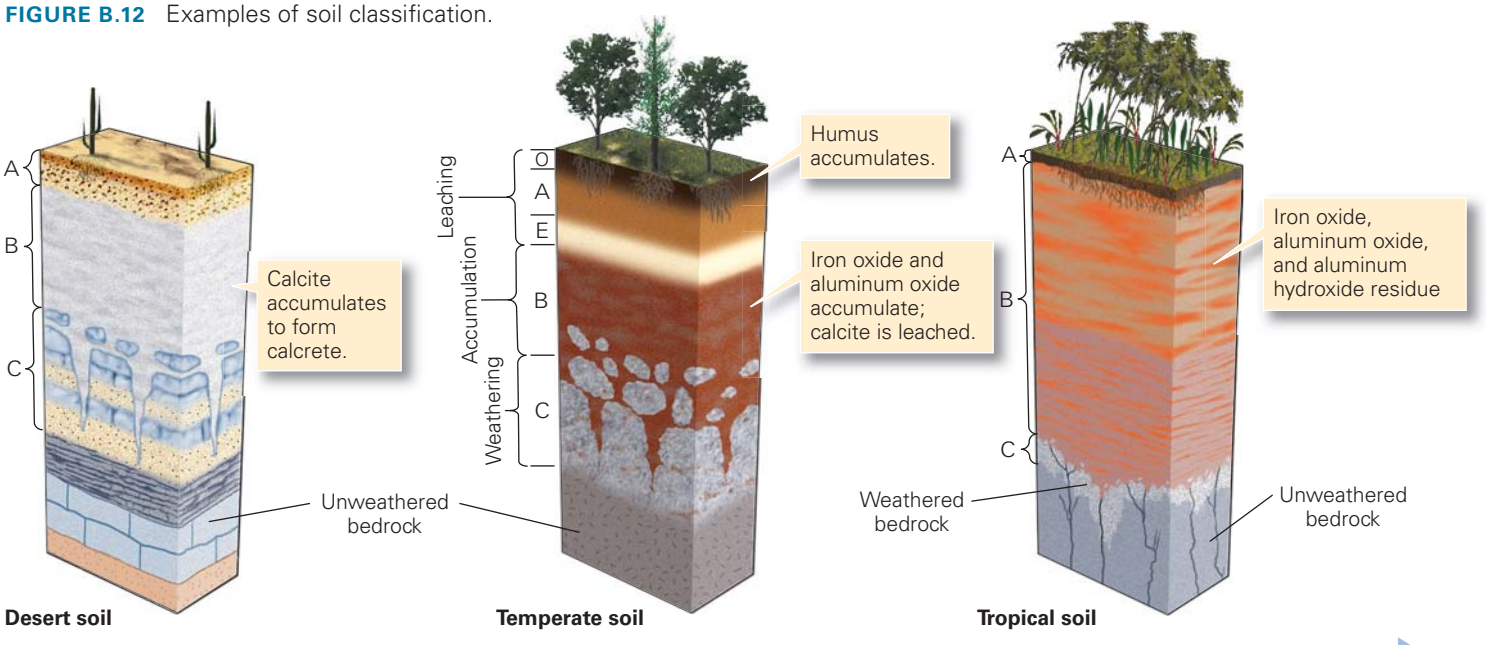


FIGURE B.12 Examples of soil classification.



(a) Aridisol forms in deserts. Rainfall is so low that no O-horizon forms, and soluble minerals accumulate in the B-horizon.

(b) Alfisol forms in temperate climates. An O-horizon forms, and less-soluble materials accumulate in the B-horizon.

(c) Oxisol forms in tropical climates where percolating rainwater leaches all soluble minerals, leaving only iron- and aluminum-rich residues.

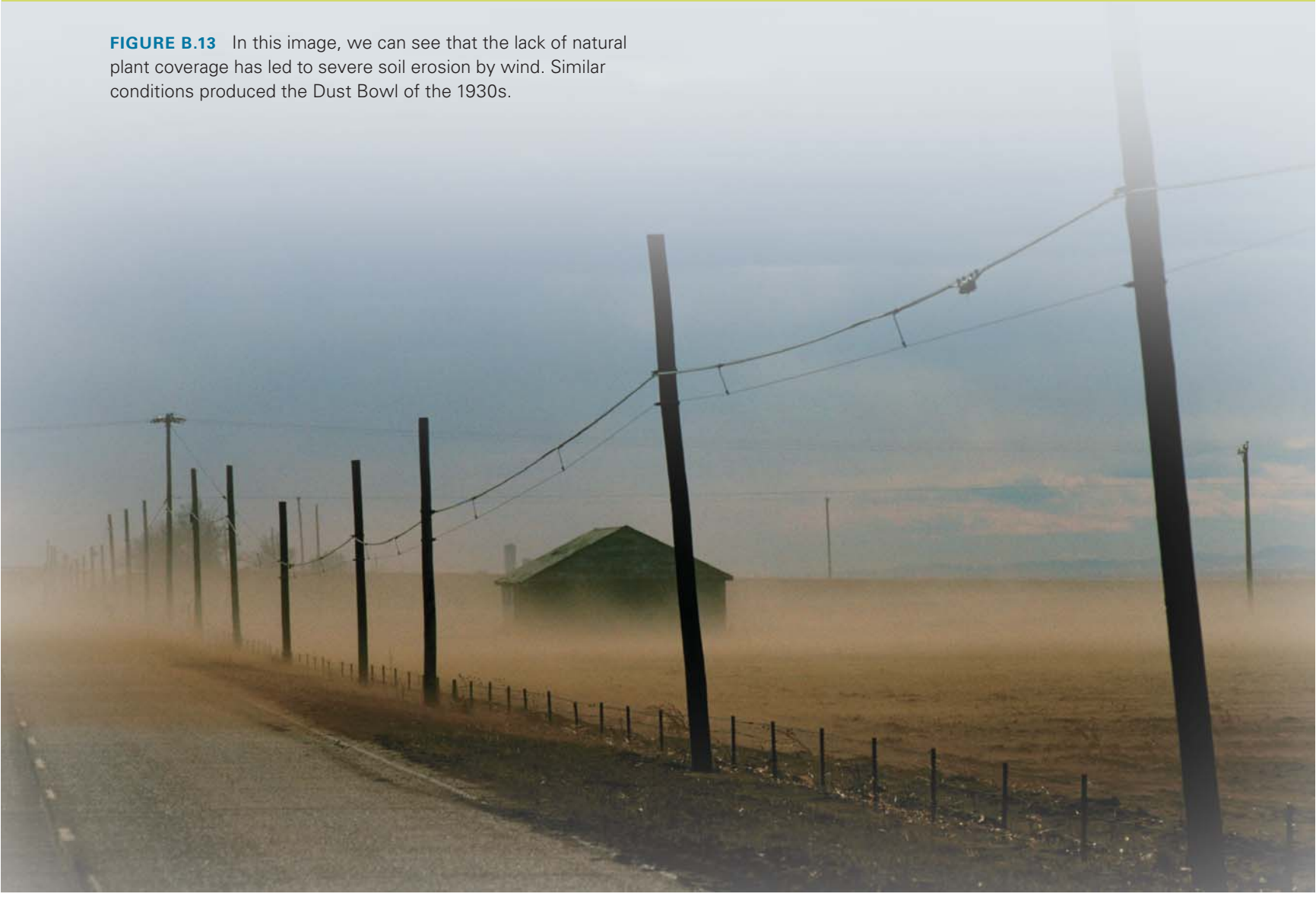


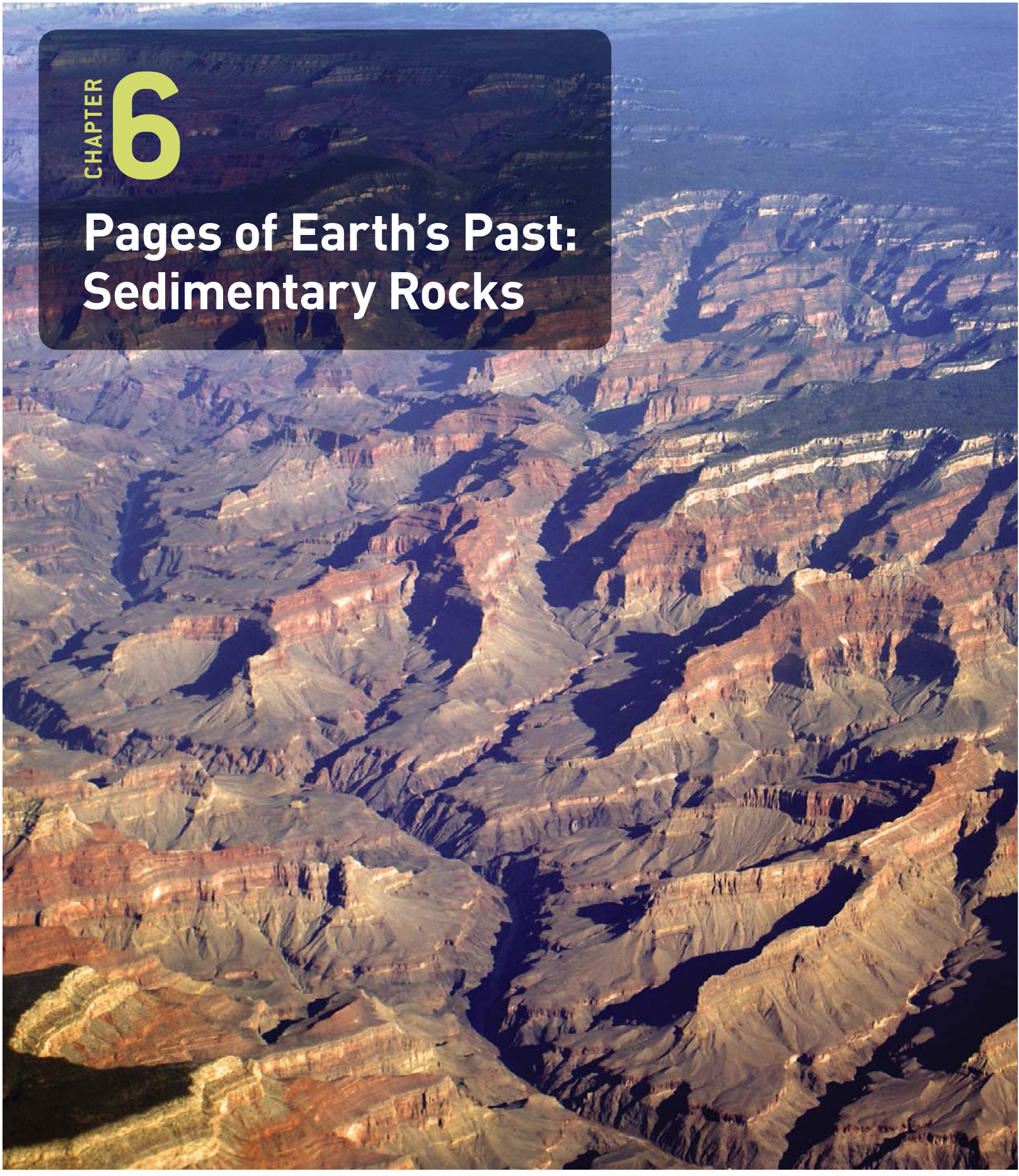
FIGURE B.13 In this image, we can see that the lack of natural plant coverage has led to severe soil erosion by wind. Similar conditions produced the Dust Bowl of the 1930s.

storms. Large numbers of people were forced to migrate away from the Dust Bowl of Oklahoma and adjacent areas.

The consequences of rainforest destruction have particularly profound effects on soil. In an established rain forest, lush growth provides sufficient organic debris so that trees can grow. But if the forest is logged, or cleared for agriculture, the humus rapidly disappears, leaving laterite that contains few nutrients. Crop plants consume whatever nutrients remain so rapidly that the soil becomes infertile after only a year or two, useless for agriculture and unsuitable for regrowth of rainforest trees.

Key Terms

chemical weathering (p. 151)
erosion (p. 150)
joint (p. 150)
physical weathering (p. 150)
sediment (p. 149)
soil (p. 157)
soil horizon (p. 157)
soil profile (p. 157)
weathering (p. 150)
zone of accumulation (p. 157)
zone of leaching (p. 157)



CHAPTER 6

Pages of Earth's Past: Sedimentary Rocks



The rugged landscape of the Grand Canyon exposes a blanket of sedimentary rock layers. These layers formed by the burial and hardening (lithification) of mud, shell accumulations, and sand. Beaches, reefs, mud flats, river floodplains, and desert sand dunes all existed here in the past.

Chapter Objectives

By the end of this chapter, you should know . . .

- how sediment produced by weathering and biologic activity at the Earth's surface can transform into sedimentary rock.
- how to interpret the past environment and sea level of the Earth by examining the composition, textures, and layering found in sedimentary rock.
- clues that geologists use to identify and classify different types of sedimentary rocks.
- where and why thick accumulations of sedimentary rocks form on Earth.

In every grain of sand there is a story of Earth.

—Rachel Carson (American marine biologist and conservationist, 1907–1964)

6.1 Introduction

On an isolated, windswept drilling platform in the North Sea off the coast of Scotland, a group of roughnecks ready a multi-million-dollar drilling rig—their plan is to penetrate the sea floor and see what layers lie beneath. The North Sea formed as a consequence of rifting that began tens of millions of years ago. During rifting, what was once dry land between Great Britain and continental Europe slowly sank or, in geologic parlance, "subsided." Rivers carried gravel, sand, and clay from the surrounding land into the newborn North Sea, and these sediments collected in layers. At certain stages in the process, salts precipitated from seawater and the shells of sea creatures settled and collected on the sea floor. As the drilling begins, a geologist stationed on the deck of the platform examines the material that has been flushed out of the lengthening drill hole. At first, drilling brings up soft mud and loose sand, silt, pebbles, and shell fragments. But as the hole goes deeper, the material coming up holds together in soft but coherent clumps. Eventually, when the hole has entered layers that now lie almost a kilometer below the sea floor, the drilling fluid flushes out chips and chunks of solid rock. When the geologist studies these fragments, she notes that the composition of fragments changes with depth. At some depths, fragments consist of grains of sand cemented together, or of tightly packed clay that is harder than pottery. At other depths, they consist of broken shell aggregates or of crystalline salt masses. The geologist has observed the transition of loose

sediment into solid layers of sedimentary rock as burial depth progressively increases.

Formally defined, **sedimentary rock** is rock that forms at or near the surface of the Earth in one of several ways: by the cementing together of loose **clasts** (fragments or grains) produced by physical or chemical weathering of preexisting rock; by the growth of shell masses or the cementing together of shells and shell fragments; by the accumulation and subsequent alteration of organic matter from dead plankton or plants; or by the precipitation of minerals from water solutions. Layers of sedimentary rock are like the pages of a book, recording tales of ancient events and ancient environments on the ever-changing face of the Earth. They occur only in the upper part of the crust, and form a "cover" that buries the underlying "basement" of igneous and/or metamorphic rock (Fig. 6.1 a, b).

In Interlude B, we introduced the concept of weathering, and showed how it attacks bedrock, breaking it down into ions and loose sediment grains. What can happen next? Some of the sediment may become incorporated in soil, as we have seen. But some becomes buried and transformed into sedimentary rock. In this chapter, we discuss the various kinds of sedimentary rock and the ways in which they form, and we consider what sedimentary rocks can tell us about the history of the Earth System.

6.2 Classes of Sedimentary Rocks

Geologists divide sedimentary rocks into four major classes, based on their mode of origin. (1) **Clastic sedimentary rock** consists of cemented-together clasts, solid fragments and grains broken off of preexisting rocks (the word comes from the Greek *klastos*, meaning broken); (2) **biochemical sedimentary rock** consists of shells; (3) **organic sedimentary rock** consists of carbon-rich relicts of plants or other organisms; and (4) **chemical sedimentary rock** is made up of minerals that precipitated directly from water solutions. Let's now look at these major classes in more detail.

Clastic Sedimentary Rocks

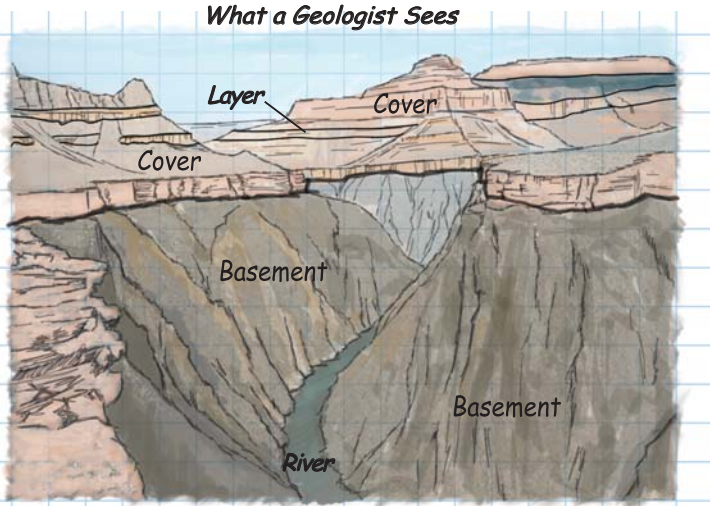
Formation. Nine hundred years ago, a thriving community of Native Americans inhabited the high plateau of Mesa Verde, Colorado. In hollows beneath huge overhanging ledges, they built multistory stone-block buildings that have survived to this day. Clearly, the blocks are solid and durable—they are, after all, rock. But if you were to rub your thumb along one, it would feel gritty, and small grains of quartz would break free and roll under your thumb, for the block consists of quartz sand grains cemented together. Geologists call such rock a **sandstone**.

Sandstone is an example of clastic sedimentary rock. It consists of loose clasts, known as **detritus**, that have been stuck together to form a solid mass. The clasts can consist of individual minerals (such as grains of quartz or flakes of clay) or of fragments of rock (such as pebbles of granite). Formation of sediment and its transformation into clastic sedimentary rock takes place via the following five steps (Fig. 6.2a, b).

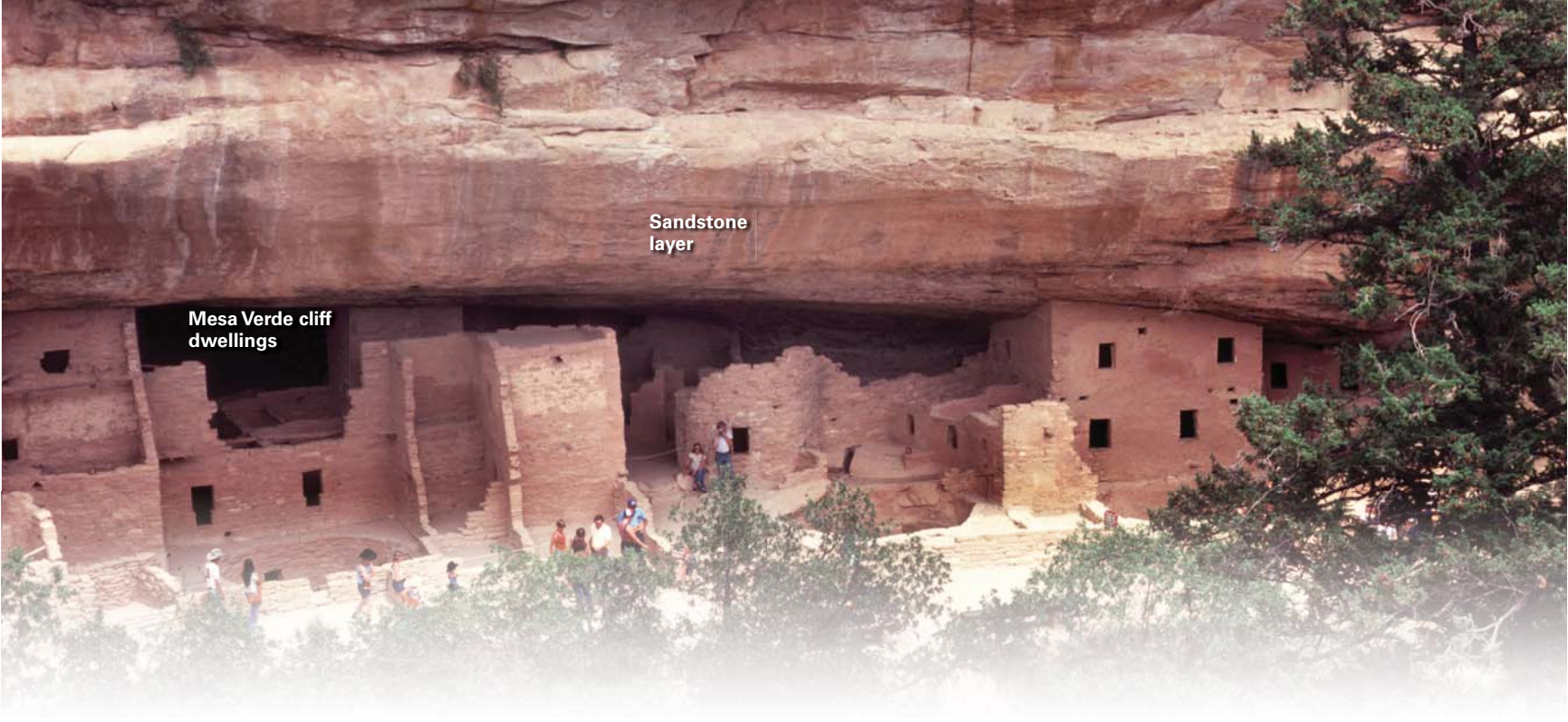
FIGURE 6.1 In this close-up of the inner gorge of the Grand Canyon, we see a sedimentary-rock blanket, that forms a "cover" over older "basement" of metamorphic and igneous rock.



(a) Sedimentary cover here consists of horizontal layers but underlying metamorphic basement does not.

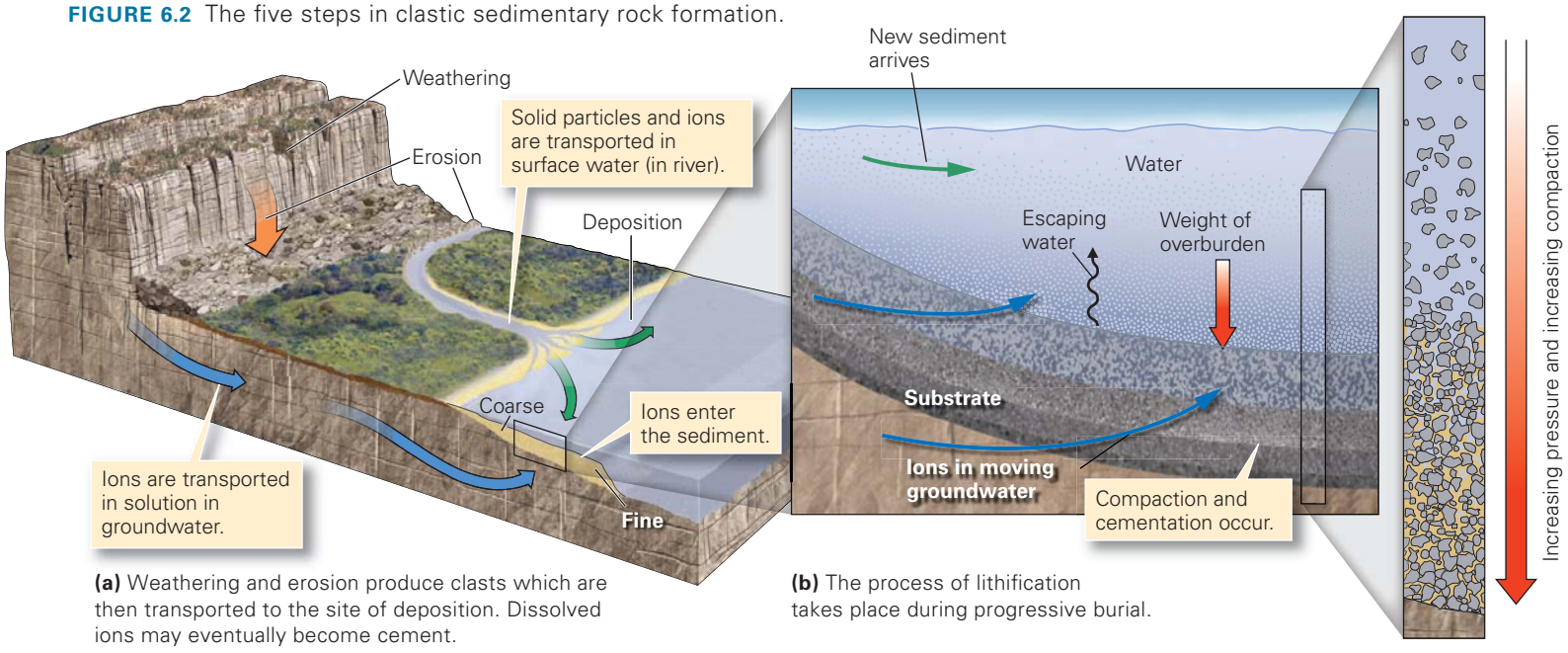


(b) A geologist's sketch emphasizes the contact between the sedimentary cover and basement.



- *Weathering*: Detritus forms by disintegration of bedrock into separate grains due to physical and chemical weathering.
- *Erosion*: **Erosion** refers to the combination of processes that separate rock or regolith (surface debris) from its substrate. Erosion involves abrasion, falling, plucking, scouring, and dissolution, and is caused by moving air, water, or ice.
- *Transportation*: Gravity, wind, water, or ice carry sediment. The ability of a medium to carry sediment depends on its viscosity and velocity. Solid ice can transport sediment of any size, regardless of how slowly the ice moves. Very fast-moving, turbulent water can transport coarse fragments (cobbles and boulders), moderately fast-moving water can carry only sand and gravel, and slow-moving water carries only silt and clay. Strong winds can move sand and dust, but gentle breezes carry only dust.
- *Deposition*: **Deposition** is the process by which sediment settles out of the transporting medium. Sediment settles out of wind or moving water when these fluids slow, because as the velocity decreases, the fluid no longer has the ability to carry sediment. Sediment is deposited by ice when the ice melts.
- *Lithification*: Geologists refer to the transformation of loose sediment into solid rock as **lithification**. The lithification of clastic sediment involves two steps. First, once the sediment has

FIGURE 6.2 The five steps in clastic sedimentary rock formation.



(a) Weathering and erosion produce clasts which are then transported to the site of deposition. Dissolved ions may eventually become cement.

(b) The process of lithification takes place during progressive burial.

been buried, pressure caused by the weight of overlying material squeezes out water and air that had been trapped between clasts, and clasts press together tightly, a process called **compaction**. Compacted sediment may then be stuck together to make coherent sedimentary rock by the process of **cementation**. Cement consists of minerals (commonly quartz or calcite) that precipitate from groundwater and fill the spaces between clasts.

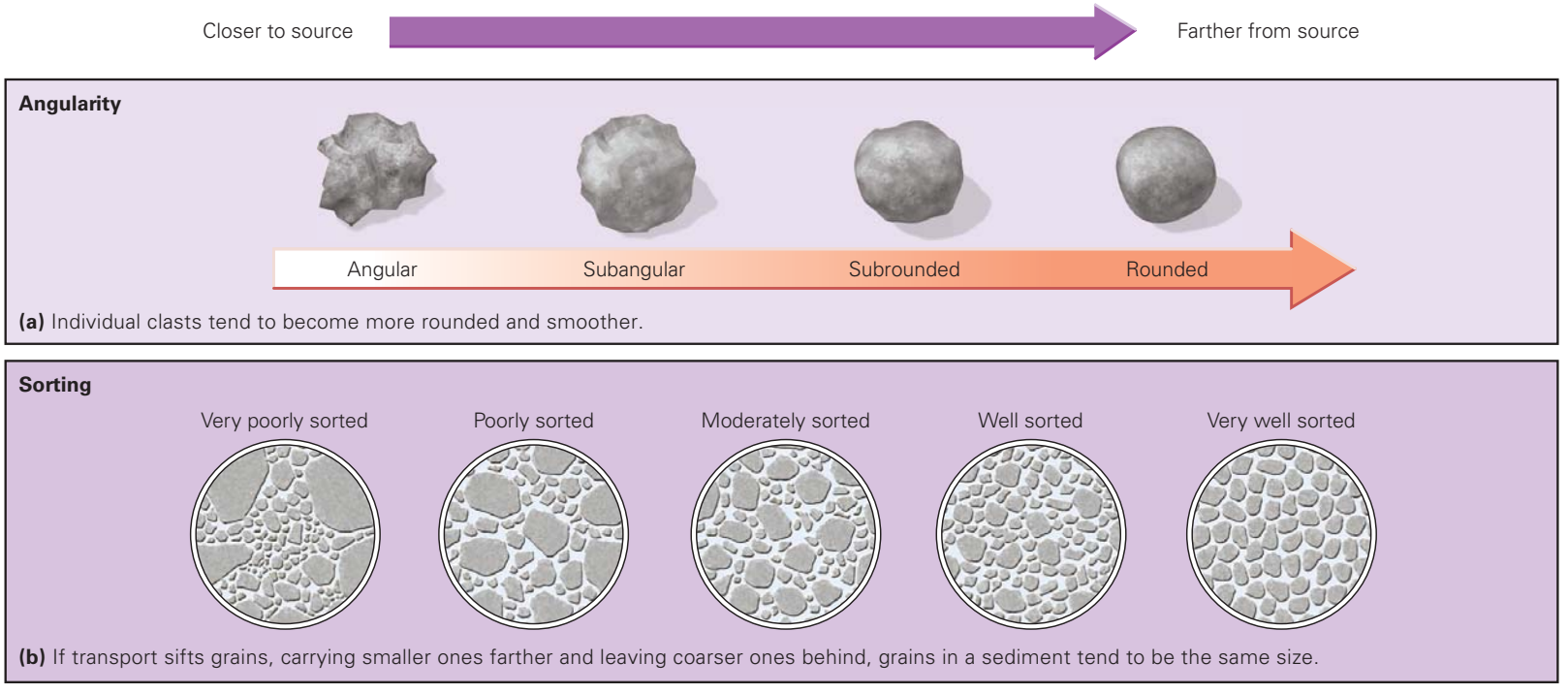
Classifying clastic sedimentary rocks. Say that you pick up a clastic sedimentary rock and want to describe it sufficiently so that, from your words alone, another person can picture the rock. What characteristics should you mention? Geologists find the following characteristics most useful.

- *Clast size*. Size refers to the diameter of fragments or grains making up a rock. Names used for clast size, listed in order from coarsest to finest, are: boulder, cobble, pebble, sand, silt, and clay (see Table B.1 in Interlude B).
- *Clast composition*. Composition refers to the makeup of clasts in sedimentary rock. Clasts may be composed of rock fragments or individual mineral grains.
- *Angularity and sphericity*. Angularity indicates the degree to which clasts have smooth or angular corners and edges (**Fig. 6.3a, b**). Sphericity, in contrast, refers to the degree to which the shape of a clast resembles a sphere.
- *Sorting*. **Sorting** of clasts indicates the degree to which the clasts in a rock are all the same size or include a variety of sizes. *Well-sorted* sediment consists entirely of sediment of the same size, whereas *poorly-sorted* sediment contains a mixture of more than one clast size.
- *Character of cement*. Not all clastic sedimentary rocks have the same kind of cement. In some, the cement consists predominantly of quartz, whereas in others, it consists predominantly of calcite.

With these characteristics in mind, we can distinguish among several common types of clastic sedimentary rocks, listed in **Table 6.1**. This table provides *common* rock names—specialists sometimes use other, more precise names based on more complex classification schemes.

The size, angularity, sphericity, and sorting of clasts depends on the medium (water, ice, or wind) that transports the clasts and, in the case of water or wind, on both the velocity of the medium and the distance of transport. The composition of the clasts depends on the composition of rock from which the clasts were derived, and on the degree of chemical weathering that the clasts have undergone. Thus, the type of clasts that accumulate in a sedimentary deposit varies with location. To see how, let's follow the fate of rock fragments as they gradually move from a cliff face in the mountains via a river to the seashore. Different kinds of sediment develop along the route. Each kind, if buried and lithified, would yield a different type of sedimentary rock.

FIGURE 6.3 Grain characteristics, and their evolution with increasing transport and weathering.



(a) Individual clasts tend to become more rounded and smoother.

(b) If transport sifts grains, carrying smaller ones farther and leaving coarser ones behind, grains in a sediment tend to be the same size.

TABLE 6.1 Classification of Clastic Sedimentary Rocks

Clast Size*	Clast Character	Rock Name (Alternative Name)
Coarse to very coarse	Rounded pebbles and cobbles	Conglomerate
	Angular clasts	Breccia
	Large clasts in muddy matrix	Diamictite
Medium to coarse	Sand-sized grains	Sandstone
	• quartz grains only	• quartz sandstone (quartz arenite)
	• quartz and feldspar sand	• arkose
	• sand-sized rock fragments	• lithic sandstone
	• quartz sand and sand-sized rock fragments in a clay-rich matrix	• wacke (informally called graywacke)
Fine	Silt-sized clasts	Siltstone
Very fine	Clay and/or very fine silt	Shale, if it breaks into platy sheets
		Mudstone, if it doesn't break into platy sheets

*For precise diameters, see Table B.1 on p. 150.

To start, imagine that some large blocks of granite tumble off a cliff and slam into other blocks already at the bottom. The impact shatters the blocks, producing a pile of angular fragments. If these fragments were to be cemented together before being transported very far, the resulting rock would be **breccia** (Fig. 6.4a). Later, a storm causes the fragments (clasts) to be carried away by a turbulent river. In the water, clasts bang into each other and into the riverbed, a process that shatters them into still smaller pieces and breaks off their sharp edges. As the clasts get carried downstream, they gradually become rounded pebbles and cobbles. When the river water slows, these clasts stop moving and form a mound or bar of gravel. Burial and lithification of these rounded clasts produces **conglomerate** (Fig. 6.4b).

Did you ever wonder . . .
where beach sand comes from?

If the gravel stays put for a long time, it undergoes chemical weathering. As a consequence, cobbles and pebbles break apart into individual mineral grains, eventually producing a mixture of quartz, feldspar, and clay. Clay is so fine that flowing water easily picks it up and carries it downstream, leaving sand containing a mixture of quartz and some feldspar grains—this sediment, if buried and lithified, becomes **arkose** (Fig. 6.4c). Over time, feldspar grains in sand continue to weather into clay so that gradually, during successive events that wash the sediment downstream, the sand loses feldspar and ends up being composed almost entirely of durable quartz grains. Some of the sand may make it to the sea, where waves carry it to beaches, and some may end up in desert dunes. This sediment, when buried and lithified, becomes quartz sandstone (Fig. 6.4d). Meanwhile, silt and clay may accumulate in the flat areas bordering streams, regions called floodplains (see Chapter 14) that become inundated only during floods. And some silt and mud settles in a wedge, called a delta, at the mouth of the river, or in lagoons or mudflats along the shore. The silt, when lithified, becomes **siltstone**, and the mud, when lithified, becomes **shale** or **mudstone** (Fig. 6.4e).

Biochemical Sedimentary Rocks

The Earth System involves many interactions between living organisms and the physical planet. Numerous organisms have evolved the ability to extract dissolved ions from seawater to make solid shells. When the organisms die, the solid material in their shells survives. This material, when lithified, comprises biochemical sedimentary rock. Geologists recognize several different types of biochemical sedimentary rocks, which we now describe.

Limestone (biochemical). A snorkeler gliding above a reef sees an incredibly diverse community of coral and algae, around which creatures such as clams, oysters, snails (gastropods), and lampshells (brachiopods) live, and above which plankton float (Fig. 6.5a). Though they look so different from each other, many of these organisms share an important characteristic: they make solid shells of calcium carbonate ($CaCO_3$). The $CaCO_3$ crystallizes either as calcite or aragonite. (These minerals have the same composition, but different crystal structures.) When the organisms die, the shells remain and may accumulate.

Rocks formed dominantly from this material are the biochemical version of **limestone**. Since the principal compound making up limestone is $CaCO_3$, geologists refer to limestone as a type of carbonate rock.

Limestone comes in a variety of textures, because the material that forms it accumulates in a variety of ways. For example, limestone can originate from reef builders (such as coral) that grew in place, from shell debris that was broken up and transported, from carbonate mud, or from plankton shells that settled like snow out of water. Because of this variety, geologists distinguish among *fossiliferous limestone*, consisting of visible fossil shells or shell fragments (Fig. 6.5b); *micrite*, consisting of very fine carbonate mud; and *chalk*, consisting of plankton shells. Experts recognize many other types as well.

Typically, limestone is a massive light-gray to dark-bluish-gray rock that breaks into chunky blocks—it doesn't look much like a pile of shell fragments (Fig. 6.5c). That's because several processes change the texture of the rock over time. For example, water passing through the rock not only precipitates cement but also dissolves some carbonate grains and causes new ones to grow.

FIGURE 6.4 Different kinds of clasts lithify into different kinds of sedimentary rocks.







(a) Lithification of an accumulation of angular clasts yields breccia.





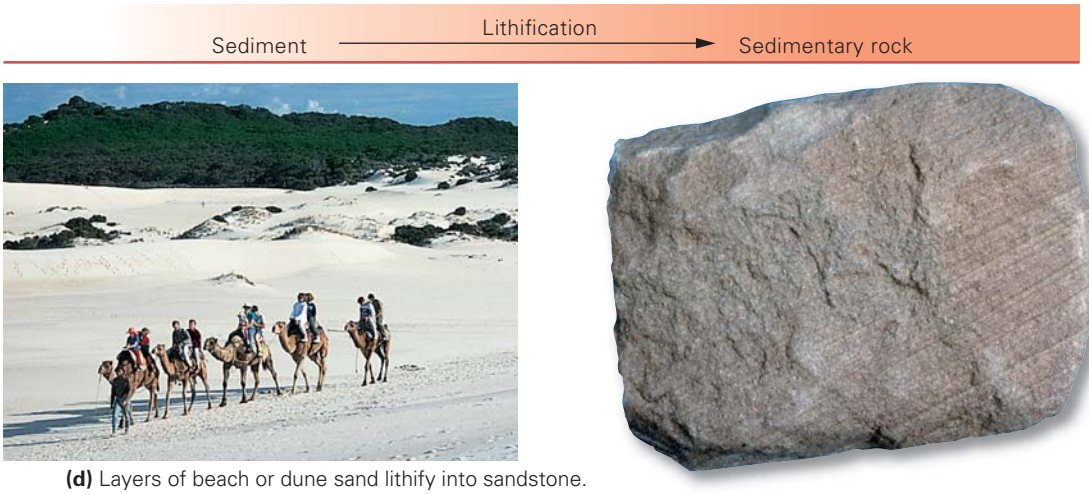
(b) Layers of river gravel lithify into conglomerate.





(c) Sediment deposited in an alluvial fan, close to its source in an arid climate, can be feldspar rich. Lithification of this sediment yields arkose.

Chert (biochemical). If you walk beneath the northern end of the Golden Gate Bridge in California, you will find outcrops of reddish, almost porcelain-like rock occurring in 3- to 15-cm-thick layers (Fig. 6.6a). Hit it with a hammer, and the rock would crack to form smooth, spoon-shaped (conchoidal) fractures. Geologists call this rock biochemical chert; it's made from cryptocrystalline quartz (*crypto* is Greek for hidden), meaning quartz grains that are too small to be seen without the extreme magnification of an electron microscope. The chert beneath the Golden Gate Bridge formed from the shells of silica-secreting plankton that accumulated on the sea floor. Gradually, after burial,



(d) Layers of beach or dune sand lithify into sandstone.



(e) Layers of mud, exposed beneath marsh grass, lithify to form shale. Here, the thin-bedded shale is interbedded with sandstone.

the shells dissolved, forming a silica-rich gel. Chert then formed when this gel solidified.

Organic Sedimentary Rocks

We've seen how the mineral shells of organisms ($CaCO_3$ or SiO_2) can accumulate and lithify to become *biochemical* sedimentary rocks. What happens to the "guts" of the organisms—the cellulose, fat, carbohydrate, protein, and other organic compounds that make up living matter? Commonly, this organic debris gets eaten by other organisms or decays at the Earth's surface. But in some environments, the organic debris settles along with other sediment and eventually gets buried. When lithified, organic-rich sediment becomes organic sedimentary rock.

Since the dawn of the industrial revolution in the early 19th century, coal, one type of organic sedimentary rock, has provided the fuel of modern industry and transportation, for the organic chemicals in the rock yield energy when burned. **Coal** is a black, combustible rock consisting of over 50 to 90% carbon. The remainder consists of oxygen, nitrogen, hydrogen, sulfur, silica, and minor amounts of other elements. Typically, the carbon in coal occurs in large, complex organic molecules made of many rings—note that the carbon does *not* occur in $CaCO_3$. As discussed further in Chapter 12, coal forms when plant remains have been buried deeply enough and long enough for the material to become compacted and to lose significant amounts of volatiles (hydrogen, water, CO_2, and ammonia); as the volatiles seep away, a concentration of carbon remains (**Fig. 6.6b**).

Chemical Sedimentary Rocks

The colorful terraces, or mounds, that grow around the vents of hot-water springs; the immense layers of salt that underlie the floor of the Mediterranean Sea; the smooth, sharp point of an ancient arrowhead—these materials all have something in common. They all consist of rock formed primarily by the precipitation of minerals from water solutions. We call such rocks chemical sedimentary rocks. They typically have a crystalline texture, partly formed during their original precipitation and partly when, at a later time, new crystals grow at the expense of old ones through a process called recrystallization. In some examples, crystals are coarse. In others, they are too small to see. Geologists distinguish among many types of chemical sedimentary rocks, primarily on the basis of composition.

Evaporites: the products of saltwater evaporation. In 1965, two daredevil drivers in jet-powered cars battled to be the first to set the land speed record of 600 mph. On November 7, Art Arfons, in the *Green Monster*, peaked at 576.127 mph; but eight days later Craig Breedlove, driving the *Spirit of America*, reached 600.601 mph. Traveling at such speeds, a driver must maintain an absolutely straight line; any turn will catapult the vehicle out of control. Thus, high-speed trials take place on extremely long and flat racecourses. Not many places can provide such conditions—the Bonneville Salt Flats of Utah do. The salt flats formed when an ancient salt lake evaporated. Under the heat of the Sun, the water turned

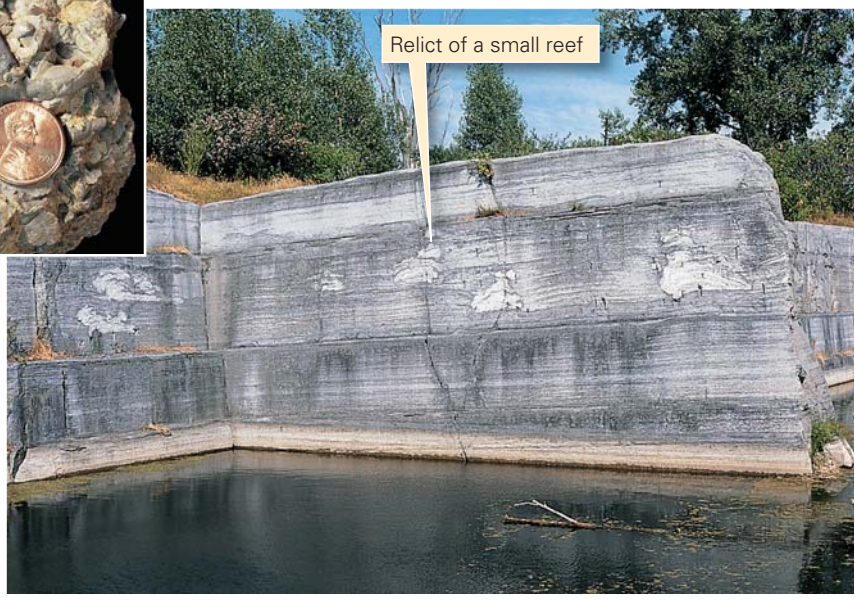
FIGURE 6.5 The formation of carbonate rocks (limestone).



(a) In this modern coral reef, corals produce shells. If buried and preserved, these become limestone.



(b) Wave energy breaks up shells, forming carbonate clasts that later become cemented together.



(c) A Vermont quarry shows the gray color of 400-Ma limestone. The white mounds are relicts of small reefs.

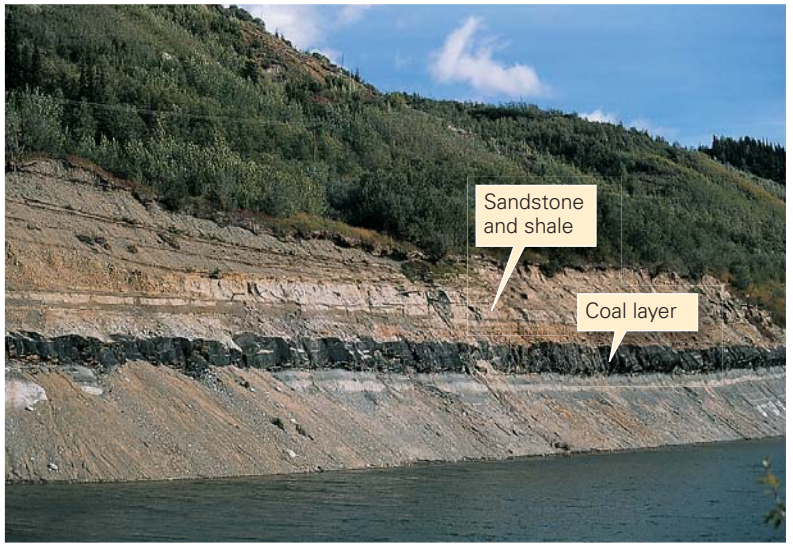
to vapor and drifted up into the atmosphere, but the salt that had been dissolved in the water stayed behind.

Salt precipitation occurs where saltwater becomes supersaturated, meaning that it has exceeded its capacity to contain more dissolved ions. In supersaturated saltwater, ions bond to form solid grains that either settle out of the water or grow on the floor of the water body. Supersaturated saltwater develops where evaporation removes water from a water body faster than the rate at which new water enters. This process takes place in desert lakes and along the margins of restricted seas (**Fig. 6.7a, b**). For thick deposits of salt to form, large volumes of water must evaporate. Because salt deposits form as a consequence of evaporation, geologists refer to them as **evaporites**. The specific type of salt minerals comprising an evaporite

FIGURE 6.6 Examples of biochemical and organic sedimentary rocks.

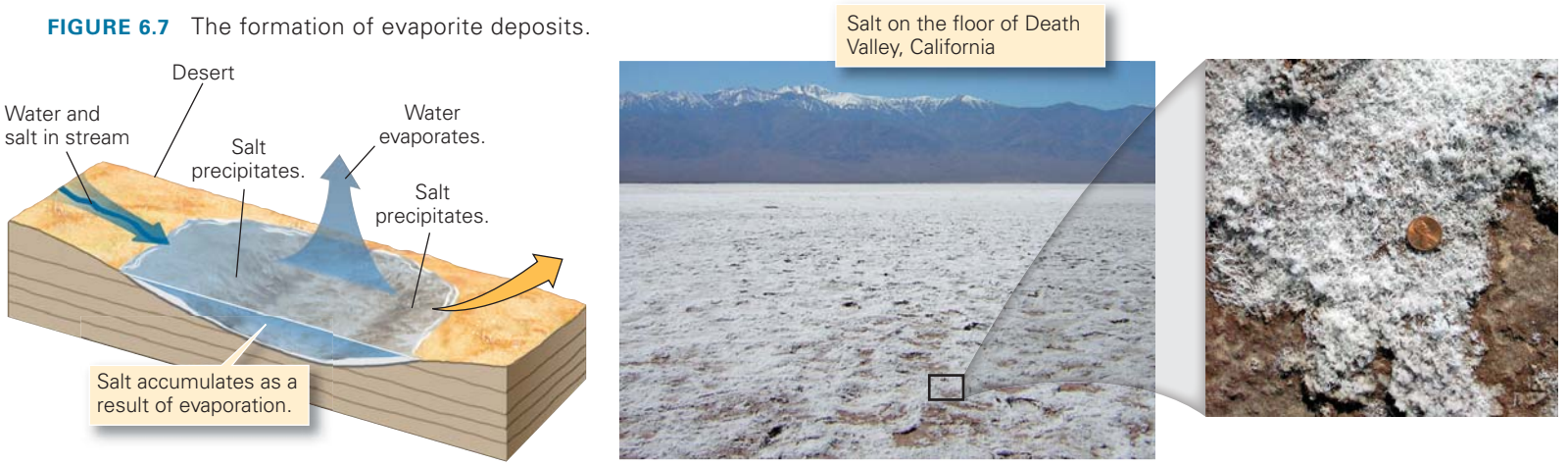


(a) This bedded chert developed on the deep-sea floor by the deposition of plankton that secrete silica shells.

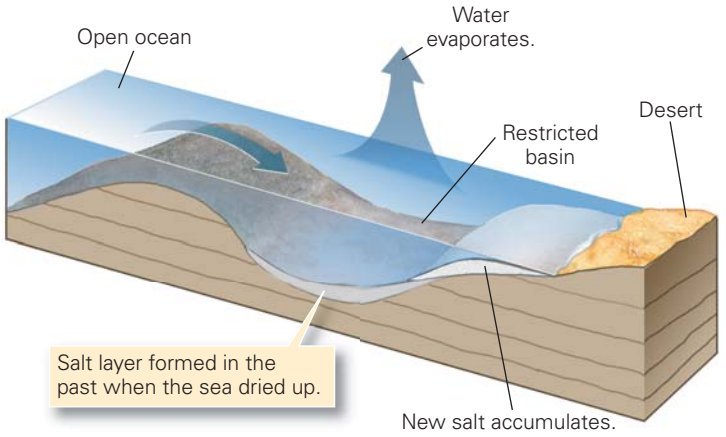


(b) Coal is deposited in layers (beds), just like other kinds of sedimentary rocks.

FIGURE 6.7 The formation of evaporite deposits.



(a) In lakes with no outlet, tiny amounts of salt brought in by streams stay behind as the water evaporates. When the water evaporates entirely, a white crust of salt remains.



(b) Salt precipitation can also occur along the margins of a restricted marine basin, if saltwater evaporates faster than it can be resupplied.

depends on the amount of evaporation. When 80% of the water evaporates, gypsum forms; and when 90% of the water evaporates, halite precipitates.

Travertine (chemical limestone). **Travertine** is a rock composed of crystalline calcium carbonate ($CaCO_3$) formed by chemical precipitation from groundwater that has seeped out at the ground surface either in hot- or cold-water springs, or on the walls of caves. What causes this precipitation? It happens, in part, when the groundwater degasses, meaning that some of the carbon dioxide that had been dissolved in the groundwater bubbles out of solution, for removal of carbon dioxide encourages the precipitation of carbonate. Precipitation also occurs when water evaporates, thereby increasing the concentration of carbonate. Various kinds of microbes live in the environments in which travertine accumulates, so biologic activity may also contribute to the precipitation process. Travertine produced at springs forms terraces and mounds that are meters or even hundreds of meters thick, such as those at Mammoth Hot Springs (**Fig. 6.8a**). Travertine also grows on the walls of caves where groundwater seeps out (**Fig. 6.8b**). In cave settings, travertine builds up beautiful and complex growth forms called speleothems (see Chapter 16).

Dolostone. Another carbonate rock, **dolostone**, differs from limestone in that it contains the mineral dolomite ($CaMg[CO_3]_2$), which contains equal amounts of calcium and magnesium. Where does the magnesium come from? Most dolostone forms by a chemical reaction between solid calcite and magnesium-bearing groundwater. Much of the dolostone you may find in an outcrop actually originated as limestone but later changed into dolostone as dolomite crystals replaced calcite. This change may take place beneath lagoons along a shore soon after the limestone formed, or a long time later, after the limestone has been buried deeply.

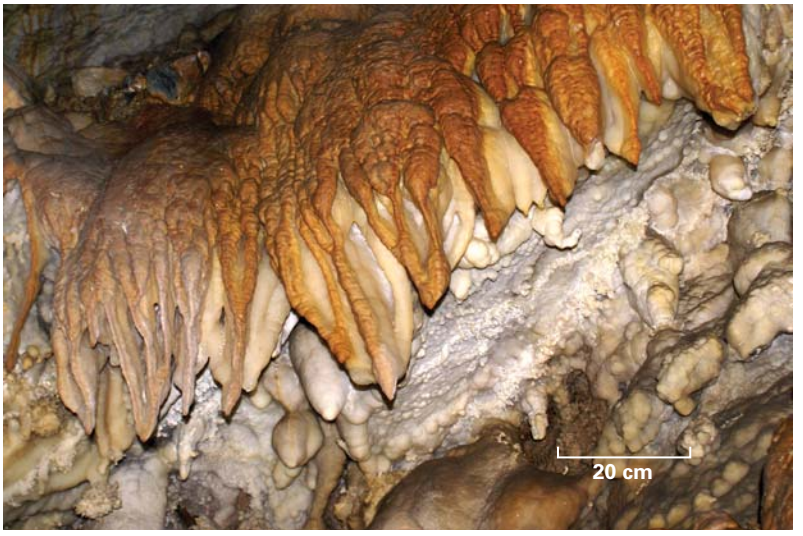
Chert (replacement). A tribe of Native Americans, the Onondaga, once lived off the land in eastern New York State. Here, outcrops of limestone contain layers or nodules (lenses or lumps) of a black chert (**Fig. 6.9a**). Because of the way it breaks, the tribe's artisans could fashion sharp-edged tools (arrowheads and scrapers) from this chert, so the Onondaga collected it for their own toolmaking industry and for use in trade with other people. Unlike the deep-sea (biochemical) chert described earlier, the chert collected by the Onondaga formed when cryptocrystalline quartz gradually *replaced* calcite crystals within a body of limestone long after the limestone was deposited; geologists call such material "replacement chert."

Did you ever wonder . . .
how flint used for arrowheads first formed?

FIGURE 6.8 Examples of travertine (chemical limestone) deposits.



(a) Travertine accumulates in terraces at Mammoth Hot Springs in Yellowstone Park, Wyoming.



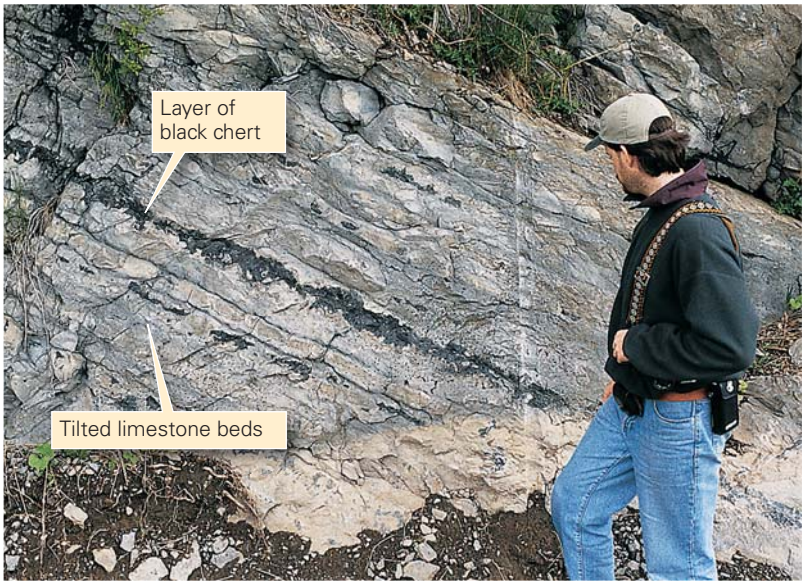
(b) Travertine speleothems form as calcite-rich water drips from the ceiling of Timpanogos Cave in Utah.

Chert comes in many colors (black, white, red, brown, green, gray), depending on the impurities it contains. Petrified wood is chert that forms when silica-rich sediment, such as ash from a volcanic eruption, buries a forest. The silica dissolves in groundwater, and then later precipitates as cryptocrystalline quartz within wood, gradually replacing the wood's cellulose. The chert deposit retains the shape of the wood and the growth rings within it. Some chert, known as agate, precipitates in concentric rings inside hollows in a rock and ends up with a striped appearance, caused by variations in the content of impurities incorporated in the chert (Fig. 6.9b).

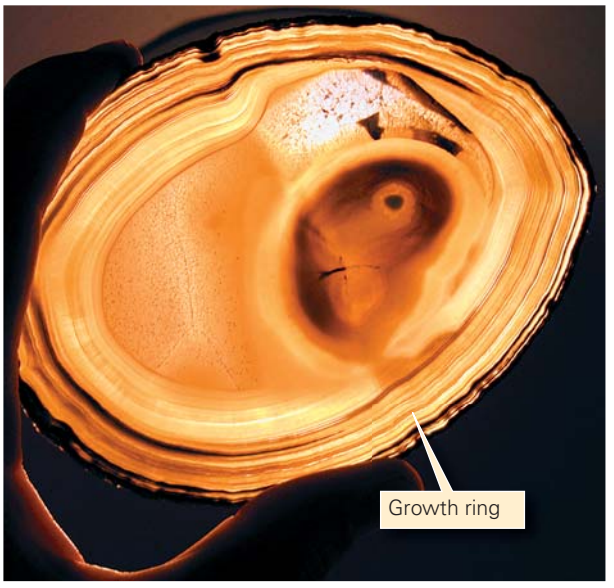
Take-Home Message

Sedimentary rocks differ from one another due to their mode of origin and/or composition. Clastic rocks form from cemented-together grains that broke off pre-existing rocks, limestones from shells or chemical precipitates, evaporites from evaporating salt water, and organic rocks from plant debris and other organic matter.

FIGURE 6.9 Examples of chert that precipitated in place.



(a) Replacement chert forms as layers of nodules between tilted limestone beds in New York.



(b) A thin slice of Brazilian agate, lit from the back, shows growth rings.

6.3 Sedimentary Structures

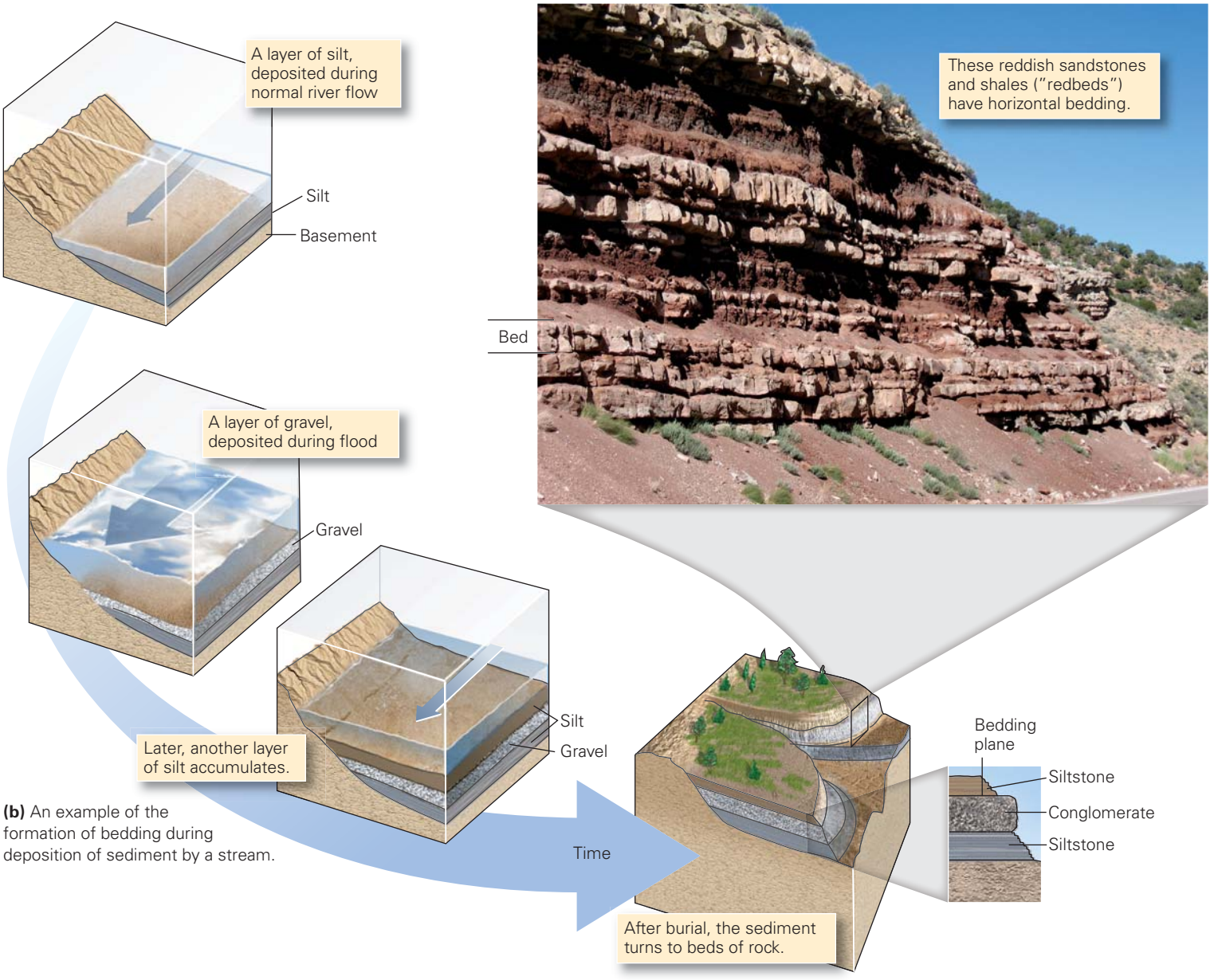
Geologists use the term **sedimentary structure** for the layering of sedimentary rocks, for surface features on layers formed during deposition, and for the arrangement of grains within layers. Here, we examine some of the more important types.

Bedding and Stratification

Let's start by introducing the jargon for discussing sedimentary layers. A single layer of sediment or sedimentary rock with a recognizable top and bottom is called a **bed**; the boundary between two beds is a bedding plane; several beds together constitute **strata** (singular stratum, from the Latin *stratum*, meaning pavement); and the overall arrangement of sediment into a sequence of beds is bedding, or stratification. From the word strata, we derive other words, such as stratigrapher (a geologist who specializes in studying strata) and stratigraphy (the study of the record of Earth history preserved in strata). In some outcrops, stratification can be quite subtle. But commonly, successive beds have different colors, textures, and resistance to erosion, so bedding gives outcrops a striped appearence (Fig. 6.10a).

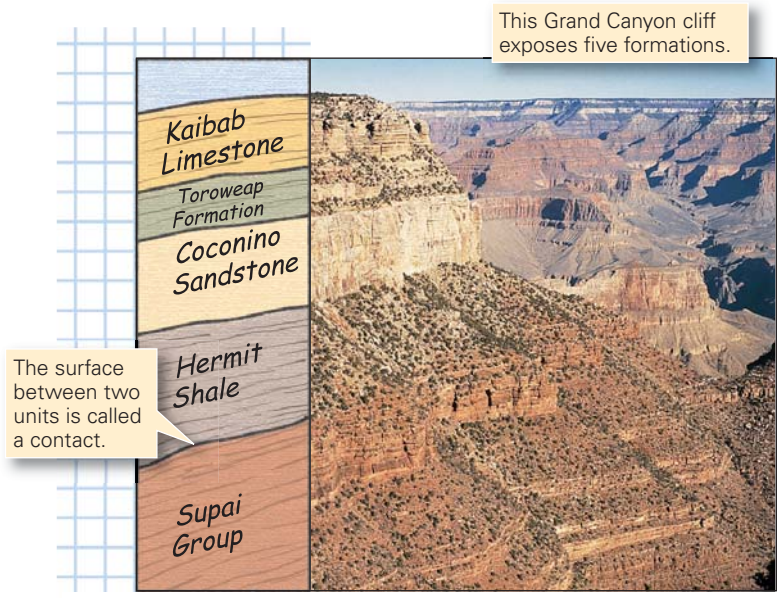
FIGURE 6.10 Bedding in sedimentary rocks.

(a) Beds of sedimentary rock exposed along a road in Utah.

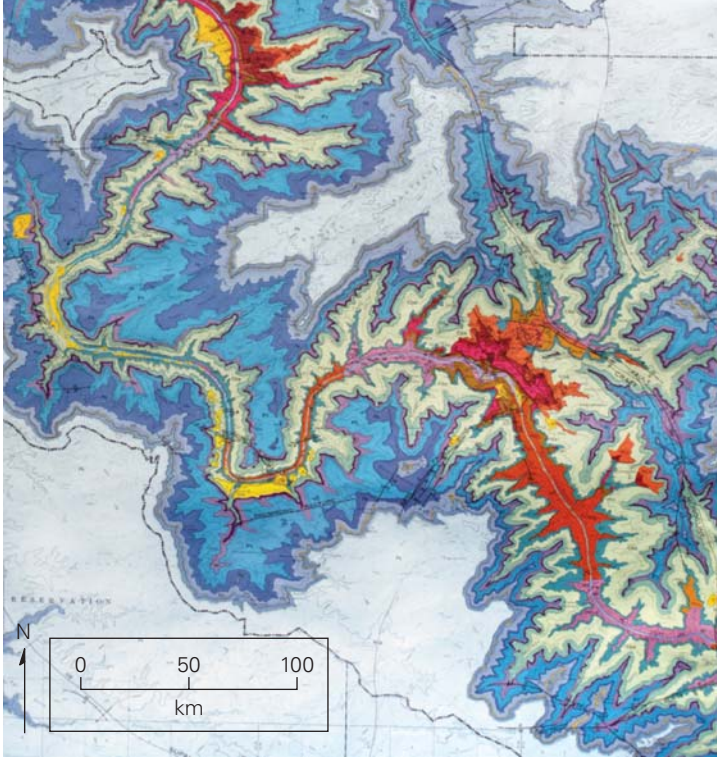


(b) An example of the formation of bedding during deposition of sediment by a stream.

FIGURE 6.11 The concept of a stratigraphic formation.



(a) The names of formations consisting of one rock type may indicate the rock type (e.g., Kaibab Limestone). The name of a formation including more than one rock type includes the word *formation* (Toroweap Formation). Several related formations comprise a group (Supai Group).



(b) A geologic map portrays the distribution of formations in a portion of the Grand Canyon. Each color band is a specific formation.

Why does bedding form? To find the answer, we need to think about how sediment accumulates. Changes in the climate, water depth, current velocity, or the sediment source control the type of sediment deposited at a location at a given time. For example, on a normal day a slow-moving river may carry only silt, which collects on the riverbed (**Fig. 6.10b**). During a flood, the river flows faster and carries sand and pebbles, so a layer of sandy gravel forms over the silt layer. Then, when the flooding stops, more silt buries the gravel. If this succession of sediments become lithified and exposed for you to see, they appear as alternating beds of siltstone and sandy conglomerate.

During geologic time, long-term changes in a depositional environment can take place. Thus, a given sequence of strata may differ markedly from sequences of strata above or below.

FIGURE 6.12 Ripple marks, a type of sedimentary structure, are visible on the surface of modern and ancient beds.

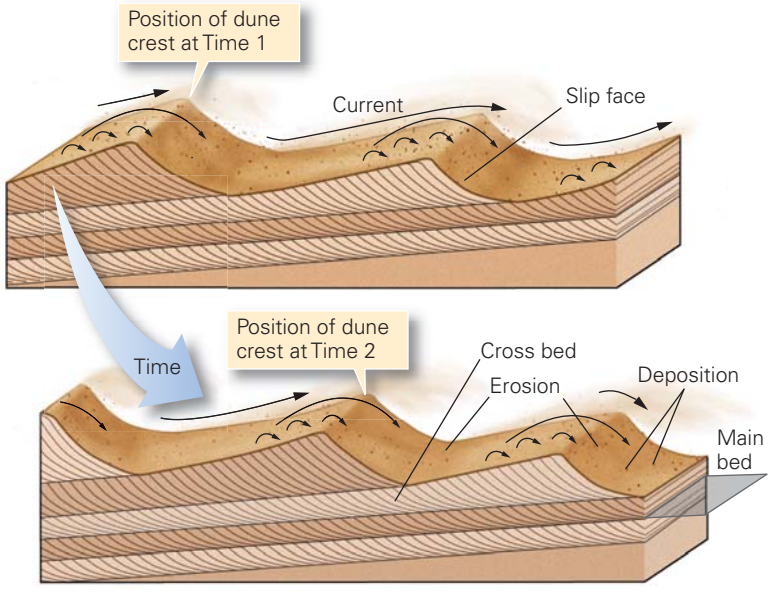


(a) Modern ripples exposed at low tide along a sandy beach on the shore of Cape Cod, Massachusetts.

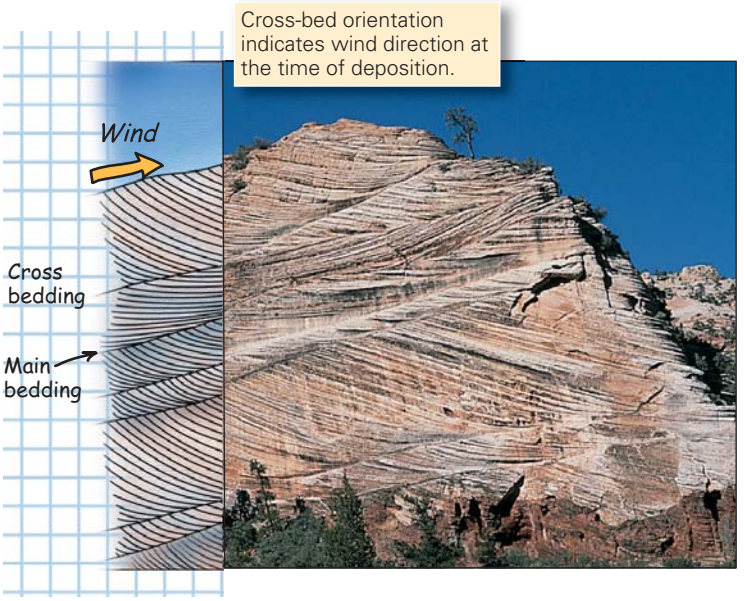


(b) These 145-million-year-old ripples are preserved on a tilted bed of solid sandstone at Dinosaur Ridge, Colorado.

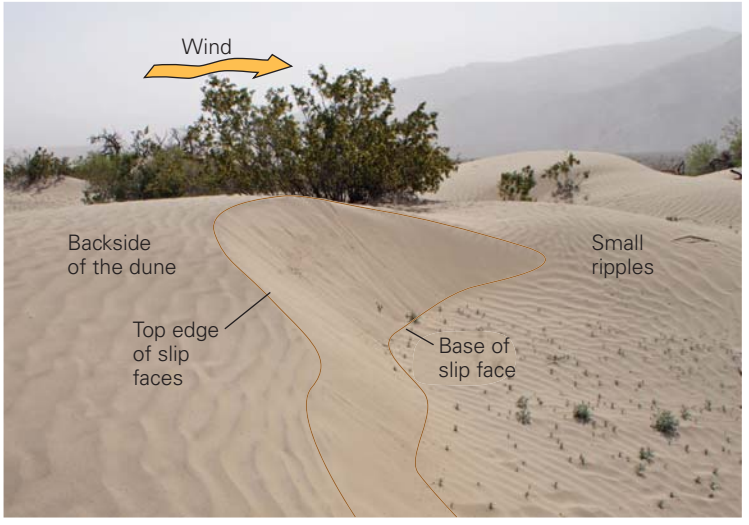
FIGURE 6.13 Cross bedding, a type of sedimentary structure within a bed.



(a) Cross beds form as sand blows up the windward side of a dune or ripple and then accumulates on the slip face. With time, the dune crest moves.



(b) A cliff face in Zion National Park, Utah, displays large cross beds formed between 200 and 180 million years ago, when the region was a desert with large sand dunes.



(c) A steep slip face occurs on the leeward side of a small dune. The edges of the slip face are highlighted.

A sequence of strata that is distinctive enough to be traced as a unit across a fairly large region is called a **stratigraphic formation**, or simply a formation (Fig. 6.11a). For example, a region may contain a succession of alternating sandstone and shale beds deposited by rivers, overlain by beds of marine limestone deposited later when the region was submerged by the sea. A stratigrapher might identify the sequence of sandstone and shale beds as one formation and the sequence of limestone beds as another. Formations are often named after the locality where they were first found and studied. A map that portrays the distribution of stratigraphic formations is called a **geologic map** (Fig. 6.11b).

Ripple Marks, Dunes, and Cross Bedding: Consequences of Deposition in a Current

Many clastic sediments accumulate in moving fluids (wind, rivers, or waves). Fascinating sedimentary structures develop at the interface between the sediment and the fluid. These structures are called bedforms. Bedforms that develop at a given location reflect such factors as the velocity of the flow and the size of the clasts. Though there are many types of bedforms, we'll focus on only two—ripple marks and dunes. The growth of both produces cross bedding, a special type of lamination within beds.

Ripple marks are relatively small (generally no more than a few centimeters high), elongated ridges that form on a bed surface at right angles to the direction of current flow. You can find ripples on modern beaches and preserved on bedding planes of ancient rocks (Fig. 6.12a, b). Dunes are relatively large, elongate ridges built of sediment transported by a current. In effect, dunes are "mega-ripples." Dunes on the bed of a stream may be tens of centimeters high, and wind-formed dunes of deserts may be tens to over 100 meters high.

If you examine a vertical slice cut into a ripple or dune, you will find distinct internal laminations that are inclined at an angle. Such laminations are called **cross beds**. To see how cross beds develop, imagine a current of air or water moving uniformly in one direction (Fig. 6.13a). The current erodes and picks up clasts from the upstream part of the bedform and deposits them on the downstream or leeward face of the crest. Sediment builds up until gravity causes it to slip down the leeward

face. With time, the dune or ripple builds in the downstream direction. The surface of the slip face establishes the shape of the cross beds. Eventually, a new cross-bedded layer builds out over a preexisting one. The boundary between two successive layers is called the "main bedding," and the internal curving surfaces within the layer constitute the cross bedding (Fig. 6.13b, c).

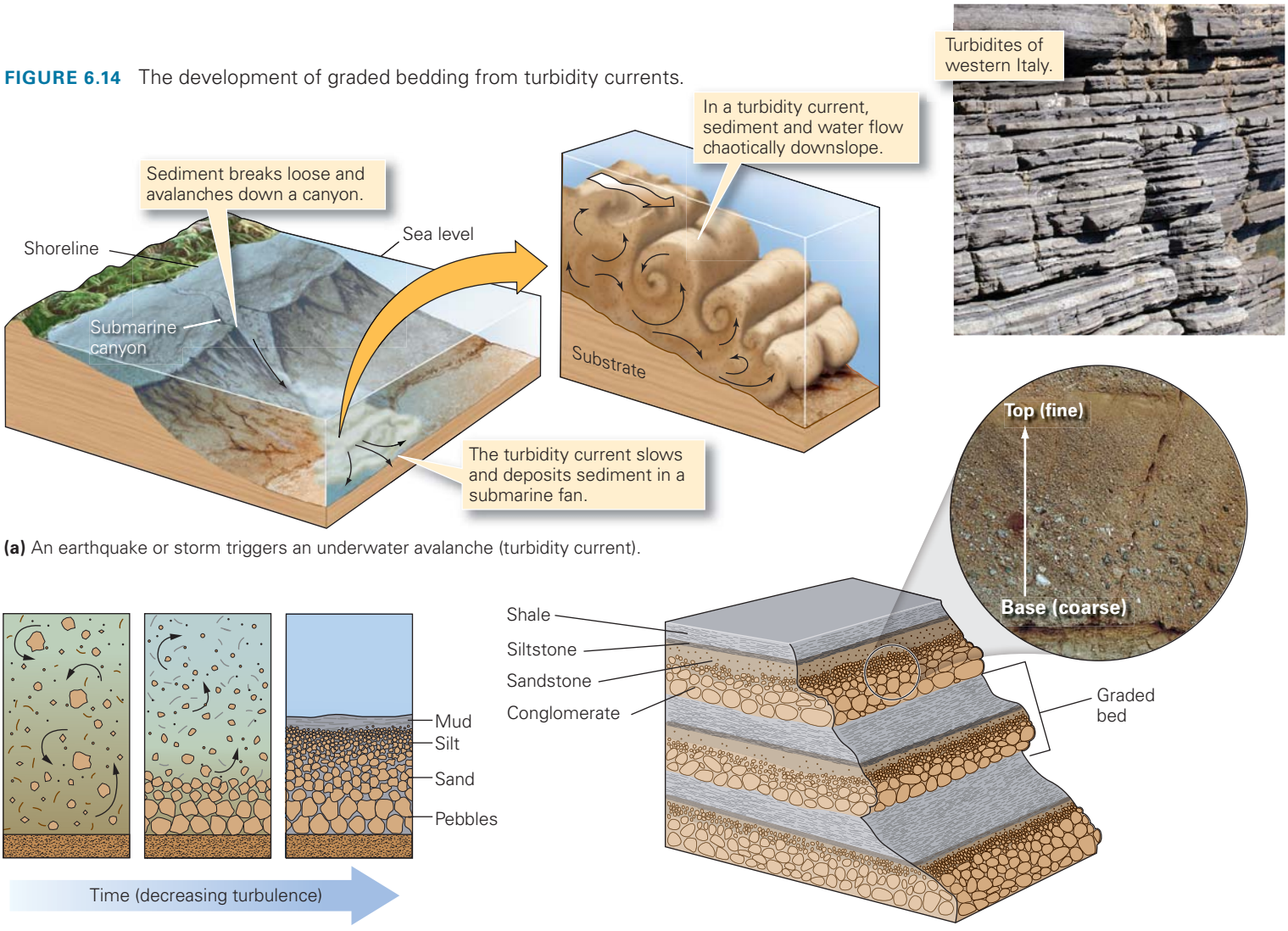
Turbidity Currents and Graded Beds

Sediment deposited on a submarine slope tends to be unstable. For example, an earthquake or storm might disturb this sediment and cause it to slip downslope and mix with water to create a murky, turbulent cloud. This cloud is denser than clear water and thus flows downslope like an underwater avalanche (Fig. 6.14a–c). We call this moving submarine suspension of sediment a **turbidity current**. Downslope, the turbidity current slows, and the sediment that it has carried starts to settle out. Larger grains sink faster through a fluid than do finer grains, so the coarsest sediment settles out first. Progressively finer grains accumulate on top, with the finest sediment (clay) settling out last. This process forms a **graded bed**—that is, a layer of sediment in which grain size varies from coarse at the bottom to fine at the top. Geologists refer to a deposit from a turbidity current as a turbidite.

Bed-Surface Markings

A number of features develop on the surface of a bed as a consequence of events that happen during deposition or

FIGURE 6.14 The development of graded bedding from turbidity currents.



(a) An earthquake or storm triggers an underwater avalanche (turbidity current).

(b) As the turbidity current slows, larger grains settle first, followed by progressively finer grains.

(c) As the process repeats, a succession of graded beds accumulates.

FIGURE 6.15 Mud cracks, a sedimentary structure formed when mud dries out.



(a) Mud cracks in red mud at Bryce Canyon, Utah. Note how the edges of the mud plates curl up.



(b) Mud cracks preserved in a 410-million-year-old bed exposed on the base of a cliff in New York.

soon after, while the sediment layer remains soft. Such bed-surface markings include the following.

- *Mud cracks*: If a mud layer dries up after deposition, it cracks into roughly hexagonal plates that typically curl up at their edges. We refer to the openings between the plates as mud cracks (**Fig. 6.15a, b**).
- *Scour marks*: As currents flow over a sediment surface, they may erode small troughs, called scour marks, parallel to the current flow.
- *Fossils*: Fossils are relicts of past life. Some fossils are shell imprints or footprints on a bedding surface (see Interlude E).

Burial and lithification of bed-surface markings can preserve them in the stratigraphic record.

Why Study Sedimentary Structures?

Sedimentary structures are not just a curiosity, but are important clues that help geologists understand the environment in which sedimentary beds were deposited. For example, the presence of ripple marks and cross bedding indicates that layers were deposited in a current, the presence of mud cracks indicates that the sediment layer was exposed to the air and dried out, and graded beds indicate deposition by turbidity currents. Also, fossil types can tell us whether sediment was deposited along a river or in the deep sea, for different species of organisms live in different environments. In the next section of this chapter, we examine these environments in greater detail.

Take-Home Message

Sedimentary rocks occur in beds, because as conditions of deposition and/or sediment source change over time, sediment character changes. Geologists refer to a succession of strata traceable over a region as a stratigraphic formation. The action of currents can produce sedimentary structures such as ripples, scours, and cross beds.

6.4 How Do We Recognize Depositional Environments?

Geologists refer to the conditions in which sediment was deposited as the **depositional environment**. Examples include beach, glacial, and river environments. To identify depositional environments, geologists, like crime scene investigators, look for clues. Detectives may seek fingerprints and bloodstains to identify a culprit. Geologists examine grain size, composition, sorting, bed-surface marks, cross bedding, and fossils to identify a depositional environment. Geological clues can tell us if the sediment was deposited by ice, strong currents, waves, or quiet water, and in some cases can provide insight into the climate at the time of deposition. With experience, geologists can examine a succession of beds and determine if it accumulated on a river floodplain, along a beach, in shallow water just offshore, or on the deep ocean floor.

Let's now explore some examples of different depositional environments and the sediments deposited in them, by imagining that we are taking a journey from the mountains to the sea, examining sediments as we go (see **Geology at a Glance** on pp. 180–181 and **See for Yourself F**). We will see that geologists distinguish among three basic categories of depositional environments: terrestrial, coastal, and marine.

Terrestrial (Nonmarine) Sedimentary Environments

We begin our exploration with terrestrial depositional environments, those that develop inland, far enough away from the shoreline that they are not affected by ocean tides and waves. The sediments settle on dry land, or under and adjacent to freshwater.

FIGURE 6.16 Examples of nonmarine depositional environments.



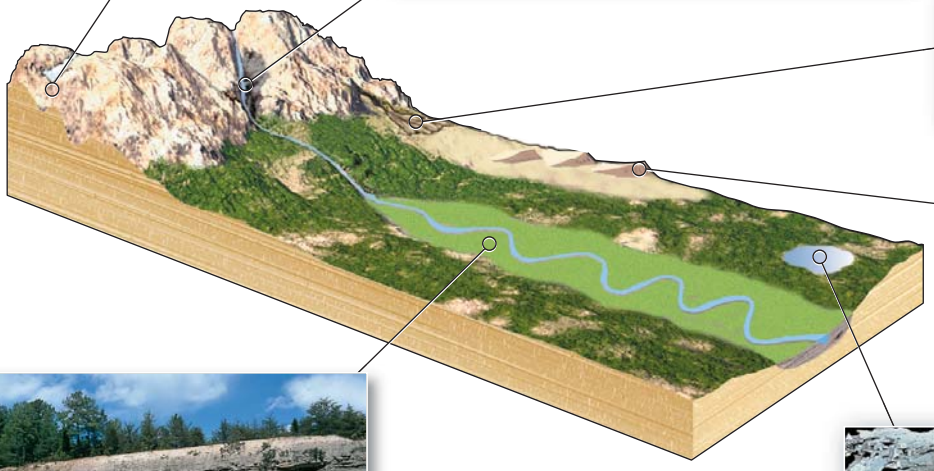
(a) Glacial till at the end of a glacier in France.



(b) Boulders and cobbles deposited by a mountain stream in Colorado.

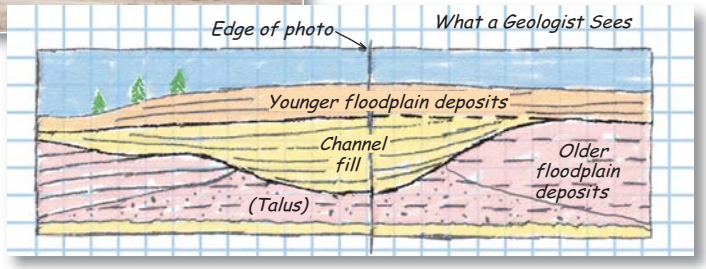


(c) An alluvial fan in Death Valley, California.





(e) Deposits of an ancient river channel in Indiana. Note how the floor of the channel cuts across older strata. The geologist's sketch emphasizes the relationship.





(d) Sand dunes in Brazil.



(f) Laminated mud from a lake bed.

In some settings, oxygen in surface water or groundwater reacts with iron to produce rust-like iron-oxide minerals in terrestrial sediments, which give the sediment an overall reddish hue. Strata with this hue are informally called redbeds.

Glacial environments. High in the mountains, where it's so cold that more snow collects in the winter than melts away, glaciers—rivers or sheets of ice—develop and slowly flow. Because ice is a solid, it can move sediment of any size. So as a glacier moves down a valley in the mountains, it carries along *all* the sediment that falls on its surface from adjacent cliffs or gets plucked from the ground at its base or sides. At the end of the glacier, where the ice finally melts away, the sediment that had been in or on the ice accumulates as "glacial till" (Fig. 6.16a). Till is unsorted and unstratified—it contains clasts ranging from clay size to boulder size all mixed together.

Mountain stream environments. As we walk down beyond the end of the glacier, we enter a realm where turbulent streams rush downslope in steep-sided valleys. This fast-moving water has the power to carry large clasts; in fact, during floods, boulders and cobbles can tumble down the stream bed. Between floods, when water flow slows, the largest clasts settle out to form gravel and boulder beds, while the stream carries finer sediments like sand and mud farther downstream (Fig. 6.16b). Sedimentary deposits of a mountain stream would, therefore, include breccia and conglomerate.

Alluvial-fan environments. Our journey now takes us to the mountain front, where the fast-moving stream empties onto a plain. In arid regions, where there is not enough water for the stream to flow continuously, the stream deposits its load of sediment near the mountain front, producing a wedge-shaped apron of gravel and sand called an alluvial fan (Fig. 6.16c). Deposition takes place here because when the stream pours from a canyon mouth and spreads out over a broader region, friction with the ground causes the water to slow down, and slow-moving water does not have the power to move coarse sediment. The sand here still contains feldspar grains, for these have not yet weathered into clay. Alluvial-fan sediments become arkose and conglomerate.

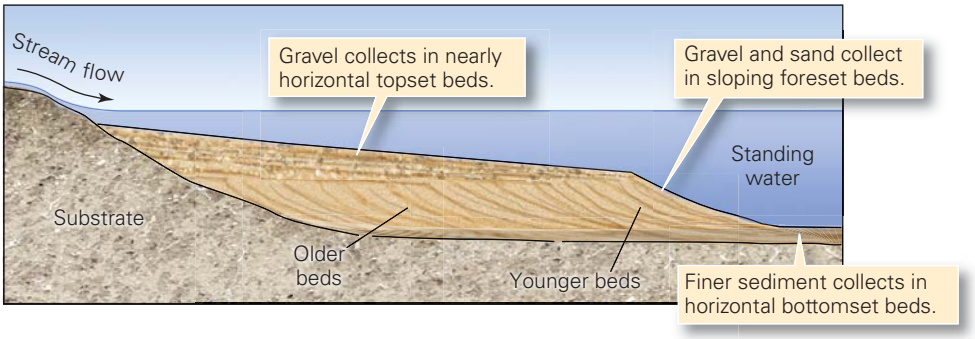
Sand-dune environments. If the climate is very dry, few plants can grow and the ground surface lies exposed. Strong winds can move dust and sand. The dust gets carried away, and the resulting well-sorted sand can accumulate in dunes. Thus, thick layers of well-sorted sandstone, in which we can find large cross beds, are relicts of desert sand-dune environments (Fig. 6.16d).

River (fluvial) environments. In climates where streams flow, we find several distinctive depositional environments. Rivers transport gravel, sand, silt, and mud. The coarser sediments tumble along the bed in the river's channel and collect in cross-bedded, rippled layers while the finer sediments drift along, suspended in the water. This fine sediment settles out along the banks of the river, or on the floodplain, the flat land on either side of the river that is covered with water only during floods. On the floodplain, mud layers dry out between floods, leading to the formation of mud cracks. River sediments lithify to form sandstone, siltstone, and shale. Typically, the coarser sediments of channels are surrounded by layers of fine-grained floodplain deposits, so in cross section, the channel has a lens-like shape (Fig. 6.16e). Geologists commonly refer to river deposits as fluvial sediments, from the Latin word *fluvius*, for river.

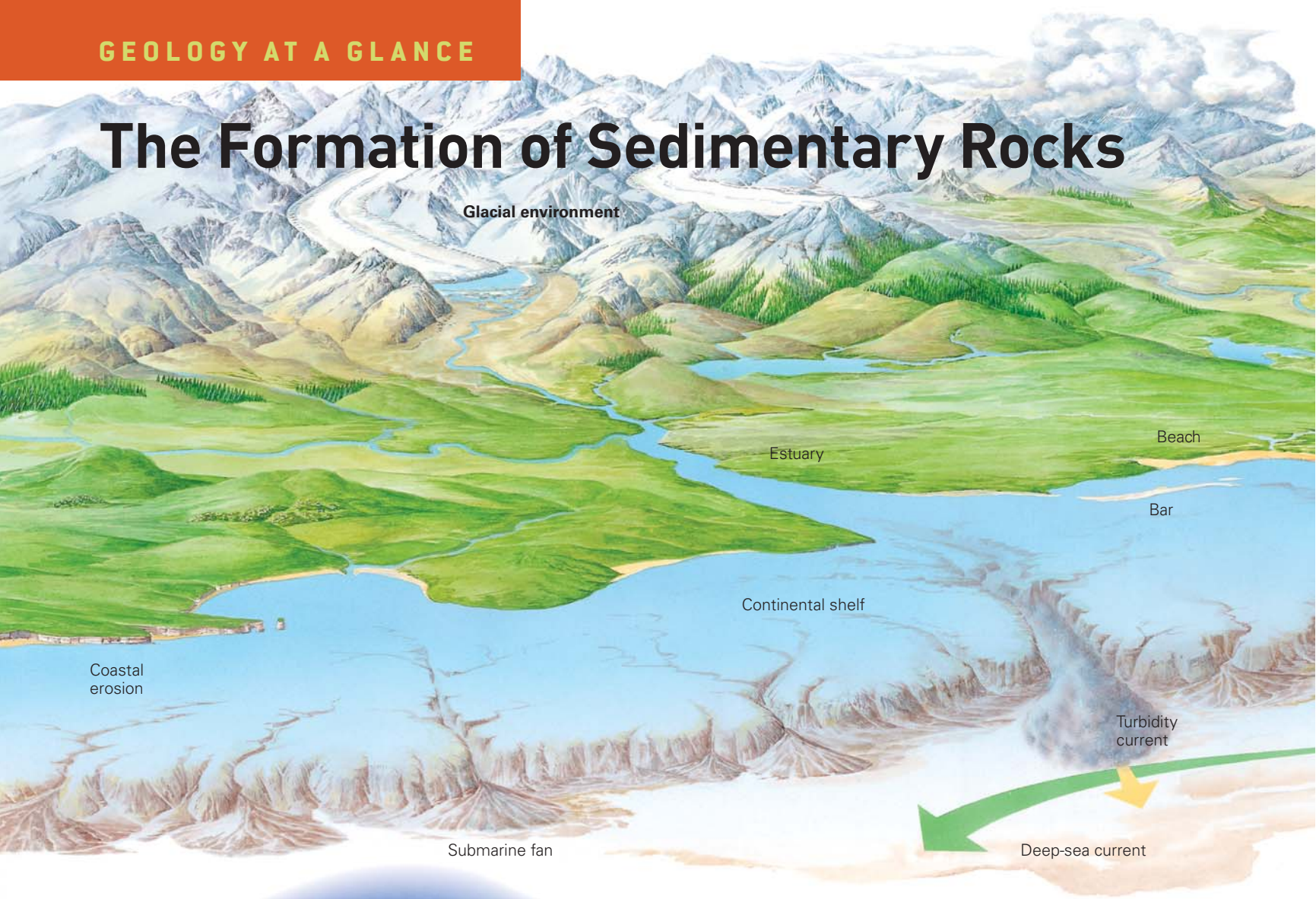
Lake environments. In temperate climates, where water remains at the surface throughout the year, lakes form. In lakes, the relatively quiet water can't move coarse sediment; any coarse sediment brought into the lake by a stream settles out at the stream's outlet. Only fine clay makes it out into the center of the lake, where it settles to form mud on the lake bed. Thus, lake sediments typically consist of finely laminated shale (Fig. 6.16f).

At the mouths of streams that empty into lakes, small deltas may form. A **delta** is a wedge of sediment that accumulates where moving water enters standing water. Deltas were so named because the map shape of some deltas resembles the Greek letter *delta* (Δ), as we discuss further in Chapter 14. In 1885, an American geologist named G. K. Gilbert showed that such deltas contain three components (Fig. 6.17): topset beds composed of gravel, foreset beds of gravel and sand, and silty bottomset beds.

FIGURE 6.17 A simple "Gilbert-type" delta formed where a stream enters a lake.

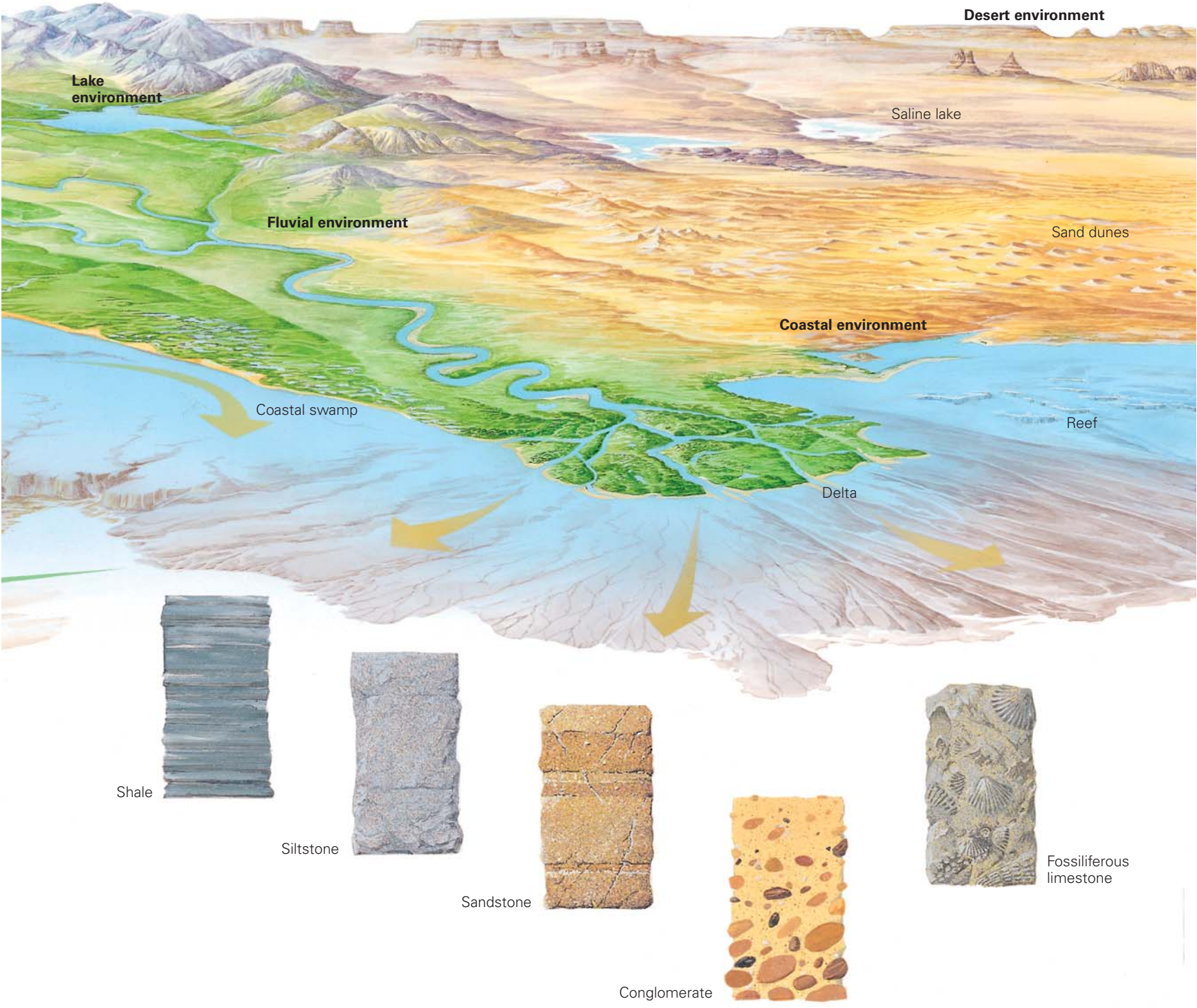


The Formation of Sedimentary Rocks





Categories of sedimentary rocks include clastic sedimentary rocks, chemical sedimentary rocks (formed from the precipitation of minerals out of water), and biochemical sedimentary rocks (formed from the shells of organisms). Clastic sedimentary rocks develop when grains (clasts) break off preexisting rock by weathering and erosion and are transported to a new



location by wind, water, or ice; the grains are deposited to create sediment layers, which are then cemented together. We distinguish among types of clastic sedimentary rocks on the basis of grain size.

The character of a sedimentary rock depends on the composition of the sediment and on the environment in which it accumulated. For example, glaciers carry sediment of all sizes, so they leave deposits of poorly sorted (different-sized) till; streams deposit coarser grains in their channels and finer ones on floodplains; a river slows down at its mouth and deposits an immense pile of silt in a delta. Fossiliferous limestone develops on coral reefs. In desert environments, sand accumulates into dunes and evaporates precipitate in saline lakes. Offshore, submarine canyons channel avalanches of sediment, or turbidity currents, out to the deep-sea floor.

Sedimentary rocks tell the history of the Earth. For example, the layering, or bedding, of sedimentary rocks is initially horizontal. So where we see layers bent or folded, we can conclude that the layers were deformed during mountain building. Where horizontal layers overlie folded layers, we have an unconformity: for a time, sediment was not deposited, and/or older rocks were eroded away.

Coastal and Marine Environments

Along the seashore, a variety of distinct coastal environments occur; the character of each reflects the nature of the sediment supply and the climate. Marine environments start at the high-tide line and extend offshore, to include the deep ocean floor. The type of sediment deposited at a location depends on the climate, water depth, and whether or not clastic grains are available.

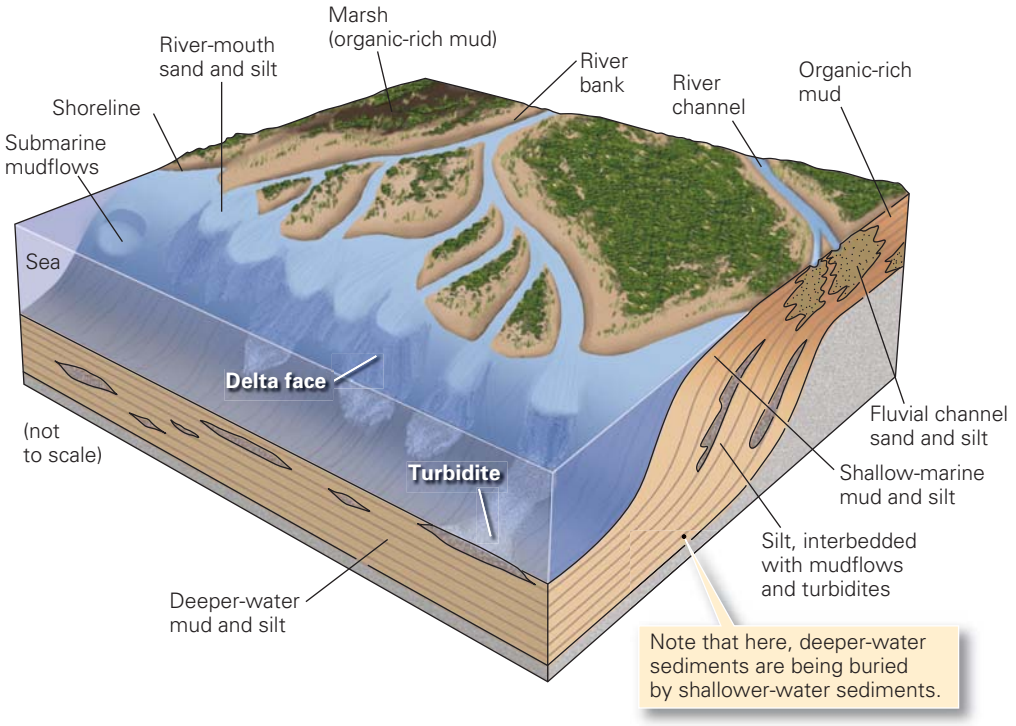
Marine delta deposits. After following the river downstream for a long distance, we reach its mouth, where it empties into the sea. Here, the river builds a delta of sediment out into the sea. River water stops flowing when it enters the sea, so sediment settles out.

Large deltas are much more complex than the lake examples that Gilbert studied, for they include many different sedimentary environments including swamps, channels, floodplains, and submarine slopes. Sea-level changes may cause the positions of the different environments to move with time. Thus, deposits of an ocean-margin delta produce a great variety of sedimentary rock types (Fig. 6.18a).

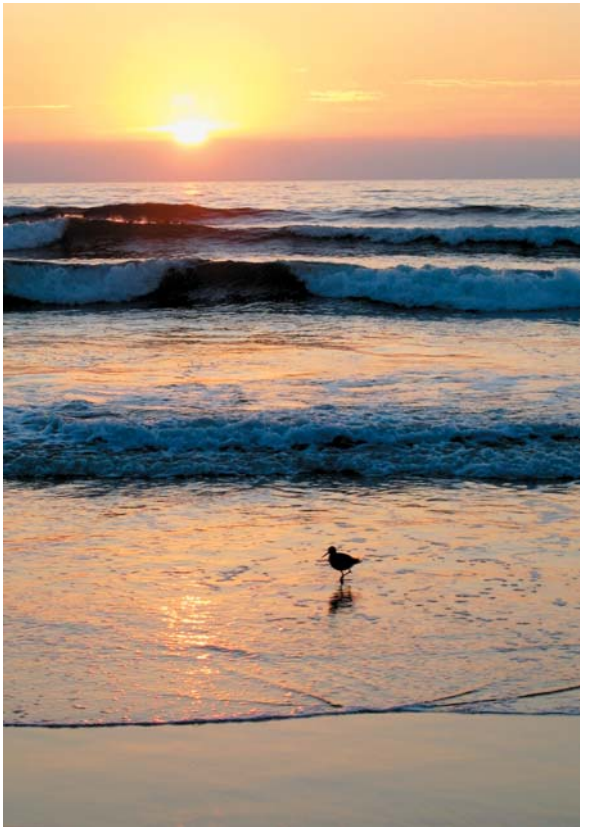
Coastal beach sands. Now we leave the delta and wander along the coast. Oceanic currents transport sand along the coastline. The sand washes back and forth in the surf, so it becomes well sorted (waves winnow out silt and clay) and well rounded, and because of the back-and-forth movement of ocean water over the sand, the sand surface may become rippled (Fig. 6.18b). Thus, if you find well-sorted, medium-grained sandstone, perhaps with ripple marks, you may be looking at the remnants of a beach environment.

Shallow-marine clastic deposits. From the beach, we proceed offshore. In deeper water, where wave energy does not stir the sea floor, finer sediment can accumulate. Because the water here may be only meters to a few tens of meters deep, geologists refer to this depositional setting as a shallow-marine environment. Clastic sedimentary layers that accumulate in this environment tend to be fine-grained, well-sorted, well-rounded silt, and they are inhabited by a great variety of organisms such as mollusks and worms. Thus, if you see beds of siltstone and mudstone containing marine fossils, you may be looking at shallow-marine clastic deposits.

FIGURE 6.18 Examples of coastal depositional environments.

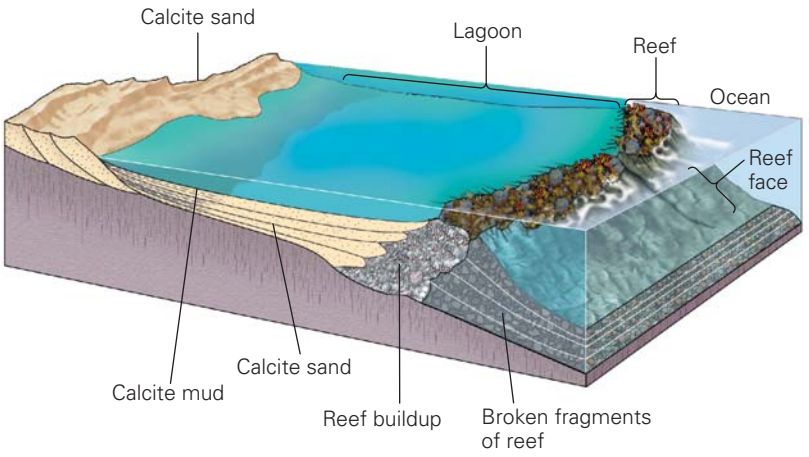


(a) A major river delta along an ocean coast is a complex depositional environment. Sea-level changes affect locations of depositional settings.



(b) Waves on this California beach wash and sort the sand.

FIGURE 6.19 Reef environments for the deposition of carbonate rocks.



(a) Carbonate reefs form along shorelines in warm-water environments. In detail, reefs include many distinct depositional environments.

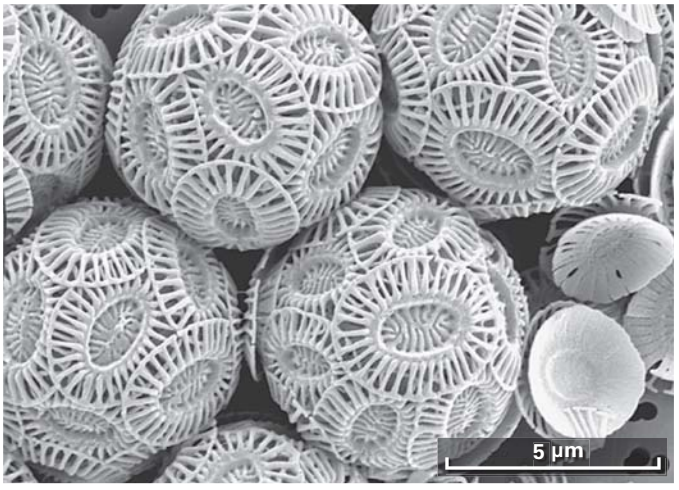


(b) A dramatic reef surrounds an island in the tropical Pacific. Deeper water is darker. Note the surf along the edge of the reef.

Shallow-water carbonate environments. In shallow-marine settings relatively free of clastic sediment, warm, clear, nutrient-rich water hosts an abundance of organisms. Their shells, which consist of carbonate minerals, make up most of the sediment that accumulates (**Fig. 6.19a, b**). The nature of carbonate sediment depends on the water depth. Beaches collect sand composed of shell fragments; lagoons (protected bodies of quiet water) are sites where carbonate mud accumulates; and reefs consist of coral and coral debris. Farther offshore of a reef, we can find a sloping apron of reef fragments. Shallow-water carbonate environments transform into various kinds of limestone.

Deep-marine deposits. We conclude our journey by sailing far offshore. Along the transition between coastal regions and the deep ocean, turbidity currents deposit graded beds. In the deep-ocean realm, only fine clay and plankton provide a source for sediment. The clay eventually settles out onto the deep-sea floor, forming deposits of finely laminated mudstones, and plankton shells settle to form chalk (from calcite shells; **Fig. 6.20a, b**) or chert (from siliceous shells). Thus, deposits of mudstone, chalk, or bedded chert indicate a deep-marine origin.

FIGURE 6.20 Examples of deep-marine sediment.



(a) These plankton shells, which make up some kinds of deep-marine sediment, are so small that 50 could fit in the eye of a needle.



(b) The chalk cliffs of southeastern England consist of plankton shells deposited on the sea floor tens of millions of years ago.

Take-Home Message

Different types of sedimentary rocks accumulate in different depositional environments. Thus, strata deposited along a river differs from strata deposited by ocean waves, by glaciers, or in the deep sea. By studying sedimentary rocks at a location, geologists can deduce environments that existed at the locality in the past.

6.5 Sedimentary Basins

The sedimentary veneer on the Earth's surface varies greatly in thickness. If you stand in central Siberia or south-central Canada, you will find yourself on igneous and metamorphic basement rocks that are over a billion years old—sedimentary rocks are nowhere in sight. Yet if you stand along the southern coast of Texas, you would have to drill through over 15 km of sedimentary beds before reaching igneous and metamorphic basement. *Thick accumulations of sediment form only in special regions* where the surface of the Earth's lithosphere sinks, providing space in which sediment collects. Geologists use the term **subsidence** to refer to the process by which the surface of the lithosphere sinks, and the term **sedimentary basin** for the sediment-filled depression. In what geologic settings do sedimentary basins form? An understanding of plate tectonics theory provides the answers.

Categories of Basins in the Context of Plate Tectonics Theory

Geologists distinguish among different kinds of sedimentary basins in the context of plate tectonics theory. Let's consider a few examples (Fig. 6.21).

- *Rift basins*: These form in continental rifts, regions where the lithosphere is stretching horizontally, and therefore thins vertically. As the rift grows, slip on faults drops blocks of crust down, producing low areas bordered by narrow mountain ridges. These troughs fill with sediment.
- *Passive-margin basins*: These form along the edges of continents that are not plate boundaries. They are underlain by stretched lithosphere, the remnants of a rift whose evolution successfully led to the formation of a mid-ocean ridge and subsequent growth of a new ocean basin. Passive-margin basins form because subsidence of stretched lithosphere continues long after rifting ceases. They fill with sediment carried to the sea by rivers and with carbonate rocks formed in coastal reefs.
- *Intracontinental basins*: These develop in the interiors of continents, initially because of subsidence over a rift. They may continue to subside in pulses even hundreds of millions of years after they formed, for reasons that are not well understood.
- *Foreland basins*: These form on the continent side of a mountain belt because the forces produced during convergence or collision push large slices of rock up faults and onto the surface of the continent. The weight of these slices pushes down on the surface of the lithosphere, producing a wedge-shaped depression adjacent to the mountain range that fills with sediment eroded from the range. Fluvial and deltaic strata accumulate in foreland basins.

Transgression and Regression

Sea-level changes, relative to the land surface, control the succession of sediments that we see in a sedimentary basin. At times during Earth history, sea level has risen by as much as a couple of hundred meters, creating shallow seas that submerge the interiors of continents. At other times, sea level has fallen by a couple of hundred meters, exposing the continental shelves to air. Global sea-level changes may be due to a number of factors, including climate change, which controls the amount of ice stored in polar ice caps and causes changes in the volume of ocean basins. Sea level at a location may also be due to the local uplift or sinking of the land surface.

When relative sea level rises, the shoreline migrates inland. We call this process **transgression**. When relative sea level falls, the coast migrates seaward. We call this process **regression** (Fig. 6.22). The process of transgression and regression leads to the formation of broad blankets of sediment.

FIGURE 6.21 The geologic setting of sedimentary basins.

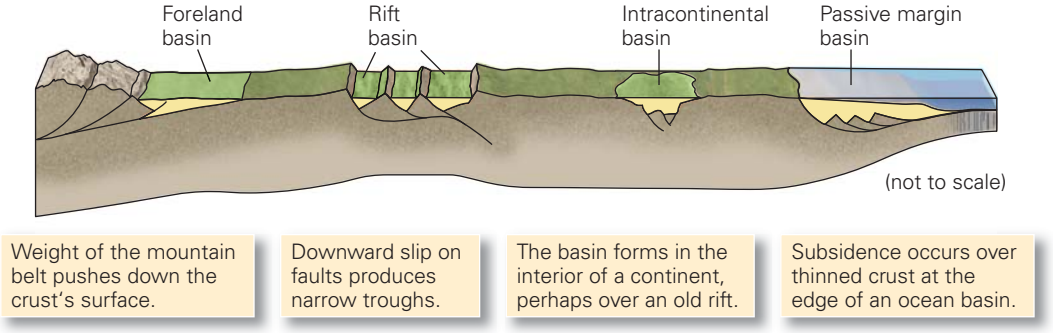
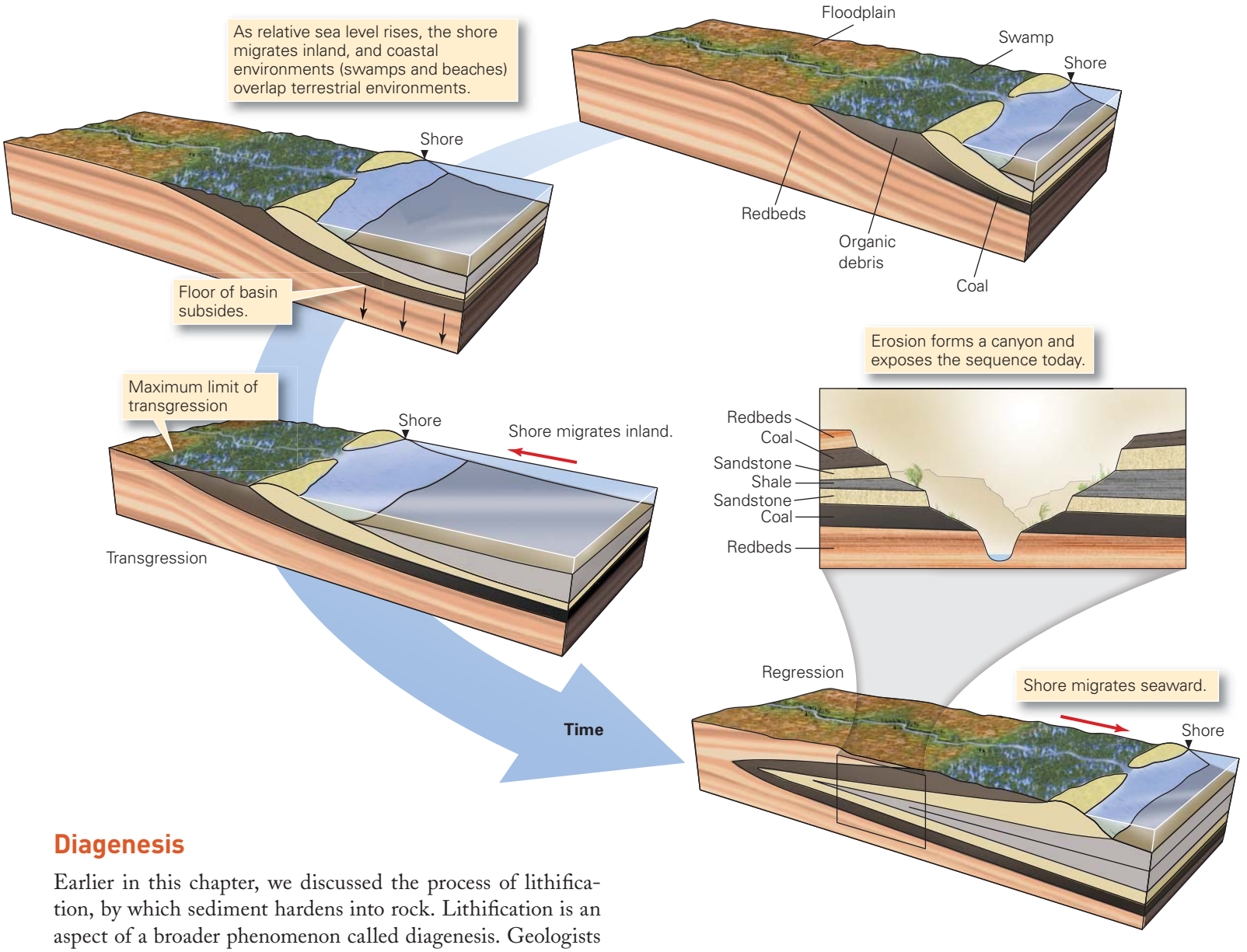


FIGURE 6.22 The concept of transgression and regression, during deposition of sedimentary sequence.



Diagenesis

Earlier in this chapter, we discussed the process of lithification, by which sediment hardens into rock. Lithification is an aspect of a broader phenomenon called diagenesis. Geologists use the term **diagenesis** for all the physical, chemical, and biological processes that transform sediment into sedimentary rock and that alter characteristics of sedimentary rock after the rock has formed.

In sedimentary basins, sedimentary rocks may become very deeply buried. As a result, the rocks endure higher pressures and temperatures and come in contact with warm groundwater. Diagenesis, under such conditions, can cause chemical reactions in the rock that produce new minerals and can also cause cement to dissolve or precipitate.

As temperature and pressure increase still deeper in the subsurface, the changes that take place in rocks become more profound. At sufficiently high temperature and pressure, metamorphism begins, in that a new assemblage of minerals forms, and/or mineral grains become aligned parallel to each other. The transition between diagenesis and metamorphism in sedimentary rocks is gradational and occurs between temperatures of 150°C and 300°C. In the next chapter, we enter the realm of true metamorphism.

Take-Home Message

In certain geologic settings, Earth's surface sinks (subsides) to form a depression that fills with sediment. The depression with its thick fill of sediment is a sedimentary basin. As sea level rises and falls, the coast, and therefore depositional environments, can migrate.

Chapter Summary

- Geologists recognize four major classes of sedimentary rocks. Clastic rocks form from cemented-together grains that were first produced by weathering, then were transported, deposited, and lithified. Biochemical rocks develop from the shells of organisms. Organic rocks consist of plant debris or of altered plankton remains. Chemical rocks precipitate directly from water.
- Sedimentary structures include bedding, cross bedding, graded bedding, ripple marks, dunes, and mud cracks. They serve as clues to depositional settings.
- Biochemical and organic rocks form from materials produced by living organisms.
- Limestone consists dominantly of calcite, chert forms from silica, coal from carbon, shale from clay, and sandstone from quartz grains.
- Evaporites consist of minerals precipitated from water.
- Glaciers, streams, alluvial fans, deserts, rivers, lakes, deltas, beaches, shallow seas, and deep seas each accumulate a different, distinctive assemblage of sedimentary strata.
- Thick piles of sedimentary rocks accumulate in sedimentary basins, regions where the lithosphere subsides.
- Transgressions occur when sea level rises and the coastline migrates inland. Regressions occur when sea level falls and the coastline migrates seaward.
- Diagenesis involves processes leading to lithification and processes that alter sedimentary rock at temperatures lower than those that cause metamorphism.

Key Terms

arkose (p. 167)
bed (p. 173)
biochemical sedimentary rock (p. 164)
breccia (p. 167)
cementation (p. 166)
chemical sedimentary rock (p. 164)
clastic sedimentary rock (p. 164)
clast (p. 164)
coal (p. 169)
compaction (p. 166)
conglomerate (p. 167)
cross bed (p. 175)
delta (p. 179)
deposition (p. 165)
depositional environment (p. 177)
detritus (p. 164)
diagenesis (p. 185)
dolostone (p. 171)
erosion (p. 165)
evaporite (p. 170)
geologic map (p. 175)
graded bed (p. 176)
limestone (p. 168)
lithification (p. 165)
mudstone (p. 167)
organic sedimentary rock (p. 164)
regression (p. 184)
ripple mark (p. 175)
sandstone (p. 164)
sedimentary basin (p. 184)
sedimentary rock (p. 164)
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stratigraphic formation (p. 175)
subsidence (p. 184)
transgression (p. 184)
travertine (p. 171)
turbidity current (p. 176)

Review Questions

1. Describe how a clastic sedimentary rock forms from its unweathered parent rock.
2. Explain how biochemical sedimentary rocks form.
3. How do grain size and shape, sorting, sphericity, and angularity change as sediments move downstream?
4. Describe the two different kinds of chert. How are they similar? How are they different?
5. Do all chemical sedimentary rocks have the same composition? What conditions produce evaporites?
6. How does dolostone differ from limestone, and how does dolostone form?
7. What are cross beds, and how do they form? How can you read the current direction from cross beds?
8. Describe how a turbidity current forms and moves. How does it produce graded bedding?
9. Compare deposits of an alluvial fan with those of a deep-marine deposit.
10. Why don't sediments accumulate everywhere? What types of tectonic conditions are required to create basins?
11. How is it possible for sandstone derived from sediment deposited in a beach environment to comprise a formation that blankets a broad region?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on sedimentary rocks and structures.
- A video exercise on the characteristics of canyons.
- An animation exercise on the formation of cross-bedding.

On Further Thought

12. Recent exploration of Mars by robotic vehicles suggests that layers of sedimentary rock cover portions of the planet's surface. On the basis of examining images of these layers, some researchers claim that the layers contain cross bedding and relicts of gypsum crystals. At face value, what do these features suggest about depositional environments on Mars in the past?
13. The Gulf Coast of the United States is a passive-margin basin that contains a very thick accumulation of sediment. Drilling reveals that the base of the sedimentary succession in this basin consists of redbeds. These are overlain by a thick layer of evaporite. The evaporite, in turn, is overlain by deposits composed of sandstone and shale. In some intervals, sandstone occurs in channels and contains ripple marks, and the shale contains mud cracks. In other intervals, the sandstone and shale contain fossils of marine organisms. Be a sedimentary detective, and explain the succession of sediment in the basin.
14. Examine the Bahamas with *Google Earth*™ or NASA World Wind. (You can find a high-resolution image at Latitude 23°58′40.98″N, Longitude 77°30′20.37″W.) Note that broad expanses of very shallow water surround the islands, that white-sand beaches occur along the coast of the islands, and that small reefs occur offshore. What does the sand consist of, and what rock will it become if it eventually becomes buried and lithified?

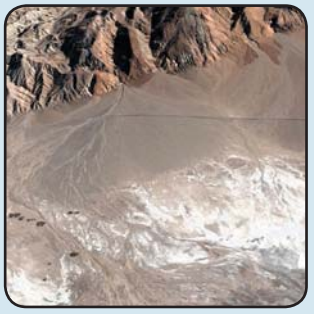
SEE FOR YOURSELF F. . . Sedimentary Rocks

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet F of our **Geotours Workbook**.



Shallow marine environments, Red Sea, Egypt
Latitude 22°38′17.70″N,
Longitude 36°13′21.27″E

From 4 km, the desert sands of the Sahara abut the blue waters of the Red Sea. What types of sedimentary rocks would form if the sediments visible in this view were to be buried and preserved?



Alluvial fans and evaporites, Death Valley, California
Latitude 36°24′20.49″N,
Longitude 116°51′12.63″W
Elev. 1.5 km (oblique, looking east)

Death Valley is a narrow rift whose floor lies below sea level; from 1.5 km, you can see alluvial fans and white evaporites.



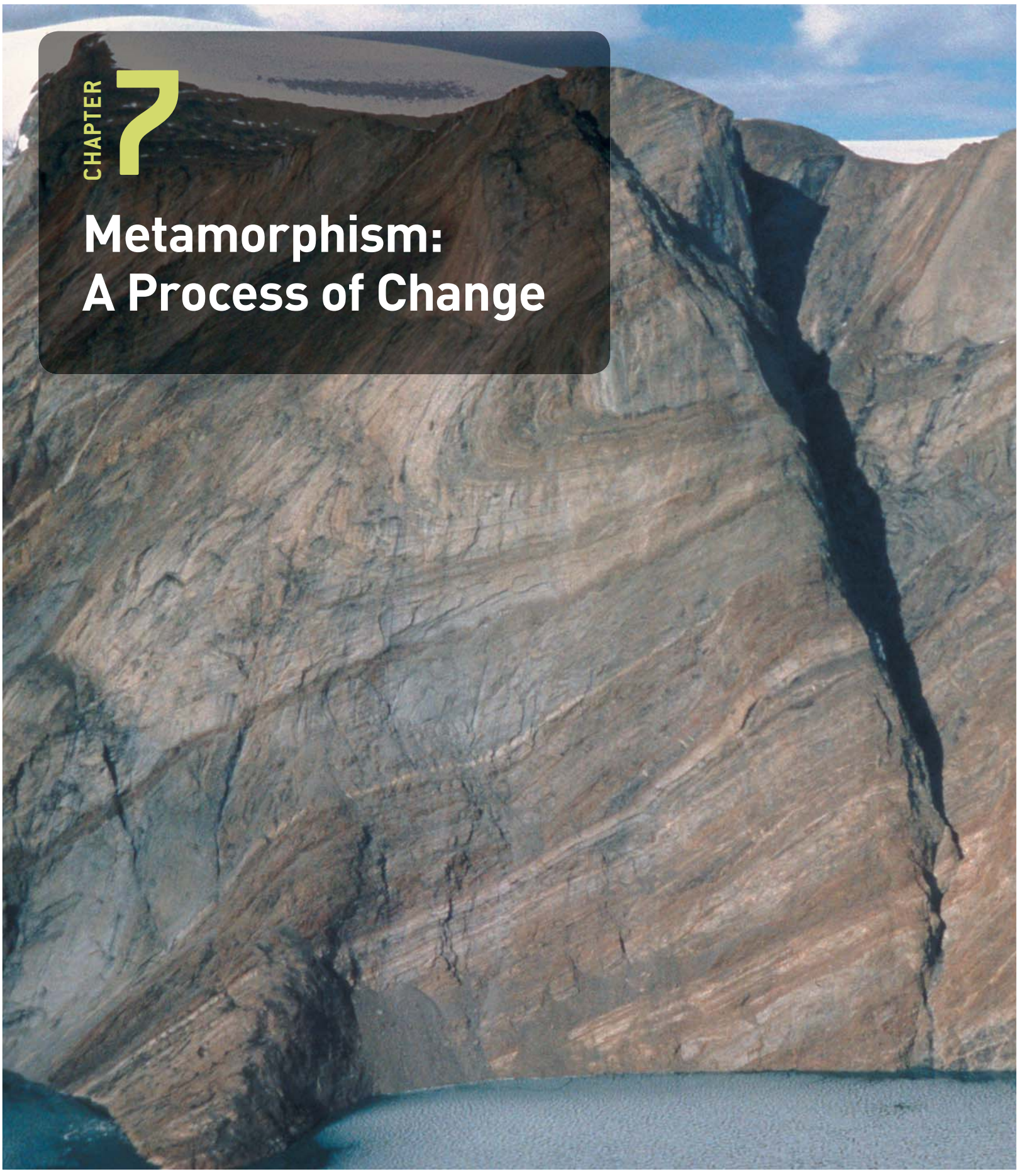
Murray River flood plain, Australia
Latitude 34°7′4.68″S,
Longitude 140°46′9.75″E

From 15 km, you see the Murray River meanders across the flat-lying landscape of South Australia. In this view, the water is restricted to the channel, exposing the sand and silt deposits that have covered its floodplain.



Grand Canyon, Arizona
Latitude 36° 8′8.94″N,
Longitude 112°15′48.56″W

Looking along the Grand Canyon, from 15 km above you can see the spectacular color banding caused by the succession of stratigraphic formations exposed on its walls. Some of these units are light gray limestone, some are tan sandstone, some are red shale.



CHAPTER 7

Metamorphism: A Process of Change



This 2-km-high cliff along Dickson Fjord, Greenland, exposes gneiss that formed when pre-existing sedimentary and igneous rocks "changed" under conditions of high temperature and pressure during a Paleozoic mountain-building event.

Chapter Objectives

By the end of this chapter, you should know . . .

- why rock, once formed, doesn't necessarily stay the same forever, and how metamorphism can change rock.
- what conditions, such as changes in temperature and pressure, can cause metamorphism.
- why metamorphism alters the texture and mineral content of rocks, and may produce layering called foliation.
- what geologic processes can lead to metamorphism, and why they do.
- how geologists classify metamorphic rocks based on the presence or absence of foliation, the character of foliation, and rock composition.

Nothing in the world lasts, save eternal change.

—Honorat de Bueil (1589–1650)

7.1 Introduction

Cool winds sweep across Scotland for much of the year. In this blustery climate, vegetation has a hard time taking hold, so the landscape provides countless outcrops of barren rock. During the latter half of the 18th century, James Hutton examined these outcrops, hoping to learn how rock formed. Hutton found that many features in the outcrops resembled the products of present-day sediment deposition and volcanic activity, and he developed an understanding of how sedimentary and igneous rock originated. But Hutton also found rock that contained minerals and textures quite different from those in sedimentary and igneous samples. He described this third, puzzling, kind of rock as "a mass of matter which had evidently formed originally in the ordinary manner . . . but which is now extremely distorted in its structure . . . and variously changed in its composition."

The rock that so puzzled Hutton is now known as metamorphic rock, from the Greek words *meta*, meaning change, and *morphe*, meaning form. In modern terms, a **metamorphic rock** is one that forms when a preexisting rock, or **protolith**, undergoes a solid-state change in response to the modification of its environment. This process of change is called **metamorphism**.

Let's look at the components of our definition more closely. By *solid-state*, we mean that a metamorphic rock does *not* form

by solidification of magma—remember that geologists consider rocks that solidified from magma to be igneous. By *change*, we mean that metamorphism produces new minerals that did not occur in the protolith, and/or produces a new texture (arrangement of mineral grains) that is distinct from that of the protolith. And by *modification of environment*, we mean that metamorphism takes place when a protolith endures a rise or fall in temperature and/or pressure, undergoes compression and shear, or reacts with "hydrothermal fluids" (very hot-water solutions).

Hutton did more than just note the existence of metamorphic rock—he also tried to understand why metamorphism takes place. Because he found some metamorphic rocks adjacent to igneous intrusions, he concluded that metamorphism can take place when heat from an intrusion "cooks" the rock into which it intrudes. And because he found that metamorphic rocks can occur over broad regions in the absence of intrusions, he speculated that metamorphism can also take place when rock ends up at great depth beneath Earth's surface.

From Hutton's day to the present, geologists have undertaken field studies, laboratory experiments, and theoretical calculations to better characterize metamorphism. In this chapter, we introduce the results of their work. We begin by explaining the causes of metamorphism and the basis for classifying metamorphic rocks. We conclude by discussing the geologic settings in which these rocks form. As you will see, Hutton's speculations on the origin of metamorphic rock were basically correct, but they represented only part of the story—the rest of the story could not take shape until the theory of plate tectonics had been proposed.

Did you ever wonder . . .
once formed, do rocks ever change?

7.2 Consequences and Causes of Metamorphism

What Is a Metamorphic Rock?

If someone were to put a rock on a table in front of you, how would you know that it is metamorphic? First, metamorphic rocks can possess **metamorphic minerals**, new minerals that grow in place within the solid rock only under metamorphic temperatures and pressures. In fact, metamorphism can produce a *group* of minerals that together make up what geologists call a "metamorphic mineral assemblage." And second, metamorphic rocks can have **metamorphic texture** defined by distinctive arrangements of mineral grains not found in other rock types. Commonly, the texture results in **metamorphic foliation**, due to the parallel alignment of platy minerals (such as mica) and/or the presence of alternating light-colored and dark-colored layers. When metamorphic minerals and/or textures develop, a metamorphic rock becomes as different from its protolith as a butterfly is from a caterpillar. For example, metamorphism of red shale can yield a metamorphic rock consisting of aligned mica flakes and brilliant garnet crystals (**Fig. 7.1a**), and metamorphism of a limestone composed of cemented-together fossil fragments can yield a metamorphic rock consisting of large interlocking crystals of calcite (**Fig. 7.1b**).

The process of forming metamorphic minerals and textures takes place very slowly—it may take thousands to millions of years—and it involves several processes, which sometimes occur alone and sometimes together. The most common processes are:

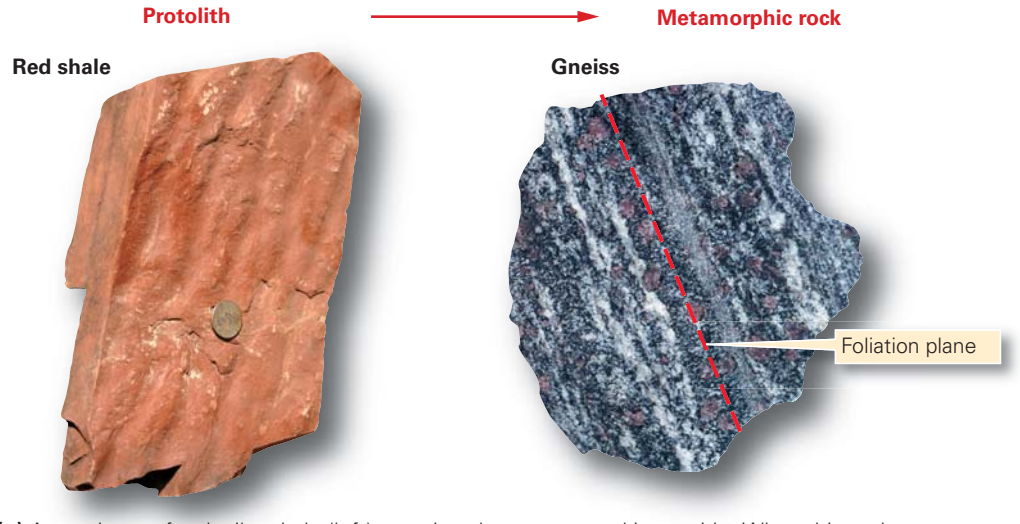
- *Recrystallization*, which changes the shape and size of grains without changing the identity of the mineral making up the grains (**Fig. 7.2a**).
- *Phase change*, which transforms one mineral into another mineral with the same composition but a different crystal structure. On an atomic scale, phase change involves the rearrangement of atoms.
- *Metamorphic reaction*, or *neocrystallization* (from the Greek *neos*, for new), which results in growth of new mineral crystals that differ from those of the protolith (**Fig. 7.2b**). During neocrystallization, chemical reactions digest minerals of the protolith to produce new minerals of the metamorphic rock.
- *Pressure solution*, which happens when a wet rock is squeezed more strongly in one direction than in others. Mineral grains dissolve where their surfaces are pressed against other grains, producing ions that migrate through the water to precipitate elsewhere (**Fig. 7.2c**).
- *Plastic deformation*, which happens when a rock is squeezed or sheared at elevated temperatures and pressures. Under these conditions, grains behave like soft plastic and change shape without breaking (**Fig. 7.2d**).

Caterpillars undergo metamorph*osis* because of hormonal changes in their bodies. Rocks undergo metamorph*ism* when they are subjected to heat, pressure, compression and shear, and/or very hot water. Let's now consider the details of how these *agents of metamorphism* operate.

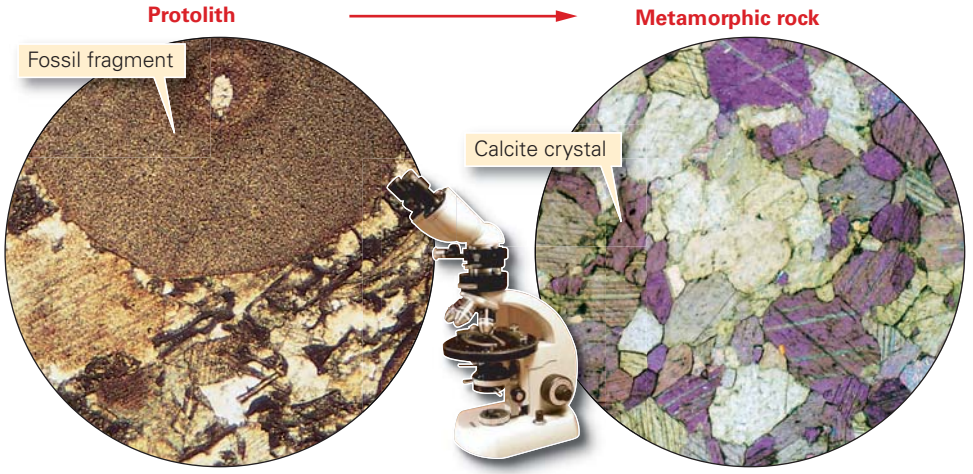
Metamorphism Due to Heating

When you heat cake batter, the batter transforms into a new material—cake. Similarly, when you heat a rock, its ingredients transform into a new material—metamorphic rock. Why? Think about what happens to atoms in a mineral grain as the grain warms. Heat causes the atoms to vibrate rapidly, stretching and bending chemical bonds that lock atoms to their neighbors. If bonds stretch too far and break, atoms detach from their original neighbors, move slightly, and form new bonds with other atoms. Repetition of this process leads to rearrangement

FIGURE 7.1 Metamorphism causes changes in mineral makeup and texture.



(a) A specimen of red, silty shale (left) contains clay, quartz, and iron oxide. When this rock undergoes intense metamorphism, it may change into a gneiss containing different minerals. This gneiss sample (right) contains biotite, quartz, feldspar, and purple garnet.



(b) A photomicrograph of a limestone in thin section (left) shows tiny fossil fragments and lime mud. After metamorphism, the texture of the rock changes completely and we see large, interlocking crystals of calcite (right). Note that the color seen here depends on the orientation of the crystals.

of atoms within grains, or to migration of atoms into and out of grains, a process called *solid-state diffusion*. As a consequence, recrystallization and/or neocrystallization take place, enabling a metamorphic mineral assemblage to grow in solid rock.

Metamorphism takes place at temperatures between those at which diagenesis (see Chapter 6) occurs and those that cause melting. Roughly speaking, this means that most metamorphic rocks you find in outcrops on continents formed at temperatures of between 250°C and 850°C.

Metamorphism Due to Pressure

As you swim underwater in a swimming pool, water squeezes against you equally from all sides—in other words, your body feels *pressure*. Pressure can cause a material to collapse inward. For example, if you pull an air-filled balloon down to a depth of 10 m in a lake, the balloon becomes significantly smaller. Pressure can have the same effect on minerals. Near the Earth's surface, minerals with relatively open crystal structures can be stable. However, if you subject these minerals to extreme pressure, the atoms pack more closely together and denser minerals tend to form. Such transformations involve phase changes and/or neocrystallization.

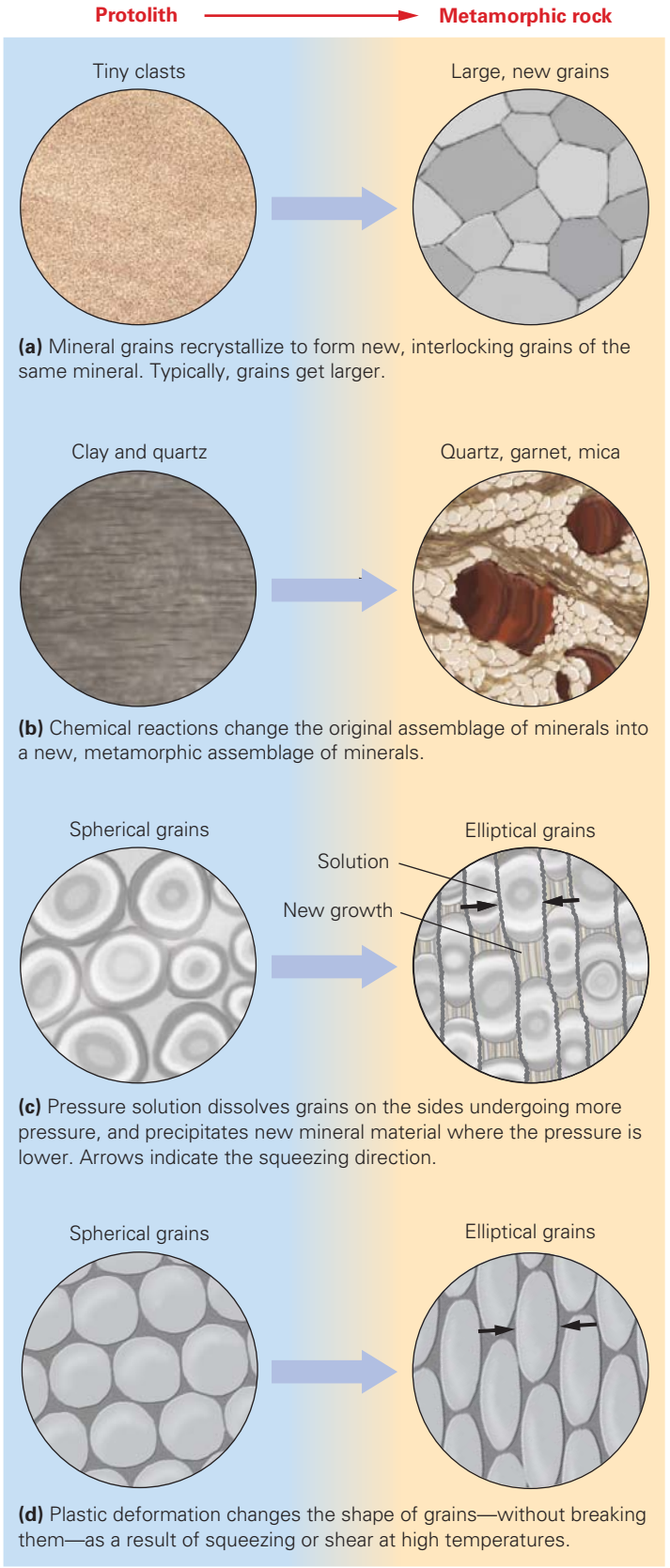
Changing Both Pressure and Temperature

So far, we've considered changes in pressure and temperature as separate phenomena. But in the Earth, pressure and temperature change together with increasing depth. For example, at a depth of 8 km, temperature in the crust reaches about 200°C and pressure reaches about 2.3 kbar. If a rock slowly becomes buried to a depth of 20 km, as can happen during mountain building, temperature in the rock increases to more than 500°C, and pressure to 5.5 kbar. Experiments and calculations show that the "stability" of certain minerals (the ability of a mineral to form and survive) depends on *both* pressure and temperature. When pressure and temperature increase, the original mineral assemblage in a rock becomes unstable, and a new assemblage forms out of minerals that are stable. Thus, a metamorphic rock formed at 8 km does not contain the same minerals as one formed at 20 km.

Compression, Shear, and Development of Preferred Orientation

Imagine that you have just built a house of cards and, being in a destructive mood, you step on it. The structure collapses because the downward push you apply with your foot exceeds the push provided by air in other directions. We can say that we have subjected the cards to **compression** (Fig. 7.3a).

FIGURE 7.2 Metamorphic processes, as seen through a microscope.



(a) Mineral grains recrystallize to form new, interlocking grains of the same mineral. Typically, grains get larger.

(b) Chemical reactions change the original assemblage of minerals into a new, metamorphic assemblage of minerals.

(c) Pressure solution dissolves grains on the sides undergoing more pressure, and precipitates new mineral material where the pressure is lower. Arrows indicate the squeezing direction.

(d) Plastic deformation changes the shape of grains—without breaking them—as a result of squeezing or shear at high temperatures.

Compression flattens a material (Fig 7.3b). **Shear,** in contrast, moves one part of a material sideways, relative to another. If, for example, you place a deck of cards on a table, then set your hand on top of the deck and move your hand parallel to the table, you shear the deck (Fig. 7.3c).

When rocks are subjected to compression and shear at elevated temperatures and pressures, they can change shape without breaking. As it changes shape, the internal texture of a rock also changes. For example, platy (pancake-shaped) grains become parallel to one another, and elongate (cigar-shaped) grains align in the same direction. Both platy and elongate grains are *inequant* grains, meaning that the dimension of a grain is not the same in all directions; in contrast, equant grains have roughly the same dimensions in all directions (Fig. 7.3d). The alignment of inequant minerals in a rock results in a **preferred orientation** (Fig. 7.3e).

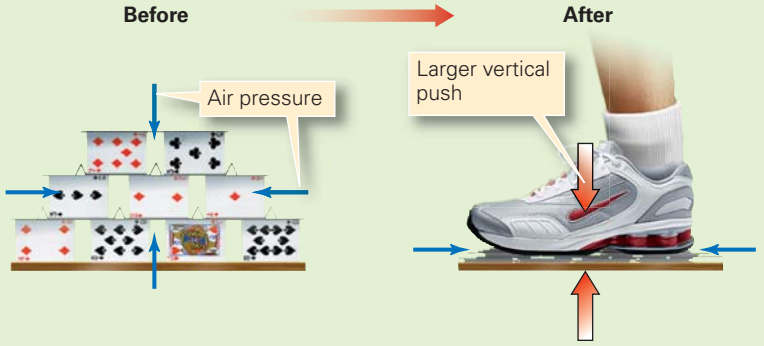
The Role of Hydrothermal Fluids

Metamorphic reactions commonly take place in the presence of *hydrothermal fluids* (very hot-water solutions). Where does the water in hydrothermal fluids come from? Some of it was originally bonded to minerals in the protolith, for metamorphic reactions can release such water into its surroundings. Some of it may seep up into the protolith from a nearby igneous intrusion, or down from overlying groundwater reservoirs. Notably, under extremely high pressures and temperatures, the water of hydrothermal fluids is in neither gas nor liquid state, but rather is in a "supercritical" state, meaning that it has characteristics of both gas and liquid. Such hydrothermal fluids chemically react with rock; they accelerate metamorphic reactions, because atoms involved in the reactions can migrate faster through a fluid than they can through a solid, and hydrothermal fluids provide water that can be absorbed by minerals during metamorphic reactions. Finally, fluids passing through a rock may pick up some dissolved ions and drop off others, as a bus picks up and drops off passengers, and thus can change the overall chemical composition of a rock during metamorphism. The process of changing a rock's chemical composition by reactions with hydrothermal fluids is called **metasomatism**.

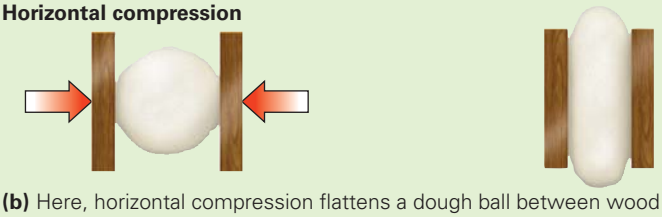
Take-Home Message

Metamorphism takes place in response to changes in temperature, pressure, application of compression and shear, and/or interaction with hydrothermal fluids. The process involves reactions that take place without melting, and can produce new foliation and minerals.

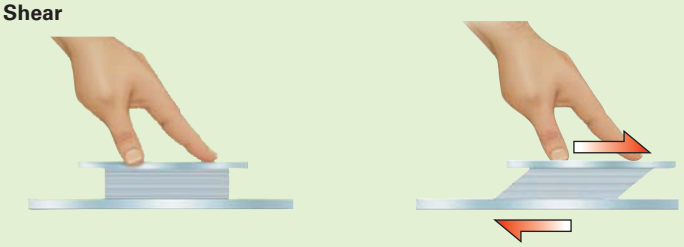
FIGURE 7.3 Compression and shear changes rock grains during metamorphism.



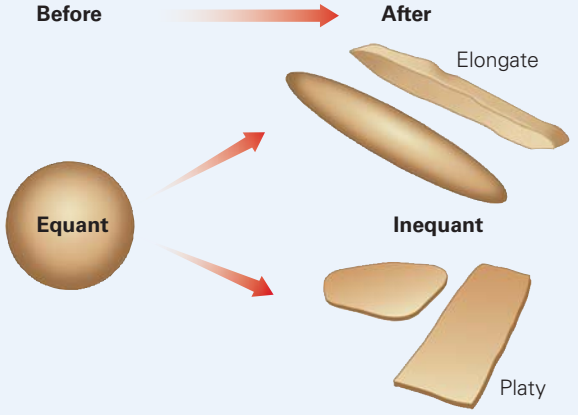
(a) A standing house of cards is subject only to air pressure, which is equal from all sides. When you step on the cards, they are pushed downward because of the vertical compression.



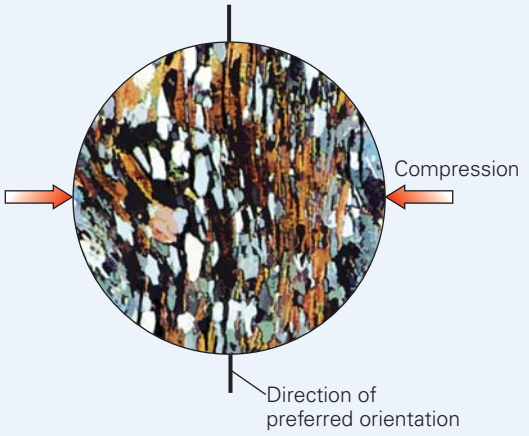
(b) Here, horizontal compression flattens a dough ball between wood blocks.



(c) Shear acts parallel to a surface. Here, shear smears out a deck of cards parallel to a table top.



(d) Compression and shear can transform equant grains into inequant grains. Inequant grains can be elongate (cigar-shaped) or platy (pancake-shaped).



(e) In metamorphic rock, inequant grains may be aligned to form a preferred orientation. As seen through a microscope, the flat planes of grains are perpendicular to the compression direction.

7.3 Types of Metamorphic Rocks

Coming up with a way to classify and name the great variety of metamorphic rocks on Earth hasn't been easy. After decades of debate, geologists have found it most convenient to divide metamorphic rocks into two fundamental classes: *foliated rocks* and *nonfoliated rocks*. Each class contains several rock types. We distinguish foliated rocks from each other partly by their component minerals and partly by the nature of their foliation, whereas we distinguish nonfoliated rocks from each other primarily by their component minerals.

Foliated Metamorphic Rocks

To understand this class of rocks, we first need to discuss the nature of **foliation** in more detail. The word comes from the Latin *folium*, for leaf. Geologists use *foliation* to refer to the parallel surfaces and/or layers that can occur in a metamorphic rock. Foliation can give metamorphic rocks a striped or streaked appearance in an outcrop, and/or can give them the ability to split into thin sheets. A foliated metamorphic rock has foliation either because it contains inequant mineral crystals that are aligned parallel to one another, defining preferred mineral orientation, and/or because the rock has alternating dark-colored and light-colored layers.

Foliated metamorphic rocks can be distinguished from one another according to their composition, their grain size, and the nature of their foliation. The most common types include

- *Slate*: The finest-grained foliated metamorphic rock, **slate**, forms by metamorphism of shale or mudstone (rocks composed dominantly of clay) under relatively low pressures and temperatures. Slate contains a type of foliation called slaty

cleavage, which allows it to split into thin sheets that make excellent roofing shingles (Fig. 7.4a). Slaty cleavage develops when pressure solution removes portions of clay flakes that are not perpendicular to the compression direction, while clay flakes that are perpendicular to the compression direction grow. During the process, some flakes passively rotate into parallelism with the cleavage plane, pushed into the new orientation by compression. For example, end-on compression of a sequence of horizontal shale beds produces vertical slaty cleavage (Fig. 7.4b). Commonly, such compression also causes the layers to bend into curves called folds.

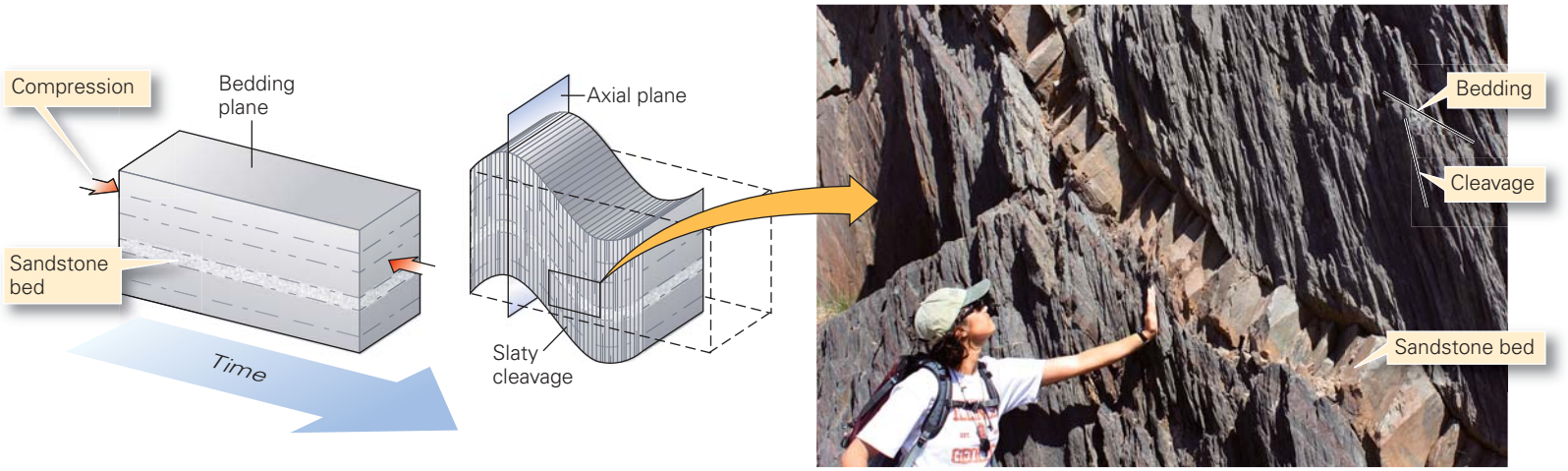
Did you ever wonder . . .
why does slate make such nice roofing shingles?

- *Phyllite*: **Phyllite** is a fine-grained metamorphic rock with a foliation caused by the preferred orientation of very fine-grained white mica. The word comes from the Greek word *phyllon*, meaning leaf, as does the word *phyllo*, the flaky dough in Greek pastry. The parallelism of translucent fine-grained mica gives phyllite a silky sheen known as phyllitic luster (Fig. 7.5a). Phyllite forms by the metamorphism of slate at a temperature high enough to cause neocrystallization of white mica.
- *Metaconglomerate*: Under the metamorphic conditions that produce slate or phyllite, a protolith of conglomerate becomes **metaconglomerate**. Specifically, pressure solution and plastic deformation flatten pebbles and cobbles into pancake-like shapes. The alignment of inequant clasts defines a foliation (Fig. 7.5b).
- *Schist*: **Schist** is a medium- to coarse-grained metamorphic rock that possesses a type of foliation, called schistosity, defined by the preferred orientation of *large* mica flakes (muscovite and/or biotite; Fig. 7.5c). Schist forms at a higher temperature than does phyllite.
- *Gneiss*: **Gneiss** is a compositionally layered metamorphic rock, typically composed of alternating dark-colored and light-colored layers that range in thickness from millimeters

FIGURE 7.4 Slate is a foliated metamorphic rock that forms at relatively low temperature and pressure.



(a) A block of slate splits easily along cleavage planes, which may be at a high angle to the bedding planes. Workers split slate to produce roof shingles that, when overlapped, make a watertight surface (see inset).



(b) Slaty cleavage forms in response to compressive stress. In this example, layers also bend to form folds, as slaty cleavage develops. The cleavage tends to be oriented parallel to the axial plane, an imaginary surface that, simplistically, divides the fold in half.

to meters. This compositional layering, or gneissic banding, gives gneiss a striped appearance (Fig. 7.6a). How does the banding in gneiss form? Some evolved directly from the original bedding in a rock. For example, metamorphism of a protolith consisting of alternating beds of sandstone and shale produces a gneiss consisting of alternating beds of quartzite and mica. Gneissic banding can also form when the protolith undergoes an extreme amount of shearing under conditions in which the rock can flow like soft plastic (Fig. 7.6b). Such flow stretches, folds, and smears out preexisting compositional contrasts in the rock and transforms them into aligned sheets. Finally, banding in some gneisses can develop by an incompletely understood process called metamorphic differentiation. During differentiation, chemical reactions segregate different minerals into different layers (Fig. 7.6c).

- *Migmatite*: Under certain conditions, gneiss may *begin* to melt, producing felsic magma and residual, still solid, mafic rock. If the melt freezes again before flowing out of the source area, a mixture of igneous rock and relict metamorphic rock forms. This mixture is called **migmatite**. In effect, a migmatite is part metamorphic and part igneous.

Nonfoliated Metamorphic Rocks

Nonfoliated metamorphic rocks contain minerals that recrystallized or grew during metamorphism, but have no foliation. The lack of foliation means either that metamorphism occurred in the absence of compression and shear, or that most of the new crystals can only grow in an equant form. We list below some of the rock types that can occur without foliation.

- *Hornfels*: **Hornfels** is a fine-grained nonfoliated rock that contains a variety of metamorphic minerals. The specific mineral assemblage in a hornfels depends on the composition of the protolith and on the temperature and pressure of metamorphism.
- *Quartzite*: **Quartzite** forms by the metamorphism of pure quartz sandstone. During metamorphism, preexisting quartz grains recrystallize, creating new, larger grains. In the process, the distinction between cement and grains disappears, open pore space disappears, and the grains become interlocking. When quartzite cracks, the fracture cuts across grain boundaries—in contrast, fractures in sandstone curve *around* grains. Quartzite looks glassier than sandstone and does not have the grainy, sandpaper-like surface characteristic of sandstone (Fig. 7.7a). Depending on the impurities it contains, quartzite can vary in color from white to gray, purple, or green.
- *Marble*: The metamorphism of limestone yields **marble**. During the formation of marble, calcite composing the protolith recrystallizes, so fossil shells, pore space, and the distinction between grains and cement disappear. Thus, marble typically consists of a fairly uniform mass of interlocking calcite crystals.

  Sculptors love to work with marble because the rock is relatively soft and has a uniform texture that gives it the

FIGURE 7.5 Examples of foliated metamorphic rocks formed at higher temperatures and pressures.



(a) During formation of phyllite, clay recrystallizes to form tiny mica flakes that reflect light, giving the rock a sheen.

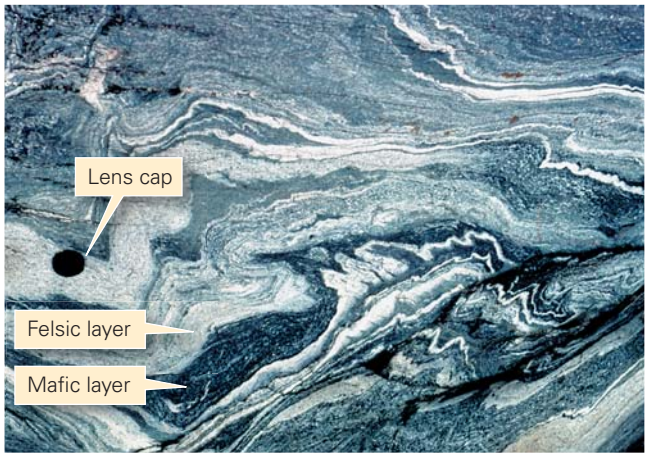


(b) In metaconglomerate, pebbles and cobbles flatten into a pancake shape without cracking. Note the coin for scale.

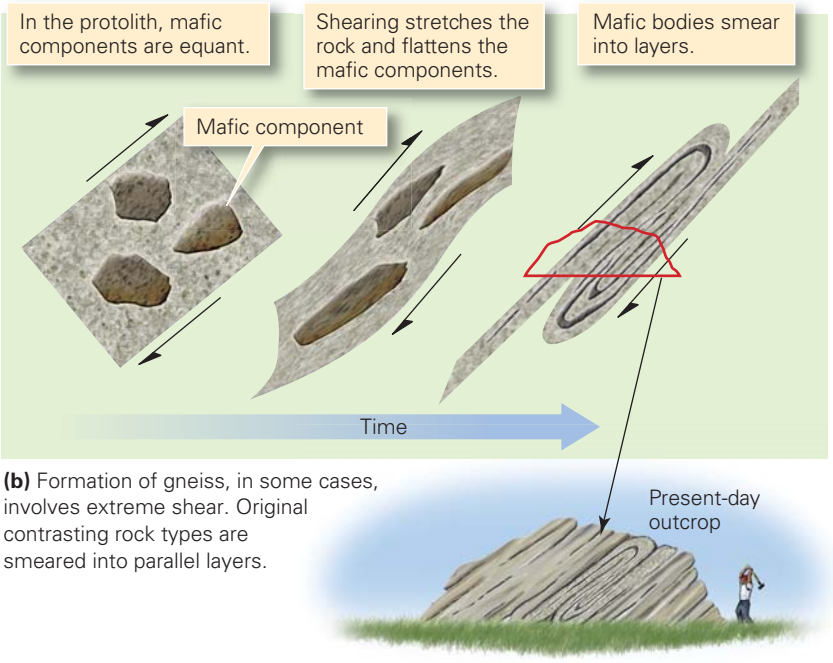


(c) A schist contains coarse mica flakes, along with other metamorphic minerals.

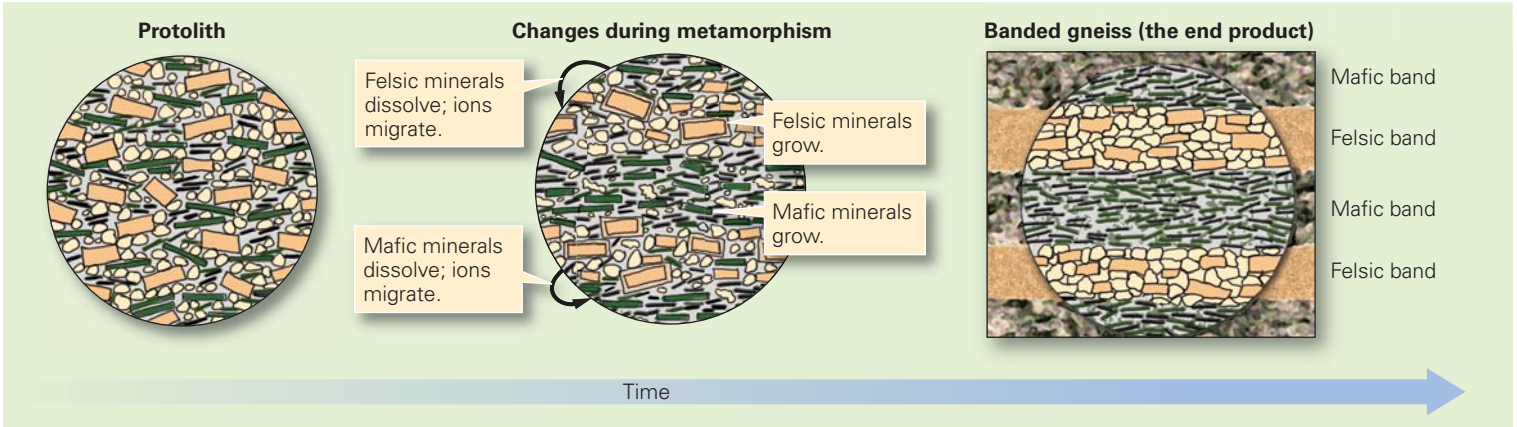
FIGURE 7.6 The formation of gneiss, which takes place at very high temperatures and pressures.



(a) Gneiss displays compositional banding (alternating felsic and mafic layers). The layers can become contorted.



(b) Formation of gneiss, in some cases, involves extreme shear. Original contrasting rock types are smeared into parallel layers.



(c) Gneiss may also form by metamorphic differentiation, during which chemical reactions cause felsic and mafic minerals to grow in distinct, separate layers.



FIGURE 7.7 Examples of quartzite and marble—typically, but not always, these are nonfoliated.



(a) This unfoliated maroon quartzite from Wisconsin breaks on smooth fractures that cut across grains.

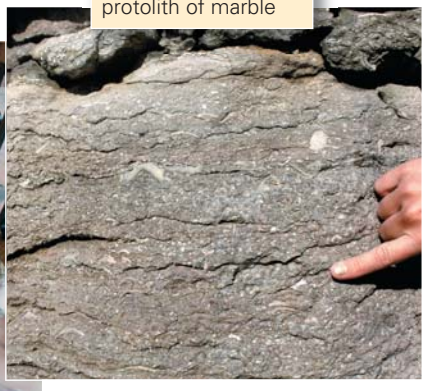






(b) Michelangelo used nonfoliated white marble for his spectacular sculptures.





(c) The marble in this floor tile has color banding inherited from original bedding. The layers became contorted during metamorphism.

cohesiveness and homogeneity needed to fashion large, smooth, highly detailed sculptures. Marble comes in a variety of colors—white, pink, green, and black—depending on the impurities it contains. Michelangelo, one of the great Italian Renaissance artists, sought large, unbroken blocks of creamy white marble from quarries in the Italian Alps for his masterpieces (**Fig. 7.7b**).

Not all marble is nonfoliated. If the original protolith contained layers with different impurities, and shear caused the marble to flow plastically, the resulting marble has color banding that makes it a prized decorative stone (**Fig. 7.7c**).

Defining Metamorphic Intensity

Not all metamorphism takes place under the same physical conditions. For example, rocks carried to a great depth beneath a mountain range undergo more intense metamorphism than do rocks closer to the surface. Geologists use the term **metamorphic grade** in a somewhat informal way to indicate the intensity of metamorphism, meaning the amount or degree of metamorphic change. (To provide a more complete indication of the intensity of metamorphism, geologists use the concept of metamorphic facies; see **Box 7.1**.) Classification of metamorphic grade depends primarily on temperature, because temperature plays the dominant role in determining the extent of recrystallization and neocrystallization during metamorphism. Metamorphic rocks that form at relatively low

temperatures (between about 250°C and 400°C) are low-grade rocks, and metamorphic rocks that form at relatively high temperatures (over about 600°C) are high-grade rocks. Intermediate-grade rocks form at temperatures between these two extremes (**Fig. 7.8a**).

Different grades of metamorphism yield different metamorphic mineral assemblages. As grade increases, recrystallization and neocrystallization tend to produce coarser grains and new mineral assemblages that are stable at higher temperatures and pressures (**Fig. 7.8b**).

Geologists discovered that the presence of certain minerals, known as *index minerals*, in a rock indicates the approximate metamorphic grade of the rock. The line on a map along which an index mineral first appears is called an isograd (from the Greek *iso*, meaning equal). All points along an isograd have approximately the same metamorphic grade. **Metamorphic zones** are regions between two isograds; zones are named after an index mineral that was not present in the previous, lower-grade zone. To compare rocks of different grades, you could take a hike from central New York State eastward into central Massachusetts in the eastern United States. Your path starts in a region where rocks were not metamorphosed, and it takes you into the internal part of the Appalachian Mountain belt, where rocks were intensely metamorphosed. As a consequence, you cross several metamorphic zones (**Fig. 7.8c**).

Take-Home Message

Geologists divide metamorphic rocks into classes based on whether the rock contains foliation. Foliated rocks include slate, schist, and gneiss. Nonfoliated rocks include marble and quartzite. The type of metamorphic rock that forms depends on the conditions of metamorphism. Specific grades of metamorphic minerals form under specific temperature and pressure ranges.

7.4 Where Does Metamorphism Occur?

So far, we've discussed the nature of changes that occur during metamorphism, the agents of metamorphism (heat, pressure, compression and shear, and hydrothermal fluids), the rock types that form as a result of metamorphism, and the concepts of metamorphic grade and metamorphic facies. With this background, let's now examine the geologic settings on Earth where metamorphism takes place, as viewed from the perspective of plate tectonics theory (see **Geology at a Glance**, pp. 204–205).

Because of the wide range of possible metamorphic environments, metamorphism occurs at a wide range of conditions in the Earth (**See for Yourself G**). You will see that the conditions under which metamorphism occurs are not the same in all geologic settings. That's because the geothermal gradient (the relation between temperature and depth), the extent to which rocks endure compression and shear during metamorphism, and the extent to which rocks interact with hydrothermal fluids all depend on the geologic environment.

Thermal or Contact Metamorphism

Imagine a hot magma that rises from great depth beneath the Earth's surface and intrudes into cooler rock at a shallow depth. Heat flows from the magma into the wall rock, for heat always flows from hotter to colder materials. As a consequence, the magma cools and solidifies while the wall rock heats up. In addition, hydrothermal fluids circulate through both the intrusion and the wall rock. As a consequence of the heat and hydrothermal fluids, the wall rock undergoes metamorphism, with the highest-grade rocks forming immediately adjacent to the pluton, where the temperatures were highest, and progressively lower-grade rocks forming farther away. The distinct belt of metamorphic rock that forms around an igneous intrusion is called a **metamorphic aureole** or contact aureole (**Fig. 7.9a**). The width of an aureole depends on the size and shape of the intrusion, and on the amount of hydrothermal circulation—larger intrusions produce wider aureoles.

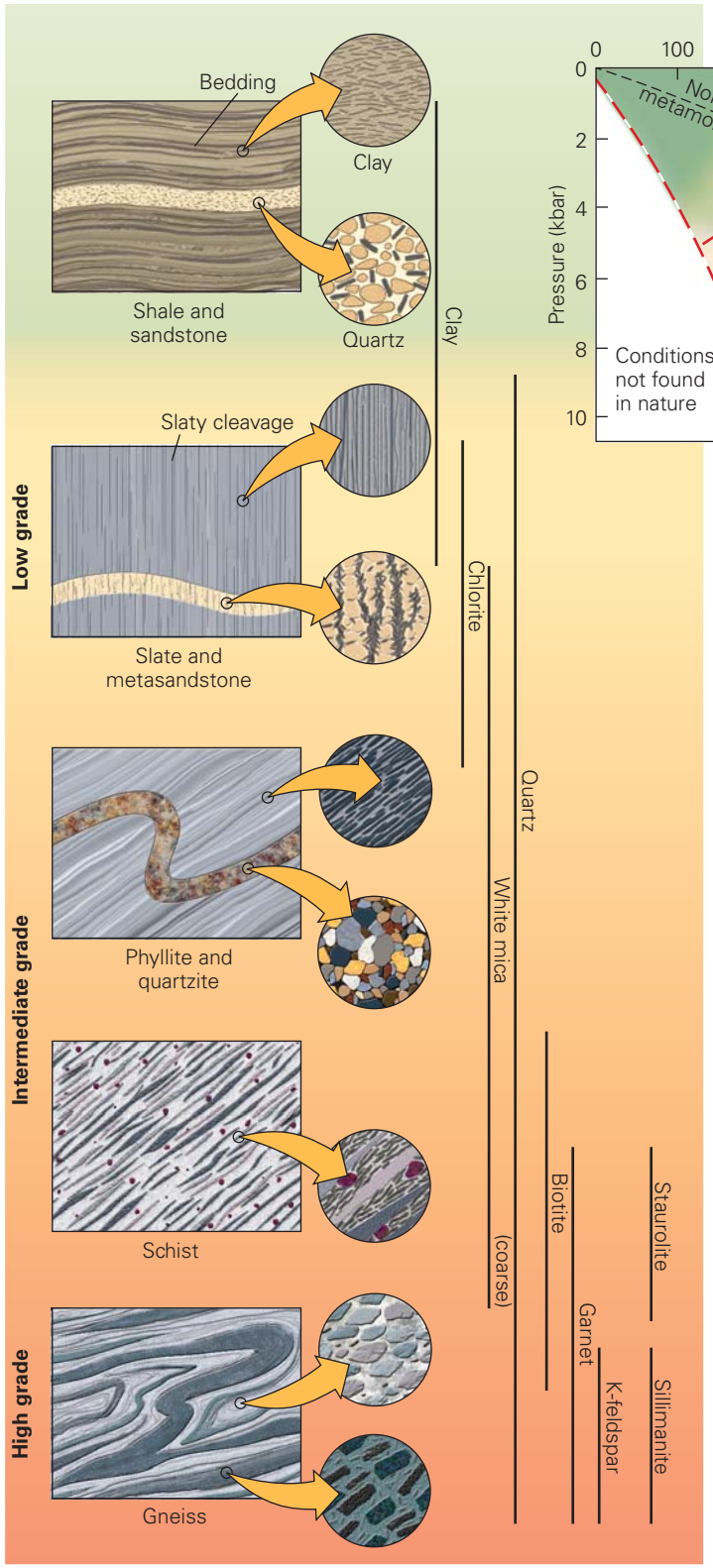
The local metamorphism caused by igneous intrusion can be called either **thermal metamorphism** (see **Box 7.2**), to emphasize that it develops in response to heat without a change in pressure and without differential stress, or **contact metamorphism**, to emphasize that it develops adjacent to the contact of an intrusion with its wall rock. Because this metamorphism takes place without application of compression or shear, aureoles contain hornfels, a nonfoliated metamorphic rock.

Contact metamorphism occurs anywhere that the intrusion of plutons occurs. In the context of plate tectonics theory, plutons intrude into the crust at convergent plate boundaries, in rifts, and during the mountain building that takes place where continents collide.

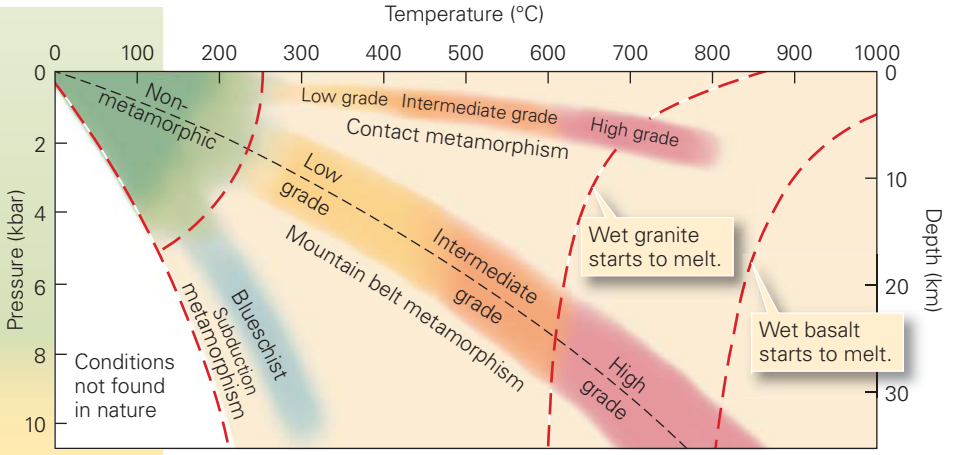
Burial Metamorphism

As sediment gets buried in a subsiding sedimentary basin, the pressure increases due to the weight of overburden, and the temperature increases due to the geothermal gradient. At depths greater than about 8 to 15 km, depending on the geothermal gradient, temperatures may be great enough for metamorphic reactions to begin, and low-grade metamorphic

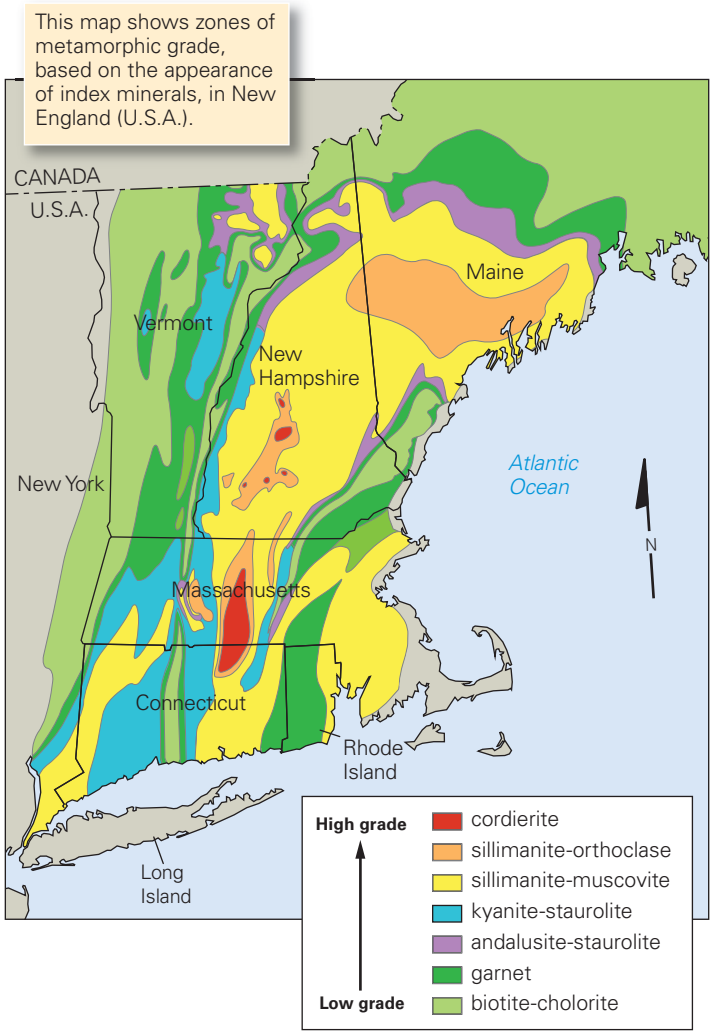
FIGURE 7.8 Intensity of metamorphism is indicated by metamorphic grade.



(b) Here, we see the consequences of the progressive metamorphism of shale and sandstone from low grade to high grade during mountain building. Lines on the right indicate the range of grade in which key metamorphic minerals form.



(a) This graph depicts the approximate temperatures and pressures of metamorphic grades. Different conditions occur in different geologic settings.



(c) Approximate metamorphic zones and isograds in New England (U.S.A.). The minerals listed are index minerals.

BOX 7.1 CONSIDER THIS . . .

Metamorphic Facies

In the early years of the 20th century, geologists working in Scandinavia, where erosion by glaciers has left beautiful, nearly unweathered exposures of rocks once buried very deeply in the crust, came to realize that metamorphic rocks, in general, do not consist of a hodgepodge of minerals formed at different times and in different places, but rather consist of a distinct set of minerals that grew in association with each other at a certain pressure and temperature. It seemed that such *mineral assemblages* more or less represent a condition of chemical equilibrium, meaning that the chemicals making up the rock had organized into a group of mineral grains that were—to anthropomorphize a bit—comfortable with each other and their surroundings, and thus did not feel the need to change further. The geologists also determined that the specific mineral assemblage in a rock depends on pressure and temperature conditions, *and* on the composition of the protolith.

This discovery led the geologists to propose the concept of metamorphic facies. A **metamorphic facies** is a set of metamorphic mineral assemblages indicative of a certain range of pressure and temperature. Each specific assemblage in a facies reflects the original protolith composition. According to this definition, a given metamorphic facies includes several different kinds of rocks that differ from each other in terms of chemical composition and, therefore, mineral content—but all the rocks of a given facies formed under roughly the same temperature and pressure conditions. Geologists recognize several facies, of which the major ones are zeolite, hornfels, greenschist, amphibolite, blueschist, eclogite, and granulite. The names of the different facies are based on a distinctive feature or mineral found in some of the rocks of the facies.

We can represent the approximate conditions under which metamorphic facies formed by using a pressure-temperature graph (**Fig. Bx7.1**). Each area on the graph, labeled with a facies name, represents the approximate range of temperatures and pressures in which mineral assemblages characteristic of that particular facies form. For example, a rock subjected to the pressure and temperature at Point A (4.5 kbar and 400°C) develops a mineral assemblage characteristic of the greenschist facies. As the graph implies, the pressure and temperature conditions defining boundaries between facies cannot be precisely determined, and the transitions between facies are gradual.

We can also portray the geothermal gradients of different crustal regions on the graph. Beneath mountain ranges, for example, the geothermal gradient passes through the zeolite, greenschist, amphibolite, and granulite facies. In contrast, in the accretionary prism that forms at a subduction zone, temperature increases slowly with increasing depth, so blueschist assemblages can form.

FIGURE Bx7.1 The common metamorphic facies. The boundaries between the facies are depicted as wide bands because they are gradational and approximate. Note that some amphibolite-facies rocks and all granulite-facies rocks form only if the protolith is dry. The relatively rare P-P ("prehnite-pumpellyite") facies, is named for two metamorphic minerals.

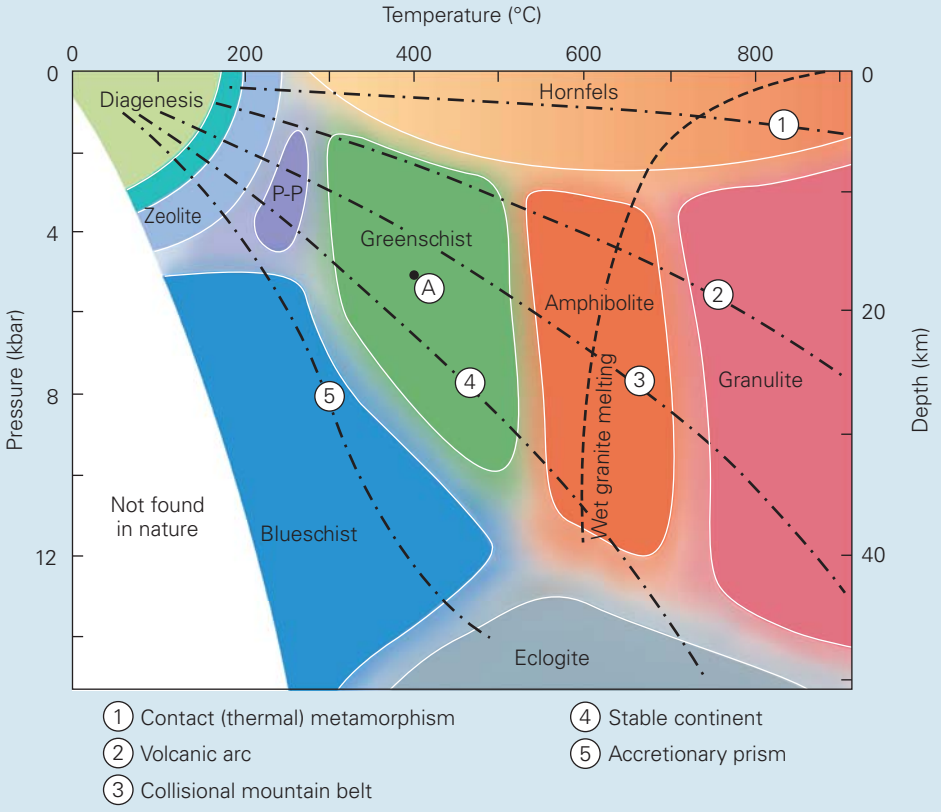
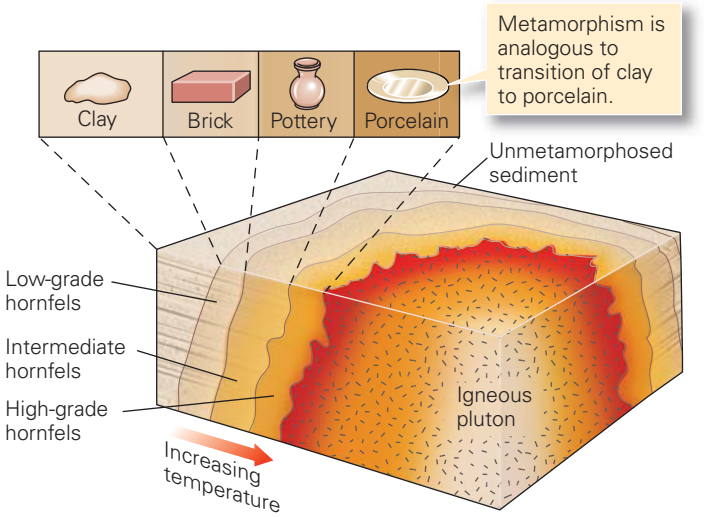
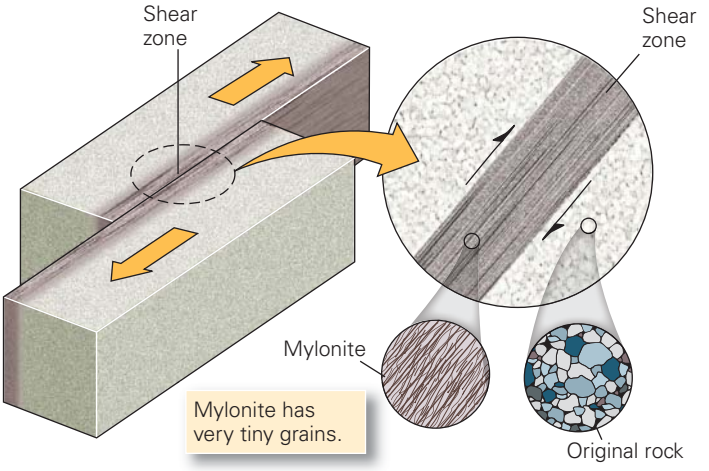


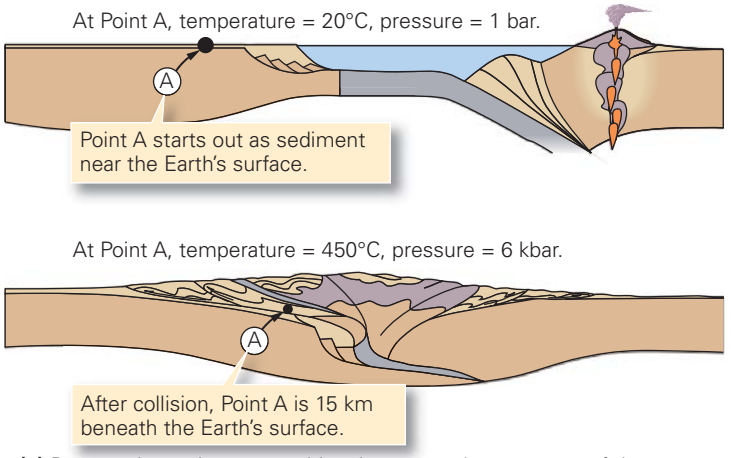
FIGURE 7.9 Geologic settings of metamorphism.



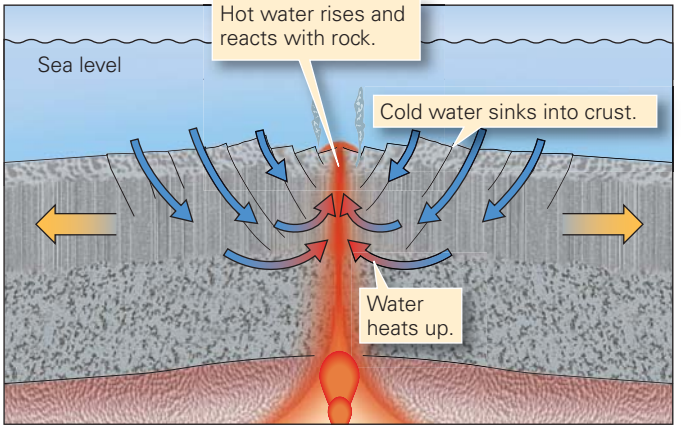
(a) Heat radiated from a large pluton can produce a metamorphic aureole, in which hornfels develops. Grade decreases progressively away from the pluton contact.



(b) Shearing of a rock under plastic conditions causes original crystals to divide into tiny crystals without breaking to form a mylonite. Mylonite has strong foliation.



(c) Dynamothermal metamorphism happens when one part of the crust shoves over another part, so that rocks once near the surface end up at great depth.



(d) The heat of rising magma at a ridge axis heats water, which then convects. The hot water reacts with the crust and forms metamorphic minerals.

rocks form. Metamorphism due only to the consequences of very deep burial is called **burial metamorphism**.

Dynamic Metamorphism

Faults are surfaces on which one piece of crust slides, or shears, past another. Near the Earth's surface (in the upper 10 to 15 km) this movement can fracture rock, breaking it into angular fragments or even crushing it to a powder. But at greater depths, rock is so warm that it behaves like soft plastic as shear along the fault takes place. During this process, the minerals in the rock recrystallize. We call this process **dynamic metamorphism**, because it occurs as a *consequence of shearing alone* under metamorphic conditions, without requiring a change in temperature or pressure. The resulting rock, a **mylonite**, has a foliation that roughly parallels the fault (Fig. 7.9b). Mylonites are very fine-grained, due to processes during dynamic metamorphism that replace larger crystals with a mass of very tiny ones. Dynamic metamorphism takes place anywhere that faulting occurs at depth in the crust. Thus, mylonites can be found at all plate boundaries, in rifts, and in collision zones.

BOX 7.2

CONSIDER THIS . . .

Pottery Making—An Analog for Thermal Metamorphism

Did you ever wonder . . .
why is porcelain harder than the clay it's made from

A brick for the wall of an adobe house, an earthenware pot, a stoneware bowl, or a translucent porcelain teacup may all be formed from the same lump of soft clay, scooped from the surface of the Earth and shaped by human hands. This pliable and slimy muck is a mixture of very fine clay minerals and quartz grains formed during the chemical weathering of rock and water. Fine potter's clay for making white china contains a particular clay mineral called kaolinite, named after the locality in China (called Kauling, meaning high ridge) where it was originally discovered.

People in arid climates make adobe bricks by forming damp clay into blocks, which they then dry in the sun. Such bricks can be used for construction *only* in arid climates, because if it rains heavily, the bricks will rehydrate and turn back into sticky muck—drying clay in the sun does not change the structure of the clay minerals.

To make a more durable material, brick makers place clay blocks in a kiln and bake ("fire") them at high temperatures. This process makes the bricks hard and impervious to water. Potters use the same process to make jugs. In fact, fired clay jugs that were used for storing wine and olive oil have been found intact in sunken Greek and Phoenician ships that have rested on the floor of the Mediterranean Sea for thousands of years! Clearly, the firing of a clay pot fundamentally and permanently changes clay in a way that makes it physically different (see Fig. 7.9a). In other words, firing causes a thermal metamorphic change in the mineral assemblage that composes pottery. The extent of the transformation depends on the kiln temperature, just as the grade of metamorphic rock depends on temperature. Potters usually fire earthenware at about 1100°C and stoneware (which is harder than a knife or fork) at about 1250°C. To produce porcelain—fine china—the clay must partially melt at even higher temperatures up to 1400°C. Just as it begins to melt, the potter cools it relatively quickly. Such cooling of the melt creates glass, which gives porcelain its translucent, vitreous (glassy) appearance.



Dynamothermal (Regional) Metamorphism

During the development of mountain ranges, in response to either convergent-margin tectonics or continental collision, regions of crust are squeezed and large slices of continental crust slip along faults and move up and over other portions of the crust. As a consequence, rock that was once near the Earth's surface along the margin of a continent ends up at great depth beneath the mountain range (Fig. 7.9c). In this environment, three changes happen to the protolith: (1) it heats up because of the geothermal gradient and because of igneous activity; (2) it endures greater pressure because of the weight of overburden; and (3) it undergoes compression and shearing. As a result of these changes, the protolith transforms into foliated metamorphic rock. The type of foliated rock that forms depends on the grade of metamorphism—slate forms at shallower depths, whereas schist and gneiss form at greater depths. Since the metamorphism we've just described involves not only heat but also compression and shearing, we can call it **dynamothermal metamorphism**. Typically, such metamorphism affects a large region, so geologists also call it **regional metamorphism**.

Erosion eventually removes the mountains, exposing a belt of metamorphic rock that once lay at depth. Such belts may be hundreds of kilometers wide and thousands of kilometers long.

Hydrothermal Metamorphism at Mid-Ocean Ridges

Hot magma rises beneath the axis of mid-ocean ridges, so when cold seawater sinks through cracks down into the oceanic crust along ridges, it heats up and transforms into hydrothermal fluid. This fluid then rises through the crust, near the ridge, causing **hydrothermal metamorphism** of ocean-floor basalt (**Fig. 7.9d**). Eventually, the fluid escapes through vents back into the sea; these vents are called black smokers (see Chapter 2).

Metamorphism in Subduction Zones

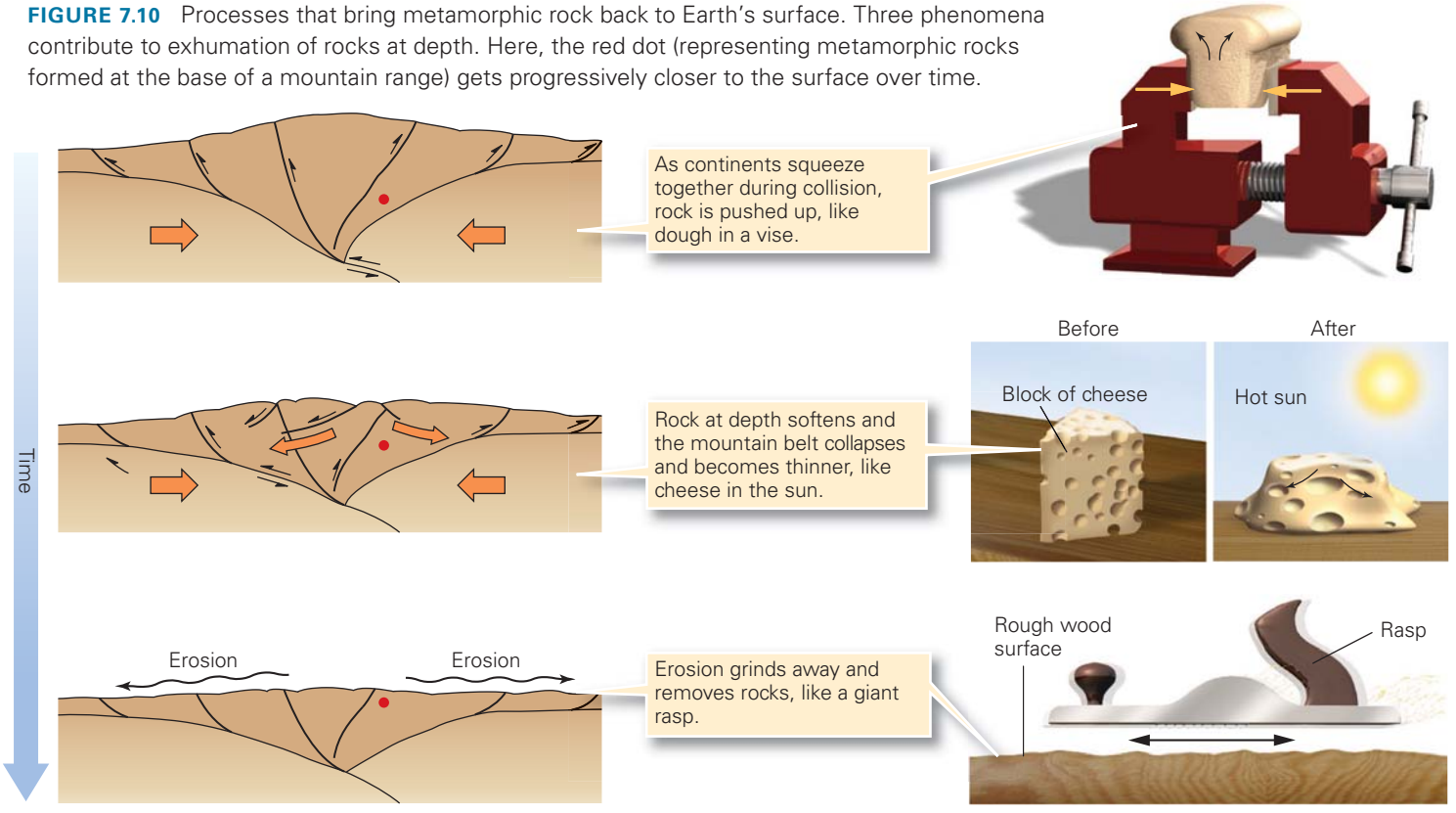
Blueschist is a relatively rare rock that contains an unusual blue-colored amphibole. Laboratory experiments indicate that formation of this mineral requires very high pressure but relatively low temperature. Such conditions do not develop in continental crust—usually, at the high pressure needed to produce blue amphibole, temperature in continental crust is also high (see Box 7.1). So to figure out where blueschist forms, we must determine where high pressure can develop at relatively low temperature.

Plate tectonics theory provides the answer to this puzzle. Researchers found that blueschist occurs only in the accretionary prisms that form at subduction zones (see Geology at a Glance, pp. 204–205). They realized that because prisms grow to be over 20 km thick, rock at the base of the prism feels high pressure (due to the weight of overburden). But because the subducted oceanic lithosphere beneath the prism is cool, temperatures at the base of the prism remain relatively low.

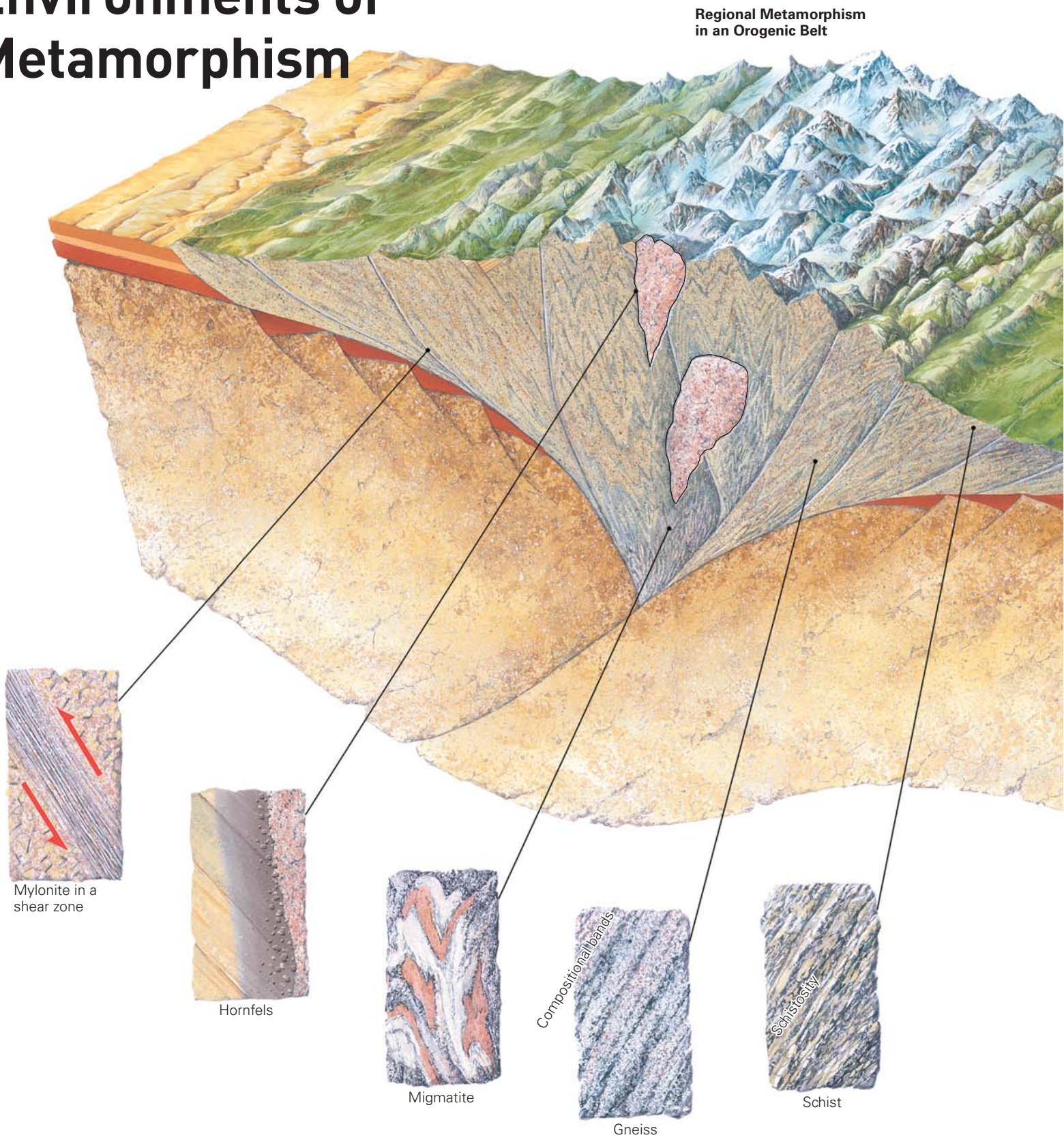
Shock Metamorphism

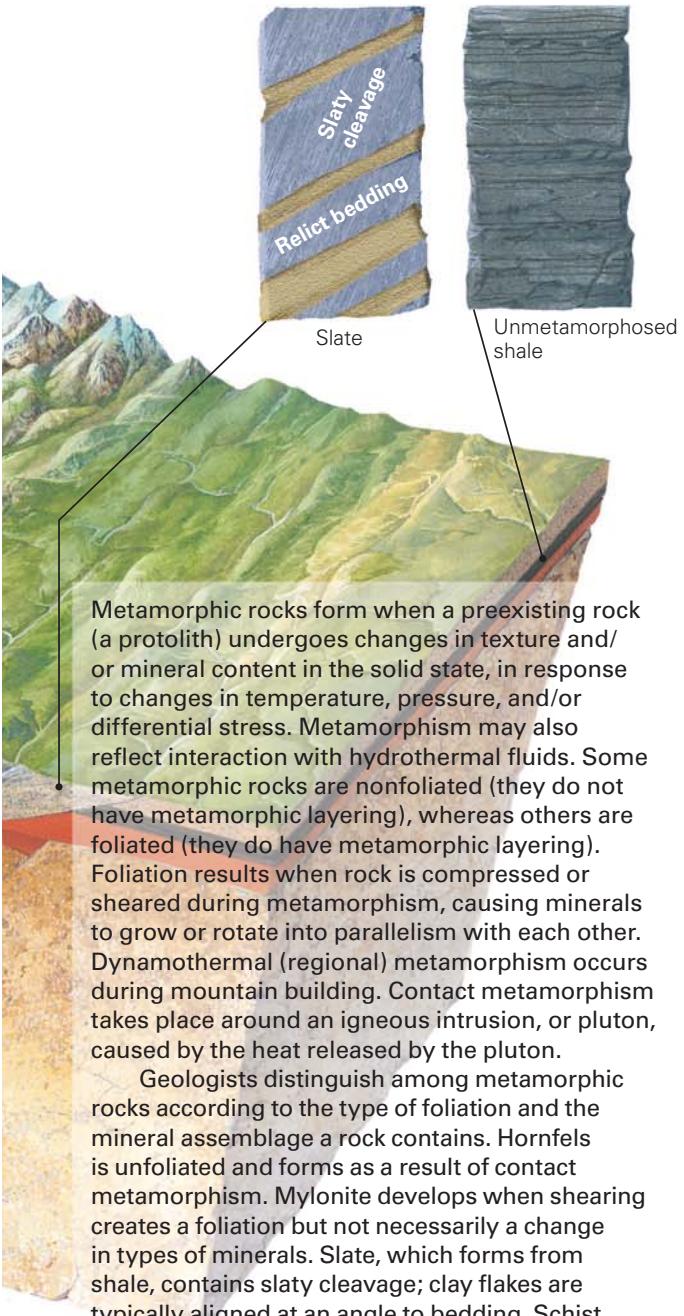
When large meteorites slam into the Earth, a vast amount of kinetic energy instantly transforms into heat, and a pulse of extreme compression (a shock wave) propagates into the Earth. The heat may be sufficient to melt or even vaporize rock at the impact site, and the extreme compression of the shock wave causes quartz in rocks below the impact site to undergo a phase change and become a more compact mineral called coesite. The changes in rock due to the passage of a shock wave are called **shock metamorphism**.

FIGURE 7.10 Processes that bring metamorphic rock back to Earth's surface. Three phenomena contribute to exhumation of rocks at depth. Here, the red dot (representing metamorphic rocks formed at the base of a mountain range) gets progressively closer to the surface over time.

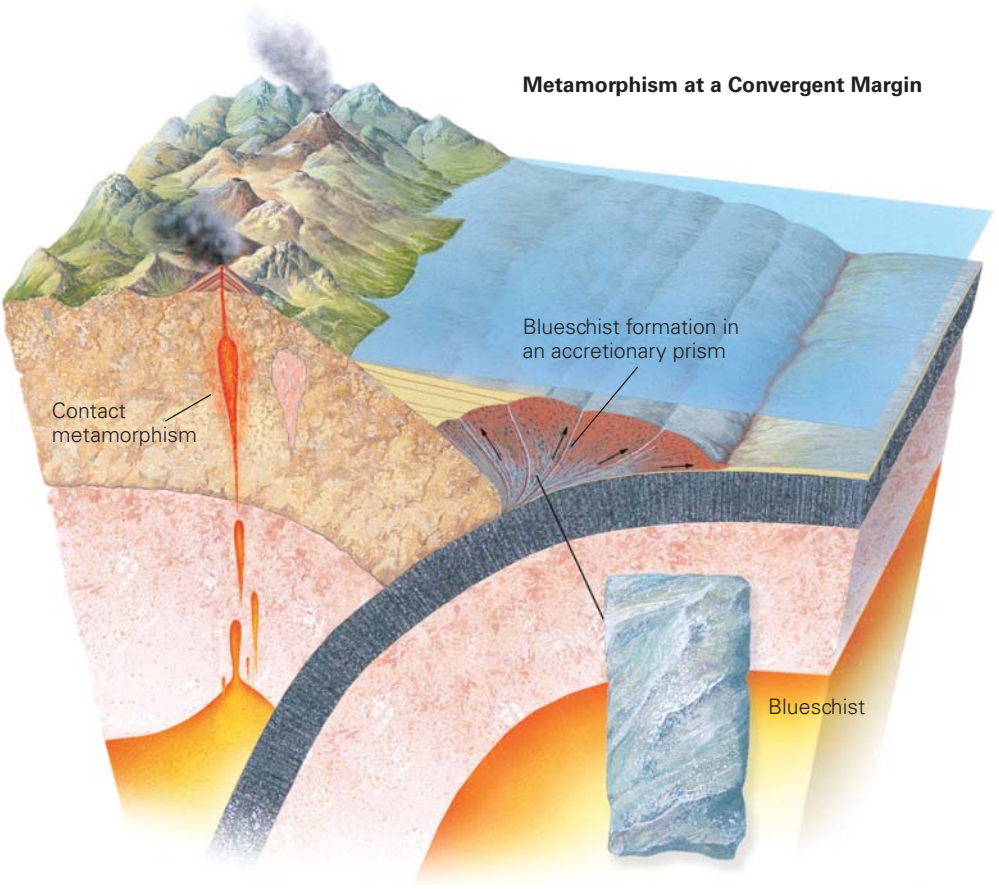


Environments of Metamorphism





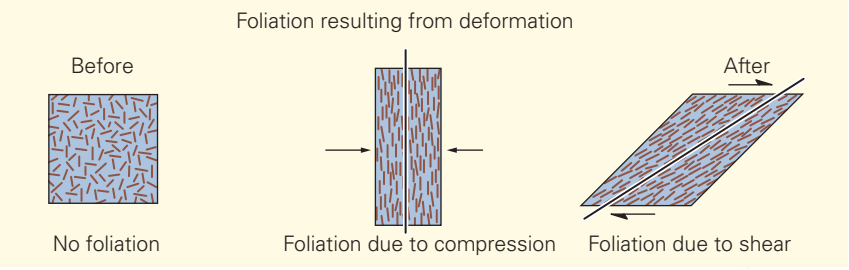
Metamorphism at a Convergent Margin

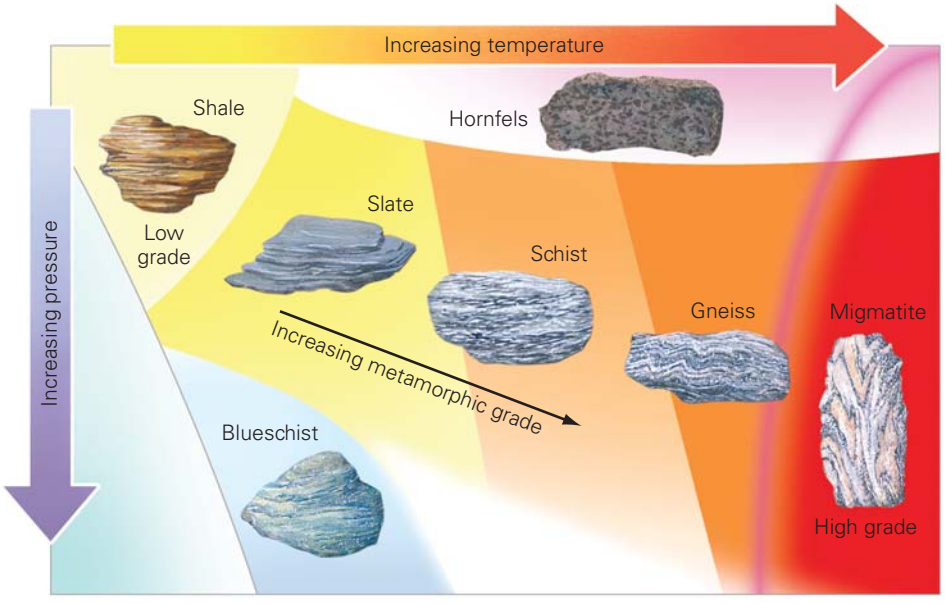


Metamorphic rocks form when a preexisting rock (a protolith) undergoes changes in texture and/or mineral content in the solid state, in response to changes in temperature, pressure, and/or differential stress. Metamorphism may also reflect interaction with hydrothermal fluids. Some metamorphic rocks are nonfoliated (they do not have metamorphic layering), whereas others are foliated (they do have metamorphic layering). Foliation results when rock is compressed or sheared during metamorphism, causing minerals to grow or rotate into parallelism with each other. Dynamothermal (regional) metamorphism occurs during mountain building. Contact metamorphism takes place around an igneous intrusion, or pluton, caused by the heat released by the pluton.

Geologists distinguish among metamorphic rocks according to the type of foliation and the mineral assemblage a rock contains. Hornfels is unfoliated and forms as a result of contact metamorphism. Mylonite develops when shearing creates a foliation but not necessarily a change in types of minerals. Slate, which forms from shale, contains slaty cleavage; clay flakes are typically aligned at an angle to bedding. Schist contains coarse grains of mica (muscovite and/or biotite) aligned parallel to each other. Gneiss has compositional banding. (Migmatite forms when part of the rock melts, and thus it is a mixture of metamorphic and igneous rock.) Quartzite is composed predominantly of quartz (it is metamorphosed sandstone), whereas marble is composed predominantly of calcite or dolomite (it is metamorphosed limestone or dolostone). Quartzite and marble are usually unfoliated.

The types of minerals and foliation in a metamorphic rock indicate the rock's grade. High-grade rocks, such as gneiss, form at higher temperatures and pressures, whereas low-grade rocks, such as schist, form at lower pressures and temperatures. Blueschist is an unusual metamorphic rock that develops under relatively high pressures but relatively low temperatures—the environment of an accretionary prism.





Where Do You Find Metamorphic Rocks?

When you stand on an outcrop of metamorphic rock, you are standing on material that once lay many kilometers beneath the surface of the Earth. How does metamorphic rock return to the Earth's surface? Geologists refer to the overall process by which deeply buried rocks end up back at the surface as **exhumation**.

To see how exhumation works, let's look at the specific processes that contribute to bringing high-grade metamorphic rocks from below a collisional mountain range back to the surface (Fig. 7.10). First, as two continents progressively push together, the rock caught between them squeezes upward, much like dough pressed in a vise; the upward movement takes place by slip on faults and by plastic-like flow of rock. Second, as the mountain range grows, the crust at depth beneath it warms up and becomes softer and weaker. Eventually, the range starts to collapse under its own weight, much like a block of soft cheese placed in the hot sun. As a result of this collapse, the upper crust spreads out laterally. Horizontal

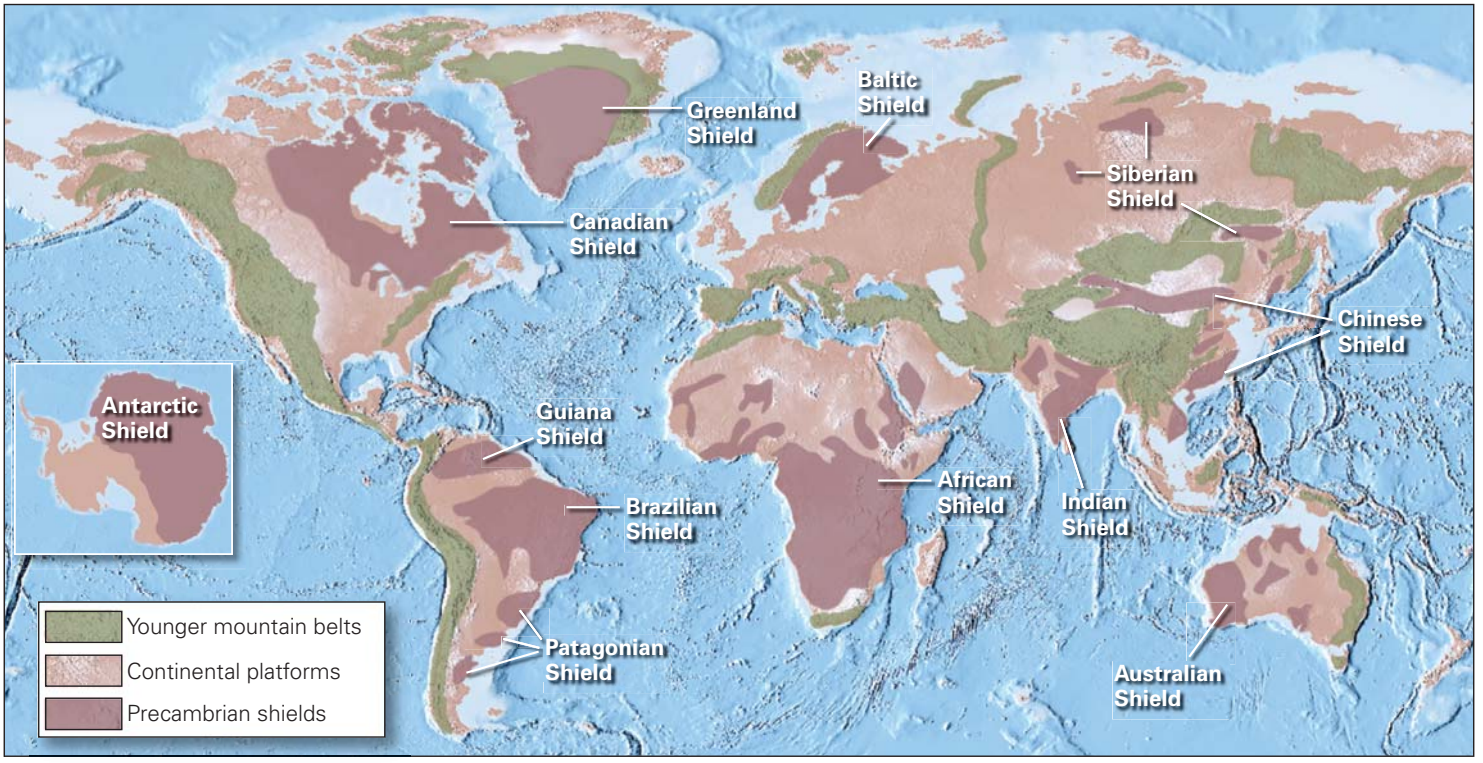
FIGURE 7.11 Examples of rock exposures consisting of Precambrian metamorphic rocks.



(a) The Gunnison River carved a deep canyon into the Precambrian basement rock in Colorado.



(b) A photograph from an airplane window of the flat landscape of the eastern Canadian Shield.



(c) A map showing the distribution of shields, areas where broad expanses of Precambrian crust, including Precambrian metamorphic rocks, crop out.

stretching of the upper part of the crust causes it to become thinner in the vertical direction, and as the upper part of the crust becomes thinner, the deeper crust ends up closer to the surface. Third, erosion takes place at the surface; weathering, landslides, river flow, and glacial flow together play the role of a giant rasp, stripping away rock at the surface and exposing rock that was once below the surface.

Keeping in mind the processes that form metamorphic rock and cause exhumation, let's ask the question, "Where are metamorphic rocks presently exposed?" You can start your quest to find metamorphic rock outcrops by hiking into a mountain range. As we've seen, the process of mountain building produces and eventually exhumes metamorphic rocks. The towering cliffs in the interior of a mountain range typically reveal schist, gneiss, and quartzite (**Fig. 7.11a**). Even after the peaks have eroded away, the record of mountain building remains in the form of a belt of metamorphic rock at the ground surface.

Vast expanses of metamorphic rock crop out in continental shields. A **shield** is a broad region of long-lived, stable continental crust where Phanerozoic sedimentary cover either was not deposited or has been eroded away so that Precambrian rocks are exposed (**Fig. 7.11b, c**). These rocks were metamorphosed during a succession of Precambrian mountain-building events that led to the original growth of continents.

Take-Home Message

Thermal (contact) metamorphism develops around igneous intrusions, due to heat from the intrusion. Dynamothermal (regional) metamorphism develops beneath mountain ranges where rock undergoes compression and shear at high temperatures and pressures. Erosion and uplift may eventually expose metamorphic rock in mountain ranges or continental shields.

ANOTHER VIEW This outcrop of marble (metamorphosed limestone) forms the wall of Mosaic Canyon, near Death Valley, California. Shear caused the rock to flow plastically during metamophism, producing foliation represented by the horizontal color banding.



Chapter Summary

- Metamorphism refers to changes in a rock that result in the formation of a metamorphic mineral assemblage, and/or metamorphic texture, in response to change in temperature and/or pressure, to the application of differential stress, and to interaction with hydrothermal fluids (hot-water solutions).
- Metamorphism involves recrystallization, phase changes, metamorphic reactions (neocrystallization), pressure solution, and/or plastic deformation. If hydrothermal fluids bring in or remove elements, we say that metasomatism has occurred.
- Metamorphic foliation can be defined either by preferred mineral orientation (aligned inequant crystals) or by compositional banding. Preferred mineral orientation develops where differential stress causes the compression and shearing of a rock so that its inequant grains align parallel with each other.
- Geologists separate metamorphic rocks into two classes, foliated rocks and nonfoliated rocks.
- The class of foliated rocks includes slate, phyllite, schist, and gneiss. The class of nonfoliated rocks includes hornfels, quartzite, and marble. Migmatite is a mixture of igneous and metamorphic rock.
- Rocks formed under relatively low temperatures are known as low-grade rocks, whereas those formed under high temperatures are known as high-grade rocks. Intermediate-grade rocks develop between these two extremes. Different metamorphic mineral assemblages form at different grades.
- Geologists track the distribution of different grades of rock by looking for index minerals. Isograds indicate the location at which index minerals first appear. A metamorphic zone is the region between two isograds.
- A metamorphic facies is a group of metamorphic mineral assemblages that develop under a specified range of temperature and pressure conditions.
- Thermal (contact) metamorphism occurs in an aureole surrounding an igneous intrusion. Burial metamorphism occurs at depth in a sedimentary basin. Dynamically metamorphosed rocks form along faults. Dynamothermal (regional) metamorphism results when rocks undergo heating and shearing during mountain building. Hydrothermal metamorphism can take place due to the circulation of hot water in oceanic crust at mid-ocean ridges. Shock metamorphism happens during the impact of a meteorite.
- We find belts of metamorphic rocks in mountain ranges. Blueschist forms in accretionary prisms. Shields expose broad areas of Precambrian metamorphic rocks.

Key Terms

burial metamorphism (p. 201)
compression (p. 191)
contact metamorphism (p. 198)
dynamic metamorphism (p. 201)
dynamothermal metamorphism (p. 202)
exhumation (p. 206)
foliation (p. 193)
gneiss (p. 194)
hornfels (p. 195)
hydrothermal metamorphism (p. 203)
marble (p. 195)
metaconglomerate (p. 194)
metamorphic aureole (p. 198)
metamorphic facies (p. 200)
metamorphic foliation (p. 190)
metamorphic grade (p. 197)
metamorphic mineral (p. 190)
metamorphic rock (p. 189)
metamorphic texture (p. 190)
metamorphic zone (p. 198)
metamorphism (p. 189)
metasomatism (p. 192)
migmatite (p. 195)
mylonite (p. 201)
phyllite (p. 194)
preferred orientation (p. 192)
protolith (p. 189)
quartzite (p. 195)
regional metamorphism (p. 202)
schist (p. 194)
shear (p. 192)
shield (p. 207)
shock metamorphism (p. 203)
slate (p. 193)
thermal metamorphism (p. 198)

Review Questions

1. How are metamorphic rocks different from igneous and sedimentary rocks?
2. What two features characterize most metamorphic rocks?
3. What phenomena can cause metamorphism?
4. What is metamorphic foliation, and how does it form?
5. How does slate differ from a phyllite? How does phyllite differ from a schist? How does schist differ from a gneiss?
6. Why is hornfels nonfoliated?
7. What is a metamorphic grade, and how can it be determined? How does grade differ from facies?
8. Describe the geologic settings where thermal, dynamic, and dynamothermal metamorphism take place.
9. Why does metamorphism happen at the site of meteor impacts and along mid-ocean ridges?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- An animation exercise on how foliation forms in metamorphic rock.
- Labeling exercises on identification of metamorphic rocks.
- What a Geologist Sees exercises on magma viscosity and mineral formation in igneous rocks.

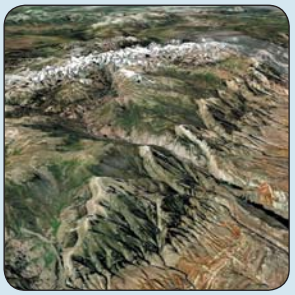
10. How does plate tectonics explain the combination of low-temperature but high-pressure minerals found in a blueschist?
11. Where would you go if you wanted to find exposed metamorphic rocks, and how did such rocks return to the surface of the Earth after being at depth in the crust?

On Further Thought

12. Do you think that you would be likely to find a broad region (hundreds of km across and hundreds of km long) in which the outcrop consists of high-grade hornfels? Why or why not? (*Hint*: Think about the causes of metamorphism and the conditions under which a hornfels forms.)
13. Would we likely find broad regions of gneiss and schist on the Moon? Why or why not?
14. Why don't builders use gneiss to make roof shingles?
15. The geothermal gradient of Mars is 8°C/km, and the crust of Mars is 30 km thick. Do high-grade metamorphic rocks form in this crust?
16. Could you find a layer of metamorphic rock sandwiched between layers of sedimentary rock in a sedimentary basin? Why or why not?

SEE FOR YOURSELF G. . . Metamorphic Rocks

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet G of our **Geotours Workbook**.



Wind River Mountains, Wyoming
Latitude 43°6′7.22″N,
Longitude 109°21′36.45″W
Faulting uplifted the Precambrian basement of western Wyoming 40 and 80 million years ago. Looking obliquely from 20 km, you can see that overlying cover of sedimentary strata was warped into a huge fold.



Canadian Shield, East of Hudson Bay
Latitude 61°09′50.15″N,
Longitude 76°42′43.88″W
The Canadian shield at this locality (viewed from 225 km) is covered by sparse vegetation. Differential erosion of the gneiss makes the foliation stand out. The east-west band of foliation delineates a zone of dynamic metamorphism associated with a fault zone.



Pilbara Craton, Western Australia
Latitude 21°40′39.20″S,
Longitude 119°40′33.69″E
This region of northwestern Australia (viewed from 48 km) is a desert in which contrasts between different types of bedrock stand out. The north-south stripe consists of meta-sedimentary and meta-volcanic rocks in a narrow belt between two large granitic batholiths.



Coast of the Red Sea, Egypt
Latitude 20°29′14.04″N,
Longitude 38°16′32.06″E
From an altitude of 4,500 km, you can see the color contrast between the dark. Precambrian metamorphic rocks and the light-colored younger rocks. The Precambrian region uplifted during rifting.

INTERLUDE C

The Rock Cycle



Beds of red sedimentary sandstone and siltstone, Red Rocks, Colorado.



Molten lava extruding from a volcano in Hawaii, in the process of freezing to form igneous rock.



Contorted layering in metamorphic rock, Italy.

These photos show three major rock groups of the Earth System. Over time, the atoms in one rock type may be incorporated in another, and then another. This transfer is called the rock cycle.

C.1 Introduction

"Stable as a rock." This familiar expression implies that a rock is permanent, unchanging over time. But it isn't. In the time frame of Earth history, a span of over 4.57 billion years, atoms making up one rock type may be rearranged or moved elsewhere, eventually becoming part of another rock type. Later, the atoms may move again to form a third rock type, and so on. Geologists refer to the progressive transformation of Earth materials from one rock type to another as the **rock cycle** (Fig. C.1), one of many examples of cycles acting in or on the Earth. A discussion of the rock cycle illustrates the relationships among the rock types described in the previous three chapters.

By following the arrows in Figure C.1, you can see many paths around or through the rock cycle. For example, igneous rock may weather and erode to produce sediment, which lithifies to form sedimentary rock. The new sedimentary rock may become buried so deeply that it transforms into metamorphic rock, which then could partially melt and produce magma. This magma later solidifies to form new igneous rock. We can symbolize this path as

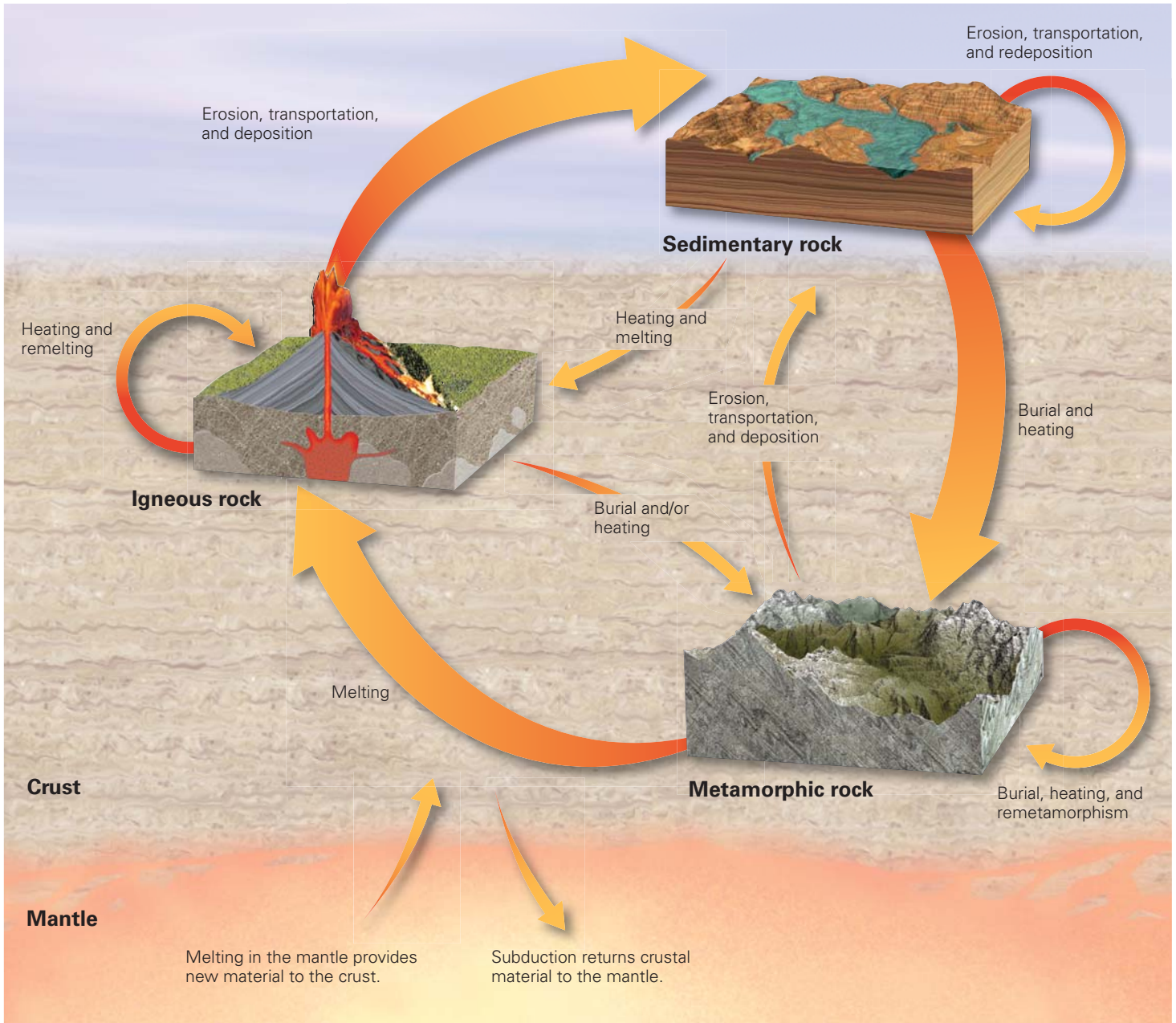
igneous → sedimentary → metamorphic → igneous.

But alternatively, the metamorphic rock could be uplifted and eroded to form new sediment which is later buried and lithified to form new sedimentary rock, without melting. This path takes a shortcut through the cycle that we can symbolize as

igneous → sedimentary → metamorphic → sedimentary.

Likewise, the igneous rock could be metamorphosed directly, without first turning to sediment. This metamorphic rock

FIGURE C.1 The stages of the rock cycle, showing various alternative pathways.



could then be eroded to produce sediment that eventually becomes sedimentary rock, defining another shortcut path:

igneous → metamorphic → sedimentary.

To get a clearer sense of how the rock cycle works, let's look at one example in the context of plate tectonics.

C.2 A Case Study of the Rock Cycle

Material can enter the rock cycle when magma rises from the mantle. Suppose the magma erupts and forms basalt (an igneous rock) at a continental hot-spot volcano (**Fig. C.2a**). Interaction with wind, rain, and vegetation gradually weathers the basalt, physically breaking it into smaller fragments and chemically transforming it to yield clay. Water washes the newly formed clay away and transports it downstream—if you've ever seen a brown-colored river, you've seen clay traveling to a site of deposition. Eventually, the river reaches the sea, where the water slows down and the clay settles out.

Let's imagine, for this example, that the clay settles out along the margin of Continent X and forms a deposit of mud. Gradually, through time, the mud becomes buried and the clay flakes pack tightly together to form a new sedimentary rock, shale. The shale resides 6 km below the continental shelf for millions of years, until the adjacent oceanic plate subducts and another Continent, Y, collides with X. The edge of the encroaching continent pushes over the shale, buries it very deeply, and shears it. As the mountains grow, the shale that had once been 6 km below the surface ends up 20 km below the surface, and under the pressure and temperature conditions present at this depth, it metamorphoses into schist (**Fig. C.2b**).

The story's not over. Once mountain building stops, erosion grinds away the mountain range, and exhumation brings some of the schist to the ground surface. This schist erodes to form sediment, which is carried off and deposited elsewhere to form new sedimentary rock. But other schist remains preserved below the surface (**Fig. C.2c**). Eventually, continental rifting takes place at the site of the former mountain range, and the crust containing the schist begins to split apart. Rifting causes decompression melting in the mantle. The rising melts bring so much heat into the crust that some of the schist partially melts and a new felsic magma forms. This felsic magma rises to the surface of the crust and freezes into rhyolite, a new igneous rock (**Fig. C.2d**). In terms of the rock cycle, we've gone full circle, having once again made igneous rock.

Not all atoms pass through the rock cycle at the same rate, and for that reason we find rocks of many different ages at the surface of the Earth. Some rocks remain in one form for less than a few million years, while others stay unchanged for most of Earth history. A rock in the Appalachian Mountains has passed through stages of the rock cycle many times during the past few hundred million years, because the eastern margin of North America has been subjected to multiple events of basin formation, mountain building, and rifting during the last billion years. In contrast, some 3 billion-year-old mafic and ultramafic rocks found in the interiors of continents have not yet passed the first stage of the rock cycle. Studies show, however, that such long-lived rocks account for a very small proportion of the crust—most crust has been through at least a couple of stages in the rock cycle.

Most atoms that comprise continental rocks never return to the mantle, because continental crust is buoyant and does not subduct. However, a small amount of sediment that erodes off a continent ends up in deep-ocean trenches, and some of this gets carried back into the mantle by subduction. And recent research suggests that metamorphic and igneous rocks at the base of the continental crust may be scraped off and transported down into the mantle by subduction.

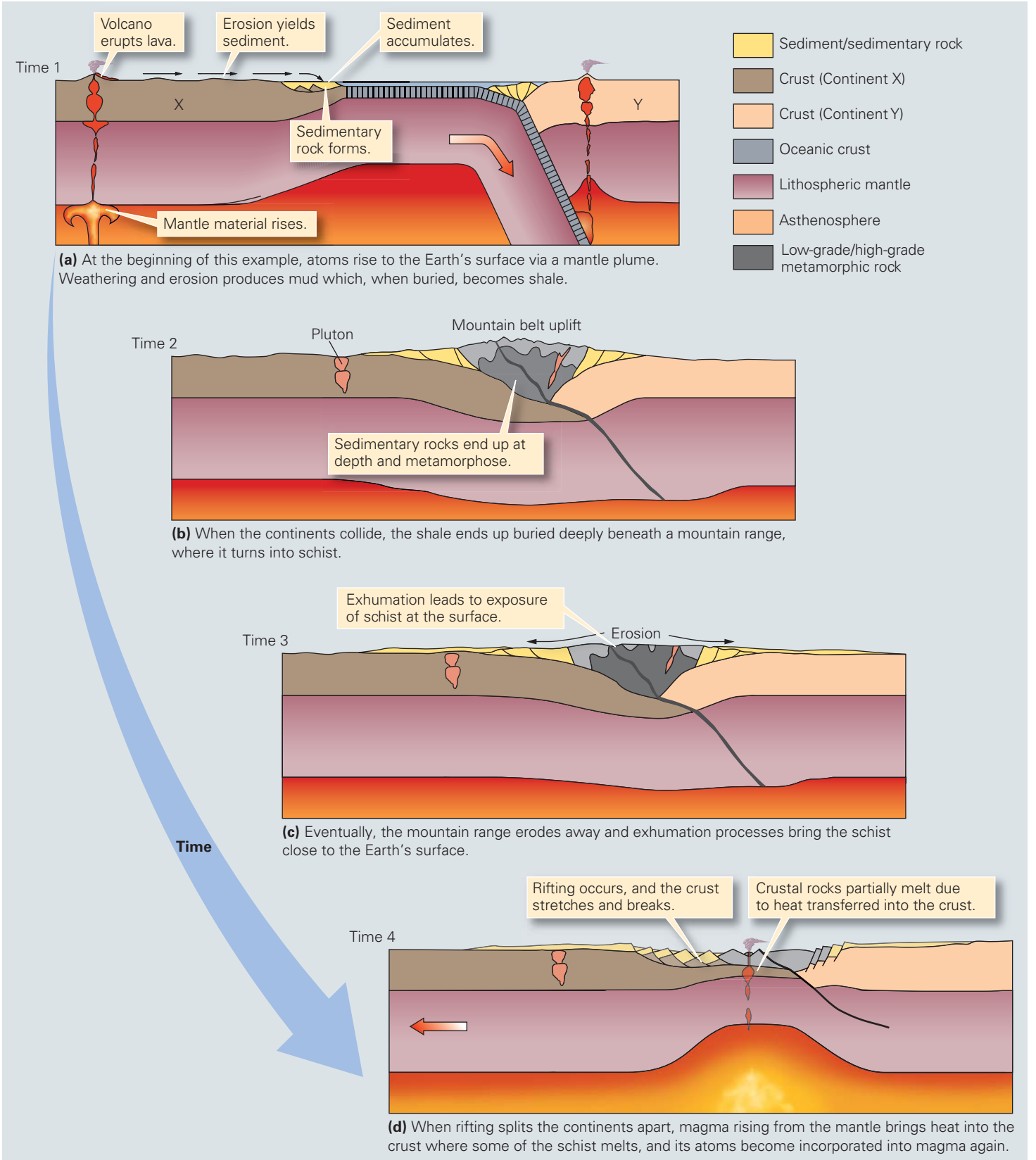
Our tour of the rock cycle has focused on continental rocks. What about the oceans? Oceanic crust consists of igneous rock (basalt and gabbro) overlain by sediment. Because a layer of water blankets oceanic crust, oceanic crustal rock does not erode and generally does not follow the path into the sedimentary loop of the rock cycle. But sooner or later, oceanic crust subducts. When this happens, the rock of the crust undergoes metamorphism, for as it sinks, it is subjected to progressively higher temperatures and pressures.

C.3 What Drives the Rock Cycle in the Earth System?

The rock cycle occurs because the Earth is a dynamic planet and there are many rock-forming environments (see **Geology at a Glance**, pp. 214–215). The planet's internal heat and gravitational field drive plate movements and plume-associated hot spots. Plate interactions cause the uplift of mountain ranges, a process that leads to weathering, erosion, and sediment production. Plate interactions also generate settings in which metamorphism occurs, where rock melts, and where sedimentary basins develop.

At the surface of the Earth, the gases initially released by volcanism collect to form the ocean and atmosphere. Heat (from the Sun) and gravity drive convection in the atmosphere and oceans, leading to wind, rain, ice, and currents—the agents of weathering and erosion. In the Earth System, life also plays a key role by adding corrosive oxygen to the atmosphere and by directly contributing to weathering. In sum, external energy (solar heat), internal energy (Earth's internal heat), gravity, and life all play a role in driving the rock cycle by keeping the mantle, crust, atmosphere, and oceans in motion.

FIGURE C.2 An example of the rock cycle in the context of plate tectonics.



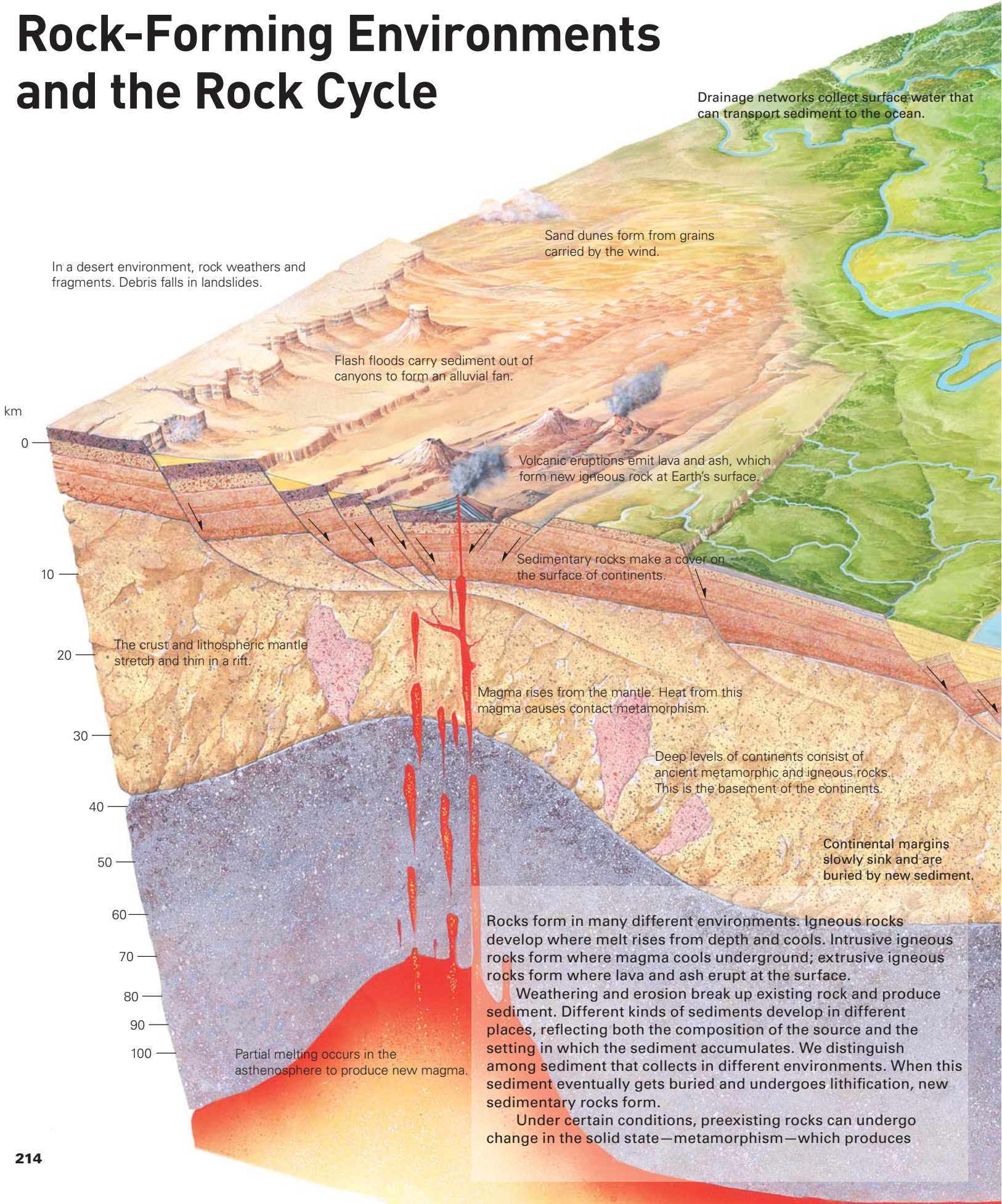
(a) At the beginning of this example, atoms rise to the Earth's surface via a mantle plume. Weathering and erosion produces mud which, when buried, becomes shale.

(b) When the continents collide, the shale ends up buried deeply beneath a mountain range, where it turns into schist.

(c) Eventually, the mountain range erodes away and exhumation processes bring the schist close to the Earth's surface.

(d) When rifting splits the continents apart, magma rising from the mantle brings heat into the crust where some of the schist melts, and its atoms become incorporated into magma again.

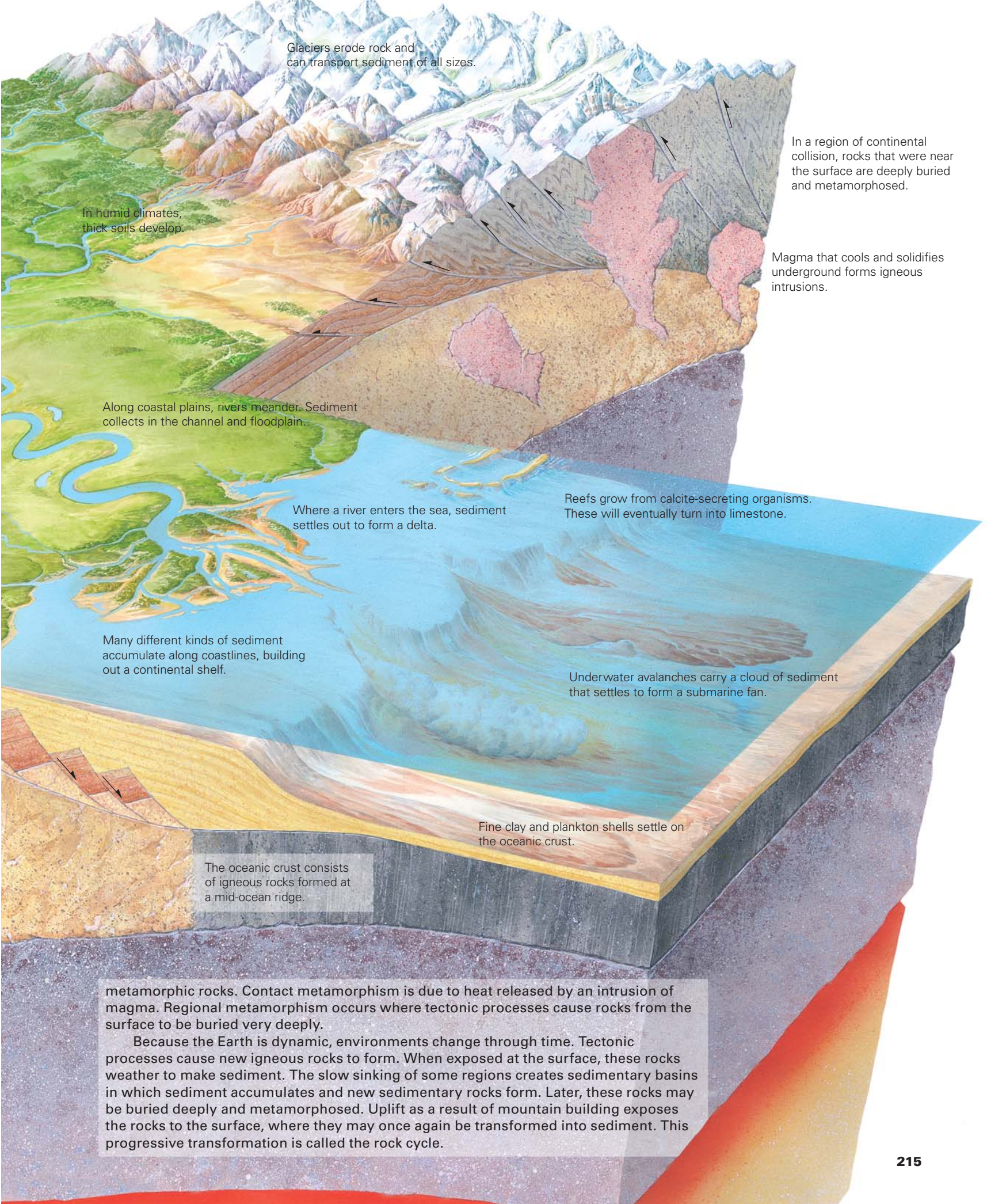
Rock-Forming Environments and the Rock Cycle



Rocks form in many different environments. Igneous rocks develop where melt rises from depth and cools. Intrusive igneous rocks form where magma cools underground; extrusive igneous rocks form where lava and ash erupt at the surface.

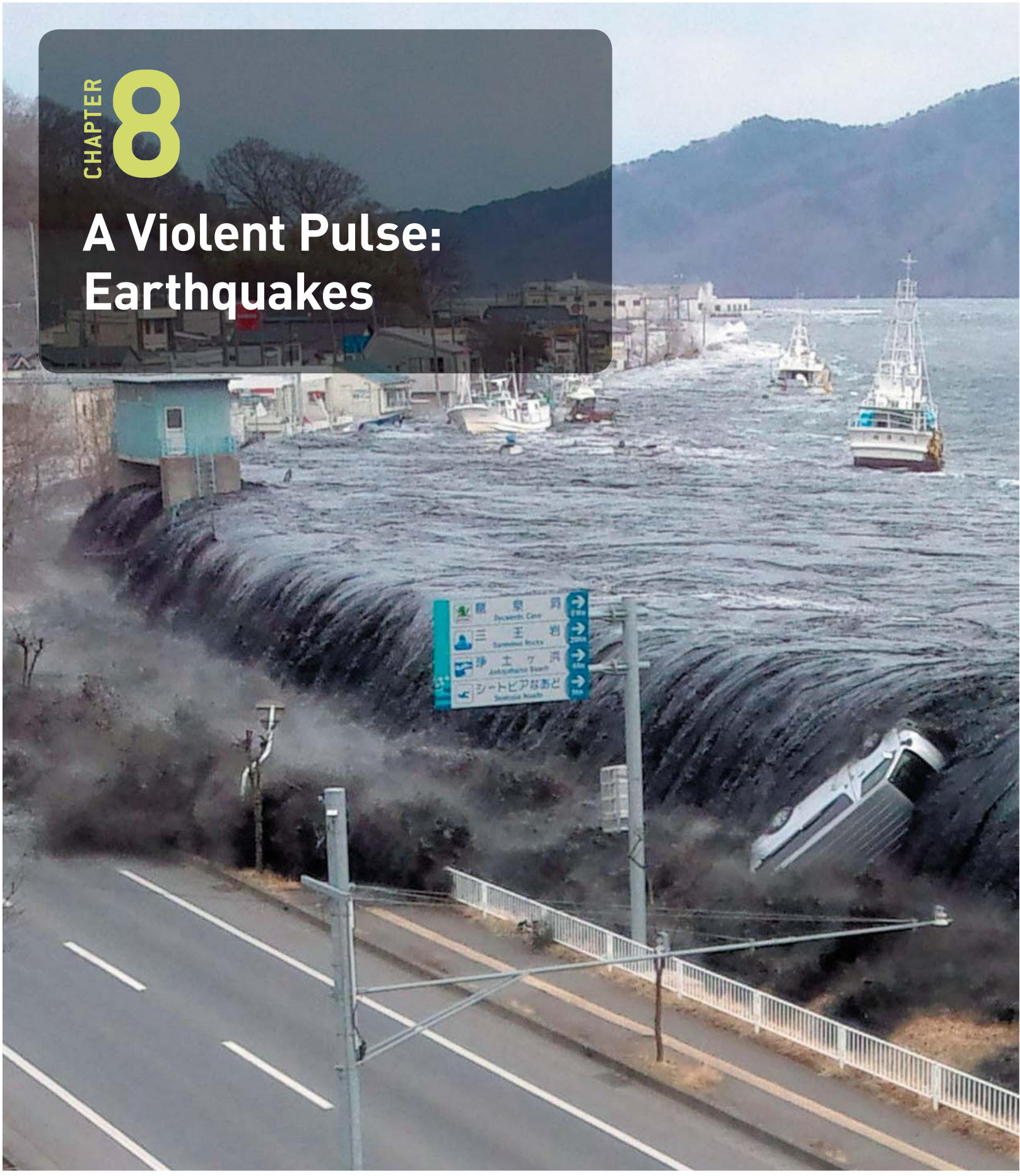
Weathering and erosion break up existing rock and produce sediment. Different kinds of sediments develop in different places, reflecting both the composition of the source and the setting in which the sediment accumulates. We distinguish among sediment that collects in different environments. When this sediment eventually gets buried and undergoes lithification, new sedimentary rocks form.

Under certain conditions, preexisting rocks can undergo change in the solid state—metamorphism—which produces



metamorphic rocks. Contact metamorphism is due to heat released by an intrusion of magma. Regional metamorphism occurs where tectonic processes cause rocks from the surface to be buried very deeply.

Because the Earth is dynamic, environments change through time. Tectonic processes cause new igneous rocks to form. When exposed at the surface, these rocks weather to make sediment. The slow sinking of some regions creates sedimentary basins in which sediment accumulates and new sedimentary rocks form. Later, these rocks may be buried deeply and metamorphosed. Uplift as a result of mountain building exposes the rocks to the surface, where they may once again be transformed into sediment. This progressive transformation is called the rock cycle.



CHAPTER 8

A Violent Pulse: Earthquakes



Earthquakes that happen under the sea can generate waves known as tsunamis. This tsunami, generated by an earthquake near Japan in 2011, just overtopped a seawall and is about to flood a town. The consequences of earthquakes can be deadly!

Chapter Objectives

By the end of this chapter, you should know . . .

- the causes of earthquakes and why they occur where they do.
- how to determine the size and location of an earthquake.
- the many ways in which earthquakes cause damage.
- the limitations on people's ability to predict earthquakes.
- steps that people can take to prevent earthquake damage.

We learn geology the morning after the earthquake.

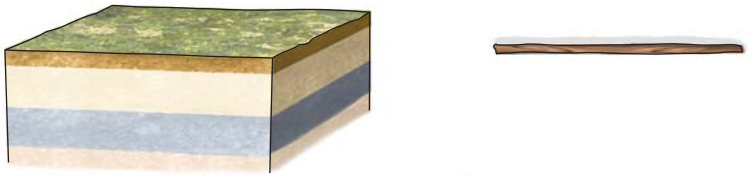
—Ralph Waldo Emerson (American poet, 1803–1882)

8.1 Introduction

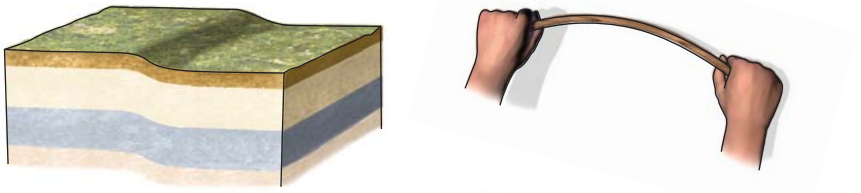
As the afternoon of March 11, 2011, began, fishing fleets unloaded their catch, factories churned out goods, shoppers filled stores, and children studied in numerous towns along the eastern coast of Honshu, the northern island of Japan. All this changed at 2:46 P.M. Japan lies along a convergent plate boundary, where the Pacific Plate sinks back into the mantle underneath the edge of the Eurasian Plate. The boundary between the two plates is a **fault**, a large fracture on which sliding occurs, that slopes gently to the west. Motion along a fault doesn't happen continuously. Rather, for many years, rocks along the fault slowly bend to accommodate the motion. But like a stick that you flex with your hands, rock can bend only so far before it snaps (**Fig. 8.1a–c**). The "snap" on March 11 happened about 130 km (80 miles) east of Japan's coast, at a depth of about 24 km (15 miles) below the sea floor. Eurasia lurched eastward by a few meters, relative to the Pacific Plate. During the event, rocks cracked and ruptured over an area of the fault that measured 600 km long by 200 km wide. This movement abruptly uplifted the overlying sea floor by as much as tens of centimeters. A triple disaster was about to strike Japan.

Shock waves generated by the shearing and fracturing of rock along the fault raced through the crust at an average speed of 11,000 km (7,000 miles) per hour, ten times the speed of sound in air. When the vibrations reached Japan, the land surface lurched back and forth and bounced

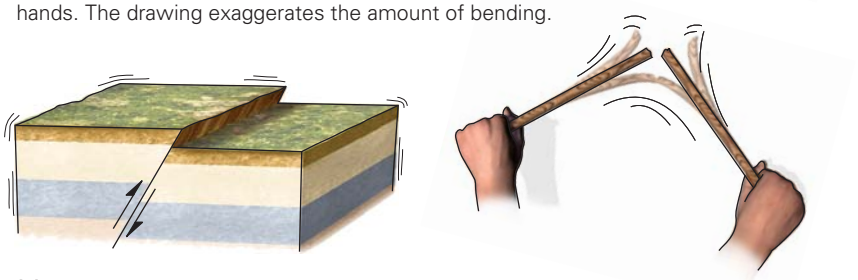
FIGURE 8.1 What happens during an earthquake?



(a) Before deformation, rock layers in this example are not bent.



(b) Before an earthquake, rock bends elastically, like a stick that you arch between your hands. The drawing exaggerates the amount of bending.



(c) Eventually, the rock breaks, and sliding suddenly occurs on a fault. This break generates vibrations. You feel such vibrations when you break a stick.

up and down for over a minute. People lost their balance and crouched or fell, bottles and plates flew off shelves and crashed to the floor, buildings twisted and swayed, causing their ceilings and facades to collapse in a shower of debris, and power lines stretched and sparked. In addition, natural gas tanks and pipes broke, sending flammable vapors into the air—in places, the gas ignited in billows of flame that set fire to damaged buildings. A major **earthquake**—an episode of ground shaking—had occurred. The 2011 event is now known as the Great Tohoku earthquake—Tohoku is the eastern province of Honshu.

In most cases, the societal calamity due to an earthquake is a direct consequence of ground shaking, because many buildings collapse and crush their inhabitants, and debris tumbles down slopes in landslides. For example, during the May 12, 2008, earthquake of Sichuan, in central China, shaking leveled cities—70,000 people died, and millions were left homeless. And in February 2011, sudden rupture on a fault near Christchurch, New Zealand, toppled buildings and a stalwart stone cathedral (**Fig. 8.2a**). But in Japan, a country struck by earthquakes fairly frequently, officials have established stringent building codes that successfully prevented widespread building collapse. Unfortunately, even strong buildings could not resist what happened minutes after the earthquake shock. When the sea floor off Japan's coast suddenly uplifted during the Tohoku earthquake, a massive amount of water was displaced. This water moved away from the site of the earthquake in immense waves, known as tsunamis, that swept over low-lying coastal areas (**Fig. 8.2b**). To make matters worse, the water destroyed power sources used to run the pumps that cooled reactors in a coastal nuclear power plant, causing partial meltdown and release of radioactivity. The immensity of the devastation was the worst to impact Japan since World War II.

Earthquakes have affected the Earth since the solid lithosphere first formed. Most are a consequence of plate movement; they punctuate each step in the growth of mountains, the drift of continents, and the opening and closing of ocean basins. Almost 1 million detectable earthquakes happen every year. Fortunately, most cause no damage or casualties, because they are too small or they occur in unpopulated areas. But a few hundred earthquakes per year rattle the ground sufficiently to damage buildings and injure their occupants, and every 5 to 20 years, on average, a great earthquake triggers a horrific calamity. Earthquakes have killed over 3.5 million people during the past two millennia. What geologic phenomena generate earthquakes? Why do earthquakes take place where they do? How do they cause damage? Can we predict when earthquakes will happen, or even prevent them from happening? These questions have puzzled seismologists (from the Greek word *seismos*, for shock or earthquake), the geoscientists who study earthquakes, for decades. In this chapter, we seek some of the answers.

8.2 What Causes Earthquakes?

Ancient cultures offered a variety of explanations for **seismicity** (earthquake activity), most of which involved the action or mood of a giant animal or god. Scientific study suggests that seismicity instead occurs for several reasons, including:

- the sudden formation of a new fault (a fracture or rupture on which sliding occurs)
- sudden slip on an already existing fault

- a sudden change in the arrangement of atoms in rock minerals
- movement of magma in, or explosion of, a volcano
- a giant landslide
- a meteorite impact
- an underground nuclear-bomb test

Of these various reasons, faulting related to plate movements is by far the most significant. In other words, *most earthquakes are due to slip on faults*.

The place within the Earth where rock ruptures and slips, or the place where an explosion occurs, is the **hypocenter** or **focus** of the earthquake. Energy radiates from the focus. The point on the surface of the Earth that lies directly above the focus is the **epicenter**, so maps can portray the position of epicenters (**Fig. 8.3a, b**). Since slip on faults causes most earthquakes, we focus our discussion on faults.

FIGURE 8.2 Recent earthquake devastation.

(a) Damage caused by the 2011 Christchurch, New Zealand earthquake.



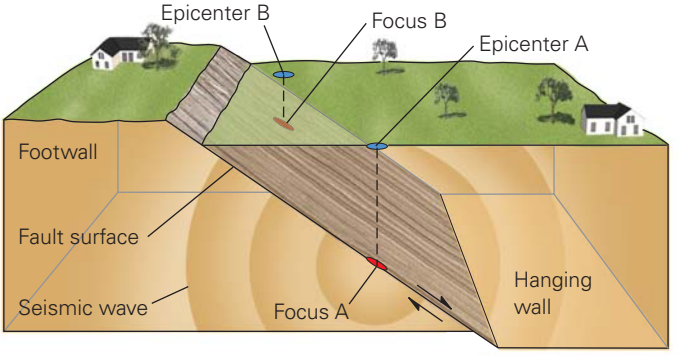
(b) A tsunami washes over coastal Japan (March 11, 2011).



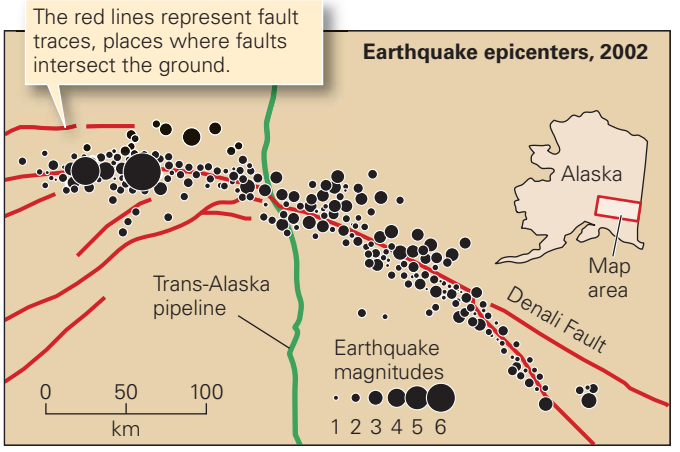
Faults in the Crust

At first glance, a fault may look simply like a fracture or break that cuts across rock or sediment. But on closer examination, you may be able to see evidence of sliding that occurred on a fault. For example, the rock adjacent to the fault may be broken up into angular fragments or may be pulverized into tiny grains, due to the crushing and grinding that can accompany slip, and the surface of a fault may be polished and grooved as if scratched by a rasp. In some localities, a fault cuts through a distinct marker (a sedimentary bed, an igneous dike, or a fence); where this happens, the end of the marker on one side of the fault is offset relative to the end on the other side. The distance between two ends of the marker,

FIGURE 8.3 Earthquake hypocenters and epicenters.



(a) The hypocenter, or focus, is the place underground where rock breaks and generates earthquake waves. The epicenter is the point on the surface of the Earth directly above the focus.



(b) Geologists represent epicenters as dots on a map; dot size indicates the size (magnitude) of the earthquake. Epicenters typically lie on or near a fault trace.

as measured along the fault surface in the direction of slip, is the fault's **displacement** (Fig. 8.4a, b). Many faults are completely underground, and will be visible only if exposed by erosion of overlying rock. But some faults intersect and offset the ground surface, producing a step called a **fault scarp** (Fig. 8.5a). The ground surface exposure of a fault is called the fault line or **fault trace**.

19th-century miners who encountered faults in mine tunnels referred to the rock mass above a sloping fault plane as the *hanging wall*, because it hung over their heads, and the rock mass below the fault plane as the *footwall*, because it lay beneath their feet. The miners described the direction in which rock masses slipped on a sloping fault by specifying the direction that the hanging wall moved in relation to the footwall, and we still use these terms today (see **Geology at a Glance**, pp. 222–223). When the hanging wall slips down the slope of the fault, it's a normal fault. When the hanging wall slips up the slope, it's a reverse fault if steep, and a thrust fault if shallowly sloping (Fig. 8.5a–c). Strike-slip faults are near-vertical planes on which slip occurs parallel to an imaginary horizontal line, called a strike line, on the fault plane—no up or down motion takes place on such faults (Fig. 8.5d).

Faults are found in many locations—but don't panic! Not all of them are likely to be the source of earthquakes. Faults that have moved recently or are likely to move in the near future are called *active* faults (and if they generate earthquakes, news media sometimes refer to them as "earthquake faults"). Faults that last moved in the distant past and probably won't move again in the near future are called *inactive* faults.

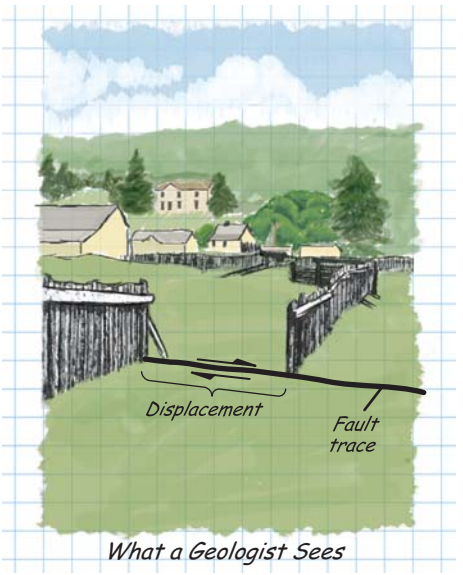
Generating Earthquake Energy: Stick-Slip

What is the relationship between faulting and earthquakes? Earthquakes can happen either when rock breaks and a new fault forms, or when a preexisting fault suddenly slips again. Let's look more closely at these two causes.

- *Earthquakes due to fault formation*: Imagine that you grip each side of a brick-shaped block of rock with a clamp. Apply an upward push on one of the clamps and a downward push on the other. By doing so, you have applied a "stress" to the rock. (**Stress** refers to a push, pull, or shear.) At first, the rock bends slightly but doesn't break (Fig. 8.6a). In fact, if you were to stop applying stress at this stage, the rock would return to its original shape. Geologists refer to such a phenomenon as *elastic behavior*—the same phenomenon happens when a rubber band returns to its original shape or a bent stick straightens out after you let go. Now repeat the experiment, but bend the rock even more. If you bend the rock far enough, a number of small cracks or breaks start to form. Eventually the cracks connect to one another to form a fracture that cuts across the entire block of rock (Fig. 8.6b). The instant that this fracture forms, the block breaks in two and the rock on one side suddenly slides past the rock on the other side, and any elastic bending that had built up is released so the rock straightens out or rebounds (Fig. 8.6c). Because sliding occurs, the fracture has become a fault. A fault can't slip forever, for friction eventually slows and stops

FIGURE 8.4 Examples of fault displacement on the San Andreas fault in California.



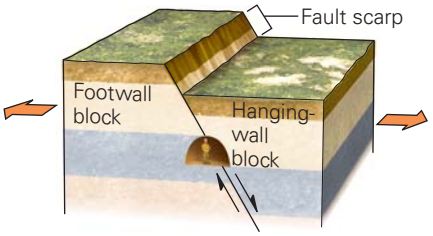


(a) A wooden fence built across the fault was offset during the 1906 San Francisco earthquake. The displacement indicates that the motion was strike-slip.

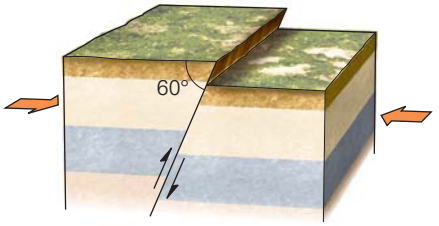


(b) An aerial photograph shows offset of a dirt road by slip on the fault in 1999.

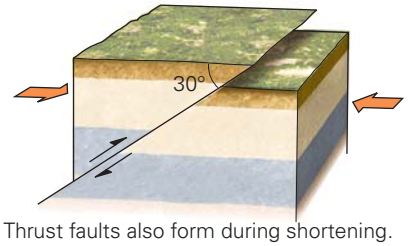
FIGURE 8.5 The basic types of faults. Fault types are distinguished from one another by the direction of slip relative to the fault surface.



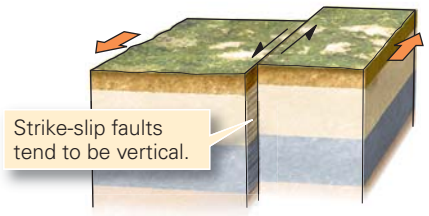
(a) Normal faults form during extension of the crust. The hanging wall moves down.



(b) Reverse faults form during shortening of the crust. The hanging wall moves up and the fault is steep.



(c) Thrust faults also form during shortening. The fault's slope is gentle (less than 30°).



(d) On a strike-slip fault, one block slides laterally past another, so no vertical displacement takes place.

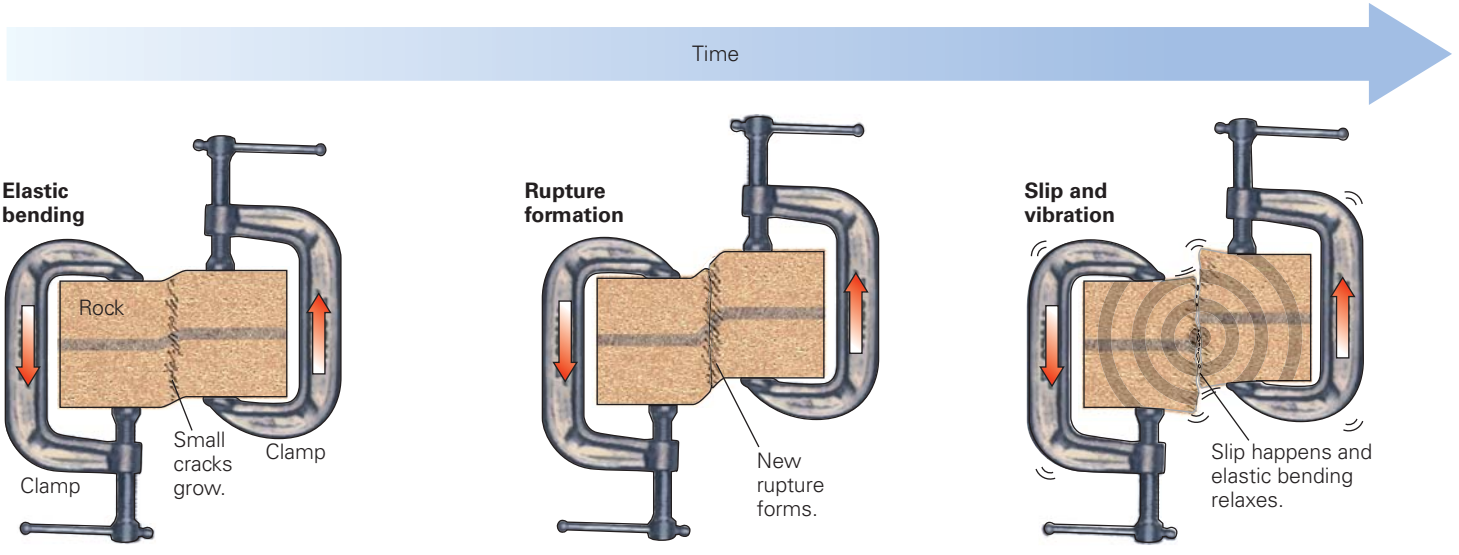
the movement. **Friction**, defined as the force that resists sliding on a surface, is caused by the existence of bumps on surfaces—these bumps act like tiny anchors and snag on the opposing surface.

- *Earthquakes due to slip on a preexisting fault*: Once a fault comes into being, it is a scar in the Earth's crust that can remain weaker than surrounding, intact crust. When stress builds sufficiently, it overcomes friction and the preexisting fault slips again. This movement takes place before stress becomes great enough to cause new fracturing of surrounding intact rock. Note that after each slip event, friction prevents the fault from slipping again until stress builds again. Geologists refer to such alternation between stress buildup and slip events (earthquakes) as **stick-slip behavior**.

The breaking of rock that occurs when a fault slips, like the snap of a stick, generates earthquake energy. The concept that earthquakes happen because stresses build up, causing rock adjacent to the fault to bend elastically until slip on the fault occurs is called the **elastic-rebound theory**.

Of note, the major earthquake (or "mainshock") along a fault may be preceded by smaller ones, called **foreshocks**, which possibly result from the development of the smaller cracks in the vicinity of what will be the major rupture. Smaller earthquakes, called **aftershocks**, occur in the days to months following a large earthquake. The largest aftershock tends to be ten times smaller than the mainshock, and most are even

FIGURE 8.6 A model representing the development of a new fault. Rupturing can generate earthquake-like vibrations.

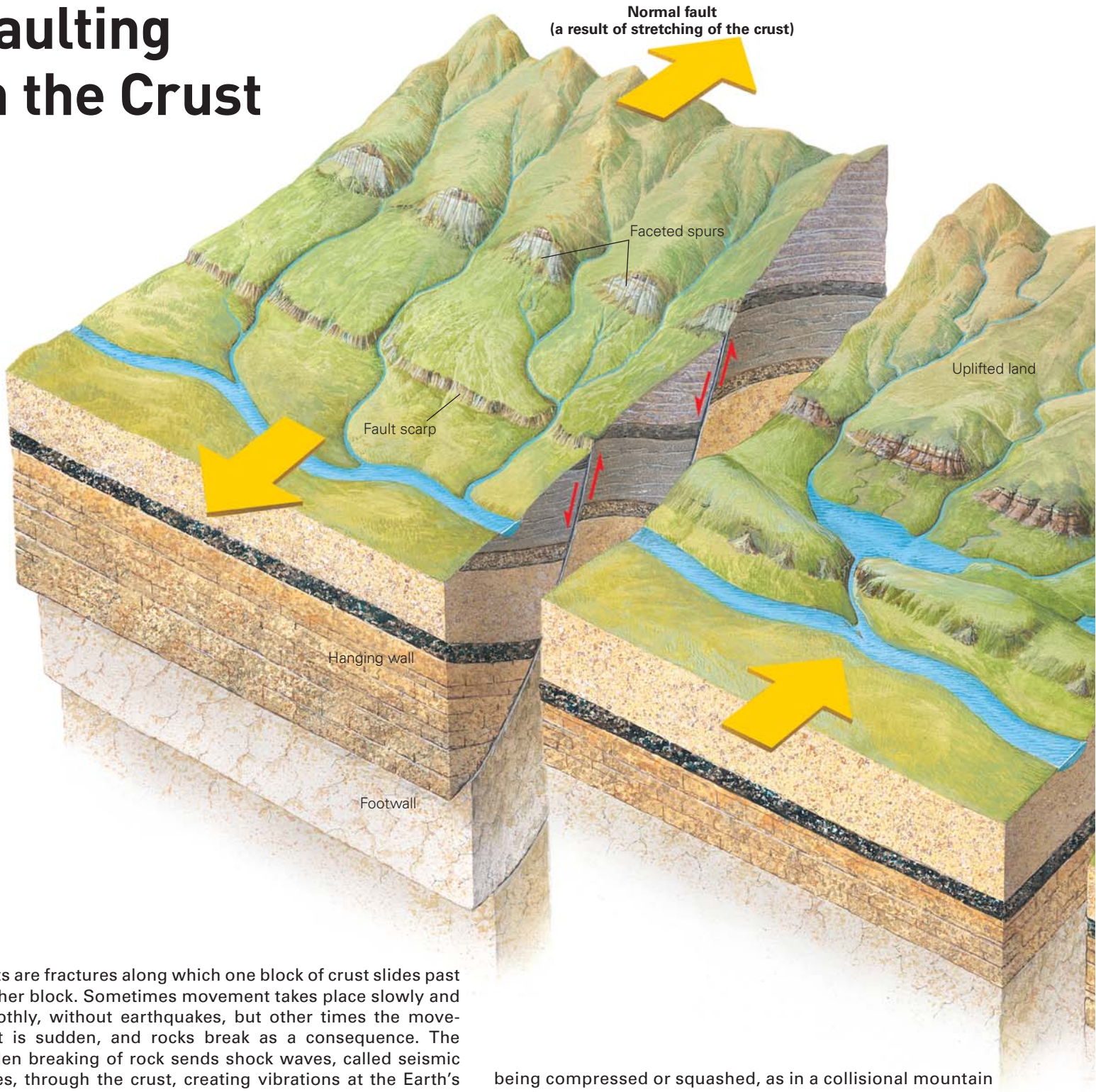


(a) Imagine a block of rock gripped by two clamps. Move one clamp up, and the rock starts to bend. Small cracks develop along the bend.

(b) Eventually, the cracks link. When this happens, a throughgoing rupture forms.

(c) The instant that the rupture forms, the rock breaks into two pieces that slide past each other. The energy that is released generates vibrations (earthquake energy).

Faulting in the Crust

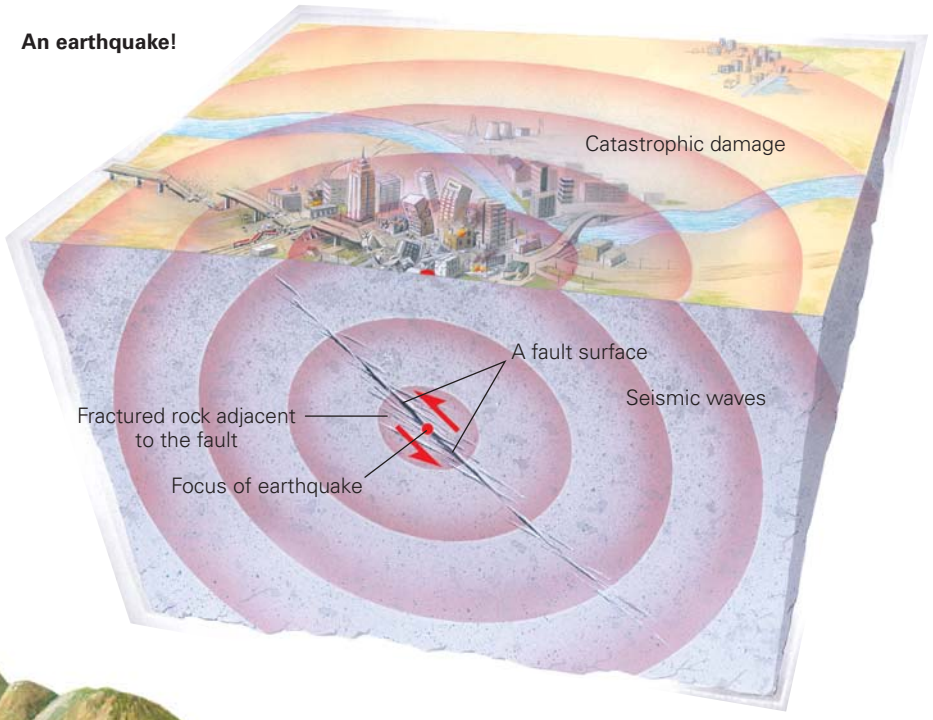


Faults are fractures along which one block of crust slides past another block. Sometimes movement takes place slowly and smoothly, without earthquakes, but other times the movement is sudden, and rocks break as a consequence. The sudden breaking of rock sends shock waves, called seismic waves, through the crust, creating vibrations at the Earth's surface—an earthquake.

Geologists recognize three types of faults. If the hanging-wall block (the rock above a fault plane) slides down the fault's slope relative to the footwall block (the rock below the fault plane), the fault is a normal fault. (Normal faults form where the crust is being stretched apart, as in a continental rift.) If the hanging-wall block is being pushed up the slope of the fault relative to the footwall block, then the fault is a reverse fault. (Reverse faults develop where the crust is being compressed or squashed, as in a collisional mountain belt.) If one block of rock slides past another and there is no up or down motion, the fault is a strike-slip fault. Strike-slip fault planes tend to be nearly vertical.

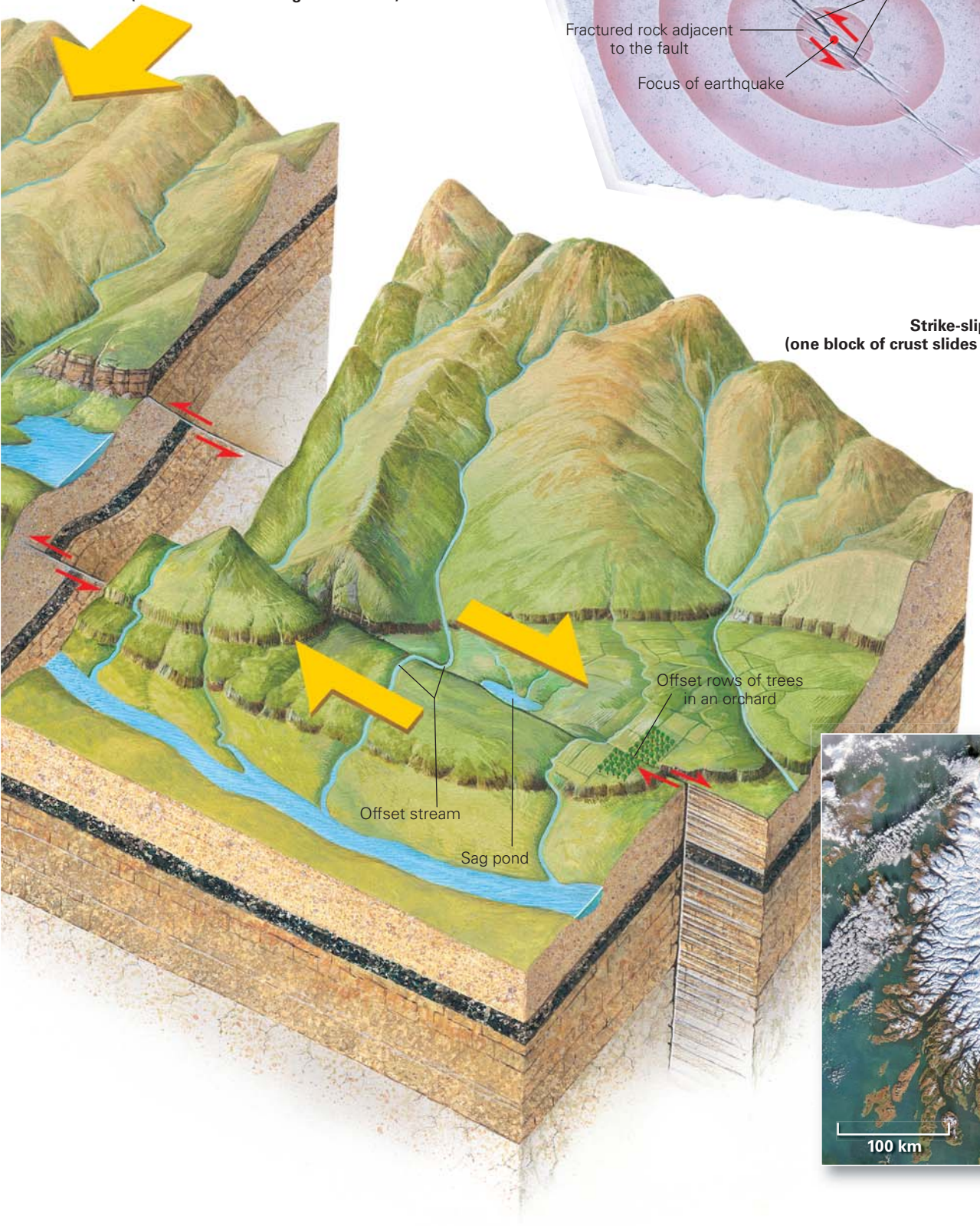
If a fault displaces the ground surface, it creates a ledge called a fault scarp. Where fault scarps cut a system of rivers and valleys, the ridges are truncated to make triangular facets. Strike-slip faults may offset ridges, streams, and orchards sideways. If there is a slight extension along the fault, the land surface sinks, and a sag pond develops.

An earthquake!

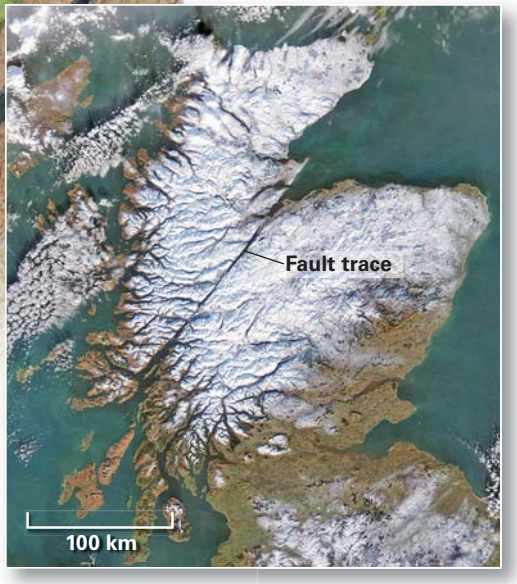


Reverse fault
(a result of shortening of the crust)

Strike-slip fault
(one block of crust slides laterally past another)



Erosion along the Great Glen fault produced a linear valley.



smaller. Aftershocks happen because slip during the mainshock does not leave the fault in a perfectly stable configuration. For example, after the mainshock, irregularities on one side of the fault surface, in their new position, may push into the opposing side and generate new stresses. Such stresses may become large enough to cause a small portion of the fault around the irregularity to slip again, or may trigger slip in a nearby fault.

The Amount of Slip during an Earthquake

How much of a fault surface slips during an earthquake? The answer depends on the size of the earthquake: the larger the earthquake, the larger the slipped area and the greater the displacement. For example, the major earthquake that hit San Francisco, California, in 1906 ruptured a 430-km-long (measured parallel to the Earth's surface) by 15-km-deep (measured perpendicular to the Earth's surface) segment of the San Andreas fault. Thus, the area that slipped was almost 6500 km^2. During the 2011 Tohoku earthquake an area 300 km long by 100 km wide (30,000 km^2) slipped.

The amount of slip varies along the length of a fault—the maximum observed displacement during the 1906 earthquake was 7 m, in a strike-slip sense. Slip on a thrust fault that caused the 1964 Good Friday earthquake in southern Alaska reached a maximum of 12 m, and the maximum slip during the Tohoku earthquake was over 20 m. Smaller earthquakes, such as the one that hit Northridge, California, in 1994, resulted in only about 0.5-m slip—even so, this earthquake toppled homes, ruptured pipelines, and killed 51 people. The smallest-felt earthquakes result from displacements measured in millimeters to centimeters.

Although the cumulative movement on a fault during a human life span may not amount to much, over geologic time the cumulative movement becomes significant. For example, if earthquakes occurring on a strike-slip fault cause 1 cm of displacement per year, on average, the fault's movement will yield 10 km of displacement after 1 million years.

Take-Home Message

Most earthquakes happen when stress builds sufficiently to cause sudden formation of a fault, or slip on a preexisting fault. The focus is the point in the Earth where the slip occurs. The epicenter is the point on the surface of the Earth directly above.

8.3 Seismic Waves

How does the energy produced at the hypocenter of an earthquake travel to the surface or even pass through the entire Earth? Earthquake energy travels through rock and sediment in the form of waves. We call these waves **seismic waves** (or earthquake waves). You feel such waves when you hold one end of a brick and strike the other end with a hammer.

Seismologists distinguish among different types of seismic waves, first on the basis of where the waves move. **Body waves** pass through the interior of the Earth, whereas **surface waves** travel along the Earth's surface. Then, they consider how the waves move. Waves that cause particles of material to move back and forth *parallel* to the direction in which the wave itself moves are called **compressional waves**. As a compressional wave passes, the material first compresses (or squeezes together), then dilates (or expands). To see this kind of motion in action, push on the end of a spring and watch as the little pulse of compression moves along the length of the spring. Waves that cause particles of material to move back and forth *perpendicular* to the direction in which the wave itself moves are called **shear waves**. To see shear-wave motion, jerk the end of a rope up and down and watch how the up-and-down motion travels along the rope. With these concepts in mind, we can define four basic categories of seismic waves (**Fig. 8.7a–c**):

- P-waves (*P* stands for primary) are compressional body waves.
- S-waves (*S* stands for secondary) are shear body waves.
- L-waves (*L* stands for Love, the name of a seismologist) are surface waves that cause the ground to ripple back and forth, producing a snake-like movement.
- R-waves (*R* stands for Rayleigh, the name of a physicist) are surface waves that cause the ground to ripple up and down.

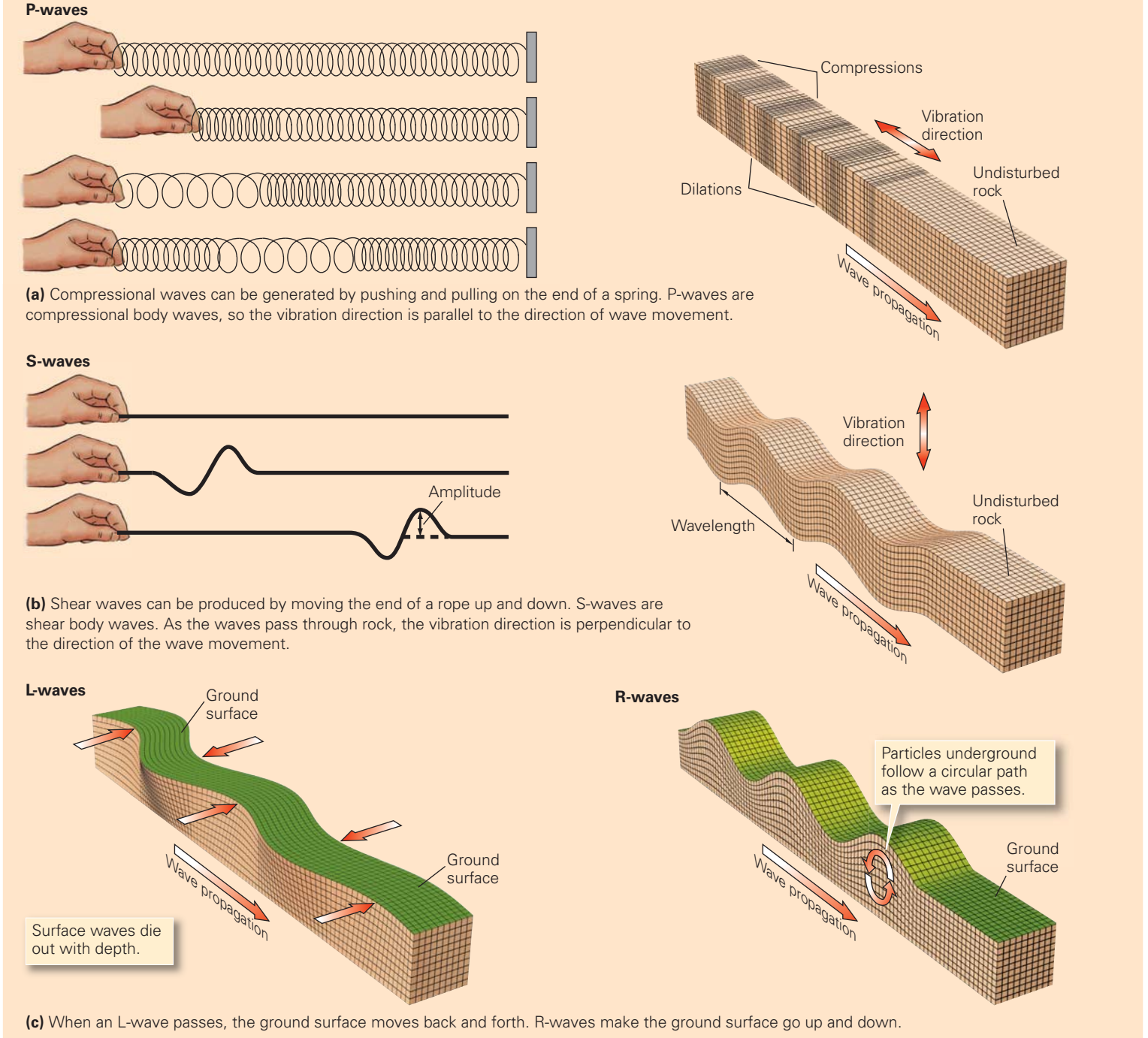
The different types of seismic waves travel at different velocities. P-waves travel the fastest and thus arrive first. S-waves travel more slowly, at about 60% of the speed of P-waves, so they arrive later. Surface waves are the slowest of all.

Friction absorbs energy as waves pass through a material, and waves bounce off layers and obstacles in the Earth, so the amount of energy carried by seismic waves decreases the farther they travel. Thus, people near the epicenter may be thrown off their feet by a large earthquake, but those 100 km away barely feel it. Similarly, an earthquake caused by slip on a fault deep in the crust causes less damage than one caused by slip on a fault near the surface.

Take-Home Message

Earthquake energy travels as seismic waves. Body waves (P-waves and S-waves) travel through the interior of the Earth, whereas surface waves travel along the surface. Ground shaking, due to arrival of waves, generally decreases with distance from the hypocenter.

FIGURE 8.7 Different types of earthquake waves.



(a) Compressional waves can be generated by pushing and pulling on the end of a spring. P-waves are compressional body waves, so the vibration direction is parallel to the direction of wave movement.

(b) Shear waves can be produced by moving the end of a rope up and down. S-waves are shear body waves. As the waves pass through rock, the vibration direction is perpendicular to the direction of the wave movement.

(c) When an L-wave passes, the ground surface moves back and forth. R-waves make the ground surface go up and down.

8.4 How Do We Measure and Locate Earthquakes?

Most news reports about earthquakes provide information on the size and location of an earthquake. What does this information mean, and how do we obtain it? What's the difference between a large earthquake and a minor one? How do seismologists locate an epicenter? To answer these questions we must first understand how a seismometer works and how to read the information it provides.

Seismometers and the Record of an Earthquake

Researchers use an instrument, called a **seismometer** (or seismograph), to systematically measure the ground motion from

an earthquake. Seismologists now use two basic configurations of seismometers, one for measuring vertical (up-and-down) ground motion and the other for measuring horizontal (back-and-forth) ground motion.

A mechanical vertical-motion seismometer consists of a heavy weight (like a pendulum) suspended from a spring (Fig. 8.8a). The spring connects to a sturdy frame that has been bolted to the ground. A pen extends sideways from the weight and touches a vertical revolving cylinder of paper that has been connected to the seismometer frame. If the ground is steady, it traces out a straight reference line as the cylinder turns under it. But when an earthquake wave arrives and causes the ground surface to move up and down, it makes the seismometer frame also move up and down. The weight, however, because of its inertia (the tendency of an object at rest to remain at rest), remains fixed in space. As a consequence, the revolving paper roll moves up and down under the pen and the position of the pen moves relatively away from the reference line. The apparent deflection of the pen, therefore, represents the up-and-down movement. As the paper cylinder revolves under the pen, the pen traces out the curves that resemble waves. A mechanical horizontal-motion seismometer works on the same principle, except that the paper cylinder is horizontal and the weight hangs from a wire (Fig. 8.8b). Sideways back-and-forth movement of the cylinder and the frame relative to the pen causes the pen to trace out waves.

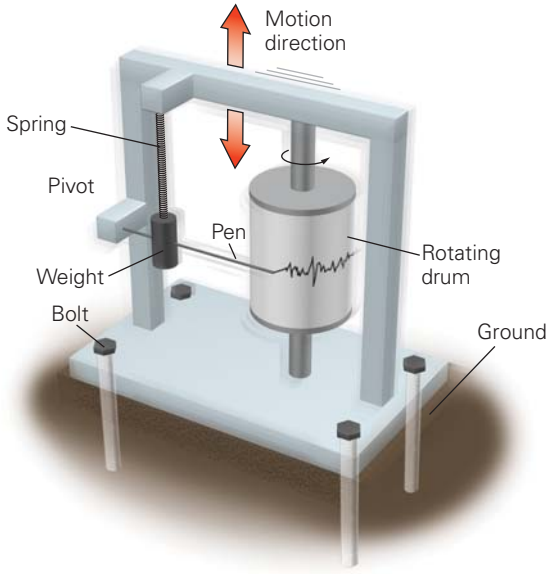
Modern seismometers work on the same principle, except the weight is a magnet that moves relative to a wire coil, producing an electric signal that can be recorded digitally. These seismometers are so sensitive that they can record ground movements of a millionth of a millimeter (only ten times the diameter of an atom)—movements that people can't feel. Typically, the instruments are placed in a vault on bedrock in sheltered areas, away from traffic and other urban noise (Fig. 8.8c). The entire configuration comprises a seismometer station.

An earthquake record produced by a seismometer is called a **seismogram** (Fig. 8.9a, b). At first glance, a typical seismogram looks like a messy squiggle of lines, but to a seismologist it contains a wealth of information. The horizontal axis represents time, and the vertical axis represents the amplitude (the size) of the seismic waves. The instant at which an earthquake wave appears at a seismometer station is the "arrival time" of the wave. The first squiggles on the record represent P-waves, because P-waves travel the fastest. Next come the S-waves, and finally the surface waves (R-waves and L-waves). Typically, the surface waves have the largest amplitude and arrive over a relatively long interval of time.

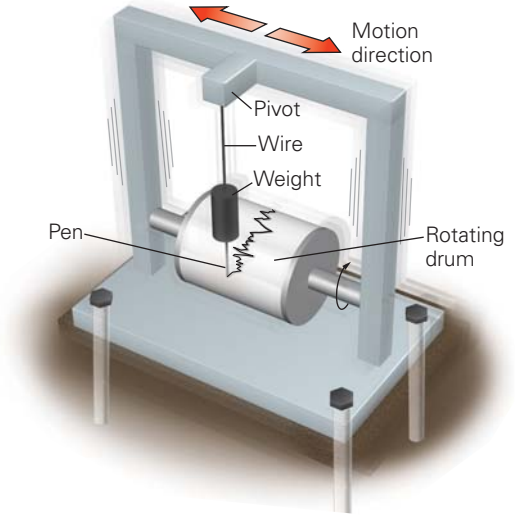
Finding the Epicenter

How do we find the location of an earthquake's epicenter? The key to this problem comes from measuring the *difference* between the time that the P-wave arrives and the time that the

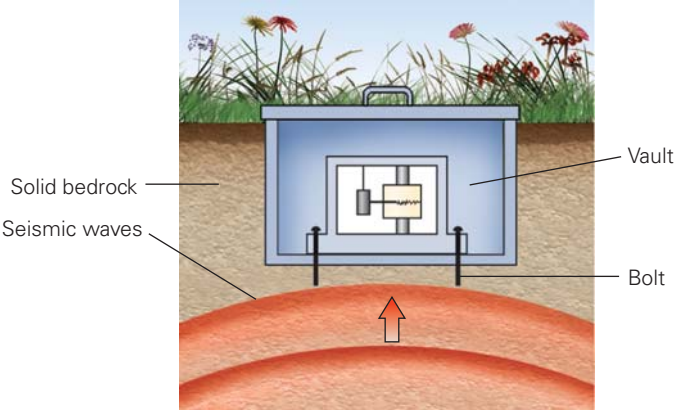
FIGURE 8.8 The basic operation of a seismometer.



(a) A vertical-motion seismometer records up-and-down ground motion.

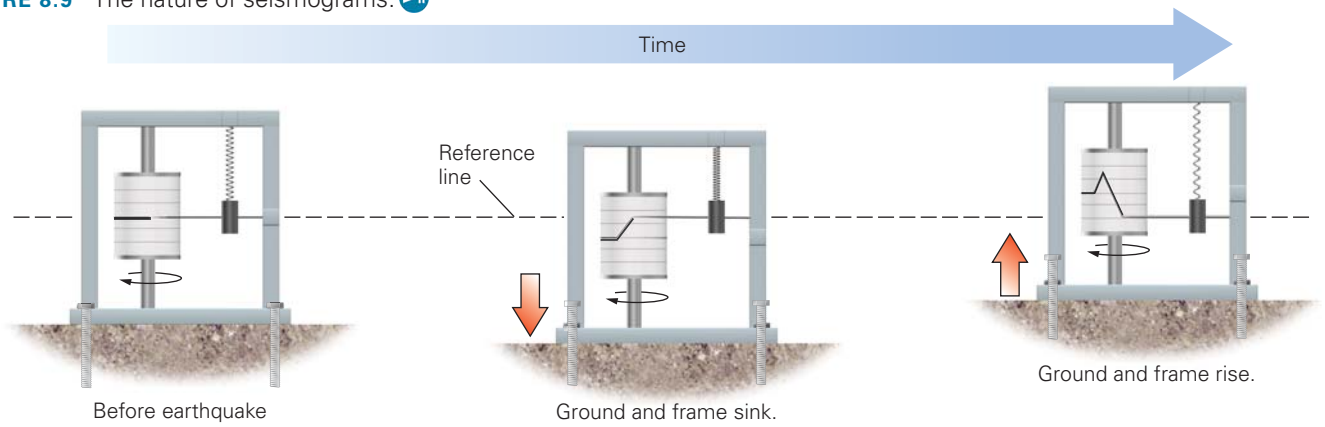


(b) A horizontal-motion seismometer records back-and-forth ground motion.

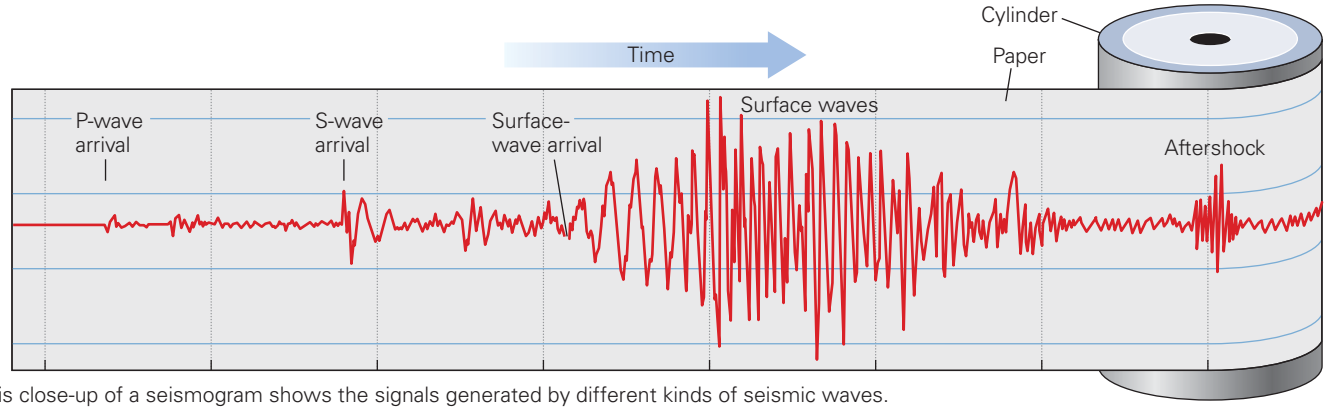


(c) Seismometers are bolted to bedrock in a protected shelter or vault.

FIGURE 8.9 The nature of seismograms.



(a) Before an earthquake, the pen traces a straight line. During an earthquake, the paper roll moves up and down while the pen stays in place.



(b) This close-up of a seismogram shows the signals generated by different kinds of seismic waves.

S-wave arrives at a seismometer station. P-waves and S-waves pass through the interior of the Earth at different velocities. The delay between P-wave and S-wave arrival times increases as the distance from the epicenter increases (Fig. 8.10a). To picture why, imagine a car race. If one car travels faster than another, the distance between them increases as the race proceeds.

We can represent the time delay between P- and S-waves on a graph whose horizontal axis indicates distance from the epicenter and whose vertical axis indicates time. A curve on the graph is called a **travel-time curve**—it shows how the time for an earthquake wave to move from its origin to a seismometer station increases as the distance between the epicenter and the seismometer station increases (Fig. 8.10b).

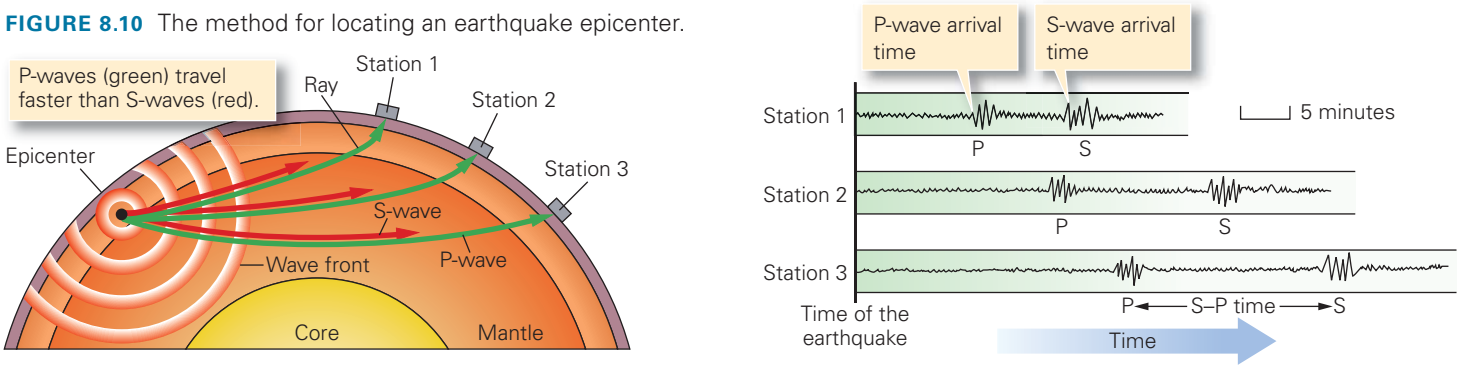
To use a graph of travel-time curves for determining the distance to an epicenter, start by measuring the time difference between the P- and S-waves on your seismogram; this is called the S − P (pronounced "S minus P") time. Then draw a line segment on a piece of tracing paper to represent this amount of time, at the scale used for the vertical axis of the graph. Orient the line segment parallel to the time axis and move it back and forth until one end lies on the P-wave curve and the other end lies on the S-wave curve (this gives the S − P time). Extend the line down to the horizontal axis, and simply read off the distance to the epicenter from the seismic station.

The analysis of one seismogram tells you only the distance between the epicenter and the seismometer station; it does not tell you in which direction from the station the epicenter lies. To determine the map position of the epicenter, we use a method called triangulation, which requires plotting the distance from the epicenter to *three* stations. For example, say you know that the epicenter lies 2,000 km from Station 1, 4,000 km from Station 2, and 6,000 km from Station 3. On a map, draw a circle around each station, such that the radius of the circle is the distance between the station and the epicenter, at the scale of the map. The epicenter lies at the intersection of the three circles, for this is the only point at which the epicenter has the appropriate measured distance from all three stations (Fig. 8.10c).

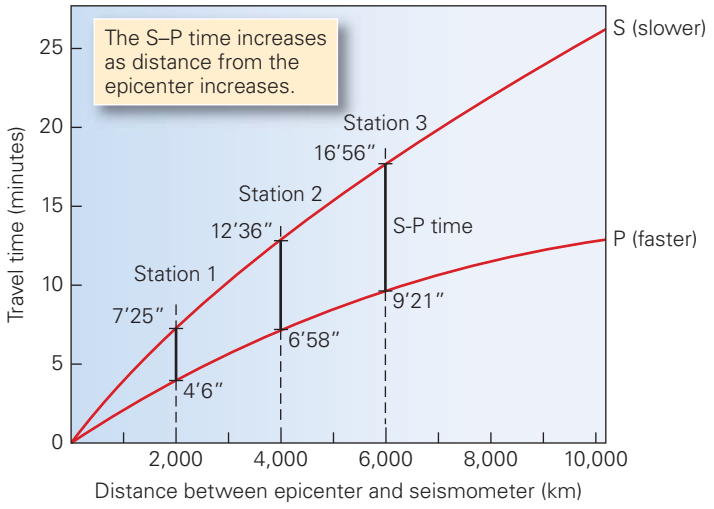
Take-Home Message

Seismometers measure earthquake vibrations. In a seismometer, a weight stays fixed due to inertia, while the frame moves with the ground during an earthquake. Measurements from three seismic stations allow seismologists to determine epicenter location.

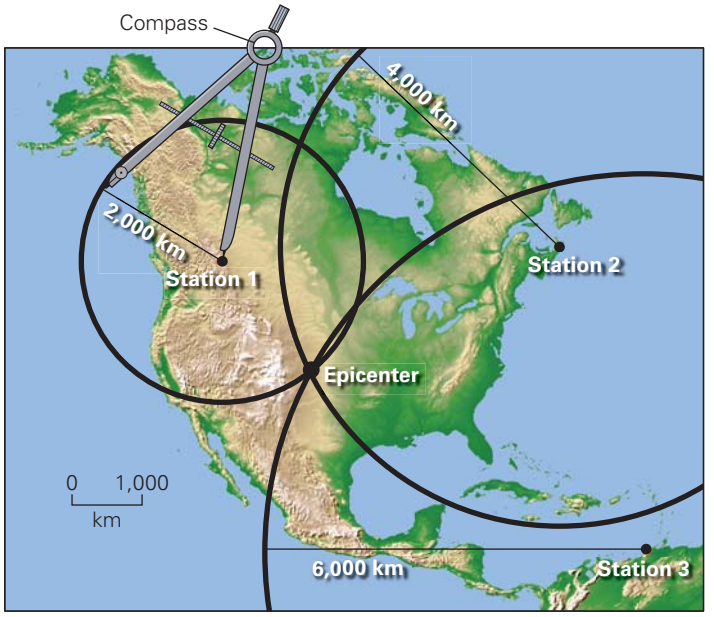
FIGURE 8.10 The method for locating an earthquake epicenter.



(a) Seismic waves travel at different velocities. The greater the distance between the epicenter and the seismometer station, the longer it takes for earthquake waves to arrive, and the greater the delay between the P-wave and S-wave arrival times.



(b) We can represent the different arrival times of P-waves and S-waves on a graph of travel-time curves.



(c) If an earthquake epicenter lies 2,000 km from Station 1, we draw a circle with a radius of 2,000 km around the station at the scale of the map. We repeat for the other two stations. The intersection is the epicenter.

8.5 Defining the "Size" of Earthquakes

Some earthquakes shake the ground violently, whereas others can barely be felt. Seismologists have developed two scales to define size in a uniform way, so that they can systematically describe and compare earthquakes. The first scale focuses on the severity of damage at a locality and is called the Mercalli Intensity scale. The second focuses on the amount of ground motion at a specific distance from the epicenter, as measured by a seismometer, and is called the magnitude scale.

Mercalli Intensity Scale

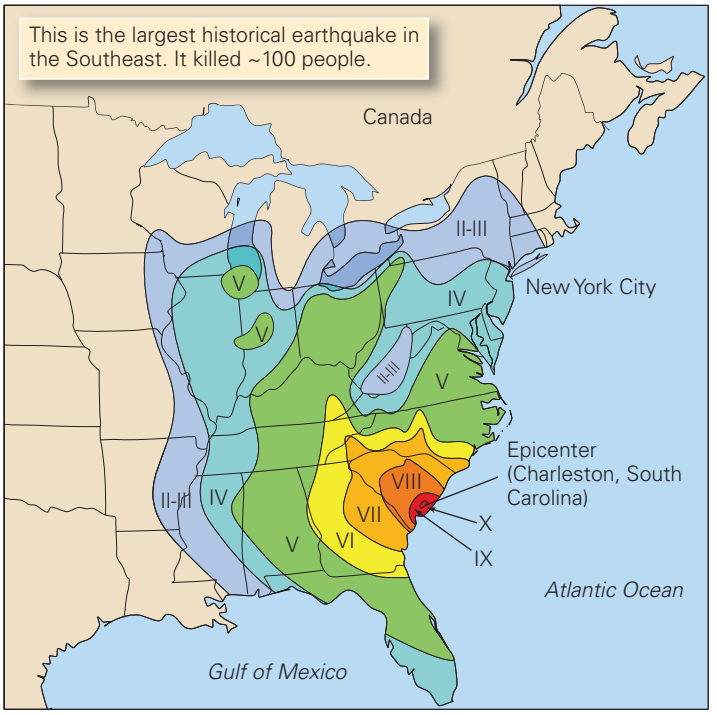
The **intensity** of an earthquake refers to the effect or consequence of an earthquake's ground shaking at a locality on the Earth's surface. In 1902, an Italian scientist named Giuseppe Mercalli devised a scale for defining intensity by systematically assessing the damage that the earthquake caused. A version of this scale, called the **Modified Mercalli Intensity scale (MMI)**, with roman numerals, continues to be used today (Table 8.1).

Note that the specification of earthquake intensity depends on a *subjective* assessment of damage, and of the perception of shaking, not on a direct measurement with an instrument. Also, the Mercalli intensity value *varies with location* for a given seismic event—we cannot assign a single Mercalli number to a given earthquake. Typically, the intensity is greater near the epicenter, and decreases progressively away from the epicenter. To illustrate how intensity varies over a region for a given earthquake, seismologists draw contour lines on a map, to delimit zones in which the earthquake had a given intensity (Fig. 8.11).

TABLE 8.1 Modified Mercalli Intensity Scale

MMI	Destructiveness (Perceptions of the Extent of Shaking and Damage)
I	Detected only by seismic instruments; causes no damage.
II	Felt by a few stationary people, especially in upper floors of buildings; suspended objects, such as lamps, may swing.
III	Felt indoors; standing automobiles sway on their suspensions; it seems as though a heavy truck is passing.
IV	Shaking awakens some sleepers; dishes and windows rattle.
V	Most people awaken; some dishes and windows break, unstable objects tip over; trees and poles sway.
VI	Shaking frightens some people; plaster walls crack, heavy furniture moves slightly, and a few chimneys crack, but overall little damage occurs.
VII	Most people are frightened and run outside; a lot of plaster cracks, windows break, some chimneys topple, and unstable furniture overturns; poorly built buildings sustain considerable damage.
VIII	Many chimneys and factory smokestacks topple; heavy furniture overturns; substantial buildings sustain some damage, and poorly built buildings suffer severe damage.
IX	Frame buildings separate from their foundations; most buildings sustain damage, and some buildings collapse; the ground cracks, underground pipes break, and rails bend; some landslides occur.
X	Most masonry structures and some well-built wooden structures are destroyed; the ground severely cracks in places; many landslides occur along steep slopes; some bridges collapse; some sediment liquifies; concrete dams may crack; facades on many buildings collapse; railways and roads suffer severe damage.
XI	Few masonry buildings remain standing; many bridges collapse; broad fissures form in the ground; most pipelines break; severe liquefaction of sediment occurs; some dams collapse; facades on most buildings collapse or are severely damaged.
XII	Earthquake waves cause visible undulations of the ground surface; objects are thrown up off the ground; there is complete destruction of buildings and bridges of all types.

FIGURE 8.11 This map shows Modified Mercalli Intensity contours for the 1886 Charleston, South Carolina, earthquake. Note that near the epicenter, ground shaking reached MMI of X, and in New York City, ground shaking reached MMI of II to III.



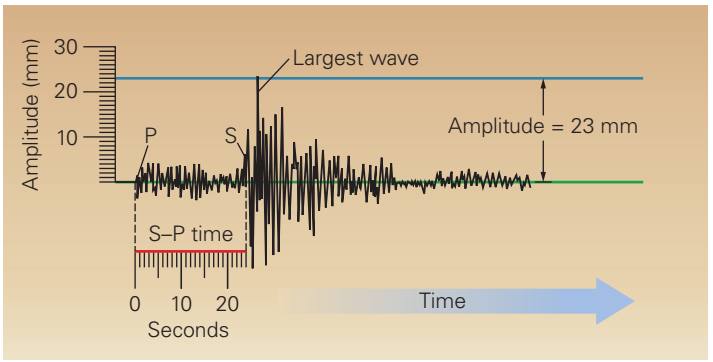
Earthquake Magnitude Scales

When you read a report of an earthquake disaster in the news, you will likely come across a phrase that reads something like, "An earthquake with a magnitude of 7.2 struck the city yesterday at noon." What does this mean? The **magnitude** of an earthquake is a number that represents the maximum amplitude of ground motion that would be measured by a seismometer placed at a specified, standard distance from the epicenter. By *amplitude of ground motion*, we mean the amount of up-and-down or back-and-forth motion of the ground. The larger the ground motion, the greater the deflection of a seismometer pen or needle as it traces out a seismogram. Since the magnitude is calculated to represent motion at a standard distance from the epicenter, there is one magnitude for an earthquake—a magnitude value does *not* depend on this distance.

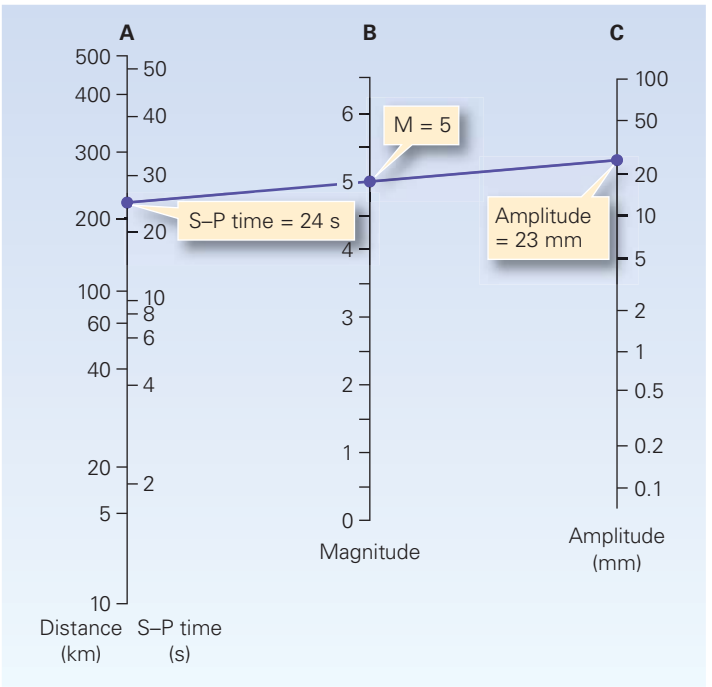
The American seismologist Charles Richter developed a method for defining and measuring earthquake magnitude in 1935. The scale he proposed came to be known as the **Richter scale** and is based on the maximum amplitude of motion that would be recorded at a station about 100 km from the epicenter. Since there's not necessarily a seismometer exactly at this distance, Richter developed a simple chart to adjust for distance of the station from the epicenter (**Fig. 8.12a, b**). Richter's scale became so widely used that news reports often include wording such as, "The earthquake registered a 7.2 on the Richter scale."

These days, seismologists actually use several different magnitude scales, not just the Richter scale, because the original Richter scale works well only for shallow earthquakes

FIGURE 8.12 Using the Richter magnitude scale.



(a) To calculate the Richter magnitude from a seismometer, first measure the S–P (S minus P) time, to determine the distance to the epicenter. Then measure the amplitude of the largest wave.



(b) Draw a line from the point on Column A representing the S–P time or the distance to the epicenter to the point on Column C representing the wave amplitude. Read the Richter magnitude off Column B.

that are close to the seismometer station. Because of the distance limitation, a number on the original Richter scale is now also called a local magnitude (M_L). The **moment magnitude scale** (M_W) provides the most accurate representation of an earthquake's size. To calculate the moment magnitude, seismologists measure the amplitude of several different seismic waves, determine the dimensions of the slipped area on the fault, and estimate the displacement that occurred. The largest recorded earthquake in history, the great 1960 Chilean quake, registered as a 9.5 on the M_W scale and the catastrophic 2011 Tohoku earthquake had a magnitude of M_W 9.0.

All magnitude scales are logarithmic, meaning that an increase of one unit of magnitude represents a tenfold increase in the maximum amplitude of ground motion. Thus, a magnitude 8 earthquake results in ground motion that is 10 times greater than that of a magnitude 7 earthquake, and 1,000 times greater than that of a magnitude 5 earthquake. To make discussion easier, seismologists use familiar adjectives to describe the size of an earthquake, as listed in **Table 8.2**.

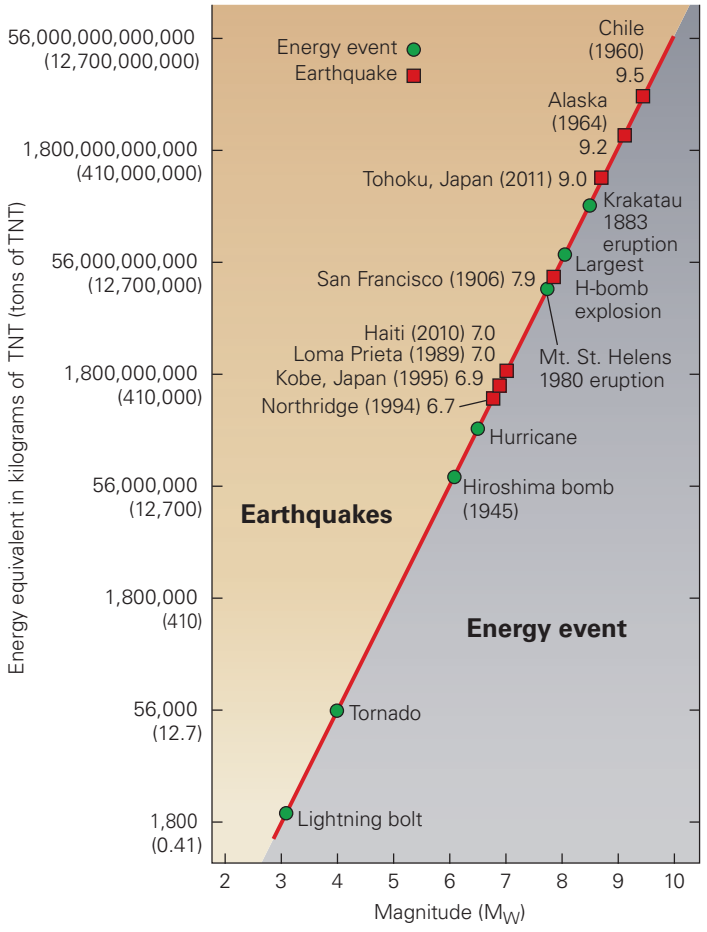
Energy Release by Earthquakes

As we pointed out earlier, earthquakes release energy. Seismologists can calculate the energy release from equations that relate moment magnitude to energy. Not all versions of this calculation yield the same result, so energy estimates must be taken as an approximation. According to some researchers, a magnitude 6 earthquake releases about as much energy as the atomic bomb that was dropped on Hiroshima in 1945. The 1964 Alaska Good Friday earthquake, during which up to 15 m of slip occurred on a thrust fault, near Anchorage, released significantly more energy than the largest hydrogen bomb ever detonated. Notably, an increase in magnitude by one integer represents approximately a 32-fold increase in energy. Thus, a magnitude 8 earthquake releases about 1 million times more energy than a magnitude 4 earthquake (**Fig. 8.13**). In fact, a single magnitude 8.9 earthquake releases as much energy as the entire *average* global annual release of seismic energy coming from all other earthquakes combined! Fortunately, such large earthquakes occur much less frequently than small earthquakes. There are about 100,000 magnitude 3 earthquakes every year, but a magnitude 8 earthquake happens only about once or twice a year.

TABLE 8.2 Adjectives for Describing Earthquakes

Adjective	Magnitude	Approximate maximum intensity at epicenter	Effects
Great	> 8.0	X to XII	Major to total destruction
Major	7.0 to 7.9	IX to X	Great damage
Strong	6.0 to 6.9	VII to VIII	Moderate to serious damage
Moderate	5.0 to 5.9	VI to VII	Slight to moderate damage
Light	4.0 to 4.9	IV to V	Felt by most; slight damage
Minor	< 3.9	III or smaller	Felt by some; hardly any damage

FIGURE 8.13 Energy released by earthquakes increases dramatically with magnitude.



Take-Home Message

We specify earthquake size by the intensity (representing damage caused) or magnitude (measurement of ground motion amplitude). An increase of one magnitude number represents a 10× increase in shaking, and a 32× increase in energy release.

8.6 Where and Why Do Earthquakes Occur?

Earthquakes do not take place everywhere on the globe. By plotting the distribution of earthquake epicenters on a map, seismologists find that most, but not all, earthquakes occur in fairly narrow **seismic belts**, or seismic zones. Most seismic belts correspond to plate boundaries, and earthquakes within these belts are called *plate-boundary* earthquakes. Earthquakes that occur away from plate boundaries are called *intraplate* earthquakes (Fig. 8.14). Eighty percent of the earthquake energy released on Earth comes from the plate-boundary earthquakes in the belts surrounding the Pacific Ocean.

Did you ever wonder . . .
will an earthquake happen near where you live?

FIGURE 8.14 A map of epicenters emphasizes that most earthquakes occur in distinct belts along plate boundaries.

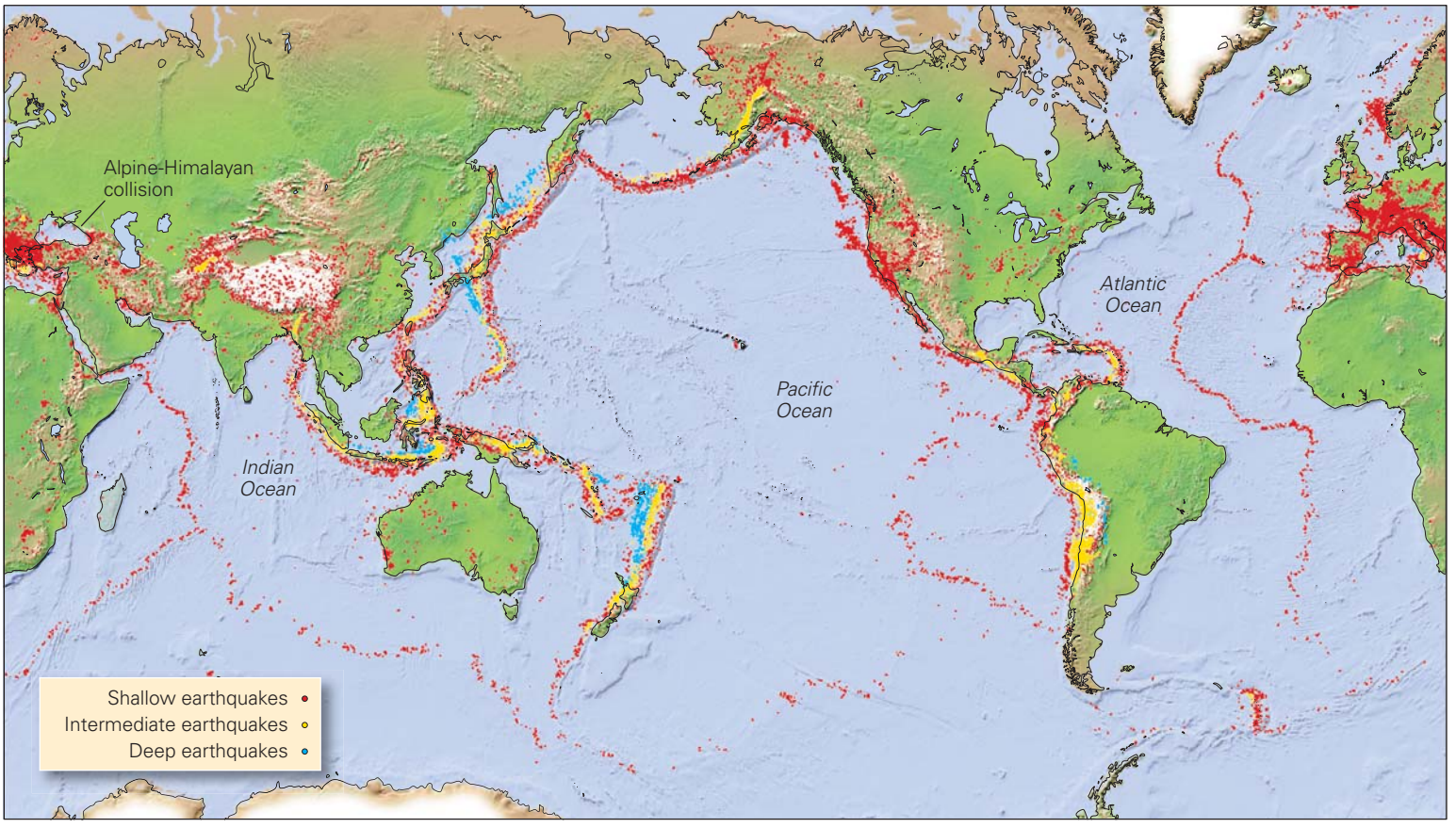
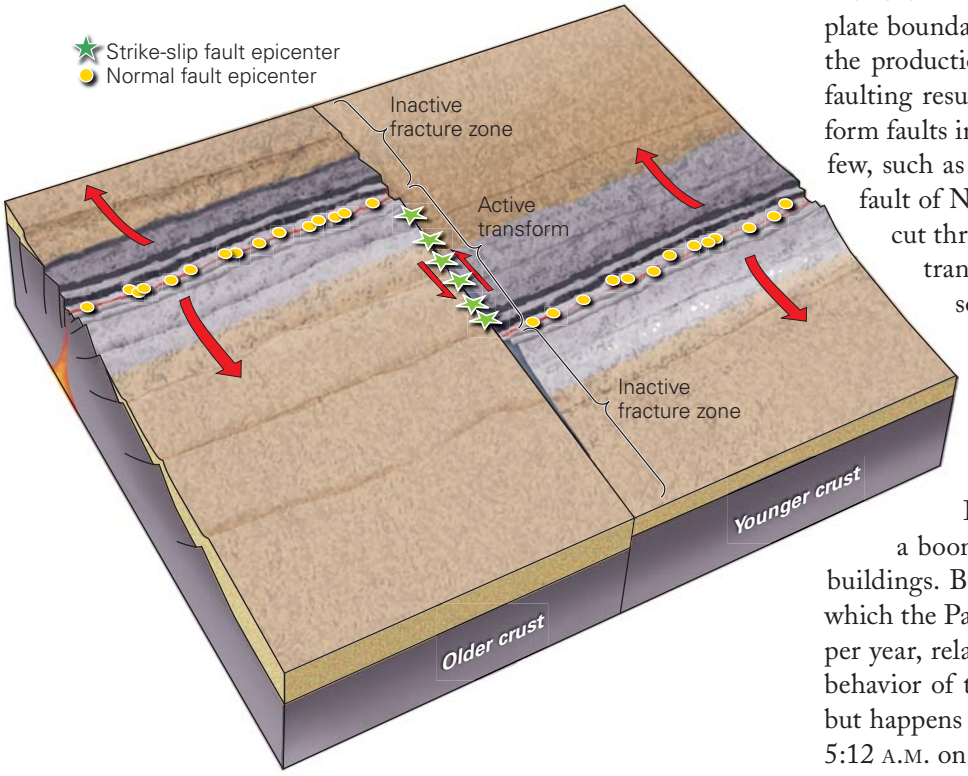


FIGURE 8.15 The distribution of earthquakes at a mid-ocean ridge. Note that normal faults occur along the ridge axis, and strike-slip faults occur along active transform faults. Earthquakes don't take place along inactive fracture zones.



Earthquakes do not occur at random depths in the Earth. Seismologists distinguish three classes of earthquakes based on focus depth: shallow-focus earthquakes occur in the top 60 km of the Earth, intermediate-focus earthquakes take place between 60 and 300 km, and deep-focus earthquakes occur down to a depth of about 660 km. Earthquakes cannot happen still deeper in the Earth, because rock at great depth cannot rupture or change in a manner that produces shock waves. In this section, we look at the characteristics of earthquakes in various geologic settings and learn why earthquakes take place where they do.

Plate-Boundary Earthquakes

As we've noted, the majority of earthquakes happen at faults along plate boundaries, for the relative motion between plates causes slip on faults. We find different kinds of faulting at different types of plate boundaries.

Divergent plate-boundary seismicity. At divergent plate boundaries (mid-ocean ridges), two oceanic plates form and move apart. Divergent boundaries are broken into spreading segments linked by transform faults. Therefore, two kinds of faults develop at divergent boundaries. Along spreading segments, stretching generates normal faults, whereas along transform faults strike-slip displacement occurs (**Fig. 8.15**). Earthquakes along mid-ocean ridges take place at depths of less than 10 km, and thus are shallow-focus earthquakes.

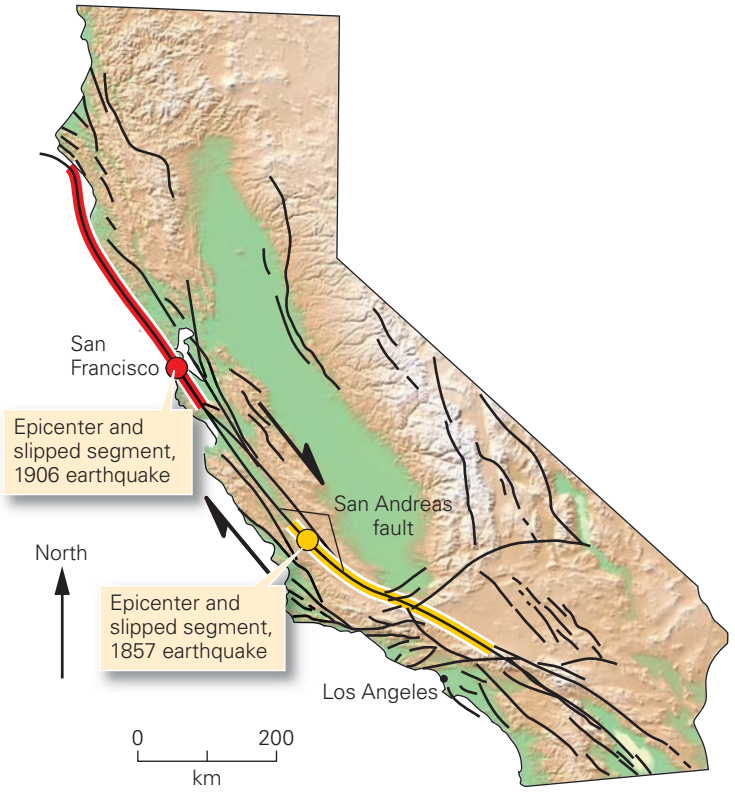
Transform plate-boundary seismicity. At transform plate boundaries, where one plate slides past another without the production or consumption of oceanic lithosphere, most faulting results in strike-slip motion. The majority of transform faults in the world link segments of oceanic ridges, but a few, such as the San Andreas fault of California, the Alpine fault of New Zealand, and the Anatolian faults in Turkey, cut through continental lithosphere or volcanic arcs. All transform-fault earthquakes have a shallow focus, so the larger ones on land can cause disaster. The 2010 earthquake in Haiti is a tragic example of such an earthquake (**Box 8.1**).

As another example of a transform-fault earthquake, consider the slip of the San Andreas fault near San Francisco in 1906 (**Fig. 8.16a**). In the wake of the gold rush, San Francisco was a booming city with broad streets and numerous large buildings. But it was built on the transform boundary along which the Pacific Plate moves north at an average rate of 6 cm per year, relative to North America. Because of the stick-slip behavior of the fault, this movement doesn't occur smoothly but happens in jerks, each of which causes an earthquake. At 5:12 A.M. on April 18, the fault near San Francisco slipped by as much as 7 m, and earthquake waves slammed into the city. Witnesses watched in horror as the street undulated like ocean waves. Buildings swayed and banged together, laundry lines stretched and snapped, church bells rang, and then towers, facades, and houses toppled. Judging from the damage, seismologists estimate that the largest shock would have registered a seismic moment magnitude of 7.9. Most building collapse took place downtown. Fire followed soon after, consuming huge areas of the city, for most buildings were made of wood (**Fig. 8.16b**). In the end, about five hundred people died, and a quarter of a million were left homeless.

The San Francisco earthquake has not been the only one to strike along the San Andreas and nearby related faults. Over a dozen major earthquakes have happened on these faults during the past two centuries, including the 1857 magnitude 7.7 earthquake just east of Los Angeles, and the 1989 M_W 7.1 Loma Prieta earthquake, which occurred 100 km south of San Francisco but nevertheless shut down a World Series game and caused the collapse of a double-decker freeway (**Fig. 8.16c**).

Convergent plate-boundary seismicity. Convergent plate boundaries are complicated regions at which several different kinds of earthquakes take place. Shallow-focus earthquakes occur in both the subducting plate and the overriding plate. Specifically, as the downgoing plate begins to subduct,

FIGURE 8.16 The San Andreas fault system is a continental transform that accommodates motion between the Pacific and North American plates.



(a) The San Andreas fault system in California. Note that the system includes many faults in a 100-km-wide band.



(b) A street in San Francisco after the 1906 earthquake. Huge fires swept through the city.



(c) The 1989 Loma Prieta earthquake near San Francisco caused a double-decker freeway to collapse, as support columns gave way.

it scrapes along the base of the overriding plate. Large thrust faults develop along the contact between the downgoing and overriding plates, and shear on these faults can produce disastrous, shallow earthquakes. In some cases, the push applied by the downgoing plate compresses the overriding plate and triggers shallow earthquakes in the overriding plate.

In contrast to other types of plate boundaries, convergent plate boundaries also host intermediate-focus and deep-focus earthquakes. These occur in the downgoing slab as it sinks into the mantle, defining the sloping band of seismicity called a **Wadati-Benioff zone**, after the seismologists who first recognized it (**Fig. 8.17a**). These earthquakes happen partly in response to stresses caused by shear between the downgoing lithosphere plate and surrounding asthenosphere, and partly by the pull of the sinking deeper part of the plate on the shallower part.

Why can intermediate- and deep-focus earthquakes of a Wadati-Benioff zone take place? Shouldn't the rock of a subducted plate at these depths be too warm and soft to break seismically? Seismologists have determined that rock is such a good insulator that the interior of a plate actually remains cool enough to break seismically, even down to a depth of about 300 km. And they found that at the extreme pressures developed in deeply subducted lithosphere, certain minerals can suddenly collapse to form new, denser minerals, a process that could generate an earthquake.

Earthquakes in southern Alaska, eastern Japan, the western coast of South America, the coast of Oregon and Washington, and along island arcs in the western Pacific serve as examples of convergent-boundary earthquakes. Some of these earthquakes are large, and occur near populated areas, so they can be devastating.

BOX 8.1 CONSIDER THIS . . .

The 2010 Haiti Catastrophe

The history of Haiti changed forever on the sunny afternoon of January 12, 2010. At 4:53 P.M., a 70-km-long segment of a large fault suddenly slipped by an average amount of 1.8 m and, locally, by as much as 4 m. The motion began at a focus only 25 km west-southwest of Port-au-Prince, and 13 km beneath the ground surface, so the shock waves of the resulting magnitude M_W 7 earthquake reached the capital city in a matter of seconds. They caused the ground to lurch violently back and forth, side to side, and up and down, over a duration of 35 seconds. The event released as much energy as a 32-megaton nuclear weapon.

Ground shaking during the quake caused insufficiently reinforced structures to crack and crumble (**Fig. Bx8.1a**). Unable to hold up the shifting weight of the building above, columns gave way, bringing floors down into gruesome pancake-like stacks. Similarly, brick or block walls broke apart, roads buckled, and hill slopes slumped (**Fig. Bx8.1b**). And beneath the harbor, sediment liquified, causing the wharfs to sink into the sea. When the shaking, which reached an intensity of IX on the Mercalli scale (**Fig. Bx8.1c**), finally stopped, most of Port-au-Prince, a city of 2 million in a country of 9 million, had collapsed. As a dense cloud of white dust slowly rose over the rubble, survivors began the frantic scramble to dig out victims, a task made more hazardous by aftershocks, of which there were over 50 with magnitudes between 4.5 and 6.1—the renewed shaking caused still-standing, but weakened walls to collapse on rescuers. Some estimates place the death toll at 230,000, about 2.5% of the country's population.

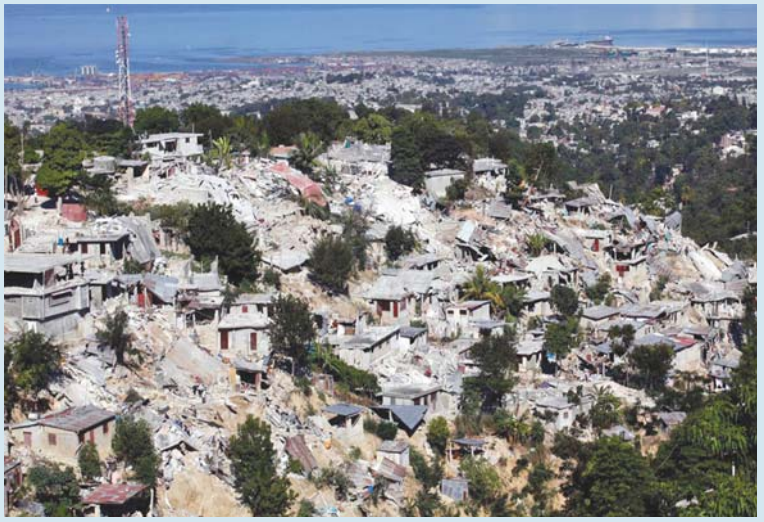
Was the earthquake a surprise? The answer depends on what is meant by surprise. Haiti sits astride the transform plate boundary along which the North American Plate moves westward at about 2 cm per year, relative to the Caribbean Plate. So earthquakes in Haiti are inevitable. The last major earthquakes on this plate boundary happened about 240 years ago, so stress has been building for quite some time.

The impact of an earthquake on society depends not only on its size but also on the nature of the substrate, on the steepness of the slopes, on construction practices, and on the quality of emergency services in the affected area. Much of Port-au-Prince was built on a basin of weak sediment, which amplified ground movements. In addition, many of the city's neighborhoods perch on steep slopes, which slumped downhill during the quake. Sadly, buildings in Haiti were not designed to withstand ground vibration, and local emergency services were overwhelmed.

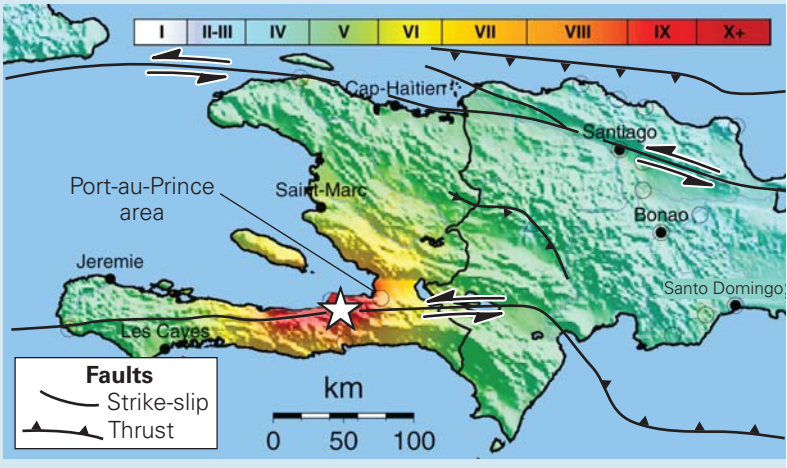
FIGURE Bx8.1 The disastrous January 2010 earthquake in Haiti.



(a) Survivors salvage what they can and try to carry on in Port-au-Prince, the capital of Haiti, after the devastating earthquake of January 2010.

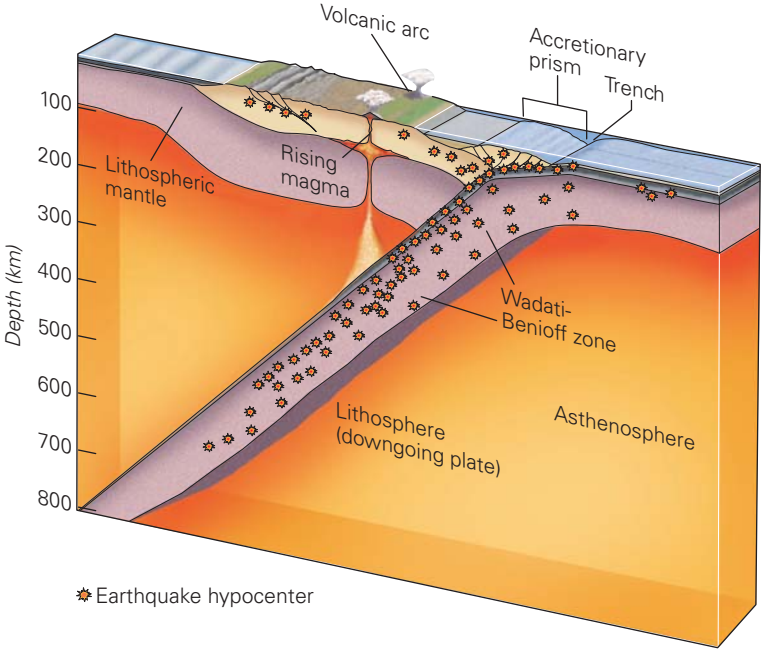


(b) Ground shaking during the 2010 Haiti earthquake caused most of the houses in this hillside neighborhood to collapse.

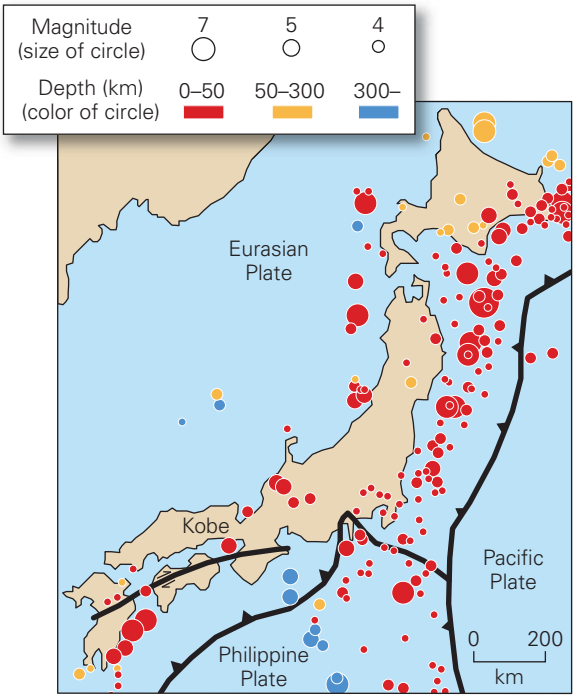


(c) The Mercalli intensity of shaking in Haiti. The star marks the epicenter.

FIGURE 8.17 An example of a convergent-boundary earthquake.



(a) At a convergent plate boundary, earthquakes occur along the contact between plates, as well as in the downgoing plate and overriding plate.



(b) Map of earthquake epicenters and subduction zones in and near Japan.



(c) A collapsed building after the Kobe earthquake in Japan.

Notable examples include the 1960 M_W 9.5 earthquake in Chile, the largest earthquake on record; the 1964 M_W 9.2 Good Friday earthquake near Anchorage, Alaska; the 1995 M_W 6.9 earthquake in Kobe, Japan, which devastated the city (**Fig. 8.17b, c**); the 2004 M_W 9.3 Sumatra earthquake, which triggered the giant Indian Ocean waves that killed 230,000 people; the 2010 M_W 8.8 Chilean earthquake; and the 2011 M_W 9.0 Tohoku earthquake, which also triggered a tsunami.

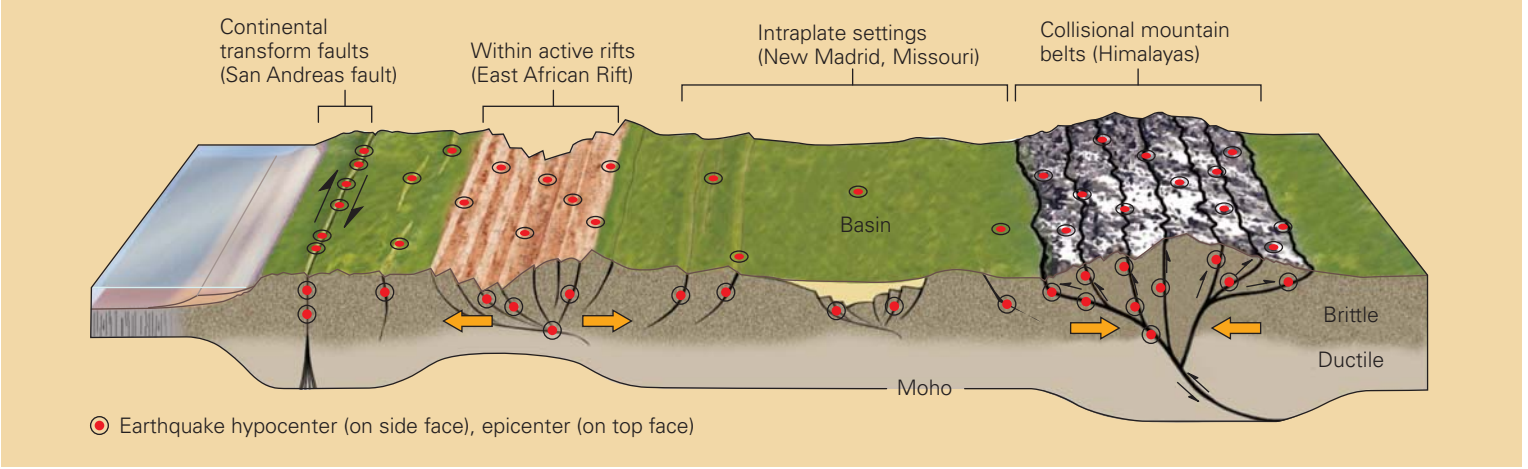
Earthquakes due to Rifting and Collision

Continental rifts. The stretching of crust at continental rifts generates normal faults (**Fig. 8.18**). Active rifts today include the East African Rift, the Basin and Range Province (mostly in Nevada, Utah, and Arizona), and the Rio Grande Rift (in New Mexico). In all these places, shallow earthquakes occur, similar in nature to the earthquakes at mid-ocean ridges. But in contrast to mid-ocean ridges, these seismic zones can be located under populated areas, and thus cause major damage.

Collision zones. Two continents collide when the oceanic lithosphere that once separated them has been completely subducted. Such collisions produce great mountain ranges such as the Alpine-Himalayan chain and caused the catastrophic 2005 earthquake in Pakistan. Though a variety of earthquakes happen in collision zones, the most common result from movement on thrust faults (see Fig. 8.18).

The magnitude 9.0 earthquake that occurred in Lisbon, Portugal, on All Saint's Day, November 1, 1755, serves as an example of a collision-related thrust event. The event happened when stresses arising from the northward push of Africa against Europe caused a thrust fault beneath the Atlantic Ocean floor west of Lisbon to slip. The resulting ground shaking toppled 85% of the city's buildings. Fires set by overturned stoves then consumed much of the wreckage. Uplift of the sea floor by the thrust movement also produced a tsunami that inundated the coast and washed away Lisbon's harbor.

FIGURE 8.18 The tectonic settings in which earthquakes occur in continental lithosphere. Subduction-related earthquakes in continental crust are not shown.



Not only did the catastrophe destroy irreplaceable structures (including the library that housed all the records of Portuguese exploration) and countless Renaissance artworks, but it led the intelligentsia of that time to question long-held beliefs about philosophy. Influential works by Voltaire (1694–1778) address the philosophical implications of the event.

Intraplate Earthquakes

Some earthquakes occur in the interiors of plates and are not associated with plate boundaries, active rifts, or collision zones (see Fig. 8.15). These **intraplate earthquakes** account for only about 5% of the earthquake energy released in a year. Almost all have a shallow focus. What causes intraplate earthquakes? Most seismologists favor the idea that force applied to the boundary of a plate can cause the interior of the plate to break suddenly at weak, preexisting fault zones, some of which may have formed initially during the Precambrian.

In Europe, a number of intraplate earthquakes have been recorded. For example, an earthquake with a magnitude of 4.8 hit central England, near Birmingham, in 2002. In North America, intraplate earthquakes occur in the vicinities of New Madrid, Missouri; Charleston, South Carolina; eastern Tennessee; and Montreal. A magnitude 7.3 earthquake occurred near Charleston in 1886, ringing church bells up and down the coast and vibrating buildings as far away as Chicago. In Charleston itself, over 90% of the buildings were damaged, and sixty people died. In 2011, a magnitude 5.9 earthquake struck central Virginia, abruptly reminding residents of the eastern United States that the region is not immune to seismicity. The tremor was felt from the Carolinas to New England.

The largest intraplate earthquakes to affect the United States happened in the early 19th century, near New Madrid, which lies near the Mississippi River in southernmost Missouri. During the winter of 1811–12, three magnitude 7 to 7.4 earthquakes struck the region. Displacement of the ground surface temporarily reversed the flow of the Mississippi River and toppled cabins (**Fig. 8.19a**). The earthquakes resulted from slip on faults that underlie the Mississippi Valley (**Fig. 8.19b**). Both St. Louis, Missouri, and Memphis, Tennessee, lie close to the epicenter, so major earthquakes in the area now could be disastrous.

Take-Home Message

Most, but not all, earthquakes happen along plate boundaries. Events also occur in rifts and collision zones, and along weak faults within plate interiors. Most catastrophic earthquakes happen at convergent boundaries and along continental transforms.

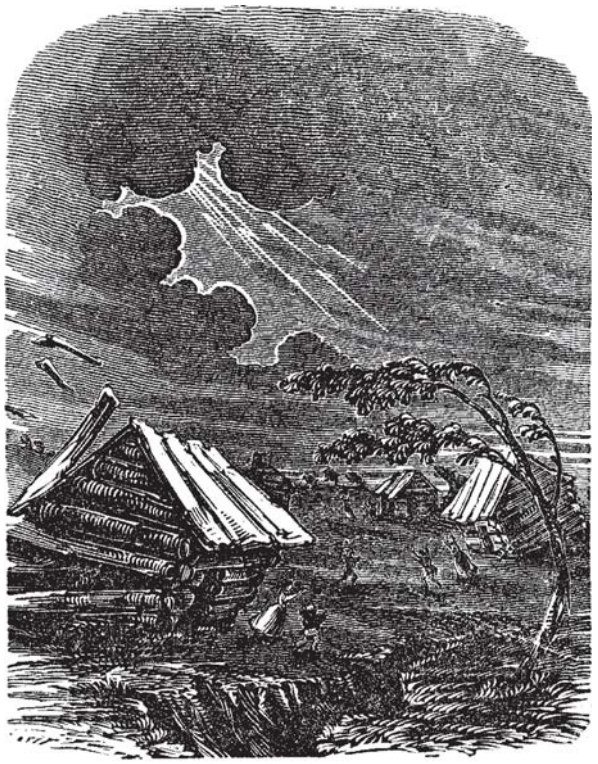
8.7 How Do Earthquakes Cause Damage?

An area ravaged by a major earthquake is a heartbreaking sight. The terror and sorrow etched on the faces of survivors mirror the inconceivable destruction. This destruction comes as a result of many processes.

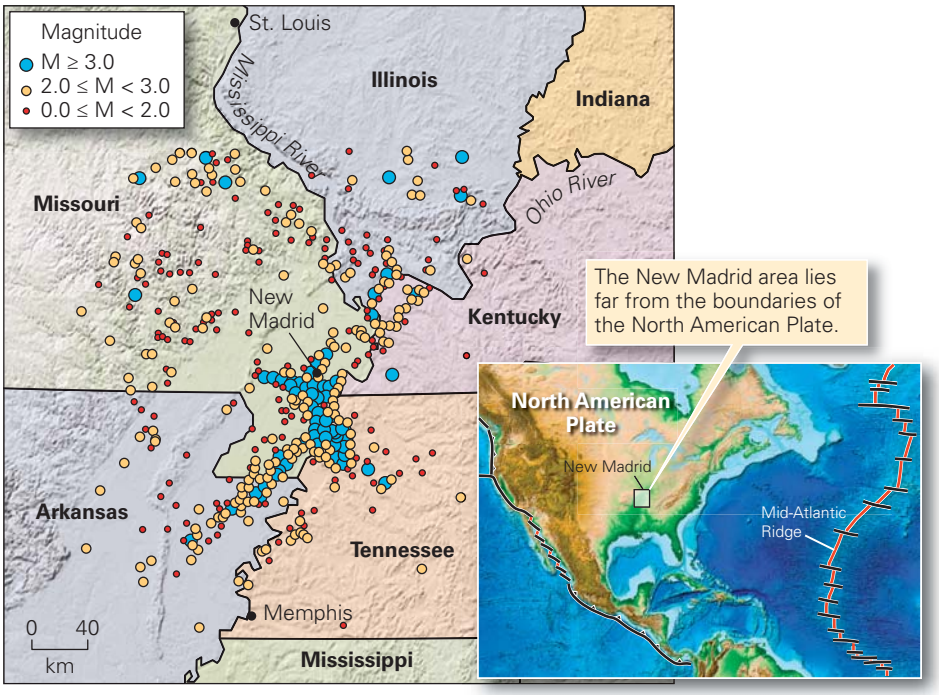
Ground Shaking and Displacement

An earthquake starts suddenly and may last from a few seconds to a few minutes. Different kinds of earthquake waves

FIGURE 8.19 New Madrid, Missouri, is an example of intraplate seismic activity.



(a) The earthquakes of 1811–1812 destroyed cabins and disrupted the Mississippi River.



(b) The epicenters of recent small earthquakes in the New Madrid area, as recorded by modern seismic instruments. The region remains active.

cause different kinds of ground motion (**Fig. 8.20**). The nature and severity of the shaking at a given location depend on four factors: (1) the magnitude of the earthquake, because larger-magnitude events release more energy; (2) the distance from the focus, because earthquake energy decreases as waves pass through the Earth; (3) the nature of the substrate at the location (that is, the character and thickness of different materials beneath the ground surface) because earthquake waves tend to be amplified in weaker substrate; and (4) the "frequency" of the earthquake waves (where frequency equals the number of waves that pass a point in a specified interval of time).

Did you ever wonder . . .
how long does an earthquake last?

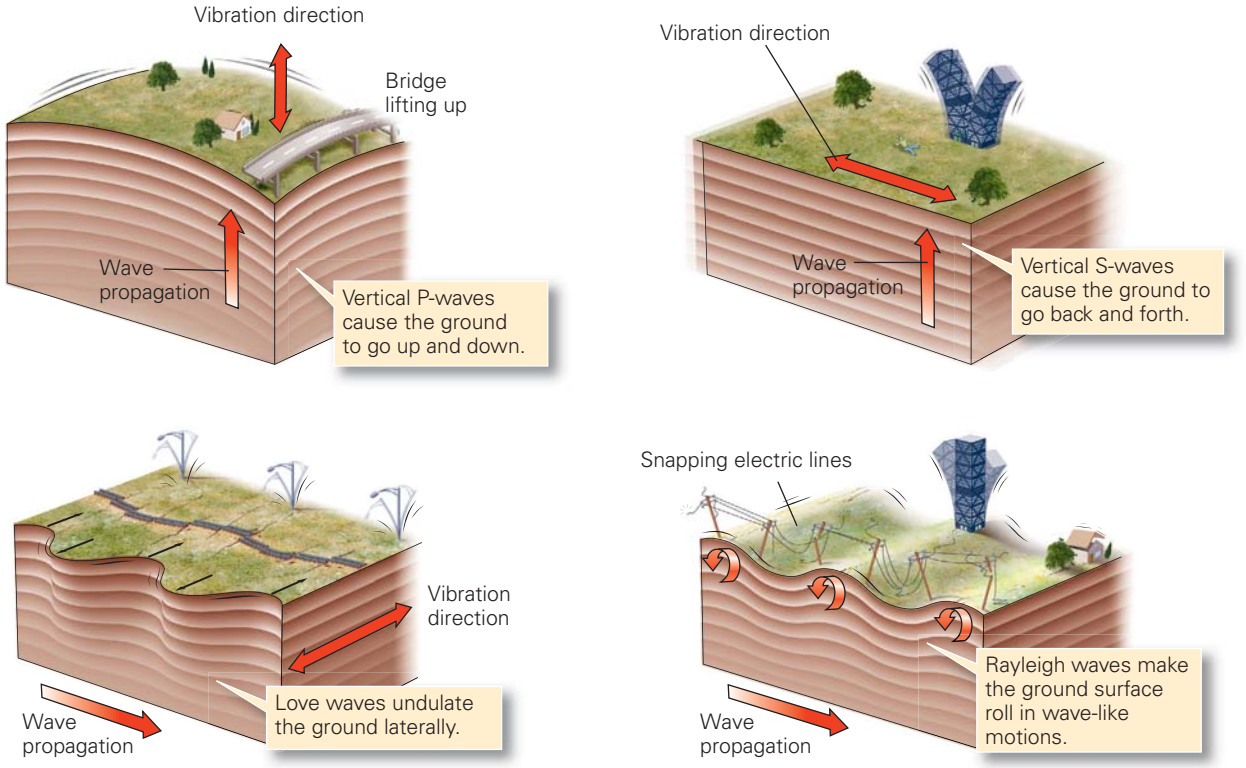
If you're out in an open field during an earthquake, ground motion alone won't kill you—you may be knocked off your feet and bounced around a bit, but your body is too flexible to break. Buildings and bridges aren't so lucky (**Fig. 8.21a–d**). When earthquake waves pass, they sway, twist back and forth, or lurch up and down, depending on the type of wave motion. As a result, connectors between the frame and facade of a building may separate, so the facade crashes to the ground. The flexing of walls shatters windows and makes roofs collapse. Floors or bridge decks may rise up and slam down on the columns that support them, thereby crushing the columns. Some buildings collapse with their floors piling on top of one another like pancakes in a stack, some crumble into fragments, and some simply tip over. The majority of earthquake-related deaths and injuries happen when people are hit by debris or are crushed beneath falling walls or roofs. Aftershocks worsen the problem, because they may topple already weakened buildings, trapping rescuers. During earthquakes, roads, rail lines, and pipelines may also buckle and rupture. If a building, fence, road, pipeline, or rail line straddles a fault, slip on the fault can crack the structure and separate it into two pieces.

Landslides

The shaking of an earthquake can cause ground on steep slopes or ground underlain by weak sediment to give way. This movement results in a landslide, the tumbling and flow of soil and rock downslope (see Chapter 13). Earthquake-triggered landslides occur commonly along the coast of California where expensive homes perch on steep cliffs looking out over

Did you ever wonder . . .
will California fall into the sea?

FIGURE 8.20 Types of ground motion during earthquakes. The ground can shake in many ways at once, causing surface structures to move.



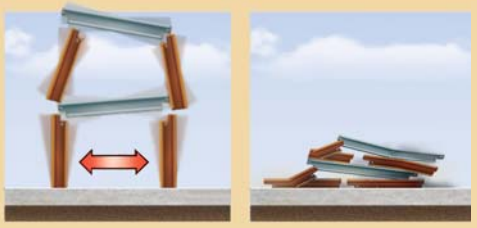
the Pacific. When the cliffs collapse, the homes may tumble to the beach below (**Fig. 8.22a, b**). Such events lead to the misperception that "California will someday fall into the sea." Although small portions of the coastline do collapse, the state as a whole remains firmly attached to the continent, despite what Hollywood scriptwriters say.

Sediment Liquefaction

In 1964, an M_W 7.5 earthquake struck Niigata, Japan. A portion of the city had been built on land underlain by wet sand. During the ground shaking, foundations of over 15,000 buildings sank into their substrate, causing walls and roofs to crack. Several four-story-high buildings in a newly built apartment complex tipped over (**Fig. 8.22c**). The same year, on Good Friday, an M_W 9.2 earthquake devastated southern Alaska. In the Turnagain Heights neighborhood of Anchorage, the event led to catastrophe. The neighborhood was built on a small terrace of uplifted sediment. The edge of the terrace was a 20-m-high escarpment that dropped down to Cook Inlet, a bay of the Pacific Ocean. As the ground shaking began, a layer of wet clay beneath the development turned into mud, and when this happened, the overlying layers of sediment, along with the houses built on top of them, slid seaward. In the process, the layers broke into separate blocks that tilted, turning the landscape into a chaotic jumble, and resulting in the destruction of the neighborhood (**Fig. 8.22d**). In 2011, an earthquake in Christchurch, New Zealand, caused sand to erupt and produce small, cone-shaped mounds on the ground surface (**Fig. 8.23a**). The transfer of sand from underground onto the surface led to formation of depressions large enough to swallow cars (**Fig. 8.23b**).

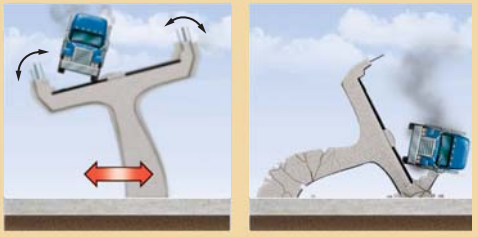
All of these examples are manifestations of a phenomenon called **sediment liquefaction**. During liquefaction, pressure in the water filling the pores between grains in wet sand push the grains apart so that they become surrounded by water and no longer rest against each other. In wet clay, shaking breaks the weak electrostatic charges that hold clay flakes together, so what had been a gel-like, stable mass becomes slippery mud. As the material above the liquefied sediment settles downward, pressure can squeeze the sand upward and out onto the ground surface. The resulting cone-shaped mounds are variously known as sand volcanoes, sand boils, or sand blows. The settling of sedimentary layers down into a liquefied layer can also disrupt bedding and can lead to formation of open fissures of the land surface (**Fig. 8.23c**).

FIGURE 8.21 Examples of earthquake damage due to vibration.



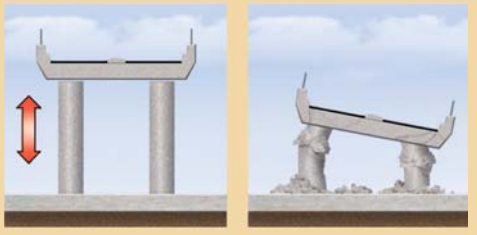
(a) During a 1999 earthquake in Turkey, concrete buildings collapsed when supports gave way, and floors piled on each other like pancakes.



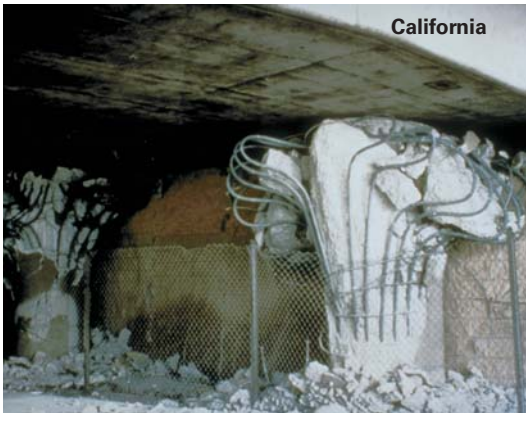


(b) An elevated bridge tipped over during the 1995 Kobe, Japan, earthquake.





(c) Concrete bridge supports were crushed during the 1994 Northridge earthquake when the overlying bridge bounced up and slammed back down.





(d) A neighborhood of masonry buildings in Armenia collapsed during a 1999 earthquake because the walls broke apart.



Fire

The shaking during an earthquake can make lamps, stoves, or candles with open flames tip over, and it may break wires or topple power lines, generating sparks. As a consequence, areas already turned to rubble, and even areas not so badly damaged may be consumed by fire. Ruptured gas pipelines and oil tanks feed the flames, sending columns of fire erupting skyward (**Fig. 8.24**). Firefighters might not even be able to reach the fires, because the doors to the firehouse won't open or rubble blocks the streets. Moreover, firefighters may find themselves without water, for ground shaking and landslides damage water lines.

Once a fire starts to spread, it can become an unstoppable inferno. Most of the destruction of the 1906 San Francisco earthquake, in fact, resulted from fire. For three days, the blaze spread through the city until firefighters contained it by blasting a firebreak. By then, 500 blocks of structures had turned to ash, causing 20 times as much financial loss as the shaking itself. When a large earthquake hit Tokyo in 1923, fires set by cooking stoves spread quickly through the wood-and-paper buildings, creating an inferno—a "firestorm"—that heated the air above the city. As hot air rose, cool air rushed in, creating wind gusts of over 100 mph, which stoked the blaze and incinerated 120,000 people.

Tsunamis

The azure waters and palm-fringed islands of the Indian Ocean's east coast hide one of the most seismically active plate

FIGURE 8.22 Examples of earthquake damage due to slumping and liquefaction.



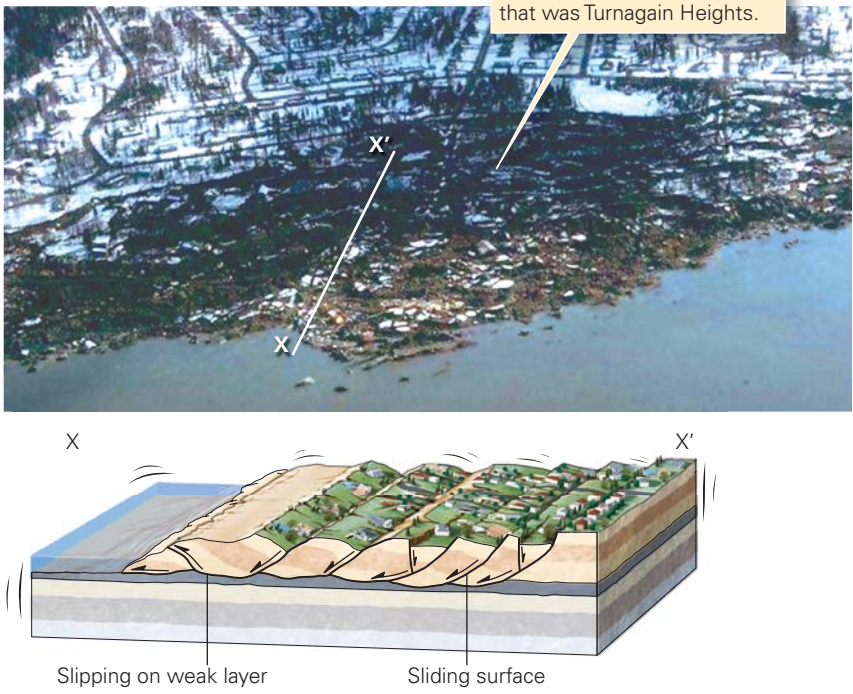
(a) Shaking triggers landslides, which caused a steep slope along the coast of California to collapse, carrying part of a home with it.



(b) During the 1964 Alaska earthquake, slumping caused the land to give way beneath parts of Anchorage.



(c) Liquefaction under their foundations caused these apartment buildings in Niigata, Japan, to tip over during a 1964 earthquake.

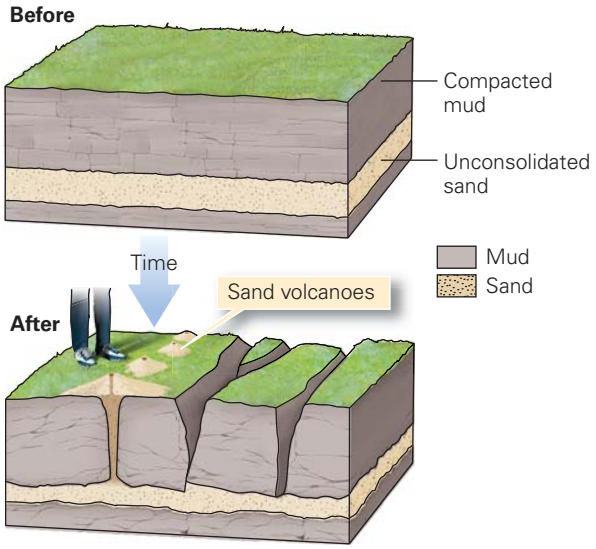


(d) During the 1964 Turnagain Heights disaster, a landslide carried a neighborhood out to sea. Slip occurred on a weak layer.

boundaries on Earth—the Sunda Trench. Along this convergent boundary, the Indian Ocean floor subducts at about 4 cm per year, leading to slip on large thrust faults. Just before 8:00 A.M. on December 26, 2004, the crust above a 1,300-km-long by 100-km-wide portion of one of these faults lurched westward by as much as 15 m. The break started at the hypocenter and then propagated north at 2.8 km/s; thus, the rupturing took 9 minutes. This slip triggered a great earthquake ($M_W = 9.3$) and pushed the sea floor up by tens of centimeters. The rise of the sea floor, in turn, shoved up the overlying water. Because the area that rose was so broad, the volume of displaced water was immense. As a consequence, a tragedy of an unimaginable extent was about to unfold. Water from above the upthrust sea floor began moving outward from above the fault zone, a process that generated a series of giant waves traveling at speeds of about 800 km per hour (500 mph)—almost the speed of a jet plane (**Fig. 8.25a**).

Geologists now use the term **tsunami** for a wave produced by displacement of the sea floor. The displacement can be due to an earthquake, submarine landslide (see Chapter 13), or volcanic explosion. *Tsunami* is a Japanese word that translates literally as harbor wave, an apt name because tsunamis can be

FIGURE 8.23 The ground shaking of an earthquake can disrupt unlithified beds of sediment. Liquefaction of sand can cause ground cracking and sand volcanoes.



(a) Liquefaction of a sand layer causes the ground to crack and sand volcanoes to erupt.



(b) During the 2011 Christchurch, New Zealand, earthquake, liquefied sand spurted out and spread over the pavement. The process produced open space underground, so the pavement collapsed to form a sinkhole.



(c) Liquefaction of a sand layer beneath the dry soil of this field caused the soil to crack and fissures to develop.

particularly damaging to harbor towns. In older literature such waves were called "tidal waves," because when one arrives, water rises as if a tide were coming in, but in fact the waves have nothing to do with daily tidal cycles.

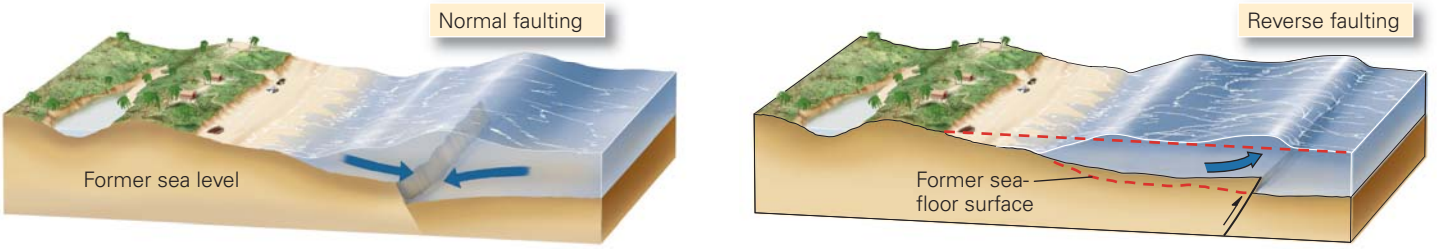
Regardless of cause, tsunamis are very different from familiar, wind-driven storm waves. Large wind-driven waves can reach heights of 10 to 30 meters in the open ocean. But even such monsters have wavelengths of only tens of meters, and thus contain a relatively small volume of water. In contrast, although a tsunami in deep water may cause a rise in sea level of at most only a few tens of centimeters—a ship crossing one wouldn't even notice—tsunamis have wavelengths of tens to hundreds of kilometers and an individual wave can be several kilometers wide, as measured perpendicular to the wave front. Thus, the wave involves a *huge volume of water*. In simpler terms, we can think of the width of a tsunami, in map view, as being more than 100 times the width of a wind-driven wave. Because of this difference, a storm wave and a tsunami have very different effects when they strike the shore.

When a wave approaches the shore, friction between the base of the wave and the sea floor slows the bottom of the wave, so the back of the wave catches up to the front, and the added volume of water builds the wave higher (**Fig. 8.25b**). The top of the wave may fall over the front of the wave and cause a breaker (see Chapter 18). In the case of a wind-driven wave, the breaker may be tall when it washes onto the beach, but because the wave doesn't contain much water, the wave runs out of water and friction slows it to a stop on the beach. Then, gravity causes the water to spill back seaward. In the case of a tsunami, the wave is so wide that, as friction slows the wave, it builds into a "plateau" of water that can be tens of meters high,

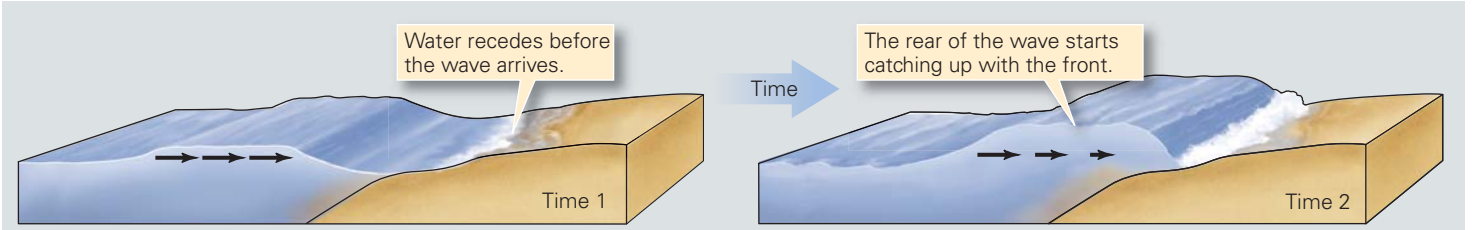


FIGURE 8.24 Broken gas tanks erupt in fountains of flame after the 2011 Tohoku, Japan, earthquake.

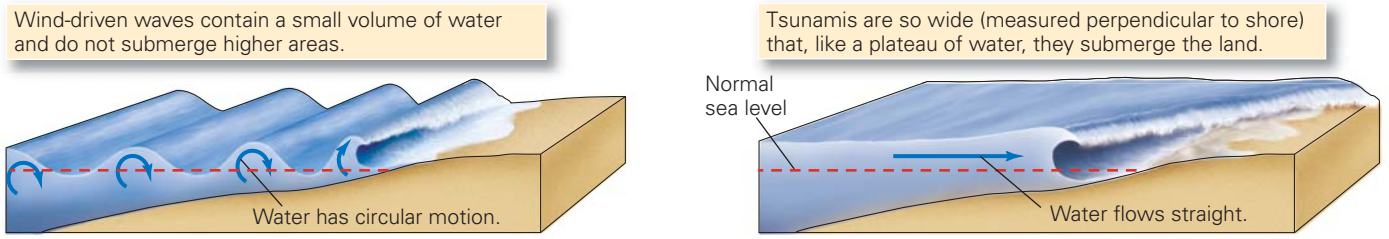
FIGURE 8.25 Tsunamis can be generated when faulting displaces the sea floor over a broad area.



(a) Tsunamis are generated by sudden displacement of the sea floor during either normal or reverse faulting.



(b) Tsunamis are not very high out in the open ocean (Time 1), but can build into monsters as they approach the shore (Time 2) and friction slows the base of the wave.



(c) Tsunamis are very different from storm-generated waves in that they contain much greater volumes of water.

many kilometers wide, and hundreds of kilometers long. Thus, when a tsunami reaches shore, it contains so much water that it crosses the beach and, if the land is low-lying, just keeps on going, eventually covering a huge area (**Fig. 8.25c**).

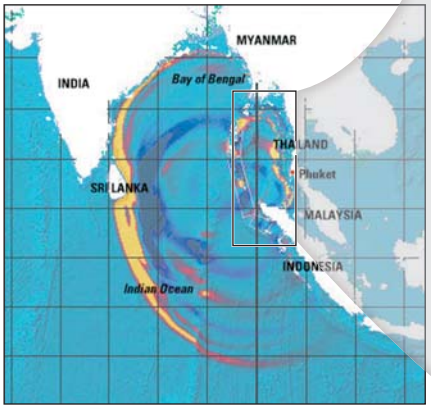
Tsunami damage can be catastrophic. The December 2004 waves struck Banda Aceh, a city at the north end of the island of Sumatra, on a beautiful, cloudless day (**Fig. 8.26a**). First, the sea receded much farther than anyone had ever seen, exposing large areas of reefs that normally remained submerged even at low tide. People walked out onto the exposed reefs in wonder. But then, with a rumble that grew to a roar, a wall of frothing water began to build in the distance and approach land (**Fig. 8.26b**). Puzzled bathers first watched, then ran inland in panic when the threat became clear. As the tsunami approached shore, friction with the sea floor had slowed it to less than 30 km an hour, but it still moved faster than people could run. In places, the wave front reached heights of 15 to 30 m (45 to 100 feet) as it slammed into Banda Aceh (**Fig. 8.26c**). The impact of the water ripped boats from their moorings, snapped trees, battered buildings into rubble, and tossed cars and trucks like toys. And the water just kept coming, eventually flooding low-lying land up to 7 km inland (**Fig. 8.26d**). It drenched forests and fields with salt water (deadly to plants) and buried fields and streets with up to a meter of sand and mud. When the water level finally returned to normal, a jumble of flotsam, as well as the bodies of unfortunate victims, were dragged out to sea and drifted away.

Geologists refer to the tsunami that struck Banda Aceh as a near-field (or local) tsunami, because of its proximity to the earthquake. But the horror of Banda Aceh was merely a preamble to the devastation that would soon visit other stretches of Indian Ocean coast. Far-field (or distant) tsunamis crossed the ocean and struck Sri Lanka 2.5 hours after the earthquake, the coast of India half an hour after that, and the coast of Africa, on the west side of the Indian Ocean, 5.5 hours after the earthquake. In the end, more than 230,000 people died that day.

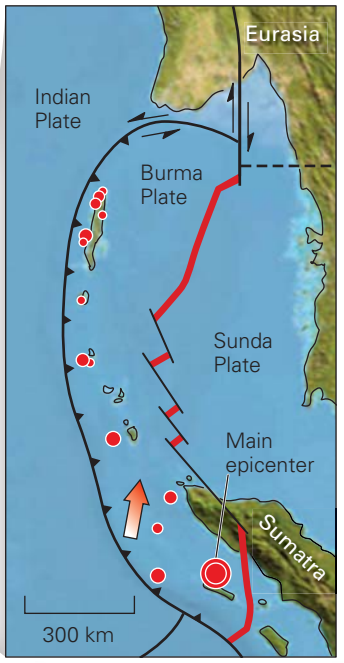
The tsunami that struck Japan soon after the 2011 Tohoku earthquake was vividly captured in high-definition video that was seen throughout the world, generating a new level of international awareness. Though much of the coast was fringed by seawalls, they proved to be a minor impediment to the advance of the wave, which, in places, was 10 to 30 m high when it

FIGURE 8.26 The great Indian Ocean tsunami of 2004.

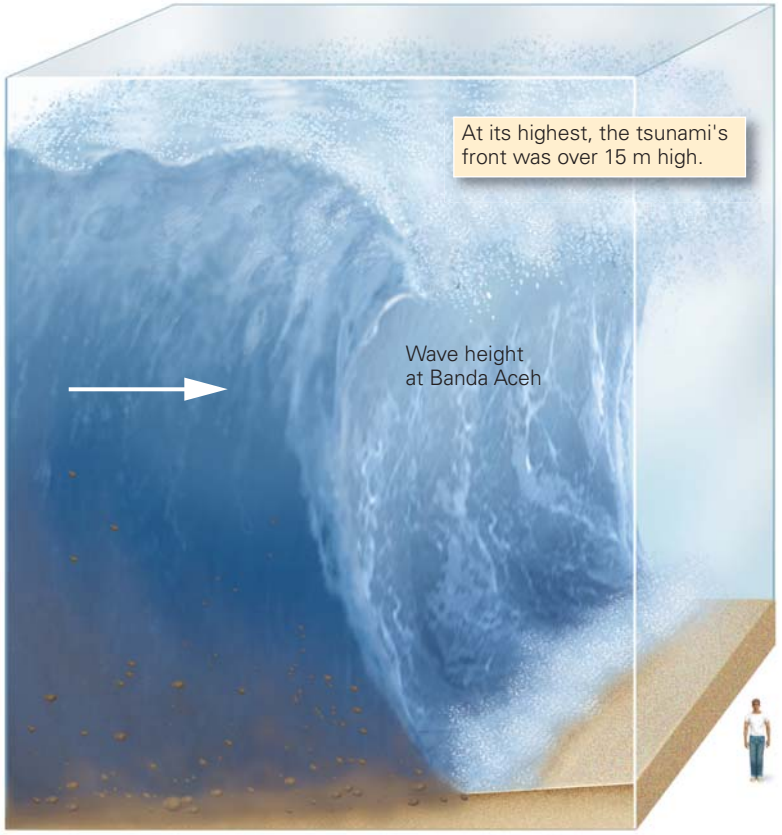
(a) A devastating tsunami was triggered by an earthquake off Sumatra. Three hours later, the leading wave struck the coasts of Sri Lanka and India. A computer model shows the wave.



Colors represent wave height—yellow is highest. There were several waves.



The earthquake was caused by subduction at a trench. Red dots are epicenters.





(b) This snapshot shows the wave rushing toward the coast of Sumatra. Recession of water in advance of the wave exposed a reef.



(c) The wave blasts through a grove of palm trees as it strikes the coast of Thailand.



(d) Satellite photos of the Indonesian province of Aceh before and after the tsunami struck. Note that the vegetation vanished.

reached shore. Racing inland the wave erased whole towns, submerging airports and fields (see Fig. 8.2b). As the wave picked up dirt and debris, it became a viscous slurry, moving with such force that nothing could withstand its impact. The devastation of coastal towns was so complete that they looked as though they had been struck by nuclear bombs (**Fig. 8.27a**).

But the catastrophe was not over. The wave had also hit a nuclear power plant. Though the plant had withstood ground shaking and had automatically shut down, its radioactive core still needed to be cooled by water in order to remain safe. The tsunami not only destroyed power lines, cutting the plant off from the electrical grid, but it also eliminated backup diesel generators and cut water lines. Thus, cooling pumps stopped functioning. Eventually, water surrounding the heat-producing radioactive core of the reactors, as well as the water cooling spent fuel, boiled away. Some of the water separated into hydrogen and oxygen gas, which exploded, and ultimately, the integrity of the nuclear plant was breached so that radioactivity entered the environment (**Fig. 8.27b**).

Because tsunamis are so dangerous, predicting their arrival can save thousands of lives. A tsunami warning center in Hawaii keeps track of earthquakes around the Pacific and uses data relayed from tide gauges and seafloor pressure gauges to determine whether a particular earthquake has generated a tsunami. If observers detect a tsunami, they flash warnings to authorities around the Pacific.

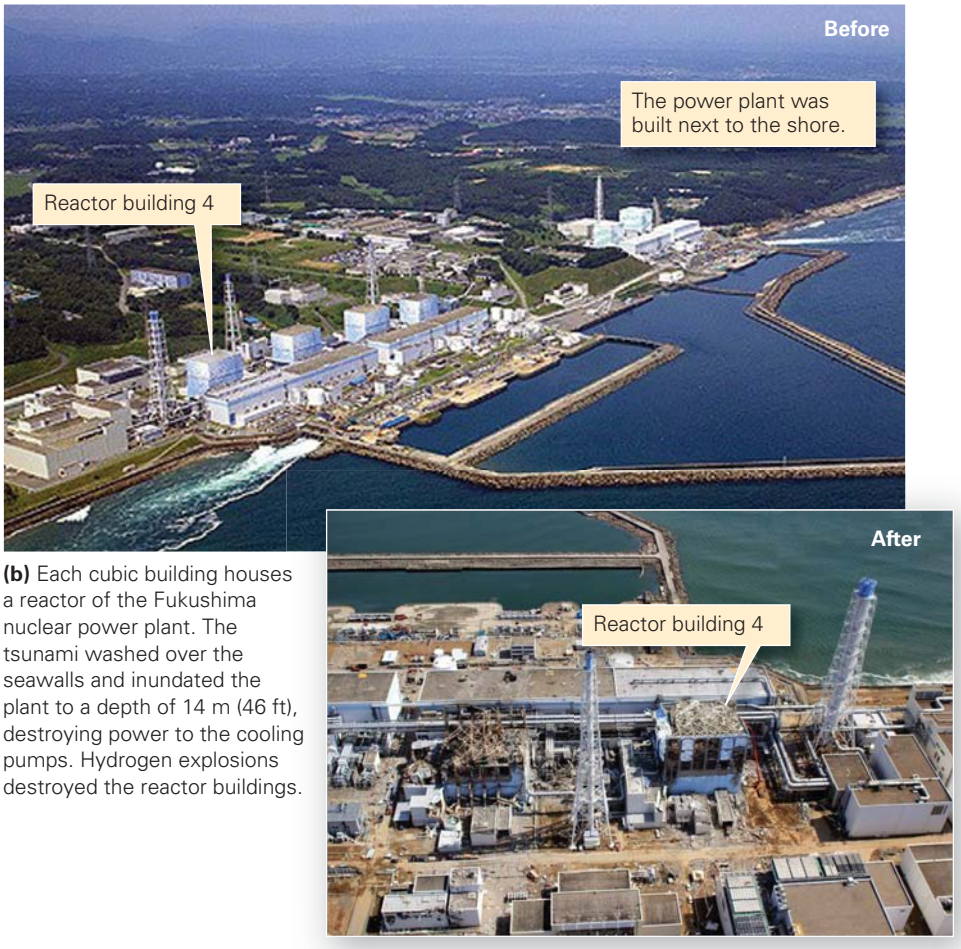
Disease

Once the ground shaking and fires have stopped, disease may still threaten lives in an earthquake-damaged region. Earthquakes cut water and sewer lines, destroying clean-water supplies and exposing the public to bacteria, and they cut transportation lines, preventing food and medicine from reaching the area. The severity of such problems depends on the ability of emergency services to cope. The lack of sufficient clean water after the 2010 Haiti earthquake led to a cholera epidemic later that year.

FIGURE 8.27 Damage due to the 2011 Tohoku tsunami.



(a) The complete destruction of a Japanese coastal town by a tsunami, which followed the Tohoku, Japan, earthquake of March 2011.



(b) Each cubic building houses a reactor of the Fukushima nuclear power plant. The tsunami washed over the seawalls and inundated the plant to a depth of 14 m (46 ft), destroying power to the cooling pumps. Hydrogen explosions destroyed the reactor buildings.

Take-Home Message

Earthquakes cause devastation because ground shaking topples buildings. But destruction can also be caused by landslides, tsunamis, and sediment liquefaction triggered by the shaking. Fire and disease may follow an earthquake.

8.8 Can We Predict the "Big One"?

Can seismologists predict earthquakes? The answer depends on the time frame of the prediction. With our present understanding of the distribution of seismic zones and the frequency at which earthquakes occur, we can make *long-term* predictions (on the time scale of decades to centuries). For example, with some certainty, we can say that a major earthquake will rattle Istanbul during the next 100 years, and that a major earthquake probably won't strike central Canada during the next 10 years. But despite extensive research, seismologists cannot make accurate *short-term* predictions (on the time scale of hours to weeks or even years). Thus we cannot say, for example, that an earthquake will happen in Montreal at 2:43 P.M. on January 17. In this section, we look at the scientific basis of both long- and short-term predictions and consider the consequences of a prediction. Seismologists refer to studies leading to predictions as seismic-risk, or seismic-hazard assessment.

Long-Term Predictions

A long-term prediction estimates the *probability*, or likelihood that an earthquake will happen during a specified time range. For example, a seismologist may say, "The probability of a major earthquake occurring in the next 20 years in this state is 20%." This sentence implies that there's a 1-in-5 chance that the earthquake will happen before 20 years have passed. Urban planners and civil engineers can use long-term predictions to help create building codes for a region—codes requiring stronger, more expensive buildings make sense for regions with greater seismic risk. They may also use predictions to determine whether it is reasonably safe to build vulnerable structures such as nuclear power plants, hospitals, or dams in a given region. Seismologists base long-term earthquake predictions on two pieces of information: the identification of seismic zones and the **recurrence interval** (the average time between successive events).

To identify a seismic zone, seismologists produce a map showing the epicenters of earthquakes that have happened during a set period of time (say, 30 years). Clusters or belts of epicenters define the seismic zone. The basic premise of long-term earthquake prediction can be stated as follows: a region in which there have been many earthquakes in the past will be more likely to experience earthquakes in the future. Seismic zones, therefore, are regions of greater seismic risk. This doesn't mean that a disastrous earthquake can't happen far from a seismic zone—they can and do—but the probability that an event will happen in a given time window is less.

To determine the recurrence interval for large earthquakes within a given seismic zone, seismologists must determine when large earthquakes happened there in the past. Since the historical record does not provide information far enough back in time, they study geologic evidence for great earthquakes. For example, recognition of a fresh, unweathered fault scarp or trace may indicate that faulting affected an area relatively recently. A trench cut into sedimentary strata near a fault may reveal layers of sand volcanoes and disrupted bedding in the stratigraphic record. Each layer, whose age can be determined by using radiocarbon dating of plant fragments, records the time of an earthquake (**Fig. 8.28**). By calculating the number of years between successive events and taking the average, seismologists obtain the recurrence interval. Note that a recurrence interval does not specify the exact number of years between events, only the average number. Since stress builds up over time on a fault, the probability that an earthquake will happen in any given year probably increases as time passes.

FIGURE 8.28 Identifying recent fault movement and recurrence interval. The block shows the walls of two trenches cut into the ground at a fault zone.

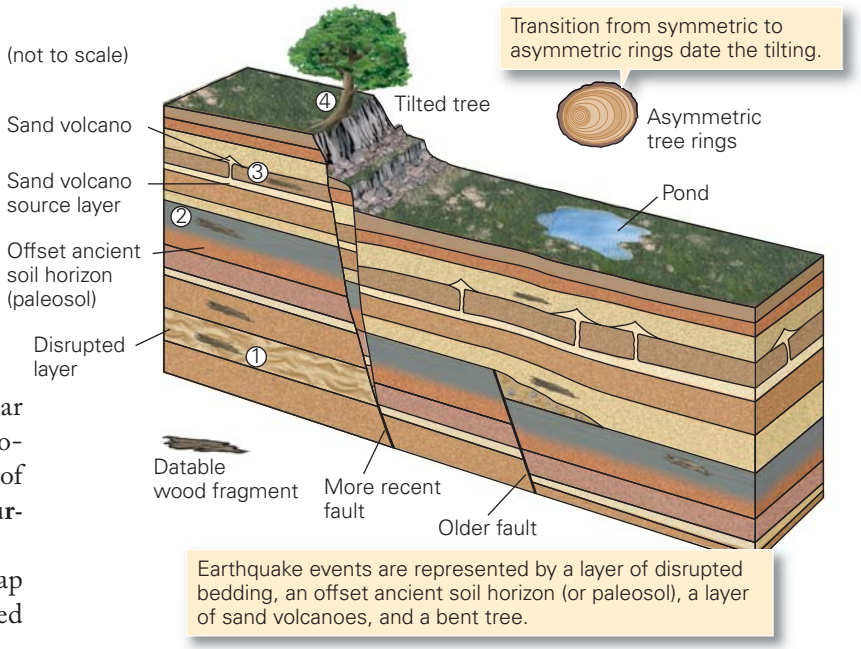
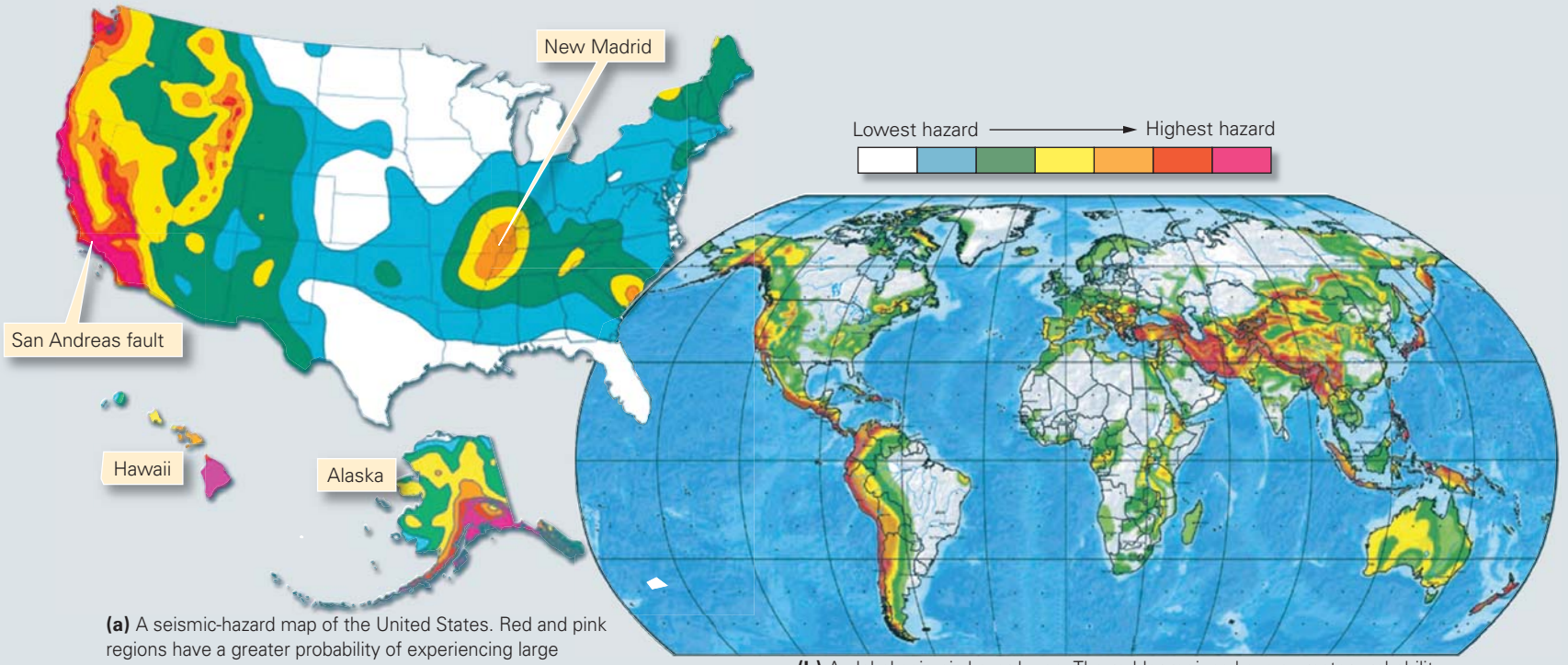


FIGURE 8.29 Examples of seismic-hazard maps.



(a) A seismic-hazard map of the United States. Red and pink regions have a greater probability of experiencing large earthquakes. The San Andreas fault plate boundary is particularly hazardous. Risk in the New Madrid area remains subject to debate.

(b) A global seismic-hazard map. The redder regions have a greater probability of experiencing a large earthquake. Probability is high along plate boundaries.

Information on a recurrence interval allows seismologists to refine regional maps illustrating seismic risk (**Fig. 8.29a, b**).

Short-Term Predictions

Short-term predictions, specifying that an earthquake will happen on a given date or within a time window of days to years, are not and may never be reliable. Seismologists have considered, and discounted as unreliable, many supposed bases for short-term prediction. For example, a swarm of foreshocks may indicate that rock is beginning to crack in advance of a mainshock, but such swarms can be identified only in hindsight. Precise surveys show that the surface of the ground may warp slightly prior to an earthquake, but no one can determine how much warping will take place before an earthquake will happen. Prediction studies focused on measuring changes in water levels in wells, radon gas in spring water, electrical signals emitted by minerals, or agitation of animals have met with similar skepticism.

The concept of a short-term prediction should not be confused with the concept of an **earthquake early warning** system. An early warning system works as follows. When an earthquake happens, the seismic waves it produces start traveling through the Earth. Seismic stations closer to the epicenter may detect an earthquake before the seismic waves have had time to reach populated areas farther from the epicenter. The instant that seismic stations detect the earthquake, a computer approximates the epicenter location, then sends a signal to a control center, which automatically sends out emergency signals to areas that might be affected. The signals shut down gas pipelines, trains, nuclear reactors, power lines, and other vulnerable infrastructure. The signal also sets off sirens and alerts broadcasters to send out warnings on radio, TV, and cell-phone networks to warn people that an earthquake is about to begin. Unless the focus is directly under the city, the warning may precede the arrival of the first earthquake waves by several seconds, not a lot of time, but hopefully enough to prevent some infrastructure damage and perhaps enough for people to seek a safer location.

Take-Home Message

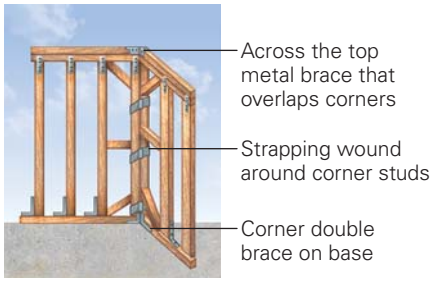
Researchers can determine regions where earthquakes are more likely, but not exactly when and where an event will occur. Seismic hazard is greater where seismicity has happened more frequently in the past and therefore has a shorter recurrence interval.

8.9 Earthquake Engineering and Zoning

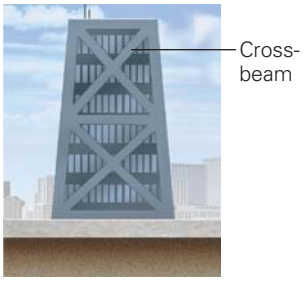
The loss of human life from an earthquake of a given size varies widely and depends on a number of factors. The most important include the proximity of an epicenter to a population center, the depth of the focus, the style of construction in the epicentral region, whether the earthquake occurred in a region of steep slopes or along the coast, whether building foundations are on solid bedrock or on weak substrate, whether the earthquake happened when people were outside or inside, and whether the government was able to provide emergency services promptly.

For example, a 1988 earthquake in Armenia was not much bigger than the 1971 San Fernando earthquake in southern California, but it caused almost 400 times as many deaths (24,000 versus 65). The difference in death toll

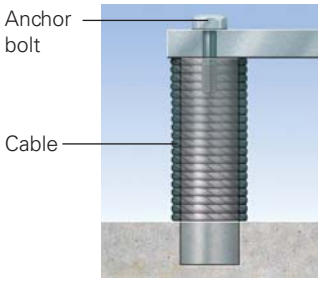
FIGURE 8.30 Preventing damage and injury during an earthquake.



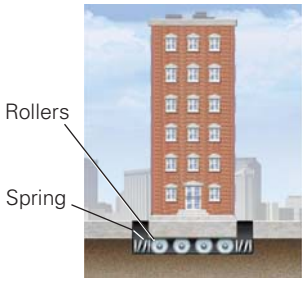
Adding corner struts, braces, and connectors can substantially strengthen a wood-frame house.



Buildings are less likely to collapse if they are wider at the base and if crossbeams are added for strength.

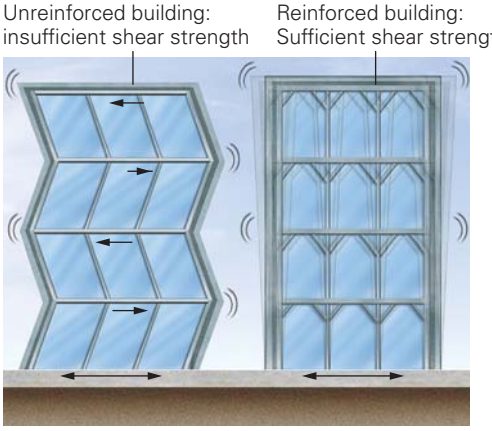


Wrapping a bridge's support columns in cable and bolting the span to the columns will prevent the bridge from collapsing so easily.



Placing buildings on rollers or shock absorbers lessens the severity of the vibrations.

(a) Damage can be prevented if buildings are designed to withstand vibration.



(b) An unreinforced building will shear side-to-side in a way that causes floor to shift out of alignment.



(c) Buoys can detect a tsunami in the open ocean, so people on land can be warned.



(d) If an earthquake strikes, take cover under a sturdy table near a wall.

reflected differences in the style and quality of construction and the characteristics of the substrate. The unreinforced concrete-slab buildings and masonry houses of Armenia collapsed, whereas the structures in California had, by and large, been erected according to building codes that require structures to withstand stresses caused by earthquakes. Most flexed and twisted but did not fall down and crush people. The terrible 1976 earthquake in T'ang-shan, China, killed over a quarter of a million people partly because the ground beneath the epicenter had been weakened by coal mining and collapsed, and because buildings were poorly constructed. During the M_W 7.9 2008 Sichuan earthquake in China, 70,000 people died and almost 5 million were left homeless because of building failures. Mexico City's 1985 earthquake proved disastrous because the city lies over a sedimentary basin whose composition and bowl-like shape focused seismic energy. During the 1989 Loma Prieta quake in California, portions of Route 880 in Oakland that were built on a weak landfill collapsed, whereas portions built on bedrock or gravel remained standing.

We can mitigate or diminish the consequences of earthquakes by taking sensible precautions. Clearly, **earthquake engineering** (designing buildings that can withstand shaking) and earthquake zoning (determining where land is stable and where it is not) can help save lives and property. In regions prone to large earthquakes, buildings and bridges should be constructed so they are able to withstand vibrations without collapsing (**Fig. 8.30a, b**). They should be somewhat flexible so that ground motions can't crack them, but they should have sufficient bracing so movements don't become too severe. Also, supports should be strong enough to maintain loads far in excess of the loads caused by their static (nonmoving) weight. Wrapping steel cables around bridge support columns makes them many times stronger. Bolting the bridge spans to the top of a column prevents the spans from bouncing off. Bolting buildings to foundations keeps them in place, and adding diagonal braces to frames keeps them from twisting and shearing too much.

Certain kinds of construction should be avoided. For example, concrete-block, unreinforced concrete, and unreinforced brick buildings crack and tumble under conditions in which wood-frame, steel girder, or reinforced concrete buildings remain standing. Traditional heavy, brittle tile roofs can shatter and bury the inhabitants inside, whereas sheet-metal or asphalt-shingle roofs do not. Loose decorative stone and huge open-span roofs also do not fare well when vibrated. Of note, inadequate structures can be made safer by **seismic retrofitting**, the process of strengthening existing buildings in potentially seismically hazardous areas. An example of retrofitting is adding vibration dampening to foundations.

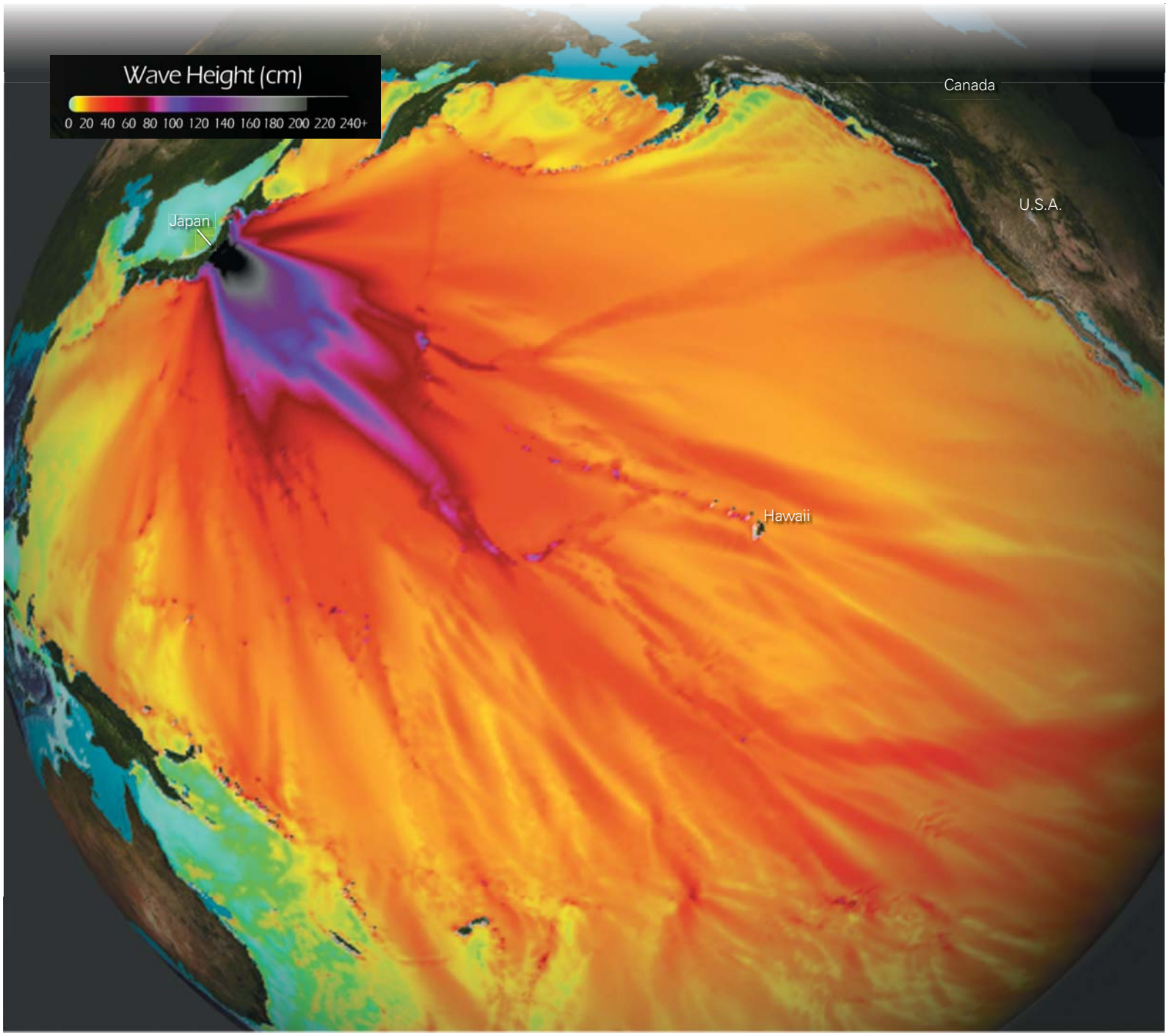
Similarly, developers should avoid construction on land underlain by weak mud that could liquefy. They should not build on top of, on, or at the base of steep escarpments because the escarpments could fail and produce landslides, and they should avoid locating large population centers downstream of dams (which could crack and collapse, causing a flood). Vulnerable buildings should not be constructed directly over active faults, because fault movement could crack and destroy the buildings. Cities in seismic zones need to draw up emergency plans to deal with disaster. Communication centers should be situated in safe localities, and strategies need to be implemented for providing supplies under circumstances where roads may be impassable. And in coastal areas, tsunami warning systems need to be implemented (**Fig. 8.30c**).

Finally, communities and individuals in vulnerable regions should learn to protect themselves during an earthquake. In your home, keep emergency supplies, bolt bookshelves to walls, strap the water heater in place, install locking latches on cabinets, know how to shut off the gas and electricity, know how to find the exit, have a fire extinguisher handy, and know where to go to find family members. Schools and offices should have earthquake-preparedness drills. When an earthquake strikes, stay away from buildings. If you are trapped inside, a heavy table or solid door frame may provide some protection (**Fig. 8.30d**). As long as lithosphere plates continue to move, earthquakes will continue to shake. But we can learn to live with them.

Take-Home Message

Earthquakes are a fact of life on this dynamic planet. People in regions facing high seismic risk should build on stable ground, avoid unstable slopes, and design construction that can survive shaking. Evacuation planning saves lives after an event.

ANOTHER VIEW A model showing the predicted height of the tsunami in the Pacific Ocean generated by the 2011 Tohoku earthquake. Height depends on both water depth, and on distance from the source. Note that the height generally decreases away from the source off eastern Japan, but increases near coasts.



CHAPTER 8 REVIEW

Chapter Summary

- Earthquakes are episodes of ground shaking. Earthquake activity is called seismicity.
- Most earthquakes happen when rock slips during faulting. The place where rock breaks and earthquake energy is released is called the hypocenter, and the point on the ground directly above the focus is the epicenter.
- Active faults are faults on which movement is likely. Inactive faults ceased being active long ago. Displacement on active faults that intersect the ground surface may yield a fault scarp.
- During fault formation, rock elastically bends, then ruptures. When this happens, the rock vibrates, and this generates an earthquake.
- Faults exhibit stick-slip behavior, in that they move in sudden increments. Most earthquakes happen when stress overcomes friction on a preexisting fault, and the fault slips again.
- Earthquake energy travels in the form of seismic waves. Body waves, which pass through the interior of the Earth, include P-waves and S-waves. Surface waves, which pass along the surface of the Earth, include R-waves and L-waves.
- We can detect earthquake waves by using a seismometer. Seismograms, records of earthquakes, demonstrate that different earthquake waves travel at different velocities. Using the difference between P-wave and S-wave arrival times, seismologists can pinpoint the epicenter location.
- The Mercalli Intensity scale is based primarily on documenting the damage caused by an earthquake. Magnitude scales are based on measuring the amount of ground motion, as indicated by a seismogram.
- An M_w 8 earthquake yields about 10 times as much ground motion as M_w 7 earthquake, and releases about 32 times as much energy.
- Most earthquakes occur in seismic belts, of which the majority lie along plate boundaries. Intraplate earthquakes happen in the interior of plates.
- Earthquake damage results from ground shaking, landslides, sediment liquefaction, fire, and tsunamis.
- Seismologists predict that earthquakes are more likely in seismic zones than elsewhere, and can determine the recurrence interval for great earthquakes. But it may never be possible to pinpoint the exact time and place at which an earthquake will happen.
- Earthquake hazards can be reduced with better construction practices and zoning, and by educating people about what to do during an earthquake.

Key Terms

aftershock (p. 221)
body wave (p. 224)
compressional wave (p. 224)
displacement (p. 220)
earthquake (p. 218)
earthquake early warning (p. 246)
earthquake engineering (p. 248)
elastic-rebound theory (p. 221)
epicenter (p. 219)
fault (p. 217)
fault scarp (p. 220)
fault trace (p. 220)
focus (p. 219)
foreshock (p. 221)
friction (p. 221)
hypocenter (p. 219)
intensity (p. 228)
intraplate earthquake (p. 236)
magnitude (p. 229)
Modified Mercalli Intensity scale (p. 228)
moment magnitude scale (p. 230)
recurrence interval (p. 245)
Richter scale (p. 229)
sediment liquefaction (p. 238)
seismic belt (p. 231)
seismicity (p. 218)
seismic retrofitting (p. 248)
seismic wave (p. 224)
seismogram (p. 226)
seismometer (p. 225)
shear wave (p. 224)
stick-slip behavior (p. 221)
stress (p. 220)
surface wave (p. 224)
travel-time curve (p. 227)
tsunami (p. 240)
Wadati-Benioff zone (p. 233)

Review Questions

1. Compare normal, reverse, and strike-slip faults.
2. Describe elastic-rebound theory and the concept of stick-slip behavior.
3. Describe the motions of the four types of seismic waves. Which are body waves, and which are surface waves?
4. Explain how the vertical and horizontal components of an earthquake are detected on a seismometer.
5. Explain the differences among the scales used to describe the "size" of an earthquake.
6. How does seismicity on mid-ocean ridges compare with seismicity at convergent or transform boundaries? Do all earthquakes occur at plate boundaries?
7. What is a Wadati-Benioff zone, and why was it important in understanding plate tectonics?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Drag n' Drop, Hot Spot, and other exercises on metamorphism.
- Interactive exercises on finding epicenter location.
- Animation exercises on seismic wave motion and seismograms.

8. Describe the types of damage caused by earthquakes.
9. What is a tsunami, and why does it form?
10. Explain how liquefaction occurs in an earthquake and how it can cause damage.
11. How are long-term and short-term earthquake predictions made? What is the basis for determining a recurrence interval, and what does a recurrence interval mean?
12. What types of structure are most prone to collapse in an earthquake? What types are most resistant to collapse? What causes most loss of life during an earthquake?

On Further Thought

13. Is seismic risk greater in a town on the west coast of South America or in one on the east coast? Explain your answer.
14. The northeast-trending Ramapo fault crops out north of New York City. (You can see the fault on *Google Earth*™ by going to Lat. 41°10′21.12″ N Long. 74°5′12.36″ W. The fault trace follows a distinct escarpment.) Where the fault crosses the Hudson River, there is an abrupt bend in the river. A nuclear power plant was built near this bend on sediments deposited by the river. Imagine that you are a geologist with the task of determining the seismic risk of the fault. What evidence of prehistoric seismic activity could you look for?
15. On the seismogram of an earthquake recorded at a seismic station in Paris, France, the S-wave arrives six minutes after the P-wave. On the seismogram obtained by a station in Mumbai, India, for the same earthquake, the difference between the P-wave and S-wave arrival times is 4 minutes. Which station is closer to the epicenter? From the information provided, can you pinpoint the location of the epicenter? Explain.
16. Will the duration of shaking recorded at a seismic station be longer or shorter as the distance between the epicenter and the station increases?

SEE FOR YOURSELF H. . . Earthquakes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet H of our **Geotours Workbook**.



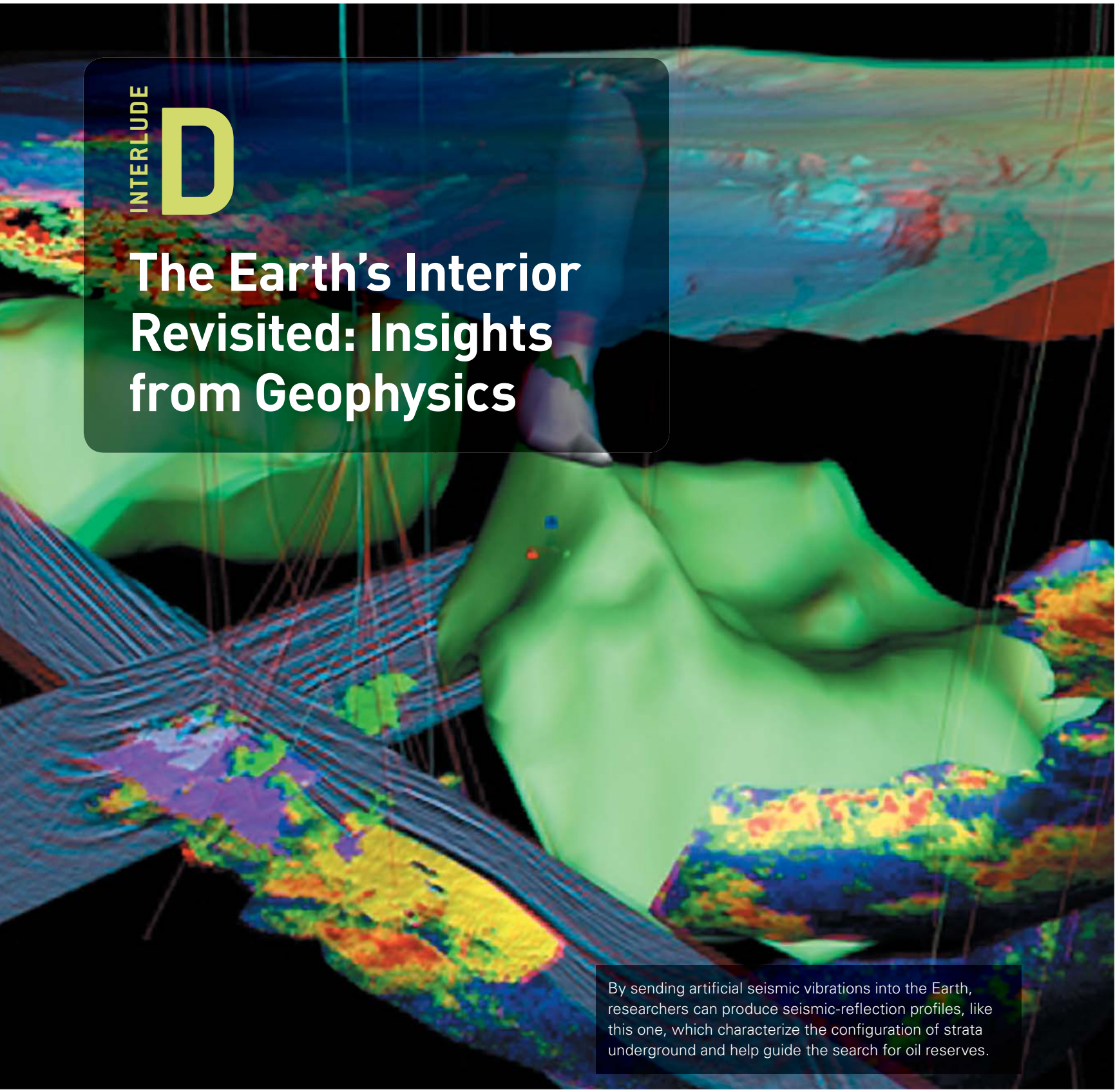
San Andreas Fault, Near San Francisco, California
Latitude 37°31′12.66″N,
Longitude 122°21′41.04″W
Looking along the fault to the NE from an elevation of about 2 km, you can see very narrow lakes filling a narrow valley, south of San Francisco. The valley is the trace of the San Andreas fault.



Banda Aceh, *Before* Tsunami
Latitude 5°33′31.82″N,
Longitude 95°17′13.01″E
Open the "historical imagery tool," and set the clock back to June 22, 2004. From an elevation of 1.5 km you can see dense housing built along the shore of the seaside town of Banda Aceh, on the island of Sumatra. Now set the clock to 2006 and compare the views.

INTERLUDE D

The Earth's Interior Revisited: Insights from Geophysics



By sending artificial seismic vibrations into the Earth, researchers can produce seismic-reflection profiles, like this one, which characterize the configuration of strata underground and help guide the search for oil reserves.

D.1 Introduction

At various points in this book so far, we have described basic features of the Earth's interior and have noted how characteristics of the interior affect the Earth's surface and the space around our planet. We needed to provide a rudimentary understanding of the interior in order to be able to discuss several key topics, such as plate tectonics, that were introduced in early chapters. But to provide the *rest of the story* about our planet's interior, and its influence on its surroundings, we had to wait until now, after you have been introduced to Earth materials, plate tectonics, and earthquakes. In this Interlude, we build on your foundation of knowledge by introducing some additional insights into the nature of the Earth's interior that come from the broader study of geophysics. **Geophysics** is a subdiscipline of geoscience focused on the study of seismic waves, magnetism, gravity, and other physical characteristics of the Earth to understand the planet's character and behavior. Geophysicists use mathematical calculations, measurements with instruments, and computer simulations to conduct their work. Seismology, the subject of Chapter 8, is one aspect of geophysics.

At the level of this book, we can't provide much detail about geophysics. But we can introduce some of the key concepts supported by its study. We begin by examining how seismic waves interact with layer boundaries, in a general sense, and then discuss the discoveries of specific layer boundaries within the Earth and of three-dimensional variations within each layer. We then turn our attention to the gravity field of the Earth and examine why gravitational pull varies with location. We conclude by reconsidering the Earth's magnetic field, this time focusing on the question of why the magnetic field exists. Interlude D ties together material covered in Chapters 1, 2, and 8, so we recommend that you read (or reread) relevant parts of these chapters before proceeding.

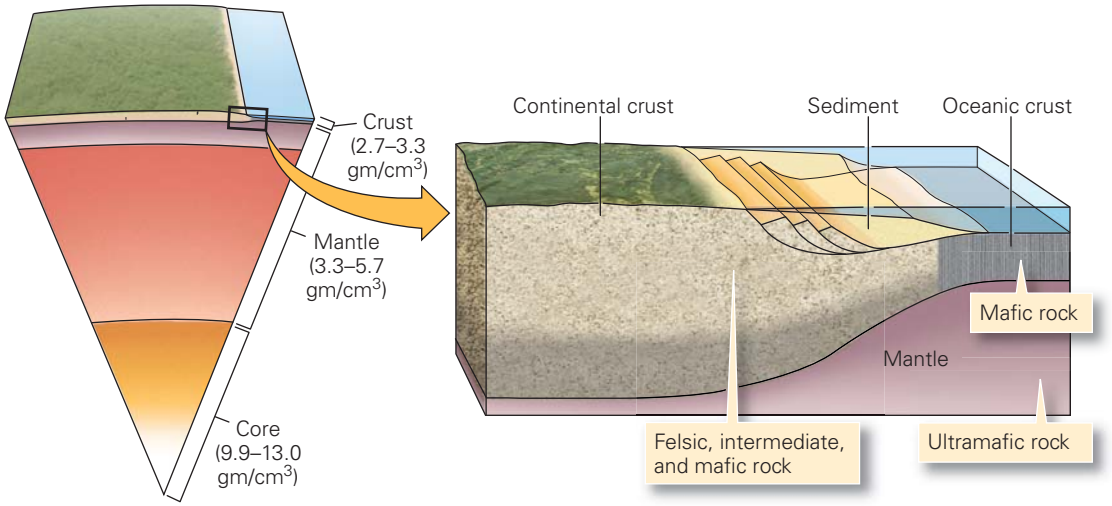
D.2 Setting the Stage for Seismic Study of the Interior

As we discussed in Chapter 1, the first clues to what's inside this planet came from measurements of the Earth's overall mass and shape. These measurements led geologists to conclude that the Earth consists of three concentric layers that differ from each other in terms of relative density (**Fig. D.1a**). From the surface down, these are (1) the crust (of low density); (2) the mantle (of intermediate density); and (3) the core (of very high density).

To gain further insight into the nature of the crust, geologists examined samples of rocks exposed on land or dredged and drilled from the sea floor. To characterize the mantle and core, geologists studied igneous rocks solidified from mantle melts, because the composition of magma provides information about the composition of the magma's source. They also analyzed xenoliths of mantle rocks brought up with magmas, and meteorites, because meteorites come from the interiors of planetesimals and protoplanets similar to those from which the Earth formed. Overall, such work has led geologists to conclude that, beneath a veneer of sediment, the oceanic crust consists dominantly of mafic rock (basalt), whereas the continental crust consists of a variety of igneous and metamorphic rocks ranging from mafic to felsic in composition. The mantle consists of ultramafic rock (peridotite), and the core consists of iron alloy (metal) (**Fig. D.1b**).

To go beyond this basic understanding, researchers searched for a tool that could provide an actual image of the interior. Study of seismic waves provides that tool. By measuring *how fast seismic waves travel* through the Earth, and how the waves bend and/or reflect as they travel, researchers can determine the exact depth to the crust-mantle boundary and to the mantle-core boundary, and they can identify sublayers within the crust, mantle, and core.

FIGURE D.1 Simplified images of the Earth's interior.



(a) The 19th century three-layer image of the Earth.

(b) Oceanic crust is thinner than continental crust and has a different composition. The lower part of the continental crust tends to be more mafic than the upper.

D.3 The Movement of Seismic Waves Through the Earth

Wave Fronts and Travel Times

The energy released by an earthquake moves through rock in the form of waves, just as waves propagate outward from the impact point of a pebble on the surface of a pond. The boundary between the rock through which a wave has passed and the rock through which it has not yet passed is called a **wave front**. In 3-D, a wave front expands outward from the earthquake focus like a growing bubble. We can represent a succession of waves in a drawing by a series of concentric wave fronts. The changing position of an imaginary point on a wave front as the front moves through rock is called a **seismic ray**. You can picture a seismic ray as a line drawn perpendicular to a wave front; each point on a curving wave front follows a slightly different ray (Fig. D.2a). The time it takes for a wave to travel from the focus to a seismometer along a given ray is the **travel time** along that ray.

The ability of a seismic wave to travel through a certain material, as well as the velocity at which it travels, depends on the character of the material. Factors such as density (mass per unit volume), rigidity (how stiff or resistant to bending a material is), and compressibility (how easily a material's volume changes in response to squashing) all affect seismic-wave movement. Studies of seismic waves reveal the following:

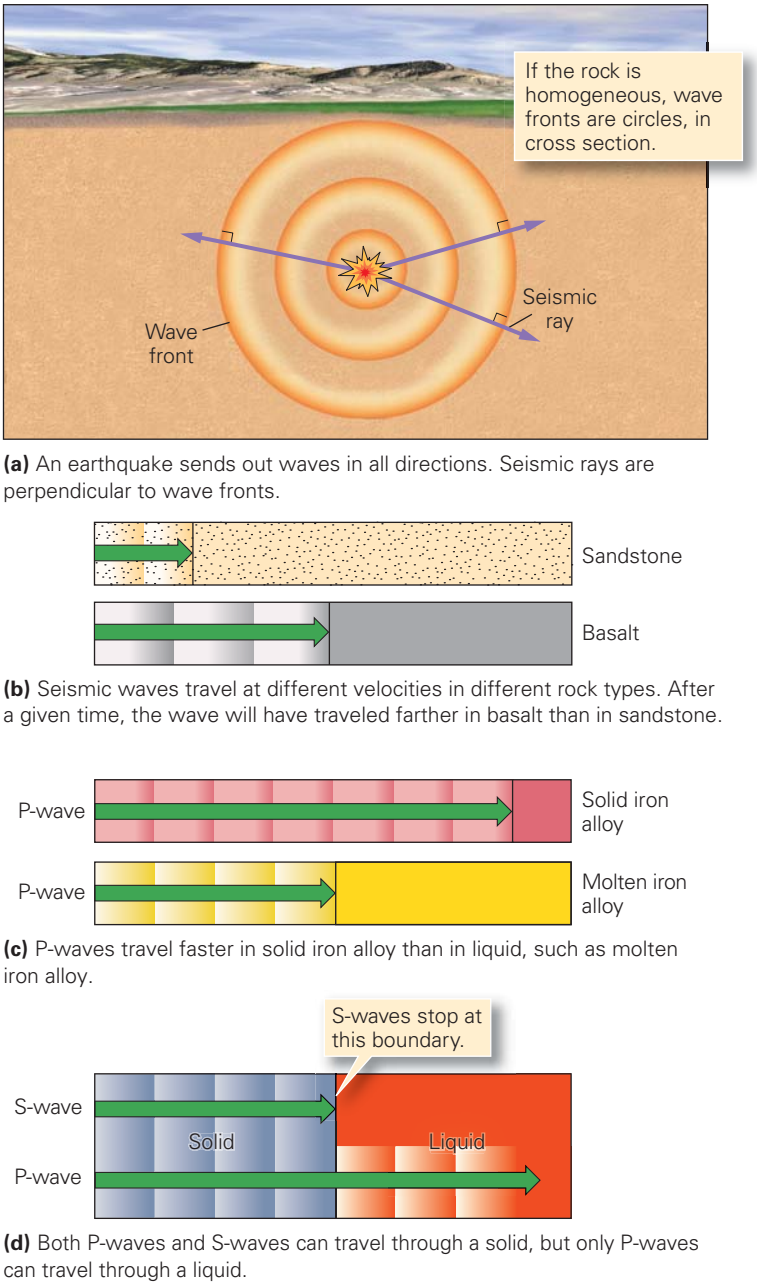
- Seismic waves travel at different velocities in different rock types (Fig. D.2b). For example, P-waves travel at 8 km per second in peridotite (an ultramafic igneous rock), but at only 3.5 km per second in sandstone (a porous sedimentary rock). Therefore, waves accelerate or slow down if they pass from one rock type into another.
- Seismic waves travel more slowly in magma than in solid rock of the same composition, and more slowly in molten iron alloy than in solid iron alloy (Fig. D.2c).
- Both P-waves and S-waves can travel through a solid, but only P-waves can travel through a liquid (Fig. D.2d).

Reflection and Refraction of Wave Energy

Shine a flashlight into a container of water so that the light ray hits the boundary (or interface) between water and air at an angle. Some of the light bounces off the water surface and heads back up into the air, while some enters the water (Fig. D.3a). The light ray that enters the water bends at the air-water boundary so the angle between the ray and the boundary in the air is different from the angle between the ray and the boundary in the water. Physicists refer to the light ray that bounces off the air-water boundary and heads back into the air as the *reflected* ray, and the ray that bends at the boundary as the *refracted* ray. The phenomenon of bouncing off is **reflection**, and the phenomenon of bending is **refraction**. Wave reflection and refraction take place at the interface between two materials, if the wave travels at different velocities in the two materials.

Seismic energy travels in the form of waves, so seismic waves reflect and/or refract when reaching the interface between two rock layers if the waves travel at different velocities in the two layers. For example, imagine a layer of sandstone overlying a layer of basalt. Seismic velocities in sandstone are slower than in basalt, so as seismic waves reach the boundary, some reflect and some refract. The amount and direction of refraction at a boundary

FIGURE D.2 The propagation of earthquake waves.



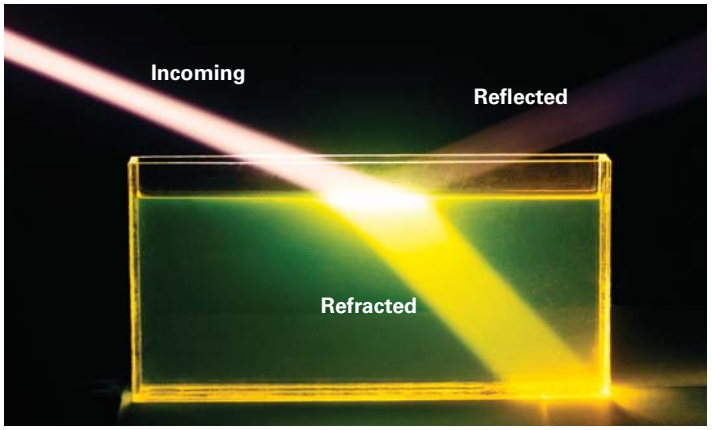
(a) An earthquake sends out waves in all directions. Seismic rays are perpendicular to wave fronts.

(b) Seismic waves travel at different velocities in different rock types. After a given time, the wave will have traveled farther in basalt than in sandstone.

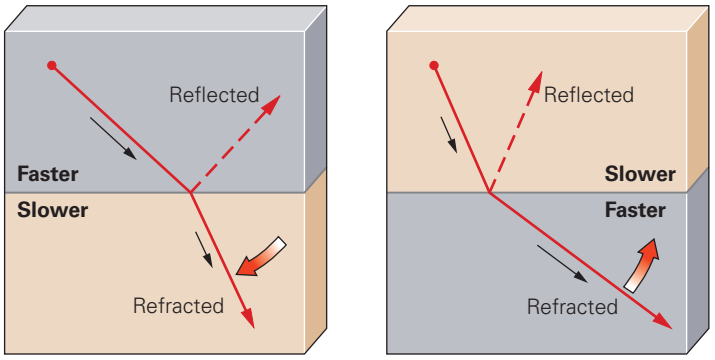
(c) P-waves travel faster in solid iron alloy than in liquid, such as molten iron alloy.

(d) Both P-waves and S-waves can travel through a solid, but only P-waves can travel through a liquid.

FIGURE D.3 Refraction and reflection of waves.



(a) A lab experiment showing how a ray of light reflects and partly refracts when it crosses the boundary between two different materials.



(b) A ray that enters a material through which it travels more slowly bends away from the boundary. A ray that enters a faster medium bends toward the boundary.

depend on the contrast in wave velocity across the boundary and on the angle at which a wave hits the interface. As a rule, if waves enter a material through which they will travel more slowly, the rays representing the waves bend down and away from the interface. For example, the light ray in **Figure D.3b** bends down when hitting the air-water boundary because light travels more slowly in water. This relation makes sense if you picture a car driving from a paved surface diagonally onto a sandy beach—the wheel that rolls onto the sand first slows down relative to the wheel still on the pavement, causing the car to turn toward the sand. Alternatively, if the ray were to pass from a layer in which it travels slowly into one in which it travels more rapidly, the rays representing the waves would bend up and toward the interface (Fig. D.3b).

D.4 Seismic Study of Earth's Interior

Let's now utilize your knowledge of seismic velocity, refraction, and reflection to see how each of the major layer boundaries inside the Earth was discovered.

Discovering the Crust-Mantle Boundary

The concept that seismic waves refract at boundaries between different layers led to the first documentation of the core-mantle boundary. In 1909, Andrija Mohorovičić, a Croatian seismologist, noted that P-waves arriving at seismometer stations less than 200 km from the epicenter traveled at an *average* speed of 6 km per second, whereas P-waves arriving at seismometers more than 200 km from the epicenter traveled at an *average* speed of 8 km per second. To explain this observation, he suggested that P-waves reaching nearby seismometers followed a shallow path through the crust, in which they traveled relatively slowly, whereas P-waves reaching distant seismometers followed a deeper path through the mantle, in which they traveled relatively rapidly (**Fig. D.4a, b**).

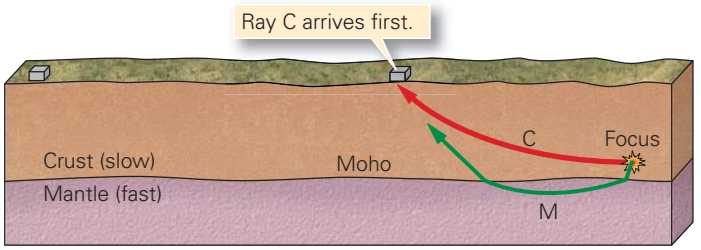
Calculations based on this observation require the crust-mantle boundary beneath most continental regions to be at a depth of about 35 to 40 km. Later studies showed that the crust-mantle boundary beneath oceanic regions lies at a depth of about 7 to 10 km. As you learned in Chapter 1, the crust-mantle boundary is now called the **Moho**, in honor of Mohorovičić.

Defining the Structure of the Mantle

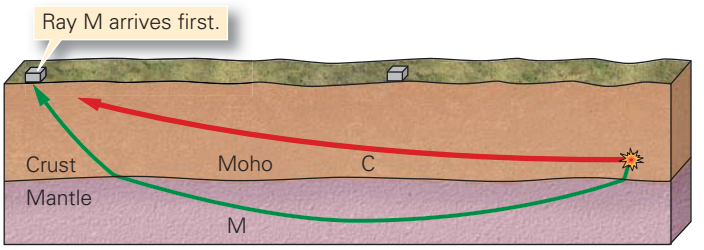
By studying travel times, seismologists have determined that seismic waves travel at different speeds at different depths in the mantle. Between a depth of about 100 and 200 km in the asthenosphere beneath oceanic lithosphere, seismic velocities are slower than in the overlying lithospheric mantle (**Fig. D.5a**). This 100- to 200-km-deep layer is called the **low-velocity zone** (**LVZ**); here, the prevailing temperature and pressure conditions cause peridotite to partially melt by up to 2%. The melt, a liquid, coats solid grains and fills voids between grains. Because seismic waves travel more slowly through liquids than through solids, the coatings of melt slow seismic waves down. In the context of plate tectonics theory, the low-velocity zone is the weak layer on which oceanic lithosphere plates move. Below the low-velocity zone, the asthenosphere does not contain melt. (Of note, seismologists do not find a well-developed low-velocity zone beneath continents.)

Below about 200 km, seismic-wave velocities in the mantle increase with depth (**Fig. D.5b**). Seismologists interpret this increase to mean that mantle peridotite becomes progressively less compressible, more rigid, and denser with depth. This proposal makes sense, considering that the weight of overlying rock increases with depth, and as pressure increases, the atoms making up rock squeeze together more tightly and are not so free to move. Because of refraction, the increase in seismic velocity with depth causes seismic rays to curve in the mantle. To understand the shape of a curved ray, let's represent a portion of the mantle by a series of imaginary layers,

FIGURE D.4 Discovery of the Moho.



(a) Seismic waves traveling only in the crust reach a nearby seismometer first.



(b) Seismic waves traveling for most of their path in the mantle reach a distant seismometer first.

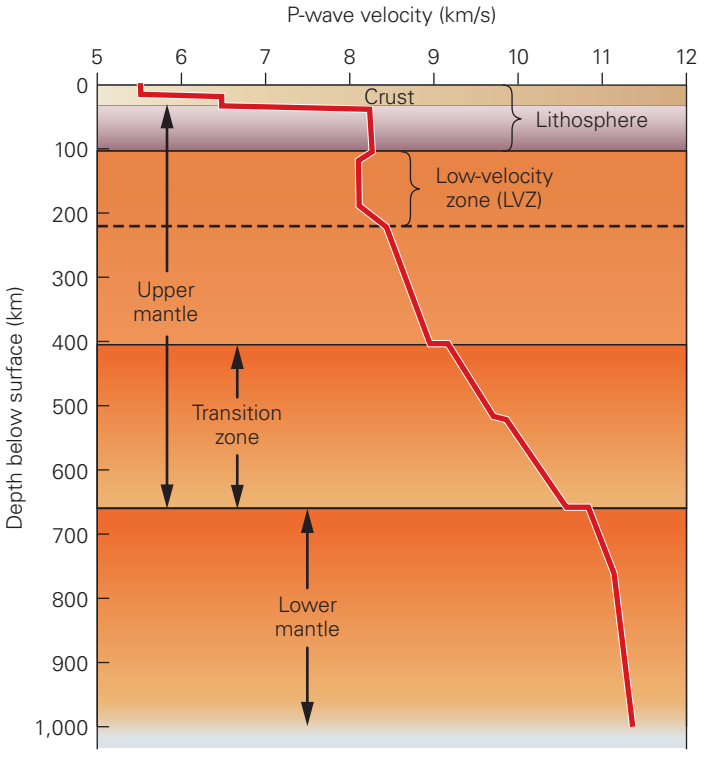
each of which has a slightly greater seismic-wave velocity than the layer above (Fig. D.5c). Every time a seismic ray crosses the boundary between adjacent layers, it refracts a little toward the boundary. After the ray has crossed several layers, it has bent so much that it begins to head back up toward the top of the stack. Now if we replace the stack of distinct layers with a single layer in which velocity increases with depth at a constant rate, the wave follows a smoothly curving path (Fig. D.5d).

At depths between 410 km and 660 km, seismic velocity increases in a series of abrupt steps (see Fig. D.5a), so the stack of layers in Figure D.5c is actually a somewhat realistic image. A major step occurs at a depth of 660 km. Experiments suggest that such **seismic-velocity discontinuities** occur at depths where pressure abruptly causes atoms in minerals to rearrange and pack together more tightly, thereby changing the rock's compressibility and rigidity. Researchers are still unsure if chemical changes also occur at the discontinuities. Because of these seismic-velocity discontinuities, as you learned in Chapter 1 but now can see more clearly, seismologists subdivide the mantle into the **upper mantle** (above 660 km), the **transition zone** (between 410 and 660 km), and **lower mantle** (below 660 km). Note that seismologists consider the transition zone to be part of the upper mantle.

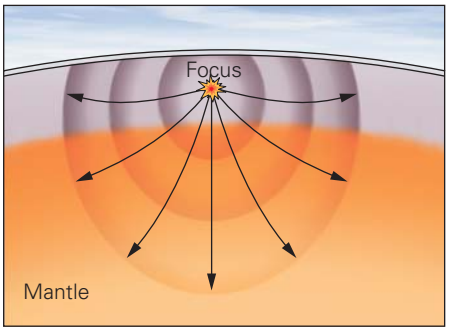
Discovering the Core-Mantle Boundary

During the first decade of the 20th century, seismologists installed seismometers at many stations around the world, expecting to be able to record waves produced by a large earthquake anywhere on Earth. In 1914, one of these seismologists, Beno Gutenberg, discovered that P-waves from a given

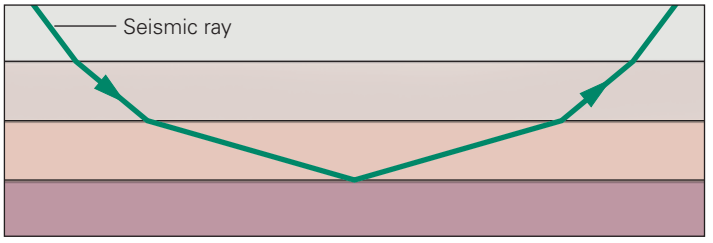
FIGURE D.5 The velocity of P-waves in the mantle changes because the physical properties of the mantle change with depth.



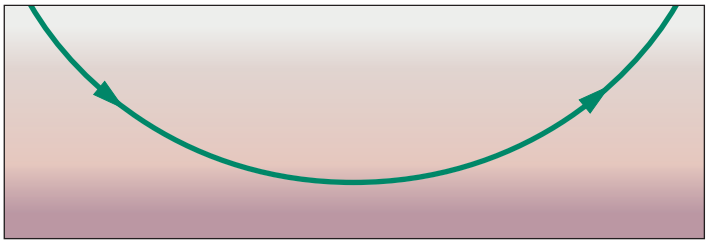
(a) The velocity of P-waves changes with depth in the mantle.



(b) The velocity of seismic waves increases with depth in the mantle, so rays curve and wave fronts are oblong.

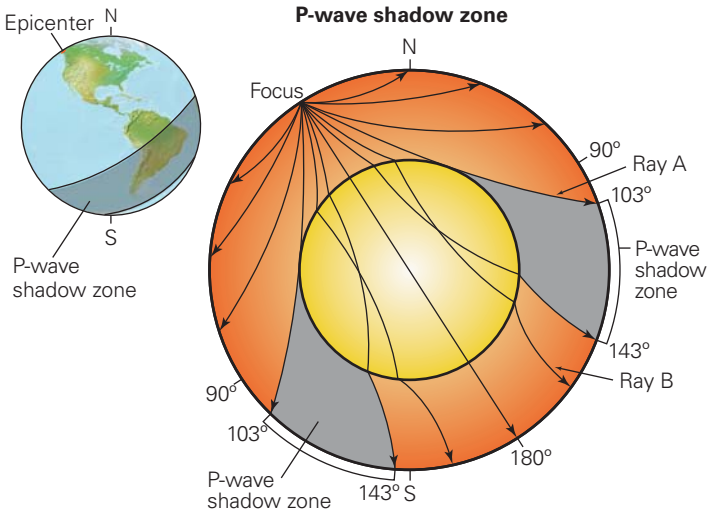


(c) In a stack of discrete layers, rays bend at each boundary. If the velocity is progressively faster in each lower layer, the ray eventually bends back and returns to the surface.

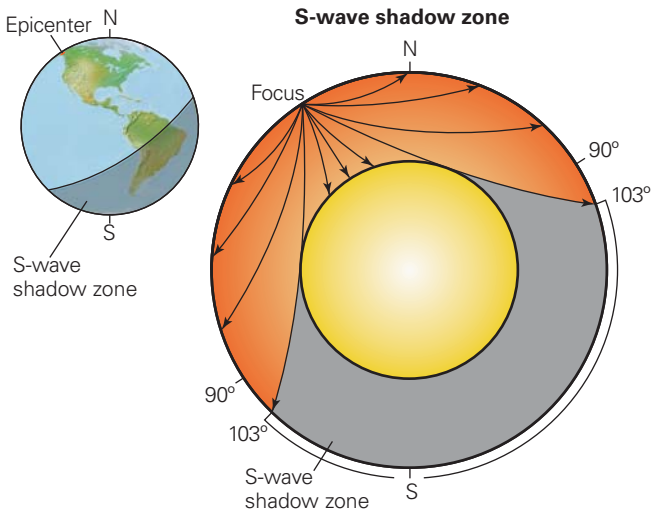


(d) In a material in which the velocity increases gradually with depth, rays curve smoothly and eventually return to the surface.

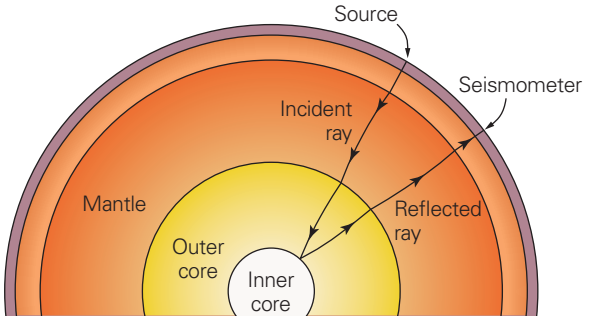
FIGURE D.6 Shadow zones and the discovery of the Earth's core. (Note that the circumference of a circle is 360°, so it is 180° from a given point to a locality on the other side of the planet.)



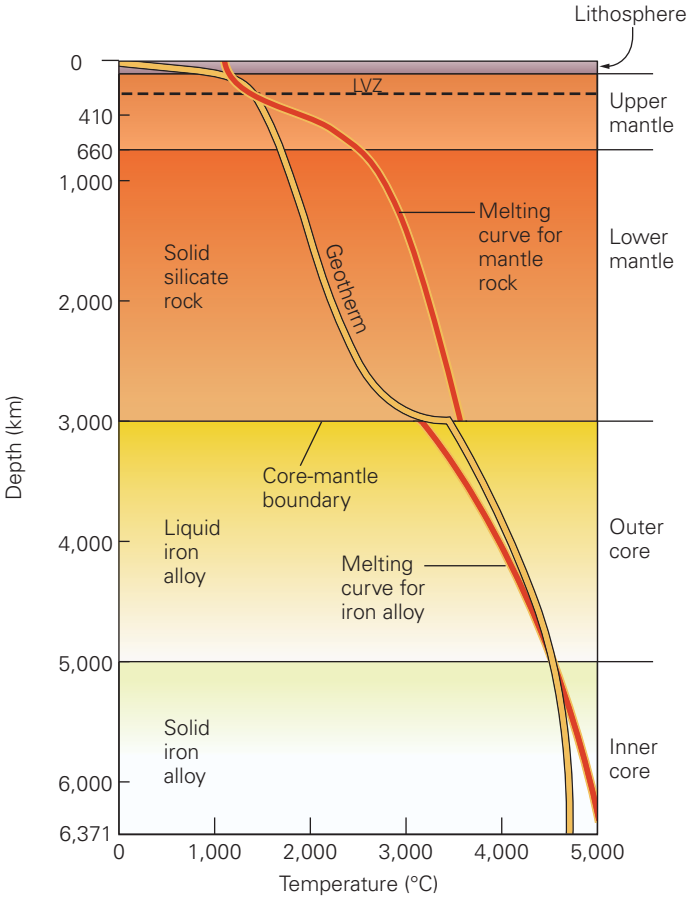
(a) P-waves do not arrive in the P-wave shadow zone because they refract at the core-mantle boundary.



(b) S-waves do not arrive in the S-wave shadow zone because they cannot pass through the liquid outer core.



(c) Seismic waves reflect off the inner core–outer core boundary.



(d) A graph of the geotherm and melting curve for the Earth. Note that the melting temperature is less than the Earth's temperature in the outer core, so the outer core is molten.

earthquake do not arrive at seismometers lying in a band at a distance of between 103° and 143°, as measured along the surface of the Earth from the earthquake epicenter. This band is now called the **P-wave shadow zone** (Fig. D.6a). If the density of the Earth increased *gradually* with depth all the way to the center, the shadow zone would not exist because rays passing into the interior would curve up and reach every point on the surface. Thus, the presence of a shadow zone means that deep in the Earth a major interface exists where seismic waves *abruptly* refract down (implying that the velocity of seismic waves suddenly decreases). This interface, the **core-mantle boundary**, lies at a depth of about 2,900 km.

To see why the P-wave shadow zone exists, follow the two seismic rays labeled A and B in Figure D.6a. Ray A curves smoothly in the mantle (we are ignoring seismic-velocity discontinuities in the mantle) and passes just above the core-mantle boundary before returning to the surface. It reaches the surface 103° from the epicenter. In contrast, Ray B penetrates the boundary and refracts down into the core. Ray B then curves through the core and refracts again when it crosses back into the mantle. As a consequence, Ray B intersects the surface at more than 143° from the epicenter.

Discovering the Nature of the Core

Based on the study of meteorites thought to be fragments of a large planetesimal's interior, and on density calculations, seismologists concluded that the core consists of iron alloy.

This alloy contains about 85% iron, 5% nickel, and 10% of a lighter element (probably oxygen, silicon, and/or sulfur). But the downward bending of seismic waves when they pass from the mantle down into the core indicates that seismic velocities in, at least, the outer core are *slower* than in the mantle. Thus, even though the core is deeper and denser than the mantle, at least the outer part of the core must be less rigid than the mantle. How can this be?

Seismologists found that S-waves do not arrive at stations located between 103° and 180° from the epicenter (a band called the **S-wave shadow zone**). This means that S-waves *cannot* pass through the core at all—otherwise, an S-wave headed straight down through the Earth would appear on the other side. S-waves are shear waves, which by their nature can travel only through solids. Thus, the fact that S-waves do not pass through the core means that the core, or at least part of it, *consists of liquid* (**Fig. D.6b**).

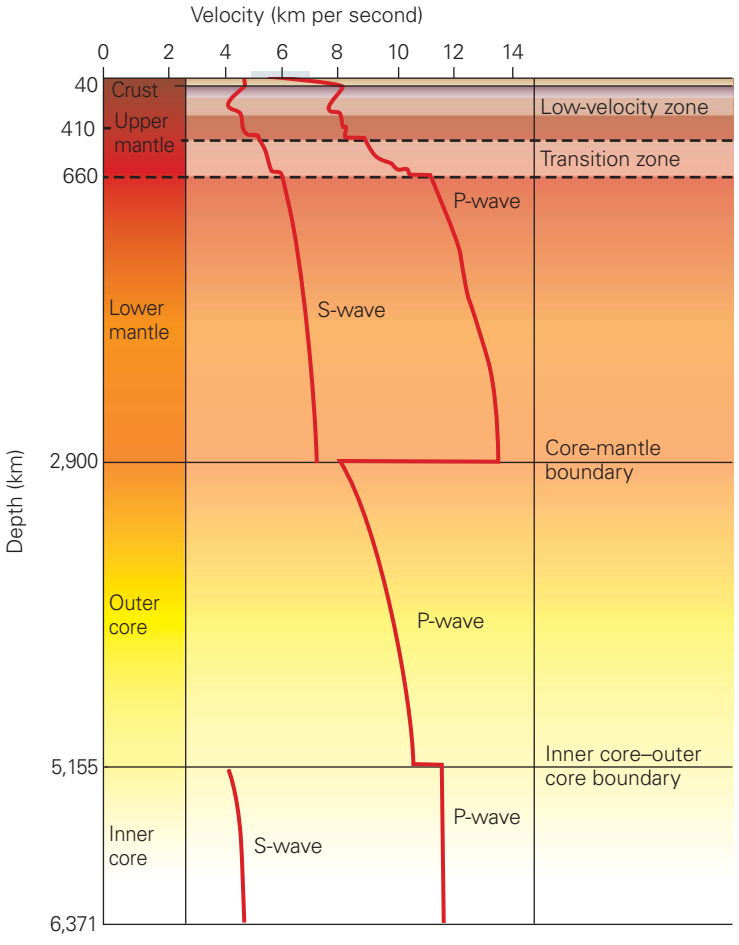
At first, seismologists thought that the entire core might be liquid iron alloy. But in 1936, a Danish seismologist, Inge Lehmann, discovered that P-waves passing through the core reflected off a boundary within the core. She proposed that the core is made up of two parts: an **outer core** consisting of liquid iron alloy and an **inner core** consisting of solid iron alloy. Lehmann's work defined the existence of the inner core but could not locate the depth at which the inner core–outer core interface occurs. This depth was eventually located by measuring the exact time it took for seismic waves to penetrate the Earth, bounce off the inner core–outer core boundary, and return to the surface (**Fig. D.6c**). The measurements showed that the inner core–outer core boundary occurs at a depth of about 5,155 km.

Why does the core have two layers—a liquid outer layer and a solid inner one? An examination of **Figure D.6d** provides some insight. This graph shows two curves: (1) the *geotherm*, which indicates how temperature changes with increasing depth in the Earth; and (2) the *melting curve*, which indicates that the temperature at which materials melt changes with increasing depth in the Earth. At temperatures to the right of the melting curve, Earth materials are molten. As the graph shows, the geotherm lies to the left of the melting curve through most of the mantle and in the inner core. This means that temperatures in most of the mantle and in the inner core are not high enough to cause melting, under the very high pressures found in these regions, so these regions are solid. But the geotherm lies to the right of the melting curve in the low-velocity zone of the mantle and in the outer core, so these regions contain molten material.

A Modern Image of Earth's Layers

Through painstaking effort, seismologists used data from this array to develop a graph, known as a **velocity-versus-depth curve**, that shows the depths at which seismic velocity suddenly changes. These changes define the principal layers and sublayers in the Earth (**Fig. D.7**). Note that the graph does not show a velocity for S-waves in the outer core because S-waves cannot travel through molten iron (a liquid).

FIGURE D.7 The velocity-versus-depth profile of the whole Earth.



Seismic Tomography

In recent years, seismologists have developed a technique, called **seismic tomography**, to produce three-dimensional images of variation in seismic velocities in the Earth's interior. This technique resembles the method used to produce three-dimensional CAT (or CT) scans of the human body. In seismic tomography studies, researchers compare the *observed* travel time of seismic waves following a specific ray path with the *predicted* travel time that waves following the same path would have if the average velocity-versus-depth model depicted by Figures D.5 and D.6 were completely correct.

Tomographic studies emphasize that the simple onion-like layered image of the Earth, with velocities increasing with depth at the same rate everywhere, is an oversimplification. In reality, the velocities of seismic waves vary significantly with location at a given depth. Results of tomographic studies can be displayed by

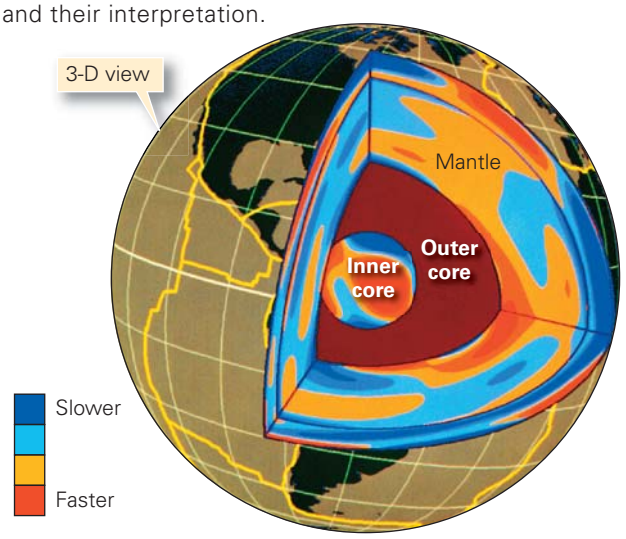
three-dimensional models, cross sections, or maps (Fig. D.8a, b). Generally, warmer colors (reds) on these images indicate slower and presumably warmer regions, whereas cooler colors (blues and purples) indicate faster and presumably cooler regions.

Even though many important questions remain, tomography has led geologists to picture the Earth's insides as a dynamic place (Fig. D.8c). This image should become even clearer, because a major research initiative, called **EarthScope**, has begun. This initiative involves placing hundreds of seismometers in an array across the United States. Just as digital photographs have higher resolution when taken by a camera with a 14-megapixel sensor than one with a 2-megapixel sensor, the greater number of seismometers in the EarthScope array provides a higher-resolution tomographic image of the Earth's interior.

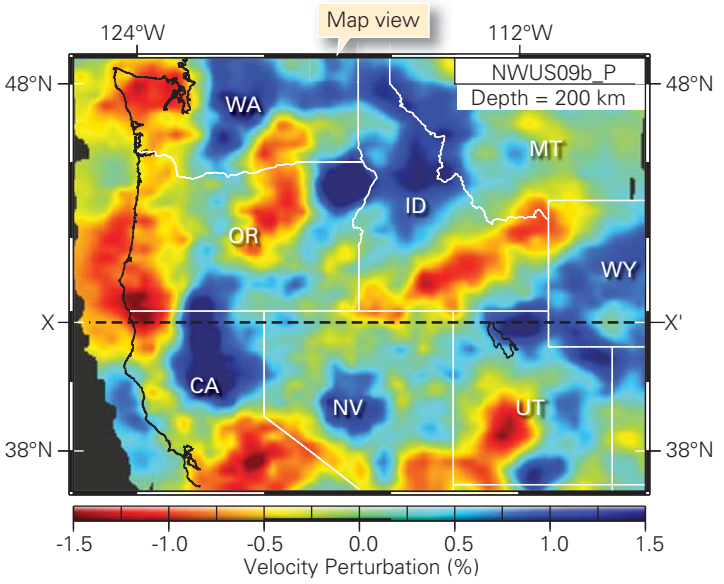
Seismic-Reflection Profiling

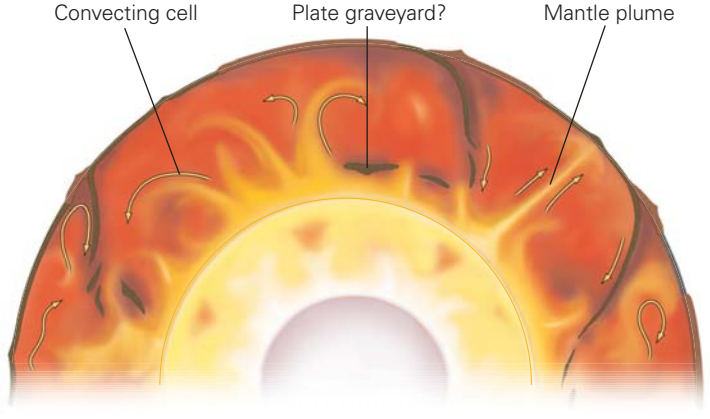
Seismic techniques are also letting us fine-tune our image of the upper crust. During the past half century, geologists have found that by exploding dynamite, by banging large weights against the Earth's surface, or by releasing bursts of compressed air into the water, they can create artificial seismic waves that propagate down into the Earth and reflect off the boundaries between different layers of rock in the crust. By recording the time at which these reflected waves return to the surface, geologists can determine the depth to these boundaries. With this information, they can produce a cross-sectional view of the crust called a **seismic-reflection profile** (Fig. D.9a, b). This image can define subsurface bedding and stratigraphic formation contacts, and can reveal the presence of subsurface

FIGURE D.8 Tomographic images of the Earth's interior, and their interpretation.

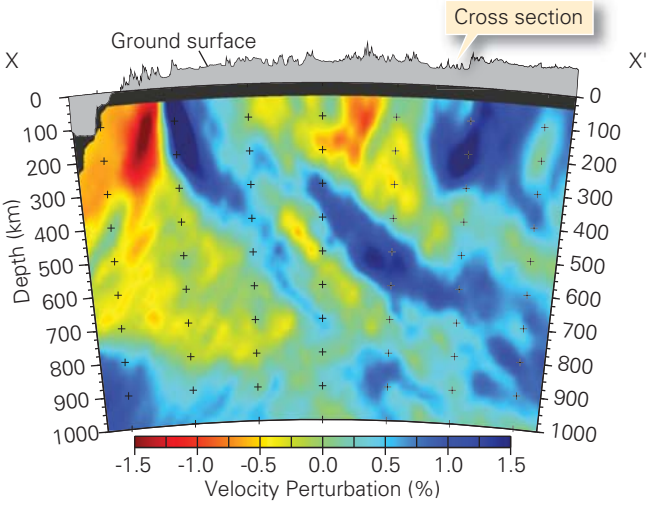


(a) Tomographic image of the Earth. Slower areas may be relatively cooler than their surroundings, and faster areas may be relatively warmer.





(c) An artist's rendition of a modern view of the complex and dynamic Earth interior. Note the convecting cells, the mantle plumes, and the graveyards of subducted plates.



(b) A map (of a surface at a depth of 200 km) and cross section of the Earth beneath the western United States, constructed using tomographic data from the EarthScope array.

folds (bends in layers) and faults. Oil companies obtain many seismic-reflection profiles, despite their high cost, because they allow geologists to identify likely locations for oil and gas reserves underground.

In the past decade, computers have become so sophisticated that geologists can now produce three-dimensional seismic-reflection images of the crust. From the 3-D data, they can produce profiles and maps in any orientation desired. These provide so much detail that geologists can even trace out a ribbon of sand, representing the channel of an ancient stream, now buried kilometers below the Earth's surface.

D.5 Earth's Gravity

Now that we have an image of the complexity of the Earth's interior, from our study of seismic waves, we can see how an understanding of gravity and magnetism, the two field forces that emanate from our planet, can provide even more information. Recall that a **field force** is a push or pull that applies across a distance—a field force exerted by one object can cause another object to *accelerate* (change speed and/or direction) without ever touching it. In this section, we discuss gravity, and in the next, we turn our attention to magnetism.

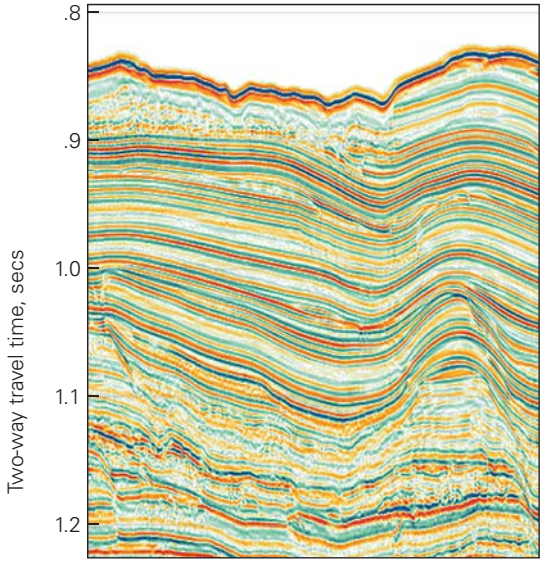
The Geoid

Gravity is an *attractive* field force that one mass exerts on another. As Newton showed, the magnitude of gravitational pull depends on the size of the masses and on the distance between them—larger masses exert stronger pulls than do smaller ones, and closer masses produce stronger pulls than do farther ones. When gravity acts on an object but can't make the object move, then the object has **gravitational potential energy**. For example, a boulder sitting at rest on a hill slope has gravitational potential energy. Every point on the surface of standing water in a still pond has the same gravitational potential energy. A surface on which all points have the same potential energy, such as the surface of standing water in a pond, is an **equipotential surface**.

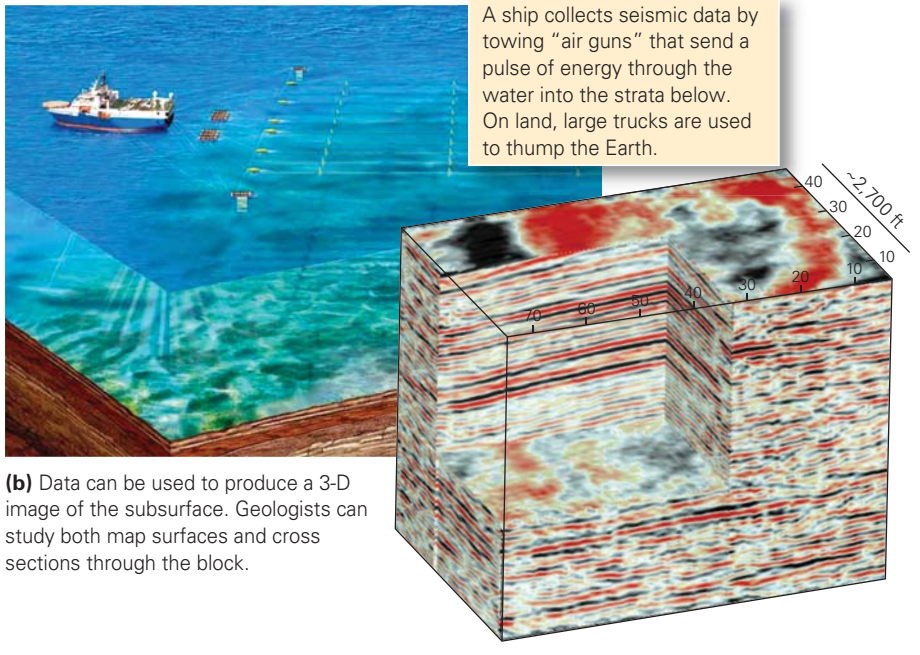
What does the gravitational field produced by a planet look like? In the jargon of physics, we can restate this question by asking, what does the gravitational equipotential surface of the Earth look like? We can picture this surface by imagining what sea level *would look like* (not what it really is) if an ocean completely surrounded the world and was not subjected to winds or currents. If the Earth were a stationary, perfect sphere, the equipotential surface representing its gravity would itself be a sphere. In reality, however, the equipotential surface is *not* a perfect sphere, in part because the Earth spins on an axis. Rotation produces centrifugal force, which flattens the Earth into a spheroid (**Fig. D.10a**). The imaginary spheroid that is closest to the Earth's shape is not exactly the real Earth, because in reality our planet has continents, ocean basins, mountains, and valleys—has a radius at the equator of 6,378 km (3,963 miles) and a radius at the pole of 6,357 km (3,950 miles). Put another way, we can say that the equipotential surface has a slight equatorial bulge. Geologists refer to this imaginary equipotential surface as the *reference geoid*.

While the reference geoid is a starting point for describing the Earth's gravity, it doesn't provide a completely accurate picture for many reasons, including (1) the density of material within the Earth's layers is not uniform through-

FIGURE D.9 Seismic-reflection profiling. The method allows geologists to see layers underground.

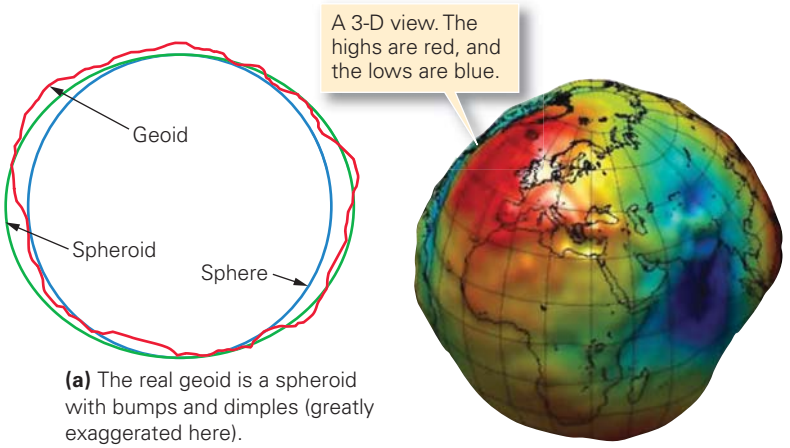


(a) After computer analysis, the data yield a seismic-reflection profile. Color bands represent horizons in the stratigraphic sequence.

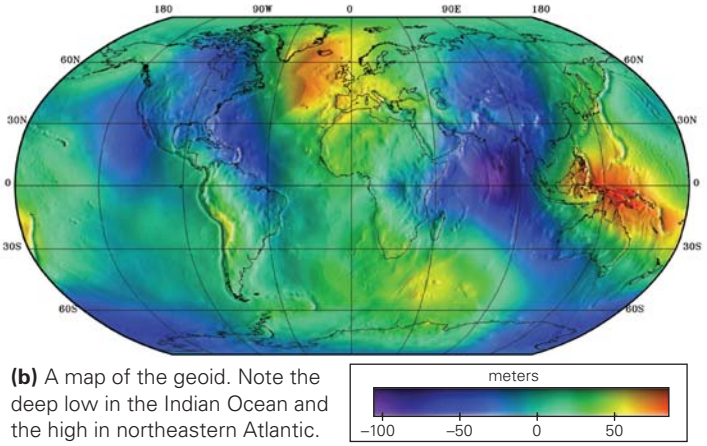


(b) Data can be used to produce a 3-D image of the subsurface. Geologists can study both map surfaces and cross sections through the block.

FIGURE D.10 Representations of the geoid, the shape of an equipotential surface representing Earth's gravity. Colors represent *elevations* of the geoid relative to the reference geoid.



(a) The real geoid is a spheroid with bumps and dimples (greatly exaggerated here).



(b) A map of the geoid. Note the deep low in the Indian Ocean and the high in northeastern Atlantic.

out the layer, as shown by tomographic studies; and (2) the lithosphere is strong enough to hold up heavy loads such as volcanoes or glaciers, or to allow depressions such as trenches to persist. Because of these factors, and others, there can be more mass or less mass at a location than the reference geoid predicts, so the *real* equipotential surface for the Earth has lumps and dimples. Geologists refer to this irregular surface, that provides the best representation of the Earth's gravity, simply as the **geoid** (Fig. D.10b). The surface of the Earth's real geoid differs from that of the reference geoid only slightly—the highest point on the real geoid lies 85 m above the reference geoid, and the lowest point lies 107 m below the reference geoid. But even these small differences can noticeably influence the orbits of satellites or the accuracy of surveys.

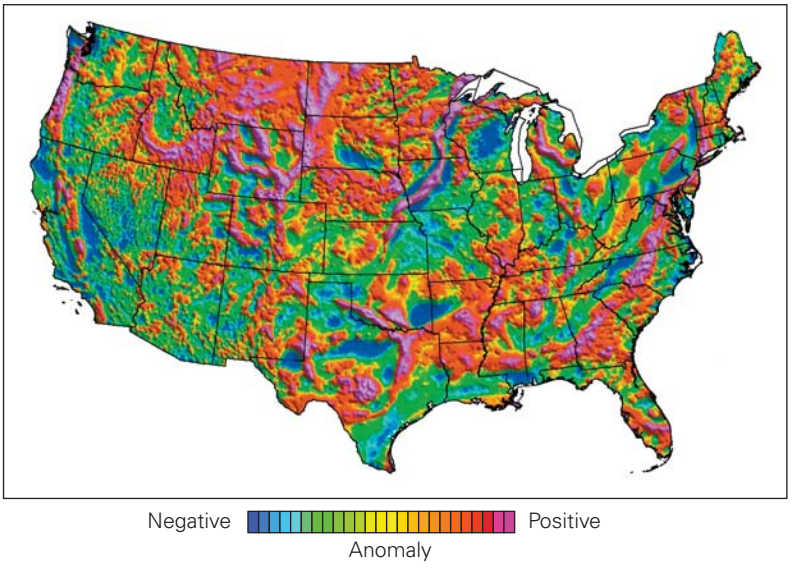
Gravity Anomalies and Isostasy

Geologists refer to a deviation of the observed (real) geoid from the reference geoid as a **gravity anomaly**. Over a positive anomaly, the pull is stronger, whereas over a negative anomaly, the pull is weaker. A positive anomaly indicates that there is extra mass below the site, perhaps due to a body of particularly dense rock underground, whereas a negative anomaly means that there is a deficit of mass, perhaps due to the presence of less-dense rock (Fig. D.11).

Gravity anomalies also provide key information about the nature of the Earth's interior. To see why, we need to introduce the concept of isostasy, whose basis stems from the work of a Greek mathematician, Archimedes (ca. 287–212 B.C.E.). Archimedes had been puzzling over the question of why some objects float and others sink, until one day when, according to legend, he noticed the water level rise in a tub as he stepped in to take a bath. He realized that this meant that an object displaces water as it sinks into it, and that if the density of the object exceeds that of water, it sinks, but if it is less dense, it floats. Further, a floating object sinks into water only until it has displaced an amount of water whose mass equals the mass of the whole object. These relationships are now known as **Archimedes' principle**.

According to Archimedes' principle, a cargo ship anchored in a harbor floats at just the right level so that the mass of the water displaced by the ship equals the mass of the whole ship. Even though the ship consists of heavy steel, the inside of the ship is filled with air, so the ship, in effect, is a steel-sheathed bubble—it floats because its overall *average* density is less than that of water. When the ship remains empty, the distance that its deck lies above the water, its so-called "freeboard", is large (Fig. D.12). Addition of heavy cargo causes the ship's keel to sink deeper into the water, the deck to move down, and the freeboard, therefore, to decrease. This movement can take place because the water beneath the ship can flow out of the way as the ship settles downward. When the freeboard of the ship is just right for a given cargo, we say that the ship is in "isostatic equilibrium," or that a condition of **isostasy** exists.

FIGURE D.11 A gravity anomaly map of the United States. On this map, colors represent variations in the magnitude of gravitational pull.



As you learned in Chapter 2, the outer layer of the Earth, the lithosphere, can be thought of as a relatively rigid shell that "floats" on the underlying, relatively soft asthenosphere. Asthenosphere can flow out of the way of sinking lithosphere or flow in under rising lithosphere, just like water does beneath a ship, but much more slowly. Thus the lithosphere approaches a condition of isostatic equilibrium in many places, so the elevation of the lithosphere's surface reflects the density and thickness of the lithosphere.

The lithosphere behaves somewhat like the ship—addition of a load, such as growth of an ice sheet or the building of a volcano, causes the surface of the lithosphere to sink, whereas removal of a load, say by melting of an ice sheet, causes the surface of the lithosphere to rise as it tries to attain isostatic equilibrium. But since asthenosphere flows so slowly, there are places on Earth where isostasy has not yet been achieved. We observe gravity anomalies over such places. We discuss isostasy again in Chapter 9, to see how it is involved in the uplift of mountain ranges.

D.6 Earth's Magnetic Field, Revisited

As we discussed in Chapters 1 and 2, the Earth behaves like a weak magnet and thus produces a magnetic field, which is a "dipole" with a north end and a south end. Information about this magnetic field can be locked into rock and preserved as paleomagnetism. Here, in Interlude D, we look more closely at the magnetic field, focusing on why the field exists and on why there are variations in the field strength on land and on sea.

Origin of the Earth's Magnetic Field

Why does the Earth have a magnetic field? We take the existence of the field for granted because we are so accustomed to using compasses. But not all planets have fields—in fact, neither Mars nor Venus, the two planets most like the Earth, has measurable fields. The path toward discovering the origin of the Earth's field started in 1926, when researchers learned that our planet's outer core consists of liquid iron alloy. Physicists demonstrated that flow of metal can produce an electric current, so it seemed that the flow of the outer core must be responsible for the magnetic field. But how?

Clues to understanding the generation of the Earth's magnetic field come from understanding how an electric power plant works. In a power plant, water or wind power spins a wire coil (an electrical conductor) around an iron bar (a permanent magnet); the motion of the wire in the bar's magnetic field generates an electric current in the wire. Such an apparatus is called a **dynamo**. In the case of the Earth, flow in the outer core serves the role of the spinning wire coil, making the outer core behave like an electromagnet. But the inner core probably can't serve the role of the permanent magnet, because it is too hot—magnets can only be permanent at relatively low temperatures. Researchers suggest instead that the Earth is a **self-exciting dynamo**. Evidently, during the Earth's early history, flow in the outer core took place in the presence of a magnetic field. This flow generated an electric current, and once the current existed it generated a magnetic field. Continued flow in the presence of the generated magnetic field produced more electric current that, in turn, maintained the magnetic field. Once started, the system perpetuates itself, as long as there's an input of energy to keep the liquid iron alloy of the outer core in motion.

So the question now becomes, what causes the outer core to keep moving? Recent calculations suggest that as the Earth cools overall, the diameter of the solid inner core grows (by about 0.1 to 1 mm in diameter per year) at the expense of the outer core. The process of crystallization releases both heat and lower-density elements (such as silicon, sulfur, hydrogen, carbon, or oxygen) into the base of the outer core. The expulsion of "light" elements occurs because the solid iron crystals comprising the inner core do have room in their crystal structure for atoms of these elements. The higher temperatures and higher concentration of lighter elements makes the base of the outer core *less dense* than the top, so the base of the outer core becomes buoyant. Since the molten outer core is liquid, and therefore weak, the buoyancy force can cause the less-dense material at the base of the outer core to rise. As this happens, denser material at the top of the outer core starts to sink. During such convection, material follows a curving path known as a convection cell.

The key to understanding the *polarity* of the Earth's magnetic field comes from understanding the *geometry* of the convection cells in the outer core. Researchers suggest that the Coriolis force (see Chapter 15) causes convective cells in the outer core to become spirals that align roughly with the

FIGURE D.12 A ship analog for the concept of isostasy. At isostatic equilibrium, the freeboard reflects Archimedes' principle, so the freeboard decreases as the mass of the ship increases. Water flows out of the way as the ship moves down (right image).

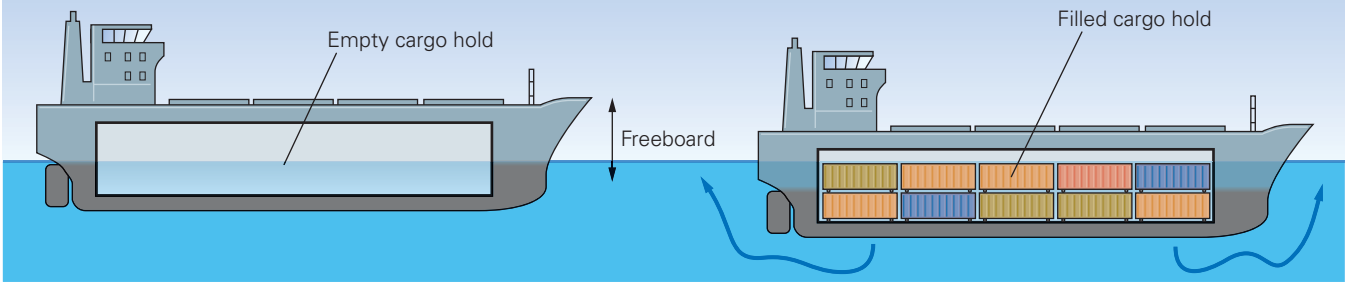
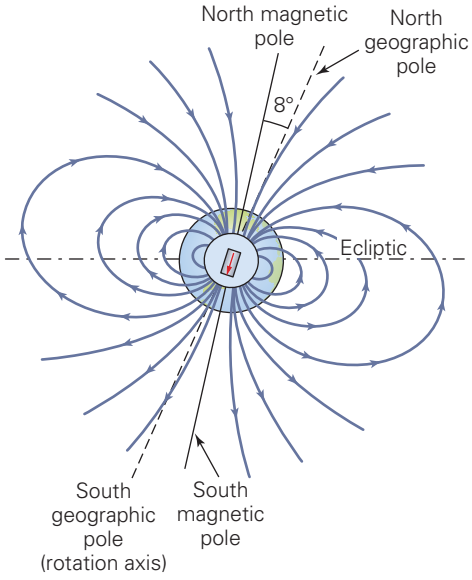
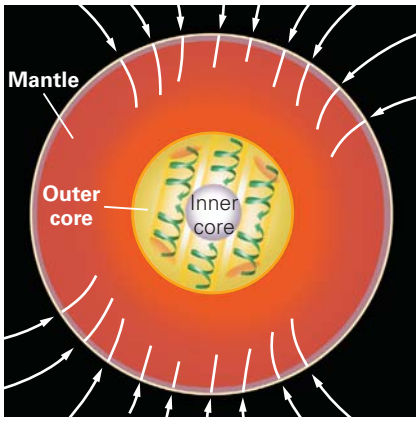


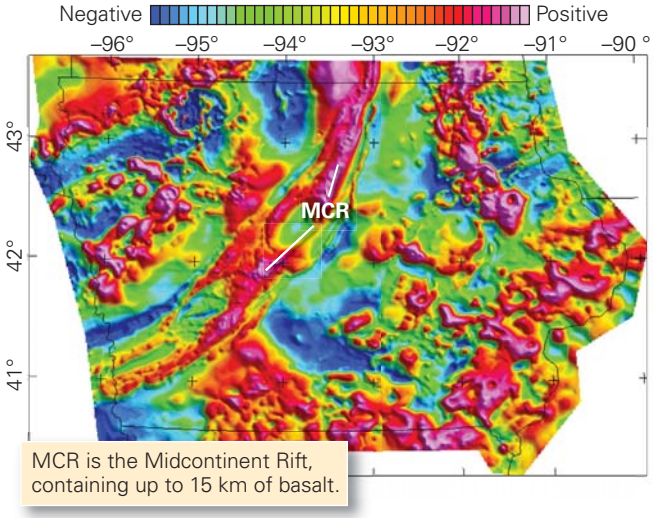
FIGURE D.13 Earth's magnetic field may be due to spiral-like convection cells in the outer core.



(a) The geometry of Earth's dipole field.



(b) An artist's image of spiral convection cells in the outer core.



(c) Gravity anomaly map of Iowa. Red areas have anomalously high gravity, and blue areas have anomalously low gravity.

Earth's spin axis. The spirals wobble, so that at any given time, the overall dipole axis they generate is not exactly parallel to the spin axis. Notably, the spirals may apply a force to the inner core, causing it to rotate slightly faster than the rest of the Earth. This phenomenon is known as **superrotation**. Computer models suggest that polarity reversals happen because the spirals are unstable. Over time, spirals slow and fade away causing the magnetic field to weaken or disappear temporarily. As new spirals become established, the field reappears, possibly with a different polarity.

Magnetic Anomalies, Revisited

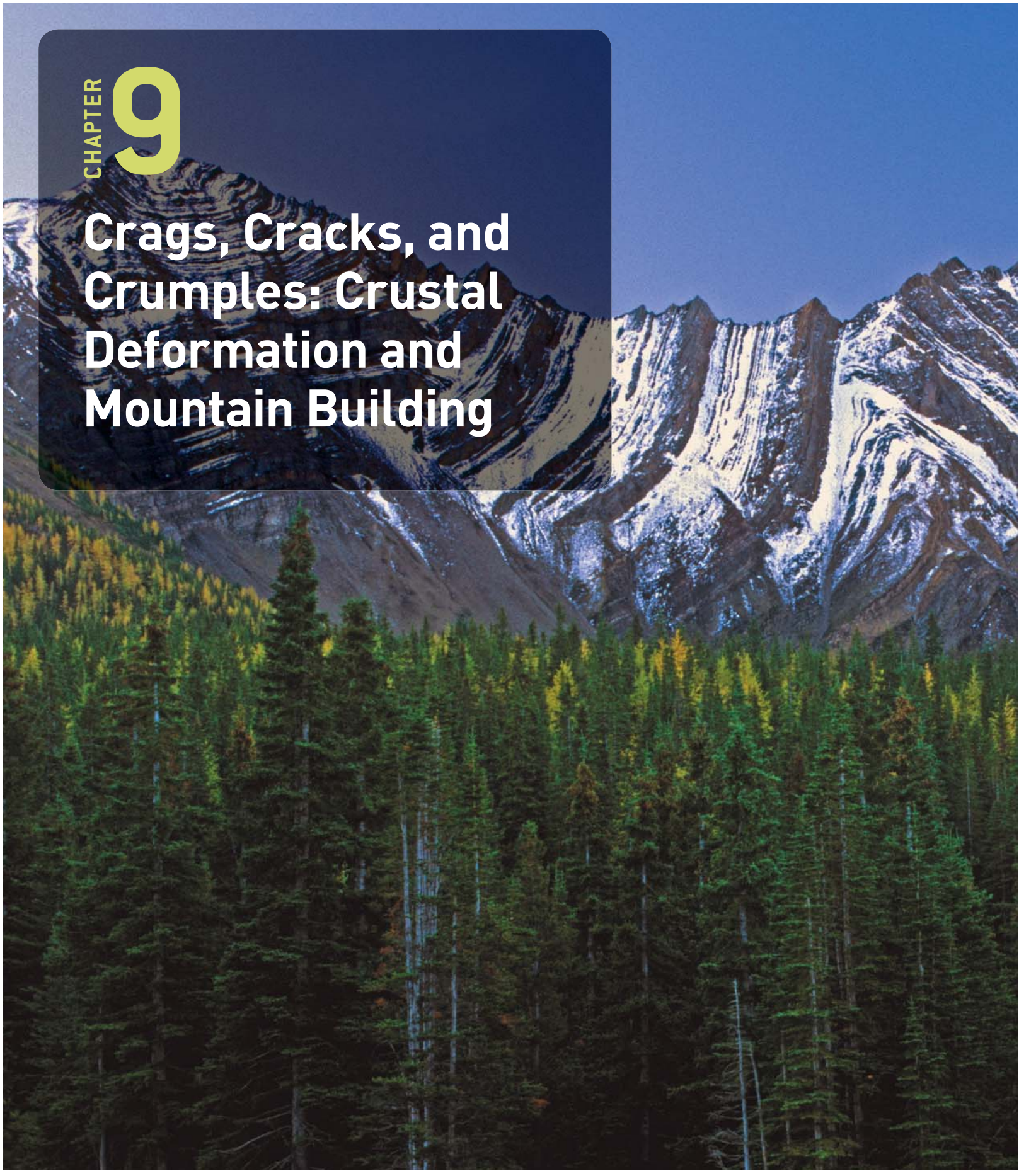
Close examination of the Earth's magnetic field indicates that it *is not a perfect dipole*. If it were, physicists could predict what the field strength would be at every point on the planet with a high degree of confidence. That isn't the case, because two other factors contribute to the field strength measured at a given location, and cause the field to be either stronger than or weaker than expected at the location. As mentioned in Chapter 2, the difference between the expected field and the measured field at a locality is called a **magnetic anomaly**. A positive anomaly occurs where the field is stronger than expected, and a negative anomaly occurs where the field is weaker than expected.

The presence of magnetic rocks in the crust will produce local magnetic anomalies that are independent of the Earth's internal magnetic field (**Fig. D.13a, b**). We've seen in Chapter 2 that magnetic anomalies due to the magnetization of rocks take the form of parallel stripes on the sea floor.

On continents, in contrast, the pattern of magnetic anomalies is much more complex, for the distribution of rock types is more complex (**Fig. D.13c**). We see anomalies due to igneous intrusions, due to lava flows, due to concentrations of iron-rich sediments, and due to variations in the depth to basement.

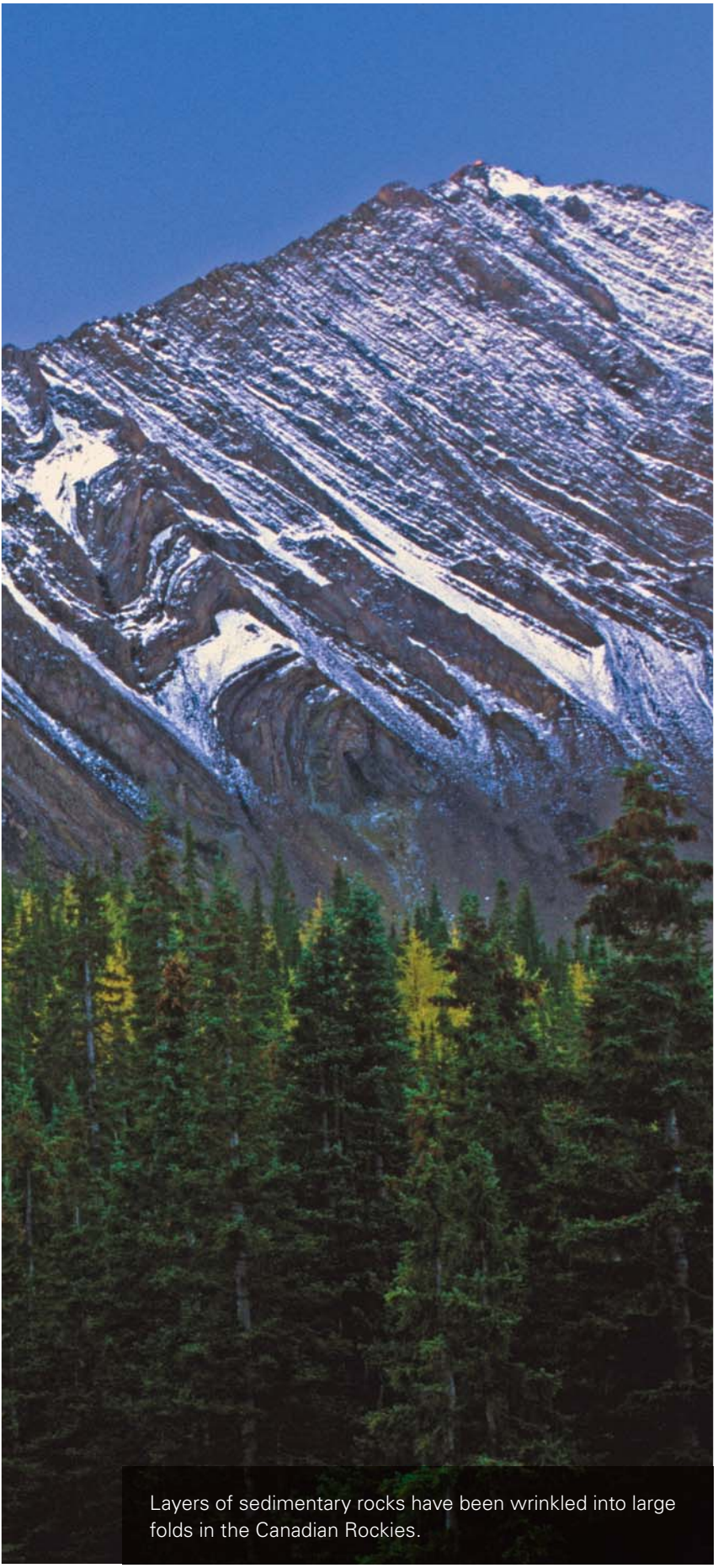
Key Terms

Archimedes' principle (p. 261)
core-mantle boundary (p. 257)
dynamo (p. 262)
EarthScope (p. 259)
equipotential surface (p. 260)
field force (p. 260)
geoid (p. 261)
geophysics (p. 253)
gravitational potential energy (p. 260)
gravity anomaly (p. 261)
inner core (p. 258)
isostasy (p. 261)
lower mantle (p. 256)
low-velocity zone (LVZ) (p. 255)
magnetic anomaly (p. 263)
Moho (p. 255)
outer core (p. 258)
P-wave shadow zone (p. 257)
reflection (p. 254)
refraction (p. 254)
seismic ray (p. 254)
seismic-reflection profile (p. 259)
seismic tomography (p. 258)
seismic-velocity discontinuity (p. 256)
self-exciting dynamo (p. 262)
superrotation (p. 263)
S-wave shadow zone (p. 258)
transition zone (p. 256)
travel time (p. 254)
upper mantle (p. 256)
velocity-versus-depth curve (p. 258)
wave front (p. 254)



CHAPTER 9

Crags, Cracks, and Crumples: Crustal Deformation and Mountain Building



Layers of sedimentary rocks have been wrinkled into large folds in the Canadian Rockies.

Chapter Objectives

By the end of this chapter, you should know . . .

- how rocks can deform (crack, bend, or flow) during mountain building, in response to stresses.
- the characteristics of basic geologic structures (joints, faults, folds, foliations) and how to describe them.
- where and why mountain belts form, what processes cause their uplift, and how their formation relates to plate tectonics.

Innumerable peaks, black and sharp, rose grandly into the dark blue sky, their bases set in solid white, their sides streaked and splashed with snow, like ocean rocks with foam. . . . [Mountains] are nature's poems carved on tables of stone.

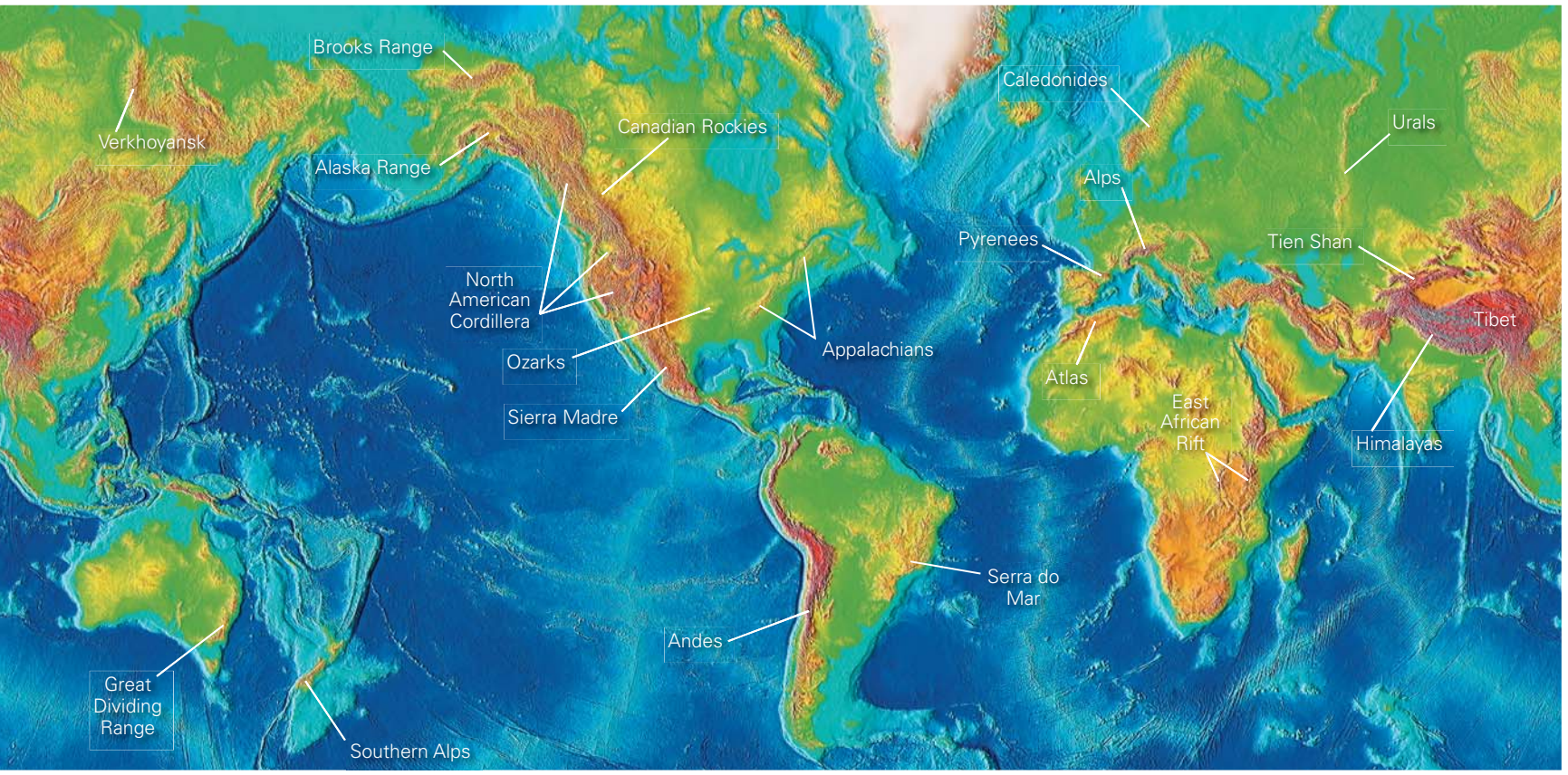
—John Muir (1838–1914), American naturalist

9.1 Introduction

Geographers call the peak of Mt. Everest "the top of the world," for this mountain, which lies in the Himalayas of south Asia, rises higher than any other on Earth. The cluster of flags on Mt. Everest's summit flap at 8.85 km (29,029 feet) above sea level—almost the cruising height of modern jets. No one can survive very long at the top, for the air there is too thin to breathe. In 1953, Sir Edmund Hillary, from New Zealand, and Tenzing Norgay, a Nepalese guide, became the first to reach the summit. More than 4,500 other people have also succeeded—but more than 200 people have died trying.

Mountains draw nonclimbers as well, for everyone loves a vista of snow-crested peaks. The stark cliffs, clear air, meadows, forests, streams, and glaciers of mountains provide a refuge from the mundane. Geologists are fascinated with mountains, for they provide one of the most obvious indications of dynamic activity on Earth. To make a mountain, cubic kilometers of rock must rise skyward against the pull of gravity. With the exception of the large volcanoes formed over hot spots, a mountain does not occur in isolation, but rather as part of a linear range called a mountain belt or **orogen** (from the Greek words *oros*, meaning mountain, and *genesis*, meaning formation). Geographers define about a dozen major orogens and numerous smaller ones worldwide (**Fig. 9.1**).

FIGURE 9.1 Digital map of world topography, showing the locations of major mountain ranges.



The process of forming a mountain belt not only raises the surface of the crust, a process called **uplift**, but also causes rocks to undergo **deformation**, a process by which rocks bend, break, or flow in response to "stress" (compression, tension, or shearing). Deformation produces geologic structures, including **joints** (cracks), **faults** (fractures on which one body of rock slides past another), **folds** (bends, curves, or wrinkles of rock layers), and **foliation** (layering of fabrics resulting from the alignment of mineral grains or the development of compositional bands). Mountain building may also involve metamorphism and igneous activity.

A mountain-building event, or *orogeny*, may last for tens of millions of years. As the land rises, erosion starts to grind it away, producing sediment and sculpting awesome, jagged topography. When the process of uplift ceases, erosion can eventually bevel a range down to near sea level in tens of millions of years. But even after the high peaks are gone, a low-lying belt of fractured, contorted, and metamorphosed rock remains. Such crustal scars serve as a permanent monument to what had once been a region of high peaks.

Did you ever wonder . . .
do mountain belts last forever?

In this chapter, we first learn about the process of deforming rocks, and about how to describe and interpret the geologic structures that result from deformation. Then, we turn our attention to the question of why mountain belts form, in the context of plate tectonics theory. Finally, we consider the phenomena that sculpt uplifts to form the spectacular peaks and valleys that we can see when visiting mountains.

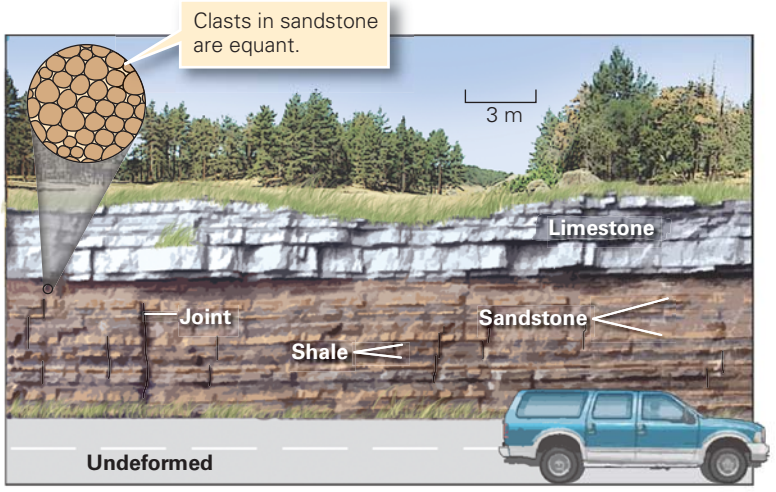
9.2 Rock Deformation

What Are Deformation and Strain?

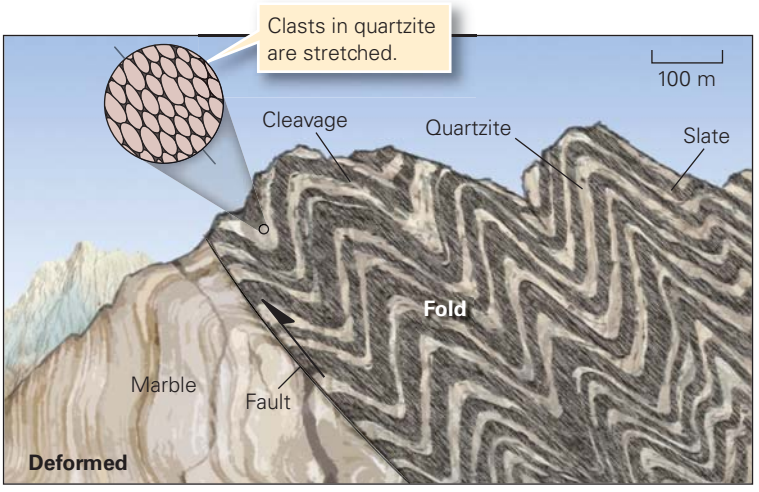
To get a visual sense of what geologists mean by the term deformation, let's contrast rock that has *not* been affected by an orogeny with rock that has been affected. Our "undeformed" example comes from a road cut in the Great Plains of North America, and our "deformed" example comes from a cliff in the Alps of Europe (**Fig. 9.2a, b**).

The road cut, which lies at an elevation of only 100 m above sea level, exposes nearly horizontal beds of sandstone, shale, and limestone—these beds have the same orientation that they had when first deposited. Sand grains in the sandstone of this outcrop have a nearly spherical shape (the same shape they had when deposited), and clay flakes in the shale

FIGURE 9.2 Deformation changes the character and configuration of rocks.



(a) Flat-lying beds of strata along a highway in the Great Plains of North America are essentially undeformed. A few joints, formed when overlying rock eroded away, are visible.



(b) In a mountain belt, deformation may cause layers to undergo folding and faulting. In addition, foliation (such as slaty cleavage) and stretched clasts may develop.

lie roughly parallel to the bedding (because of compaction). When we say that rock of this outcrop is undeformed, we mean that it contains no geologic structures other than a few joints.

Rocks of the Alpine cliff, exposed at an elevation of 3 km, look very different. Here, we find layers of quartzite, slate, and marble (the metamorphic equivalents of sandstone, shale, and limestone). The layers are cut by joints, but they have also been contorted into folds. On closer examination, we also note that the grains in the quartzite aren't spherical, like those of a sandstone, but have been flattened so that they are somewhat elliptical. And in the slate, clay flakes are aligned to form a type of foliation called slaty cleavage (see Chapter 7). Finally, if we try tracing the quartzite and slate layers along the outcrop face, we might find that they abruptly terminate at a sloping surface marked by broken-up rock. This surface is a fault. In our example, thick layers of marble lie below the fault—the quartzite and slate must have moved along the fault from where they first formed to get to their present location juxtaposed against the marble.

Study of the types of geologic structures that we see in the Alpine cliff emphasize that during deformation, rocks can undergo one or more of the following (Fig. 9.3a–c): (1) a change in location (displacement); (2) a change in orientation (rotation); and (3) a change in shape (distortion). Geologists commonly refer to distortion as **strain**. We distinguish among different kinds of strain according to the nature of the shape change developed during deformation. If a layer of rock becomes longer, it has undergone *stretching*, but if the layer becomes shorter, it has undergone *shortening* (Fig. 9.4a–c). And, if a change in shape involves the movement of one part of a rock body past another so that angles between features in the rock change, the result is called *shear strain* (Fig. 9.4d, e).

Brittle versus Ductile Deformation

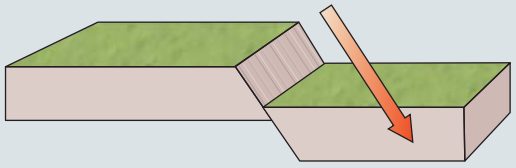
Imagine that a plate tumbles off a table and lands on a hard floor—the plate breaks and smashes into pieces. Similarly, if you strike a glass window with a hammer, the window cracks and may even shatter. Such cracking and breaking serve as familiar examples of **brittle deformation** (Fig. 9.5a, b). Now, imagine that you squeeze a ball of soft dough between a book and a tabletop—the dough flattens into a pancake. Similarly, if you bend a stick of chewing gum, it changes from a plane into a curve. During such **ductile deformation**, objects change shape without visibly breaking (Fig. 9.5c, d).

What actually happens within mineral grains during these two different kinds of deformation? Recall that the atoms that make up mineral grains are connected by chemical bonds. During brittle deformation, many bonds break and stay broken, leading to the formation of a permanent crack across which material no longer connects. During ductile deformation, some bonds break but new ones quickly form. In this way, the atoms within grains rearrange, and the grains change shape without permanent cracks forming.

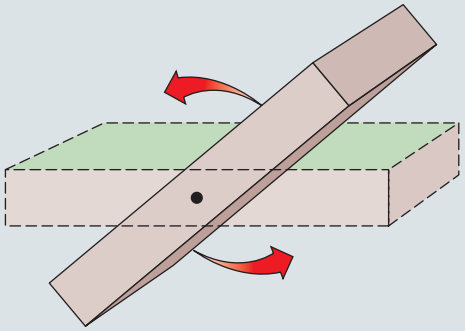
Why do rocks inside the Earth sometimes deform brittlely and sometimes ductilely? The behavior of a rock depends on:

- *Temperature*: Warmer rocks tend to deform ductilely, whereas colder rocks tend to deform brittlely. Heat makes materials softer.
- *Pressure*: Under great pressures deep in the Earth, rock behaves more ductilely than it does under low pressures near the surface. Pressure effectively prevents rock from separating into fragments.
- *Deformation rate*: A sudden change in shape causes brittle deformation, whereas a slow change in shape causes ductile

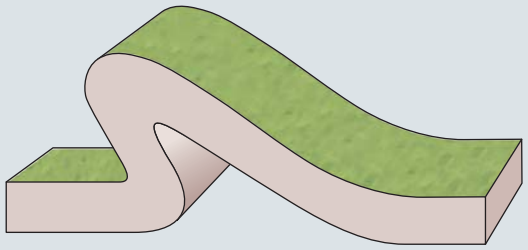
FIGURE 9.3 The components of deformation include displacement, rotation, and distortion.



(a) Displacement occurs when a block of rock moves from one place to another.

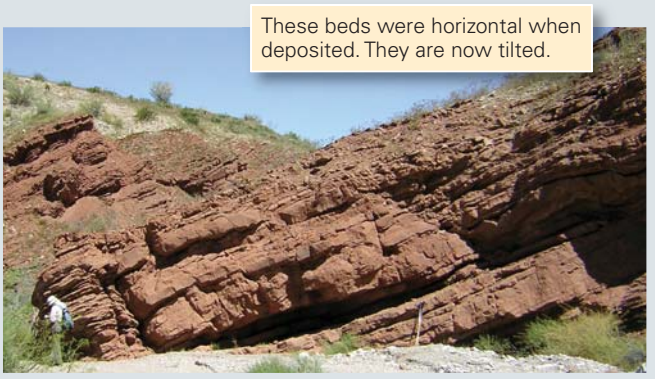


(b) Rotation occurs when a body of rock undergoes tilting.



(c) Distortion occurs when rock changes shape. The development of a fold represents one type of distortion.







deformation. For example, if you hit a marble bench with a hammer, it shatters, but if you leave the bench alone for a century, it gradually sags without breaking.

- *Composition*: Some rock types are softer than others; for example, halite (rock salt) deforms ductilely under conditions in which granite deforms brittlely.

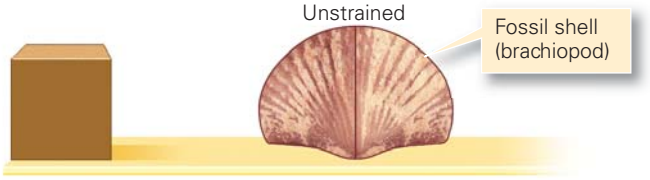
Considering that pressure and temperature both increase with depth in the Earth, geologists find that, in typical continental crust, rocks generally behave brittlely above a depth of about 10 to 15 km, and ductilely below this depth. The depth at which this change in behavior takes place is called the *brittle–ductile transition*. Earthquakes in continental crust happen only above this depth because these earthquakes involve brittle breaking.

Stress and the Causes of Deformation

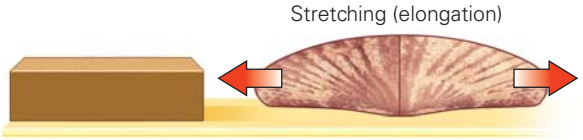
Up to this point, we've focused on picturing the consequences of deformation. Describing the causes of deformation is a bit more challenging. In captions for displays about mountain building, museums and national parks typically dispense with the issue by using the phrase "The mountains were caused by forces deep within the Earth." But what does this mean? Isaac Newton stated that a force can cause an object to speed up, slow down, or change direction. In the context of geology, plate interactions and continent-continent collisions apply forces to rock and thus cause rock to change location, orientation, or shape. In other words, the application of forces in the Earth indeed causes deformation.

Geologists, however, use the word *stress* instead of *force* when talking about the cause of deformation. We define the **stress** acting on a plane as the force applied per unit area of the plane. The need to distinguish between stress and force arises because the actual consequences of applying a force depend not just on the amount of force but also on the area over which the force acts. A pair of simple experiments shows why (Fig. 9.6a). Experiment 1: Stand on a single, empty aluminum can. All of your weight—a force—focuses entirely on the can, and the can crushes. Experiment 2: Place a board atop 100 cans and stand on the board. In this case, your weight is distributed across 100 cans, and the cans don't crush. In both experiments, the force caused by the weight of your body was the same, but in Experiment 1 the force was applied over a small area so a large stress developed, whereas in Experiment 2 the same force was

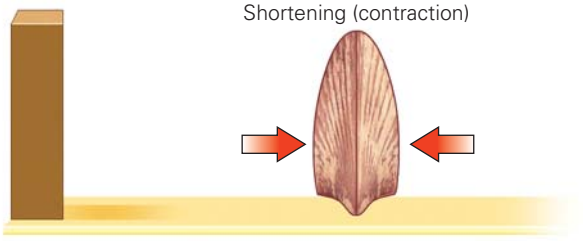
FIGURE 9.4 Different kinds of strain in rock. Strain is a measure of the distortion, or change in shape, that takes place in rock during deformation.



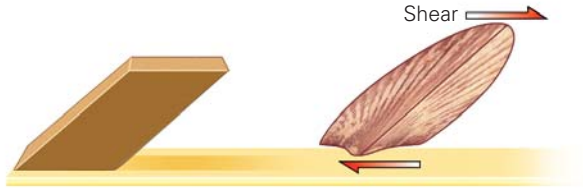
(a) An unstrained cube and an unstrained fossil shell (brachiopod).



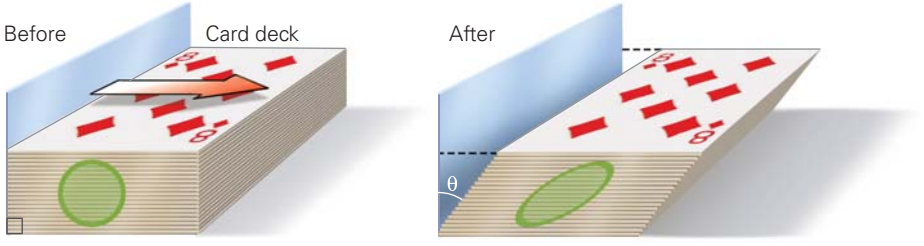
(b) Horizontal stretching changes the cube into a horizontal brick and elongates the shell.



(c) Horizontal shortening changes the cube into a vertical brick and makes the shell narrower.

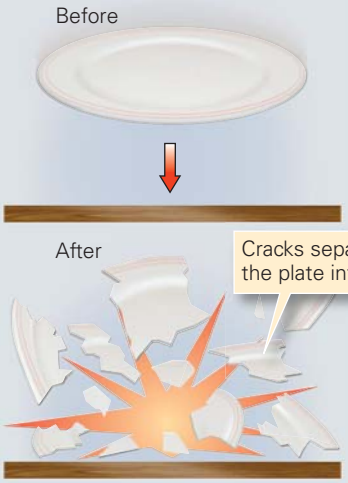


(d) Shear strain tilts the cube and transforms it into a parallelogram, and changes angular relationships in the shell.

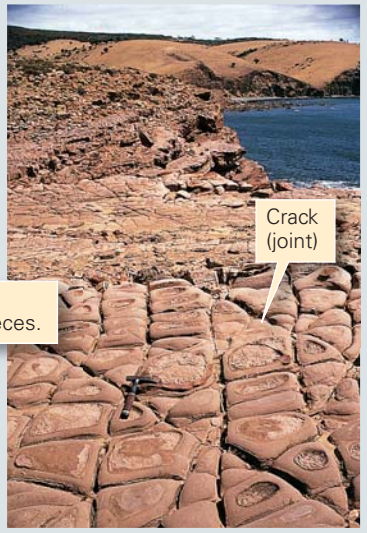


(e) You can produce shear strain by moving a deck of cards so that each card slides a little with respect to the one below.

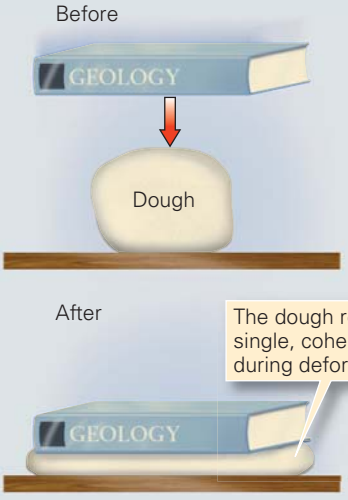
FIGURE 9.5 Brittle versus ductile deformation.



(a) Brittle deformation occurs when you drop a plate and it shatters.



(b) Cracks in an Australian outcrop are due to brittle deformation.

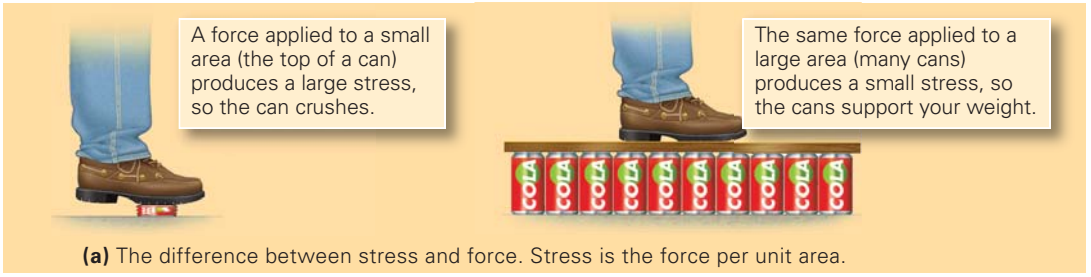


(c) Ductile deformation occurs when you squash a ball of dough.

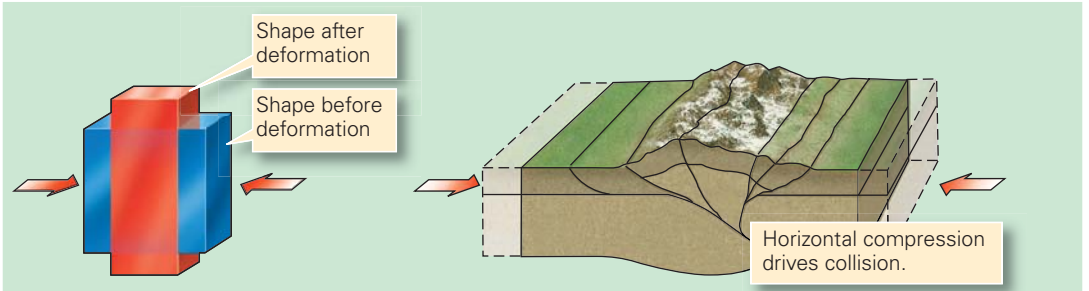


(d) Swirls in the marble of this Brazilian cliff formed ductilely.

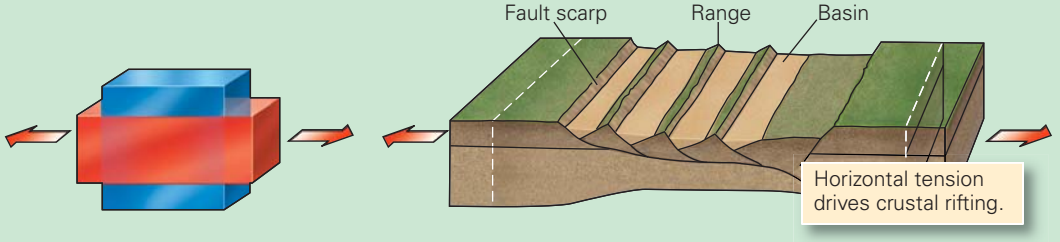
FIGURE 9.6 There are several kinds of stress.



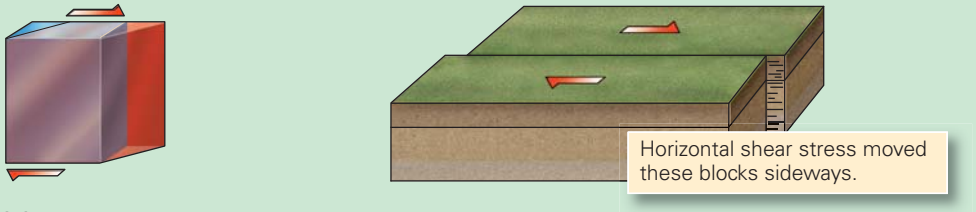
(a) The difference between stress and force. Stress is the force per unit area.



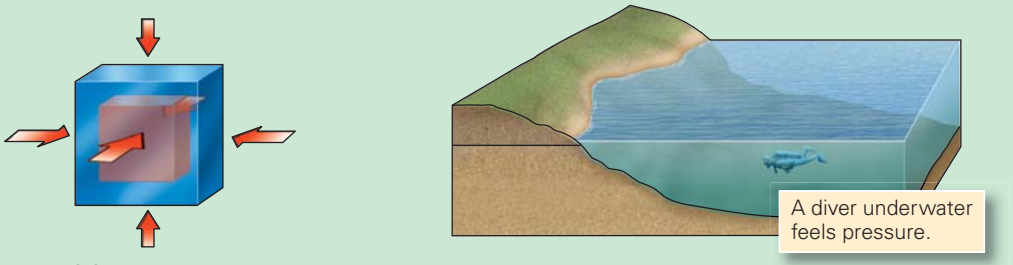
(b) Compression takes place when an object is squeezed.



(c) Tension occurs when the opposite ends of an object are pulled in opposite directions.



(d) Shear stress develops when one surface of an object slides relative to the other surface.



(e) Pressure occurs when an object feels the same stress on all sides.

Different kinds of stress occur in rock bodies (Fig. 9.6b–e). **Compression** takes place when a rock is squeezed, **tension** occurs when a rock is pulled apart, and **shear stress** develops when one part of a rock body moves sideways past another. **Pressure** refers to a special stress condition that happens when the same push acts on all sides of an object.

Note that *stress* and *strain* have very different meanings to geologists, even though we tend to use the words interchangeably in everyday English: stress refers to the amount of force applied per unit area of a rock, whereas strain refers to a change in shape of a rock. Thus, *stress causes strain*. Specifically, compression causes shortening, tension leads to stretching, and shear stress produces shear strain. Pressure can cause an object to become smaller, but will not cause it to change shape. With our knowledge of stress and strain, we can now look at the nature and origin of various classes of geologic structures.

Take-Home Message

Stress (compression, tension, shear) can cause rocks to change shape, position, and orientation. During brittle deformation, rocks break, whereas during ductile deformation, rocks bend and distort without breaking. Strain is a measure of shape change.

applied over a large area so only a small stress developed. How does this concept apply to geology? During mountain building, the force of one plate interacting with another is distributed across the area of contact between the two plates, so the deformation resulting at any specific location actually depends on the stress developed at that location, not on the total force produced by the plate interaction.

9.3 Brittle Structures

Joints and Veins

If you look at the photographs of rock outcrops in this book, you'll notice thin dark lines that cross the rock faces. These lines represent traces of natural cracks along which the rock broke

and separated into two pieces during brittle deformation. Geologists refer to such natural cracks as **joints** (Fig. 9.7a, b). Rock bodies do *not* slide past each other on joints. Since joints are roughly planar structures, we define their orientation by their strike and dip, as described in Box 9.1.

Joints develop in response to tensile stress in brittle rock: a rock splits open because it has been pulled slightly apart. Joints may form for a variety of geologic reasons. For example, some joints form when a rock cools and shrinks because the process makes one part of a rock pull away from the adjacent part. Others develop when rock formerly at depth undergoes a decrease in pressure as overlying rock erodes away, and thus changes shape slightly. Still others form when rock layers bend.

Geotechnical engineers, people who study the geologic setting of construction sites, pay close attention to jointing when recommending where to put roads, dams, and buildings. Water flows much more easily through joints than it does through solid rock, so it would be a bad investment to situate a water reservoir over rock containing lots of joints—the water would leak down into the joints. Also, building a road on a steep cliff composed of jointed rock could be risky, for joint-bounded blocks separate easily from bedrock, and the cliff might collapse.

If groundwater or hydrothermal fluids seep through cracks in rocks, minerals such as quartz or calcite may precipitate out of the groundwater and fill the crack. A mineral-filled crack is called a **vein**. Veins may look like white stripes cutting across a body of rock (Fig. 9.7c). Some veins contain small quantities of valuable metals, such as gold.

Faults: Surfaces of Slip

After the San Francisco earthquake of 1906, geologists found a rupture that had torn through the land surface near the city. Where this rupture crossed orchards, it offset rows of trees, and where it crossed a fence, it broke the fence in two; the western side of the fence moved northward by about 2 m (see Fig. 8.4a). The rupture represents the trace of the San Andreas Fault. As we have seen, a fault is a fracture on which sliding occurs, and slip events, or faulting, can generate earthquakes. Faults, like joints, are planar structures, so we can represent their orientation by strike and dip.

Faults have formed throughout Earth history. Some are currently *active* in that sliding has been occurring on them in recent geologic time, but most are *inactive*, meaning that sliding on them ceased long ago. Some faults, such as the San Andreas, intersect the ground surface and thus displace the ground when they move. Others accommodate the sliding of rocks in the crust at depth and remain invisible at the surface unless they are later exposed by erosion.

Fault Classification

Not all faults result in the same kind of crustal deformation—some accommodate horizontal shear, some accommodate shortening, and some accommodate stretching. It's important for geologists to distinguish among different kinds of faults in order to interpret their tectonic significance. Fault classification focuses on two characteristics of faults: (1) the *dip* of the fault surface (see Box 9.1)—the dip can be vertical, horizontal, or any angle in between; and (2) the *shear sense* across the fault—by shear sense, we mean the direction that material on one side of the fault moved relative to the material on the other side. With this concept in mind, let's consider the principal kinds of faults.

- *Strike-Slip Faults*: A **strike-slip fault** is a fault on which the slip direction is parallel to a strike line, a horizontal line on

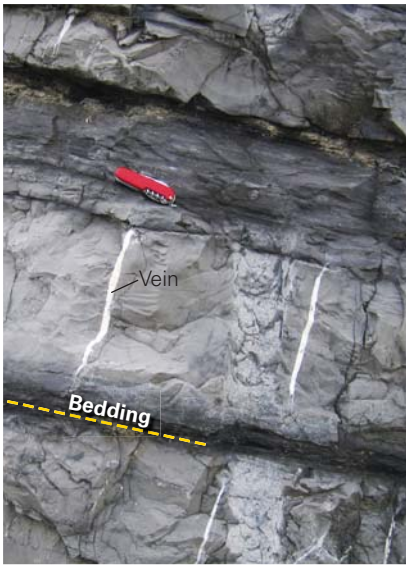
FIGURE 9.7 Examples of joints and veins.



(a) Prominent vertical joints cut red sandstone beds in Arches National Park, Utah, as seen from the air.



(b) Vertical joints on a cliff face in shale near Ithaca, New York.



(c) Milky white quartz veins cut across gray limestone beds.

BOX 9.1 CONSIDER THIS . . .

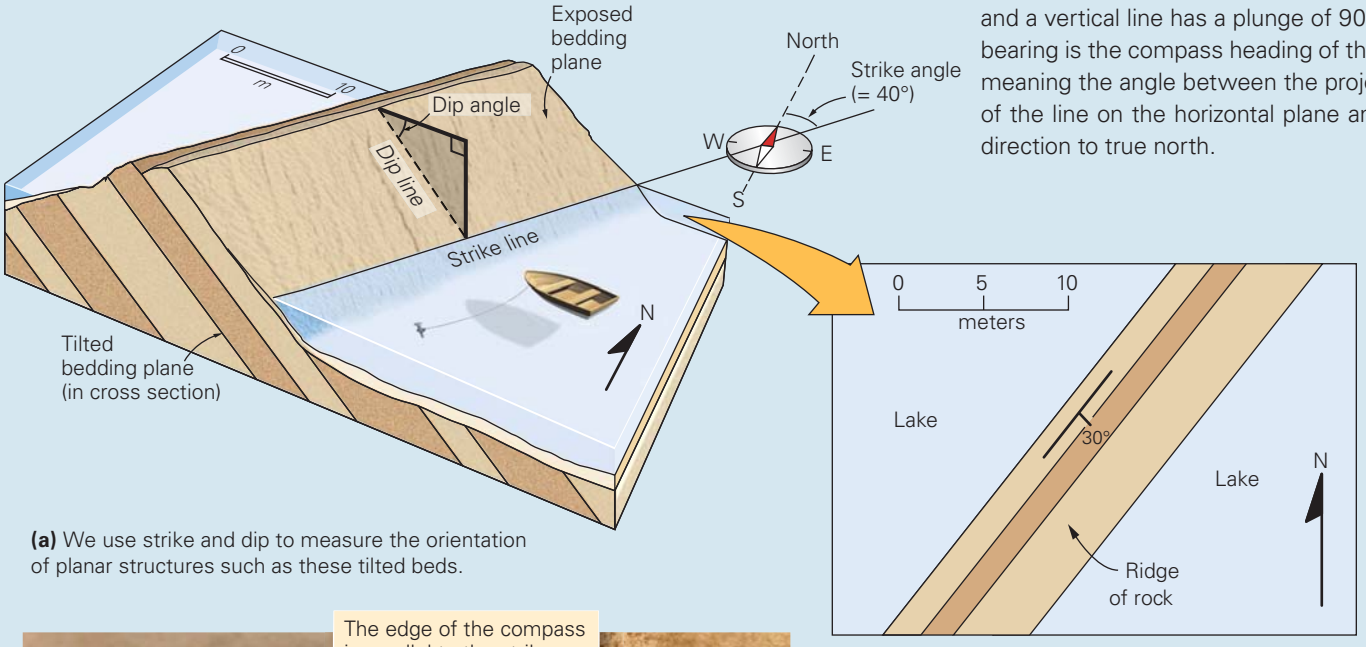
Describing the Orientation of Geologic Structures

When discussing geologic structures, it's important to be able to communicate information about their orientation. For example, does a fault exposed in an outcrop at the edge of town continue beneath the nuclear power plant 3 km to the north, or does it go beneath the hospital 2 km to the east? If we knew the fault's orientation, we might be able to answer this question. To describe the orientation of a geologic structure, geologists picture the structure as a simple geometric shape, then specify the angles that the shape makes with respect to a horizontal plane (a flat surface parallel to sea level), a vertical plane (a flat surface perpendicular to sea level), and the north direction (a line of longitude).

Let's start by considering planar structures such as faults, beds, and joints. We call these structures *planar* because they resemble a geometric plane. A planar structure's orientation can be specified by its strike and dip. The **strike** is the angle between an imaginary horizontal line (the strike line) on the plane and the direction to true north (**Fig. Bx9.1a, b**). We measure the strike with a special type of compass (**Fig. Bx9.1c**). The **dip** is the angle of the plane's slope—more precisely, it is the angle between a horizontal plane and the dip line (an imaginary line parallel to the steepest slope on the structure), as measured in a vertical plane perpendicular to the strike. We measure the dip angle with a clinometer, a type of protractor. A horizontal plane has a dip of 0°, and a vertical plane has a dip of 90°. We represent strike and dip on a geologic map using the symbol shown in Figure Bx9.1b.

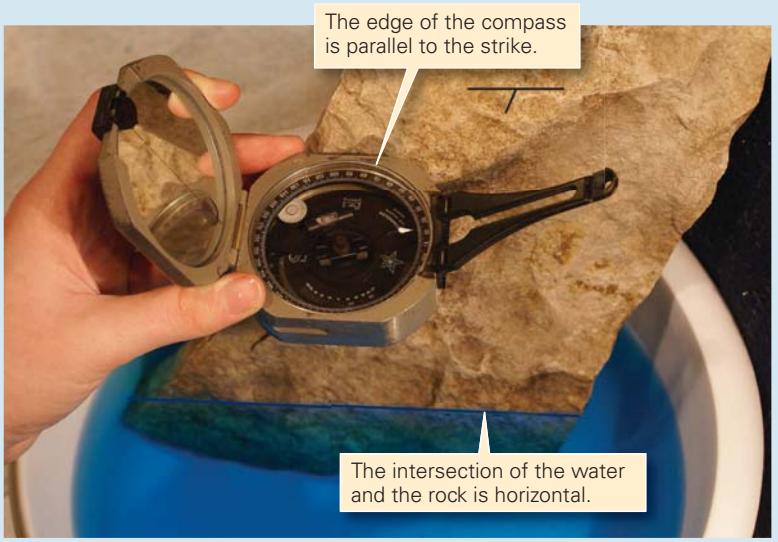
A *linear* structure resembles a geometric line rather than a plane; examples of linear structures include scratches or grooves on a rock surface. Geologists specify the orientation of a line by giving its plunge and bearing (**Fig. Bx9.1d**). The plunge is the angle between a line and horizontal in the vertical plane that contains the line. A horizontal line has a plunge of 0°, and a vertical line has a plunge of 90°. The bearing is the compass heading of the line, meaning the angle between the projection of the line on the horizontal plane and the direction to true north.

FIGURE Bx9.1 Specifying the orientation of planar and linear structures.

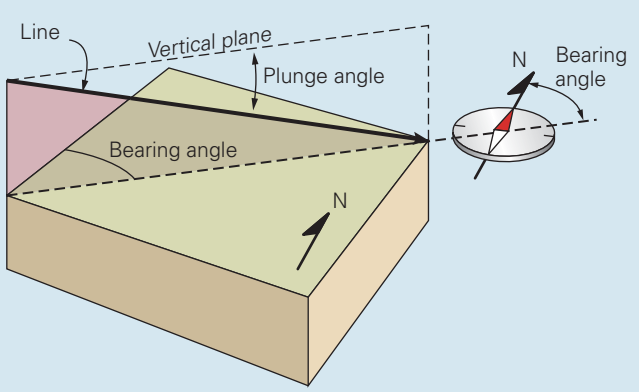


(a) We use strike and dip to measure the orientation of planar structures such as these tilted beds.

(b) On a map, the line segment represents the strike direction and the tick on the segment represents the dip direction. The number indicates the dip angle as measured in degrees.



(c) Geologists use a Brunton compass to measure strike and dip.

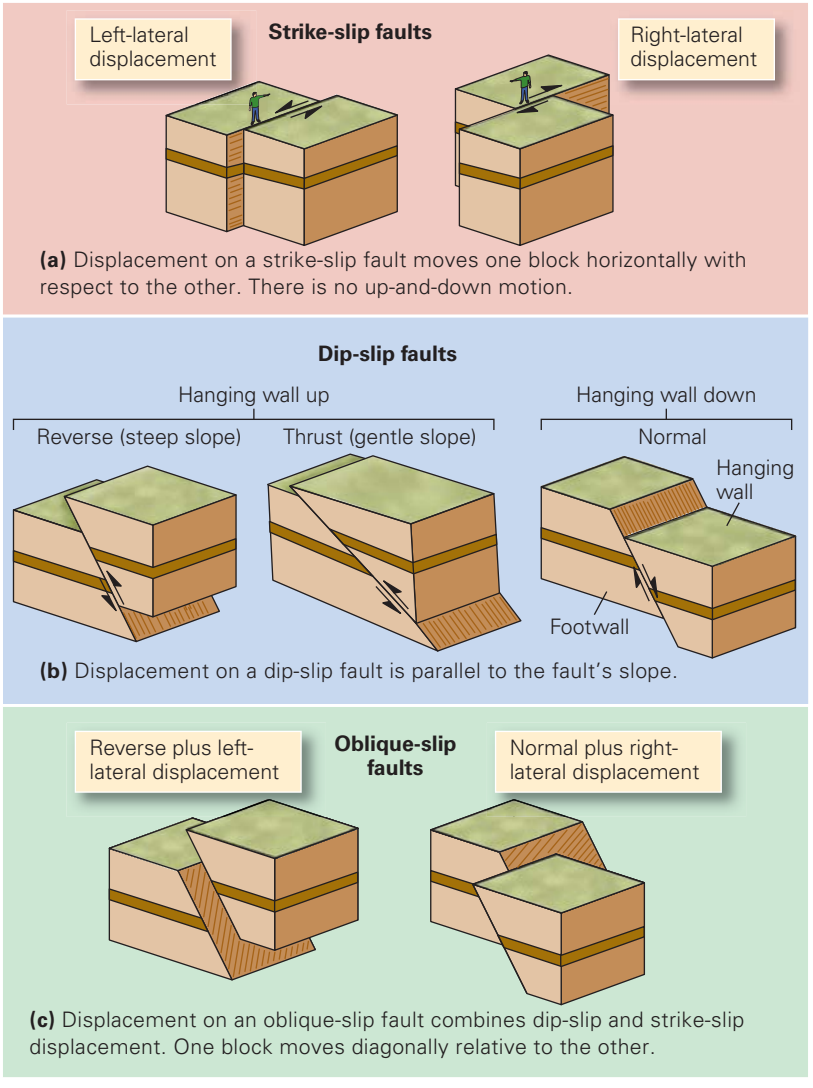


(d) To specify the orientation of a line, we use plunge and bearing.

the fault surface (see Box 9.1). This means that the block on one side of the fault slips sideways, relative to the block on the other side, and there is *no* up-or-down motion. Most strike-slip faults have a steep to vertical dip. Geologists distinguish between two types of strike-slip faults based on the shear sense as viewed when you are facing the fault and looking across it. If the block on the far side slipped to your left, the fault is a *left-lateral* strike-slip fault, and if the block slipped to the right, the fault is a *right-lateral* strike-slip fault (**Fig. 9.8a**). The faults that occur at transform plate boundaries are strike-slip faults.

- *Dip-Slip Faults:* On a dip-slip fault, movement is parallel to the dip line, a line parallel to the slope of the fault surface (see Box 9.1), so the *hanging-wall block*, meaning the material above the fault surface, slides up or down relative to the *footwall block*, the material below the fault surface (**Fig. 9.8b**). If the hanging-wall block slides up, the fault is a **reverse fault**; a reverse fault with a gentle dip is also known as **thrust fault**. Reverse faults accommodate shortening of the crust, as happens during continental collision. If the hanging-wall block slides down, the fault is a **normal fault**. Normal faults accommodate stretching of the Earth's crust, as happens during rifting.
- *Oblique-Slip Faults*: On an oblique-slip fault, sliding occurs diagonally on the fault plane. In effect, an oblique-slip fault is a combination of a strike-slip and a dip-slip fault (**Fig. 9.8c**).

FIGURE 9.8 The different categories of faults.



(a) Displacement on a strike-slip fault moves one block horizontally with respect to the other. There is no up-and-down motion.

(b) Displacement on a dip-slip fault is parallel to the fault's slope.

(c) Displacement on an oblique-slip fault combines dip-slip and strike-slip displacement. One block moves diagonally relative to the other.

Recognizing Faults

How do you recognize a fault when you see one? The most obvious criterion is the occurrence of **displacement**, meaning the movement across a fault plane. Displacement offsets the layers in rocks, so that layers on one side of a fault are not continuous with layers on the other side (**Fig. 9.9a, b**).

Faults may also leave their mark on the landscape. Those that intersect the ground surface while they are active can displace natural landscape features such as stream valleys or glacial moraines (**Fig. 9.9c**), and human-made features such as highways, fences, or rows of trees in orchards. Displacement on a dip-slip or oblique-slip fault will make a step on the ground surface; this step is called a **fault scarp** (**Fig. 9.10a**). And because faults tend to break up and weaken rock, the "fault trace" (the line of intersection between the fault and the ground surface) preferentially erodes to become a linear valley (see inset photo on p. 223).

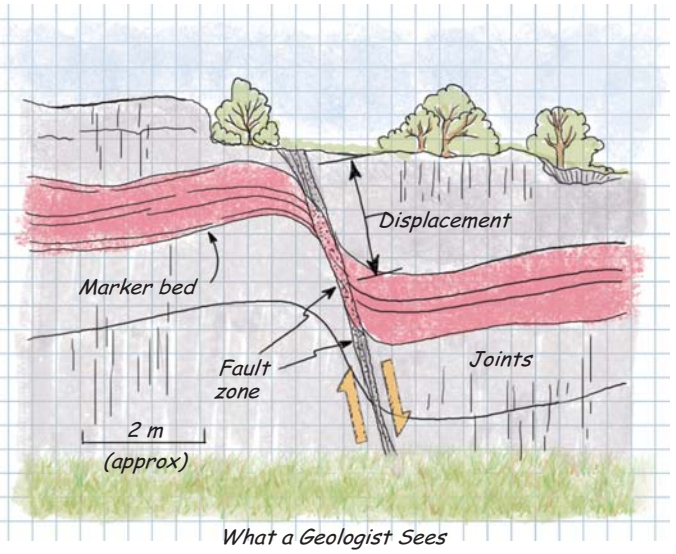
Faulting under brittle conditions may crush or break rock. If this shattered rock consists of visible angular fragments, then it is called *fault breccia* (**Fig. 9.10b**), but if it consists of a fine powder, then it is called *fault gouge*. Some fault surfaces are polished and grooved by the movement on the fault. Polished fault surfaces are called *slickensides*, and linear grooves on fault surfaces are slip lineations or fault striations (**Fig. 9.10c**). We specify the orientation of a slip lineation by giving its plunge and bearing (see Box 9.1).

Take-Home Message

Brittle structures include joints (cracks), veins (mineral-filled cracks), and faults (fractures on which sliding occurs). Geologists distinguish among different kinds of faults based on the relative displacement across the fault. Faulting can break and scratch rock.

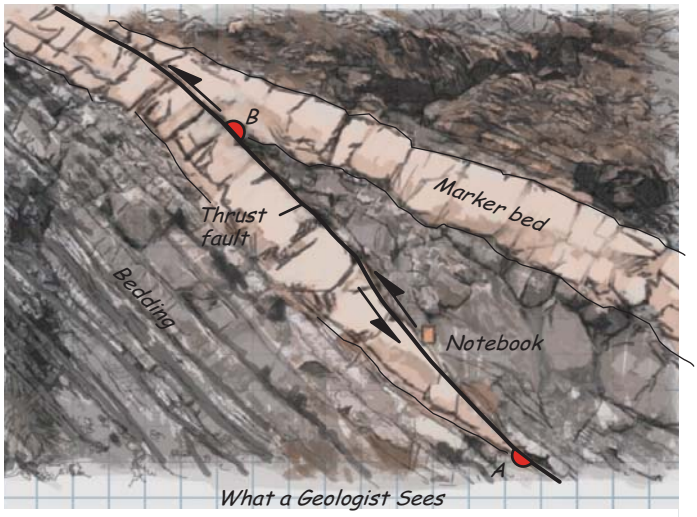
FIGURE 9.9 Recognizing fault displacement in the field.





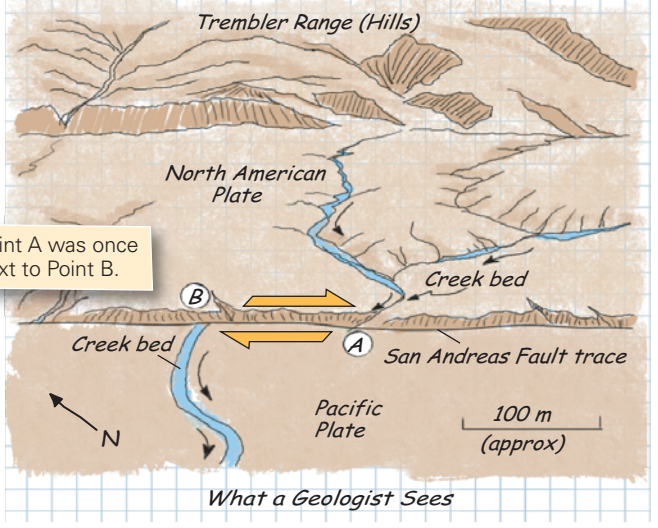
(a) A steep normal fault has displaced a distinctive red bed (a marker layer). Note that the displacement formed a 0.5-m-wide fault zone of broken rock.





(b) Slip on a thrust fault caused one part of the light-colored marker bed to be shoved over another part, as emphasized in the drawing. Note that the beds are tilted to the right. The distance between the red dots is the displacement.





(c) An aerial photograph of a portion of the San Andreas Fault. As emphasized by the sketch, the fault offsets a stream channel in a right-lateral sense.

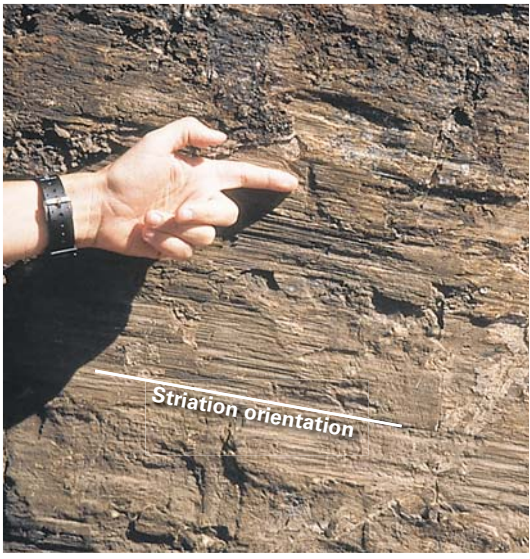
FIGURE 9.10 Features of exposed fault surfaces.



(a) A fault scarp develops where faulting displaces the land surface.



(b) This fault breccia consists of irregular fragments of light-colored rock.



(c) Striations on the surface of a strike-slip fault may look like grooves or scratches.

9.4 Folds and Foliations

Geometry of Folds

Imagine a carpet lying flat on the floor. Push on one end of the carpet, and it will wrinkle or contort into a series of wave-like curves. Stresses developed during mountain building can similarly warp or bend bedding and foliation (or other planar features) in rock. The result—a curve in the shape of a rock layer—is called a **fold**.

Not all folds look the same—some look like arches, some look like troughs, and some have other shapes. To describe these shapes, we must first label the parts of a fold (**Fig. 9.11a**). The **hinge** refers to a line along which the curvature is greatest, and the **limbs** are the sides of the fold that display less curvature. The **axial surface** is an imaginary plane that contains the hinges of successive layers and effectively divides the fold into two halves. With these terms in hand, we distinguish among the following:

- *Anticlines, synclines, and monoclines*: Folds that have an arch-like shape in which the limbs dip away from the hinge are called **anticlines** (Fig. 9.11a), whereas folds with a trough-like shape in which the limbs dip toward the hinge are called **synclines** (**Fig. 9.11b**). A **monocline** has the shape of a carpet draped over a stair step (**Fig. 9.11c**).
- *Nonplunging and plunging folds*: If the hinge is horizontal, the fold is called a nonplunging fold, but if the hinge is tilted, the fold is called a plunging fold (**Fig. 9.11d**).
- *Domes and basins*: A fold with the shape of an overturned bowl is called a **dome**, whereas a fold shaped like an upright bowl is called a **basin** (**Fig. 9.11e, f**). Domes and basins both display circular outcrop patterns that look like bull's-eyes—the oldest layer occurs in the center of a dome, whereas the youngest layer is located in the center of a basin.

Using these terms, now see if you can identify the various folds shown in **Figure 9.12a–e**.

Formation of Folds

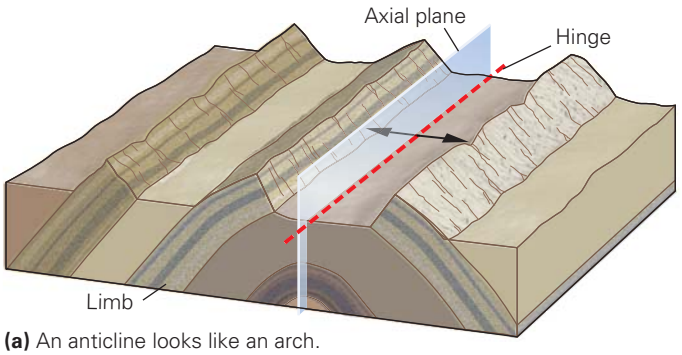
Folds develop in two principal ways (**Fig. 9.13a, b**). During formation of flexural-slip folds, a stack of layers bends, and slip occurs between the layers. The same phenomenon happens when you bend a deck of cards—to accommodate the change in shape, the cards slide with respect to each other. Passive-flow folds form when the rock, overall, is so soft that it behaves like weak plastic and slowly flows; these folds develop simply because different parts of the rock body flow at different rates.

Why do folds form? Some layers wrinkle up, or buckle, in response to end-on compression (**Fig. 9.14a–d**). Others form where shear stress gradually shifts one part of a layer up and over another part. Still others develop where rock layers move up and over step-like bends in a fault and must curve to conform with the fault's shape. Finally, some folds form when new slip on a fault causes a block of basement to move up so that the overlying sedimentary layers must warp.

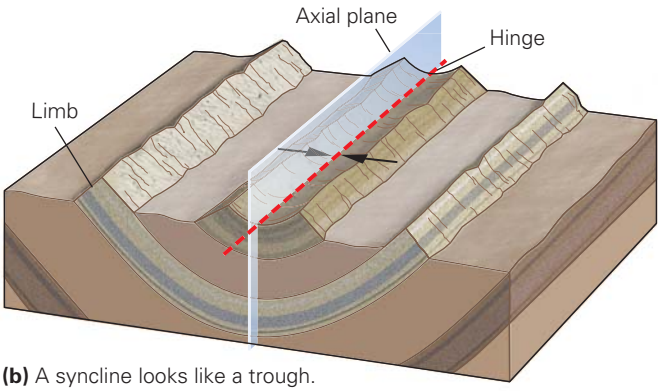
Tectonic Foliation in Rocks

In an undeformed sandstone, the grains of quartz are roughly spherical, and in an undeformed shale, clay flakes press

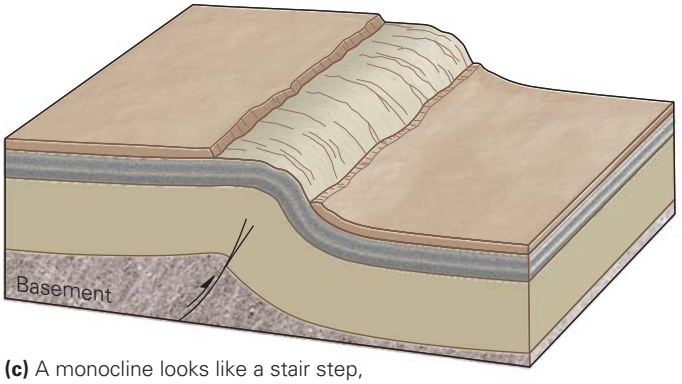
FIGURE 9.11 Geometric characteristics of folds.



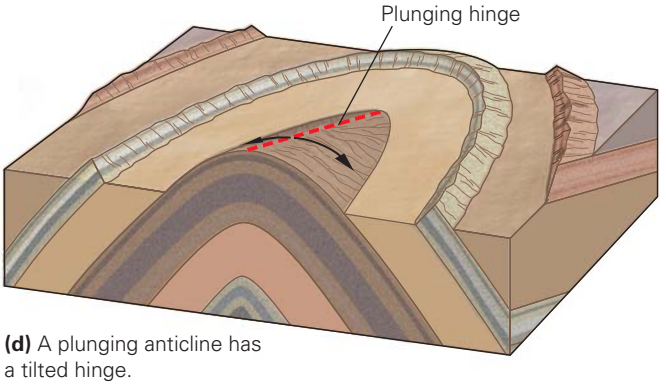
(a) An anticline looks like an arch. The beds dip away from the hinge.



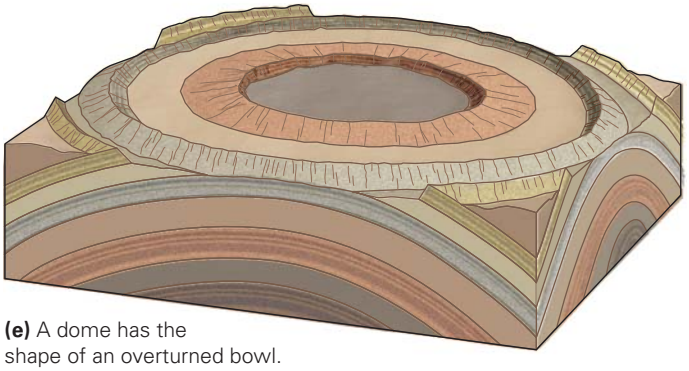
(b) A syncline looks like a trough. The beds dip toward the hinge.



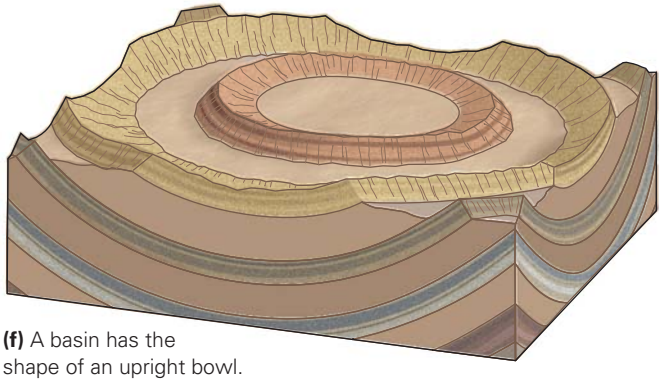
(c) A monocline looks like a stair step, and is commonly draped over a fault block.



(d) A plunging anticline has a tilted hinge.



(e) A dome has the shape of an overturned bowl.



(f) A basin has the shape of an upright bowl.

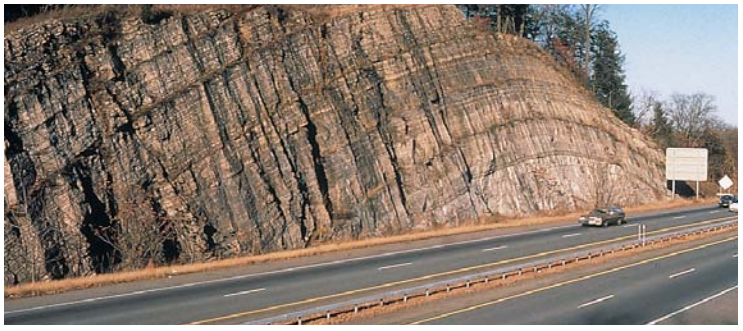
together into the plane of bedding so that shales tend to split parallel to the bedding. During ductile deformation, however, internal changes take place in a rock that gradually modify the original shape and arrangement of grains. For example, quartz grains may transform into cigar shapes, elongate ribbons, or tiny pancakes, and clay flakes may recrystallize or reorient so that they lie at an angle to the bedding. Overall, deformation can produce inequant grains and can cause them to align parallel to each other. We refer to layering developed by the alignment of grains in response to deformation as **tectonic foliation**.

We introduced foliation, such as slaty cleavage, schistosity, and gneissic layering, in Chapter 7 while discussing the effects of metamorphism. Here we add to the story by noting that such foliation forms in response to flattening and shearing in ductilely deforming rocks—in other words, foliation indicates that the rock has developed a strain under metamorphic conditions (Fig. 9.15a, b).

Take-Home Message

Folds are bends or curves defined by the shape of rock layers. Arch-like folds are anticlines, and trough-like folds are synclines. Deformation can change the shape and orientation of grains, aligning them to produce a planar fabric called foliation.

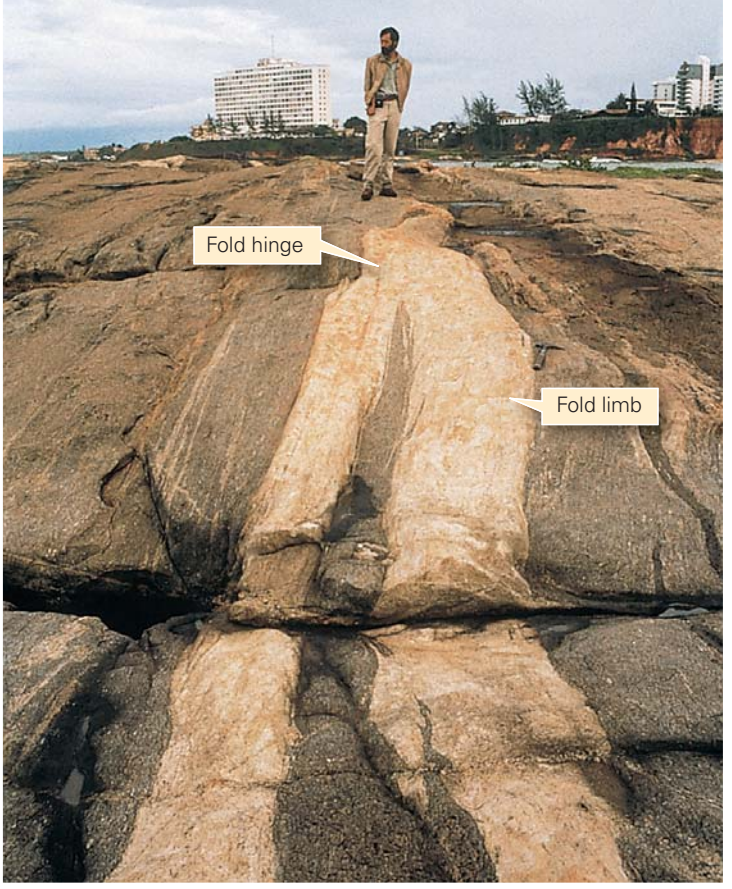
FIGURE 9.12 Characteristics of folds on outcrops and in the landscape.



(a) This anticline, exposed in a road cut near Kingston, New York, involves beds of Paleozoic limestone.

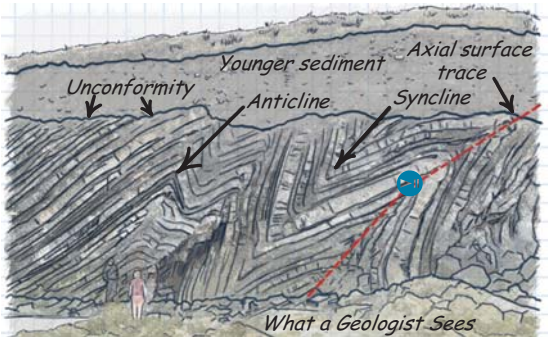


(b) This syncline, exposed in a road cut in Maryland, involves beds of Paleozoic sandstone and shale.



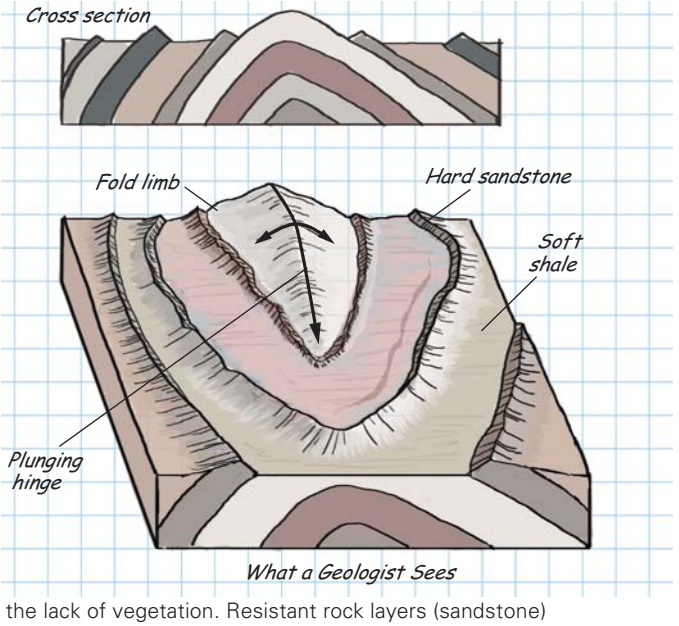
(c) This fold, exposed along the coast of Brazil, occurs in Precambrian gneiss.





(d) A train of folds exposed in sea cliffs in eastern Ireland includes anticlines and synclines. The folds affect beds of Paleozoic sandstone and shale.





(e) The plunging anticline of Sheep Mountain, Wyoming, is easy to see because of the lack of vegetation. Resistant rock layers (sandstone) stand out as ridges, whereas weak rock layers (shale) erode away.

FIGURE 9.13 Fold development in flexural-slip and passive-flow folding.

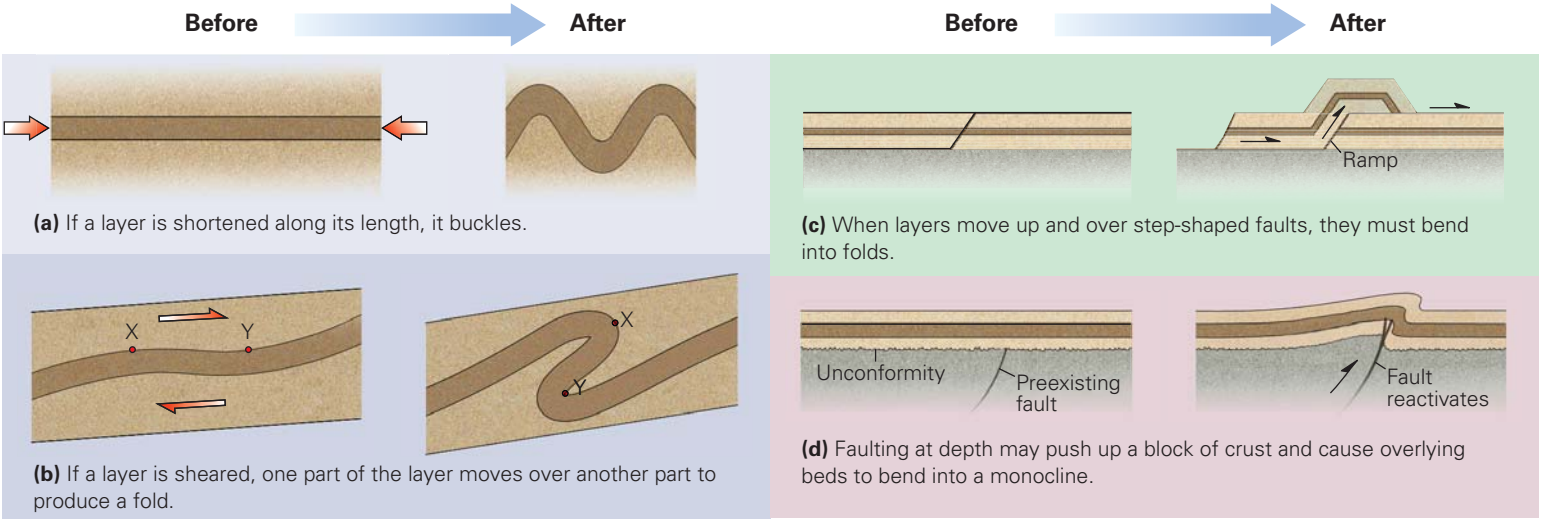


(a) During the formation of flexural-slip folds, layers maintain constant thickness, so for the fold to form, layers must bend. To accommodate the bending, each bed slips relative to its neighbor.



(b) During the formation of passive-flow folds, the rock slowly flows. Different points along a marker line flow at different rates, causing the layer to become folded. Note that the layer's thickness doesn't stay constant during folding.

FIGURE 9.14 Folding is caused by several different processes, as illustrated by the following cross sections.



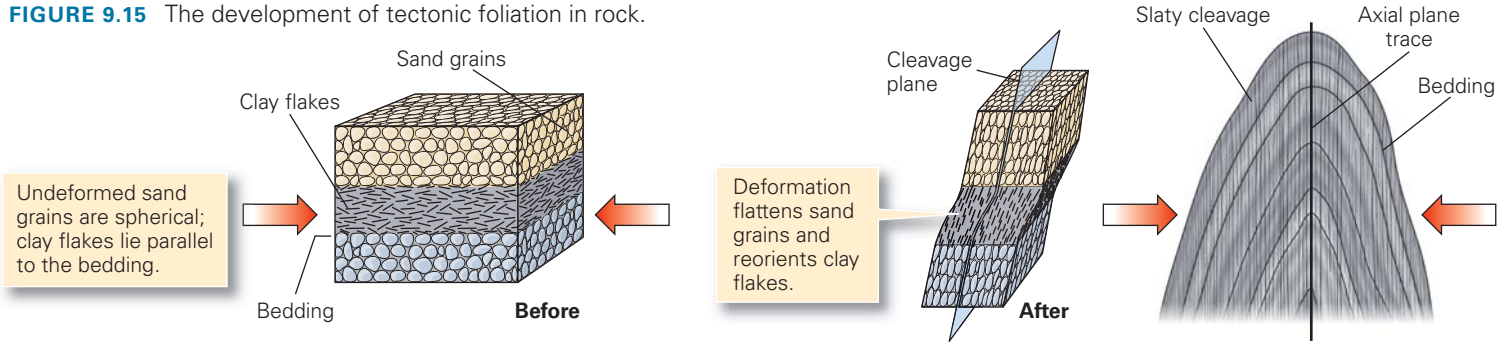
(a) If a layer is shortened along its length, it buckles.

(b) If a layer is sheared, one part of the layer moves over another part to produce a fold.

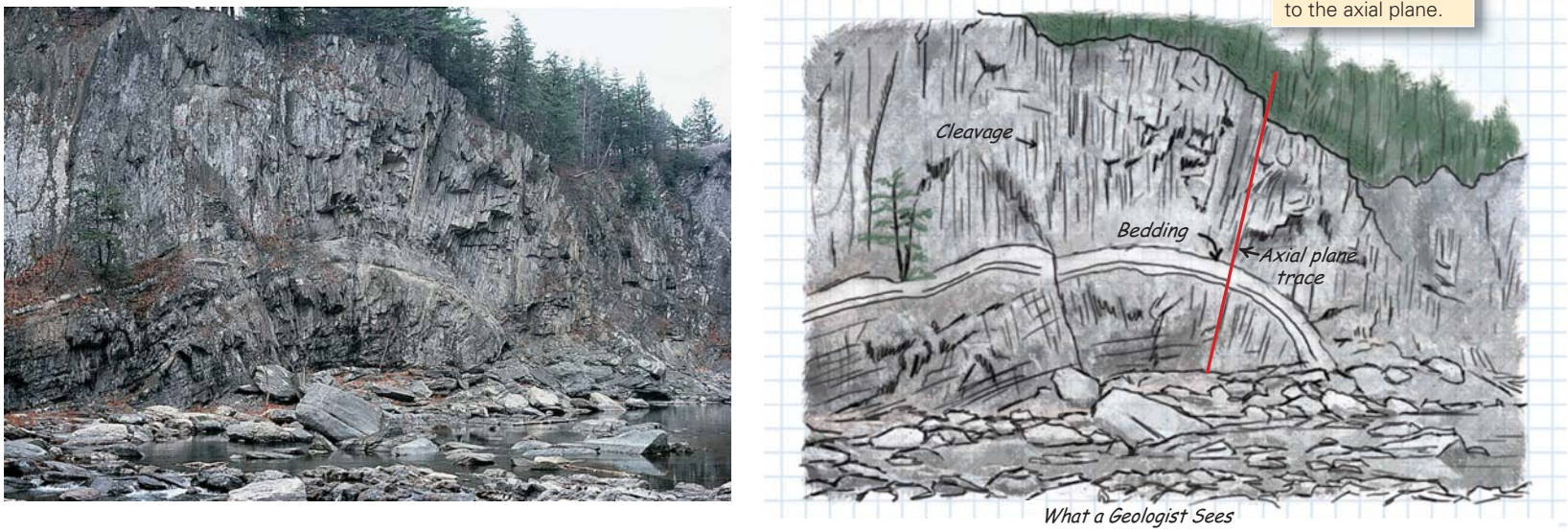
(c) When layers move up and over step-shaped faults, they must bend into folds.

(d) Faulting at depth may push up a block of crust and cause overlying beds to bend into a monocline.

FIGURE 9.15 The development of tectonic foliation in rock.



(a) Compression shortens beds, flattens sand grains, and reorients clay flakes. Clay flakes were originally parallel to bedding, but they become parallel to slaty cleavage during deformation. Folding may accompany cleavage formation.



(b) An example of slaty cleavage developed in Paleozoic strata exposed in a stream cut in New York. Relict bedding is still visible, but note that the rock breaks more easily on the cleavage. This cleavage formed in association with folding.

9.5 Mountain Building

Before plate tectonics theory became established, geologists were just plain confused about how mountains formed. In the context of the new theory, however, the many processes driving mountain building became clear: mountains form primarily in response to convergent-boundary deformation, continental collisions, and rifting. Since collison zones, rifts, and plate boundaries are linear, mountain belts are linear. Below, we look at these different settings and the types of mountains and geologic structures that develop in each one.

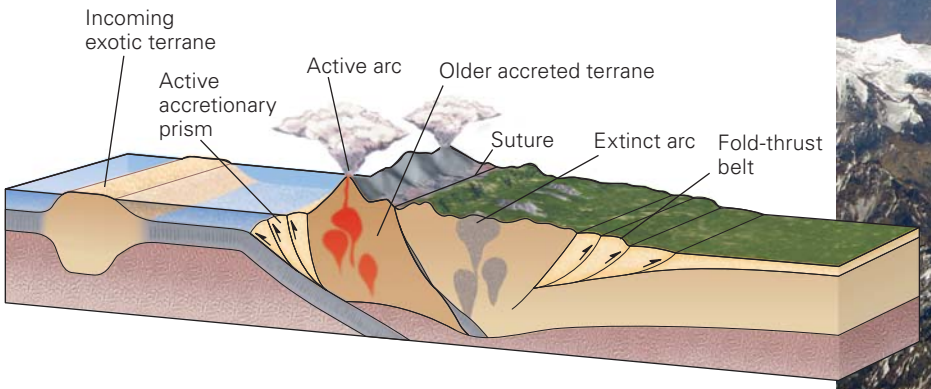
Did you ever wonder . . .
why do mountains occur in distinct belts?

Mountains Related to Subduction

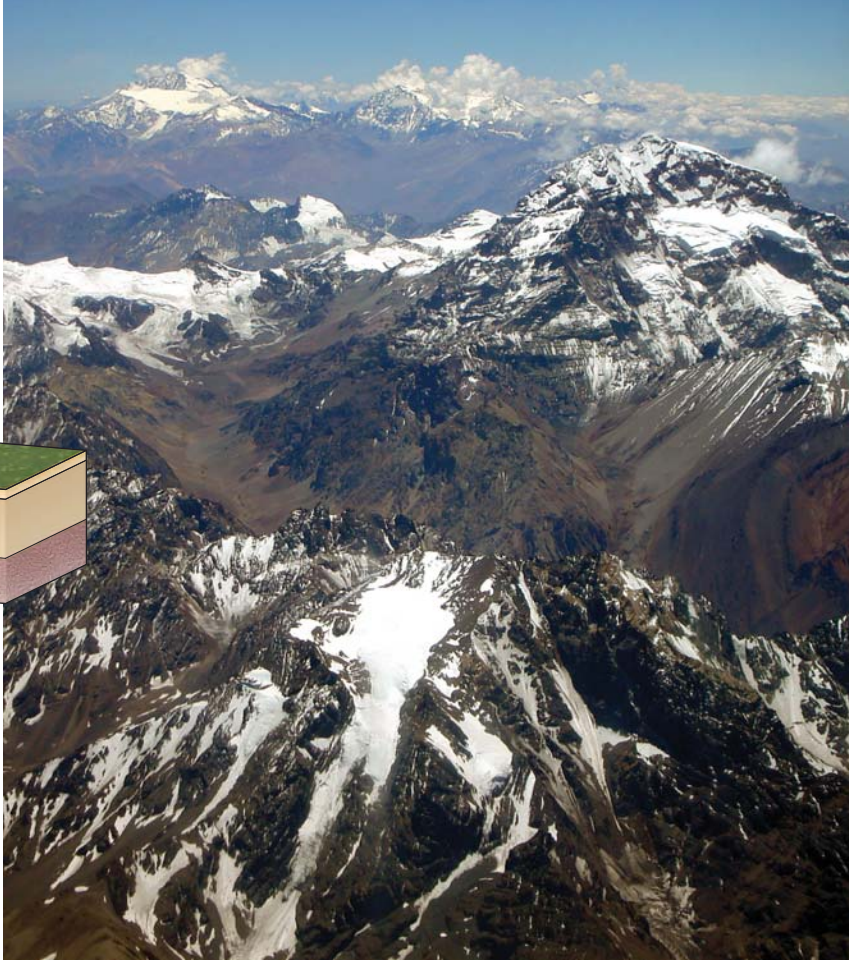
At some convergent plate boundaries, compressional stresses develop, and these cause crustal shortening and uplift in the overriding plate. Such shortening may produce a **fold-thrust belt**, in which a thrust system develops (Fig. 9.16a). As a consequence of this faulting, thrust slices (sheets of rock above a thrust fault) push up and over their neighbors, and rocks within thrust slices bend and become folded. The thrust faults merge with a subhorizontal fault, called a detachment, at depth. The Andes orogen of western South America displays the rugged topography that can develop in compressional convergent-margin orogens (Fig. 9.16b).

If subduction continues over a long time, offshore volcanic arcs, oceanic plateaus, and microcontinents may drift into the convergent margin (see Fig. 9.16a). Such crustal blocks are too buoyant to subduct and sink back into the mantle, so instead they collide with the overriding plate and "suture" (attach) to the edge of the overriding plate. Geologists refer to this process as accretion; the buoyant crustal block is called an **exotic terrane** when it is offshore, and an accreted terrane once it has attached to the overriding plate. Once accretion occurs, the convergent plate boundary may jump to the seaward side of the accreted terrane, so that subduction can continue. The process of accretion can add substantial new crust to a convergent-margin

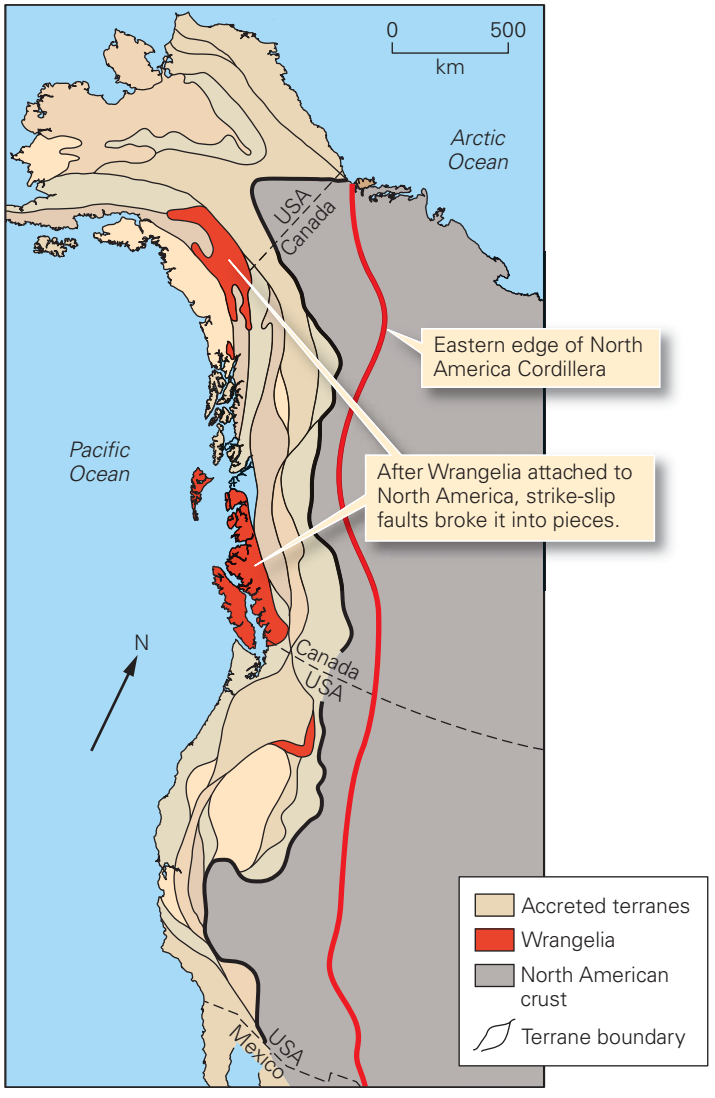
FIGURE 9.16 Characteristics of convergent-margin orogens.



(a) At some convergent margins, compression between the downgoing and overriding plates uplifts a mountain range in which volcanism occurs. Subduction may bring in exotic crustal blocks that collide and become incorporated in the orogen.



(b) The Andes in Chile formed along a convergent margin.



(c) The western portion of the North American Cordillera consists of accreted terranes that attached to the continent during the Mesozoic. During docking, a distinct terrane called Wrangelia (highlighted in red) was sliced into pieces that were displaced by strike-slip faults.

orogen. For example, the western half of the North American Cordillera, a region that is up to 500 km wide, consists of accreted terranes (**Fig. 9.16c**). Orogens that grew laterally by the attachment of exotic terranes have come to be known as **accretionary orogens**.

Mountains Related to Continental Collision

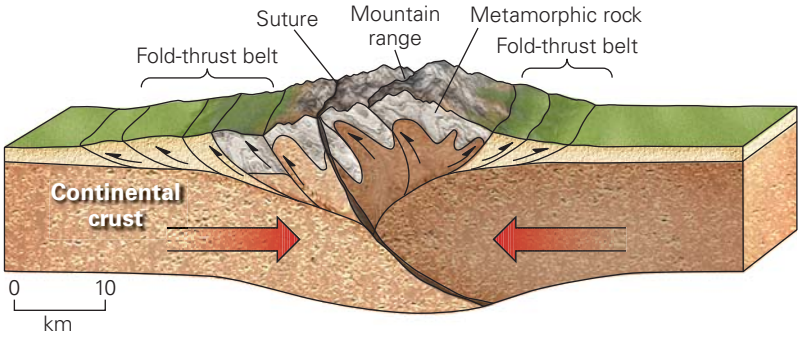
Once the oceanic lithosphere between two continents completely subducts, the continents themselves collide with each other. Continental collision results in the formation of large mountain ranges such as the present-day Himalayas or the Alps and the Paleozoic Appalachian Mountains (**Geology at a Glance**, pp. 282–283). The final stage in the growth of the Appalachians happened when Africa and North America collided.

During collision, intense compression generates fold-thrust belts on the margins of the orogen (**Fig. 9.17a–c**). In the interior of the orogen, where one continent overrides the edge of the other, high-grade metamorphism occurs, accompanied by formation of passive-flow folds and tectonic foliation. During this process, the crust below the orogen thickens to as much as twice its normal thickness. During such **crustal thickening**, rocks squeeze upward in the hanging walls of large thrust faults.

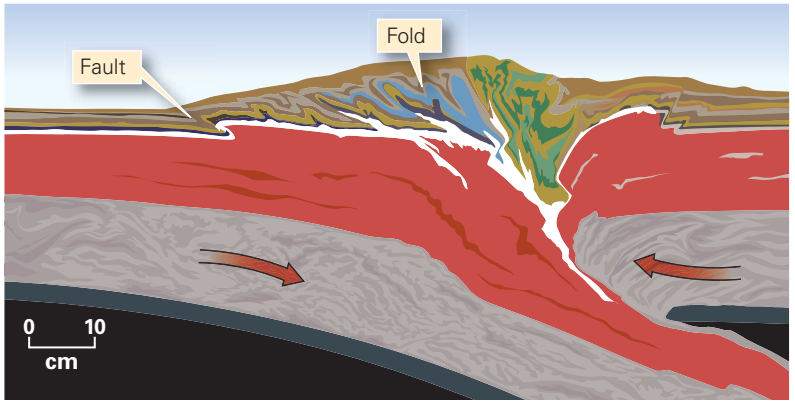
Mountains Related to Continental Rifting

Continental rifts are places where continents are splitting in two. During rifting, stretching causes normal faulting in the brittle

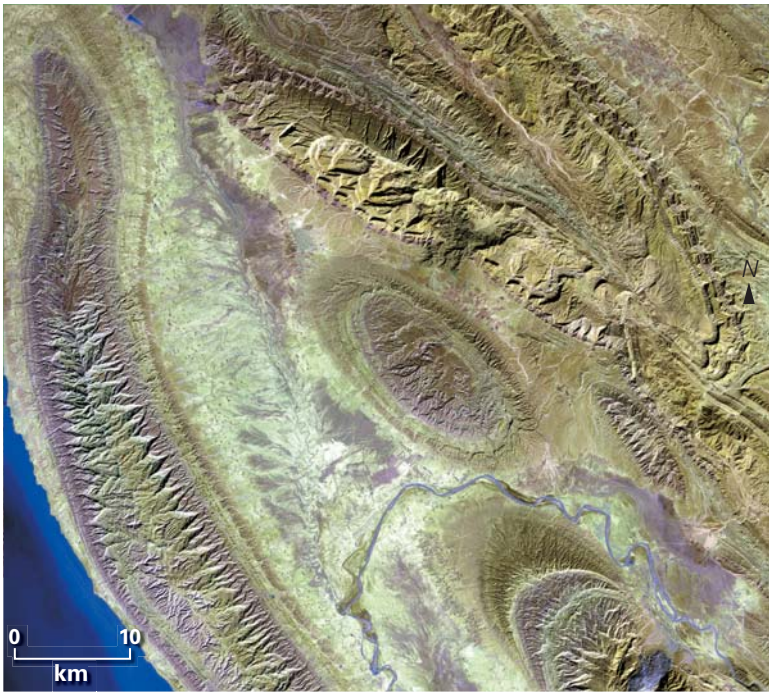
FIGURE 9.17 Characteristics of collisional orogens.



(a) During collision, continents squeeze together and deform. Thrusting brings metamorphic rock up to shallower levels.



(b) Geologists simulate collision in the laboratory using layers of colored sand. Dragging the left side of the model under the right produces structures and uplift, as shown in this sketch of a model.



(c) In this satellite photo the ridges and valleys of the Zagros Mountains along the coast of Iran represent eroded folds of a collisional orogen. Ridges consist of durable sandstone beds.

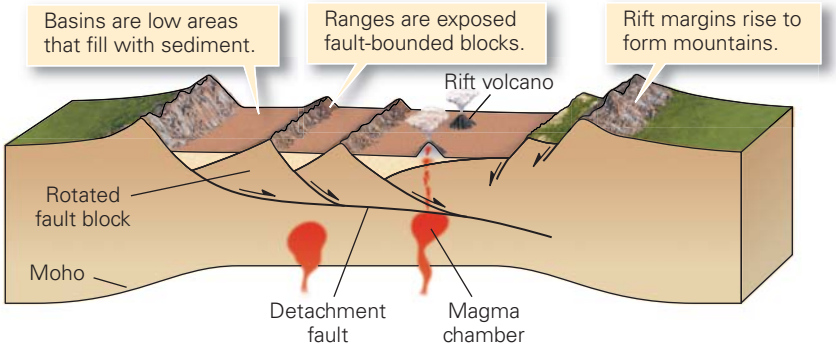
crust (Fig. 9.18a). Movement on the normal faults drops down blocks of crust, producing deep, sediment-filled basins separated by narrow, elongate mountain ranges that contain tilted rocks. These ranges are sometimes called *fault-block mountains*. Stretching thins the lithosphere, allowing hot asthenosphere to rise and undergo decompression melting (see Chapter 4). This process produces magmas that rise to form volcanoes within the rift. Today, the East African Rift clearly shows the configuration of rift-related mountains and volcanoes. And in North America, rifting yielded the broad Basin and Range Province of Utah, Nevada, and Arizona (Fig. 9.18b).

Forming Rocks in and Near Mountains

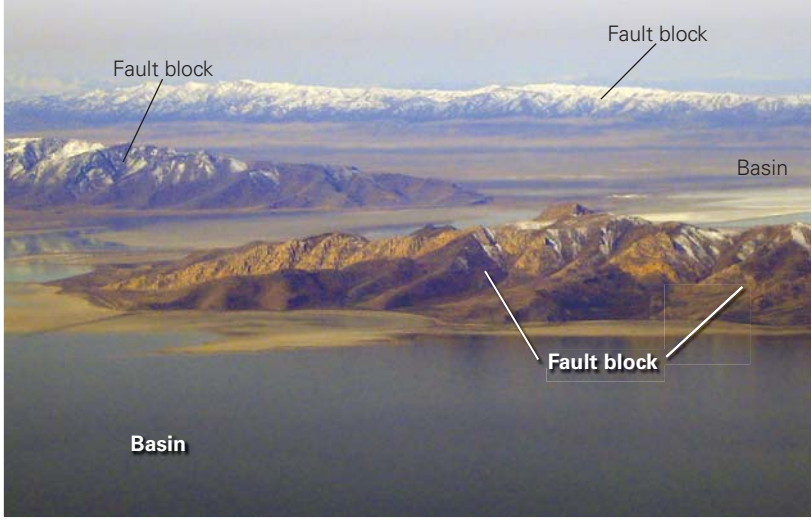
The process of orogeny establishes geologic conditions appropriate for the formation of a great variety of rocks. We'll consider examples from all three rock categories (Fig. 9.19):

- *Igneous activity during orogeny*: In convergent plate boundaries, melting takes place in the mantle above the subducting

FIGURE 9.18 Rift-related mountains.

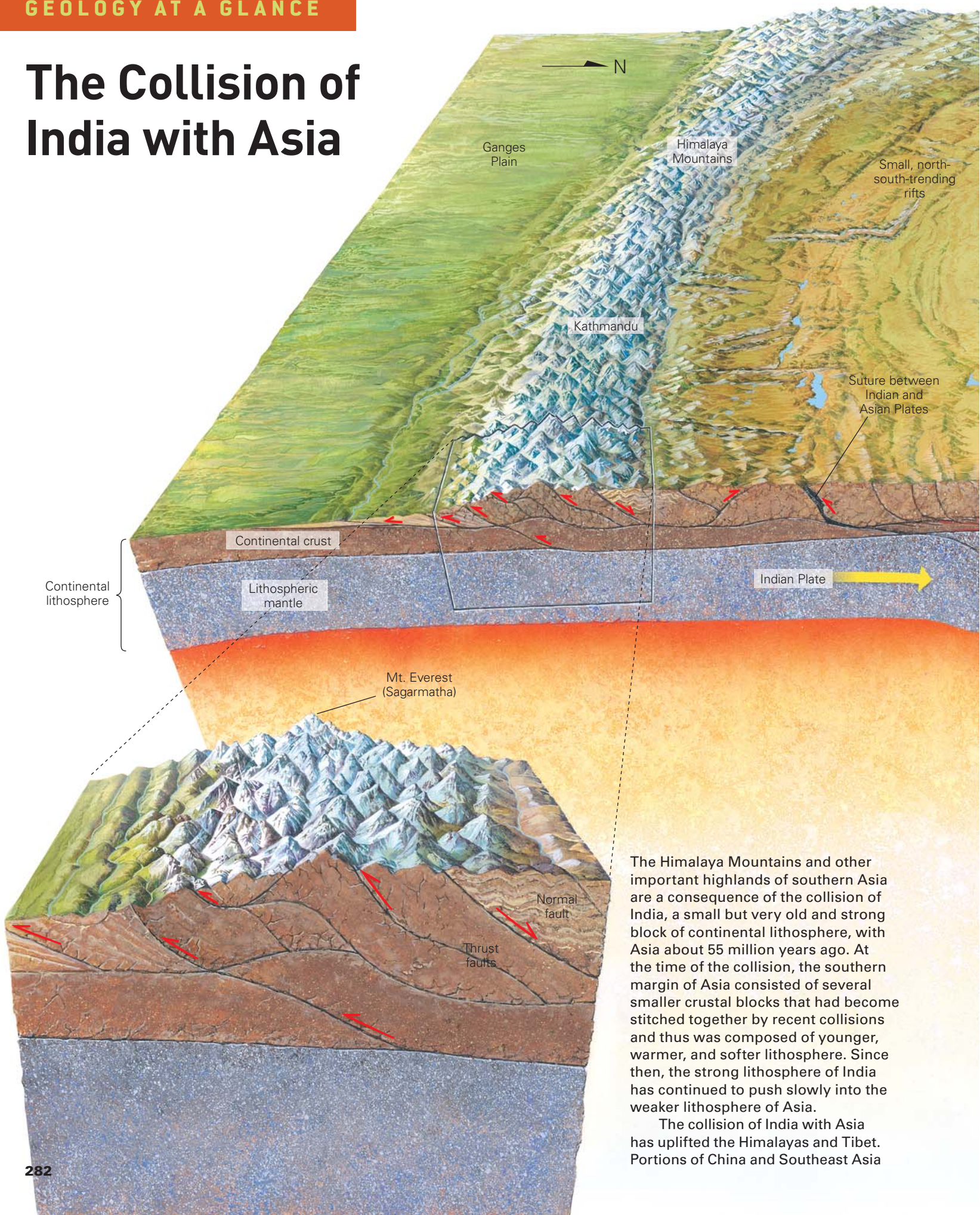


(a) Rifting leads to the development of numerous narrow mountain ranges. Rift-margin mountains also may form.



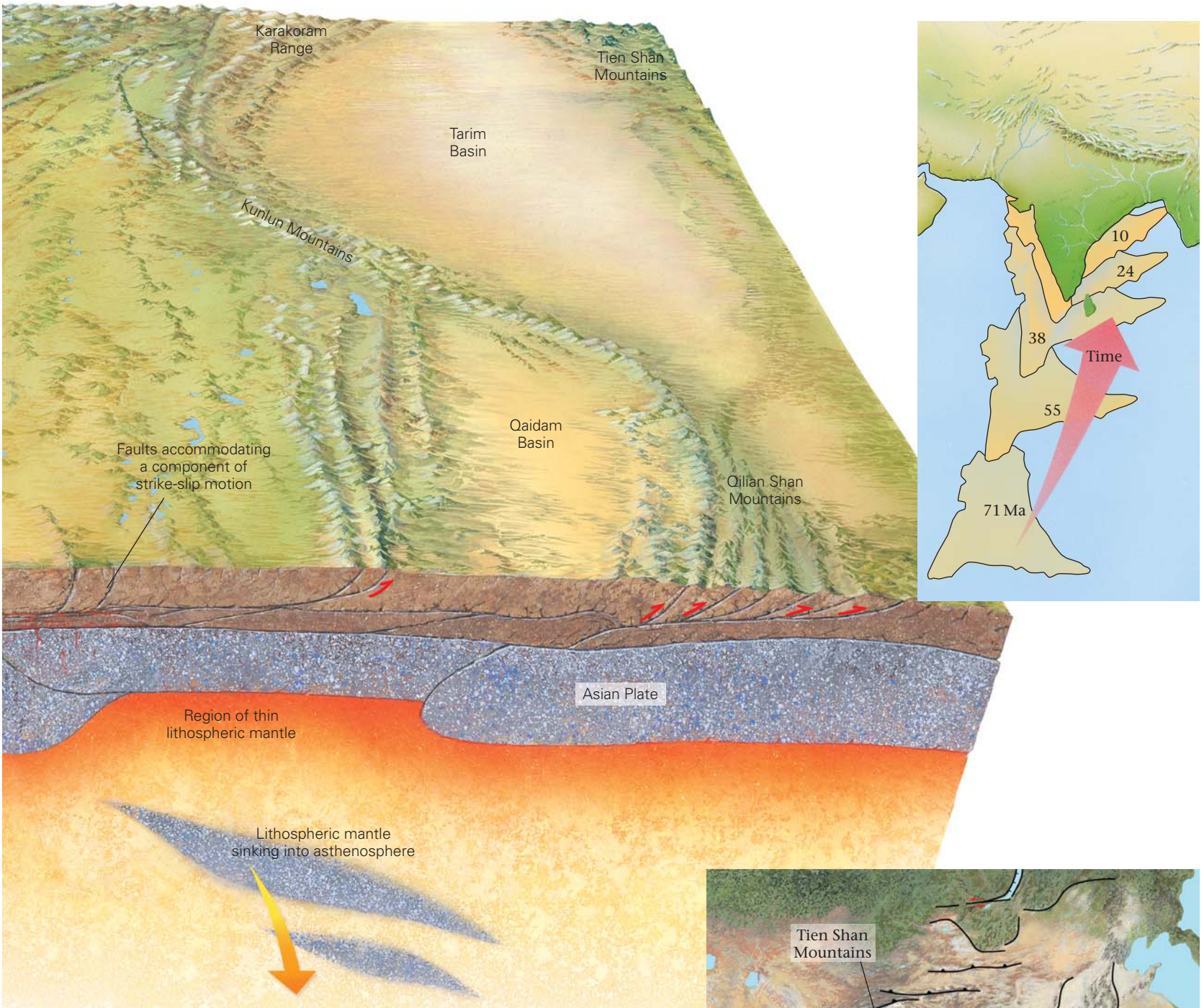
(b) The Basin and Range Province of the western United States formed during Cenozoic rifting.

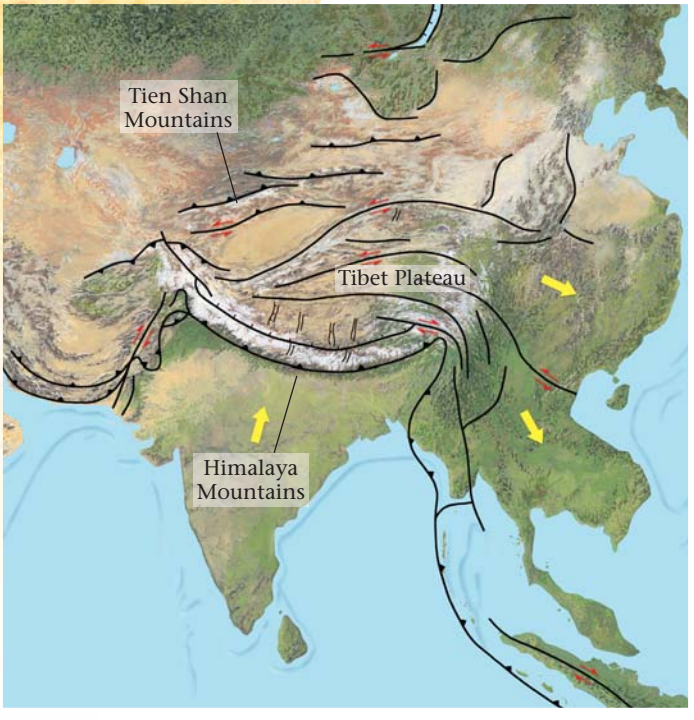
The Collision of India with Asia



The Himalaya Mountains and other important highlands of southern Asia are a consequence of the collision of India, a small but very old and strong block of continental lithosphere, with Asia about 55 million years ago. At the time of the collision, the southern margin of Asia consisted of several smaller crustal blocks that had become stitched together by recent collisions and thus was composed of younger, warmer, and softer lithosphere. Since then, the strong lithosphere of India has continued to push slowly into the weaker lithosphere of Asia.

The collision of India with Asia has uplifted the Himalayas and Tibet. Portions of China and Southeast Asia





have slipped to the east to "escape" the collision. Faults in central Asia have become active, causing the uplift of ranges such as the Tien Shan, as compressive forces build up.

The development of large thrust faults has uplifted the curving Himalayan chain where Asia begins to thrust over India. Why the broad plateau of Tibet has risen remains something of a mystery. In part, the uplift may be a consequence of the thickening of the crust as it is squashed horizontally; continental crust is relatively weak, and so may spread laterally (like soft cheese in the sun), leading to the formation of normal faults and small rifts in the upper crust and a plastic-like flow in the deep crust. The uplift may also be due to the heating of the region when slabs of the underlying lithospheric mantle drop off and sink, to be replaced by hot asthenosphere.

As India has pushed into Asia, it may have squeezed blocks of China and Southeast Asia sideways, toward the east; this motion is accommodated by slip on strike-slip faults. The collision may also have caused reverse faults in the interior of Asia to become active, uplifting a succession of small mountain ranges, such as the Tien Shan.

FIGURE 9.19 Various rocks form during orogeny.

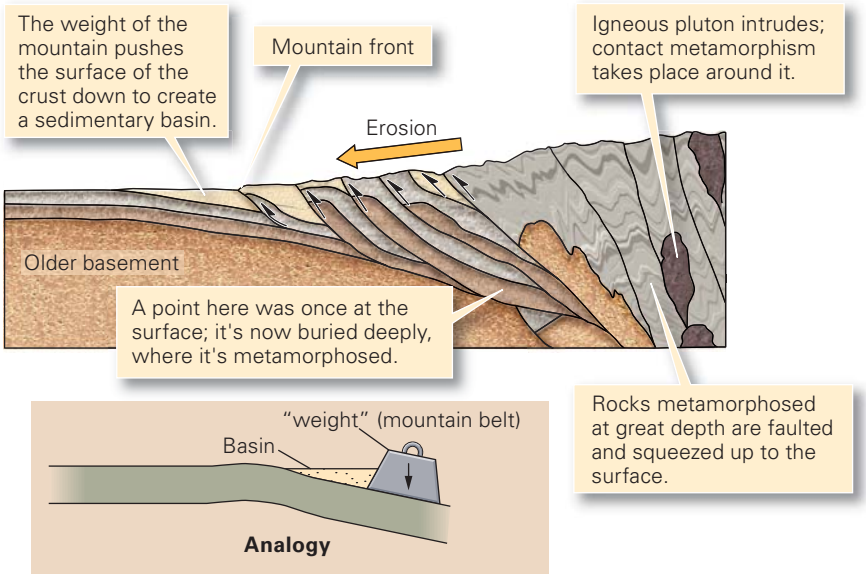


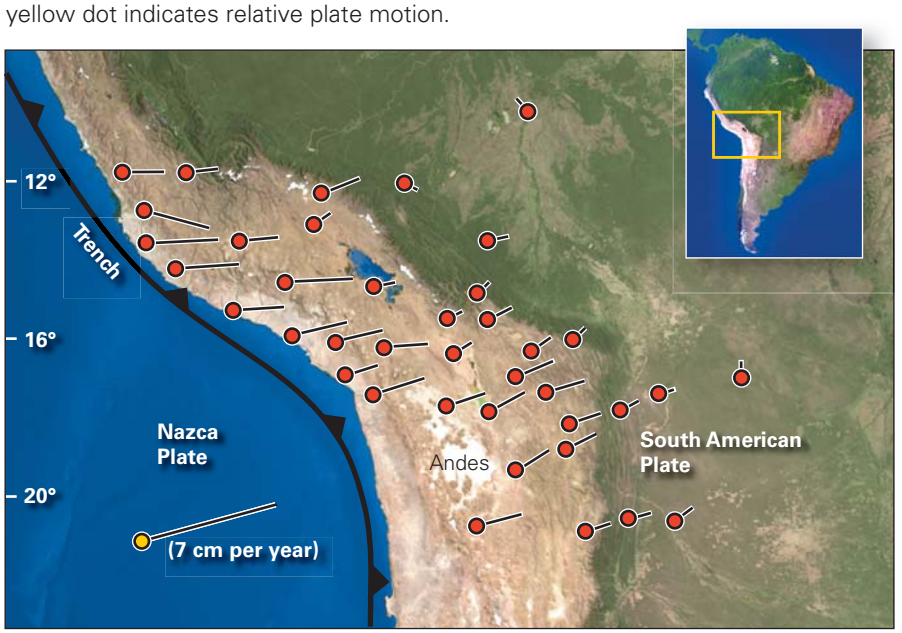
plate. In rifts, stretching and thinning of lithosphere causes decompression melting of the underlying mantle. And during continental collision, melting may take place where deep portions of the crust undergo heating. All of these melting regimes produce magma, which rises and freezes to form igneous rocks in the overlying mountains.

- *Sedimentation during orogeny*: Weathering and erosion in mountain belts generate vast quantities of sediment. This sediment tumbles down slopes and gets carried away by glaciers or streams that transport it to low areas where it accumulates in alluvial fans or deltas. In some locations, the weight of mountain belts pushes down the surface of the lithosphere, thereby producing a deep sedimentary basin at the border of the range.
- *Metamorphism during orogeny*: Contact metamorphic aureoles (see Chapter 7) form adjacent to igneous intrusions in orogens. And regional metamorphism occurs where mountain building thrusts one part of the crust over another; when this happens, rock of the footwall ends up at great depth and thus can be subjected to high temperature and pressure. Because deformation accompanies this process, the resulting metamorphic rocks contain tectonic foliation.

Measuring Mountain Building in Progress

Not all mountains are just "old monuments," as John Muir mused. The rumblings of earthquakes and the eruptions of volcanoes attest to present-day, continuing movements in some ranges. Geologists can measure the rates of these movements through field studies and satellite technology. For example, geologists can determine where coastal areas have been rising relative to the sea level by locating ancient beaches that now lie high above the water. And they can tell where the land surface has risen relative to a river by identifying places where a river has recently carved a new valley. In addition, geologists now use the **global positioning system** (**GPS**) to measure rates of uplift and horizontal shortening in orogens. Though standard hand-held GPS devices provide locations with accuracies of only about ±2 m, research-quality GPS systems can specify locations to within ±2 mm. By comparing the position of a location within an orogen to a location outside an orogen over a time period of a few years, it is possible to detect crustal motion. Thus, we can "see" the Andes shorten horizontally at a rate of a couple of centimeters per year (Fig. 9.20), and we can "watch" as mountains along this convergent boundary rise by a couple of millimeters per year.

FIGURE 9.20 GPS measurements of shortening in the Andes. The lines indicate the velocity of the red dots relative to the interior of South America. The line at the yellow dot indicates relative plate motion.



Take-Home Message

Mountain belts form in association with convergence, collision, and rifting. During continental collisions, and at some convergent margins, the crust thickens, large thrust faults and folds form, and regional metamorphism develops. Rifting yields fault-block mountains.

9.6 Mountain Topography

Leonardo da Vinci, the Renaissance artist and scientist, enjoyed walking in the mountains, sketching ledges and examining the rocks he found there. In the process, he discovered marine shells (fossils) in limestone beds cropping out a kilometer above sea level, and he suggested that the rock containing the fossils had risen from below sea level up to its present elevation. Modern geologists agree with Leonardo, and they now refer to processes causing the surface of the Earth to move vertically from a lower to a higher elevation as **uplift**. In this section, we look at why uplift occurs, how erosion carves rugged landscapes out of uplifted crust, and why Earth's mountains can't get much higher than Mt. Everest.

Why Are Mountains High?

What processes can cause the surface of the Earth to rise? There are many because, as we have seen, mountain building happens in numerous different geologic settings. To understand how uplift processes work, we must begin by remembering the concept of isostasy introduced in Interlude D.

The lithosphere, which consists of relatively rigid crust and lithospheric mantle, "floats" on the softer asthenospheric mantle below. As a consequence, the elevation of the top surface of the lithosphere, over a broad region, represents a balance between buoyancy force pushing lithosphere up, and gravitational force pulling the lithosphere down. Geologists refer to the condition that exists when this balance has been achieved as **isostasy**, or isostatic equilibrium (see Interlude D). Put another way, isostasy exists where the elevation of the Earth's surface reflects the level at which the lithosphere naturally floats. (Note that because asthenosphere flows only very slowly, and because lithosphere is strong enough to hold up loads, isostasy does not exist everywhere; see Interlude D.)

To picture the relation between isostasy and mountains, imagine placing a block of wood into a bathtub full of water. If the block is less dense than water, it floats, with part of the block remaining above the water surface, and most of the block submerged below. Now, place a denser block of the same thickness next to the first block. The top of the denser block sits lower than that of the less-dense block of the same thickness. Similarly, the top surface of a thicker block sits higher than the top surface of a thinner block of the same density. If you were to add another block of wood on top of one that is already floating, the lower block would sink to adjust for the addition, so as to maintain isostatic equilibrium.

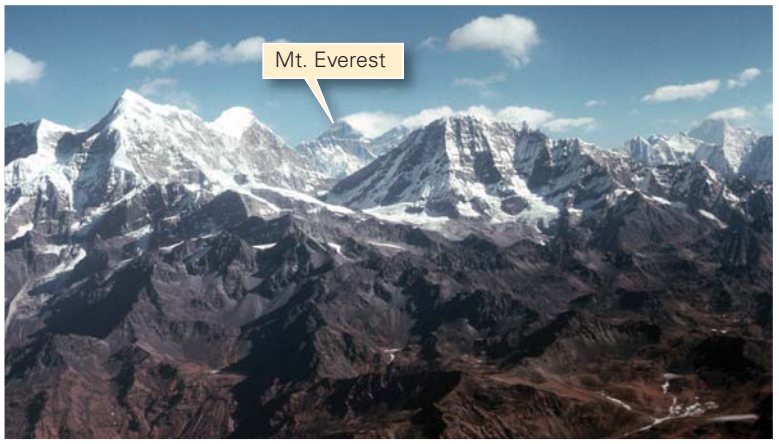
From our bathtub experiment, we can deduce that any phenomenon that changes the thickness and/or density of a floating block will affect the elevation of the block's surface above the water surface. Since the lithosphere floats on the asthenosphere, the elevation of the lithosphere's surface depends on the thickness and density of the lithosphere. So to answer the question of why mountain belts can rise, we must identify geologic processes that can change the thickness and/or density of layers in the lithosphere. Let's consider some examples of how these charges take place.

Crustal shortening and thickening. During collisional orogeny or during certain types of convergent-margin orogeny, horizontal compression causes the crust to shorten horizontally and thicken vertically. In fact, the folding, faulting, and plastic flow that take place during such events can almost double the crust's thickness. For example, the crust beneath the tallest range, the Himalayas, is 70 km thick, whereas crust beneath the plains of the central United States is 35 km thick (**Fig. 9.21a**; see also Geology at a Glance, pp. 304–305). To isostatically compensate for the thickening of the crust (the geologic equivalent to adding another block of low-density wood to the top of a floating block), the base of the crust and underlying lithospheric mantle subside (**Fig. 9.21b**). Indeed, since the Himalayas are about 8 km high, most of the thickened crust extends downward beneath the range just as most of an ice cube lies under water. This downward protrusion of crust is called a **crustal root**. We can illustrate this relationship in a bathtub model by lining up a row of floating blocks of different thickness—if all the blocks have the same density, the thicker blocks rise farther above water and protrude deeper below the surface (**Fig. 9.21c**).

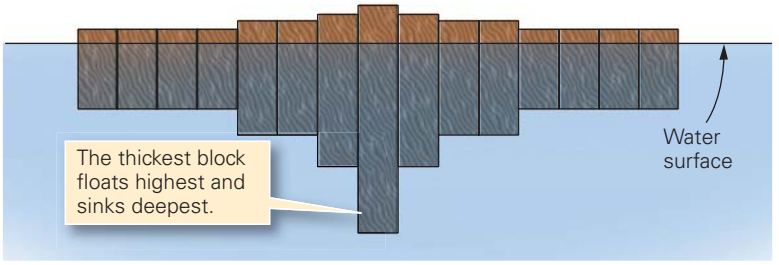
Adding igneous rock to the crust. When lava and/or pyroclastic debris is deposited onto the surface, a volcano grows and may become a mountain. Growth of mountains associated with igneous activity may also occur because intrusions at depth may add material to the crust and, therefore, thicken it.

Removal of lithospheric mantle. The weight of the lithospheric mantle (composed of very dense rock) pulls the lithosphere down, just as heavy ballast makes a ship settle deeper into the water. Removal of some or all of the lithospheric mantle from the base of a plate, therefore, causes the surface of the remaining lithosphere to rise to maintain isostasy,

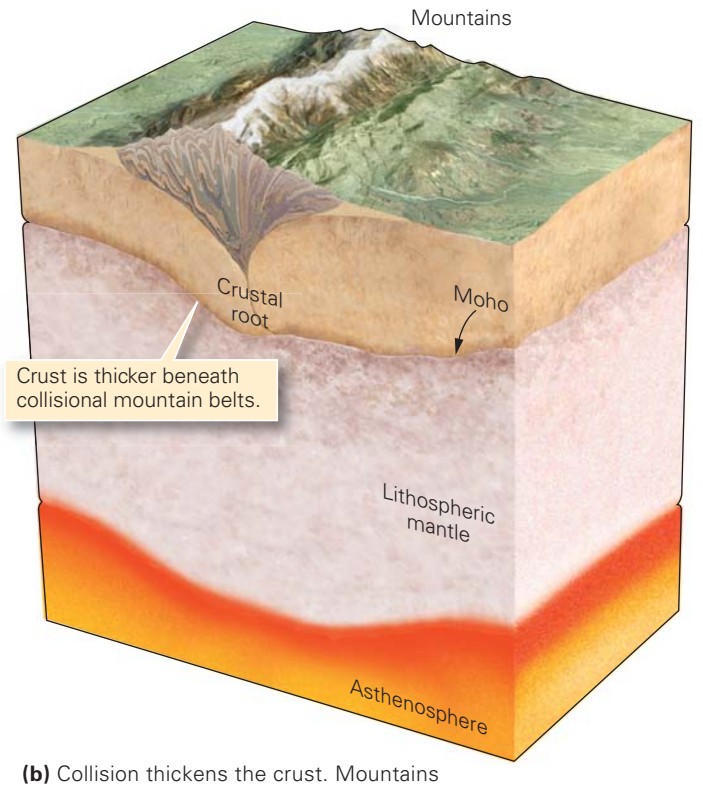
FIGURE 9.21 The concept of isostasy as applied to collisional mountain ranges.



(a) The Himalayas are the world's highest mountain range. The crust beneath them is almost twice the normal thickness.



(c) Because of isostasy, blocks of wood floating in water sink to a depth such that the mass of the water displaced is the same as the mass of the block.

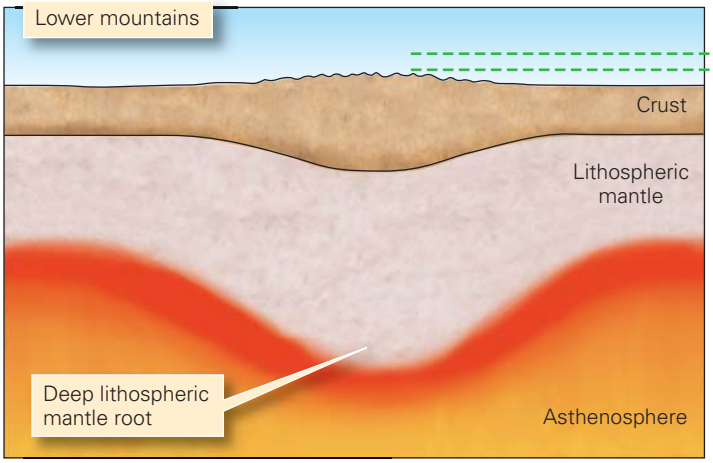


(b) Collision thickens the crust. Mountains form where the low-density crust is thicker.

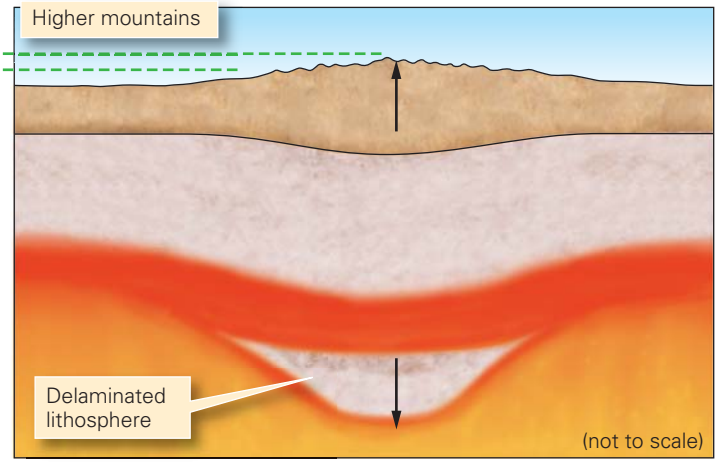
even if the thickness of the crustal component remains unchanged (Fig. 9.22a, b). Such removal, a process known as **delamination**, resembles removal of ballast from the hold of a ship—as the weight of the ballast disappears, the deck of the ship rises.

Thinning and heating the lithosphere. In rifts, the lithosphere undergoes stretching and thinning. As a result, relatively less-dense asthenosphere rises beneath the rift, and the remaining lithosphere heats up. Replacing dense lithospheric mantle with less-dense hot asthenosphere, and heating the

FIGURE 9.22 Uplift, due to delamination of the lithosphere root, may happen after collision.



(a) Soon after collision, the crust and lithospheric mantle have thickened. The lithospheric mantle root is like ballast, holding the surface of the crust down.



(b) If the lithospheric mantle root detaches and sinks, a process called delamination, the surface of the lithosphere may rise, like a balloon dropping ballast.

FIGURE 9.23 Manifestations of erosion in mountain ranges. When land rises, water and ice start cutting into it.



(a) Glaciers carved these rugged peaks in Switzerland.



(b) Streams cut valleys into weathered bedrock in Brazil.

remaining, overlying lithosphere (thereby causing rocks to expand so their density increases) results in uplift of the rift and its borders.

What Goes Up Must Come Down

When the land surface rises significantly, for whatever reason, it doesn't remain a smooth welt or bulge on the Earth's surface. As soon as a difference in elevation between one location and an adjacent one develops, gravity begins to drive a variety of erosive processes. For example, as slopes steepen, landslides of various types cause rock and debris to tumble from higher to lower elevations (see Chapter 13); when rain falls, streams form and sculpt valleys and canyons (see Chapter 14); and if it remains cold enough, glaciers grow and flow, carving peaks and deepening valleys (see Chapter 17). The net result of all these processes is to grind away elevated areas and produce the jagged landscapes that we associate with mountain terrains (**Fig. 9.23a, b**). It's important to keep in mind that uplift and erosion happen simultaneously in active mountain belts, so for the elevation of a range to increase over time, the rate of uplift must *exceed* the rate of erosion.

The highest point on Earth, the peak of Mt. Everest, lies 8.85 km above sea level—can our planet's mountain ranges get significantly higher? Probably not. Mountains as high as Olympus Mons on Mars, which rises 27 km above the plain at its base, couldn't form on Earth because of the relatively high geothermal gradient (the rate of increase in temperature with depth) in Earth's crust. Due to the gradient, quartz-rich crustal rocks at mid-crustal depths (15–30 km) become so warm and weak that they can flow ductilely. When this flow begins, overlying mountains above begin to collapse under their own weight, and spread laterally like soft cheese that has been left out in the summer sun. Geologists call this process **orogenic collapse**. During orogenic collapse, the upper crust breaks and a system of normal faults develop, to accommodate the horizontal stretching.

The simultaneous activity of uplift, erosion, and organic collapse ultimately brings rock that was metamorphosed at great depth up to the surface of the Earth. This process of revealing deeper rocks by removal of the overlying crust is called unroofing or **exhumation**.

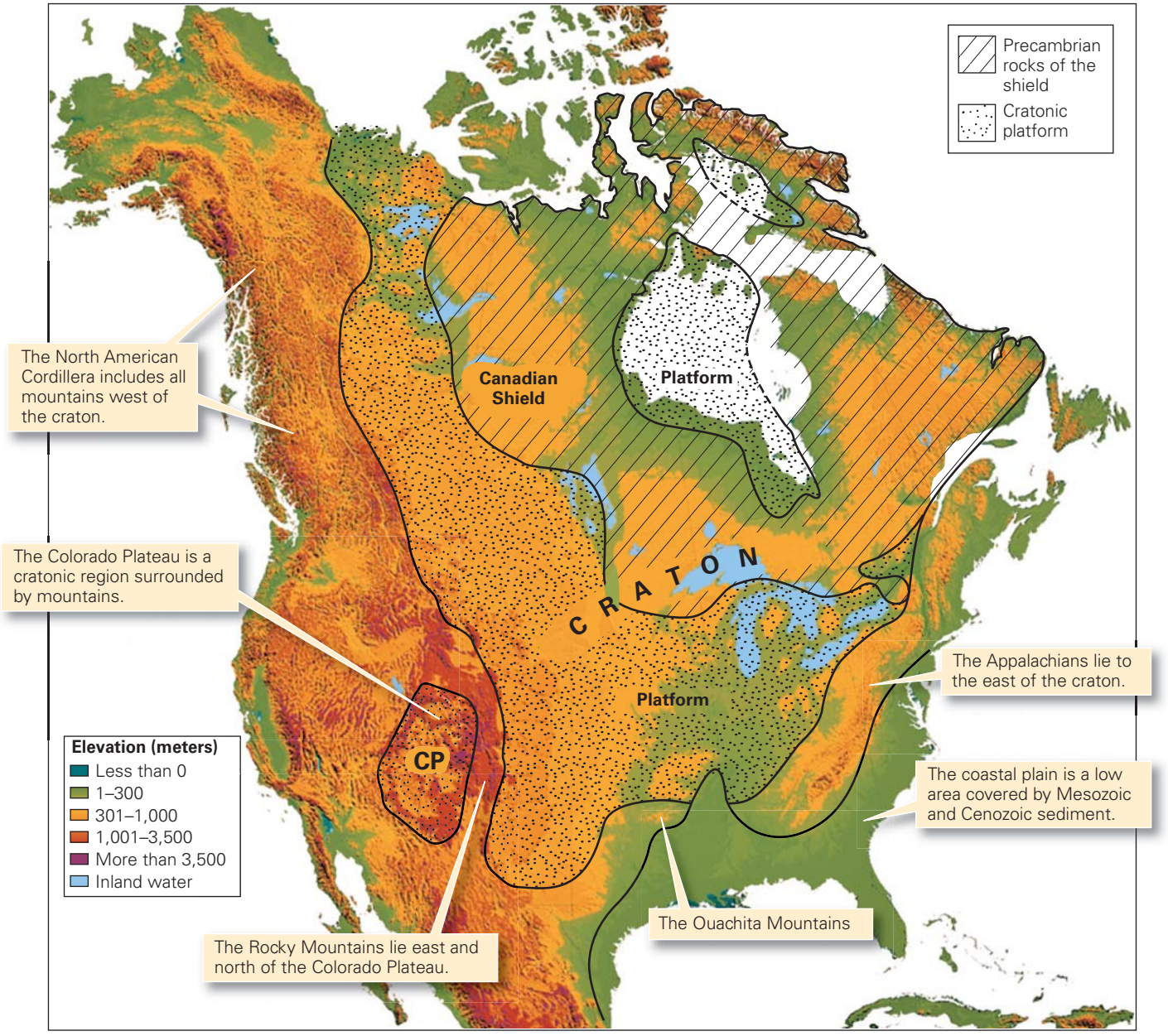
Take-Home Message

Mountains exist where major uplift occurs. Beneath some belts, the relatively buoyant crust has thickened, so the lithosphere "floats" higher. Once uplifted, erosion sculpts rugged topography. Mountain belts may eventually collapse under their own weight.

9.7 Basins and Domes in Cratons

A **craton** consists of crust that has not been affected by orogeny for at least about the last 1 billion years. As a result, cratons have cooled substantially, and therefore have become relatively strong and stable. Geologists divide cratons into two provinces: **shields**, in which Precambrian

FIGURE 9.24 North America's craton consists of a shield, where Precambrian rock is exposed, and a platform, where Paleozoic sedimentary rock covers the Precambrian.

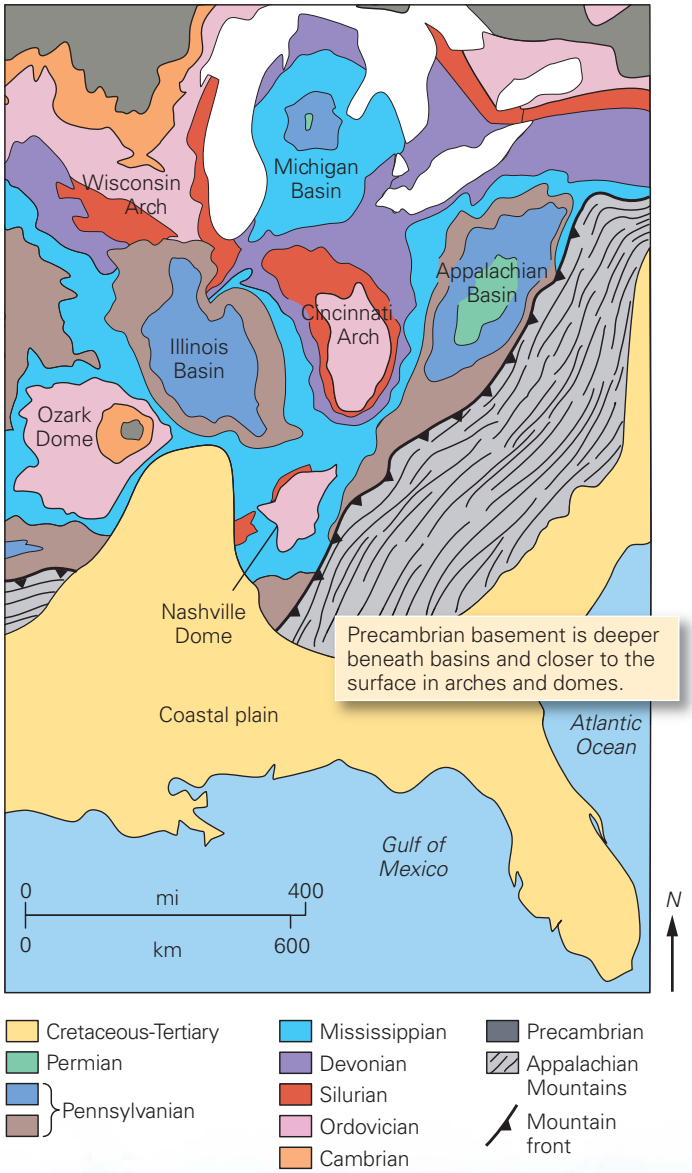


metamorphic and igneous rocks crop out at the ground surface, and **cratonic platforms**, where a relatively thin layer of Phanerozoic sediment covers the Precambrian rocks (Fig. 9.24).

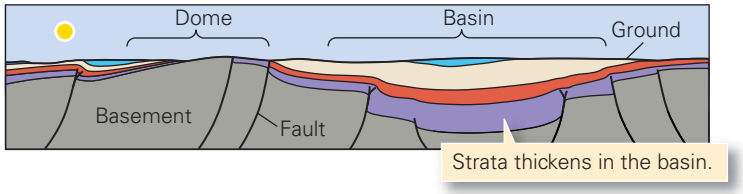
In shield areas, we find widespread exposures of intensively deformed metamorphic rocks with abundant examples of flow folds and tectonic foliation. That's because the crust making the cratons was deformed during a succession of orogenies in the Precambrian. These orogens are so old that erosion has worn away the original topography, in the process exhuming deep crustal rocks.

In the cratonic platform, the pattern of contacts between stratigraphic formations defines regional domes and basins. These are broad areas that gradually sank or rose, respectively, over geologic time (Fig. 9.25a, b). For example, in Missouri, strata arch across a broad dome, the Ozark Dome, whose diameter is 300 km. Individual sedimentary layers thin toward the top of the dome, because less sediment

FIGURE 9.25 Domes and basins of the North American cratonic platform.



(a) A geologic map of the U.S. mid-continent platform region showing the locations of basins and domes.



(b) A cross section showing how strata thin toward the crest of a dome and thicken toward the center of a basin. The cross section is vertically exaggerated. This cross section symbolically represents the Ozark Dome and Illinois Basin.

accumulated on the dome than in adjacent basins. Erosion during more recent geologic history has produced the characteristic bull's-eye pattern of a dome, with the oldest rocks (Precambrian granite) exposed near the center. In the Illinois Basin, strata warp downward into a huge bowl that is also about 300 km across. Strata get thicker toward the basin center, indicating that the floor of the basin was subsiding *as* sediment was accumulating—there was more room for sediment to accumulate where the basin subsided the most. The basin also has a bull's-eye shape, but here the youngest strata are exposed in the center. Geologists refer to the broad vertical movements that generate huge, but gentle, mid-continent domes and basins as **epeirogeny**.

Take-Home Message

Cratons are portions of continents that consist of old (Precambrian) and relatively stable crust. Parts of cratons may be covered by Paleozoic sedimentary strata. Variations in the dip and thickness of these strata define regional basins, arches, and domes.

ANOTHER VIEW There are over 2 km of vertical relief between the base of Wyoming's Grand Teton Mountains and the peak. And the base already lies at a high elevation. The exposed rocks once lay 12 km or more beneath the surface of the Earth. Clearly, mountain building results in large vertical displacements of the surface of the crust.



Chapter Summary

- Mountains occur in linear ranges called orogens. An orogen forms during an orogeny, or mountain-building event.
- Mountain building causes rocks to bend, break, shorten, stretch, and shear. Because of such deformation, rocks can change their location, orientation, and shape.
- During brittle deformation, rocks break into pieces. During ductile deformation, rocks change shape without breaking.
- Rocks undergo three kinds of stress: compression, tension, and shear. Strain refers to the way rocks change shape when subjected to a stress.
- Deformation results in the development of geologic structures.
- Joints are natural cracks in rock, formed in response to tension under brittle conditions. Veins develop when minerals precipitate out of water passing through cracks.
- Faults are fractures on which there has been shear. Geologists distinguish among normal, reverse, strike-slip, and oblique-slip faults.
- Folds are curved layers of rock. Anticlines are arch-like, synclines are trough-like, monoclines resemble the shape of a carpet draped over a stair step, basins are shaped like a bowl, and domes are shaped like an overturned bowl.
- Tectonic foliation forms when grains flatten, rotate, or grow so that they align parallel with one another.
- Uplift in mountains, over broad regions, is controlled by the isostasy, meaning that the elevation of the Earth's surface reflects the level at which lithosphere naturally floats.
- Large collisional mountain ranges are underlain by buoyant roots and contain folds, faults, and foliations.
- With modern GPS technology, it is now possible to measure the slow shortening and uplift of mountains.
- Once uplifted, mountains are sculpted by erosion. When crust thickens during mountain building, the deep crust eventually becomes weak, leading to orogenic collapse.
- Mountain belts formed by convergent-margin tectonism may incorporate accreted terranes.
- Cratons are the old, relatively stable parts of continental crust. They include shields and platforms. Broad regional domes and basins form in platform areas.

Key Terms

accretionary orogen (p. 280)
anticline (p. 275)
axial surface (p. 275)
basin (p. 275)
brittle deformation (p. 267)
compression (p. 270)
craton (p. 287)
cratonic platform (p. 288)
crustal root (p. 285)
crustal thickening (p. 280)
deformation (p. 266)
delamination (p. 286)
dip (p. 272)
displacement (p. 273)
dome (p. 275)
ductile deformation (p. 267)
epeirogeny (p. 289)
exhumation (p. 287)
exotic terrane (p. 279)
fault (p. 266)
fault scarp (p. 273)
fold (pp. 266, 275)
fold-thrust belt (p. 279)
foliation (p. 266)
global positioning system (GPS) (p. 284)
hinge (p. 275)
isostasy (p. 285)
joint (pp. 266, 271)
limb (of fold) (p. 275)
monocline (p. 275)
normal fault (p. 273)
orogen (p. 265)
orogenic collapse (p. 287)
pressure (p. 270)
reverse fault (p. 273)
shear stress (p. 270)
shield (p. 287)
strain (p. 267)
stress (p. 269)
strike (p. 272)
strike-slip fault (p. 271)
syncline (p. 275)
tectonic foliation (p. 276)
tension (p. 270)
thrust fault (p. 273)
uplift (pp. 266, 285)
vein (p. 271)

Review Questions

1. What changes do rocks undergo during formation of an orogenic belt such as the Alps?
2. Contrast brittle and ductile deformation.
3. What factors determine whether a rock will behave in brittle or ductile fashion?
4. How are stress and strain different?
5. How is a fault different from a joint?
6. Compare normal, reverse, and strike-slip faults.
7. How do you recognize faults in the field?
8. Describe the differences between an anticline, a syncline, and a monocline.
9. Discuss the relationship between foliation and deformation.
10. Describe the principle of isostasy.
11. Discuss the processes by which mountain belts form in convergent margins, during collisions, and in continental rifts.
12. How are the structures of a craton different from those of an orogenic belt?

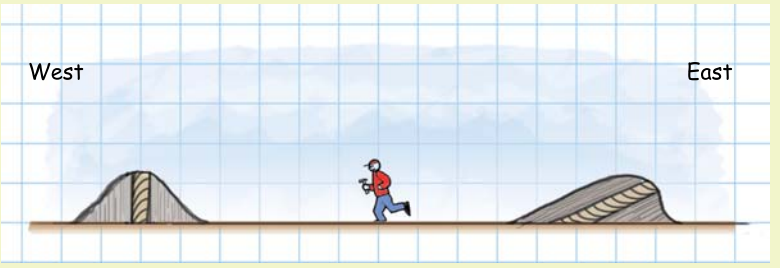
smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Interactive exercises on folds and isostasy.
- An interactive exercise on rock deformation.
- What a Geologist Sees exercises on fault and fold classification.

On Further Thought

13. Imagine that a geologist sees two outcrops of resistant sandstone, as depicted in the cross-section sketch. The region between the outcrops is covered by soil. A distinctive bed of cross-bedded sandstone occurs in both outcrops, so the geologist correlated the western outcrop (on the left) with the eastern outcrop. The curving lines in the bed indicate the shape of the cross beds. Keeping in mind how cross beds form (see Chapter 6), sketch how the cross-bedded bed connected from one outcrop to the other, before erosion. What geologic structure have you drawn?



14. Imagine a coal bed in the strata of a large, cratonic-platform basin. Will mines dug to reach the coal be deeper in the central region of the basin on along the margin?

SEE FOR YOURSELF I. . . Geologic Structures

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet I of our **Geotours Workbook**.



Joints in Arches National Park
Latitude 38°47′45.10″N,
Longitude 109°35′34.19″W

The white area of this view is a white sandstone bed; the reddish areas are other stratigraphic units. Looking straight down from 6 km, you can see that the sandstone has been broken by a prominent set of NW-SE-trending joints.



Folds, Central Australia
Latitude 24°18′44.08″S,
Longitude 132°10′34.02″E

Here, in the stark desert of central Australia, we see alternating beds of resistant and nonresistant sedimentary strata that have been warped into plunging folds. From 30 km, you can trace individual beds around the fold hinge.



Mount Everest, Nepal
Latitude 27°59′17.84″N,
Longitude 86°55′18.01″E

Tilt the view and look east from 8.5 km, and you'll see this view of the highest mountain on our planet. Note the glaciers carving valleys at lower elevations. Zoom up to a higher elevation, and you'll see that the Himalayas lie between the Tibetan Plateau to the north and the Ganges Plain to the south.



Appalachian Fold Belt
Latitude 40°53′24.28″N,
Longitude 77°4′28.11″W

Tilt the view and look west from an elevation of 20 km to see relicts of large folds formed when Africa collided with North America to produce the Appalachians at about 280 Ma. Erosion removed the high mountains. Now, the region is the Valley and Ridge Province; hard sandstone beds form the ridges.

INTERLUDE E

Memories of Past Life: Fossils and Evolution



Fossils of organisms, such as these ammonites that went extinct millions of years ago, tell us the history of life in the past.

E.1 The Discovery of Fossils

If you look at bedding surfaces of sedimentary rock, you may find shapes that resemble shells, bones, leaves, or footprints (Fig. E.1a). The origin of these shapes mystified early thinkers. Some thought that the shapes had simply grown underground, in solid rock. Today, geologists consider such **fossils** (from the Latin word *fossilis*, which means dug up) to be remnants or traces of ancient living organisms now preserved in rock, and that fossils formed when organisms were buried by sediment. This viewpoint, though first proposed by the Greek historian Herodotus in 450 B.C.E. and revived by Leonardo da Vinci in 1500 C.E., did not become widely accepted until the publication in 1669 of a book on the subject by a Danish physician named Nicholaus Steno (1638–1686). Steno argued that, when buried, shells, teeth, and bones could become part of the rock without losing their distinctive shape. The understanding of fossils increased greatly thanks to the efforts of a British scientist, Robert Hooke (1635–1703), who realized that most fossils represent **extinct** species, meaning species that lived in the past but no longer exist today. During the following two centuries, **paleontologists**, scientists who study fossils, have described thousands of specimens and have established museum collections to preserve and display them (Fig. E.1b, c).

The 19th century saw **paleontology**, the study of fossils, ripen into a science. Work with fossils went beyond description alone when William Smith, a British engineer who surveyed canal construction sites in England during the 1790s, noted that different fossils occur in different layers of strata within a sequence of sedimentary rocks. In fact, Smith realized that strata contain a predictable succession of fossils, and that a given species can be found only in a specific interval of strata. This discovery made it possible for geologists to use fossils as a basis for determining the age of one sedimentary rock layer relative to another. Fossils, therefore, have become an indispensable tool for studying geologic history and the evolution of life. In this interlude, we introduce fossils, an understanding of which serves as background for the next two chapters.

FIGURE E.1 Paleontologists collect fossils for study.



(a) This bedding plane contains the imprint of an extinct marine reptile that lived about 250 million years ago.



(b) Paleontologists painstakingly chip and dig away at rock layers in search of fossils.



(c) A drawer of labeled fossils in a museum. Paleontologists study such collections to help identify new specimens.

E.2 Fossilization

What Kinds of Rocks Contain Fossils?

Most fossils are found in sediments or sedimentary rocks. Fossils form when organisms die and become buried by sediment, or when organisms travel over or through sediment and leave imprints or debris. The degree of preservation of a fossil reflects the context of burial. For example, rocks formed from sediments deposited under anoxic (oxygen-free) conditions in quiet water (such as lake

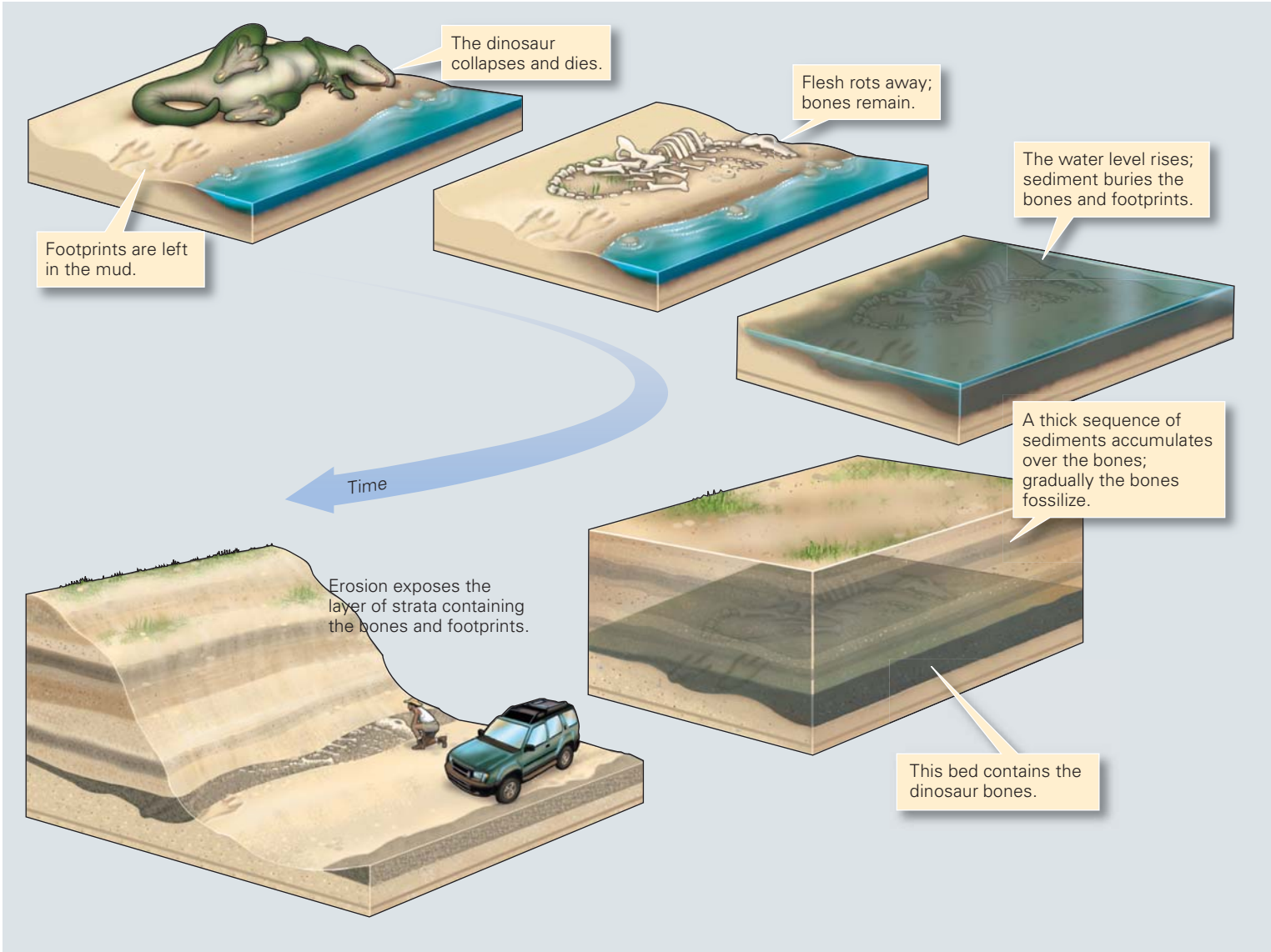
beds or lagoons) can preserve particularly fine specimens. In contrast, rocks made from sediments deposited in high-energy environments—where strong currents tumble shells and bones and break them up—contain at best only small fragments of fossils mixed with other clastic grains. Fossils sometimes occur in volcaniclastic rocks, but they are not found in intrusive igneous rocks and tend to be destroyed by metamorphism.

Forming a Fossil

Paleontologists refer to the process of forming a fossil as **fossilization**. To see how a typical fossil develops in sedimentary rock, let's follow the fate of an old dinosaur as it searches for food along a riverbank (**Fig. E.2**). On a scalding summer day, the hungry dinosaur, plodding through the muddy ground, succumbs to the heat and collapses dead into the mud. Soon after, scavengers strip the skeleton of meat and scatter the bones. But before the bones have had time to weather away, the river floods and buries the bones, along with the dinosaur's footprints, under a layer of silt. More sediment from succeeding floods buries the bones and prints still deeper, so that the bones cannot be reworked by currents or disrupted by burrowing organisms. Later, sea level rises and a thick sequence of marine sediment buries the fluvial sediment.

Eventually, the sediment containing the bones and footprints turns to rock (siltstone and shale). The footprints remain outlined by the contact between the siltstone and shale, while the bones reside within the siltstone. Minerals precipitating

FIGURE E.2 How a dinosaur eventually becomes a fossil. This takes many steps, over a long period of time.



from groundwater passing through the siltstone gradually replace some of the chemicals constituting the bones, until the bones themselves have become rock-like. The buried bones and footprints are now fossils. One hundred million years later, uplift and erosion expose the dinosaur's grave. Part of a fossil bone protrudes from a rock outcrop. A lucky paleontologist observes the fragment and starts excavating, gradually uncovering enough of the bones to permit reconstruction of the beast's skeleton. Further digging uncovers the footprints. The dinosaur rises again, but this time in a museum. In recent years, bidding wars have made some fossil finds extremely valuable. For example, a skeleton of a *Tyrannosaurus rex*, a 67-million-year-old dinosaur, sold at auction in 1997 for $7.6 million. The specimen, named Sue after its discoverer, now stands in the Field Museum of Chicago.

Similar tales can be told for fossil seashells buried by sediment settling in the sea, for insects trapped in hardened tree sap (amber), and for mammoths drowned in the muck of a tar pit. In all cases, fossilization involves the burial and preservation of an organism or the trace (a footprint or burrow) of an organism.

The Many Different Kinds of Fossils

Perhaps when you think of a fossil, you picture either a dinosaur bone or the imprint of a seashell in rock. In fact, paleontologists distinguish many different kinds of fossils, according to the specific way in which the organism was fossilized. Let's look at examples of these categories.

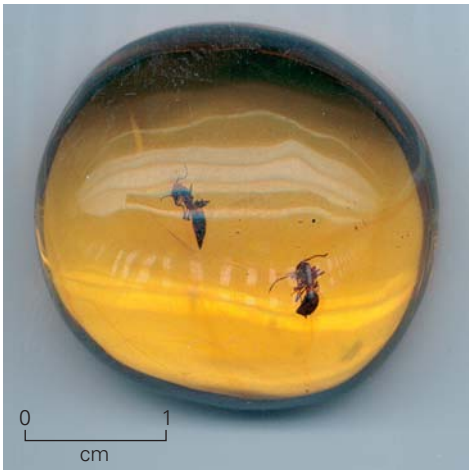
- *Frozen or dried body fossils*: In a few environments, whole bodies of organisms may be preserved. Most of these fossils are fairly young, by geologic standards—their ages can be measured in thousands, not millions, of years. Examples include woolly mammoths that became incorporated in the permafrost (permanently frozen ground) of Siberia (**Fig. E.3a**). In desert climates, organisms can become desiccated (dried out). Such "mummified" corpses can survive for millennia in caves.
- *Body fossils preserved in amber or tar*: Insects landing on the bark of trees may become trapped in the sticky sap or resin the trees produce. This golden syrup envelops the insects and over time hardens into **amber**, the semiprecious "stone" used for jewelry. Amber can preserve insects, as well as other delicate organic material such as feathers, for 40 million years or more (**Fig. E.3b**). Tar similarly acts as a preservative. In isolated regions where oil has seeped to the surface, the more volatile components of the oil evaporate away and bacteria degrade what remains, leaving behind a sticky residue of tar. At one such locality, the La Brea Tar Pits in Los Angeles, tar accumulated in a swampy area. While grazing, drinking, or hunting at the swamp, animals became mired in the tar and sank into it. Their bones have been remarkably well preserved for over 40,000 years (**Fig. E.3c**).
- *Preserved or replaced bones, teeth, and shells*: Bones (the internal skeletons of vertebrate animals) and shells (the external skeletons of invertebrate animals) consist of durable minerals, which may survive in rock (**Fig. E.3d**). Some bone or shell minerals are not stable, and they recrystallize. But even when this happens, the shape of the bone or shell can be preserved in the rock.
- *Molds and casts of bodies*: As sediment compacts around a shell, it conforms to the shape of the shell or body. If the shell or body later disappears, because of weathering and dissolution, a cavity called a **mold** remains (**Fig. E.3e**). (Sculptors use the same term to refer to the receptacle into which they pour bronze or plaster.) A mold preserves the delicate shape of the organism's surface; it looks like an indentation on a rock bed. The sediment that had filled the mold also preserves the organism's shape; this **cast** protrudes from the surface of the adjacent bed.
- *Carbonized impressions of bodies*: Impressions are simply flattened molds created when soft or semisoft organisms (leaves, insects, shell-less invertebrates, sponges, feathers, jellyfish) get pressed between layers of sediment. Chemical reactions eventually remove the organic material, leaving only a thin film of carbon on the surface of the impression (**Fig. E.3f**).
- *Permineralized organisms*: Permineralization refers to the process by which minerals precipitate in porous material, such as wood or bone, from groundwater solutions that have seeped into the pores. **Petrified wood**, for example, forms by permineralization of wood, causing the wood to become chert. In fact, the word *petrified* literally means turned to stone. When the wood dries out, open spaces form inside the cells because the protoplasm of cells is 80% water. The chert precipitates inside these spaces and the organic matter of the cell walls becomes carbonized. The fine detail of the wood's cell-wall structure can be seen in a petrified log (**Fig. E.3g**).
- *Trace fossils*: These include footprints, feeding traces, burrows, and dung (coprolites) that organisms leave behind in sediment (**Fig. E.3h, i**).
- *Chemical fossils*: Living things consist of complex organic chemicals. When buried with sediment and subjected to diagenesis, some of these chemicals are destroyed, but some either remain intact or break down to form different, but still distinctive, chemicals. A distinctive chemical derived from an organism and preserved in rock is called a chemical fossil. (Such chemicals may also be called molecular fossils or **biomarkers**.)

Paleontologists also find it useful to distinguish among different fossils on the basis of their size. **Macrofossils** are large enough to be seen with the naked eye. But some rocks and sediments also contain abundant **microfossils**, which can be seen only with a microscope or even an electron microscope (**Fig. E.4**). Microfossils include remnants of plankton, algae, bacteria, and pollen.

FIGURE E.3 Examples of different kinds of fossils.



(a) A 100,000-year-old frozen mammoth found in Siberia still has flesh and fur.



(b) A piece of amber containing two fossil insects.



(c) A fossil skeleton of a 2-m-high giant ground sloth from the La Brea Tar Pits in California.



(d) Fossil dinosaur bones on a tilted bed of sandstone in Utah.



(e) Molds and casts of a shell. Even fine detail is preserved.



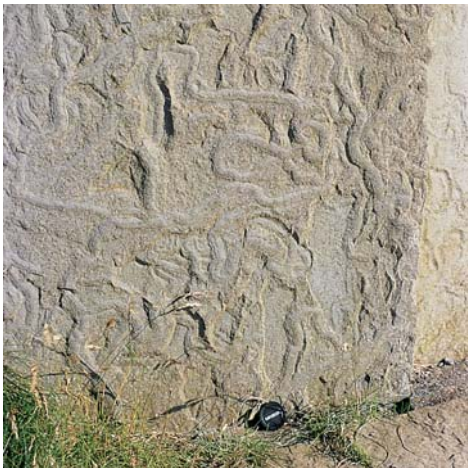
(f) The carbonized impressions of fern fronds in a shale.



(g) Petrified wood from Arizona. It is so hard that it remains after the rock that surrounded it has eroded away.



(h) Dinosaur footprints in a mudstone in Arizona.



(i) Worm burrows on siltstone in Ireland (lens cap for scale).

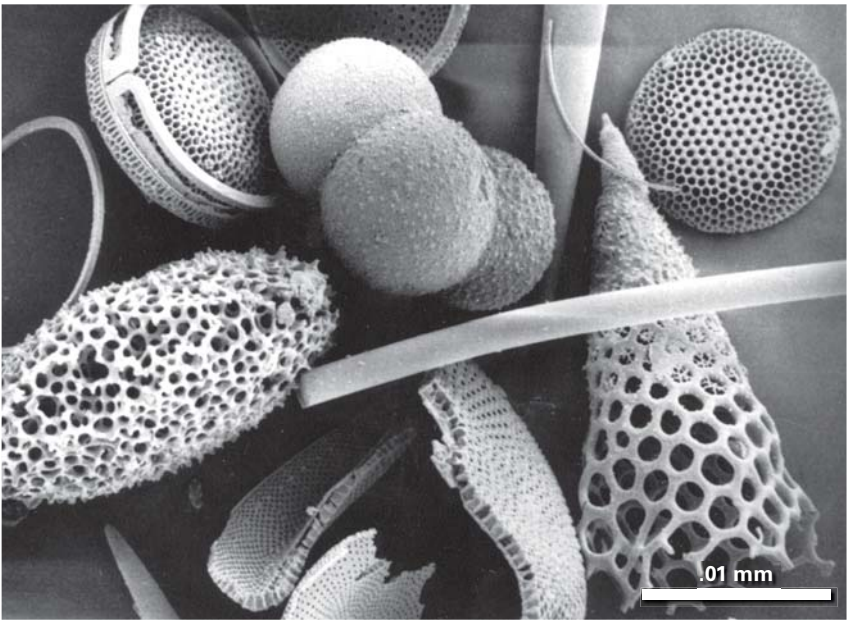


FIGURE E.4 Examples of fossil plankton shells. Because of their size, geologists refer to these as microfossils or nannofossils.

Fossil Preservation

Not all living organisms become fossils when they die. In fact, only a small percentage do, for it takes special circumstances—namely, one or more of the following three—to produce a fossil and allow it to survive.

- *Death in an anoxic (oxygen-poor) environment*: A dead squirrel by the side of the road won't become a fossil. As time passes, birds, dogs, or other scavengers may come along and eat the carcass. And if that doesn't happen, maggots, bacteria, and fungi infest the carcass and gradually digest it. As the flesh rots, some reacts with oxygen in the atmosphere and transforms into carbon dioxide gas. The remaining skeleton weathers in air and turns to dust. Thus, before roadkill can become incorporated in sediment, it has vanished. If, however, a carcass settles into an oxygen-poor environment, oxidation reactions happen slowly, scavenging organisms aren't abundant, and bacterial metabolism takes place very slowly. In such environments, the organism won't rot away before it has a chance to be buried and preserved, so the likelihood that the organism becomes fossilized increases.
- *Rapid burial*: If an organism dies in a depositional environment where sediment accumulates rapidly, it may be buried before it has time to rot, oxidize, be eaten, or undergo complete weathering. For example, if a storm suddenly buries an oyster bed with a thick layer of silt, the oysters die and become part of the sedimentary rock derived from the sediment.
- *The presence of hard parts*: Organisms without durable shells or skeletons, or other "hard parts," usually won't be fossilized, for soft flesh decays long before hard parts do under most depositional conditions. For this reason, paleontologists have learned more about the fossil record of bivalves (a class of organisms, including clams and oysters, with strong shells) than they have about the fossil record of jellyfish (which have no shells) or spiders (which have very fragile exoskeletons).

By carefully studying modern organisms, paleontologists have been able to provide rough estimates of the **preservation potential** of organisms, meaning the likelihood that an organism will be buried and eventually transformed into a fossil. For example, in a typical modern-day shallow-marine environment, such as the mud-and-sand sea floor close to a beach, about 30% of the organisms have sturdy shells and thus a high preservation potential, 40% have fragile shells and a low preservation potential, and the remaining 30% have no hard parts at all and are not likely to be fossilized except in special circumstances. Of the 30% with sturdy shells, though, only a few happen to die in a depositional setting where they actually *do* become fossilized. Thus, fossilization is the exception rather than the rule.

Extraordinary Fossils: A Special Window to the Past

Though only hard parts survive in most fossilization environments, paleontologists have discovered a few special locations where rock contains fossils of *soft parts* as well; such fossils are known as **extraordinary fossils** (Fig. E.5a, b). We've already seen how extraordinary fossils such as insects and even feathers can be preserved in amber, and how complete skeletons have been found in tar pits. In a few cases, such finds include actual tissue, a discovery that has led to a research race to find the oldest preserved DNA. Extraordinary fossils may also be preserved in sediment that accumulates on the anoxic floor of lakes or lagoons or the deep ocean. Here, oxidation cannot occur, and flesh does not rot before burial.

E.3 Taxonomy and Identification

The study of how to identify and name organisms is **taxonomy**. Taxonomic classification of fossils follows the same principles used for the classification of living organisms and has a hierarchy of divisions. These principles were first proposed in the 18th century by Carolus Linnaeus, a Swedish biologist.

First, all life is divided into three *domains*, named Archaea, Bacteria, and Eukarya. The domains differ from one another based on fundamental characteristics of their genes. **Archaea** include a vast array of tiny single-celled microorganisms that occur not only in the mild environments of oceans, soils, and

FIGURE E.5 Extraordinary fossils. These fossils are particularly well preserved.



(a) A 50-million-year-old mammal fossil was chiseled from oil shale near Messel, Germany. It still contains the remains of skin.



(b) *Archaeopteryx* from the 150-million-year-old Solenhofen Limestone of Germany. The imprints of feathers are clearly visible.

wetlands but also in the harsh environments of hot springs, black smokers, salt lakes, very acidic sediments, and deep subsurface water. Those organisms that can survive in harsh environments are referred to as "extremophiles;" they do not need light, but rather live off the energy stored in the chemical bonds of minerals. **Bacteria** are also tiny single-celled organisms, species of which inhabit almost all livable environments on Earth. Visually, it may be difficult to distinguish Bacteria from Archaea, but on a genetic level they are profoundly different. Nevertheless, both Archaea and Bacteria have prokaryotic cells, meaning that their cells *do not* contain nuclei or other organelles surrounded by membranes. In this regard, Archaea and Bacteria differ from **Eukarya**, for the eukaryotic cells of organisms of the latter domain do contain nuclei and other organelles. Taxonomists divide Eukarya into kingdoms:

- *Protista*: various unicellular and simple multicellular organisms such as diatoms and forams, two of the major plankton types in the oceans;
- *Fungi*: mushrooms and yeast;
- *Plantae*: trees, grasses, mosses, and ferns; and
- *Animalia*: sponges, corals, snails, dinosaurs, ants, lizards, birds, tigers, fish, and people.

Each kingdom consists of one or more phyla. A phylum, in turn, consists of several classes; a class, of several orders; an order, of several families; a family, of several genera; and a genus, of one or more species. Kingdoms, therefore, are the broadest category of Eukarya and species are the narrowest.

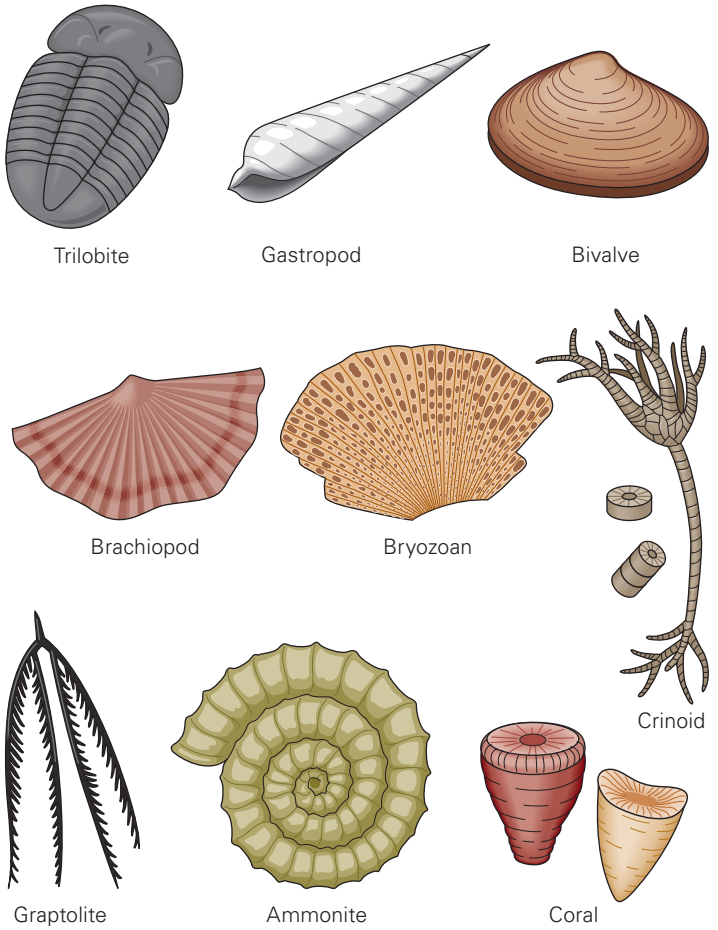
There's nothing magical about identifying fossils. You can often recognize common fossils in the field by examining their **morphology** (form or shape). If the fossil is well preserved and has distinctive features, the process can be straightforward, but if fossils are broken into fragments and parts are missing, or if the fossil shares many characteristics with others, identification can be challenging.

Many fossil organisms resemble modern organisms, so it is relatively easy to figure out how to classify them taxonomically. For example, a fossil clam (class Bivalvia) looks like a clam and doesn't look like, say, a snail (class Gastropoda). At the taxonomic levels below class, identification may involve recognizing such details as the number of ridges on the surface of the shell. Not all fossils, however, resemble living organisms, and figuring out their taxonomic relation to other organisms may be a challenge. Some interpretations remain controversial.

Figure E.6 shows examples of some of the major types of invertebrate fossils. With this figure, you should be able to identify many of the fossils you'll find in a bed of sedimentary rock. Some of the notable characterisitics of these fossils include:

- *Trilobites*: These have a segmented shell that is divided lengthwise into three parts. They are a type of arthropod.
- *Gastropods* (snails): Most fossil specimens of gastropods have a shell that does not contain internal chambers.
- *Bivalves* (clams and oysters): These have a shell that can be divided into two similar halves.

FIGURE E.6 Common types of invertebrate fossils.



(a) Sketches of representative fossils.



(b) An artist's reconstruction of a Cambrian ecosystem. The painting is based on Burgess Shale fossils.

- *Brachiopods* (lamp shells): The top and bottom parts of these shells have different shapes, and the plane of symmetry is perpendicular to the plane of the shell. Examples typically have ridges radiating out from the hinge.
- *Bryozoans*: These are colonial invertebrates. Their fossils commonly resemble a screen-like grid. Each opening in the grid is the shell of a single animal.
- *Crinoids* (sea lilies): These organisms look like flowers but actually are animals. Their shells have a stalk consisting of numerous circular plates stacked one on top of the other.
- *Graptolites*: These look like tiny carbon-saw blades in a rock. They are remnants of colonial animals that floated in the sea.
- *Cephalopods*: These include ammonites, with a spiral shell, and nautiloids, with a straight shell. Their shells contain internal chambers and have ridged surfaces. These organisms had a squid-like head.
- *Corals*: These include colonial organisms that form distinctive mounds or columns as well as solitary, cone-shaped species.

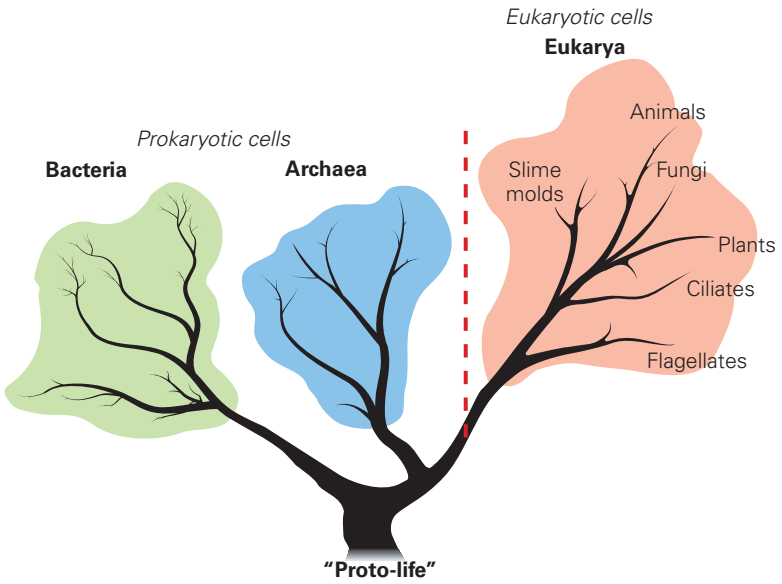
E.4 The Fossil Record

A Brief History of Life

Based on laboratory experiments conducted in the 1950s, researchers speculated that reactions in concentrated "soups" of chemicals that formed when seawater evaporated in shallow, coastal pools led to the formation of the earliest protein-like organic chemicals ("proto-life"). More recent studies suggest, instead, that such reactions took place in warm groundwater beneath the Earth's surface or at hydrothermal vents on the sea floor. While the nature of proto-life remains a mystery, an image of early life has begun to take shape, based on detailed analysis of the oldest sedimentary rocks. The fossil record defines the subsequent long-term record of life's evolution on planet Earth. And, of course, that record is more complete in younger strata.

Archaea and Bacteria fossils appear in rocks as old as about 3.7 billion years. For the next billion years or so of life history, cells of these organisms were the *only* types of life on Earth. Then, about 2.5 Ga, organisms of the Protista kingdom first appeared. Early multicellular organisms, shell-less invertebrates of the animal kingdom, and fungi came into existence at perhaps 1.0 to 1.5 Ga. Within each kingdom, life radiated (divided) into different phyla, and within each phylum, life radiated into different classes. The great variety of shelly invertebrate classes appeared a little over 530 million years ago, during an event called the **Cambrian explosion**, named for the geologic era in which it occurred. Many organisms that persist today appeared at different times since then. After the appearance of invertebrates came in

FIGURE E.7 The "tree of life" symbolically illustrates relations among different domains of organisms on Earth. Archaea and Bacteria are both prokaryotic and don't have nuclei. All other life forms are eukaryotic because they have cells with a nucleus.



sequence: fish, land plants, amphibians, reptiles, and finally birds and mammals.

Researchers have been working hard to understand the phylogeny (the evolutionary relationships) among organisms, using both the morphology of organisms and, more recently, the study of genetic material. Ideas about which groups radiated from which ancestors are shown in a chart called the "tree of life", or, more formally, the **phylogenetic tree** (Fig. E.7). Study of the DNA of different organisms is beginning to enable researchers to understand the relationship between molecular processes and evolutionary change.

Is the Fossil Record Complete?

By some estimates, more than 250,000 species of eukaryote fossils have been collected and identified to date, by thousands of paleontolgists working on all continents during the past two centuries. These fossils define the framework of life's evolution. But the record is not complete—known fossils cannot account for every intermediate step in the evolution of every organism. Over the billions of years that life has existed there may have been 5 billion to 50 billion species of life in the three domains. Clearly, known fossils represent at most a tiny percentage of these species. Why is the record so incomplete?

First, despite all the fossil-collecting efforts of the past two centuries, paleontologists have not even come close to sampling every cubic centimeter of sedimentary rock exposed on Earth. Just as biologists have not yet identified every living species of insect, paleontologists have not yet identified every species of fossil. New species and even genera of fossils continue to be discovered every year.

Second, not all organisms are represented in the rock record, because not all organisms have a high preservation potential. As noted earlier, fossilization occurs only under special conditions, and thus only a minuscule fraction of the organisms that have lived on Earth have left a fossil record. There may be few, if any, fossils of a vast number of extinct species, so we have no way of knowing what they looked like or even that they ever existed.

Finally, as you will learn in Chapter 10, the sequence of sedimentary strata that exists on Earth does not account for every minute of time at every location since the formation of our planet. Sediments accumulate only in environments where conditions are appropriate for deposition and not for erosion—sediments do not accumulate, for example, on dry plains or on steep mountain peaks, but do accumulate in the sea and in the floodplains and deltas of rivers. Because Earth's climate changes through time and because the sea level rises and falls, certain locations on continents are sometimes sites of deposition and sometimes aren't, and on occasion are sites of erosion. Therefore, strata accumulate only episodically.

E.5 Evolution and Extinction

Darwin's Grand Idea

As a young man in England in the early 19th century, Charles Darwin had been unable to settle on a career but had developed a strong interest in natural history. Therefore, he jumped at the opportunity to serve as a naturalist aboard HMS *Beagle* on an around-the-world surveying cruise. During the five years of the cruise, from 1831 to 1836, Darwin made detailed observations of plants, animals, and geology in the field and amassed an immense specimen collection from South America, Australia, and Africa. Just before Darwin departed on the voyage, a friend gave him a copy of Charles Lyell's 1830 textbook, *Principles of Geology*, which argued in favor of James Hutton's proposal that the Earth had a long history and that geologic time extended much further into the past than did human civilization.

A visit to the Galápagos Islands, off the coast of Ecuador, led to a turning point in Darwin's thinking during the voyage. The naturalist was most impressed with the variability of Galápagos finches. He marveled not only at the

fact that different varieties of the bird occurred on different islands, but at how each variety had adapted to utilize a particular food supply. With Lyell's writings in mind, Darwin developed a hypothesis that the finches had begun as a single species but had branched into several different species when populations of the birds became isolated on different islands. This can happen because offspring can differ from their parents and new traits can be transferred to succeeding generations. If enough change accumulates over many generations, the living population ends up being so different from its distant ancestors that the population can be classified as a new species. During the course of evolution, old species vanish and new species appear. The accumulation of changes may eventually yield a population that is so different from its ancestors that taxonomists consider it to be a new genus—greater differences may result in a new class, an order, or even a new phylum. Such change in a population over a succession of generations, due to the transfer of inheritable characteristics, is the process of **evolution**.

Darwin and his contemporary, Alfred Russel Wallace, not only proposed that evolution took place, but also came up with an explanation for why it occurs. The crux of the explanation is simply this: populations of organisms cannot increase in numbers forever, because they are limited by competition for scarce resources in the environment. In nature, only organisms capable of survival can pass on their characteristics to the next generation. In each new generation, some individuals have characteristics that make them more fit, whereas some have characteristics that make them less fit. The fitter organisms are more likely to survive and produce offspring. Thus, beneficial characteristics that they possess get passed on to the next generation. Darwin called this process **natural selection**, because it occurs on its own in nature. According to Darwin, when natural selection takes place over long periods of time—geologic time—it eventually yields a population of new organisms that differ so significantly from their distant ancestors that the new organisms can be considered to constitute a new species. If environmental conditions change, or if competitors enter the environment, species that do not evolve and become better adapted to survive the new conditions eventually die off.

Darwin's view of evolution has been successfully supported by many observations, and so far has not been definitively disproved by any observation or experiment. Also, it can be used to make testable predictions. Thus, scientists now refer to Darwin's idea as the **theory of evolution** by natural selection (see Box P.1 in the Prelude for the definition of a theory). The theory of evolution provides a conceptual framework in which to understand paleontology. By studying fossils in sequences of strata, paleontologists are able to observe progressive changes in a species and in an assemblage of species through time, and can determine when some species die out and other species appear. But because of the incompleteness of the fossil record, many questions remain as to the *rates* at which evolution takes place during the course of geologic time. Originally, it was assumed that evolution happened at a constant, slow rate—this concept is called **gradualism**. More recently, researchers have suggested that evolution takes place in fits and starts: it occurs very slowly for quite a while (the species are in equilibrium), and then, during a relatively short period, it takes place very rapidly. This concept is called **punctuated equilibrium**. Factors that could cause sudden pulses of evolution include (1) a geologic catastrophe that causes many species to go extinct, leaving ecological niches open for new species to colonize; (2) a sudden change in the Earth's climate that puts stress on organisms—organisms that evolve to survive the new stress survive, whereas others become extinct; (3) the sudden formation of new environments, as may happen when rifting splits apart a continent and generates a new ocean with new coastlines; and (4) the isolation of a breeding population.

Regardless of the process of evolution, the survivability of different kinds of organisms are not all the same. Some populations are very durable, in that they survive as an identifiable genus or even species for long intervals of geological time (tens to over 100 million years). But others appear and then disappear within a relatively short interval of geologic time (less than a few million years).

Extinction: When Species Vanish

Extinction occurs when the last members of a species die, so there are no parents to pass on their genetic traits to offspring. Some species become extinct as a population evolves into new species, whereas other species just vanish, leaving no hereditary offspring. These days, we take for granted that species become extinct, because we've seen a great number vanish during human history. Before the 1770s, however, few geologists thought that extinction occurred; they thought instead that fossils that didn't resemble known species must have living relatives somewhere on this planet. Considering that large parts of the Earth remained unexplored, this idea wasn't so farfetched. But by the end of the 18th century, it became clear that numerous fossil organisms did not have modern-day counterparts anywhere. The bones of mastodons and woolly mammoths, for example, were too different from those of elephants to be of the same species, but the animals were too big to hide. 20th-century studies led to the conclusion that many different phenomena can contribute to extinction.

Some of the geologic factors that cause extinction include:

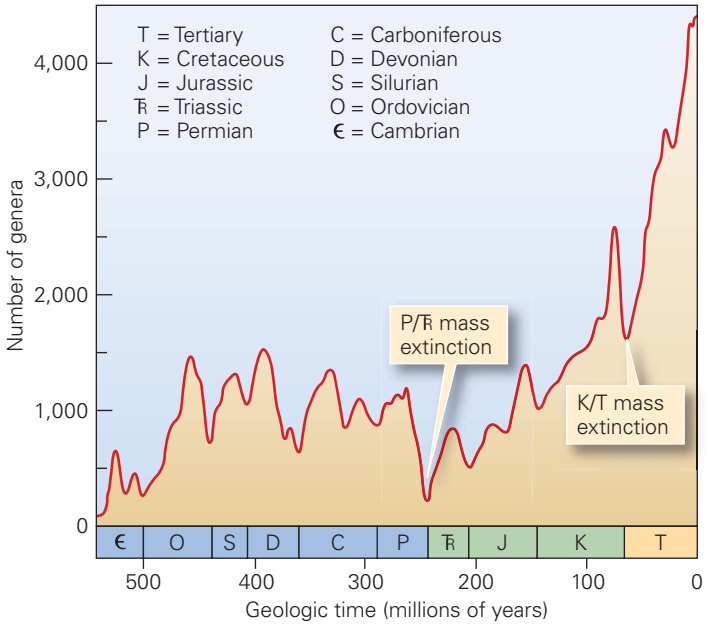
- *Global climate change*: At times, the Earth's mean temperature has been significantly colder than today's, whereas at other

times it has been much warmer. Because of a change in climate, an individual species may lose its habitat, and if it cannot adapt to the new habitat or migrate to stay with its old one, the species will disappear.

- *Tectonic activity*: Tectonic activity causes vertical movement of the crust over broad regions, changes in sea-floor spreading rates, and changes in the amount of volcanism. These phenomena can modify the distribution and area of habitats. Species that cannot adapt die off.
- *Asteroid or comet impact*: Many geologists have concluded that impacts of large meteorites with the Earth have been catastrophic for life. A large impact would send dust and debris into the atmosphere that could blot out the Sun and plunge the Earth into darkness and cold (see Chapter 19). Such a change, though relatively short lived, could interrupt the food chain.
- *Voluminous volcanic eruption*: Several times during Earth history, incredible quantities of lava have spilled out on the surface and/or incredible volumes of ash and gas have spewed into the air. These eruptions, perhaps due to the rise of superplumes in the mantle, were accompanied by the release of enough gas into the atmosphere to alter the climate.
- *The appearance of a new predator or competitor*: Some extinctions may happen simply because a new predator appears on the scene. Researchers suggest that this phenomenon explains the mass extinction that occurred during the past 20,000 years, when a vast number of large mammal species vanished from North America. The timing of these extinctions appears to coincide with the appearance of the first humans (fierce predators) on the continent. If a more efficient competitor appears, the competitor steals an ecological niche from the weaker species, whose members can't obtain enough food and thus die.

Some extinctions happen over long time intervals, when the replacement rate of a population simply becomes lower than the mortality rate, but others happen suddenly, when a cataclysmic event leads to the rapid extermination of many organisms. For example, in 1870 the global population of passenger pigeons in North America exceeded 3 billion. Due to widespread hunting by people, the population dropped rapidly during the next two decades and the last member of the species died in 1914.

FIGURE E.8 This graph shows how the diversity of life has changed with time. Sudden drops indicate periods when mass extinctions occurred. The abbreviations refer to geologic periods that will be discussed in Chapter 10.



Of note, paleontologists have found that the number of different genera of fossils, a representation of **biodiversity** (the overall variation of life), changes over time and has abruptly decreased at specific times during Earth history. A worldwide abrupt decrease in the number of fossil genera is called a **mass extinction event**. At least five major mass extinction events have happened during the past half-billion years (**Fig. E.8**). These events define the boundaries between some of the major intervals into which geologists divide time. For example, a major extinction event marks the end of the Cretaceous Period, 65 million years ago. During this event, all dinosaur species (with the exception of their modified descendants, the birds) vanished, along with most marine invertebrate species. A huge extinction event also brought the Permian to a close. Some researchers have suggested that extinction events are periodic, but this idea remains controversial.

Key Terms

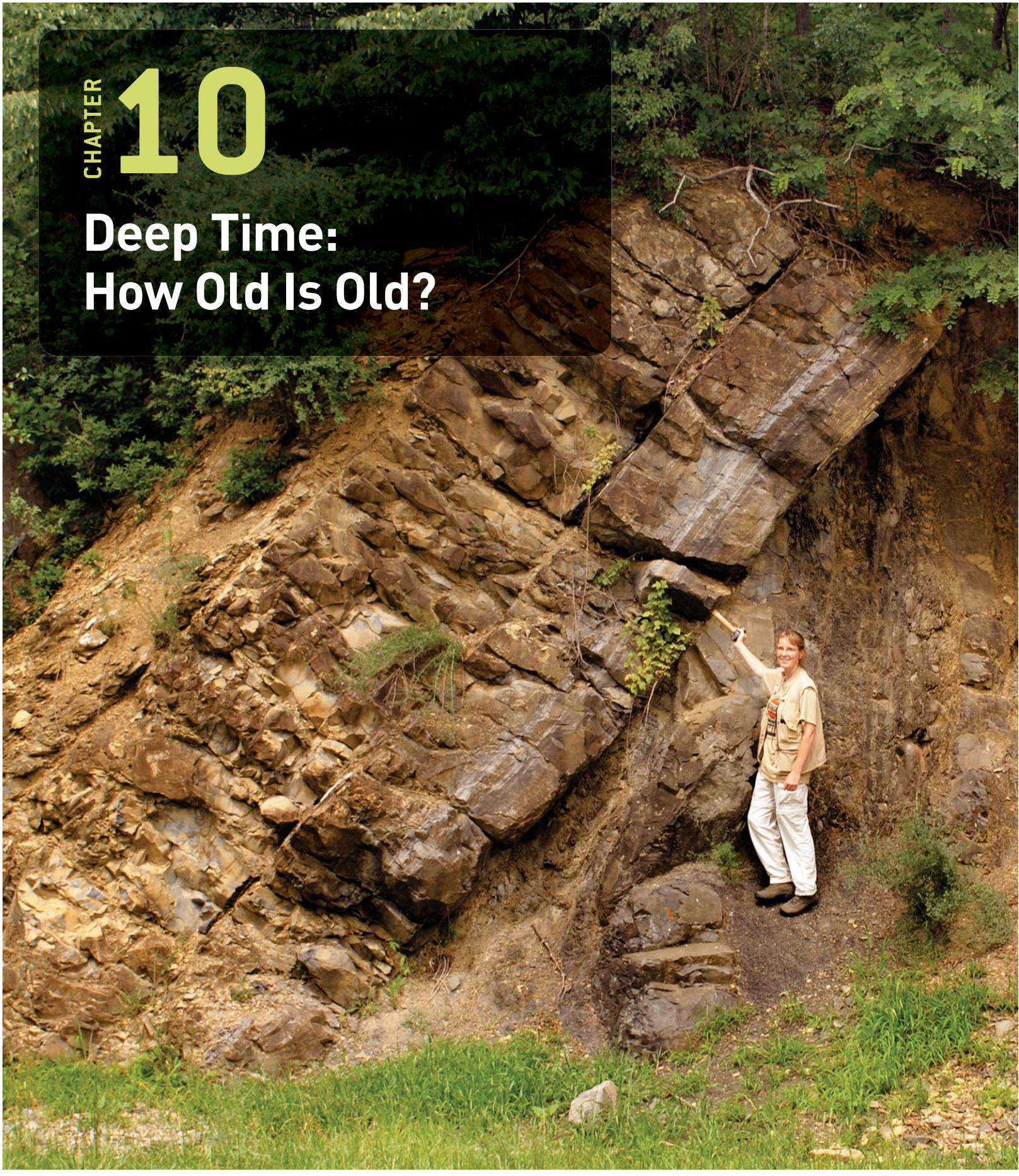
amber (p. 295)
Archaea (p. 297)
Bacteria (p. 298)
biomarker (p. 295)
Cambrian explosion (p. 299)
cast (p. 295)
Eukarya (p. 298)
evolution (p. 301)
extinction (p. 301)
extraordinary fossil (p. 297)
fossil (p. 293)
fossilization (p. 294)
gradualism (p. 301)
macrofossil (p. 295)
mass extinction event (p. 302)
microfossil (p. 295)
mold (p. 295)
morphology (p. 298)
natural selection (p. 301)
paleontologist (p. 293)
paleontology (p. 293)
petrified wood (p. 295)
phylogenetic tree (p. 300)
preservation potential (p. 297)
punctuated equilibrium (p. 301)
taxonomy (p. 297)
theory of evolution (p. 301)

ANOTHER VIEW This Cretaceous fish fossil was found in a sandstone bed in Brazil.



ANOTHER VIEW Fossils of a variety of shelly invertebrates (including brachiopods, crinoids, and bryozoans) protrude from the surface of a Paleozoic limestone bed from Missouri. This specimen comes from a highway roadcut.





CHAPTER 10

Deep Time: How Old Is Old?



This road cut in New York contains a wealth of information about Earth's past. Fossils in the strata tell us of ancient environments and the tilting of the beds tells us about ancient mountain-building events.

Chapter Objectives

By the end of this chapter, you should know . . .

- the meaning of geologic time, and the difference between relative and numerical ages.
- geologic principles (uniformitarianism, superposition, fossil succession) and their implications.
- how unconformities form and what they represent.
- the basis for correlating stratigraphic formations, and how correlation led to development of the geologic column.
- how geologists determine the numerical age of rocks by using isotopic dating.
- the basis for determining dates on the geologic time scale, and for determining the age of the Earth.

If the Eiffel Tower were now representing the world's age, the skin of paint on the pinnacle-knob at its summit would represent man's share of that age; and anybody would perceive that that skin was what the tower was built for. I reckon they would, I dunno.

—Mark Twain (1835–1910)

10.1 Introduction

In May of 1869, a one-armed Civil War veteran named John Wesley Powell set out with a team of nine geologists and scouts to explore the previously unmapped expanse of the Grand Canyon, the greatest gorge on Earth. Though Powell and his companions battled fearsome rapids and the pangs of starvation, most managed to emerge from the mouth of the canyon three months later. During their voyage, seemingly insurmountable walls of rock both imprisoned and amazed the explorers, and led them to pose important questions about the Earth and its history, questions that even casual tourists to the canyon ponder today: Did the Colorado River sculpt this marvel, and if so, how long did it take? When did the rocks making up the walls of the canyon form? Was there a time *before* the colorful layers accumulated? Such questions pertain to **geologic time**, the span of time since Earth's formation.

In this chapter, we first cover the geologic principles that allowed geologists to develop the concept of geologic time and develop a reference frame for describing the *relative*

ages of rocks, fossils, structures, and landscapes. This information sets the stage for introducing the geologic column, the way that geologists divide time into intervals. Then we look at the tools geologists use to determine the *numerical age* of the Earth and its features in years; specifically, we introduce isotopic (radiometric) dating and the geologic time scale. With the concept of geologic time in hand, a hike down a trail into the Grand Canyon becomes a trip into what authors call *deep time*. The geological discovery that our planet's history extends billions of years into the past changed humanity's perception of time and the Universe as profoundly as did the astronomical discovery that the limit of space extends billions of light years beyond the edge of our Solar System.

10.2 The Concept of Geologic Time

Setting the Stage for Studying the Past

Until relatively recently, people in most cultures believed that geologic time began about the same time that human history began, and that our planet has been virtually unchanged since its birth. This view was challenged by James Hutton (1726–1797), a Scottish gentleman farmer and doctor. Hutton lived during the Age of Enlightenment, when, sparked by the discovery of physical laws by Sir Isaac Newton, many people sought natural, rather than supernatural, explanations for features of the world around them. While wandering in the highlands of Scotland, a region where rocks are well exposed, Hutton noted that many features (such as ripple marks and cross beds) found in sedimentary rocks resembled features that he could see forming today in modern depositional environments. These observations led Hutton to speculate that the formation of rocks and landscapes, in general, were a consequence of processes that he could see happening today.

Hutton's idea came to be known as the principle of **uniformitarianism**. According to this principle, physical processes that operate in the modern world also operated in the past, at roughly the same rates, and these processes were responsible for forming geologic features preserved in outcrops. More concisely, the principle can be stated as: *the present is the key to the past*. Hutton deduced that the development of individual geologic features took a long time, and that not all features formed at the same time, so the Earth must have a history that includes a succession of slow geologic events. Since no one in recorded history has seen the entire process of sediment first turning into rock and then later rising into mountains, Hutton also realized that there must have been a long time *before* human history began.

Hutton was not a particularly clear writer, and it took the efforts of subsequent geologists to clarify the implications of the principle of uniformitarianism and to publicize them. Once this had been accomplished, geologists around the world began to apply their growing understanding of geologic processes to define and interpret geologic events of the Earth's past.

Relative versus Numerical Age

Like historians, geologists strive to establish both the sequence of events that produced an array of geologic features (such as rocks, structures, and landscapes) and, when possible, the date on which each event happened. We specify the age of one feature with respect to another in a sequence as its **relative age**, and the age of a feature given in years as its **numerical age** (or, in older literature, its "absolute age"). Geologists learned how to determine relative age long before they could determine numerical age, so we look next at the principles leading to relative-age determination.

Take-Home Message

The principle of uniformitarianism—the present is the key to the past—implies that the Earth must be very old, for geologic processes happen slowly. Geologists distinguish between relative age (older or younger?) and numerical age (how many years ago?).

10.3 Geologic Principles for Defining Relative Age

Building from the work of Steno, Hutton, and others, the British geologist Charles Lyell (1797–1875) laid out a set of formal, usable geologic principles in the first modern textbook of geology. These principles, defined below, continue to provide the basic framework within which geologists read the record of Earth history and determine relative ages.

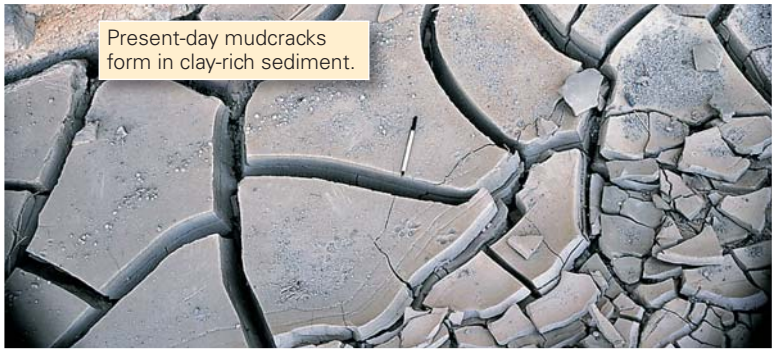
- *The principle of uniformitarianism* states that physical processes we observe operating today also operated in the past, at roughly comparable rates, so the present is the key to the past (**Fig. 10.1a**).
- *The principle of* ***original horizontality*** states that layers of sediment, when first deposited, are fairly horizontal (**Fig. 10.1b, c**), because sediments accumulate on surfaces of low relief (such as floodplains or the sea floor) in a gravitational field. If sediments were deposited on a steep slope, they would likely slide downslope before they could be buried and lithified. With this principle in mind, geologists conclude that examples of folds and tilted beds represent the consequences of deformation after deposition.

- *The principle of* ***superposition*** states that in a sequence of sedimentary rock layers, each layer must be younger than the one below, for a layer of sediment cannot accumulate unless there is already a substrate on which it can collect. Thus, the layer at the bottom of a sequence is the oldest, and the layer at the top is the youngest (**Fig. 10.1d**).
- *The principle of lateral continuity* states that sediments generally accumulate in continuous sheets within a given region. If today you find a sedimentary layer cut by a canyon, then you can assume that the layer once spanned the area that was later eroded by the river that formed the canyon (**Fig. 10.1e**).
- *The principle of* ***cross-cutting relations*** states that if one geologic feature cuts across another, the feature that has been cut is older. For example, if an igneous dike cuts across a sequence of sedimentary beds, the beds must be older than the dike (**Fig. 10.1f**). If a fault cuts across and displaces layers of sedimentary rock, then the fault must be younger than the layers. But if a layer of sediment buries a fault, the sediment must be younger than the fault.
- *The principle of baked contacts* states that an igneous intrusion "bakes" (metamorphoses) surrounding rocks, so the rock that has been baked must be older than the intrusion (**Fig. 10.1g**).
- *The principle of inclusions* states that a rock containing an inclusion (fragment of another rock) must be younger than the inclusion. For example, a conglomerate containing pebbles of basalt is younger than the basalt, and a sill containing fragments of sandstone must be younger than the sandstone (**Fig. 10.1h**).

Geologists apply geologic principles to determine the relative ages of rocks, structures, and other geologic features at a given location. They then go further by interpreting the formation of each feature to be the consequence of a specific "geologic event." Examples of geologic events include: deposition of sedimentary beds; erosion of the land surface; intrusion or extrusion of igneous rocks; deformation (folding and/or faulting); and episodes of metamorphism. The succession of events in order of relative age that have produced the rock, structure, and landscape of a region is called the **geologic history** of the region.

We can use these principles to determine relative ages of the features shown in **Figure 10.2a**. In so doing, we develop a geologic history of the region, defining the relative ages of events that took place there. For this example, we propose the following

FIGURE 10.1 Examples of the major geologic principles.

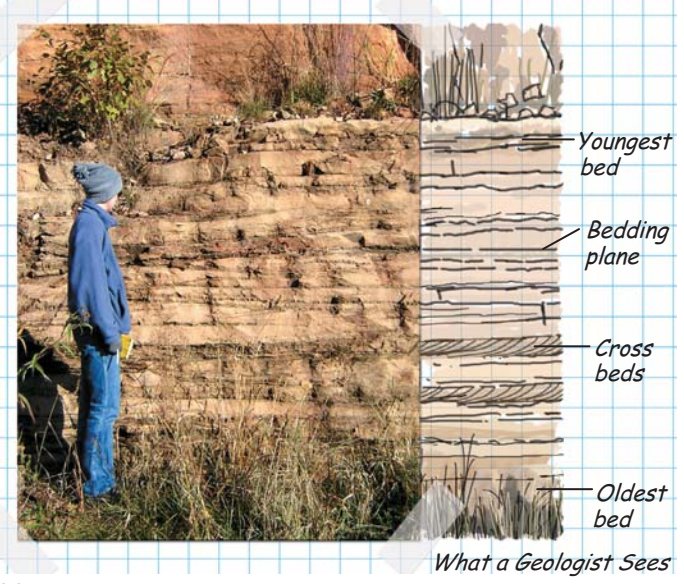




(a) Uniformitarianism: The processes that formed cracks in the dried-up mud puddle on the left also formed the mudcracks preserved in the ancient, solid rock on the right. We can see these ancient mudcracks because erosion removed the adjacent bed.



(b) Original horizontality: Gravity causes sediment to accumulate in fairly horizontal sheets on a flat plain.

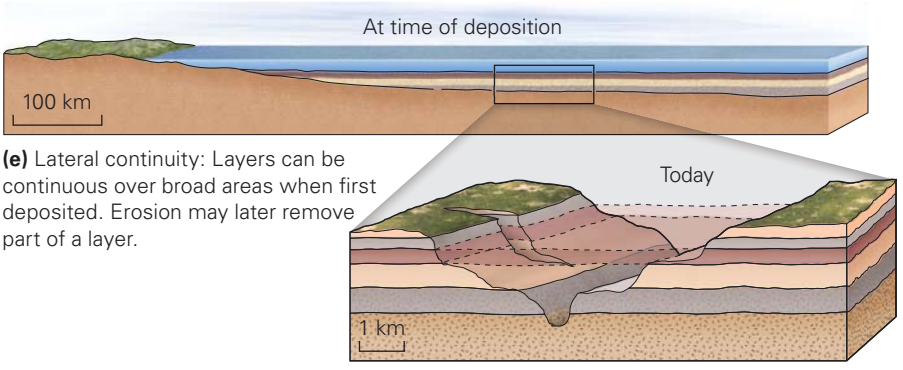


(c) Horizontal bedding in an outcrop of sandstone in Wisconsin.

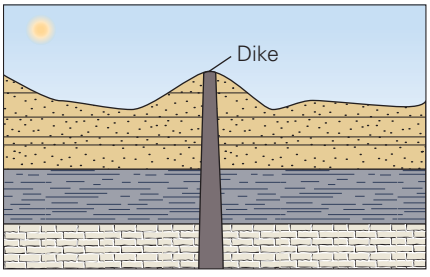
FIGURE 10.1 *(continued)*



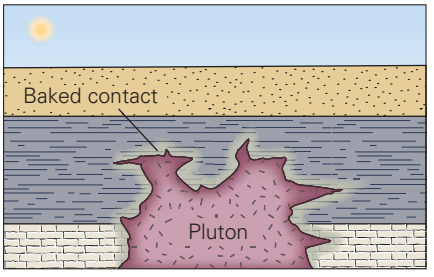
(d) Superposition: In a sequence of strata, the oldest bed is on the bottom, and the youngest on top. Pouring sand into a glass illustrates this point.



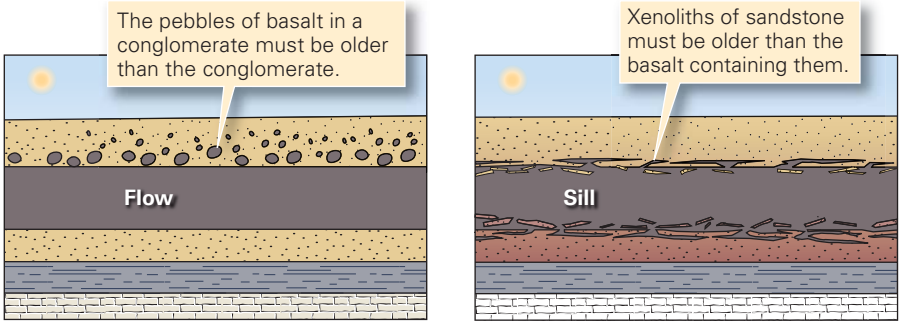
(e) Lateral continuity: Layers can be continuous over broad areas when first deposited. Erosion may later remove part of a layer.



(f) Cross-cutting relations: The dike cuts across the sedimentary beds, so the dike is younger.



(g) Baked contact: The pluton baked the adjacent rock, so the adjacent rock is older.



(h) Inclusions: Rock that occurs as an inclusion in another rock must be the older of the two.

geologic history for this region (Fig. 10.2b): deposition of the sedimentary sequence in order from beds 1 to 7; intrusion of the sill; folding of the sedimentary beds and the sill; intrusion of the granite pluton; faulting; intrusion of the dike; erosion to form the land surface.

Adding Fossils to the Story: Fossil Succession

As Britain entered the industrial revolution in the late 18th and early 19th centuries, new factories demanded coal to fire their steam engines and needed an inexpensive means to transport goods. Investors decided to construct a network of canals to transport coal and iron, and hired an engineer named William Smith (1769–1839) to survey some of the excavations. Canal digging provided fresh exposures of bedrock, which previously had been covered by vegetation. Smith learned to recognize distinctive layers of sedimentary rock and to identify the **fossil assemblage** (the group of fossil species) that they contained. He also realized that a particular assemblage can be found only in a limited interval of strata, and not above or below this interval. Thus, once a fossil species disappears at a horizon in a sequence of strata, it never reappears higher in the sequence or, put another way, extinction is forever. Smith's observation has been repeated at millions of locations around the world, and has been codified as the *principle of* **fossil succession**. It provides the geologic underpinning for the theory of evolution (see Interlude E).

To see how this principle works, examine Figure 10.3, which depicts a sequence of strata. Bed 1 at the base contains fossil species A, Bed 2 contains fossil species A and B, Bed 3 contains B and C, Bed 4 contains C, and so on. From these data, we can define the *range* of specific fossils in the sequence, meaning the interval in the sequence in which the fossils occur. Note that the sequence contains a definable succession of fossils (A, B, C, D, E, F), that the range in which a particular species occurs may overlap with the range of other species, and that once a species vanishes, it does not reappear higher in the sequence. Once the relative ages of a number of fossils have been determined, the fossils can be used to determine the relative age of the beds containing them. For example, if a bed contains Fossil F (from the succession specified above), geologists can say the bed is older than a bed containing Fossil A, even if the two beds do not crop out in the same area. As we will see, painstaking work over many years eventually allowed geologists to assign numerical age ranges to fossil species. Of note, some fossil

species are widespread, but survived only for a realtively short interval of geologic time. Such species are called **index fossils** (or guide fossils), because they can be used by geologists to associate the strata with the specific time interval.

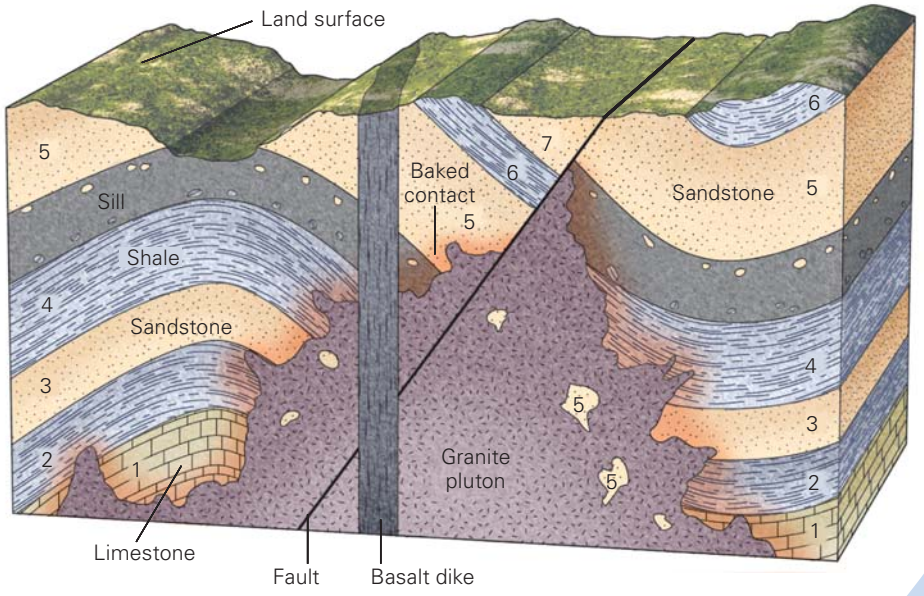
Take-Home Message

Relative-age determination is based on geologic principles, including uniformitarianism, superposition (younger strata overlie older strata), cross-cutting relations (younger features cut older ones), and fossil succession (fossil species occur in a predictable order).

10.4 Unconformities: Gaps in the Record

To find good exposures of rock, James Hutton sometimes boated along the coast of Scotland, where waves of the stormy North Sea have stripped away soil and shrubbery. He was particularly puzzled by an outcrop at Siccar Point, where two distinct sequences of sedimentary rock lie in contact (Fig. 10.4a, b). In the lower portion of the outcrop, beds of gray sandstone and shale dip nearly vertically, whereas in the upper portion, beds of red sandstone and conglomerate display a dip of less than 20°. Further,

FIGURE 10.2 Interpreting the geologic history of a region, using geologic principles as a guide.



(a) Geologic principles help us unravel the sequence of events leading to the development of the features shown above. Layers 1 to 7 were deposited first. Intrusion of the sill came next, followed by folding, intrusion of the granite pluton, faulting, intrusion of the dike, and erosion.

(b) The sequence of geologic events leading to the geology shown above. Note that the youngest bed, Bed 8, has been eroded away entirely.

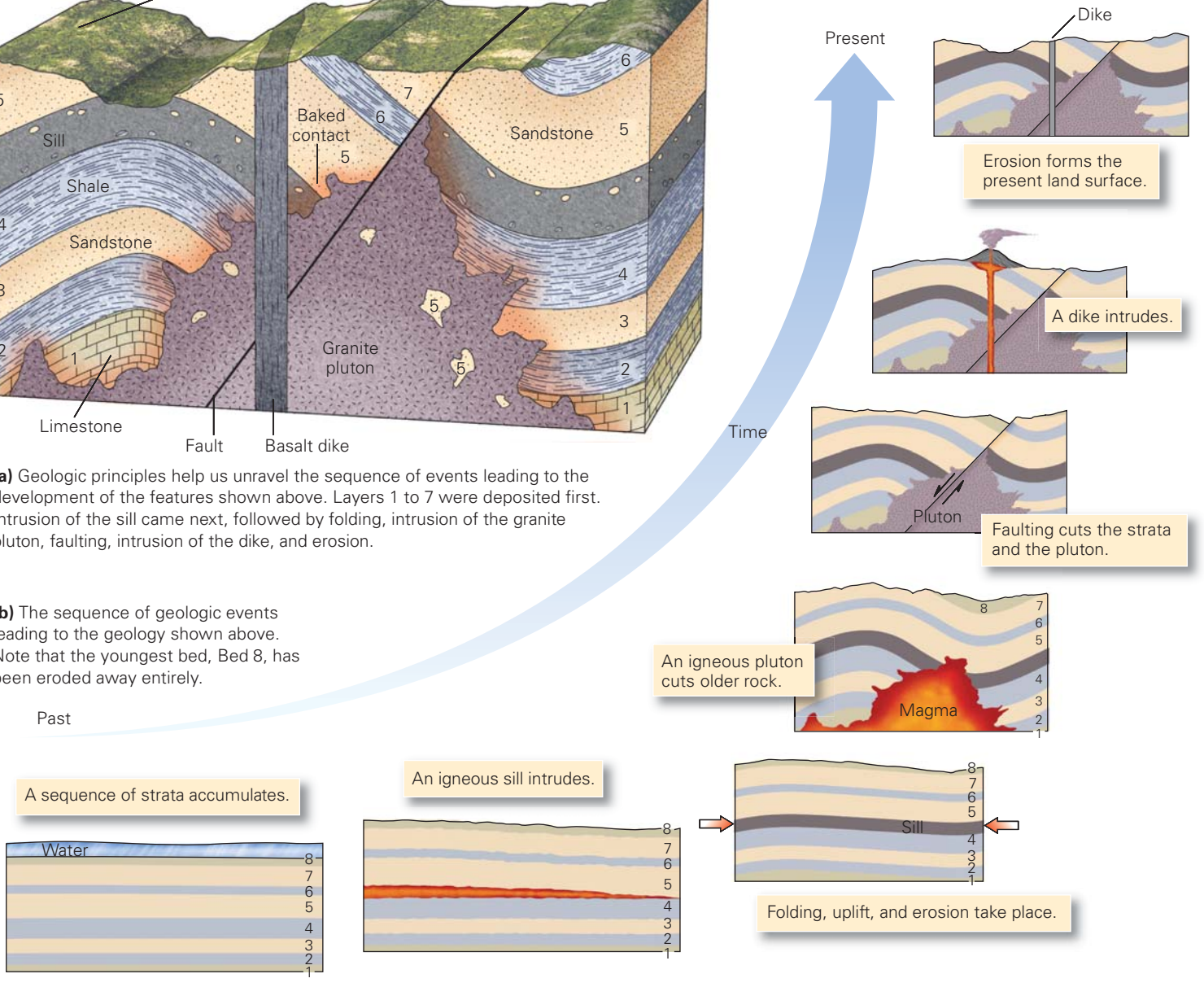
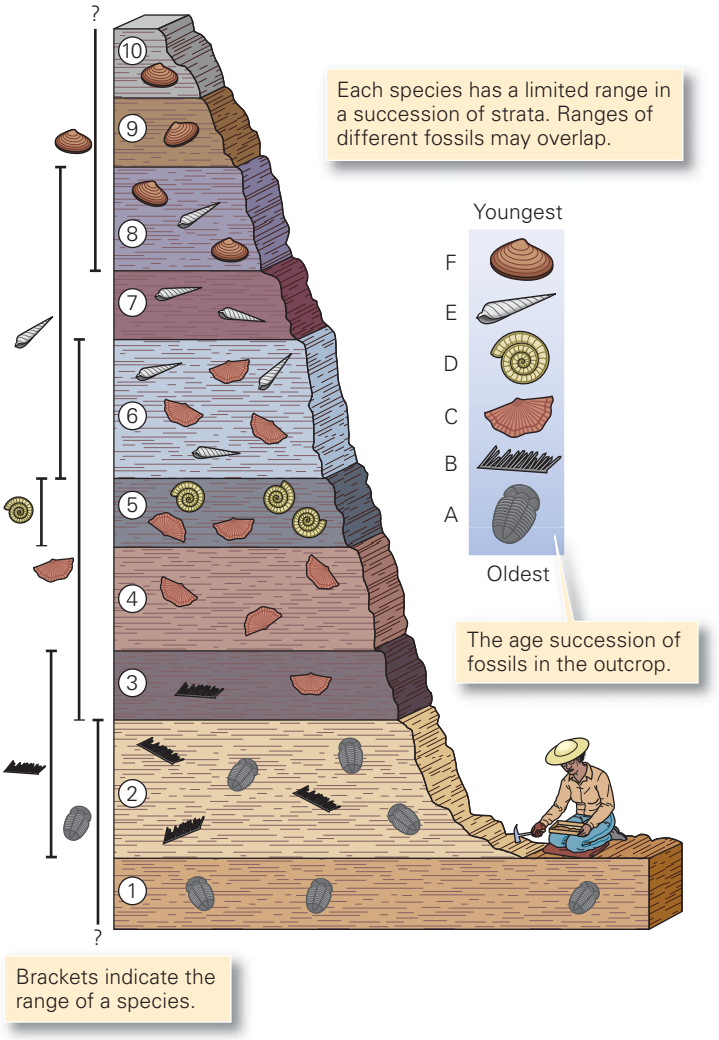


FIGURE 10.3 The principle of fossil succession.



the gently dipping layers seem to lie across the truncated ends of the vertical layers, like a handkerchief lying across a row of books. We can imagine that as Hutton was examining this odd geometric relationship, the tide came in and deposited a new layer of sand on top of the rocky shore. With the principle of uniformitarianism in mind, Hutton suddenly realized the significance of what he saw. The gray sandstone–shale sequence had been deposited, turned into rock, tilted, and truncated by erosion *before* the red sandstone–conglomerate beds had been deposited.

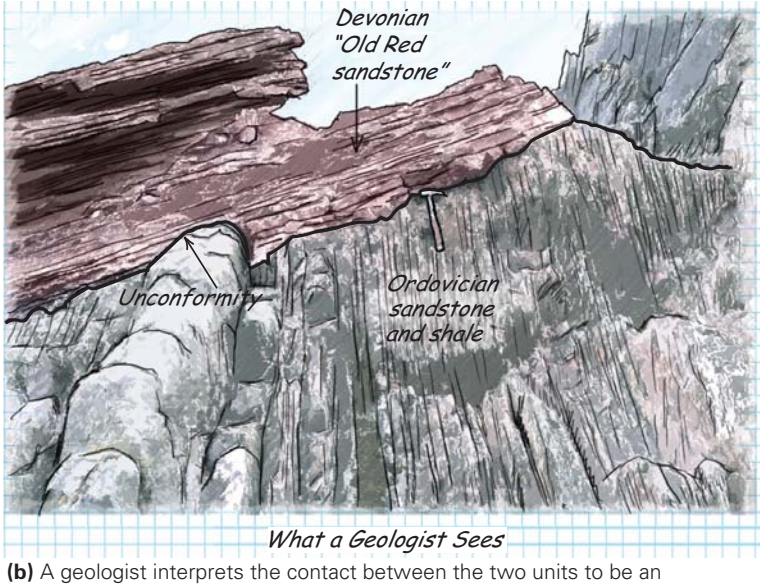
Hutton deduced that the surface between the gray and red rock sequences represented a time interval during which new strata had not been deposited at Siccar Point and the older strata had been eroded away. We now call such a surface, representing a period of nondeposition and possibly erosion, an **unconformity**. The gap in the geologic record that an unconformity represents is called a hiatus. Geologists recognize three kinds of unconformities:

- *Angular unconformity*: Rocks below an angular unconformity were tilted or folded before the unconformity developed (**Fig. 10.5a**). Thus, an angular unconformity cuts across the underlying layers, and the orientation of layers below an unconformity differs from that of the layers above. (The outcrop at Siccar Point exposes an angular unconformity.)
- *Nonconformity*: A nonconformity is a type of unconformity at which sedimentary rocks overlie generally much older intrusive igneous rocks and/or metamorphic rocks (**Fig. 10.5b**). The igneous or metamorphic rocks underwent cooling, uplift, and erosion prior to becoming the substrate, or *basement*, on which new sediments accumulated.
- *Disconformity*: Imagine that a sequence of sedimentary beds has been deposited beneath a shallow sea. Then sea level drops,

FIGURE 10.4 The unconformity at Siccar Point, Scotland.

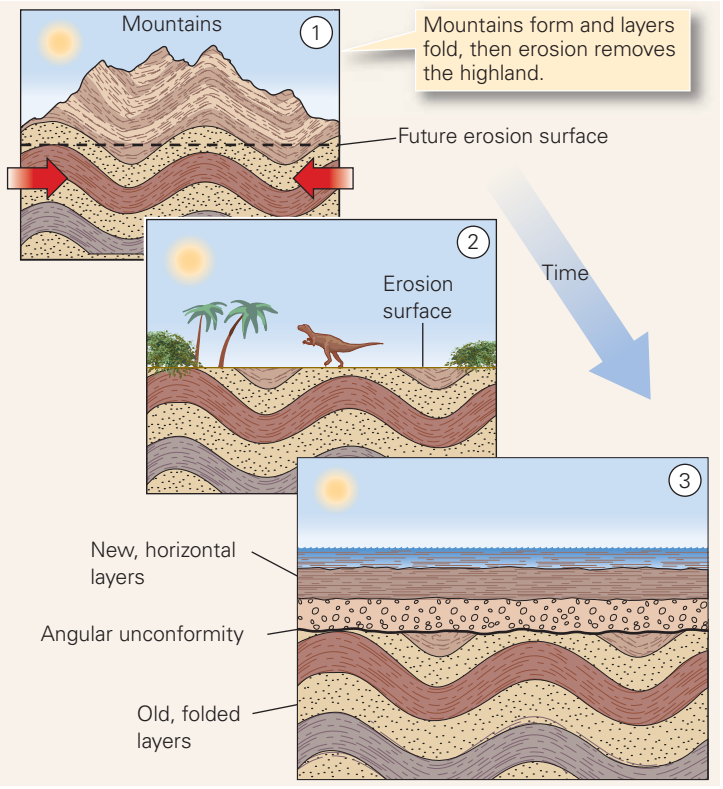


(a) James Hutton found this unconformity and deduced that the layers above were deposited long after the beds below had been tilted.

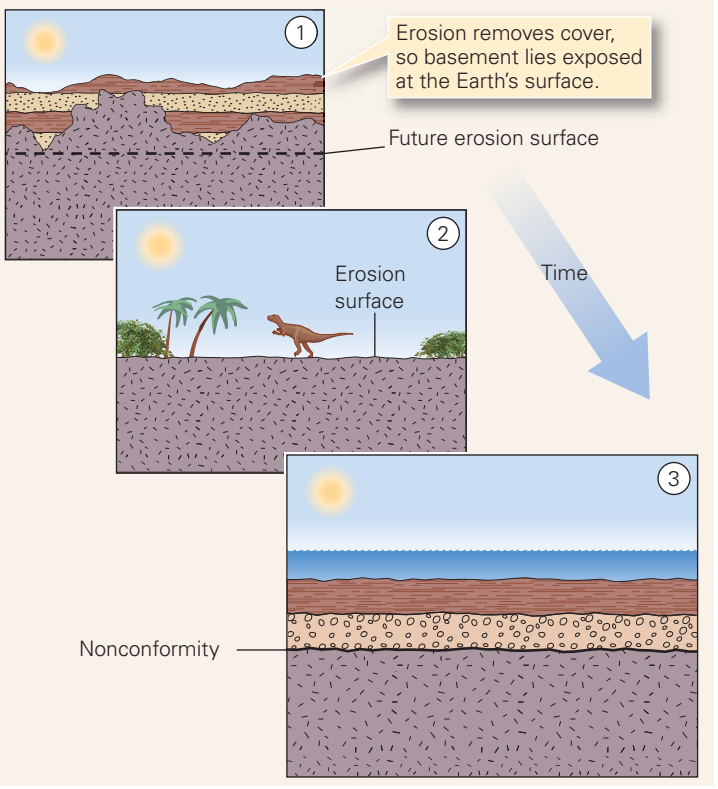


(b) A geologist interprets the contact between the two units to be an unconformity. Subsequent studies indicate that strata above are about 50 million years younger than strata below.

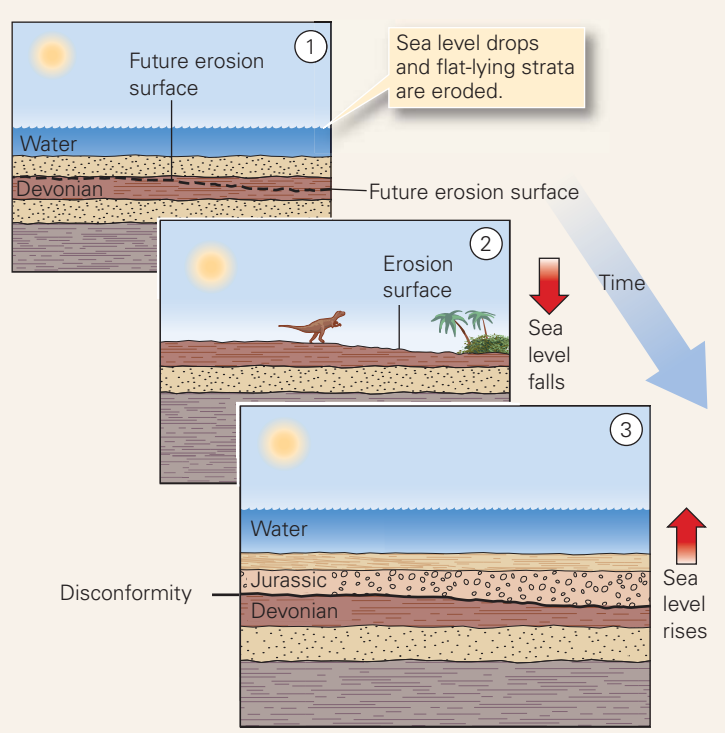
FIGURE 10.5 The three kinds of unconformities and their formation.



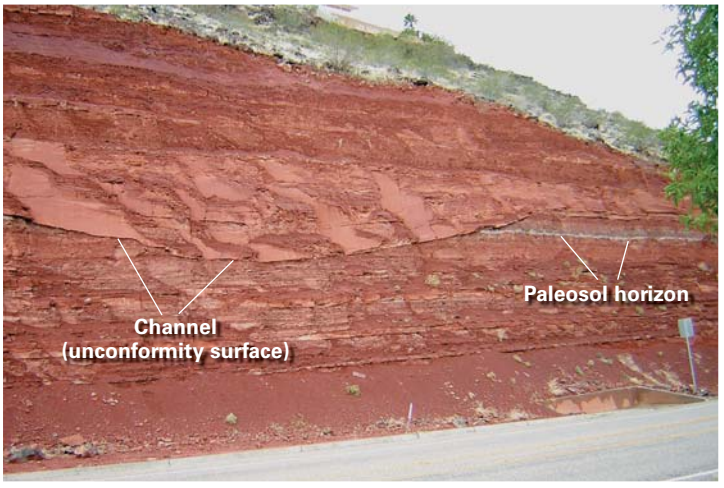
(a) An angular unconformity: (1) layers undergo folding; (2) erosion produces a flat surface; (3) sea level rises and new layers of sediment accumulate.



(b) A nonconformity: (1) a pluton intrudes; (2) erosion cuts down into the crystalline rock; (3) new sedimentary layers accumulate above the erosion surface.



(c) A disconformity: (1) layers of sediment accumulate; (2) sea level drops and an erosion surface forms; (3) sea level rises and new sedimentary layers accumulate.



(d) This roadcut in Utah shows a sand-filled channel cut down into floodplain mud. The mud was exposed between floods, and a soil formed on it. When later buried, all the sediment turned into rock; the channel floor is an unconformity, and the ancient soil is a "paleosol." Note that the channel cut across the paleosol. The paleosol also represents an unconformity, a time during which deposition did not occur.

exposing the beds for some time. During this time, no new sediment accumulates, and some of the preexisting sediment gets eroded away. Later, sea level rises, and a new sequence of sediment accumulates over the old. The boundary between the two sequences is a disconformity (Fig. 10.5c, d). Even though the beds above and below the disconformity are parallel, the contact between them represents an interruption in deposition.

The succession of strata at a particular location provides a record of Earth history there. But because of unconformities, *the record preserved in the rock layers is incomplete.* It's as if geologic history is being chronicled by a tape recorder that turns on only intermittently—when it's on (times of deposition), the rock record accumulates, but when it's off (times of nondeposition and possibly erosion), an unconformity develops. Because of unconformities, no single location on Earth contains a complete record of Earth history.

Did you ever wonder . . .
do Grand Canyon strata represent all Earth's history?

Take-Home Message

At a given location, sediments do not accumulate continuously, so unconformities, surfaces representing intervals of nondeposition and/or erosion, can form. Because of unconformities, the geologic record at any given location is incomplete.

10.5 Stratigraphic Formations and Their Correlation

We can summarize information about the sequence of sedimentary strata at a location by drawing a **stratigraphic column**. Typically, we draw columns to scale, so that the relative thicknesses of layers portrayed on the column reflect the thicknesses of layers in the outcrop. Then, we divide the sequence of strata represented on a column into **stratigraphic formations** ("formations," for short), a sequence of beds of a specific rock type or group of rock types that can be traced over a fairly broad region. The boundary surface between two formations is a type of geologic **contact**. (Fault surfaces and the boundary between an igneous intrusion and its wallrock are also types of contacts.) Typically, a formation has a specific geologic age.

Let's see how the concept of a stratigraphic formation applies to the Grand Canyon. The walls of the canyon look striped, because they expose a variety of rock types that differ in color and in resistance to erosion. Geologists identify major contrasts distinguishing one interval of strata from another, and use them as a basis for dividing the strata into formations, each of which may consist of many beds (Fig. 10.6a–c). Some formations include a single rock type, whereas others include interlayered beds of two or more rock types. Not all formations have the same thickness, and the thickness of a single formation can vary with location. Commonly, geologists name a formation after a locality where it was first identified or first studied. For example, the "Schoharie Formation" was first defined based on exposures in Schoharie Creek, in New York.

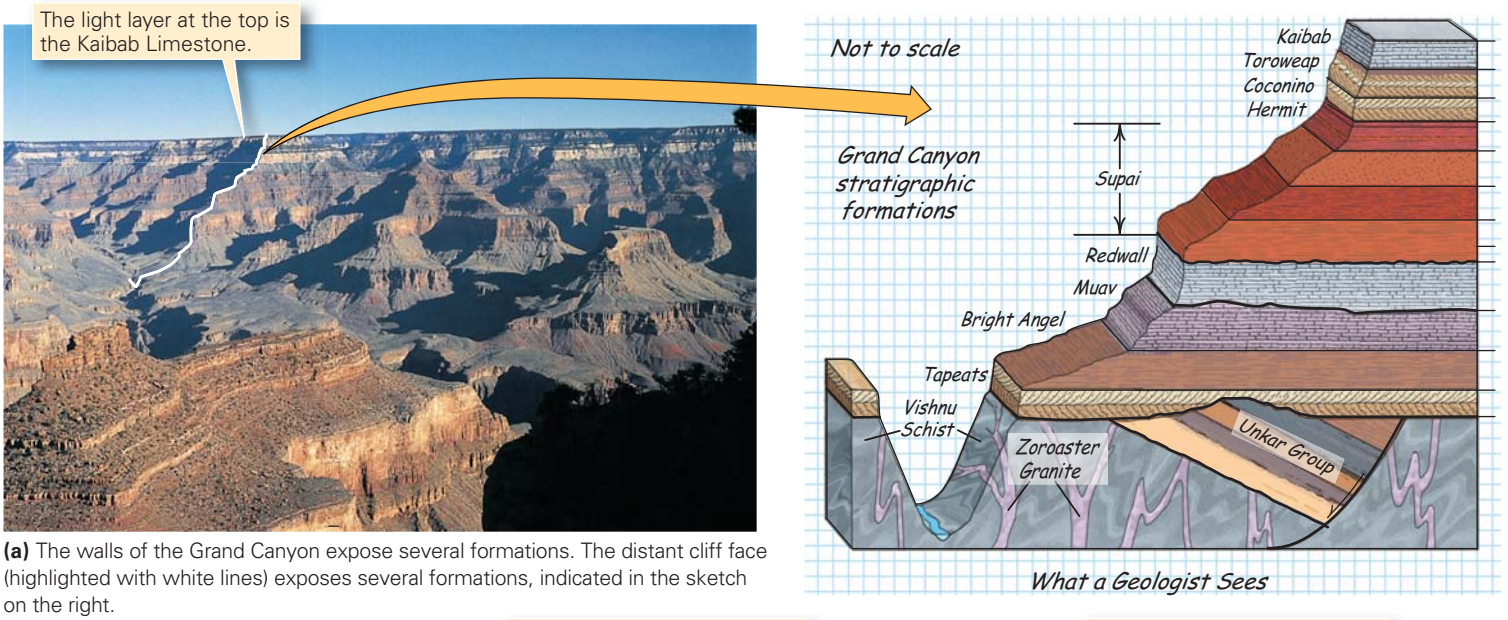
If a formation consists of only one rock type, we may incorporate that rock type in the name (for example, Kaibab Limestone), but if a formation contains more than one rock type, we use the word "formation" in the name (such as Toroweap Formation). Note that in the formal name of a formation, all words are capitalized. Several adjacent formations in a succession may be lumped together as a **stratigraphic group**.

Where did the concept of a stratigraphic formation come from? While excavating canals in England, William Smith discovered that formations cropping out at one locality resembled formations cropping out at another, in that their beds looked similar and contained similar fossil assemblages. In other words, Smith was able to define the stratigraphic relationship between the strata at one locality and the strata at another, a process now called **correlation**.

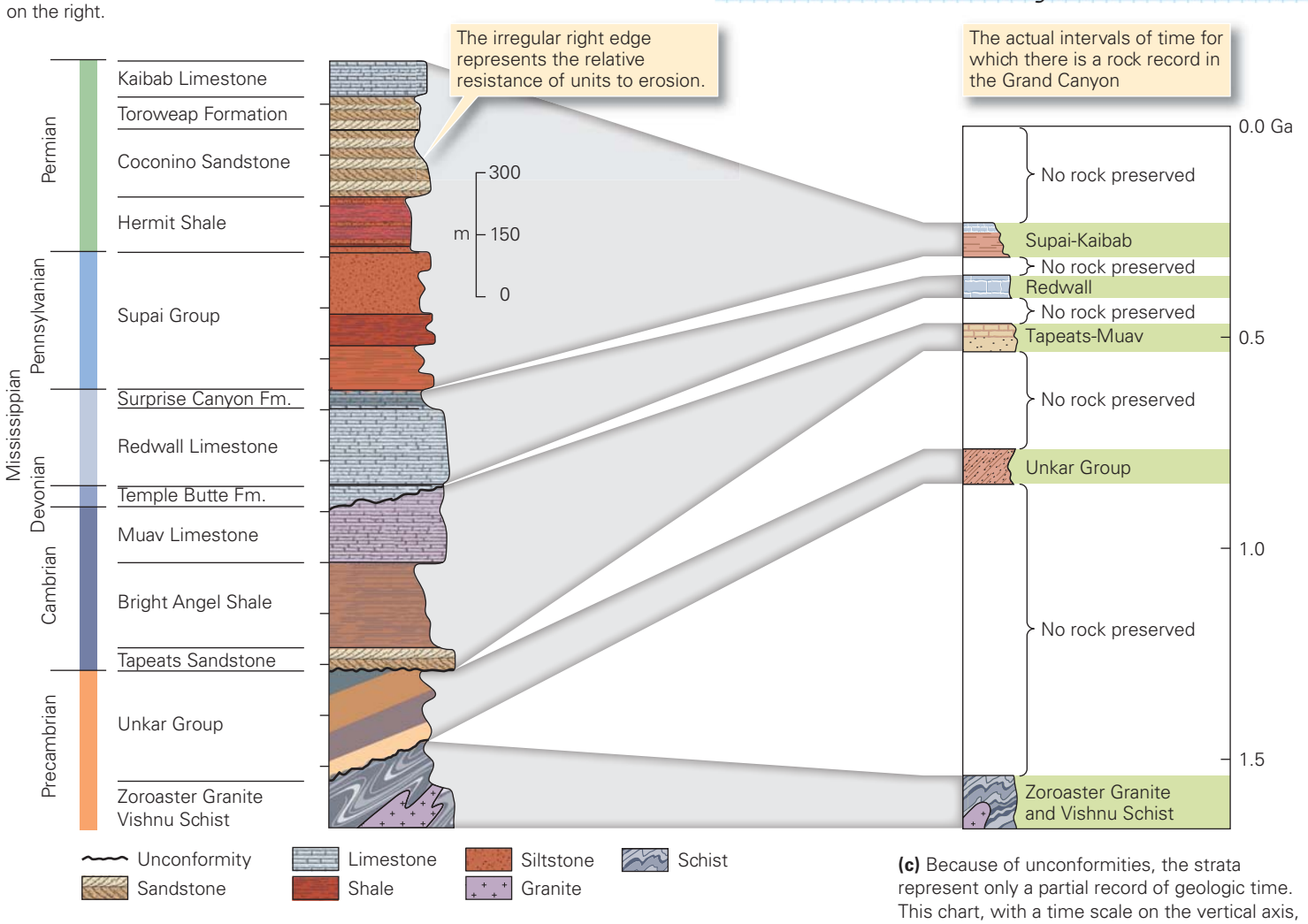
How does correlation work? Typically, geologists correlate formations between *nearby* regions based on similarities in rock type. We call this method *lithologic correlation* (Fig. 10.7a, b). For example, the sequence of strata on the southern rim of the Grand Canyon clearly correlates with the sequence on the northern rim, because they contain the same rock types in the same order. In some cases, a sequence contains a key bed, or **marker bed**, which is a particularly unique layer that provides a definitive basis for correlation.

To correlate rock units over *broad* areas, we must rely on fossils to define the relative ages of sedimentary units. We call this method *fossil correlation*. Geologists use fossil correlation for studies of broad areas because sources of sediments and depositional environments may change from one location to another. The beds deposited at one location during a given time interval may look quite different from the beds deposited at another location during the same time interval. But if fossils of the same relative age occur at both locations, we can say

FIGURE 10.6 The stratigraphic formations and stratigraphic column for the Grand Canyon in Arizona.



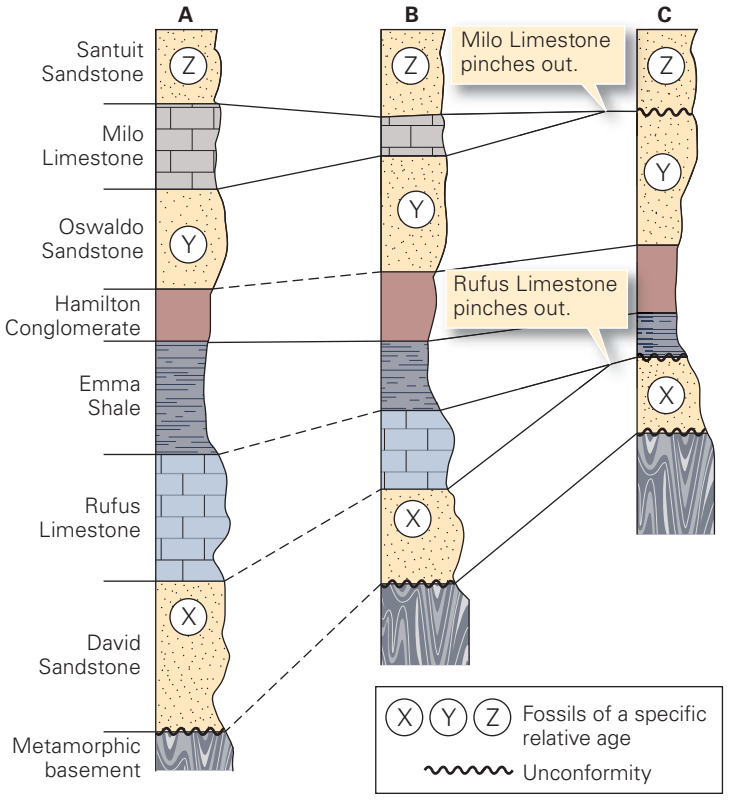
(a) The walls of the Grand Canyon expose several formations. The distant cliff face (highlighted with white lines) exposes several formations, indicated in the sketch on the right.



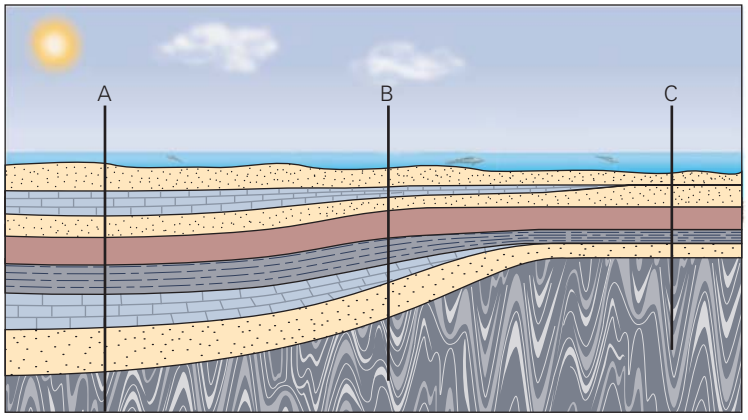
(b) A formalized stratigraphic column for strata of the Grand Canyon. The vertical scale indicates unit thickness. Patterns represent different rock types. The Unkar Group is one of three units that together comprise the Grand Canyon Supergroup.

(c) Because of unconformities, the strata represent only a partial record of geologic time. This chart, with a time scale on the vertical axis, shows large gaps in the record.

FIGURE 10.7 The principles of correlation.

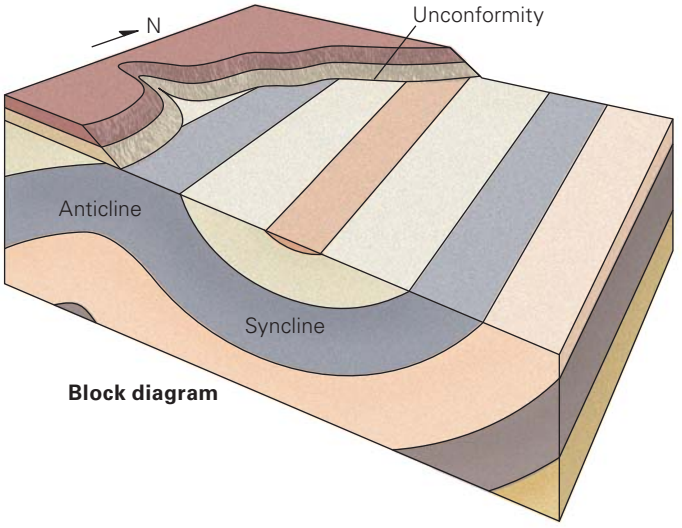


(a) Stratigraphic columns can be correlated by matching rock types (lithologic correlation). The Hamilton Conglomerate is a marker horizon. Because some strata pinch out, Column C contains unconformities. Fossil correlation indicates that the youngest beds in C are Santuit Sandstone.

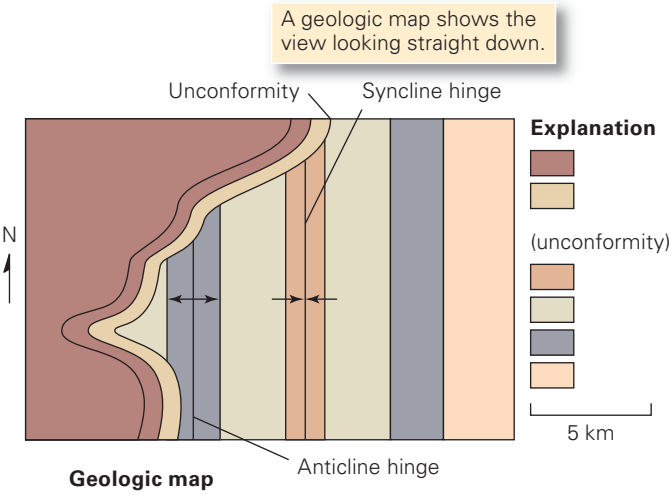


(b) At the time of deposition, locations A, B, and C were in different parts of a basin. The basin floor was subsiding fastest at A.

FIGURE 10.8 A geologic map depicts the distribution of rock units and structures.



(a) A block diagram provides a three-dimensional representation. Here, we see an angular unconformity over folded strata.

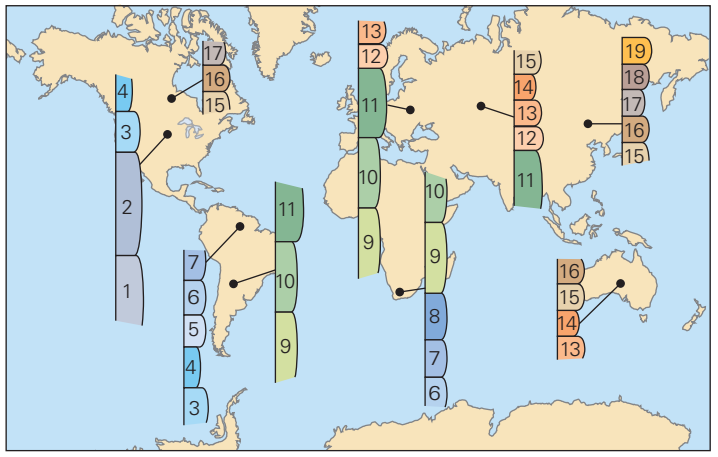


(b) A geologic map shows the distribution of units. Contacts occur between units. Note that the map also shows geologic structures.

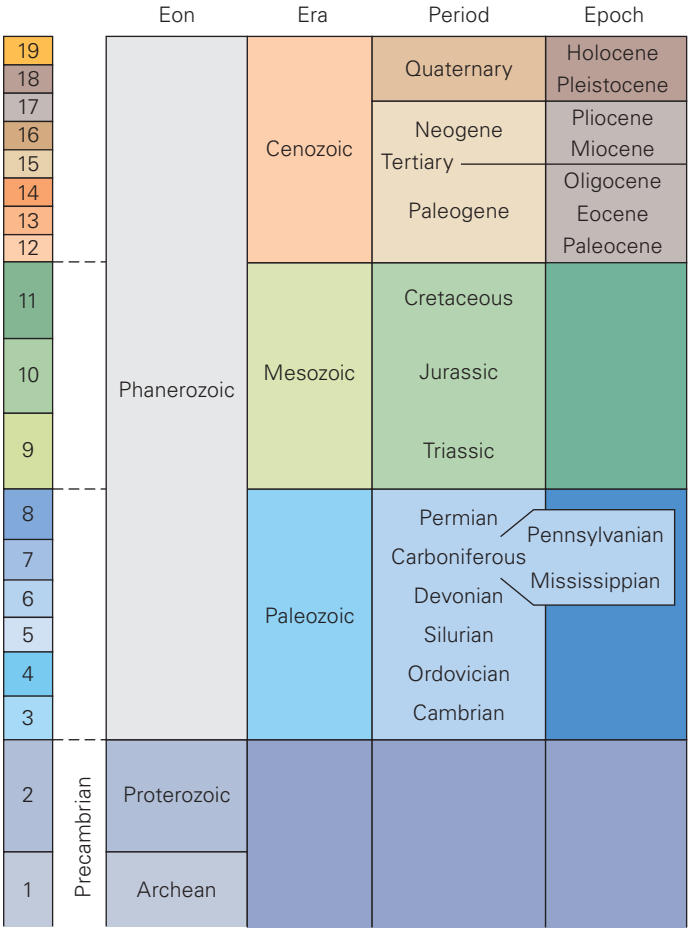
that the strata at the two locations correlate. (Note that the fossils are not necessarily of the same species—they won't be if the depositional environments are different—but they are of the same age.) Fossil correlation may also come in handy when rock types are not distinctive enough to allow correlation. For example, imagine that the Santuit Sandstone and Oswaldo Sandstone of Figure 10.7a look the same. Only fossils may distinguish one layer from the other, if the intervening Milo Limestone is absent.

Once William Smith succeeded in correlating stratigraphic formations throughout central England, he faced the challenge of communicating his ideas to others. One way would be to create a table that compared stratigraphic columns from different locations. But since Smith was a surveyor, and worked with maps, it occurred to him that he could outline and color in areas on a map to represent areas in which strata of a given relative age occurred. He did this using the data he had collected, and in 1815, produced the first modern geologic map. In general, a **geologic map** portrays the spatial distribution of rock units at the Earth's surface. Significantly, the pattern displayed on a geologic map provides insight into

FIGURE 10.9 Global correlation of strata led to the development of the geologic column (not to scale).



(a) Each of these small columns represents the stratigraphy at a given location. By correlating these columns, geologists determined their relative ages, filled in the gaps in the record, and produced the geologic column.



(b) By correlation, the strata from localities around the world were stacked in a chart representing geologic time to create the Geologic Column. Geologists assigned names to time intervals, but since the column was built without knowledge of numerical ages, it does not depict the duration of these intervals. Subdivisions of eons in the Precambrian are not shown. The Hadean is not shown because rocks do not preserve a record of it.

the presence and orientation of geologic structures in the map area (Fig. 10.8a, b). The inside of this book's back cover provides a geologic map of North America.

Take-Home Message

A stratigraphic formation is a recognizable sequence of beds that can be mapped across a broad region. Geologists correlate formations regionally on the basis of rock type and fossil content, and portray the configuration of formations in a region on a geologic map.

10.6 The Geologic Column

As stated earlier, no one locality on Earth provides a complete record of our planet's history, because stratigraphic columns can contain unconformities. But by correlating rocks from locality to locality at millions of places around the world, geologists have pieced together a *composite* stratigraphic column, called the **geologic column**, that represents the entirety of Earth history (Fig. 10.9a, b). The column is divided into segments, each of which represents a specific interval of time. The largest subdivisions break Earth history into the Hadean, Archean, Proterozoic, and Phanerozoic **Eons**. (The first three together constitute the **Precambrian**.) The suffix *–zoic* means life, so Phanerozoic means visible life, and Proterozoic means first life. (It wasn't until after the eons had been named that geologists determined that the earliest life, cells of Bacteria and Archaea, appeared in the Archean Eon.) The Phanerozoic Eon is subdivided into **eras**. In order from oldest to youngest, they are the Paleozoic (ancient life), Mesozoic (middle life), and Cenozoic (recent life) Eras. We further divide each era into **periods** and each period into **epochs**.

Where do the names of the periods come from? They refer either to localities where a fairly complete stratigraphic column representing that time interval was first identified (for example, rocks representing the Devonian Period crop out near Devon, England) or to a characteristic of the time (rocks from the Carboniferous Period contain a lot of coal). The terminology was not set up in a planned fashion that would make it easy to learn. Instead, it grew haphazardly in the years between 1760 and 1845, as geologists began to refine their understanding of geologic history and fossil succession. Also, because the divisions were defined before numerical ages could be determined, they are all of different durations.

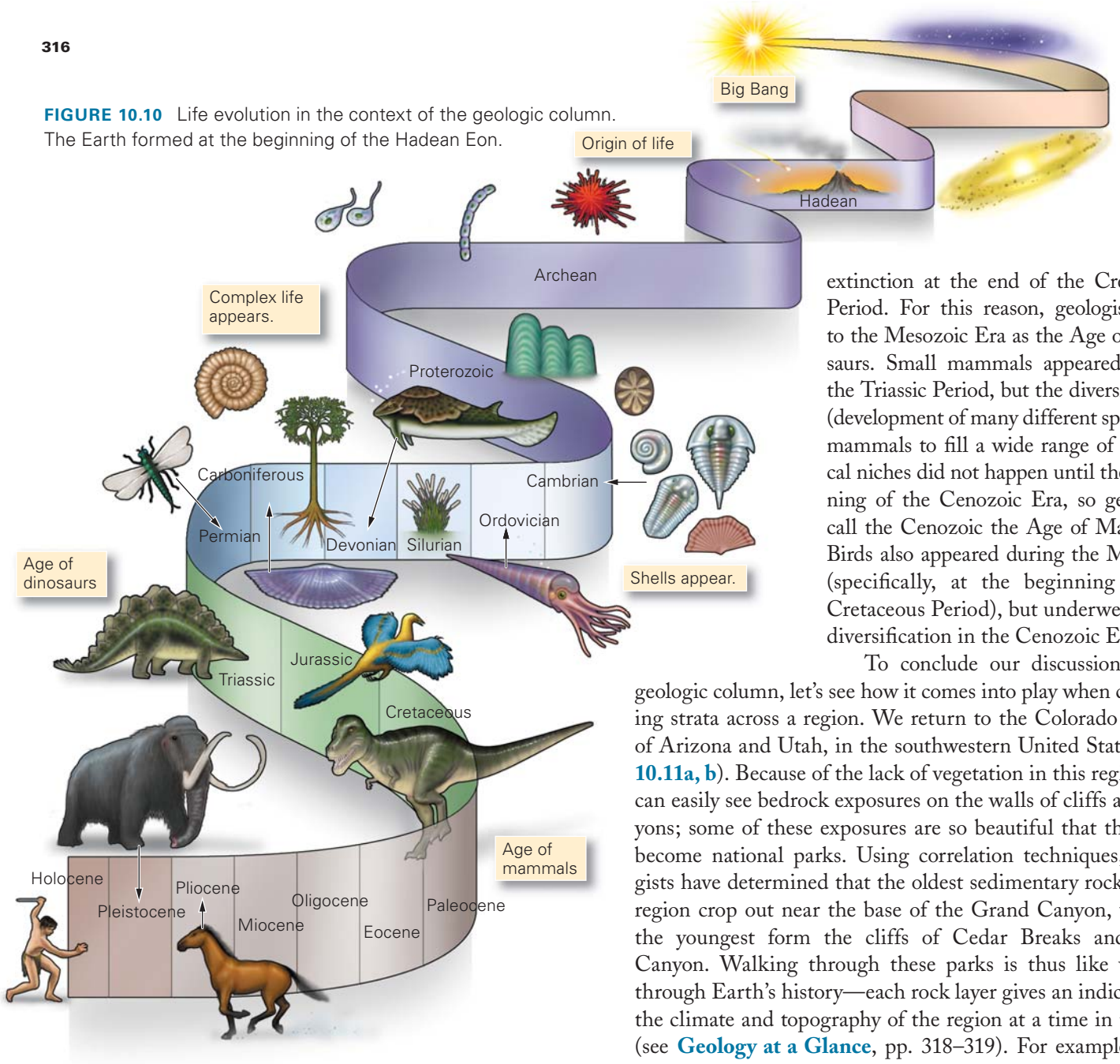


FIGURE 10.10 Life evolution in the context of the geologic column. The Earth formed at the beginning of the Hadean Eon.

The succession of fossils preserved in strata of the geologic column defines the course of life's evolution throughout Earth history (**Fig. 10.10**). Simple bacteria and archaea appeared during the Archean Eon, but complex shell-less invertebrates did not evolve until the late Proterozoic. The appearance of invertebrates with shells defines the Precambrian-Cambrian boundary. At this time, there was a sudden diversification in life, with many new types of organisms appearing over a relatively short interval—this event is called the **Cambrian explosion**.

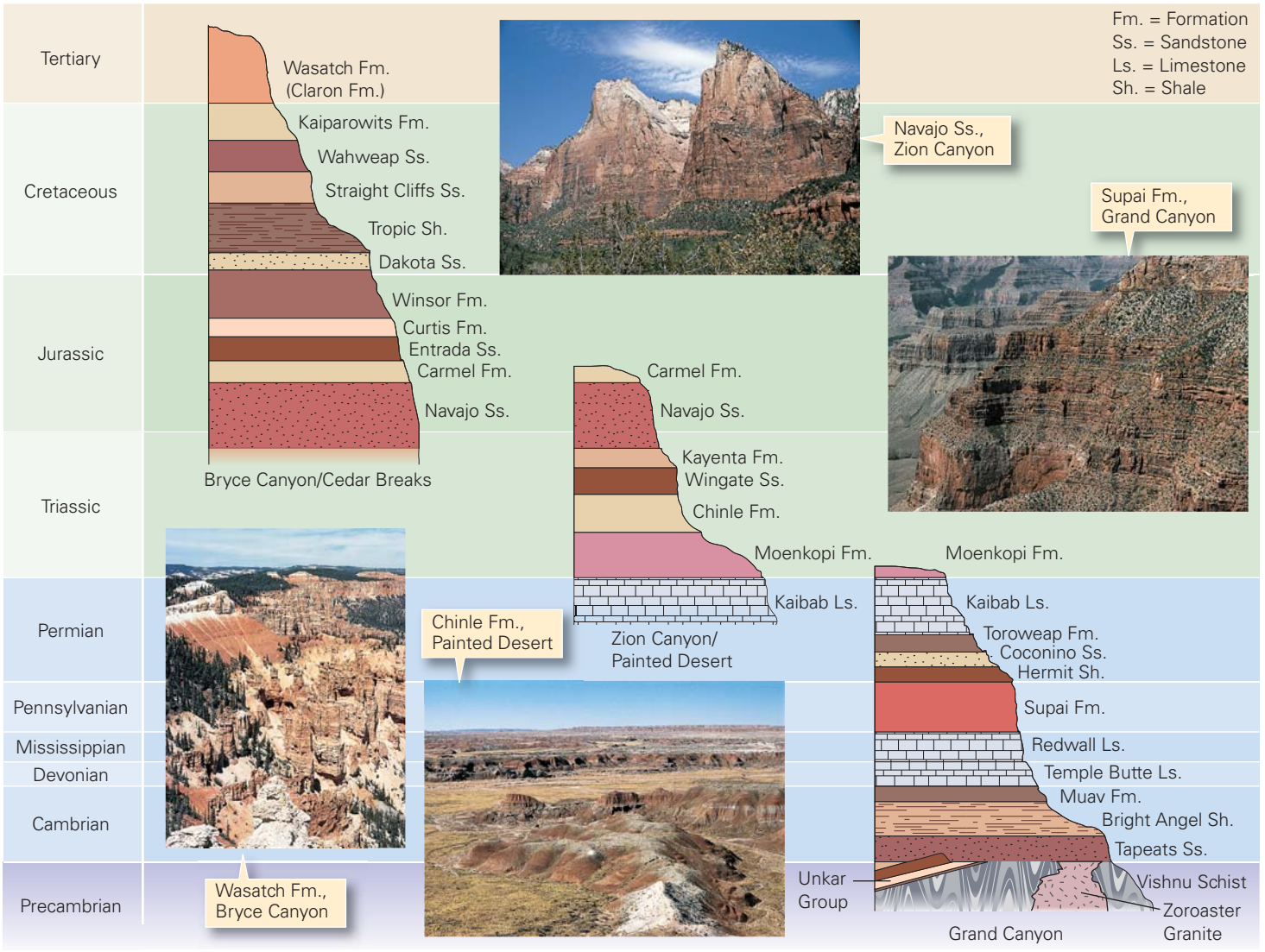
Progressively more complex organisms populated the Earth during the Paleozoic. For example, the first fish appeared in Ordovician seas, land plants started to spread over the continents during the Silurian (prior to the Silurian, the land surface was unvegetated), and amphibians appeared during the Devonian. Though reptiles appeared during the Pennsylvanian Period, the first dinosaurs did not stomp across the land until the Triassic. Dinosaurs continued to inhabit the Earth until their sudden extinction at the end of the Cretaceous Period. For this reason, geologists refer to the Mesozoic Era as the Age of Dinosaurs. Small mammals appeared during the Triassic Period, but the diversification (development of many different species) of mammals to fill a wide range of ecological niches did not happen until the beginning of the Cenozoic Era, so geologists call the Cenozoic the Age of Mammals. Birds also appeared during the Mesozoic (specifically, at the beginning of the Cretaceous Period), but underwent great diversification in the Cenozoic Era.

To conclude our discussion of the geologic column, let's see how it comes into play when correlating strata across a region. We return to the Colorado Plateau of Arizona and Utah, in the southwestern United States (**Fig. 10.11a, b**). Because of the lack of vegetation in this region, you can easily see bedrock exposures on the walls of cliffs and canyons; some of these exposures are so beautiful that they have become national parks. Using correlation techniques, geologists have determined that the oldest sedimentary rocks of the region crop out near the base of the Grand Canyon, whereas the youngest form the cliffs of Cedar Breaks and Bryce Canyon. Walking through these parks is thus like walking through Earth's history—each rock layer gives an indication of the climate and topography of the region at a time in the past (see **Geology at a Glance**, pp. 318–319). For example, when the Precambrian metamorphic and igneous rocks exposed in the inner gorge of the Grand Canyon first formed, the region was a high mountain range, perhaps as dramatic as the Himalayas today. When the fossiliferous beds of the Kaibab Limestone at the rim of the canyon first developed, the region was a Bahama-like carbonate reef and platform, bathed in a warm, shallow sea. And when the rocks making up the towering red cliffs of sandstone in Zion Canyon were deposited, the region was a Sahara-like desert, blanketed with huge sand dunes.

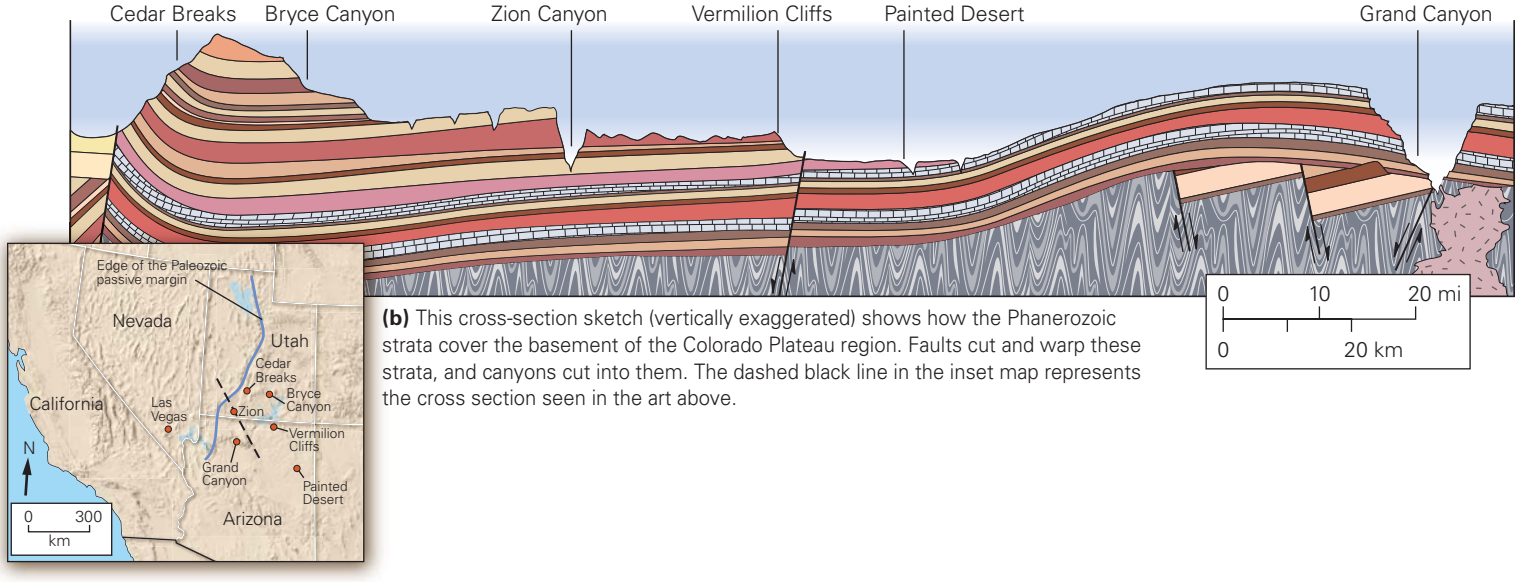
Take-Home Message

Correlation of stratigraphic sequences from around the world led to the production of a chart, the geologic column, that represents the entirety of Earth history. The column, developed using only relative-age relations, is subdivided into eons, eras, periods, and epochs.

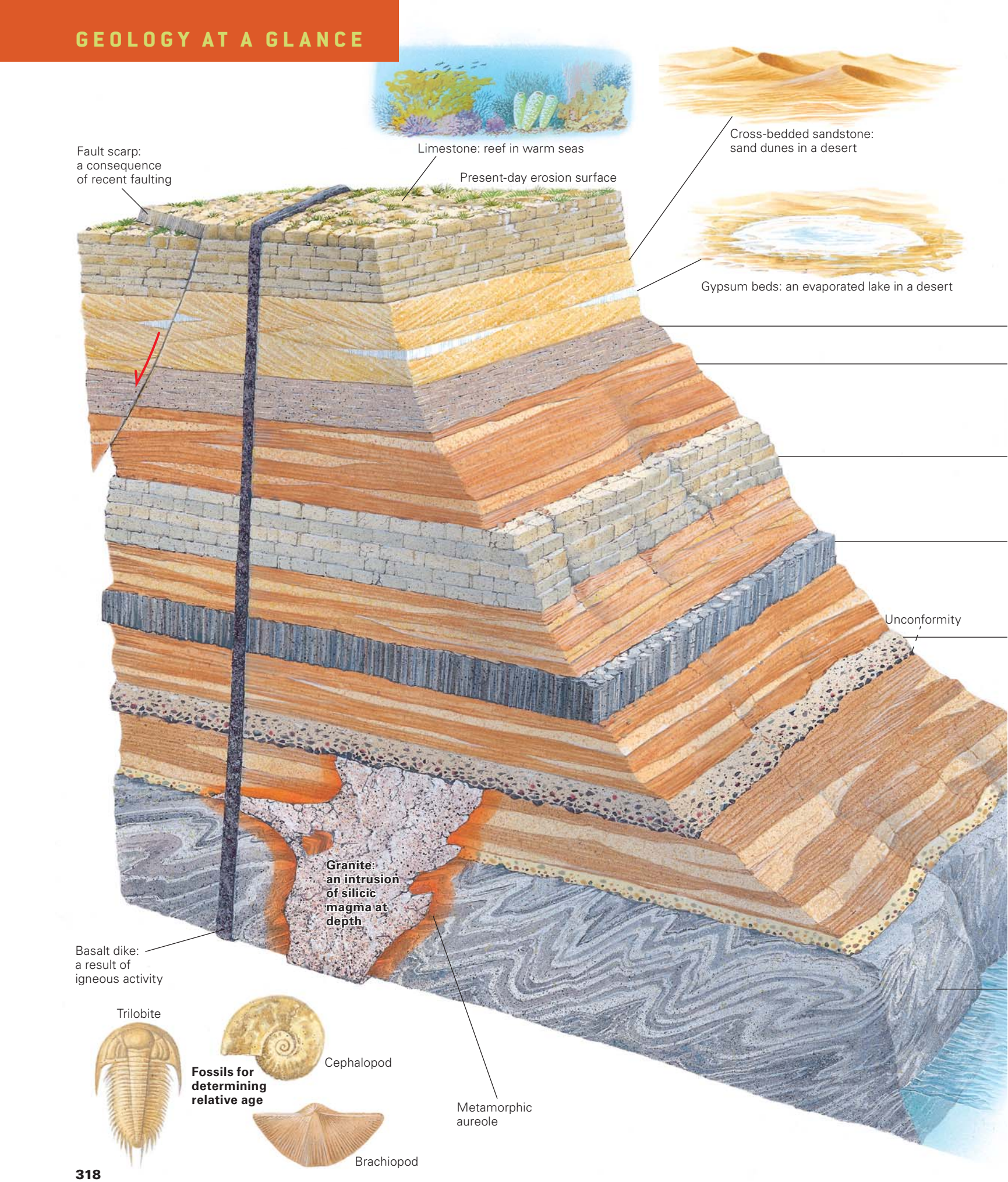
FIGURE 10.11 Correlation of strata among the national parks of Arizona and Utah.



(a) Different intervals of geologic time are represented by the strata of different parks.



(b) This cross-section sketch (vertically exaggerated) shows how the Phanerozoic strata cover the basement of the Colorado Plateau region. Faults cut and warp these strata, and canyons cut into them. The dashed black line in the inset map represents the cross section seen in the art above.


Limestone: reef in warm seas
Cross-bedded sandstone: sand dunes in a desert
Fault scarp: a consequence of recent faulting
Present-day erosion surface
Gypsum beds: an evaporated lake in a desert
Unconformity
Granite: an intrusion of silicic magma at depth
Basalt dike: a result of igneous activity
Trilobite
Cephalopod
Fossils for determining relative age
Brachiopod
Metamorphic aureole

The Record in Rocks: Reconstructing Geologic History

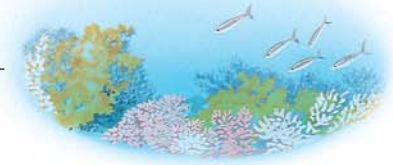


Ignimbrite (welded tuff): an explosive volcanic eruption



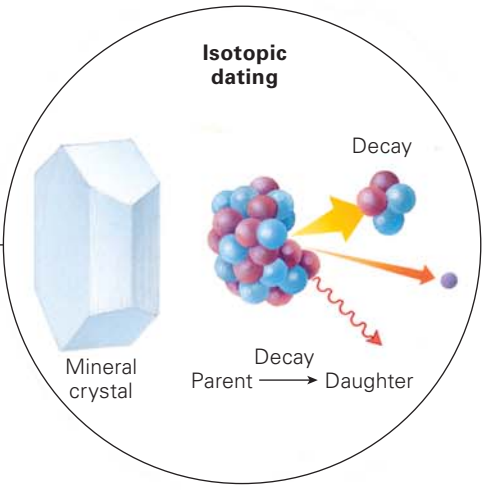
Redbeds: sand and mud deposited in a river channel and bordering floodplain

Limestone: reef in warm seas



Basalt lava: flows from a volcano





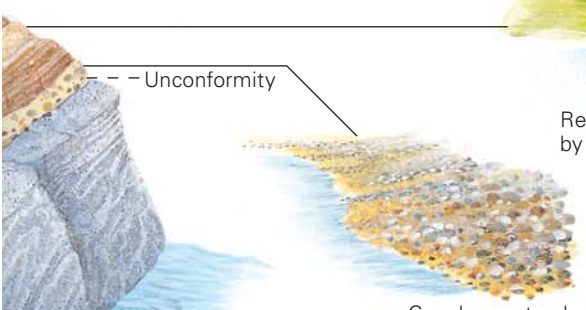


Conglomerate: debris eroded from a cliff



Redbeds: sand and mud deposited by distributaries of a delta plain

Unconformity



Conglomerate: deposits of a pebble beach



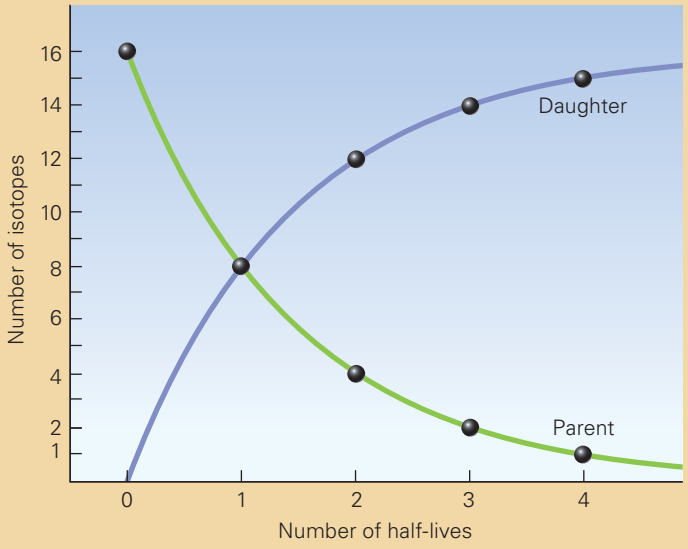
Gneiss: metamorphism at depth beneath a mountain belt

When geologists examine a sequence of rocks exposed on a cliff, they see a record of Earth history that can be interpreted by applying the basic principles of geology, by searching for fossils, and by using isotopic dating. On this cliff, we see evidence for many geologic events. The layers of sediment (and the sedimentary structures they contain), the igneous intrusions, and the geologic structures tell us about past climates and past tectonic activity.

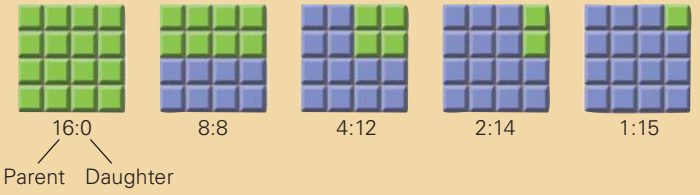
The insets show the way the region looked in the past, based on the record in the rocks. For example, the presence of gneiss at the base of the canyon indicates that at one time the region was a mountain belt, for the protoliths of the gneiss were buried deeply. Unconformities indicate that the region underwent uplift and erosion. Sedimentary successions record transgressions and regressions of the sea, igneous rocks are evidence of volcanic and intrusive activity, and faults indicate deformation.

Clearly, the land surface portrayed in this painting was sometimes a river floodplain or a delta (indicated by redbeds), sometimes a shallow sea (limestone), and sometimes a desert dune field (cross-bedded sandstone). And at several times in the past, volcanic activity occurred in the region. We can gain insight into the age of the sedimentary rocks by studying the fossils they contain, and into the age of the igneous and metamorphic rocks by using isotopic dating methods.

FIGURE 10.12 The concept of a half-life, in the context of radiaoctive decay.



(a) This graph shows how the number of parent isotopes decreases and the number of daughter isotopes increases, as time passes. The rate of change decreases with time.



(b) The ratio of parent-to-daughter isotopes changes with the passage of each successive half-life.



(c) In a cluster of isotopes undergoing decay, there is no way to predict which parent will decay next.

10.7 How Do We Determine Numerical Age?

Geologists since the days of Hutton could determine the relative ages of geologic events, but they had no way to specify numerical ages (called "absolute ages" in older literature). Thus, they could not define a timeline for Earth history or determine the duration of events. This situation changed with the discovery of radioactivity. Simply put, radioactive elements decay at a constant rate that can be measured in the lab and can be specified in years. In the 1950s, geologists developed techniques for using measurements of radioactive elements to calculate the numerical ages of rocks. Geologists originally referred to these techniques as radiometric dating; more recently, this has come to be known as **isotopic dating**. The overall study of numerical ages is **geochronology**. Since the 1950s, isotopic dating techniques have steadily improved, and geologists have learned how to make very accurate measurements from very small samples. But the basis of the techniques remains the same, and to explain them, we must first review radioactive decay.

Did you ever wonder . . .
how geologists can specify the age of some rocks in years?

Radioactive Decay

All atoms of a given element have the same number of protons in their nucleus—we call this number the atomic number (see Chapter 1). However, not all atoms have the same number of neutrons in their nucleus. Therefore, not all atoms of a given element have the same atomic weight (roughly, the number of protons plus neutrons). Different versions of an element, called **isotopes** of the element, have the same atomic number but a different atomic weight (see Box 1.1). For example, all uranium atoms have 92 protons, but the uranium-238 isotope (abbreviated ^{238}U) has an atomic weight of 238 and thus has 146 neutrons, whereas the ^{235}U isotope has an atomic weight of 235 and thus has 143 neutrons.

Some isotopes of some elements are stable, meaning that they last essentially forever. Radioactive isotopes are unstable in that eventually, they undergo a change called **radioactive decay**, which converts them to a different element. Radioactive decay can take place by a variety of reactions that change the atomic number of the nucleus and thus form a different element. In these reactions, the isotope that undergoes decay is the **parent isotope**, while the decay product is the **daughter isotope**. For example, rubidium-87 (^{87}Rb) decays to strontium-87 (^{87}Sr), potassium-40 (^{40}K) decays to argon-40 (^{40}Ar), and uranium-238 (^{238}U) decays to lead-206 (^{206}Pb). In some cases, decay takes many steps before yielding a stable daughter.

Physicists cannot specify how long an individual radioactive isotope will survive before it decays, but they can measure how long it takes for half of a group of parent isotopes to decay. This time is called the **half-life** of the isotope. Figure 10.12a–c can help you visualize the concept of a half-life. Imagine a crystal containing 16 radioactive parent isotopes. (In real crystals, the number of atoms would be much larger.) After one half-life, 8 isotopes have decayed, so the crystal now contains 8 parent and 8 daughter isotopes. After a second half-life, 4 of the remaining parent isotopes have decayed, so the crystal contains 4 parent and 12 daughter isotopes. And after a third half-life, 2 more parent isotopes have decayed, so the crystal contains 2 parent and 14 daughter isotopes. For a given decay reaction, the half-life is a constant.

Isotopic Dating Techniques

Since radioactive decay proceeds at a known rate, like the ticktock of a clock, it provides a basis for telling time. In other

TABLE 10.1 Isotopes Used in the Isotopic Dating of Rock

Parent → Daughter	Half-Life (years)	Minerals Containing the Isotopes
$^{147}Sm \rightarrow {}^{143}Nd$	106.0 billion	Garnets, micas
$^{87}Rb \rightarrow {}^{87}Sr$	48.8 billion	Potassium-bearing minerals (mica, feldspar, hornblende)
$^{238}U \rightarrow {}^{206}Pb$	4.5 billion	Uranium-bearing minerals (zircon, uraninite)
$^{40}K \rightarrow {}^{40}Ar$	1.3 billion	Potassium-bearing minerals (mica, feldspar, hornblende)
$^{235}U \rightarrow {}^{207}Pb$	713.0 million	Uranium-bearing minerals (zircon, uraninite)

Sm = samarium, Nd = neodymium, Rb = rubidium, Sr = strontium, U = uranium, Pb = lead, K = potassium, Ar = argon

words, because an element's half-life is a constant, we can calculate the age of a mineral by measuring the ratio of parent to daughter isotopes in the mineral.

In practice, how can we obtain an isotopic date? First, we must find the right kind of elements to work with. Although there are many different pairs of parent and daughter isotopes among the known radioactive elements, only a few have long enough half-lives, and occur in sufficient abundance in minerals, to be useful for isotopic dating. **Table 10.1** lists particularly useful elements. Each radioactive element has its own half-life. (Note that carbon dating is *not* used for dating rocks because appropriate carbon isotopes occur only in organisms and radioactive carbon has a very short half-life).

Second, we must identify the right kind of minerals to work with. Not all minerals contain radioactive elements, but fortunately some fairly common minerals do. Once we have found the right kind of minerals, we can set to work using the following steps.

- *Collecting the rocks*: We need to find unweathered rocks for dating, for the chemical reactions that happen during weathering may lead to the loss of some isotopes.
- *Separating the minerals*: The rocks are crushed, and the appropriate minerals are separated from the debris.
- *Extracting parent and daughter isotopes*: To separate out the parent and daughter isotopes from minerals, we can use several techniques, including dissolving the minerals in acid or evaporating portions of them with a laser.
- *Analyzing the parent-daughter ratio*: Once we have a sample of appropriate atoms, we pass them through a mass spectrometer, an instrument that uses a strong magnet to separate isotopes from one another according to their respective weights (**Fig. 10.13**). The instrument can count the number of atoms of specific isotopes separately.

At the end of the laboratory process, we can define the ratio of parent to daughter isotopes in a mineral, and from this ratio calculate the age of the mineral. Needless to say, the description of the procedure here has been simplified—in reality, obtaining an isotopic date is time-consuming and expensive and requires complex calculations.

What Does an Isotopic Date Mean?

At high temperatures, atoms in a crystal lattice vibrate so rapidly that chemical bonds can break and reattach relatively easily. As a consequence, isotopes can escape from or move into crystals, so parent-daughter ratios are meaningless. Because isotopic dating is based on the parent-daughter ratio, the "isotopic clock" starts only when crystals become cool enough for isotopes to be locked into the lattice. The temperature below which isotopes are no longer free to move is called the **closure temperature** of a mineral. When we specify an isotopic date for a mineral, we are defining the time at which the mineral cooled below its closure temperature.

With the concept of closure temperature in mind, we can interpret the meaning of isotopic dates. In the case of igneous rocks, isotopic dating tells you when a magma or lava cooled to form a solid, cool igneous rock. In the case of metamorphic rocks, an isotopic date tells you when a rock cooled from a metamorphic temperature above the closure temperature to a temperature below. Not all minerals have the same closure temperature, so different minerals in a rock that cools very slowly will yield different dates.

Can we isotopically date a clastic sedimentary rock directly? No. If we date minerals in a sedimentary rock, we determine only when these minerals first crystallized as part of an igneous or metamorphic rock, not the time when the minerals were deposited as sediment nor the time when the sediment lithified to form a sedimentary rock. For example, if we date the feldspar grains contained within a granite pebble in a conglomerate, we're dating the time the granite cooled below feldspar's closure temperature, not the time the pebble was deposited by a stream.

FIGURE 10.13 In an isotopic dating laboratory, samples are analyzed using a mass spectrometer. This instrument measures the ratio of parent to daughter isotopes.



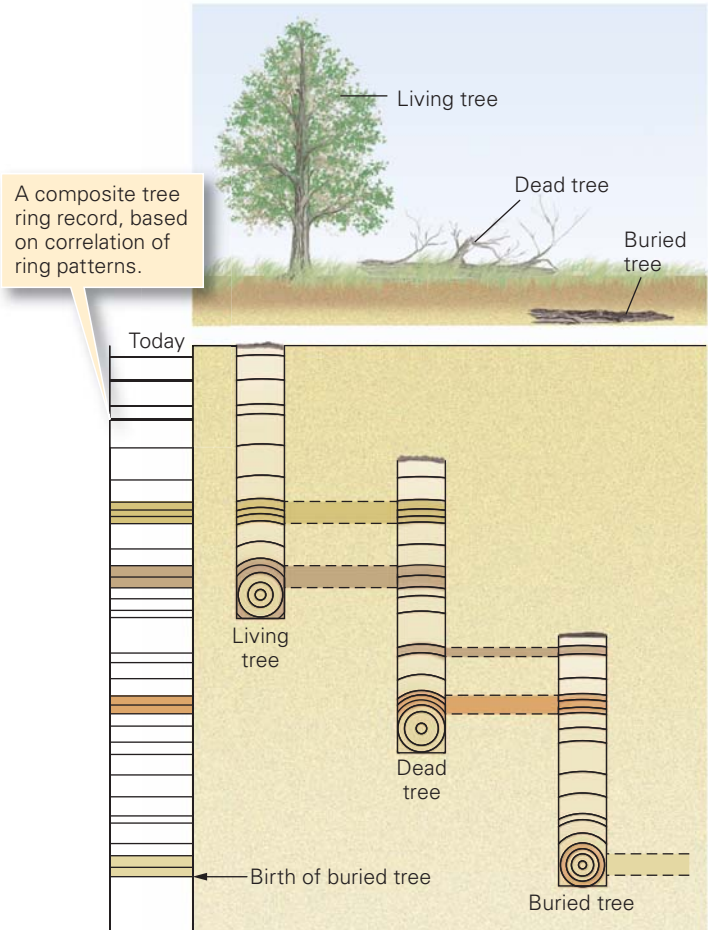
FIGURE 10.14 Using tree rings as a basis for dating.



(a) Dust settling during the summer highlights boundaries between snow layers, now turned to ice in this Oregon glacier.



(b) Patterns of rings are like bar codes. Each ring in this slice of wood represents the growth of one year.



(c) Dendrochronology is based on the correlation of tree rings. Each of the columns in the diagram represents a core drilled out of a tree. By correlation, researchers extend the climate record back in time before the oldest living tree started to grow.

Other Methods of Determining Numerical Age

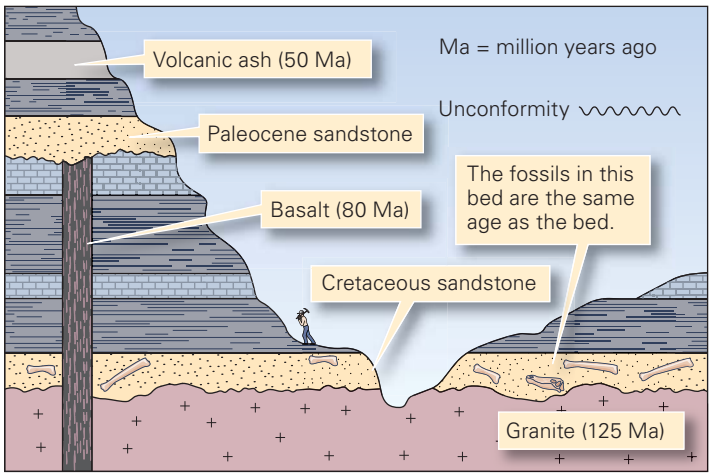
The rate of tree growth depends on the season. During the spring, trees grow rapidly and produce lighter, less-dense wood, but during the winter trees grow slowly or not at all, and produce darker, denser wood. Thus, wood contains recognizable annual growth rings. Such tree rings provide a basis for determining age. If you've ever wondered how old a tree that's just been cut down might be, just look at the stump and count the rings. Notably, by correlating clusters of distinctive rings in the older parts of living trees with comparable clusters of rings in dead logs, scientists can extend the tree-ring record back for many thousands of years, allowing geologists to track climate changes back into prehistory.

Seasonal changes also affect rates of such phenomena as shell growth, snow accumulation, clastic sediment deposition, chemical sediment precipitation, and production of organic material. Geologists have learned to use growth rings in shells, as well as rhythmic layering in sediments and in glacial ice (Fig. 10.14 a–c), to date events numerically back through recent Earth history.

Take-Home Message

Isotopic dating specifies numerical ages in years. To obtain an isotopic date, we measure the ratio of parent radioactive isotopes to stable daughter products in a mineral. A date for a mineral gives the time at which the mineral cooled below a closure temperature.

FIGURE 10.15 The Cretaceous sandstone bed was deposited on the granite, so it must be younger than 125 Ma. The dike cuts the bed, so the bed must be older than 80 Ma. Thus, the Cretaceous sandstone bed was deposited between 125 and 80 Ma. The Paleocene sandstone was unconformably deposited over the dike and lies beneath a 50-million-year-old layer of ash. Therefore, it must have been deposited between 80 and 50 Ma.



10.8 Numerical Age and Geologic Time

Dating Sedimentary Rocks?

The mind grows giddy gazing so far back into the abyss of time.

—John Playfair (1747–1819),
British geologist who popularized the works of Hutton

We have seen that isotopic dating can be used to date the time when igneous rocks formed and when metamorphic rocks metamorphosed, but not when sedimentary rocks were deposited. So how do we determine the numerical age of a sedimentary rock? We must answer this question if we want to add numerical ages to the geologic column.

Geologists obtain dates for sedimentary rocks by studying cross-cutting relationships between sedimentary rocks and datable igneous or metamorphic rocks. For example, if we find a sequence of sedimentary strata deposited unconformably on a datable granite, the strata must be younger than the granite (**Fig. 10.15**). If a datable basalt dike cuts the strata, the strata must be older than the dike. And if a datable volcanic ash buried the strata, then the strata must be older than the ash.

The Geologic Time Scale

Geologists have searched the world for localities where they can recognize cross-cutting relations between datable igneous rocks and sedimentary rocks or for layers of datable volcanic rocks interbedded with sedimentary rocks. By isotopically dating the igneous rocks, they have been able to provide numerical ages for the boundaries between all geologic periods. For example, work from around the world shows that the Cretaceous Period began about 145 million years ago and ended 65 million years ago. So the Cretaceous sandstone bed in Figure 10.15 was deposited during the middle part of the Cretaceous, not at the beginning or end.

The discovery of new data may cause the numbers defining the boundaries of periods to change, which is why the term *numerical age* is preferred to *absolute age*. In fact, around 1995, new dates on rhyolite ash layers above and below the Cambrian-Precambrian boundary showed that this boundary occurred at 542 million years ago, in contrast to previous, less definitive studies that had placed the boundary at 570 million years ago. **Figure 10.16** shows the currently favored numerical ages of periods and eras in the geologic column as of 2009. This dated column is commonly called the **geologic time scale**.

What Is the Age of the Earth?

During the 18th and 19th centuries, before the discovery of isotopic dating, scientists came up with a great variety of clever solutions to the question, "How old is the Earth?"—all of which have since been proven wrong. Lord William Kelvin, a 19th-century physicist renowned for his discoveries in thermodynamics, made the most influential scientific estimate of the Earth's age of his time. Kelvin calculated how long it would take for the Earth to cool down from a temperature as hot as the Sun's, and concluded that this planet is about 20 million years old.

Kelvin's estimate contrasted with those being promoted by followers of Hutton, Lyell, and Darwin, who argued that if the concepts of uniformitarianism and evolution were correct, the Earth must be much older. They argued that physical processes that shape the Earth and form its rocks, as well as the process of natural selection that yields the diversity of species, all take a very long time. Geologists and physicists continued to debate the age issue for many years. The route to a solution didn't appear until 1896, when Henri Becquerel announced the discovery of radioactivity. Geologists immediately realized that the Earth's interior was producing heat from the decay of radioactive material. This realization uncovered one of the flaws in Kelvin's argument: Kelvin had assumed that no new heat was produced after the Earth first formed. Because radioactivity constantly generates new heat in the Earth, the planet has cooled down much more slowly than Kelvin had calculated and could be much older. The discovery of radioactivity not only invalidated Kelvin's estimate of the Earth's age, it also led to the development of isotopic dating.

Since the 1950s, geologists have scoured the planet to identify its oldest rocks. Rocks younger than 3.85 Ga are fairly common. Rock samples from several localities (Wyoming,

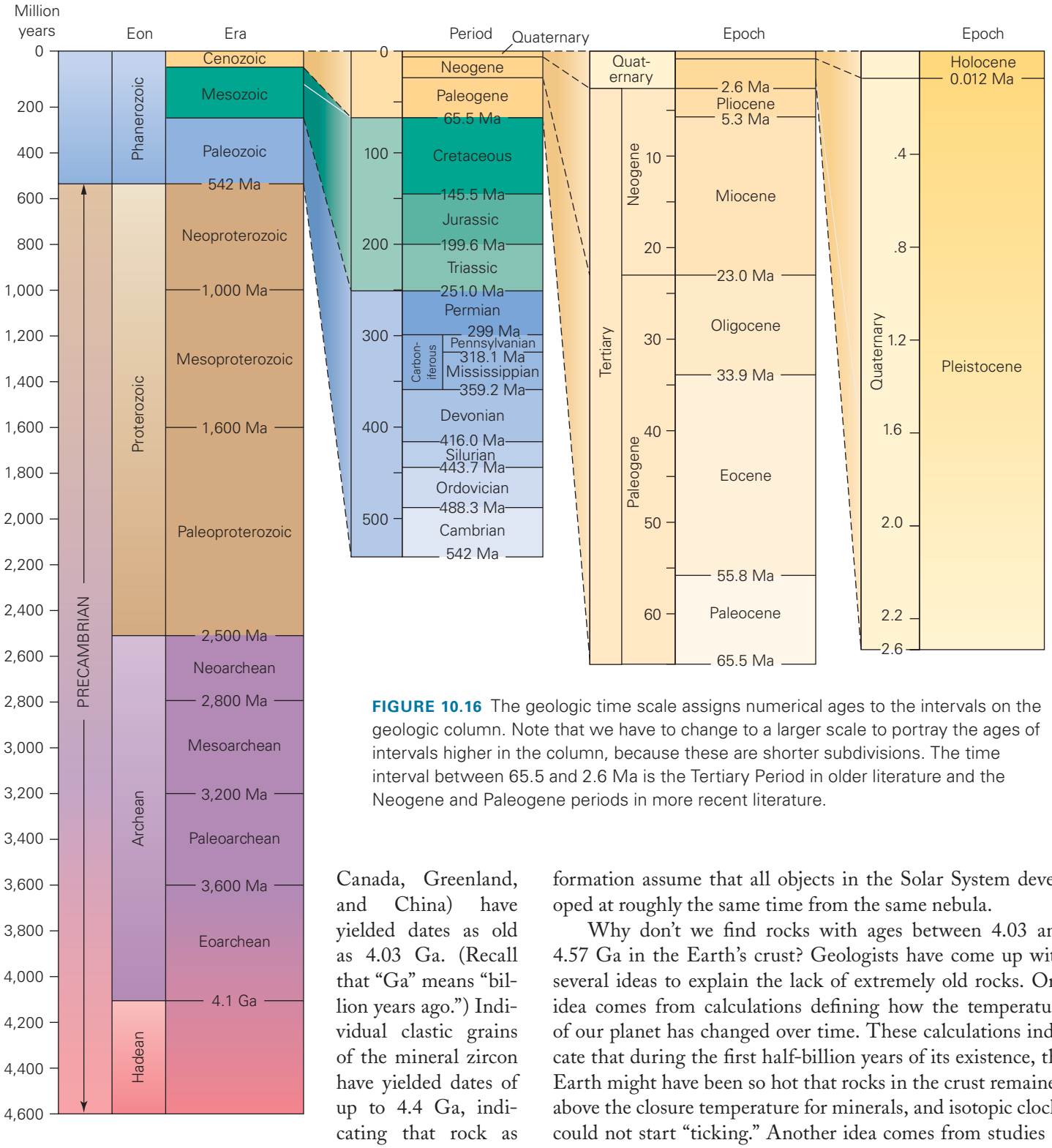


FIGURE 10.16 The geologic time scale assigns numerical ages to the intervals on the geologic column. Note that we have to change to a larger scale to portray the ages of intervals higher in the column, because these are shorter subdivisions. The time interval between 65.5 and 2.6 Ma is the Tertiary Period in older literature and the Neogene and Paleogene periods in more recent literature.

Canada, Greenland, and China) have yielded dates as old as 4.03 Ga. (Recall that "Ga" means "billion years ago.") Individual clastic grains of the mineral zircon have yielded dates of up to 4.4 Ga, indicating that rock as old as 4.4 Ga did once exist. Isotopic dating of Moon rocks yields dates of up to 4.50 Ga, and dates on meteorites have yielded ages as old as 4.57 Ga. Geologists consider 4.57-Ga meteorites to be fragments of planetesimals like those from which the Earth first formed. Thus, these dates are close to the age of the Earth's birth, for models of the Earth's formation assume that all objects in the Solar System developed at roughly the same time from the same nebula.

Did you ever wonder . . .
how old is the Earth's oldest rock?

Why don't we find rocks with ages between 4.03 and 4.57 Ga in the Earth's crust? Geologists have come up with several ideas to explain the lack of extremely old rocks. One idea comes from calculations defining how the temperature of our planet has changed over time. These calculations indicate that during the first half-billion years of its existence, the Earth might have been so hot that rocks in the crust remained above the closure temperature for minerals, and isotopic clocks could not start "ticking." Another idea comes from studies of cratering events on other moons and planets. These studies indicate that the inner planets were bombarded so intensely by meteorites at about 4.0 Ga that almost all crust formed earlier than 4.0 Ga was completely destroyed.

Picturing Geologic Time

The number 4.57 billion is so staggeringly large that we can't begin to comprehend it. If you lined up this many pennies in

a row, they would make an 87,400-km-long line that would wrap around the Earth's equator more than twice. Notably, at the scale of our penny chain, human history is only about 100 city blocks long.

Another way to grasp the immensity of geologic time is to equate the entire 4.57 billion years to a single calendar year. On this scale, the oldest rocks preserved on Earth date from early February, and the first bacteria appear in the ocean on February 21. The first shelly invertebrates appear on October 25, and the first amphibians crawl out onto land on November 20. On December 7, the continents coalesce into the supercontinent of Pangaea. Birds and the ancestors of mammals appear about December 15, along with the dinosaurs, and the Age of Dinosaurs ends on December 25. The last week of December represents the last 65 million years of Earth history, including the entire Age of Mammals. The first human-like ancestor appears on December 31 at 3 P.M., and our species, *Homo sapiens*, shows up an hour before midnight. The last ice age ends a minute before midnight, and all of recorded human history takes place in the last 30 seconds. To put it another way, human history occupies the last 0.000001% of Earth history. The Earth is so old that there has been more than enough time for the rocks and life forms of Earth to have formed and evolved.

Take-Home Message

Numerical dates for sedimentary rocks come from isotopic dating of cross-cutting datable rocks. Such work led to the geologic time scale, assigning ages to periods. The oldest rock of Earth's crust is about 4.0 Ga. Dating of meteorites indicates the Earth is 4.57 Ga.



ANOTHER VIEW The pages of Earth history stand on end in Namibia, southwestern Africa. Here, in a false-color image, the Ugab River cuts across layer upon layer of strata that were tilted to near-vertical by a Precambrian mountain-building event. Subsequent erosion exposed the strata, and the desert climate keeps it clear of vegetation. The field of view is 45 km.

CHAPTER 10 REVIEW

Chapter Summary

- Geologic time refers to the time span since the Earth's formation.
- Relative age specifies whether one geologic feature is older than or younger than another; numerical age provides the age of a geologic rock or feature in years.
- Using such principles as uniformitarianism, original horizontality, superposition, and cross-cutting relations, we can construct the geologic history of a region.
- The principle of fossil succession states that the assemblage of fossils in strata changes from base to top of a sequence. Once a species becomes extinct, it never reappears.
- Strata are not necessarily deposited continuously at a location. An interval of nondeposition and/or erosion is called an unconformity. Geologists recognize three kinds: angular unconformity, nonconformity, and disconformity.
- A stratigraphic column shows the succession of strata in a region. A given succession of strata that can be traced over a fairly broad region is called a stratigraphic formation. The process of determining the relationship between strata at one location and strata at another is called correlation. A geologic map shows the distribution of formations and geologic structures.
- A composite chart that represents the entirety of geologic time is called the geologic column. The column's largest subdivisions, each of which represent a specific interval of time, are eons. Eons are subdivided into eras, eras into periods, and periods into epochs.
- The numerical age of rocks can be determined by isotopic (radiometric) dating. This is because radioactive elements decay at a rate characterized by a known half-life.
- The isotopic age of a mineral specifies the time at which the mineral cooled below a closure temperature. We can use isotopic dating to determine when an igneous rock solidified and when a metamorphic rock cooled. To date sedimentary strata, we must examine cross-cutting relations with dated igneous or metamorphic rock.
- Other methods for dating materials include counting growth rings in trees and seasonal layers in glaciers.
- Isotopic dating indicates that the Earth is 4.57 billion years old.

Key Terms

Cambrian explosion (p. 316)
closure temperature (p. 321)
contact (p. 310)
correlation (p. 312)
cross-cutting relations (p. 307)
daughter isotope (p. 320)
eon (p. 315)
epoch (p. 315)
era (p. 315)
fossil assemblage (p. 308)
fossil succession (p. 308)
geochronology (p. 320)
geologic column (p. 315)
geologic history (p. 307)
geologic map (p. 314)
geologic time (p. 305)
geologic time scale (p. 323)
half-life (p. 320)
index fossil (p. 309)
isotope (p. 320)
isotopic dating (p. 320)
marker bed (p. 312)
numerical age (p. 306)
original horizontality (p. 306)
parent isotope (p. 320)
period (p. 315)
Precambrian (p. 315)
radioactive decay (p. 320)
relative age (p. 306)
stratigraphic column (p. 312)
stratigraphic formation (p. 312)
stratigraphic group (p. 312)
superposition (p. 307)
unconformity (p. 310)
uniformitarianism (p. 306)

Review Questions

1. Explain the concept of uniformitarianism.
2. Compare numerical age and relative age.
3. Describe the principles that allow us to determine the relative ages of geologic events.
4. How does the principle of fossil succession allow us to determine the relative ages of strata?
5. How does an unconformity develop? Describe the differences among the three kinds of unconformities.
6. Describe two different methods of correlating rock units. How was correlation used to develop the geologic column? What is a stratigraphic formation?
7. Is there one place on Earth where we can see the complete geologic column?
8. What does the process of radioactive decay entail?
9. How do geologists obtain an isotopic date? What are some of the pitfalls in obtaining a reliable one?
10. Why can't we date sedimentary rocks directly? Why don't all periods on the geologic column last for the same amount of time?
11. What is the age of the oldest rocks on Earth? What is the age of the oldest rocks known? Why is there a difference?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Interactive exercise on biostratigraphy.
- What a Geologist Sees Exercises on strata and unconformities.
- An animation exercise on geologic history.

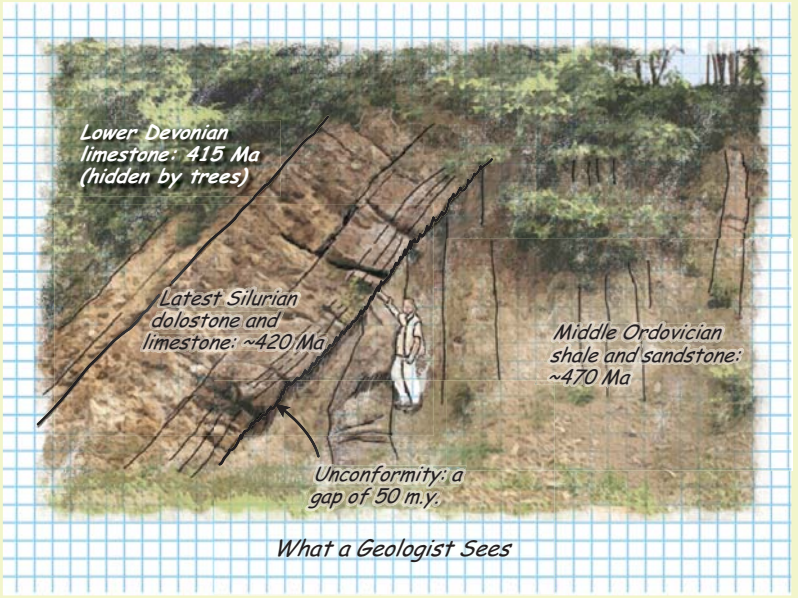
On Further Thought

12. Imagine an outcrop exposing a succession of alternating sandstone and conglomerate beds. A geologist studying the outcrop notes the following:

    - The sandstone beds contain land plants, but the fragments are too small to permit identification.
    - A layer of volcanic ash overlies the sandstone bed. Isotopic dating indicates that this ash is 300 Ma.
    - A paleosol occurs at the base of the ash layer.
    - A basalt dike, dated at 100 Ma, cuts both the ash and the sandstone-conglomerate sequence.
    - Pebbles of granite in the conglomerate yield radiometric dates of 400 Ma.

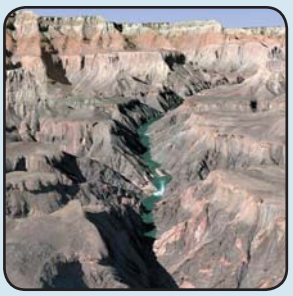
    On the basis of these observations, how old is the sandstone and conglomerate? (Specify both the numerical age range and the period or periods of the geologic column during which it formed.)

13. The figure below shows a geologist's interpretation of the chapter-opening photo. Describe the geologic history that led to the features visible in this outcrop.



SEE FOR YOURSELF J. . . Geologic Time

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet J of our **Geotours Workbook**.



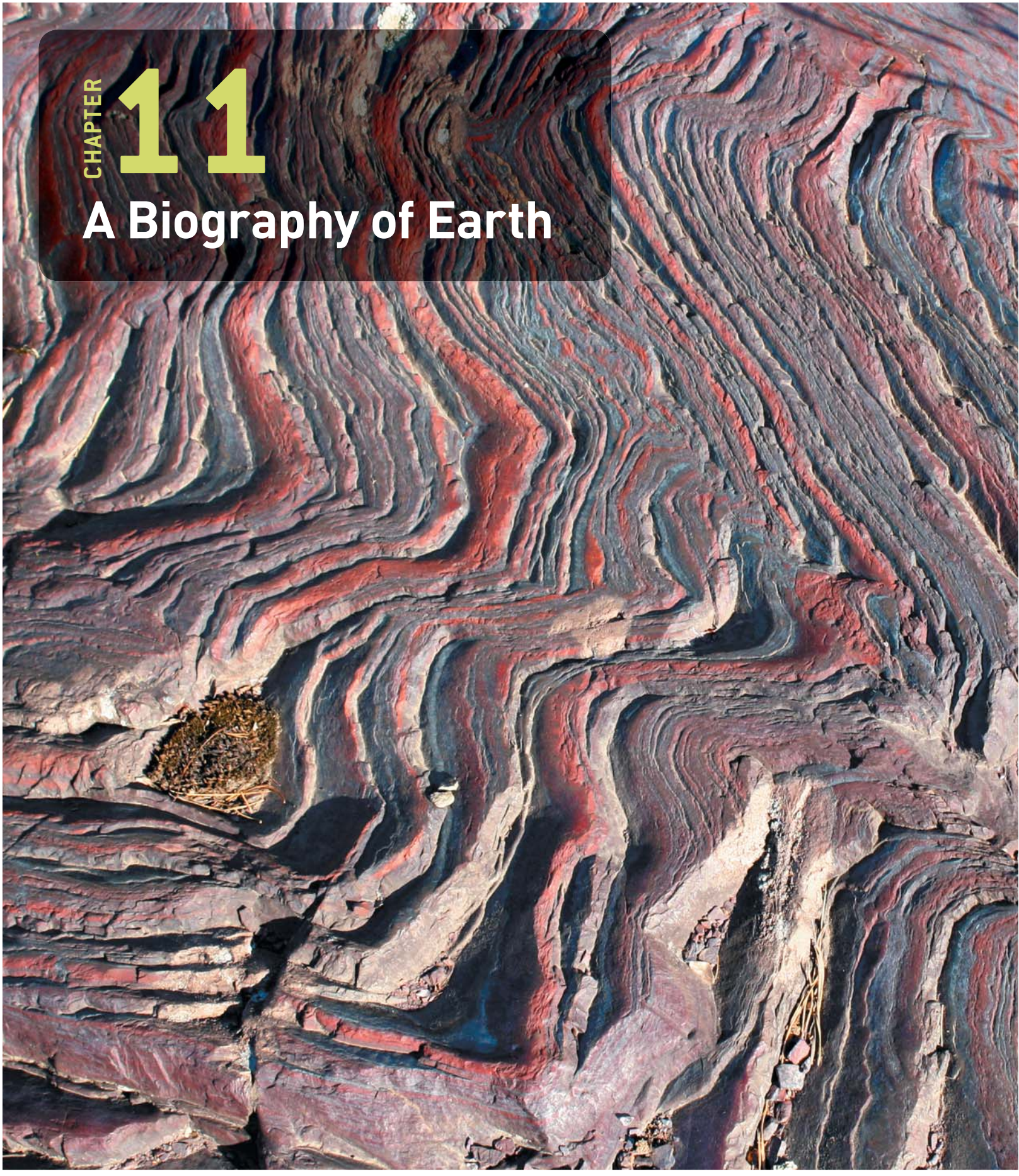
Grand Canyon, Arizona
Latitude 36°5′53.99″N,
Longitude 112°10′58.58″W

Looking obliquely downstream from an elevation of 1.5 km, we see strata representing an immense amount of geologic time. The dark metamorphic rocks of the inner gorge are ~1.75 Ga. An unconformity separates them from overlying Paleozoic strata. The youngest unit is the ~270 Ma Kaibab Limestone.



Vermilion Cliffs, Arizona
Latitude 36°49′4.81″N,
Longitude 111°37′56.59″W

This locality shows Marble Canyon, the entry to the Grand Canyon. Outcrops in the distance comprise the Vermilion Cliffs, exposing reddish brown sandstone and shale of the Moenkopi Formation. The walls of Marble Canyon consist of the underlying Kaibab Limestone.



CHAPTER 11

A Biography of Earth



Every outcrop tells a story of our planet's past. Here, in an outcrop from Michigan, we see banded iron formation that was deposited about 2.1 Ga. Folding of the layers happened over 200 million years later.

Chapter Objectives

By the end of this chapter, you should know . . .

- what conditions have permitted oceans and life to exist and continents to form.
- when continental blocks came together to form supercontinents and rifted apart to form smaller continents.
- the nature of the earliest life, how life evolution and the atmospheric composition are related, and how life diversified when shells appeared.
- that what is dry land on continents today hasn't always been so, because of global change in relative sea level.
- that the mountain belts of today are relatively young—earlier belts have since eroded away.

. . . the man who should know the true history of the bit of chalk which every carpenter carries about in his breeches pocket, though ignorant of all other history, is likely . . . to have a truer and therefore a better conception of this wonderful universe and of man's relation to it than the most learned student who [has] deep-read the records of humanity [but is] ignorant of those of nature.

—Thomas Henry Huxley, from *On a Piece of Chalk* (1868)

11.1 Introduction

In 1868, a well-known British scientist, Thomas Henry Huxley, presented a public lecture on geology to an audience in Norwich, England. Seeking a way to convey his fascination with Earth history to people with no previous geologic knowledge, he focused his audience's attention on the piece of chalk he had been using (see the epigraph above). And what a tale the chalk has to tell! Chalk, a type of limestone, consists of microscopic marine algae shells and shrimp feces. The specific chalk that Huxley held came from beds deposited in the Cretaceous Period (the name *Cretaceous*, in fact, derives from the Latin word for chalk). These beds are now exposed in white cliffs bordering the coast of England. Geologists in Huxley's day knew of similar chalk beds throughout much of Europe, and had discovered that the chalk contains fossils of bizarre swimming reptiles, fish, and invertebrates—species absent in the seas of today. Clearly, when the chalk was deposited,

warm seas holding unfamiliar creatures covered some of what is dry land today. Clues in his humble piece of chalk allowed Huxley to demonstrate to his audience that the geography and inhabitants of the Earth in the past differed markedly from those today, and thus that *the Earth has a history*.

In this chapter, we offer a concise geologic biography of our planet, from its birth 4.57 billion years ago to the present. During its infancy, the Earth was vastly different from the green and blue globe we know today. We discuss how it started as a semi-molten ball, undergoing incessant bombardment by meteorites. We then watch as the oceans form, continents come into existence and move about the surface, and collisions yield mountain ranges that later succumb to erosion. All the while, sea level rises and falls, so the land is sometimes submerged and sometimes not, the atmosphere progressively changes composition, and life evolves to fill a great diversity of environments. To simplify the discussion, remember that we use the following abbreviations: Ga (for billion years ago), Ma (for million years ago), and Ka (for thousand years ago).

11.2 The Hadean Eon: Before the Rock Record

James Hutton, the 18th-century Scottish geologist who was the first to provide convincing evidence that the Earth was very old, could not measure Earth's age directly, and indeed speculated that there may be "no vestige of a beginning." But isotopic dating studies conducted in recent decades have shown that it is possible, in fact, to assign a numerical age to our planet's formation. Specifically, dates obtained for a class of meteorites thought to be remnants of the planetesimal cloud out of which the Earth formed yield an age of 4.57 Ga. Geologists currently take this age to be the Earth's birth date. But the oldest whole rock yet found is only 4.03 Ga, and a clear record of Earth history, as recorded in continental crustal rocks, does not begin until about 3.85 Ga. Geologists refer to the mysterious time interval between the birth of Earth and 3.85 Ga as the **Hadean Eon** (from Hades, the Greek god of the underworld) because during this interval the Earth's surface was, at times, like an inferno.

Many major events happened during the Hadean. By about 4.5 Ga, the Earth underwent internal **differentiation**—gravity pulled molten iron down to the center of the Earth, where it accumulated to form the core, leaving a mantle composed of ultramafic rock. Researchers suggest that soon after—or perhaps during—differentiation, a Mars-sized protoplanet collided with the Earth. The energy of this collision blasted away a significant fraction of Earth's mantle; the resulting debris formed a ring of silicate-rock debris orbiting the Earth. This ring then coalesced to form the Moon, which, when first formed, was less than 20,000 km away. (By comparison, the Moon is 384,000 km from Earth today.)

In the wake of differentiation and Moon formation, the Earth was so hot that much of its surface was an ocean of seething magma (**Fig. 11.1**). Rafts of solid rock formed temporarily on the surface of the magma ocean, but these eventually sank and remelted. This stage lasted at least until about 4.4 Ga. After that time, the amount of radioactive heat generation decreased (because elements with short half-lives had decayed), so the Earth *might* have become cool enough for solid rocks to form at its surface. The evidence for this statement comes from western Australia, where geologists have found 4.4-Ga grains of a durable mineral called zircon.

During the Hadean Eon, outgassing of the Earth's mantle began to take place. This means that volatile (gassy) elements or compounds originally incorporated in mantle minerals were released and bubbled out of volcanoes, along with lava. The gases accumulated into a toxic atmosphere of water (H_2O), methane (CH_4), ammonia (NH_3), hydrogen (H_2), nitrogen (N_2), carbon dioxide (CO_2), sulfur dioxide (SO_2), and other gases. Some researchers speculate that gases from comets colliding with Earth may have contributed additional gases to the early atmosphere. If the Hadean Earth's surface was sufficiently cool for an extensive solid crustal rock to form beginning at 4.4 Ga, then the first oceans may have accumulated soon thereafter, when water in the atmosphere condensed and fell as rain.

Though mineral grains as old as 4.4 Ga exist, the oldest *whole rock* yet found on Earth has an age of only 4.03 Ga, and most rocks are younger than 3.85 Ga. What destroyed most, if not all, of the pre-3.85-Ga rock (and oceans, if they existed) of the Earth? The answer comes from studies of cratering on the Moon. These studies suggest that the Moon—and, therefore, all inner planets of the Solar System—underwent intense meteor bombardment between 4.0 and 3.85 Ga. Researchers speculate that this bombardment would have pulverized and/or melted almost all crust that had existed on Earth at the

FIGURE 11.1 This speculative painting depicts the Hadean Earth's surface as a magma ocean pummeled by meteorites. The Moon was much closer then, but might not have been visible through the dense atmosphere.



time, and would have destroyed the existing atmosphere and ocean. Only after the bombardment ceased could long-lasting crust, atmosphere, and oceans begin to form. The discovery of 3.85-Ga marine sedimentary rocks in Greenland suggests that the appearance of land and sea happened quite soon after bombardment ceased. What did the Earth's surface look like at 3.85 Ga? An observer probably would have found small, barren landmasses, spotted with volcanoes, poking up above an acidic sea. But both land and sea would have been obscured by murky, dense (CO_2- and SO_2-rich) air.

Take-Home Message

During the Hadean (4.57–3.85 Ga), the Earth differentiated and the Moon formed. A rock record of this eon doesn't exist, because our planet's surface may have been partially molten and was pulverized by meteorites.

11.3 The Archean Eon: Birth of the Continents and Life

Land Appears

The boundary between the **Archean** (from the Greek word for beginning) **Eon** and the Hadean Eon occurs at about 3.85 Ga. Effectively, this date marks the time at which substantial quantities of crustal rocks, including rocks that originated as marine sediments, formed. With the advent of the Archean, crust was locally cool and stable enough for rocks to survive and for isotopic clocks to start ticking.

Geologists still debate about whether plate tectonics in the form that occurs today operated in the early part of the Archean Eon. Most researchers picture an early Archean Earth with rapidly moving small plates, numerous volcanic island arcs, and abundant hot-spot volcanoes. Others propose that early Archean lithosphere was too warm and buoyant to subduct, and that plate tectonics could not have operated until the later part of the Archean or later; these authors argue that plume-related volcanism or some other process was the main source of new crust until the late Archean. Regardless of which model ultimately proves more accurate, it is clear that the Archean was a time during which significant volumes of new continental crust were generated.

What processes produced continental crust? According to one model, early crust formed from mafic igneous rocks that originally extruded or intruded at convergent plate boundaries and/or hot-spot volcanoes. Once formed, these rocks were too buoyant to be subducted, so when the arcs and plateaus collided with one another, they sutured together to form larger blocks that remained at the Earth's surface. The development of convergent plate boundaries along the margins of these blocks, and of rifts and hot spots within the blocks, led to production of flood basalts. Partial melting of basaltic crust yielded felsic and intermediate rocks. As collisions continued, the blocks coalesced into still larger proto-continents (**Fig. 11.2a, b**), which slowly cooled and became stronger. As a result of these processes, the first long-lived blocks of durable continental crust came into existence between 3.2 and 2.7 Ga, and by the end of the Archean Eon, about 80% of the Earth's continental area had formed (**Fig. 11.2c**).

A clear stratigraphic record of marine sediment deposition appears in remnants of Archean crust, indicating that oceans filled in the Archean and have existed ever since. Presumably, permanent oceans could survive only after the Earth's surface had cooled below the boiling point of water. Prior to that time, gaseous H_2O saturated the atmosphere—in fact, prior to ocean formation, H_2O and CO_2 were the dominant gases of the atmosphere. Once the oceans formed, however, the atmosphere lost most of its H_2O. And once liquid water existed, most atmospheric CO_2 dissolved into it, so CO_2 also went from being a major component of the atmosphere to being a trace component. Thus, the Archean saw the atmosphere change from being a foggy mixture of H_2O and CO_2 into being a transparent gas dominantly composed of nitrogen (N_2) gas. Since nitrogen is inert (it doesn't chemically react with or dissolve in other materials), it was left behind.

The First Life

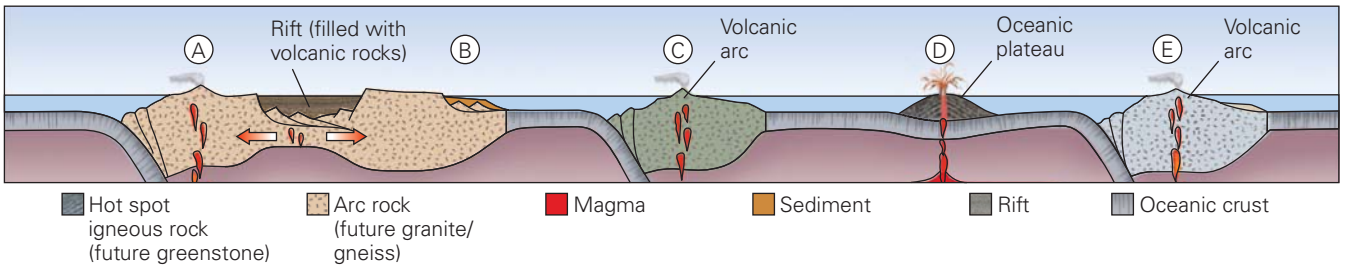
Clearly, the Archean Eon saw many firsts in Earth history. Not only did the first continents appear during the Archean, but probably also the first life.

The search for the earliest evidence of life continues to make headlines in the popular media. Most geologists currently conclude that life has existed on Earth since at least 3.5 Ga, and perhaps since 3.8 Ga, for rocks of this age contain chemical signatures of organisms. The oldest undisputed fossil forms of bacteria and archaea occur in 3.2-Ga rocks (**Fig. 11.3a**). (Shapes resembling such organisms occur in rocks as old as 3.5 Ga, but their identity remains less certain.) Archean strata at some localities contain **stromatolites**, distinctive layered mounds of sediment. Stromatolites that developed after about 3.2 Ga form because cyanobacteria secrete a mucus-like substance to which sediment settling from water sticks. As the mat gets buried, new cyanobacteria colonize the top of the sediment, building a mound upward (**Fig. 11.3b**); modern examples locally occur in shallow, tropical waters.

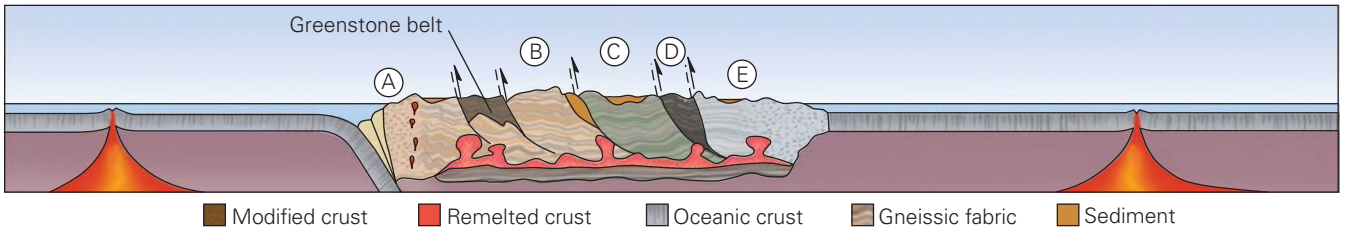
Did you ever wonder . . .
what is the oldest relict of life?

What specific environment on the Archean Earth served as the cradle of life? Laboratory experiments conducted in the 1950s led many researchers to think that life began in warm pools of surface water, beneath a methane- and ammonia-rich atmosphere streaked by bolts of lightning. More recent

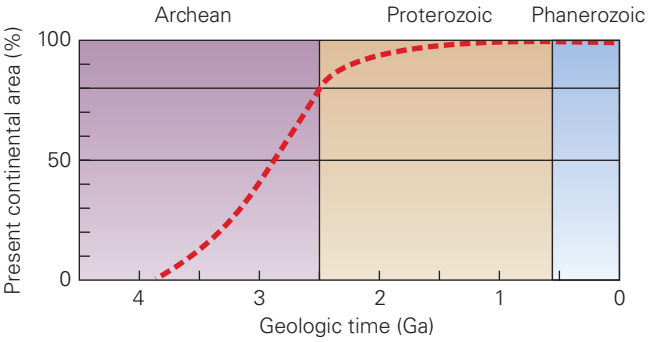
FIGURE 11.2 A model for crust formation during the Archean Eon.



(a) In the Archean, island arcs and hot-spot volcanoes built small blocks of buoyant crust. Rifting of these blocks may have produced flood basalts, and erosion of the blocks produced sediment. (Not to scale.)



(b) Buoyant blocks collided and sutured together, forming protocontinents. Melting at depth produced granite. Eventually, regions of crust cooled, stabilized, and became cratons. (Not to scale.)

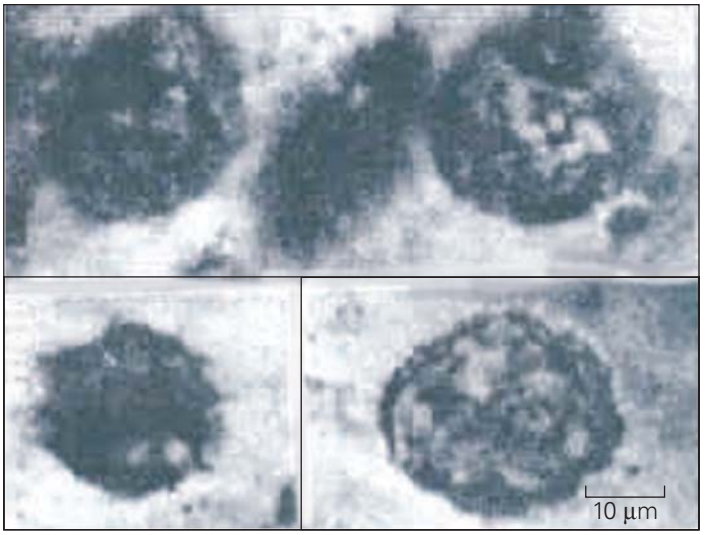


(c) The area of the Earth covered by continental crust increased over time. Most formed by the mid-Proterozoic.

researchers suggest instead that submarine hot-water vents, so-called black smokers, served as the hosts of the first organisms. These vents emit clouds of ion-charged solutions from which sulfide minerals precipitate and build chimneys. The earliest life in the Archean Eon may well have been thermophilic (heat-loving) bacteria or archaea that dined on pyrite at dark depths in the ocean alongside these vents. Later in the Archean, organisms evolved the ability to carry out photosynthesis, and moved into shallower, well lit water.

As the Archean Eon came to a close, the first continents had formed, and life had colonized not only the depths of the sea but also the shallow marine realm. Plate tectonics had commenced, continental drift was taking place, collisional mountain belts were forming, and erosion was occurring.

FIGURE 11.3 Archean life forms.



(a) These shapes in 3.2-Ga chert from South America are thought to be fossil bacteria or archaea.



(b) This weathered outcrop of 1.85-Ga dolostone near Marquette, Michigan, reveals layered mounds of stromatolites. Similar stromatolites also occur in exposures of Archean rocks.

Did you ever wonder . . .
has the atmosphere always been breathable?

The atmosphere was gradually accumulating oxygen, although probably this gas still accounted for only a very small percentage of the air; Archean air was unbreathable. The stage was set for another major change in the Earth System.

Take-Home Message

During the Archean (3.85–2.5 Ga), the first continental crust formed from colliding volcanic arcs and hot-spot volcanoes, oceans filled, the atmosphere changed, and life (archaea and bacteria) appeared.

11.4 The Proterozoic: The Earth in Transition

Growth of Continents

The **Proterozoic Eon** spans roughly 2 billion years, from about 2.5 Ga to the beginning of the Cambrian Period at 542 Ma—thus, it encompasses almost half of Earth's history. During Proterozoic time, Earth's surface environment changed from being an unfamiliar world of fast-moving plates, small continents, and an oxygen-poor atmosphere, to the more familiar world of slower plates, large continents, and an oxygen-rich atmosphere.

First, let's look at changes to the continents. New continental crust continued to form during the Proterozoic Eon, but at progressively slower rates—in fact, by the middle of the eon, over 90% of the Earth's continental crust had formed. As Archean proto-continents collided with each other and with volcanic island arcs and hot-spot volcanoes, still larger continents gradually assembled. Significantly, the interiors of these larger continents became isolated from heating by subduction-related igneous activity that happened along its margins. Interior regions, therefore, slowly cool and strengthen until they become very rigid and durable. Such a region of cold, relatively stable continental crust is called a **craton**. All cratons that exist today had formed by about 1 Ga (Fig. 11.4); therefore, crust in cratons (the old parts of continents) ranges from about 3.85 Ga to about 1 Ga.

To understand the character of a craton, let's examine North America's craton a bit more closely. We see that it consists of two regions (see Fig. 9.24). Throughout the **shield**, outcrops expose Precambrian "basement," which consists of igneous and metamorphic rocks older than about 1 Ga. The landscape of the shield tends to have fairly low relief—there are small hills and valleys, but no dramatic mountain ranges. Most of North America's shield lies in Canada, so geologists refer to it as the Canadian Shield. Throughout the **cratonic platform**, which surrounds the

FIGURE 11.4 Major crustal provinces of Earth. The black lines indicate the borders of regions underlain by Precambrian crust. Shields are regions where broad areas of Precambrian rocks are exposed.

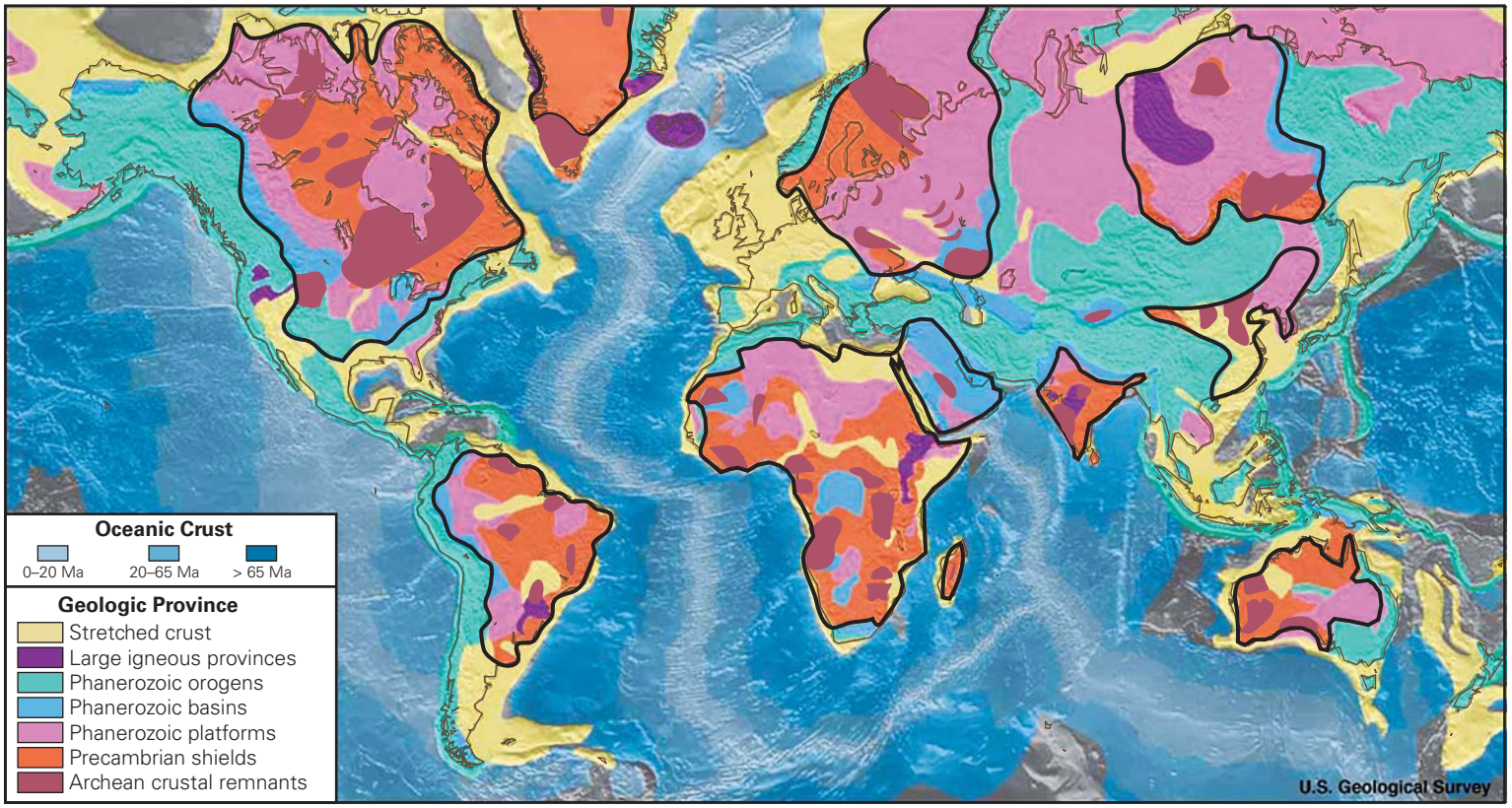
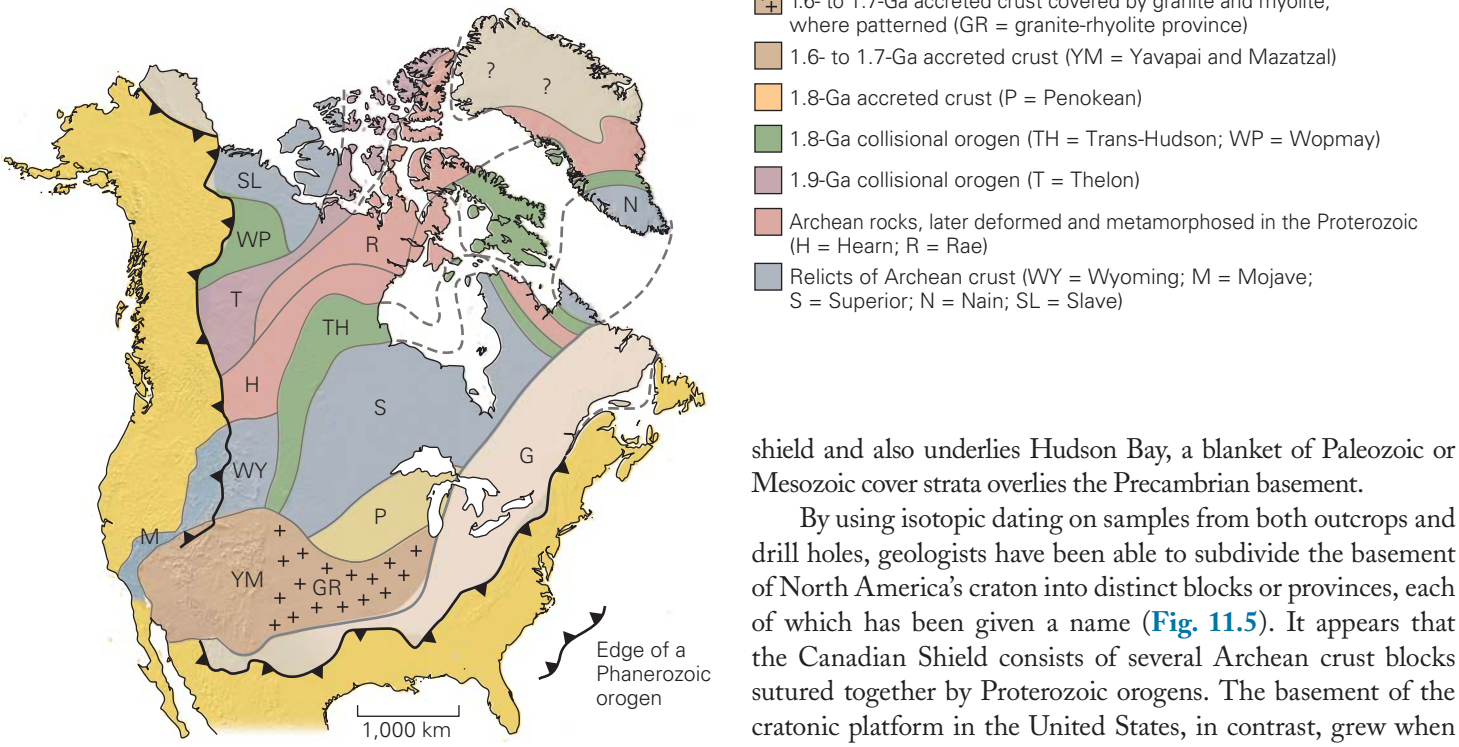


FIGURE 11.5 The North American craton consists of a collage of different belts and blocks stitched together during collisional and accretionary orogenies of Precambrian time.



shield and also underlies Hudson Bay, a blanket of Paleozoic or Mesozoic cover strata overlies the Precambrian basement.

By using isotopic dating on samples from both outcrops and drill holes, geologists have been able to subdivide the basement of North America's craton into distinct blocks or provinces, each of which has been given a name (**Fig. 11.5**). It appears that the Canadian Shield consists of several Archean crust blocks sutured together by Proterozoic orogens. The basement of the cratonic platform in the United States, in contrast, grew when

FIGURE 11.6 Supercontinents in the late Precambrian.



(a) Rodinia formed around 1 Ga and lasted until about 700 Ma. North America and Greenland together comprise Laurentia.



(b) According to one model, by 570 Ma Rodinia had broken apart; continents that once lay to the west of Laurentia ended up to the east of Africa. The resulting supercontinent, Pannotia, broke up soon after it formed.

a series of volcanic island arcs and continental slivers "accreted" (attached) to the margin of the Canadian Shield between 1.8 and 1.6 Ga. In the Midwest, granite plutons intruded much of this accreted region, and rhyolite ash flows covered it, between 1.5 and 1.3 Ga.

Successive collisions ultimately brought together most continental crust on Earth into a single supercontinent, named **Rodinia**, by around 1 Ga. The last major collision during the formation of Rodinia produced a large orogen called the Grenville orogen. If you look at a popular (though not universally accepted) reconstruction of Rodinia, you can identify the crustal provinces that would eventually become the familiar continents of today (**Fig. 11.6a**).

Several studies suggest that sometime between 800 and 600 Ma, Rodinia "turned inside out," in that Antarctica, India, and Australia broke away from western North America and swung around and collided with the future South America, possibly forming a short-lived supercontinent that some geologists refer to as Pannotia (**Fig. 11.6b**).

The map of the Earth clearly changed radically during the Proterozoic. But that's not all that changed—fossil evidence suggests that this eon also saw important steps in the evolution of life. When the Proterozoic began, most life was *prokaryotic*, meaning that it consisted of single-celled organisms (archaea and bacteria) without a nucleus. Though studies of chemical fossils hint that *eukaryotic* life, consisting of cells that have nuclei, originated as early as 2.7 Ga, the first possible body fossil of a eukaryotic organism occurs in 2.1-Ga rocks, and abundant body fossils of eukaryotic organisms can be found only in rocks younger than about 1.2 Ga. Thus the proliferation of eukaryotic life, the foundation from which complex organisms eventually evolved, took place during the Proterozoic.

The last half-billion years of the Proterozoic Eon saw the remarkable transition from simple organisms into complex ones. Ciliate protozoans (single-celled organisms coated with fibers that give them mobility) appear at about 750 Ma. A great leap forward in complexity of organisms occurred during the next 150 million years of the eon, for sediments deposited perhaps as early as 620 Ma and certainly by 565 Ma contain several types of multicellular organisms that together constitute the **Ediacaran fauna**, named for a region in southern Australia where fossils of these organisms were first found. Ediacaran species survived into the beginning of the Cambrian before becoming extinct. Their fossil forms suggest that some of these invertebrate organisms resembled jellyfish, while others resembled worms (**Fig. 11.7a**).

The evolution of life played a key role in the evolution of Earth's atmosphere. Before life appeared, there was hardly any free oxygen (O_2) in the atmosphere. With the appearance of photosynthetic organisms, oxygen began to enter the atmosphere. But it was not until about 2.4 Ga that the concentration of oxygen in the atmosphere increased dramatically. This event, called the **great oxygenation event**, happened when other environments were no longer able to absorb or dissolve the oxygen produced by organisms, so the oxygen began to accumulate as a gas in air. As a result, the oceans became oxidizing environments that, for reasons described in chemistry books, could no longer contain large quantities of dissolved iron. Between 2.4 Ga and 1.8 Ga, huge amounts of iron settled out of the ocean to form colorful sedimentary beds known as **banded iron formation** (BIF). BIF consists of alternating layers of iron oxide minerals (hematite or magnetite) and jasper (red chert) as illustrated by the chapter opening photo.

Radical climate shifts occurred on Earth at the end of the Proterozoic Eon. Specifically, accumulations of glacial sediments occur worldwide in late Proterozoic stratigraphic sequences. What's strange about the occurrence of these sediments is that they can be found even in regions that were located at the equator during these times (**Fig. 11.7b**). This observation implies that the *entire* planet was cold enough for glaciers to form at the end of the Proterozoic. Geologists still are debating the history of these global ice ages (see Chapter 18); in one model, glaciers covered the land and perhaps the entire ocean surface froze, resulting in **snowball Earth** (**Fig. 11.7c**). The shell of ice cut off the oceans from the atmosphere, causing oxygen levels in the sea to drop drastically, so many life forms died off. What brought an end to snowball Earth conditions? According to one model, the icy sheath also prevented atmospheric CO_2 from dissolving in seawater, but it did not prevent volcanic activity from continuing to add CO_2 to the atmosphere. Earth would have remained a snowball forever, were it not for the addition of volcanic CO_2, a greenhouse gas that traps heat in the atmosphere much as glass panes trap heat in a greenhouse (see Chapter 19). As the CO_2 concentration increased, Earth warmed up and eventually the glaciers melted.

Did you ever wonder . . .
have the oceans ever frozen over entirely?

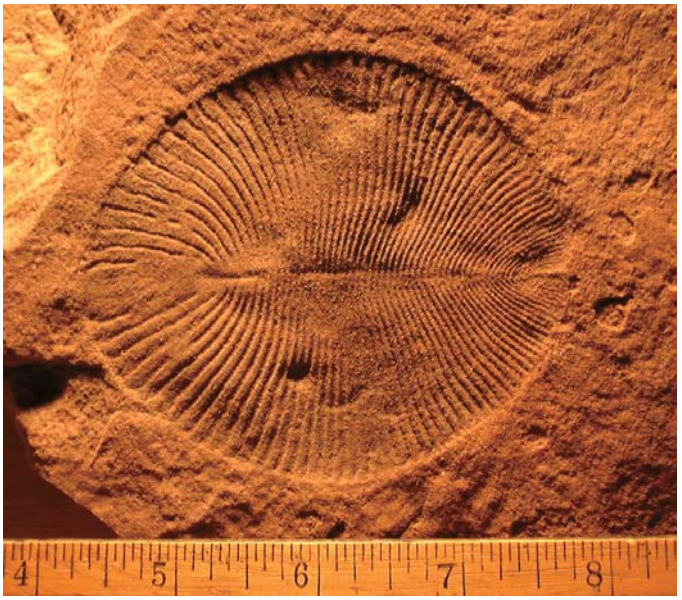
Introducing the Phanerozoic Eon

As the Proterozoic came to a close, Earth's climate warmed and continents drifted apart—life evolved and diversified to occupy the new environments that formed. Over a relatively short period of time, shells appeared and the fossil record

became much more complete. This event defines the end of the Proterozoic Eon and therefore, of the Precambrian, and the start of the Phanerozoic Eon. Of note, geologists recognized the siginificance of this event long before they could assign it a numerical age (currently 542 Ma).

The **Phanerozoic Eon** consists of three eras—the Paleozoic (Greek for ancient life), the Mesozoic (middle life), and the Cenozoic (recent life). Geologists have divided the Mesozoic and Cenozoic each into three periods and the Paleozoic into six periods. In the sections that follow, we consider changes in the map of our planet's surface (its *paleogeography*), as manifested by the distribution of continents, seas, and mountain belts, as well as life evolution that happened during the three eras.

FIGURE 11.7 Major changes in the Earth System during the Proterozoic Eon.



(a) *Dicksonia*, a fossil of the Ediacaran fauna. These complex, soft-bodied marine organisms appeared in the late Proterozoic.



(b) Layers of Proterozoic glacial sediment crop out in Africa, indicating that low-latitude landmasses were glaciated during the Proterozoic.

Take-Home Message

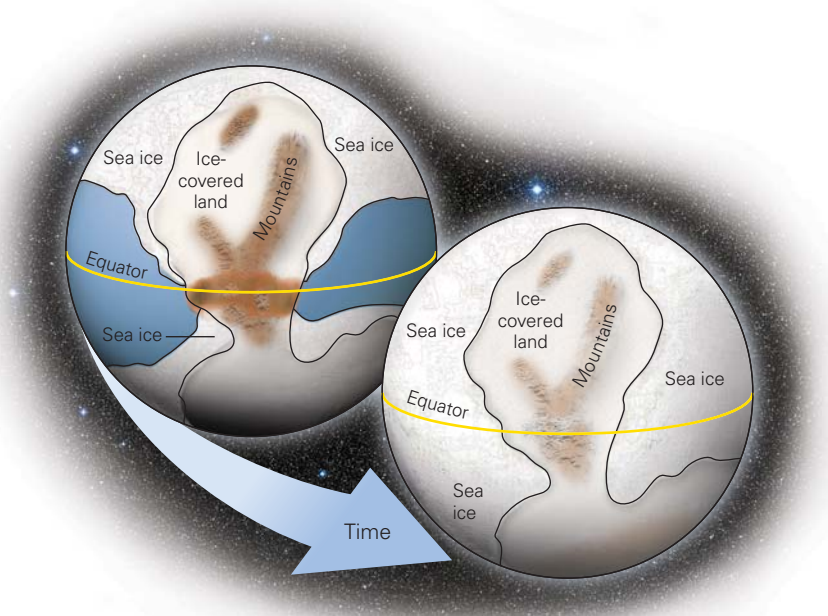
During the Proterozoic (2.5–0.54 Ga), cratons formed and then sutured together to form continents and, eventually, supercontinents, which later rifted apart. Multicellular organisms appeared, and the atmosphere began to accumulate significant oxygen.

11.5 The Paleozoic Era: Continents Reassemble, and Life Gets Complex

The Early Paleozoic Era (Cambrian–Ordovician Periods, 542–444 Ma)

Paleogeography. At the beginning of the Paleozoic Era, Pannotia broke up, yielding smaller continents including **Laurentia** (composed of North America and Greenland), **Gondwana** (South America, Africa, Antarctica, India, and Australia), Baltica (Europe), and Siberia (**Fig.11.8a**). New passive-margin basins formed along the edges of these new continents.

In addition, sea level rose, so that vast areas of continental interiors were flooded with shallow seas called **epicontinental seas** (**Fig. 11.8b**). These regions are now cratonic platforms. In many places, water depths in epicontinental seas reached only

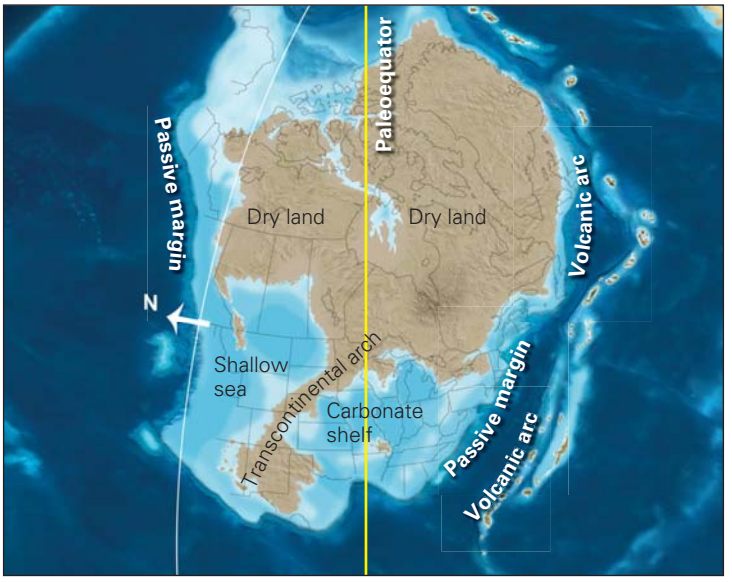


(c) This planet may have frozen over completely to form "snowball Earth." Glaciers first grew on land, and eventually the sea surface froze over.

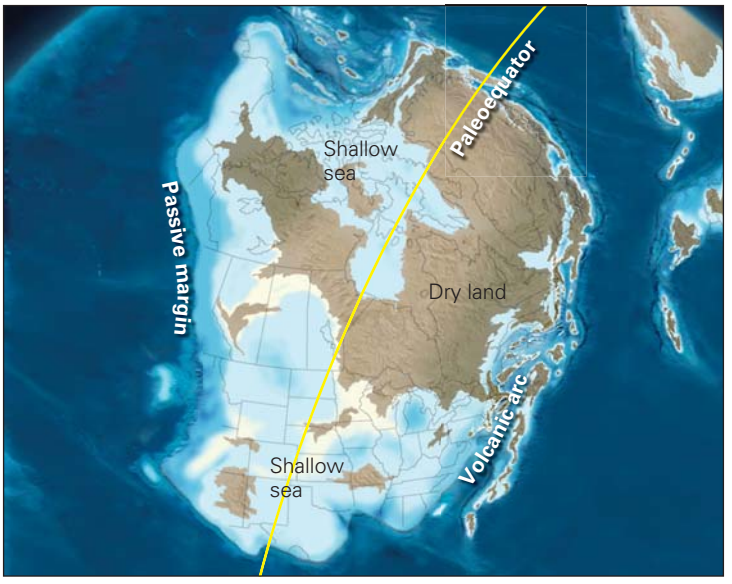
FIGURE 11.8 Land and sea in the early Paleozoic Era.



(a) The distribution of continents in the Cambrian Period (510 Ma), as viewed looking down on the South Pole.



(b) A paleogeographic map of North America shows the regions of dry land and shallow sea in the Late Cambrian Period.



(c) During the Middle Ordovician Period, shallow seas covered much of North America. A volcanic arc that formed off the east coast collided with the continent.

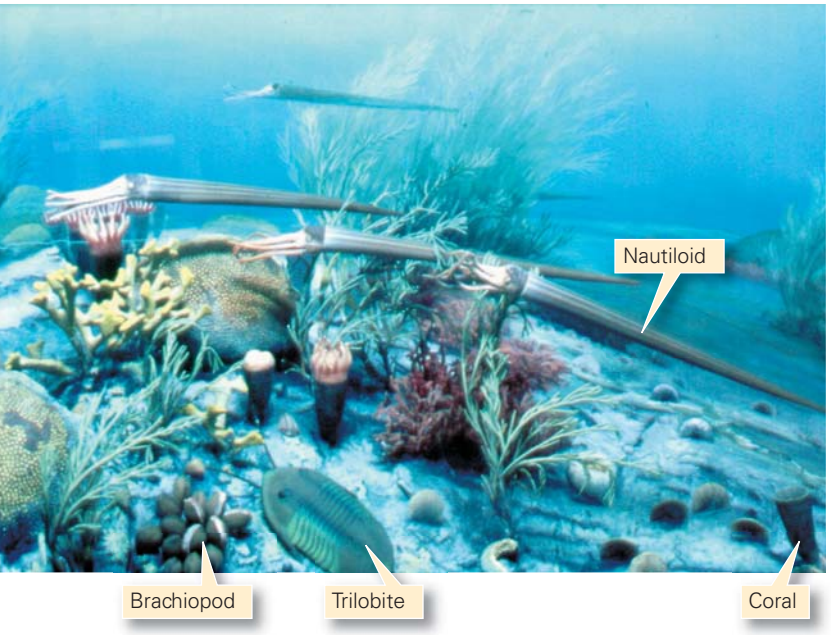
a few meters, creating a well-lit marine environment in which life abounded. Deposition in these seas, therefore, yielded layers of fossiliferous sediment. Sea level, however, did not stay high for the entire early Paleozoic Era; regressions and transgressions took place, the former marked by unconformities and the latter by accumulations of sediment. The layer cake of strata in the Grand Canyon is rock formed from such sediment.

The geologically peaceful world of the early Paleozoic Era in Laurentia abruptly came to a close in the Middle Ordovician Period, for at this time its eastern margin rammed into a volcanic island arc and other crustal fragments. The resulting collision, called the Taconic orogeny, deformed and metamorphosed strata of the continent's margin and produced a mountain range in what is now the eastern part of the Appalachians (**Fig. 11.8c**).

Life evolution. The fossil record indicates that soon after the Cambrian began, life underwent remarkable diversification. This event, which paleontologists refer to as the **Cambrian explosion**, took several million years. What caused this event? No one can say for sure, but considering that it occurred roughly at the time a supercontinent broke up, it may have had something to do with the production of new ecological niches and the isolation of populations that resulted when small continents formed and drifted apart.

The first animals to appear in the Cambrian Period had simple tube- or cone-shaped shells, but soon thereafter, the shells became more complex. Shells on other organisms may have evolved as a means of protection against predation by organisms such as conodonts, small, eel-like organisms with hard parts that resemble teeth. By the end of the Cambrian, trilobites were grazing the sea floor. Trilobites shared the environment with mollusks, brachiopods, nautiloids, gastropods, graptolites, and echinoderms (**Fig. 11.9**; see Interlude E). Thus, a complex food chain arose, which included plankton, bottom feeders, and at the top, predators. Many of the organisms crawled over or swam around reefs composed of mounds of sponges with mineral skeletons. The Ordovician Period saw the first crinoids and the first vertebrate animals, jawless fish. At the end of the Ordovician, mass extinction took place, perhaps because of the brief glaciation and associated sea-level lowering of the time.

FIGURE 11.9 A museum diorama illustrates what early Paleozoic marine organisms may have looked like.

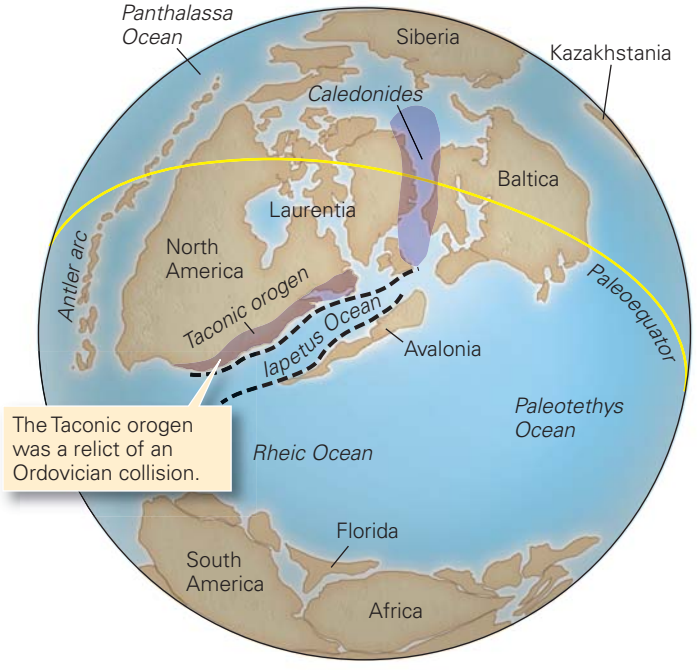


The Middle Paleozoic Era (Silurian–Devonian Periods, 444–359 Ma)

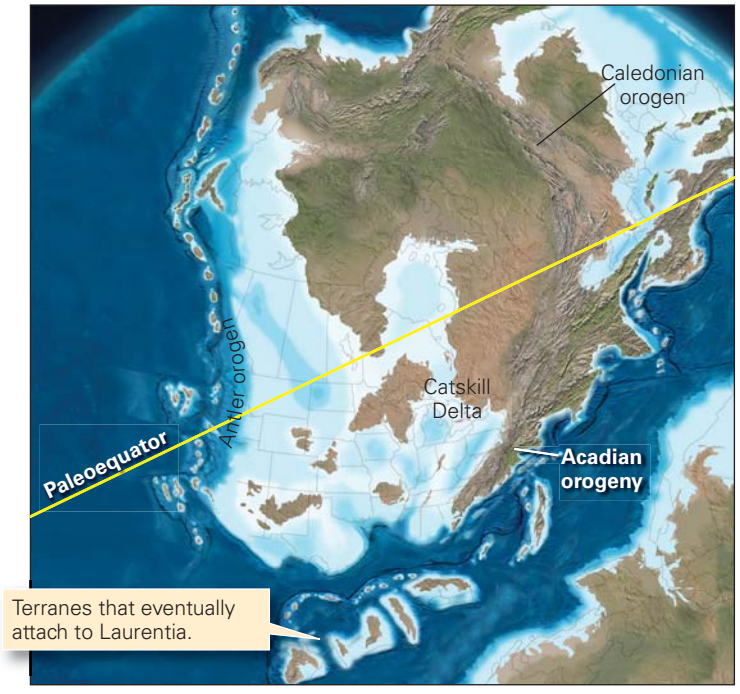
Paleogeography. As the world entered the Silurian Period, global climate warmed, sea level rose, and the continents flooded once again. In some places, where water in the epicontinental seas was clear and could exchange with water from the oceans, huge reef complexes grew, forming a layer of fossiliferous limestone on the continents. Also, distinct orogenies took place, yielding new mountain belts during the middle Paleozoic Era. For example, collisions on the eastern side of Laurentia during Silurian and Devonian time produced the Caledonian orogen (affecting eastern Greenland, western Scandinavia, and Scotland) and the Acadian orogen in the region that is now the Appalachians (Fig. 11.10a).

Throughout much of the middle Paleozoic, the western margin of North America continued to be a passive-margin

FIGURE 11.10 Paleogeography and fossils of Silurian and Devonian time.



(a) During the Silurian and Devonian Periods, Laurentia collided with Baltica, Avalonia, and South America in succession, as oceans in between were consumed. The Antler arc formed off the west coast.



(b) During the Devonian Period, the Acadian orogeny shed sediments into a shallow sea to form the Catskill Delta. The Antler orogen developed in the west.



(c) A Late Devonian fossil skeleton of *Tiktaalik*; this lobe-finned fish was one of the first animals to walk on land.

basin. Finally, in the Late Devonian, the quiet environment of the west-coast passive margin ceased, possibly because of a collision with an island arc. This event, known as the Antler orogeny, was the first of many orogenies to affect the western margin of the continent. The Caledonian, Acadian, and Antler orogenies all shed deltas of sediment onto the continents; these deposits formed thick successions of red beds, such as those visible today in the Catskill Mountains (Fig. 11.10b).

Life evolution. Life on Earth underwent radical changes in the middle Paleozoic Era. In the sea, new species of trilobites, gastropods, crinoids, and bivalves replaced species that had disappeared during the mass extinction at the end of the Ordovician Period. On land, vascular plants with woody tissues, seeds, and veins (for transporting water and food) rooted for the first time. With the evolution of veins and wood, plants could grow much larger, and by the Late Devonian Period the land surface hosted swampy forests with tree-sized relatives of club mosses and ferns. Also at this time, spiders, scorpions, insects, and crustaceans began to exploit both dry-land and freshwater habitats, and jawed fish such as sharks and bony fish began to cruise the oceans. Finally, at the very end of the Devonian Period, the first amphibians crawled out onto land and inhaled air with lungs (Fig. 11.10c).

The Late Paleozoic Era (Carboniferous–Permian Periods, 359–251 Ma)

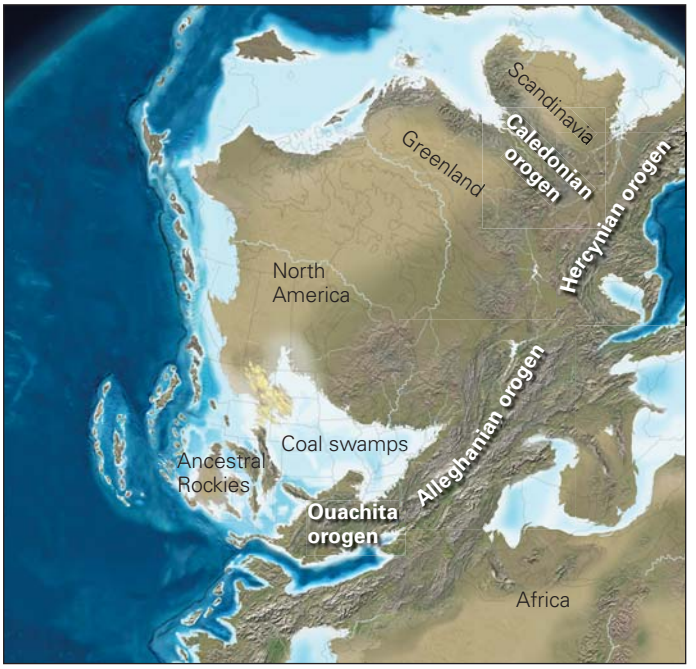
Paleogeography. The climate cooled significantly in the late Paleozoic. Seas gradually retreated from the continents, so that during the Carboniferous Period, regions that had hosted the limestone-forming reefs of epicontinental seas now became coastal areas and river deltas in which sand, shale, and organic debris accumulated. In fact, during the Carboniferous Period, Laurentia lay near the equator, so it enjoyed tropical and semitropical conditions that favored lush growth in swamps. This growth left thick piles of plant debris that transformed into coal after burial. Much of Gondwana and Siberia, in contrast, lay at high latitudes, and by the Permian Period became covered by ice sheets.

The late Paleozoic Era also saw a succession of continental collisions, culminating in the formation of a single supercontinent, **Pangaea** (Fig. 11.11a). The largest collision occurred during Carboniferous and Permian time, when Gondwana rammed into Laurentia and Baltica, causing the Alleghanian orogeny of North America (Fig. 11.11b). During this event, the final stage in the development of the Appalachians, eastern North America rammed against northwestern Africa, and what is now the Gulf Coast region of North America squashed against the northern margin of South America. A vast mountain

FIGURE 11.11 Paleogeography at the end of the Paleozoic Era.

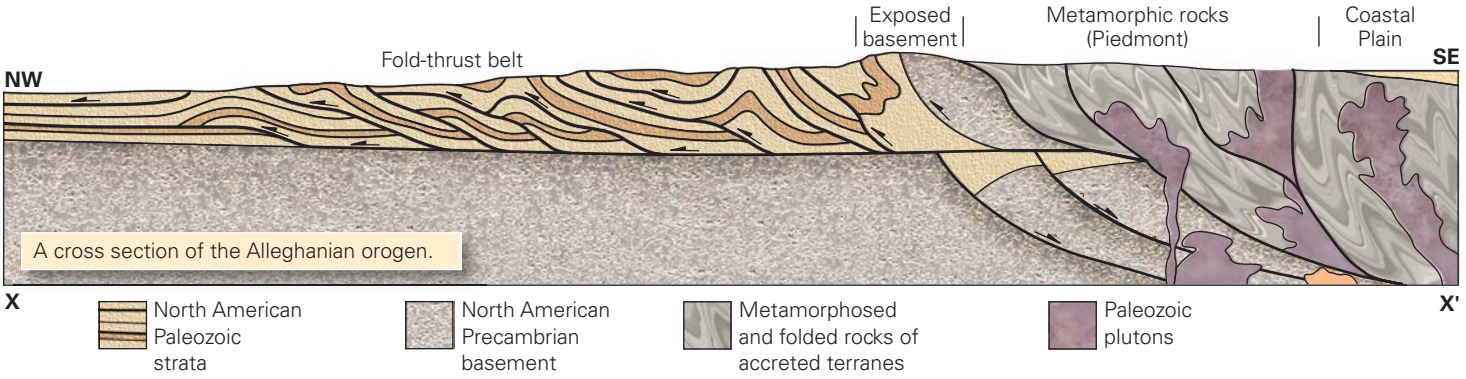


(a) At the end of the Paleozoic, almost all land had combined into a single supercontinent called Pangaea.



(b) During the Alleghanian and Hercynian orogenies, a huge mountain belt formed. The Caledonian orogen had formed earlier. Coal swamps bordered interior seas, and the Ancestral Rockies rose.

FIGURE 11.12 Features of the Appalachian Mountains in the eastern United States.



In the fold-thrust belt, strata have been pushed westward, and were folded and faulted. The Blue Ridge exposes a slice of Precambrian basement. Metamorphic and plutonic rocks underlie the Piedmont.

belt grew, in which deformation generated huge faults and folds. We now see the eroded remnants of rocks deformed during this event in the Appalachian and Ouachita Mountains. Along the continental side of the range, a wide band of deformation called the Appalachian fold-thrust belt formed (Fig. 11.12). Movement on the faults displaced strata and resulted in the formation of large folds. At depth, the thrust faults merged with a near-horizontal sliding surface, called a detachment, just above the Precambrian basement.

Stresses generated during the Alleghanian orogeny were so strong that preexisting faults in the continental crust clear across North America became active again. The movement produced uplifts and sediment-filled basins in the Midwest and in the region of the present-day Rocky Mountains. Geologists refer to the late Paleozoic uplifts of the Rocky Mountain region as the **Ancestral Rockies**.

FIGURE 11.13 A museum diorama of a Carboniferous coal swamp includes a giant dragonfly, with a wingspan of about 1 m. The inset photo gives a sense of its size relative to a human.



The assembly of Pangaea involved a number of other collisions around the world as well. Notably, Africa collided with southern Europe to form the Hercynian orogen. Also, a rift or small ocean in Russia closed, leading to the uplift of the Ural Mountains, and parts of China along with other fragments of Asia attached to southern Siberia.

Life evolution. The fossil record indicates that during the late Paleozoic Era, plants and animals continued to evolve toward more familiar forms. In coal swamps, fixed-wing insects including huge dragonflies flew through a tangle of ferns, club mosses, and scouring rushes, and by the end of the Carboniferous Period insects such as the cockroach, with foldable wings, appeared (Fig. 11.13). Forests containing gymnosperms ("naked seed" plants such as conifers) and cycads (trees with a palm-like stalk and fern-like fronds) became widespread in the Permian Period. Amphibians and, later, reptiles populated the land. The appearance of reptiles marked the evolution of a radically new component in animal reproduction: eggs with a protective covering. Such eggs permitted reptiles to reproduce without returning to the water.

The late Paleozoic Era came to a close with a major mass-extinction event, during which over 95% of marine species disappeared. Why this event occurred remains a subject of debate. According to one hypothesis, the terminal Permian mass extinction occurred as a result of an episode of extraordinary volcanic activity in the region that is now Siberia; basalt sheets extruded during the event are known as the "Siberian traps." Eruptions could have clouded the atmosphere, acidified the oceans, and disrupted the food chain.

Take-Home Message

Breakup of the late Precambrian supercontinent ushered in the Paleozoic. During the Paleozoic, shallow seas covered continents, at times, and life diversified and moved onto land. As the eon ended, collisions led to the assembly of Pangaea.

11.6 The Mesozoic Era: When Dinosaurs Ruled

The Early and Middle Mesozoic Era (Triassic–Jurassic Periods, 251–145 Ma)

Paleogeography. Pangaea, the supercontinent formed at the end of the Paleozoic Era, existed for about 100 million years, until rifting commenced during the Late Triassic and Early Jurassic Periods and the supercontinent began to break up. By the end of the Jurassic Period, rifting had succeeded in splitting North America from Europe and Africa. The Mid-Atlantic Ridge formed, and the North Atlantic Ocean started to grow (Fig. 11.14).

According to the record of sedimentary rocks, Earth overall had a warm climate during the Triassic and Early Jurassic. But during the Late Jurassic and Early Cretaceous, the climate cooled. Pangaea's interior remained a nonmarine environment in which red sandstones and shales, now exposed in the spectacular cliffs of Zion National Park, were deposited. By the Middle Jurassic Period, sea level began to rise, and a shallow sea submerged much of the Rocky Mountain region.

On the western margin of North America, convergent-margin tectonics became the order of the day. Beginning with Late Permian and continuing through Mesozoic time, subduction generated volcanic island arcs and caused them, along with microcontinents and hot-spot volcanoes, to collide with North America. Thus, North America grew in land area by the accretion of crustal fragments on its western margin. Because these fragments consist of crust that formed elsewhere, not originally on or adjacent to the continent, geologists call them **exotic terranes**. From the end of the Jurassic through the Cretaceous Period, a major continental volcanic arc, the Sierran arc, grew on the western margin of North America itself; you'll learn more about this arc later.

FIGURE 11.14 Pangaea began to break up in the Triassic, and by Jurassic time, a narrow North Atlantic Ocean existed.

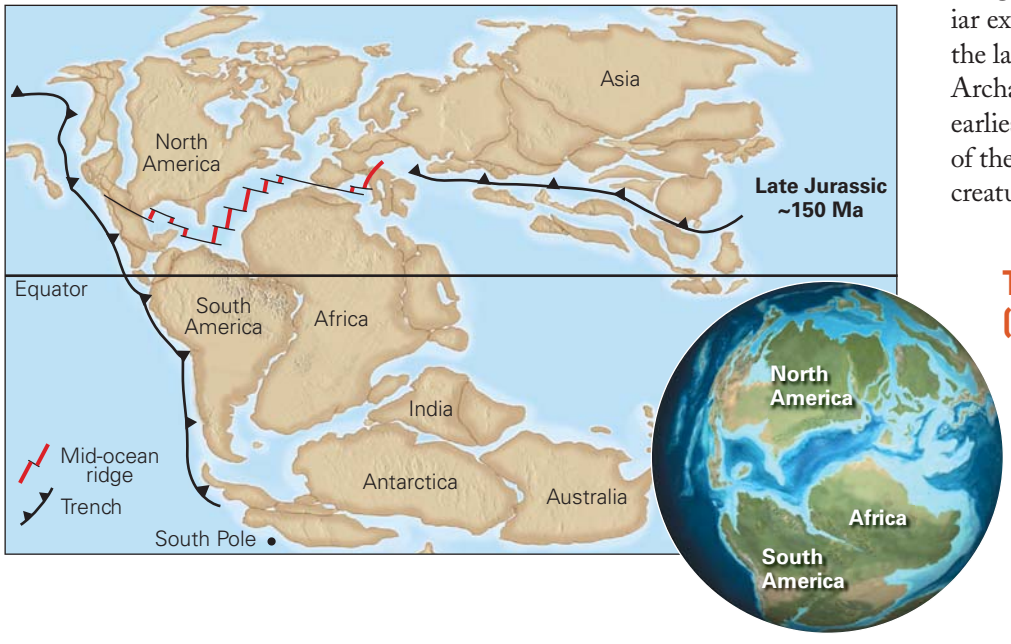
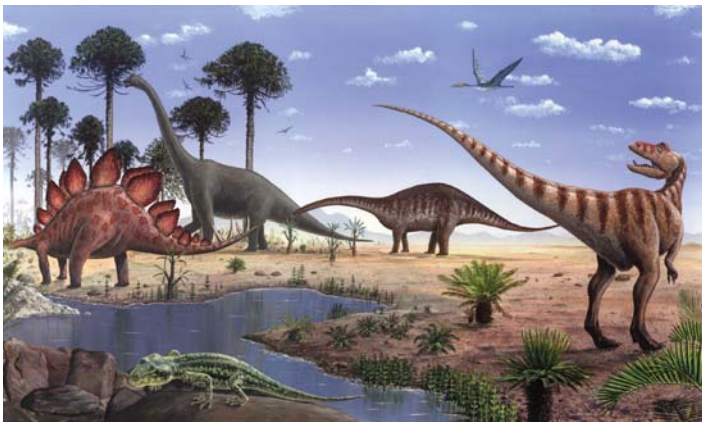


FIGURE 11.15 During the Jurassic, giant dinosaurs roamed the land. This painting shows several species.



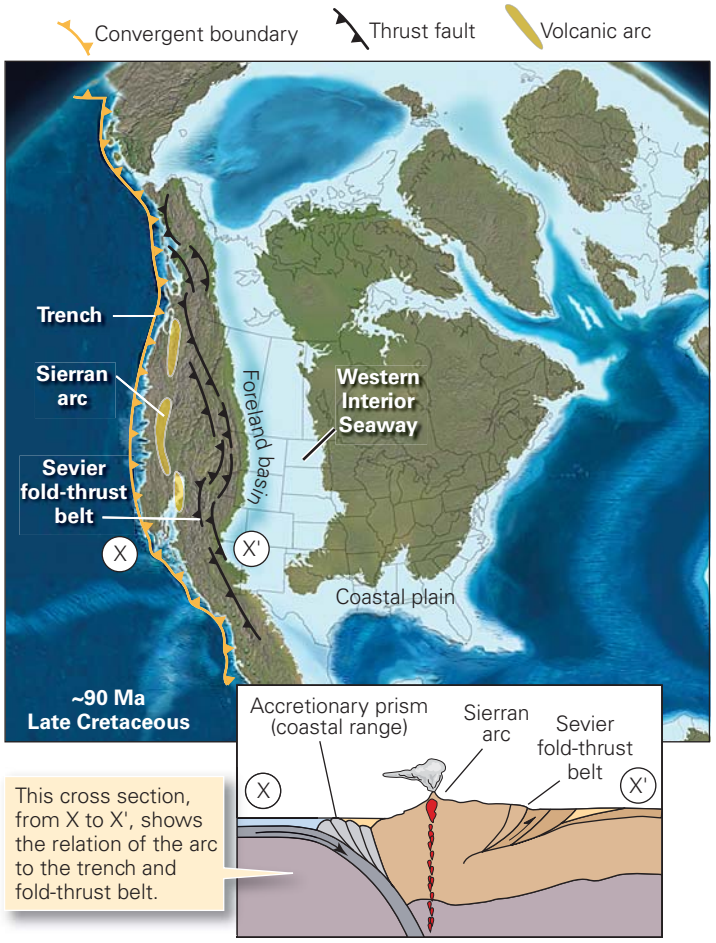
Life evolution. During the early Mesozoic Era, a variety of new plant and animal species appeared, filling the ecological niches left vacant by the Late Permian mass extinction. Reptiles swam in the oceans, and new kinds of corals became the predominant reef builders. On land, gymnosperms and reptiles diversified, and the Earth saw its first turtles and flying reptiles. And at the end of the Triassic Period, the first true dinosaurs evolved. Dinosaurs differed from other reptiles in that their legs were positioned under their bodies rather than off to the sides, and they were possibly warm-blooded. By the end of the Jurassic Period, gigantic sauropod dinosaurs (weighing up to 100 tons), along with other familiar examples such as stegosaurus, thundered across the landscape, and the first feathered birds, such as Archaepteryx, took to the skies (Fig. 11.15). The earliest ancestors of mammals appeared at the end of the Triassic Period, in the form of small, rat-like creatures.

Did you ever wonder . . .
when did the dinosaurs live?

The Late Mesozoic Era (Cretaceous Period, 145–65 Ma)

Paleogeography. During the Cretaceous Period, the Earth's climate continued to shift to warmer conditions, and sea level rose significantly, reaching levels that had not been attained for the previous 200 million years.

FIGURE 11.16 During the Late Cretaceous, a continental volcanic arc formed. A fold-thrust belt formed to the east, as did a transcontinental seaway.



Great seaways flooded most of the continents (**Fig. 11.16**). In fact, during the latter part of the Cretaceous Period, a shark could have swum from the Gulf of Mexico to the Arctic Ocean, or across much of western Europe.

The breakup of Pangaea continued through the Cretaceous Period, with the opening of the South Atlantic Ocean and the separation of South America and Africa from Antarctica and Australia. India broke away from Gondwana and headed rapidly northward toward Asia (**Fig. 11.17a, b**). Along the continental margins of the newly formed Mesozoic oceans, passive-margin basins developed that filled with great thicknesses of sediments.

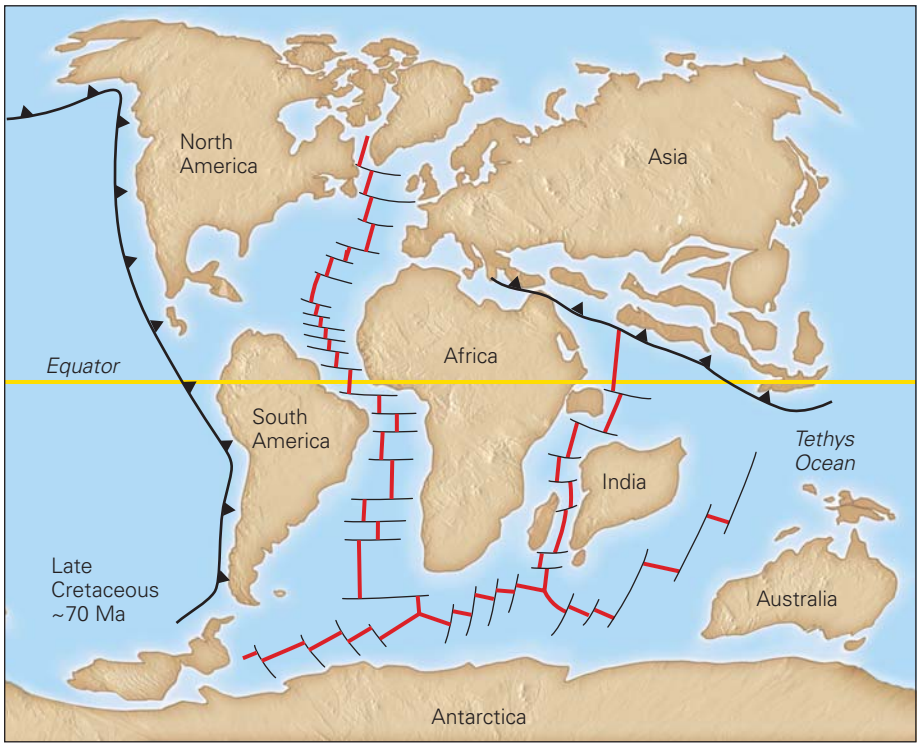
In western North America, the Sierran arc, a large continental volcanic arc that initiated at the end of the Jurassic Period, continued to be active. This arc resembled the present-day Andean arc of western South America. Though the volcanoes of the Sierran arc have long since eroded away, we can see their roots in the form of the plutons that now constitute the granitic batholith of the Sierra Nevada Mountains. Compressional stresses along the western North American convergent boundary activated large thrust faults east of the arc, an event geologists refer to as the Sevier orogeny. This orogeny produced a fold-thrust belt whose remnants you can see today in the Canadian Rockies and in western Wyoming (**Fig. 11.17c**).

At the end of the Cretaceous Period, continued compression along the convergent boundary of western North America caused slip on large faults in the region of Wyoming, Colorado, eastern Utah, and northern Arizona. In contrast to the faults of fold-thrust belts, these faults penetrated deep into the Precambrian rocks of the continent, and thus movement on them generated basement uplifts (**Fig. 11.17d**). Overlying layers of Paleozoic strata warped into large monoclines, folds whose shape resembles the drape of a carpet over a step. This event, which geologists call the **Laramide orogeny**, formed the structure of the present Rocky Mountains in the United States.

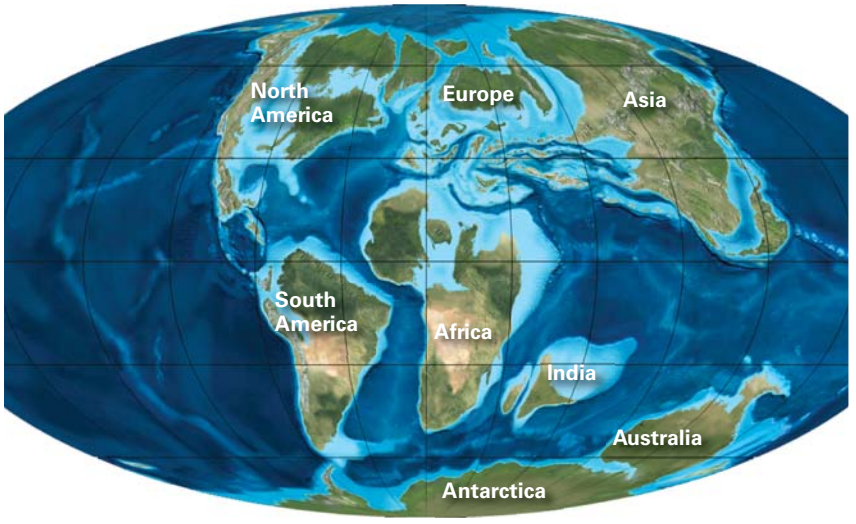
Geologists have determined that sea-floor spreading rates may have been as much as three times faster during the Cretaceous than they are today. As a result, more of the oceanic crust was younger and warmer than it is today, and since young sea floor lies at a shallower depth than does older sea floor (due to isostasy; see Interlude D), Cretaceous mid-ocean ridges occupied more volume than they do today. The extra volume of the ridges displaced sea water, causing sea level to rise. Also during the Cretaceous, huge submarine plateaus formed from basalts erupted at hot-spot volcanoes. The existence of these plateaus implies that particularly active mantle plumes, or **superplumes**, reached the base of the lithosphere. Growth of submarine plateaus displaced sea water and thus also contributed to sea-level rise. Volcanism associated with extra-rapid sea-floor spreading, as well as with submarine plateau growth, likely released CO_2 into the atmosphere. Geologists hypothesize that this increased atmospheric CO_2 concentration led to a global rise in atmospheric temperature. Rising temperatures would cause sea water to expand and polar ice sheets to melt, both phenomena that would make sea level go up even more. Considering all the phenomena that caused sea level to rise during the Cretaceous, it's no surprise that the continents flooded and that large epicontinental seas formed during this era.

Life evolution. In the seas of the late Mesozoic world, modern fish appeared and became dominant. In contrast with earlier fish, the new fish had short jaws, rounded scales, symmetrical tails, and specialized fins. Huge swimming reptiles and gigantic turtles (with shells up to 4 m across) preyed on the fish. On land, cycads largely vanished, and angiosperms (flowering plants), including hardwood trees, began to compete successfully with conifers for dominance of the forest. Dinosaurs reached their peak of success at this time, inhabiting almost all environments on Earth. Social herds of grazing dinosaurs roamed the plains, preyed on by the fearsome *Tyrannosaurus rex* (a Cretaceous, not a Jurassic, dinosaur, despite what Hollywood says!). Pterosaurs, with wingspans of up to 11 m,

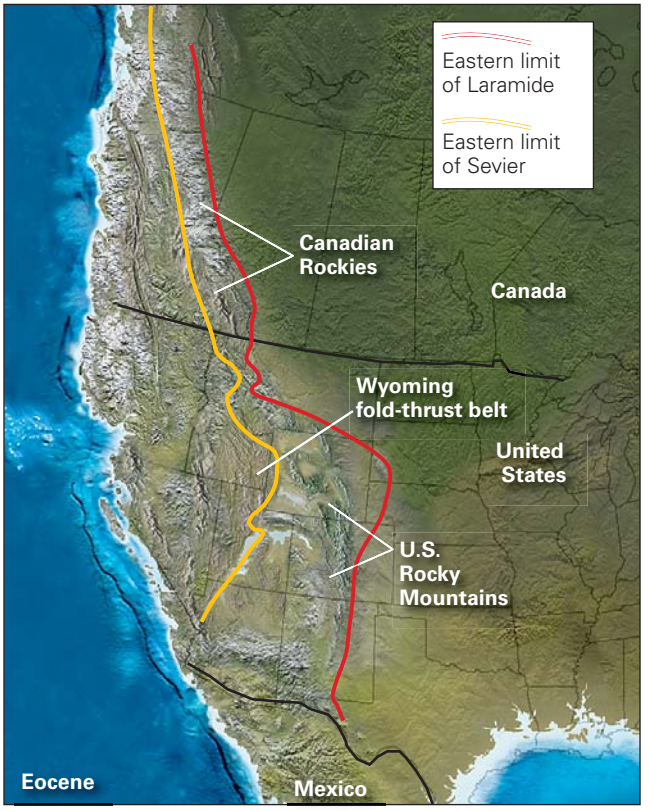
FIGURE 11.17 Paleogeography in Late Cretaceous through Eocene time.



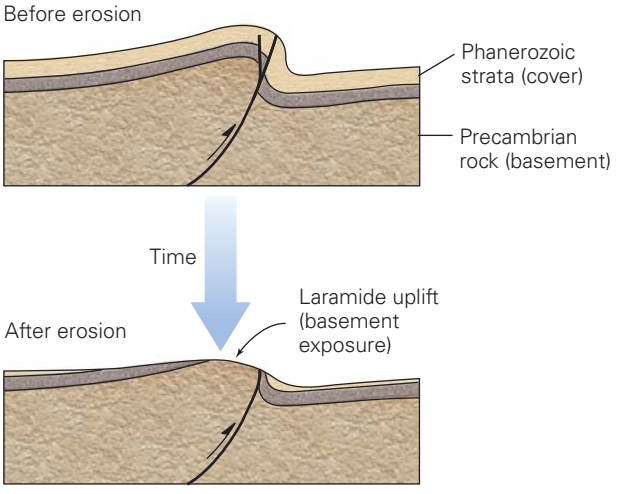
(a) By the Late Cretaceous Period, the Atlantic Ocean had formed, and India was moving rapidly northward to eventually collide with Asia.



(b) In this Late Cretaceous paleogeographic reconstruction, southern Europe and Asia are beginning to form from a collage of many crustal blocks.



(c) During the Laramide orogeny, deformation shifted eastward in the United States, moving from the Sevier belt to the Rocky Mountains, and the style of deformation changed.



(d) The Laramide orogeny produced "basement-cored uplifts." In these, faults lifted up blocks of basement, causing the overlying strata to bend into a stair-step-like fold.

soared overhead, and birds began to diversify. Mammals also diversified and developed larger brains and more specialized teeth, but for the most part, they remained small and rat-like.

The "K-T boundary event." Geologists first recognized the K-T boundary (*K* stands for Cretaceous and *T* for Tertiary) from 18th-century studies that identified an abrupt global change in fossil assemblages. Until the 1980s, most geologists assumed the faunal turnover took millions of years. But modern dating techniques indicate that this change happened almost instantaneously and that it represents a sudden mass extinction of most species on Earth. The dinosaurs, which had ruled the planet for over 150 million years, simply vanished, along with 90% of plankton species in the ocean and up to 75% of plant

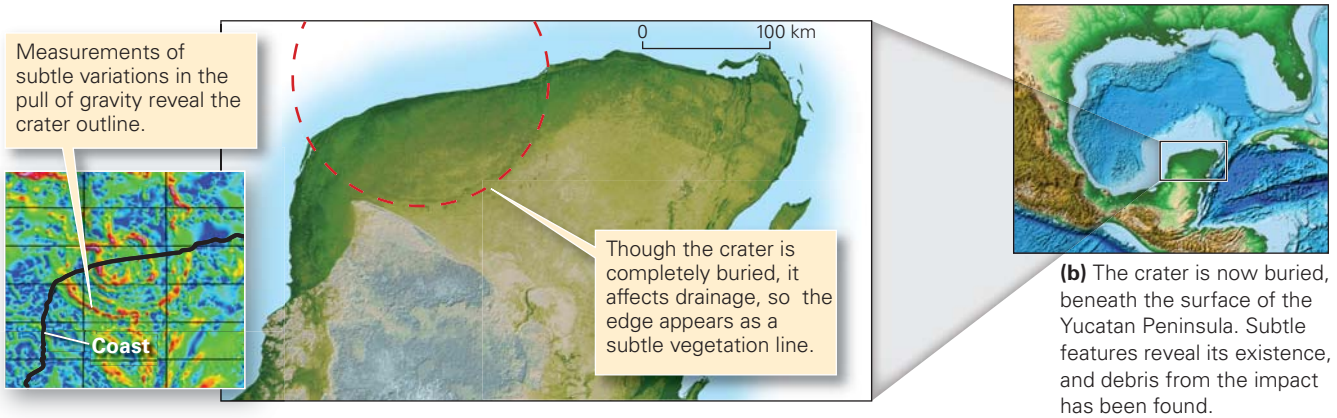
species. What kind of catastrophe could cause such a sudden and extensive mass extinction?

The cause of the K-T mass extinction remained a mystery until the late 1970s, when Walter Alvarez, an American geologist, and his colleagues examined a shale layer deposited exactly at the K-T boundary. They found that this shale contained relatively high concentrations of iridium, an element that comes primarily from meteorites. Further study showed that the clays of this age contained other unusual materials, such as tiny glass spheres formed when a spray of molten rock freezes, grains of coesite (a mineral that forms when intense shock waves pass through quartz), and even carbon from burned vegetation. All these features pointed to the occurrence of a huge meteorite impact at the time of the K-T boundary. Subsequently, geologists found a 100-km-diameter and 16-km-deep meteorite crater buried beneath younger strata of the Yucatan Peninsula in Mexico (**Fig. 11.18a, b**). Isotopic dating indicates that formation of the crater occurred at 65 ± 0.4 Ma, the time of the K-T boundary event. Because of its age and size, this crater, known as the Chicxulub crater, may be the grave of the deadly object whose impact with Earth eliminated so much life.

FIGURE 11.18 The Cretaceous-Tertiary impact. The aftermath probably caused extinction of the dinosaurs and other species.



(a) A meteorite with a diameter of ~13 km (8 miles) slammed into the Earth.



(b) The crater is now buried, beneath the surface of the Yucatan Peninsula. Subtle features reveal its existence, and debris from the impact has been found.

The impact caused so much destruction because it not only formed a crater, blasting huge quantities of debris into the sky, but probably also generated 2-km-high tsunamis that inundated the shores of continents and generated a blast of hot air that set forests on fire. The blast and the blaze together could have ejected so much debris into the atmosphere that for months there would have been perpetual night and winter-like cold. In addition, chemicals ejected into the air could have combined with water to produce acid rain. These conditions would cause photosynthesis to all but cease, and thus would break the food chain and trigger extinctions.

Take-Home Message

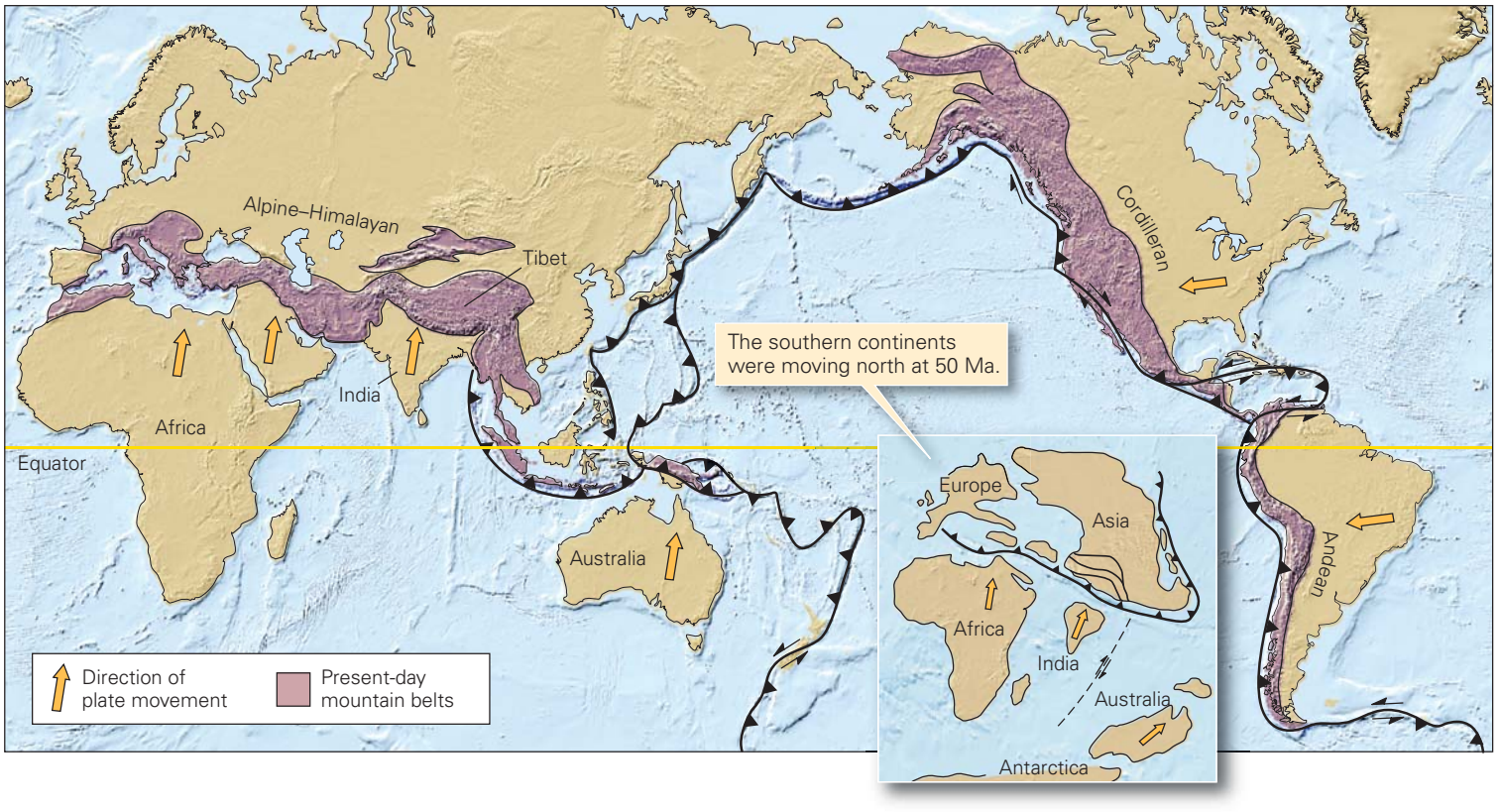
During the Mesozoic, dinosaurs roamed all continents. In North America, a convergent plate boundary formed along the west coast, eventually leading to the uplift of the Rocky Mountains. Rifting of Pangaea produced the Atlantic Ocean. A huge meteorite impact marks the end of the era.

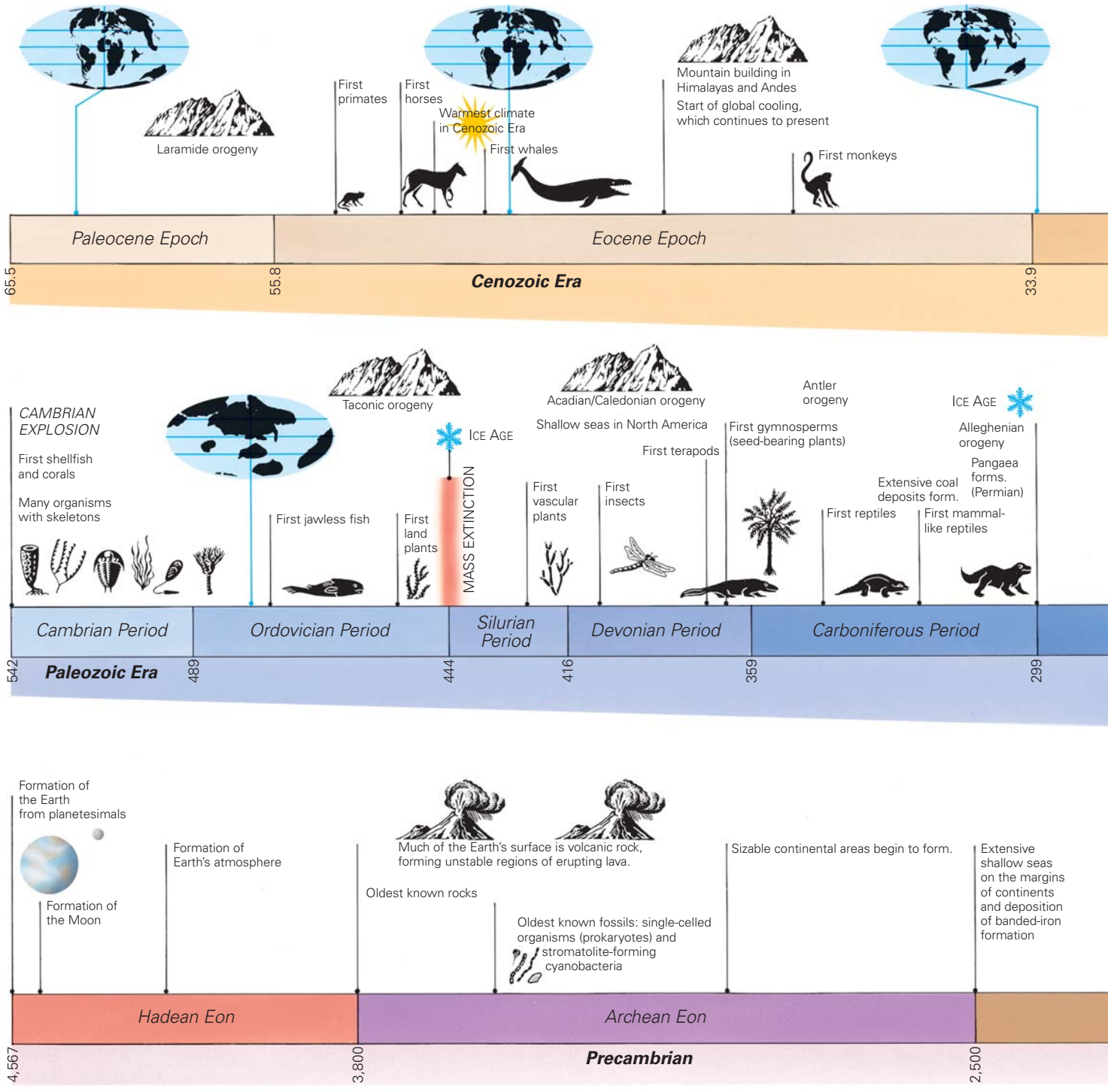
11.7 The Cenozoic Era: The Modern World Comes to Be

Paleogeography. During the last 65 million years, the map of the Earth has continued to change, gradually producing the configuration of continents and plate boundaries we see today. The final stages of the Pangaea breakup separated Australia from Antarctica and Greenland from North America, and formed the North Sea between Britain and continental Europe. The Atlantic Ocean continued to grow because of sea-floor spreading on the Mid-Atlantic Ridge, and thus the Americas have moved westward, away from Europe and Africa. Meanwhile, the continents that once constituted Gondwana drifted northward as the intervening Tethys Ocean was consumed by subduction (see Fig. 11.17). Collisions of the former Gondwana continents with the southern margins of Europe and Asia resulted in the formation of the largest orogenic belt on Earth today, the **Alpine-Himalayan chain** (Fig. 11.19). India and a series of intervening volcanic island arcs and microcontinents collided with Asia to form the Himalayas and the Tibetan Plateau to the north, while Africa along with some volcanic island arcs and microcontinents collided with Europe to produce the Alps.

As the Americas moved westward, convergent plate boundaries evolved along their western margins. In South America, convergent-boundary activity built the Andes, which remains an active orogen to the present day. In North America, convergent-boundary activity continued without interruption until about 40 Ma (the Eocene Epoch), yielding, as we have seen, the Laramide orogeny. Then, because of the rearrangement of plates off the western shore of North America, a transform

FIGURE 11.19 The two main active continental orogenic systems on the Earth today. The Alpine-Himalayan system formed when Africa, India, and Australia collided with Asia (inset). The Cordilleran and Andean systems reflect the consequences of convergent-boundary tectonism along the eastern Pacific Ocean.

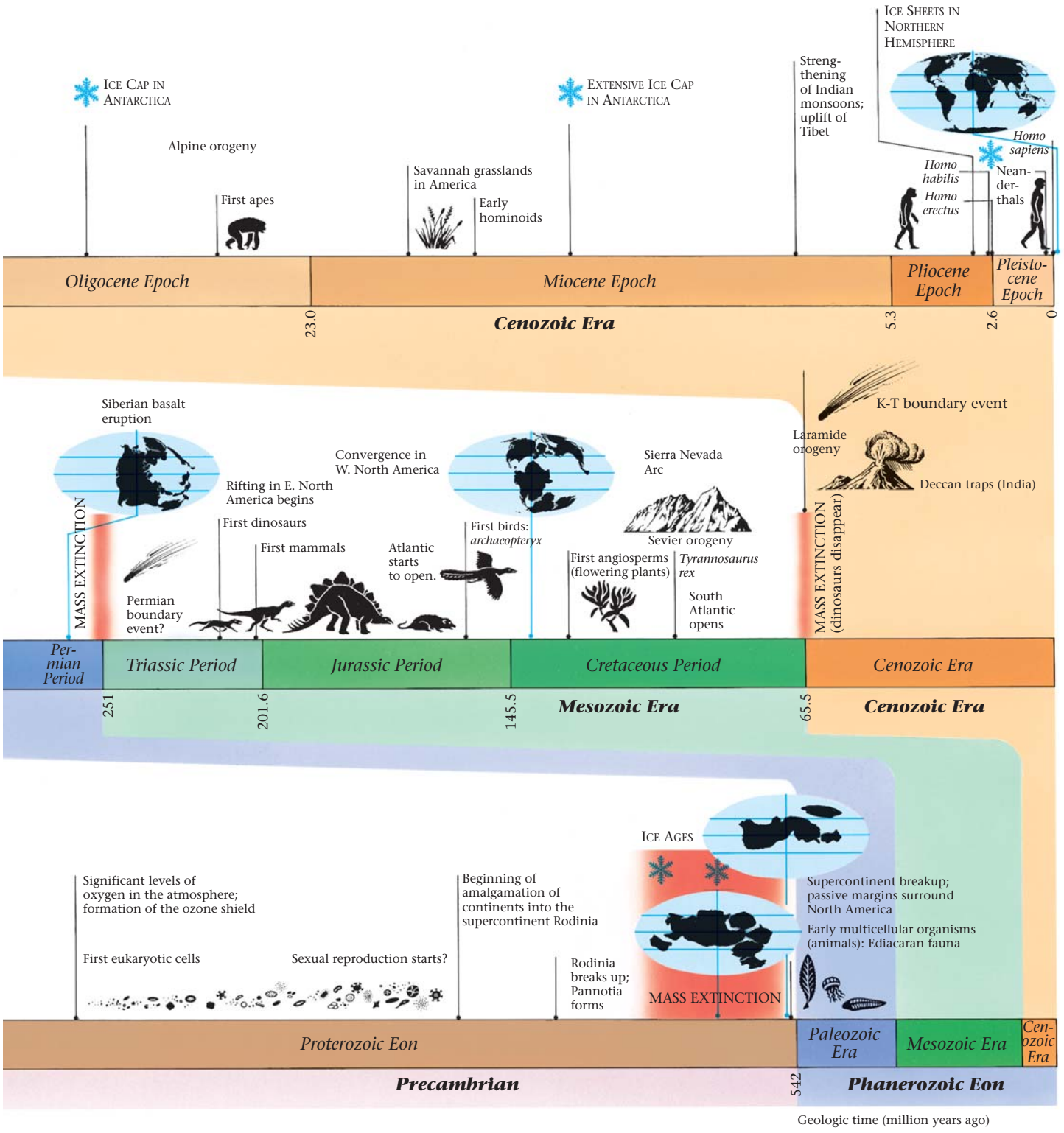




The Evolution of Earth

Earth has not had a static history; because of plate tectonics and its consequences (continental drift, sea-floor spreading, volcanism, and so on), the map of the Earth constantly changes. Distinct mountain-building events, or orogenies, have taken place during this process. The fossil record suggests that life first appeared within the first few hundred million years of our planet's existence, soon after a liquid-water ocean had accumulated; and like the planet itself, life has constantly changed ever since. The progressive change of the assemblage of species of life on Earth is called evolution.

The earliest life-forms were microscopic. By the end of the Precambrian, complex multicellular organisms had formed, and a burst of evolution at the Precambrian-Cambrian boundary yielded a diversity of invertebrates with shells. During the past half-billion years, several new major



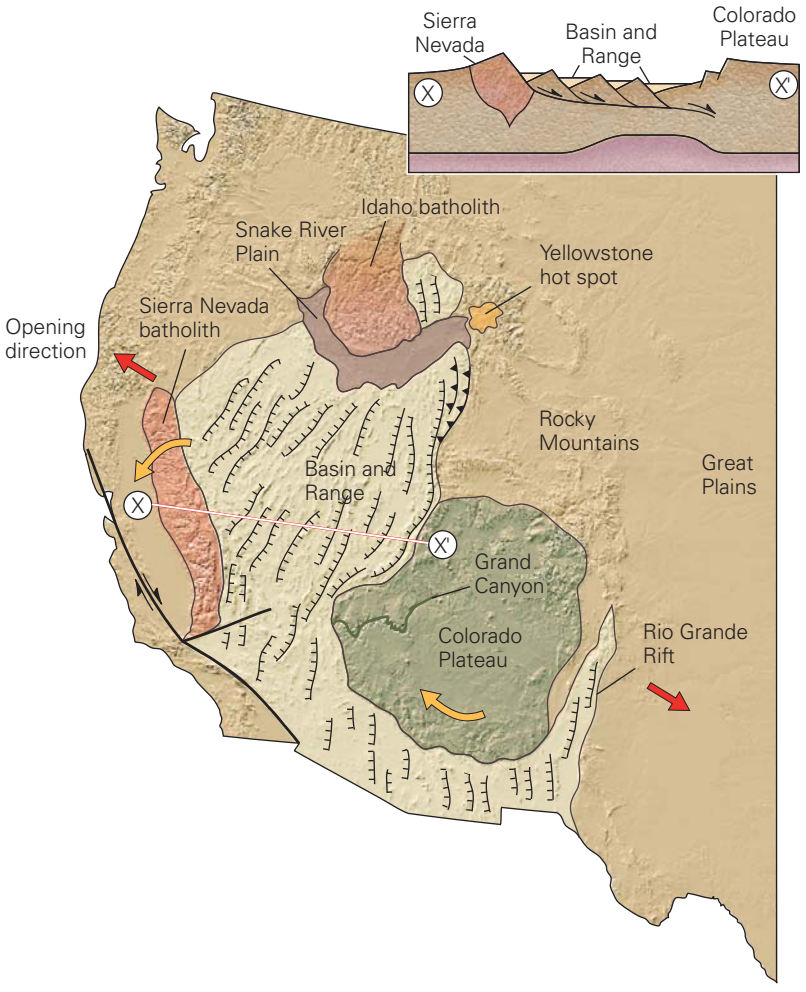
groups of organisms have appeared, and countless species have become extinct. Evidence suggests that evolution is not a continuous, gradual process, but occurs in pulses, separated by intervals of time during which the assemblage of species is fairly stable.

The last few hundred million years of Earth history have seen life leave the ocean and spread across the land. During the Mesozoic Era, dinosaurs roamed the Earth—then vanished abruptly 65 million years ago, perhaps as a result of a meteorite's colliding with the Earth. Since then, mammals have diversified into a great variety of species. And the last 100,000 years or so have witnessed the evolution of our own species, *Homo sapiens.* Considering the changes that people have brought about to the Earth System, the appearance of our species is clearly a major event in the history of the planet.

boundary replaced the convergent boundary in the western part of the continent by 25 Ma. When this happened, volcanism and compression ceased in western North America, the San Andreas Fault system formed along the coast of the United States, and the Queen Charlotte Fault system developed off the coast of Canada. Along the San Andreas and Queen Charlotte faults today, the Pacific Plate moves northward with respect to North America at a rate of about 6 cm per year. In the western United States, convergent-boundary tectonics continues only in Washington, Oregon, and northern California, where subduction of the Juan de Fuca Plate generates the volcanism of the Cascade volcanic chain.

As convergent tectonics ceased in the western United States south of the Cascades, the region began to undergo rifting (extension) in roughly an east-west direction. The result was the formation of the **Basin and Range Province**, a broad continental rift whose development has stretched the region to twice its original width (**Fig. 11.20**). The Basin and Range gained its name from its topography—the province contains long, narrow mountain ranges separated from each other by flat, sediment-filled basins. This topography formed when the crust of the region was broken up by normal faults (see Chapter 9). Blocks of crust above these faults slipped down and tilted. Crests of the tilted blocks form the ranges, and the depressions between them, which rapidly filled with sediment eroded from the ranges, became basins.

FIGURE 11.20 The Basin and Range Province is a rift. The inset shows a cross section along the red line.



The Basin and Range Province terminates just north of the Snake River Plain, the track of the hot spot that now lies beneath Yellowstone National Park. As North America drifts westward, volcanic calderas formed along the Snake River Plain; Yellowstone National Park straddles the most recent caldera (see Chapter 9).

Recall that in the Cretaceous Period, the world was relatively warm and sea level rose so that extensive areas of continents were submerged. During the Cenozoic Era, however, the global climate rapidly became cooler, and by the early Oligocene Epoch (~34 Ma), Antarctic glaciers reappeared for the first time since the Triassic. The climate continued to grow colder through the Late Miocene Epoch, leading to the formation of grasslands in temperate climates. About 2.5 Ma, the Isthmus of Panama formed, separating the Atlantic completely from the Pacific, changing the configuration of oceanic currents, perhaps leading the Arctic Ocean to freeze over.

During the overall cold climate of the past 2 million years, continental glaciers have expanded and retreated across northern continents at least 20 times, resulting in the **Pleistocene Ice Age** (**Fig. 11.21**). Each time the glaciers grew, sea level fell so much that the continental shelf became exposed to air. At times, a land bridge formed across the Bering Strait, west of Alaska, providing migration routes for animals and people from Asia into North America. A partial land bridge also formed from southeast Asia to Australia, making human migration to Australia easier. Erosion and deposition by the glaciers created much of the landscape we see today in northern temperate regions. About 11,000 years ago, the climate warmed, and we entered the interglacial time interval we are still experiencing today (see Chapter 18).

Life evolution. When the skies finally cleared in the wake of the K-T boundary catastrophe, plant life recovered, and soon forests of both angiosperms and gymnosperms grew. The grasses, which first appeared in the Cretaceous, spread across the plains in temperate and subtropical climates by the middle of the Cenozoic Era, transforming them into vast grasslands. The dinosaurs, except for their descendants the birds, were gone for good. Mammals rapidly diversified into a variety of forms to take their place. In fact, most of the modern groups of mammals that exist today originated at the beginning of the Cenozoic Era, giving this time the nickname Age of Mammals. During the latter part of the era, *huge* mammals appeared (such as mammoths, giant beavers, giant bears, and giant sloths), but these became extinct during the past 10,000 years, probably because of hunting by humans.

FIGURE 11.21 The maximum advance of the Pleistocene ice sheet in North America.



It was during the Cenozoic that our own ancestors first appeared. Ape-like primates diversified in the Miocene Epoch (about 20 Ma), and the first human-like primate appeared at about 4 Ma, followed by the first members of the human genus, *Homo*, at about 2.4 Ma. Fossil evidence, primarily from Africa, indicates that *Homo erectus*, capable of making stone axes, appeared about 1.6 Ma, and the line leading to *Homo sapiens* (our species) diverged from *Homo neanderthalensis* (Neanderthal man) about 500,000 years ago. According to the fossil record, modern people appeared about 200,000 years ago, and initially shared the planet with two other species of the genus *Homo*, the Neanderthals and the Denisovans. The last Neanderthals and Denisovans died off over 25,000 years ago, leaving *Homo sapiens* as the only human species on Earth.

As summarized in **Geology at a Glance** (pp. 346–347), Earth's history reflects the complex consequences of plate interactions, sea-level changes, atmospheric changes, life evolution, and even meteorite impact. In the past few millennia, humans have had a huge effect on the planet, causing changes significant enough to be obvious in the geologic record of the future. We'll pick up the thread of this story in Chapter 19, where we develop the concept of global change.

Did you ever wonder . . .
did dinosaurs and humans live at the same time?

Take-Home Message

The Cenozoic began when a huge meteorite impact may have caused mass extinction. During the Cenozoic, the mountain belts of today rose, modern plate boundaries became established, and mammals diversified. Recently, ice age glaciers covered large areas.

ANOTHER VIEW The present-day Bahamas serve as an example of what the interior of the United States might have looked like during intervals of the Paleozoic. Shallow land areas were submerged and became the site of shallow-marine sedimentation.



CHAPTER 11 REVIEW

Chapter Summary

- The Earth formed about 4.57 billion years ago. For part of the first 600 million years, the Hadean Eon, the planet was so hot that its surface was a magma ocean.
- The Archean Eon began about 3.85 Ga, when the first continental crust that still remains formed. This crust assembled out of volcanic arcs and hot-spot volcanoes that were too buoyant to subduct. The atmosphere contained very little oxygen, and the first life forms—bacteria and archaea—appeared.
- In the Proterozoic Eon, which began at 2.5 Ga, Archean cratons sutured together to form large cratons. Photosynthesis added oxygen to the atmosphere. By the end of the Proterozoic, soft-bodied marine invertebrates populated the planet, and continental crust had accumulated to form a supercontinent.
- As the Paleozoic Era began, rifting yielded several separate continents. Sea level rose and fell, depositing sequences of strata in continental interiors. Continents coalesced again to form another supercontinent, Pangaea. Early Paleozoic evolution produced many invertebrates with shells, and jawless fish. Land plants and insects appeared in the middle Paleozoic, and by the end of the eon, there were land reptiles and gymnosperm trees.
- In the Mesozoic Era, Pangaea broke apart and the Atlantic Ocean formed. Convergent-boundary tectonics dominated along the western margin of North America. Dinosaurs became prominent land animals through the Mesozoic Era. During the Cretaceous Period, the continents flooded. Angiosperms appeared, along with modern fish. A huge mass-extinction event wiped out the dinosaurs at the end of the Cretaceous Period, probably due to the impact of a large meteorite.
- In the Cenozoic Era, the collision of Africa and India with Asia and Europe formed the Alpine-Himalayan orogen. Convergent tectonics persisted along the margin of South America, creating the Andes, but ceased in North America when the San Andreas Fault formed. Rifting in the western United States produced the Basin and Range Province. Various kinds of mammals filled niches left vacant by the dinosaurs, and the human genus, *Homo*, appeared and evolved through the Pleistocene Ice Age.

Key Terms

Alpine-Himalayan chain (p. 345)
Ancestral Rockies (p. 340)
Archean Eon (p. 331)
banded iron formation (BIF) (p. 335)
Basin and Range Province (p. 348)
Cambrian explosion (p. 337)
craton (p. 333)
cratonic platform (p. 333)
differentiation (p. 330)
Ediacaran fauna (p. 335)
epicontinental sea (p. 336)
exotic terrane (p. 341)
Gondwana (p. 336)
great oxygenation event (p. 335)
Hadean Eon (p. 330)
Laramide orogeny (p. 342)
Laurentia (p. 336)
Pangaea (p. 339)
Phanerozoic Eon (p. 336)
Pleistocene Ice Age (p. 348)
Proterozoic Eon (p. 333)
Rodinia (p. 335)
shield (p. 333)
snowball Earth (p. 335)
superplume (p. 342)

Review Questions

1. Why are there no whole rocks on Earth that yield isotopic dates older than 4 billion years?
2. Why can we find mineral grains that are older than the oldest whole rocks?
3. Describe the condition of the crust, atmosphere, and oceans during the Hadean Eon.
4. Describe how the first continental crust might have formed.
5. How did the atmosphere and tectonic conditions change during the Proterozoic Eon?
6. What evidence do we have that the Earth nearly froze over twice during the Proterozoic Eon?
7. Did supercontinents form in the Proterozoic?
8. How did the Cambrian explosion of life change the nature of the living world?
9. Were there multicellular organisms before the Cambrian?
10. How did the Alleghenian and Ancestral Rockies orogenies affect North America?
11. What are the major types of organisms that appeared during the Paleozoic?
12. What supercontinent formed at the end of the Paleozoic, and what ocean formed when it broke apart?
13. Describe the plate-tectonic conditions that led to the formation of the Sierran arc and the Sevier thrust belt. What happened during the Laramide orogeny?
14. What life forms appeared during the Mesozoic?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist sees exercises on fossil identification.
- Labeling exercises on the geologic history of North America.
- Questions that help students identify periods in Earth's history.

15. What may have caused the flooding of the continents during the Cretaceous Period?
16. What could have caused the K-T mass extinctions?
17. What might have caused the mass extinction at the end of the Paleozoic?
18. What continents formed as a result of the breakup of Pangaea?
19. What caused the Himalayas and the Alps to form?
20. What major tectonic provinces formed in the western United States during the Cenozoic?
21. What major climatic and biologic events happened during the Pleistocene?

On Further Thought

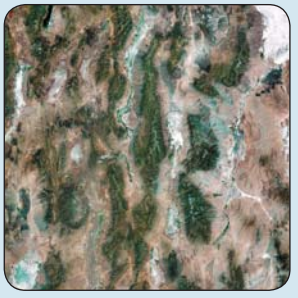
22. During intervals of the Paleozoic, large areas of continents were submerged by shallow seas. Using *Google Earth*™, tour North America from space. Do any present-day regions *within* North America consist of continental crust that was submerged by seawater? What about regions offshore? (*Hint*: Look at the region just east of Florida.)
23. Geologists have concluded that 80% to 90% of Earth's continental crust had formed by 2.5 Ga. But if you look at a geological map of the world, you find that only about 10% of the Earth's continental crustal surface is labeled "Precambrian." Why?

SEE FOR YOURSELF K. . . Earth History

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet K of our **Geotours Workbook**.



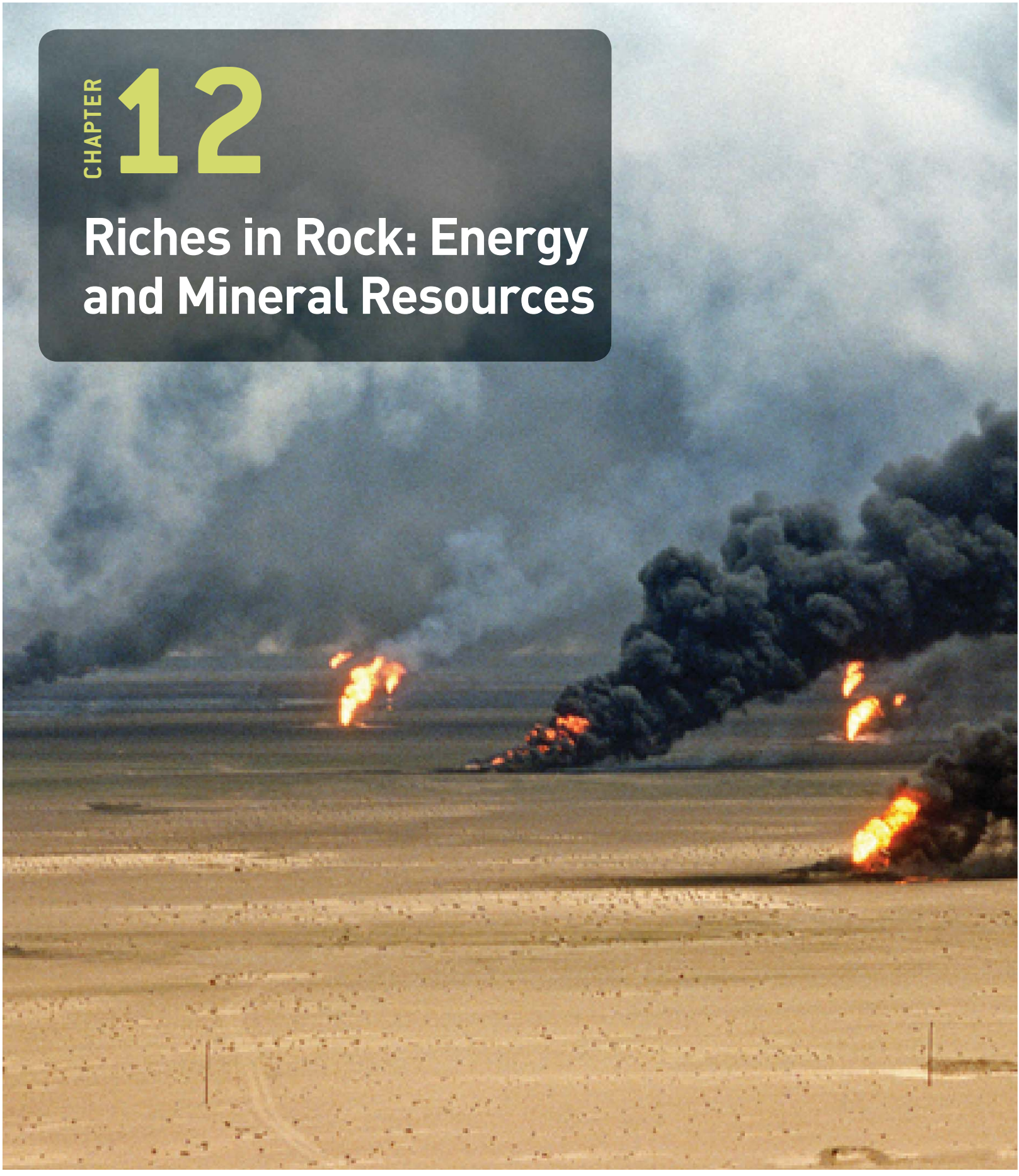
Rocky Mountain Front, Colorado
Latitude 39°46′2.32″N,
Longitude 105°13′45.35″W
Looking obliquely from 8 km up, we see the steep face of the Rocky Mountains in Colorado. These mountains were uplifted during the Laramide orogeny. During the event, reactivation of large faults thrust Precambrian rocks up and caused overlying Paleozoic strata to fold.



Basin and Range rift, Utah
Latitude 39°15′1.83″N,
Longitude 114°38′32.10″W
In this region of the Cenozoic Basin and Range rift, as viewed from 250 km, darker bands are fault-block mountains, whereas lighter areas are sediment-filled basins. White areas are evaporites, from dried-up lakes.

CHAPTER 12

Riches in Rock: Energy and Mineral Resources





Oil well fires in Kuwait, set at the end of the 1991 Gulf War, filled the sky with hot flames and dark smoke. These fires, fed by fuels trapped underground for millions of years, dramatically display the immense energy that can be held in geologic materials.

Chapter Objectives

By the end of this chapter you should know . . .

- how oil and gas form, how they are extracted, and why reserves don't occur everywhere.
- how coal forms and is mined.
- where nuclear fuel comes from, and how nuclear power plants operate.
- the nature of alternative energy sources, including hydrothermal, geothermal, and wind.
- what an ore deposit is, where ores form, and how metals can be extracted from ores.
- where nonmetallic resources (stone, gravel, salts) occur, and how they are used.
- that society faces significant challenges concerning resource sustainability in the future, and concerning environmental consequences of resource use.

All the gold which is under or upon the Earth is not enough to give in exchange for virtue.

—Plato (Greek Philosopher, ca. 428–347 B.C.E.)

12.1 Introduction

The earliest humans were hunter-gatherers and needed only food and water to survive. But when people discovered that fire could be used for cooking and heating, weapons could facilitate hunting, shelters could make daily life more comfortable, and farming could make food supplies more reliable, their needs expanded. Specifically, people began to require **energy resources** (sources of heat and/or power) and **mineral resources** (materials from which the chemicals used in making products can be derived). Before the 18th century, energy resources were used primarily for heat and to drive pumps or millstones, and mineral resources consisted just of various rocks and metals. But when industrialization took hold, society's demand for energy and mineral resources increased dramatically—citizens of modern industrialized countries use 100 times more resources per capita than our pre-industrial ancestors did. As technology became more advanced in the 20th and 21st centuries, we began to use new types of energy and mineral resources that our ancestors never dreamed of.

Where do people obtain energy and mineral resources? Most come from the Earth, and are either geological materials or the products of geologic processes. That's why we discuss these resources in a geology book. The first half of this chapter focuses on the nature and origin of energy resources. Our discussion begins with a focus on the most widely used energy sources of the past century (oil, gas, coal, nuclear, and hydroelectric). Then, we address resources that are likely to begin providing a greater proportion of our needs in the next century (hydroelectric, wind, and solar). The second half of the chapter considers both metallic and nonmetallic mineral resources. An understanding of how resources form, why they occur where they do, how they can be extracted, and how their extraction and use impacts the environment provides an essential context for facing the sustainability challenges of the future. Searching for resources, and dealing with the consequences of their production and use, provides jobs for tens of thousands of geologists worldwide.

12.2 Sources of Energy in the Earth System

What comes to mind when someone asks you to name an energy resource? Perhaps you think about the many kinds of **fuel**, materials that burn or react to produce heat. Alternatively, you may think of windmills and hydroelectric dams, or arrays of solar panels, because they are appearing on the landscape with increasing frequency. Where does the "energy" (the capacity to do work) in these energy resources originally come from? Let's consider the underlying sources:

- *Energy directly from the Sun*: Solar energy, resulting from nuclear fusion reactions in the Sun, bathes the Earth's surface. It may be converted directly to electricity, or it may be used to heat water.
- *Energy directly from gravity*: The gravitational attraction of the Moon, and to a lesser extent, the Sun, helps cause ocean tides, the daily up-and-down movement of the sea surface. The flow of water during tidal changes can drive turbines.
- *Energy involving both solar energy and gravity*: Solar radiation heats the air, which becomes less dense. In a gravitational field, this warm air rises, while cool, denser air sinks. The resulting air movement, wind, powers sails and windmills. Solar energy also evaporates water, which enters the atmosphere. When the water condenses, it rains on the land, where it accumulates in streams that flow downhill in response to gravity. This moving water can drive waterwheels and turbines.
- *Energy via photosynthesis*: Algae and green plants absorb some of the solar energy that reaches the Earth's surface. Their green color comes from a pigment called chlorophyll. With the aid of chlorophyll, plants produce sugar through a chemical reaction called **photosynthesis**. Plants use the sugar to manufacture more complex organic chemicals. Burning plant matter releases potential energy stored in the chemical bonds of organic chemicals. During burning, the molecules react with oxygen and break apart to produce carbon dioxide, water, and carbon (soot). People have burned plant material (**biomass**) to produce energy for centuries. More recently, plant material has been used to produce ethanol, a flammable alcohol.

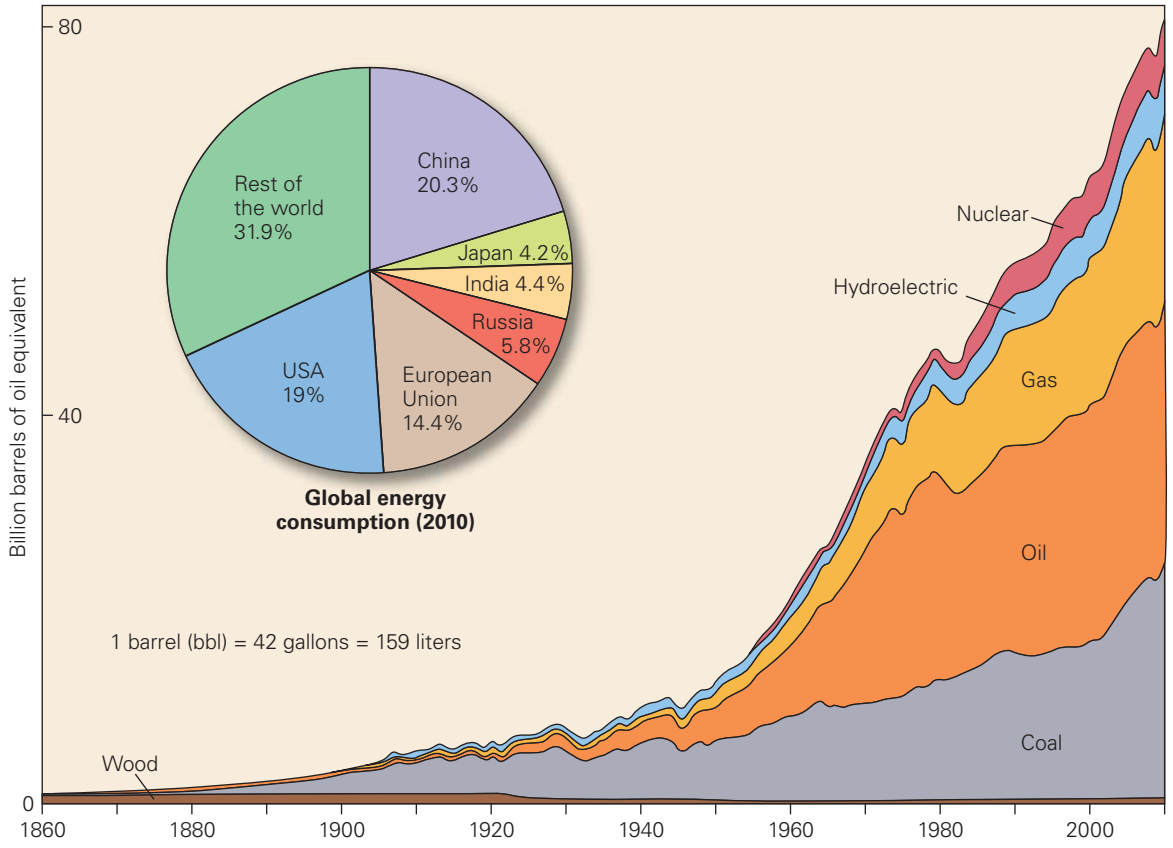
  While a portion of our energy comes from recently living biomass (wood, sugarcane, etc.) even more comes from the remains of organisms that lived either by carrying out photosynthesis or by eating algae or plants, and were then buried and preserved in sediment after they died. Because the energy stored in these substances was trapped by photosynthesis long ago, and has been preserved in rock over geologic time, we refer to these materials as **fossil fuels**.
- *Energy from chemical reactions*: A number of inorganic chemicals can burn to produce light and energy. A dynamite explosion is an extreme example of such energy production. Recently, researchers have been studying electrochemical devices, such as hydrogen fuel cells, that produce electricity directly from chemical reactions.
- *Energy from nuclear fission*: Atoms of radioactive elements can split into smaller pieces, a process called nuclear fission (see Chapter 3). During fission, a tiny amount of mass transforms into a large amount of energy, called nuclear energy. This type of energy runs nuclear power plants and nuclear submarines.
- *Energy from Earth's internal heat*: Some of Earth's internal energy dates from the birth of the planet, while some comes from radioactive decay in minerals. This internal energy heats underground water. The resulting hot water, when transformed to steam, provides geothermal energy, which can drive turbines.

During the course of civilization, the sources of energy that people use have changed (**Fig. 12.1**). Prior to the industrial age, direct burning of wood and other biomass provided most of humanity's energy. But by the second half of the 19th century, deforestation had nearly destroyed this resource, and energy needs had increased so dramatically that other fuels came into use. In the succeeding sections, we discuss various energy sources, beginning with fossil fuels (oil, gas, and coal), the dominant fuels of the present day.

Take-Home Message

Energy comes from several sources—solar radiation, gravity, chemical reactions, radioactive decay, and internal heat. Solar radiation and gravity together drive wind and water movement. Products of photosynthesis can be preserved in rocks as fossil fuels.

FIGURE 12.1 Sources of energy used by people. The proportion of sources has changed over time, but the total quantity used increases. Industrialization in Asia is now driving growth.



Hydrocarbon Systems

Oil and gas do not occur in all rocks at all locations. That's why the goal of controlling oil fields, regions that contain significant amounts of accessible oil underground, has sparked bitter wars. A known supply of oil and gas held underground is a **hydrocarbon reserve**; if the reserve consists dominantly of oil, it is usually called an oil reserve and if it consists dominantly of gas, it's a gas reserve. The development of a reserve requires a specific association of materials, conditions, and time. Geologists refer to this association as a **hydrocarbon system**. We'll now look at the components of a hydrocarbon system, namely the source rock, the thermal conditions of oil formation, the migratory pathway, and the trap.

12.3 Oil and Gas

What Are Oil and Gas?

For reasons of economics and convenience, industrialized societies today rely primarily on oil (petroleum) and natural gas for their energy needs. Oil and natural gas, both fossil fuels, consist of **hydrocarbons**, chain-like or ring-like molecules made of carbon and hydrogen atoms. Chemists consider hydrocarbons to be a type of organic chemical.

Some hydrocarbons are gaseous and invisible, some resemble a watery liquid, some appear syrupy, and some are solid. The viscosity (ability to flow) and the volatility (ability to evaporate) of a hydrocarbon product depend on the size of its molecules. Hydrocarbon products composed of short chains of molecules tend to be less viscous (meaning they can flow more easily) and more volatile (meaning they evaporate more easily) than products composed of long chains, because the long chains tend to tangle up with each other. Thus, short-chain molecules occur in gaseous form (natural gas) at room temperature, moderate-length-chain molecules occur in liquid form (gasoline and oil), and long-chain molecules occur in solid form (tar).

Source Rocks and Hydrocarbon Generation

News stories often incorrectly imply that oil and gas are derived from buried trees or the carcasses of dinosaurs. In fact, the hydrocarbon molecules of oil and gas are derived from organic chemicals, such as fatty molecules called lipids, that were once in **plankton**. Plankton is made up of very tiny floating organisms including single-celled and very small multicellular plants (algae) as well as protists and microscopic animals. Typically, most planktonic organisms range in size from 0.02 to 2.0 mm in diameter. When the organisms die, they sink to the floor of the lake or sea that they lived in, and if the water is relatively "quiet" (nonflowing), accumulate.

If the sea-floor or lake-floor environment is rich with oxygen, dead plankton may be eaten or oxidized and transformed into CO_2 and CH_4 gas, which bubbles away. But in oxygen-poor waters, the organic material can survive long enough to mix with clay and form an organic-rich, muddy ooze, that can then become buried by still more sediment so that it becomes preserved. Eventually, pressure due to the weight of overlying sediment squeezes out the water, and the ooze becomes compacted and, eventually, lithified to become black, organic shale. (Shale that does not contain organic matter tends to be gray, tan, or red.) Organic shale contains the raw materials from which hydrocarbons form, so we refer to it as a **source rock**.

If organic shale becomes buried deeply enough (2 to 4 km), it gets warmer, since temperature increases with depth in the Earth. Chemical reactions take place in warm source rocks and slowly transform the organic material in the shale into a mass of waxy molecules called **kerogen** (Fig. 12.2). Shale containing 15% to 30% kerogen is called **oil shale**. If oil shale warms to temperatures of greater than about 90°C, kerogen molecules break into smaller oil and natural gas molecules, a process known as **hydrocarbon generation**. At temperatures over about 160°C, any remaining oil breaks down to form natural gas; and at temperatures over 225°–250°C, organic matter loses all its hydrogen and transforms into graphite (pure carbon). Thus, oil itself forms only in a relatively narrow range of temperatures, called the **oil window**.

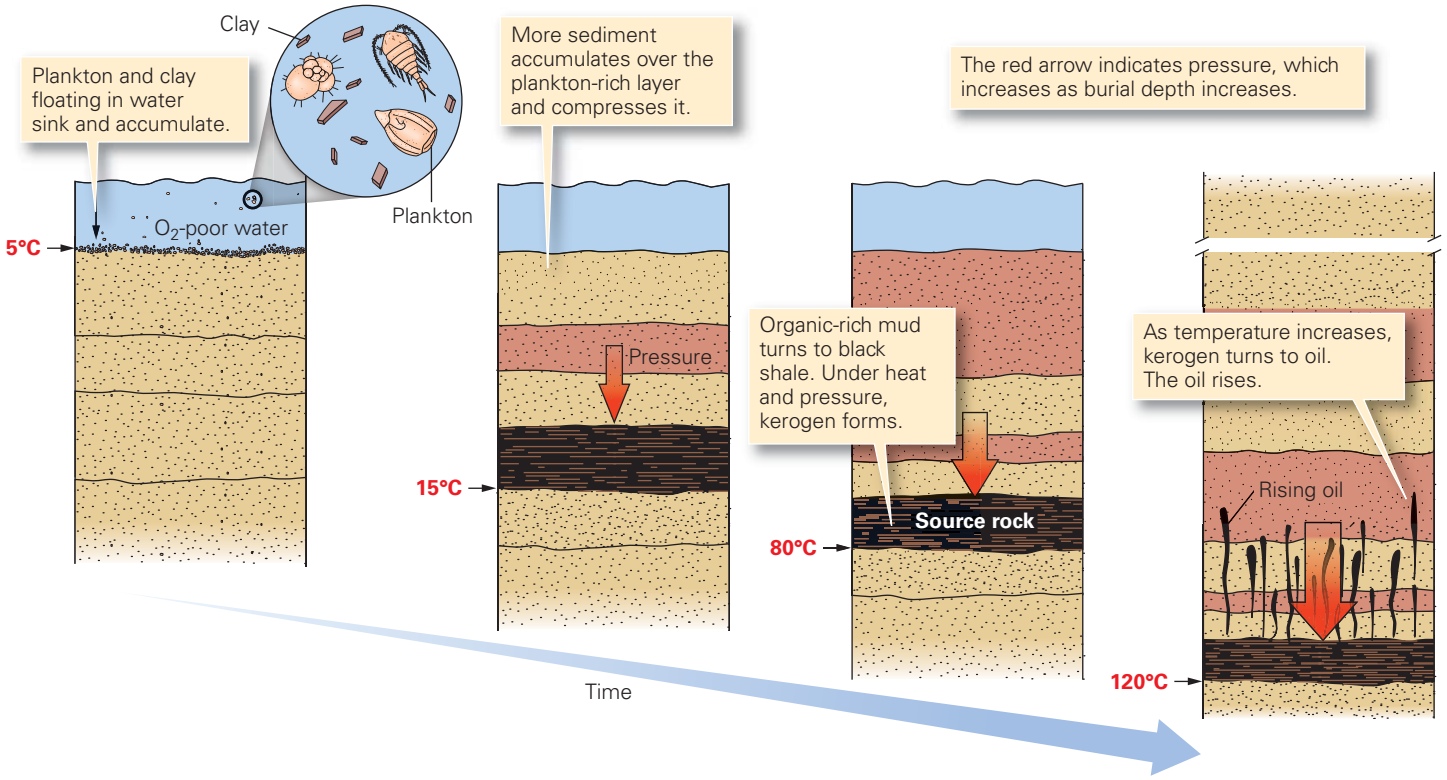
Reservoir Rocks and Hydrocarbon Migration

The clay flakes that comprise most of an oil shale fit together very tightly and thus prevent kerogen, and any liquid or gaseous hydrocarbons forming within the kerogen, from moving through the rock. Therefore, you can't simply drill a hole into a source rock and pump out oil—the oil won't flow into the well fast enough to make the process cost efficient. Instead, to obtain oil or gas, companies drill into **reservoir rocks**, rocks that contain, or could contain, *accessible* oil or gas, meaning oil or gas that can flow through rock and be sucked into a well fairly easily.

To be a reservoir rock, a body of rock must have space in which the oil or gas can reside and must have channels through which the oil or gas can move. The space can be in the form of openings, or **pores**, between clastic grains (which exist because the grains didn't fit together tightly and because cement didn't fill all the spaces during cementation) or in the form of cracks and fractures that developed after the rock formed. In some cases, groundwater passing through rock dissolves minerals to produce new pore space. **Porosity** refers to the proportion of pore space in a rock. Not all rocks have the same porosity—for example, shale has low porosity (~10%), whereas poorly cemented sandstone has high porosity (~35%). By saying that sandstone has a porosity of 35%, we mean that about a third of a block of the sandstone consists of open space. The oil or gas in a reservoir rock occurs in the pores, and thus is distributed through the rock—it does *not* occur in open pools underground. **Permeability** refers to the degree to which pore spaces are connected to one another. In a rock with high permeability, there are many tiny channelways linking pores, and/or many interconnected cracks cutting through the rock, so that fluids are not trapped in pores but rather can flow through the rock. The greater the porosity, the greater the

Did you ever wonder . . .
are there actually pools of oil underground?

FIGURE 12.2 The formation of oil. The process begins when organic debris settles with sediment. As burial depth increases, heat and pressure transform the sediment into black shale in which organic matter becomes kerogen. At appropriate temperatures, kerogen becomes oil, which then seeps upward.



capacity of a reservoir rock to hold oil; and the greater the rock's permeability, the easier it is for the oil to be extracted.

To fill the pores of a reservoir rock, oil and gas must first migrate (move) from the source rock into a reservoir rock, a process that can take thousands to millions of years to happen (**Fig. 12.3**). Why do hydrocarbons migrate? Oil and gas are less dense than water, so they try to rise toward the Earth's surface to get above groundwater, just as salad oil rises above the vinegar in a bottle of salad dressing. Natural gas, being less dense, ends up rising above oil. In other words, buoyancy drives oil and gas upward. Typically, a hydrocarbon system must have a good migration pathway, such as a set of permeable fractures, in order for large volumes of hydrocarbons to move.

Traps and Seals

If oil or gas escapes from the reservoir rock and ultimately reaches the Earth's surface, where it leaks away at an **oil seep**, there will be none left underground to extract. Thus, for an oil reserve to exist, oil and gas must be held underground in the reservoir rock by means of a geologic configuration called a **trap**.

There are two components to an oil or gas trap. First, a **seal rock**, a relatively impermeable rock such as shale, salt, or unfractured limestone, must lie above the reservoir rock and stop the hydrocarbons from rising further. Second, the seal and reservoir rock bodies must be arranged in a geometry that localizes the hydrocarbons in a restricted area. Geologists recognize several types of hydrocarbon trap geometries, four of which are described in **Box 12.1**.

Take-Home Message

Oil and gas are hydrocarbons derived from the remains of plankton buried with clay in an organic ooze. Burial transforms ooze into source rock, and heat converts organics to oil. Oil reserves form when the oil migrates into a reservoir rock within a trap.

12.4 Oil Exploration and Production

Birth of the Oil Industry

In the United States, during the first half of the 19th century, people collected "rock oil" (later called petroleum, from the Latin words *petra*, meaning rock, and *oleum*, meaning oil) at seeps and used it to grease wagon axles and to make patent medicines. But such oil was rare and expensive. In 1854, George Bissel, a New York lawyer, came to the realization that oil might have broader uses, particularly as fuel for lamps, to replace increasingly scarce whale oil. Bissel and a group of investors contracted Edwin Drake, a colorful character who had drifted among many professions, to find a way to drill for oil in rocks beneath a hill near Titusville, Pennsylvania, where oily films floated on the water of springs. Using the phony title "Colonel" to add respectability, Drake hired drillers and obtained a steam-powered drill. Work was slow and the investors became discouraged, but the very day that a letter arrived ordering Drake to stop drilling, his drillers found that the hole, which had reached a depth of 21.2 m, had filled with oil. They set up a pump, and on August 27, 1859, for the first time in history, pumped oil out of the ground. No one had given much thought to the question of how to store the oil, so workers dumped it into empty whisky barrels. This first oil well yielded 10 to 35 barrels a day, which sold for about $20 a barrel (1 barrel equals 42 gallons).

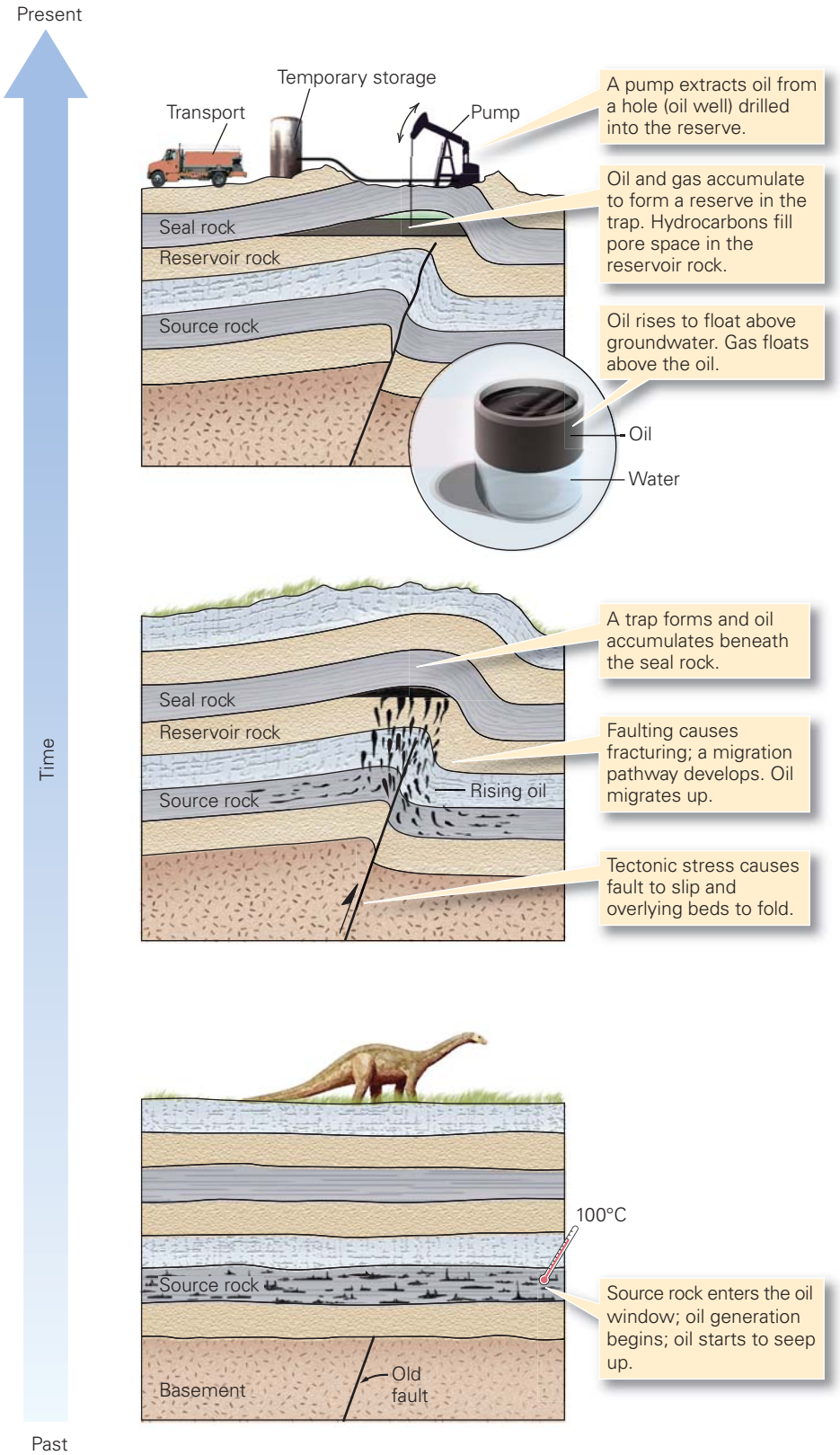
Within a few years, thousands of oil wells had been drilled in many states, and by the turn of the 20th century, civilization had begun its addiction to oil. Initially, most oil went into the production of kerosene for lamps. Later, when electricity took over from kerosene as the primary source for illumination, gasoline derived from oil became the fuel of choice for the newly invented automobile. Oil was also used to fuel electric power plants. In its early years, the oil industry was in perpetual chaos. When "wildcatters" discovered a new oil field, there would be a short-lived boom during which the price of oil could drop to pennies a barrel. In the midst of this chaos, John D. Rockefeller established the Standard Oil Company, which monopolized the production, transport, and marketing of oil. In 1911, the Supreme Court broke down Standard Oil into several companies—including Exxon (Esso), Chevron, Mobil, Sohio, Amoco, Arco, Conoco, and Marathon—some of which have recombined in recent decades. Oil became a global industry governed by the complex interplay of politics, profits, supply, and demand.

The Modern Search for Oil

Wildcatters discovered the earliest oil fields either by blind luck or by searching for surface seeps. But in the 20th century, when most known seeps had been drilled and blind luck became too risky, oil companies realized that finding new oil fields would require systematic exploration. The modern-day search for oil is a complex, sometimes dangerous, and often exciting procedure with many steps.

Source rocks are always sedimentary, as are most reservoir and seal rocks, so geologists begin their exploration by looking for a region containing appropriate sedimentary rocks. Then they compile a geologic map of the area, showing the distribution of rock units. From this information, it may be possible to construct a preliminary cross section depicting the geometry of the sedimentary layers underground as they would appear on an imaginary vertical slice through the Earth.

FIGURE 12.3 Initially, oil resides in the source rock. Because it is buoyant relative to groundwater, the oil migrates into the overlying reservoir rock. The oil accumulates beneath a seal rock in a trap.



To add detail to the cross section, an exploration company makes a **seismic-reflection profile** of the region. To obtain a seismic profile, a special vibrating truck or a dynamite explosion sends seismic waves (shock waves that move through the Earth) into the ground (see Interlude D). The seismic waves reflect off contacts between rock layers, just as sonar waves sent out by a submarine reflect off the bottom of the sea. Reflected seismic waves then return to the ground surface, where sensitive instruments (geophones) record their arrival. A computer measures the time between the generation of a seismic wave and its return, and from this information defines the depth to the contacts at which the wave reflected. With such information, the computer constructs an image of the configuration of underground rock layers and, in some cases, can "see" reserves of oil or gas.

Drilling and Refining

If geological studies identify a trap, and if the geologic history of the region indicates the presence of good source rocks and reservoir rocks, geologists make a recommendation to drill. (They do not make such recommendations lightly, as drilling a deep well may cost over $50 million.) Once the decision has been made, drillers go to work. These days, drillers use rotary drills to grind a hole down through rock. A rotary drill consists of a pipe tipped by a rotating bit, which is a bulb of metal studded with hard metal prongs (**Fig. 12.4a**). As the bit rotates, it scratches and gouges the rock, turning it into powder and chips. Drillers pump "drilling mud," a slurry of water mixed with clay and other materials, down the center of the pipe. The mud flows down, past a propeller that rotates the drill bit, and then squirts out of holes at the end of the bit. The extruded mud cools the bit head, which otherwise would heat up due to friction as it grinds against rock, then flows up the hole on the outside of the drill pipe. As it rises, the mud carries "rock cuttings" (fragments of rock that had been broken up by the drill bit) up and out of the hole. Mud also serves another very important purpose—its weight counters the pressure of the

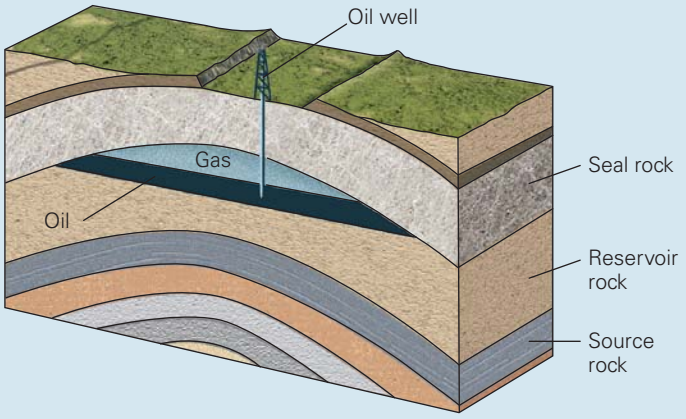
Types of Oil and Gas Traps

Geologists who work for oil companies spend much of their time trying to identify underground traps. No two traps are exactly alike, but we can classify most into the following four categories.

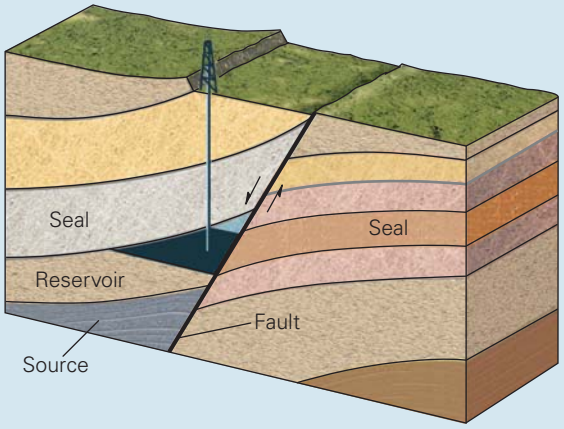
- *Anticline trap*: In some places, sedimentary beds are not horizontal, as they are when originally deposited, but have been bent by the forces involved in mountain building. These bends, as we have seen, are called folds. An anticline is a type of fold with an arch-like shape (**Fig. Bx12.1a**; see Chapter 9).

  If the layers in the anticline include a source rock overlain in turn by a reservoir rock that is overlain by a seal rock, then we have the recipe for an oil reserve. The oil and gas rise from the source rock, enter the reservoir rock, and rise to the crest of the anticline, where they are trapped by a seal.
- *Fault trap*: A fault is a fracture on which there has been sliding. If the slip on the fault crushes and grinds the adjacent rock to make an impermeable layer along the fault, then oil and gas may migrate upward along bedding in the reservoir rock until they stop at the fault surface (**Fig. Bx12.1b**). Alternatively, a fault trap develops if the slip on the fault juxtaposes an impermeable rock layer against the reservoir rock.
- *Salt-dome trap*: In some sedimentary basins, the sequence of strata contains a thick layer of salt, deposited when the basin was first formed and seawater covering the basin was shallow and very salty. Sandstone, shale, and limestone overlie the salt. The salt layer is not as dense as sandstone or shale, so it is buoyant and tends to rise up slowly through the overlying strata. Once the salt starts to rise, the weight of surrounding strata squeezes the salt out of the layer and up into a growing, bulbous **salt dome**. As the dome rises, it bends up the adjacent layers of sedimentary rock. Oil and gas in reservoir rock layers migrate upward until they are trapped against the boundary of the salt dome, for salt is not permeable (**Fig. Bx12.1c**).
- *Stratigraphic trap*: In a stratigraphic trap, a tilted reservoir rock bed "pinches out" (thins and disappears) up its dip between two impermeable layers. Oil and gas migrating upward along the bed accumulate at the pinch-out (**Fig. Bx12.1d**).

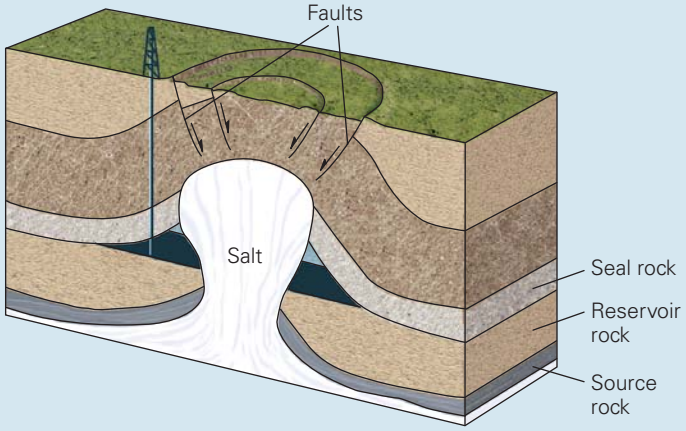
FIGURE Bx12.1 Examples of oil traps. A trap is a configuration of a seal rock over a reservoir rock, in a geometry that keeps the oil underground.



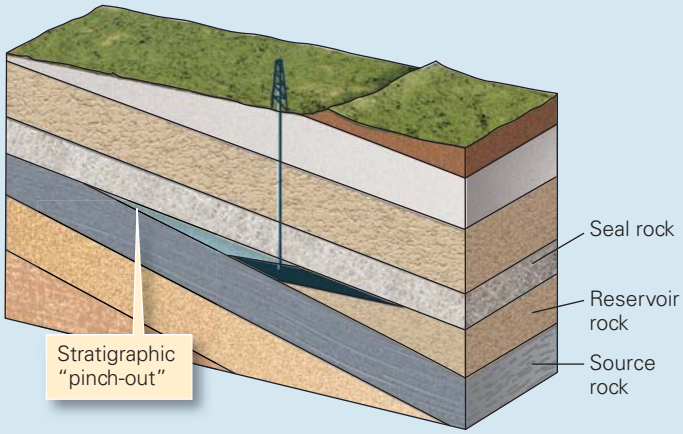
(a) Anticline trap. Oil and gas rise to the crest of the fold.



(b) Fault trap. Oil and gas collect in tilted strata adjacent to the fault.



(c) Salt-dome trap. Oil and gas collect in strata on the flanks of the dome, beneath salt.



(d) Stratigraphic trap. Oil and gas collect where the reservoir layer pinches it out.

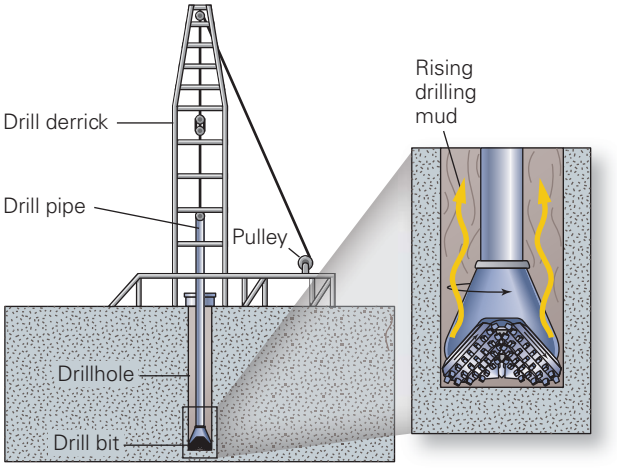
oil and gas in underground reservoir rocks. By doing so, it prevents hydrocarbons from entering the hole until drilling has been completed, the hole has been "finished" (by removing the drill pipe and sealing the walls of the drillhole with concrete), and the hole has been capped. Were it not for the mud, the natural pressure in the reservoir rock would drive oil and/or gas into the hole. And if the pressure were great enough, the hydrocarbons would rush up the hole and spurt out of the ground as a gusher or blowout. Gushers and blowouts can be disastrous, because they spill oil onto the land and, in some cases, ignite into an inferno.

Early drilling methods could produce only vertical drillholes. But as technology advanced, drillers developed methods to control the path of the drill bit so the hole can curve and become diagonal or even horizontal. Such **directional drilling** has become so precise that a driller, using a joystick to steer the bit, and sensors that specify the exact location of the bit in 3-D space, can hit an underground target that is only 15 cm wide from a distance of a few kilometers.

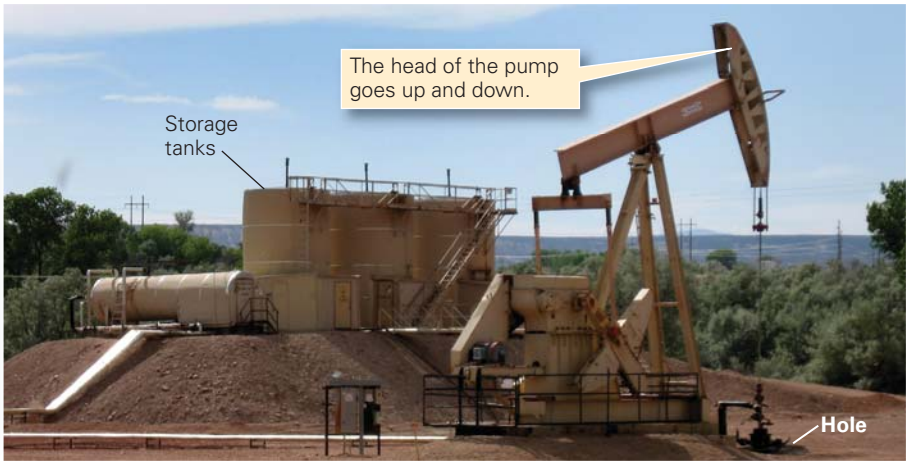
Drillers use derricks (towers) to hoist the heavy drill pipe. To drill in an offshore hydrocarbon reserve, one that occurs in strata beneath the continental shelf, the derrick must be constructed on an offshore-drilling facility. These may be built on huge towers rising from the sea floor, or on giant submerged pontoons. Using directional drilling, it's possible to reach multiple targets from the same platform.

On completion of a hole, workers remove the drilling rig and set up a pump. Some pumps resemble a bird pecking for grain; their heads move up and down to pull up oil that has seeped out of pores in the reservoir rock into the drillhole (Fig. 12.4b). You may be surprised to learn that simple pumping gets only about 30% of the oil in a reservoir rock out of the

FIGURE 12.4 The steps involved in searching for, recovering, transporting, and refining oil.



(a) A rotating pipe tipped by a drill bit grinds a hole into the ground. Drilling mud, pumped down through the pipe, comes out through holes in the bit, flushing cuttings out of the hole.



(b) When drilling is complete, the derrick is replaced by a pump, which then sucks oil out of the ground.



(c) The Trans Alaska Pipeline transports oil from fields on the Arctic coast to a tanker port on the southern coast of Alaska.



(d) Distilling columns of an oil refinery transform crude oil into gasoline and other hydrocarbon products.

ground. Thus oil companies may use secondary recovery techniques to coax out more oil (as much as 20% more). For example, a company may drive oil toward a drillhole by forcing steam into the ground nearby. The steam heats the oil in the ground, making it less viscous, and pushes it along. In some cases, drillers create artificial fractures in rock around the hole by pumping a high-pressure mixture of water, various chemicals, and sand into a portion of the hole. This process, called **hydrofracturing** (or "fracking") creates new fractures and opens up preexisting ones. The sand left by the fracturing fluid keeps the cracks from closing tightly, so they remain permeable. The fractures provide easy routes for the oil to follow from the rock to the well.

Once extracted directly from the ground, "crude oil" flows first into storage tanks and then into a pipeline or tanker, which transports it to a refinery (Fig. 12.4c; See for Yourself L). At a refinery, workers distill crude oil into several separate components by heating it gently in a vertical pipe called a **distillation column** (Fig. 12.4d). Lighter molecules rise to the top of the column, while heavier molecules stay at the bottom. The heat may also "crack" larger molecules to make smaller ones. Chemical factories buy the largest molecules left at the bottom and transform them into plastics.

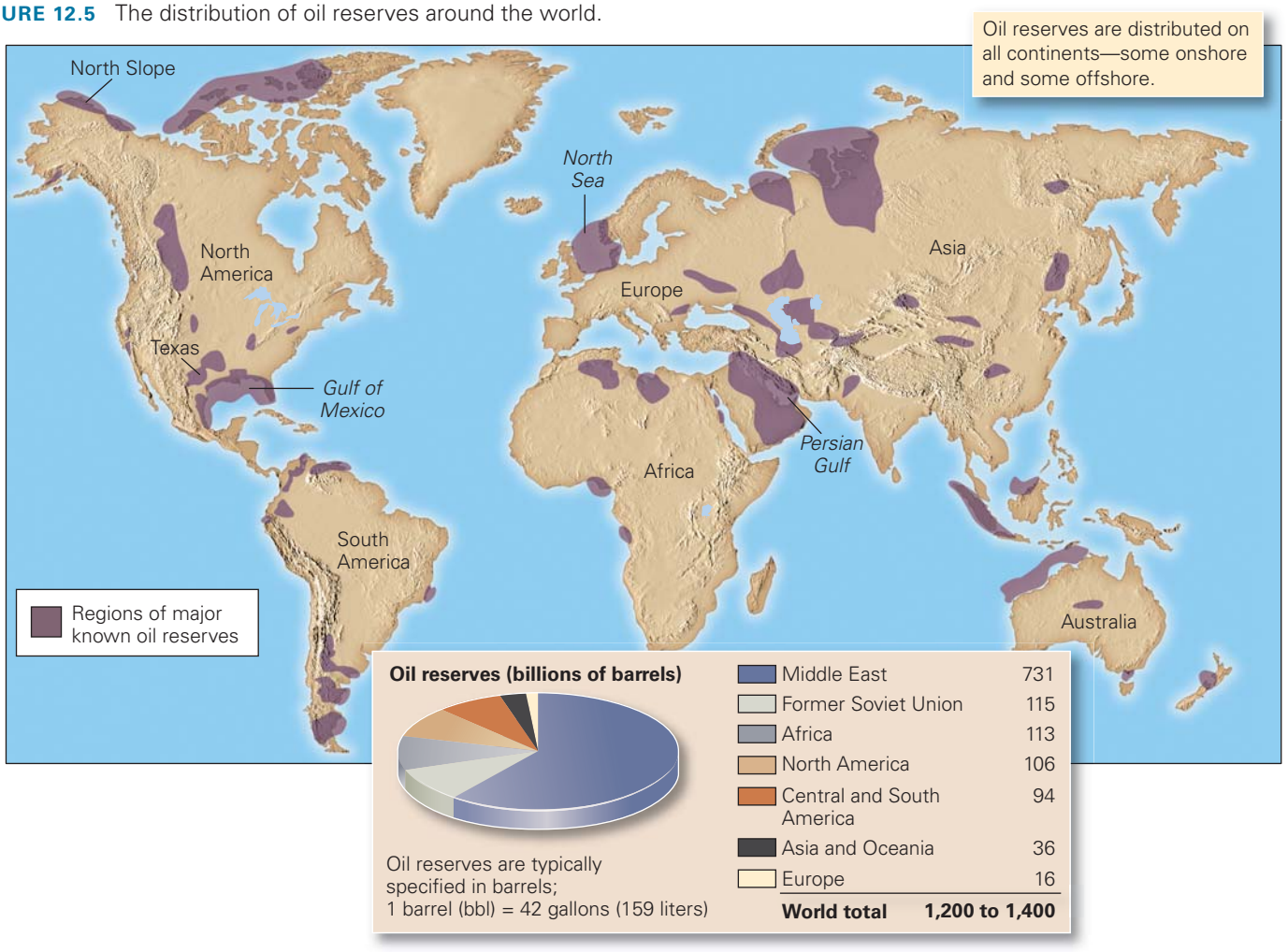
Where Does Oil Occur?

Reserves are not randomly distributed around the Earth (Fig. 12.5). Currently, countries bordering the Persian Gulf contain the world's largest reserves in 25 supergiant fields. In fact, this region has almost 60% of the world's reserves. Reserves are specified in barrels (bbl); 1 bbl = 42 gallons = 159 liters.

Why is there so much oil in the Middle East? Much of the region that is now the Middle East was situated in tropical areas between latitude 20° south and 20° north between the Jurassic (135 Ma) and the Late Cretaceous (65 Ma). Biological productivity was very high in these tropical regions, so the muds that accumulated there were very organic rich and lithified to become excellent source rocks. Thick layers of sand buried the source rocks and eventually became porous sandstones that make excellent reservoir rocks. Later, mountain-building processes folded the layers into large anticlines, which are excellent traps.

The Middle East is not the only source of oil. Reserves also occur in sedimentary basins formed along passive continental margins, such as the Gulf Coast of the United States and the Atlantic Coasts of Africa and Brazil, as well as in intracratonic and foreland basins within continents (see Chapter 6).

FIGURE 12.5 The distribution of oil reserves around the world.



Take-Home Message

Searching for oil is a complex and expensive process. Geologists use seismic-reflection profiles to locate traps. Drilling taps reserves and pumping brings crude oil to the surface, where it is processed at refineries that crack hydrocarbon molecules.

12.5 Unconventional Reserves of Hydrocarbons

So far in our discussion of hydrocarbons, we've focused on oil that can be extracted from reserves in the porous and permeable reservoir rocks of oil traps. Such reserves have come to be known as *conventional reserves*, because accessing them uses technology that has been around for years. In the past 10 to 15 years, energy companies have begun to increase their focus on extracting hydrocarbons from *unconventional reserves*, meaning reserves that had previously been left in the ground or disposed of because they cannot be tapped without using new technologies. Let's look at a few examples of these reserves.

Natural Gas

Natural gas consists of volatile, short-chain hydrocarbon molecules (methane, ethane, propane, and butane). Gas burns more cleanly than oil, in that combustion of gas produces only CO_2 and water, while the burning of oil not only produces CO_2 and water, but also complex organic pollutants. Thus, natural gas has become the preferred fuel for home cooking and heating, and in some localities, for electricity production. It can also be used to run cars and trucks, if the vehicles have been appropriately modified. Natural gas has not yet been used as widely as other hydrocarbons, because gas transportation, which requires high-pressure pipelines or special ships, is quite expensive. But its use is increasing rapidly.

As we have seen, gas often occurs in association with oil. Unfortunately, at many oil wells, it is not economical to capture and transport the gas, so this gas vents from a pipe and is burned in a flare where it enters the air. (In localities where rock has been heated to temperatures higher than the oil window, reservoir rock may contain only gas and there may be enough to be worth pumping and capturing by conventional means.)

Recently, the use of directional drilling and hydraulic fracturing has made it possible to extract large quantities of gas *directly from source rocks*. Large reserves of such **shale gas** underlie states in the northeastern United States, and are currently being drilled to provide energy for east-coast cities (**Box 12.2**). Intense exploration for shale gas reserves has begun worldwide.

Tar Sands (Oil Sands)

So far, we've focused our discussion on hydrocarbon reserves that can be pumped from the subsurface in the form of a liquid or gas. But in several locations around the world, most notably Alberta (in western Canada) and Venezuela, vast reserves of very viscous, tar-like "heavy oil" exist. This heavy oil, known also as bitumen, has the consistency of gooey molasses, and thus cannot be pumped directly from the ground. It fills the pore spaces of sand or of poorly cemented sandstone, constituting up to 12% of the sediment or rock volume. Sand or sandstone containing such high concentrations of bitumen is known as **tar sand** or oil sand.

Production of usable oil from tar sand is difficult and expensive, but not impossible. It takes about 2 tons of tar sand to produce one barrel of oil. Oil companies mine near-surface deposits in vast open-pit mines and then heat the tar sand in a furnace to extract the oil. Producers then crack the heavy oil molecules to produce smaller, more usable molecules. Trucks dump the drained sand back into the mine pit. To extract oil from deeper deposits of tar sand, oil companies drill wells and pump steam or solvents down into the sand to liquefy the oil enough so that it can be pumped out.

Oil Shale

Vast reserves of organic shale have not been subjected to temperatures of the oil window, or if they were, they did not stay within the oil window long enough to complete the transformation to oil. Such rock still contains a high proportion of kerogen. Shale that contains at least 15% to 30% kerogen is called **oil shale**. Lumps of oil shale can be burned directly and thus have been used as a fuel since ancient times. In general, however, energy companies produce liquid oil from oil shale. The process involves heating the oil shale to a temperature of 500°C; at this temperature, the shale decomposes and the kerogen transforms into liquid hydrocarbon and gas. As is the case with tar sand, production of oil from oil shale is possible, but very expensive.

Take-Home Message

Large reserves of hydrocarbons occur in tar sands and oil shale, and as natural gas. But these unconventional sources are difficult to obtain, process, and/or transport, and thus could not be exploited until new technologies evolved and the price of oil rose.

12.6 Coal: Energy from the Swamps of the Past

Coal, a black, brittle, sedimentary rock that burns, consists of elemental carbon mixed with minor amounts of organic chemicals, quartz, and clay. Typically, the carbon atoms in coal have

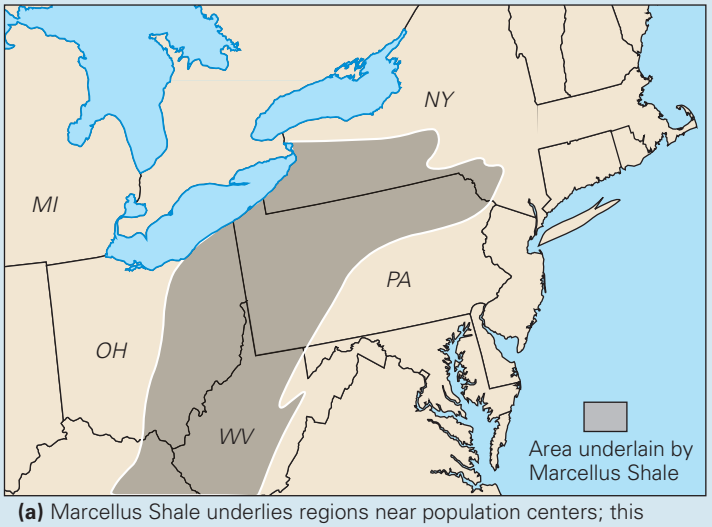
The Marcellus Gas Play

In 2008, Terry Engelder (Penn State University) and others pointed out that previous reports had greatly underestimated the amount of natural gas that is locked in the organic-rich, black Marcellus Shale of the Devonian age (**Fig. Bx12.2a**). He estimated that this 15- to 240-m-thick shale, which lies beneath a highly populated part of the United States (New York, Pennsylvania, and Ohio), contained enough gas to serve as a major energy supply for many years.

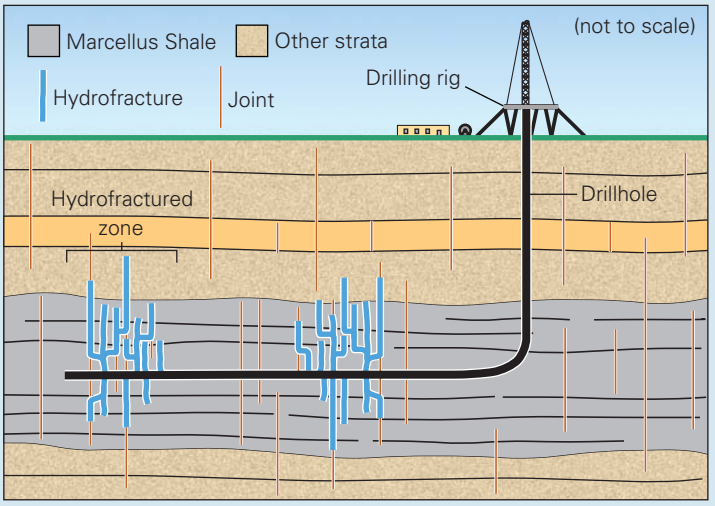
The Marcellus Shale, like all shale, has relatively low permeability. So even though it contains a huge amount of gas, it would not be a usable resource were it not for two key technologies. The first of these technologies is directional drilling. Beds of the Marcellus Formation are horizontal. Thus a single drillhole, which would intersect only a maximum of 240 m (787 feet) of shale if drilled vertically, could intersect many kilometers of shale if drilled horizontally (**Fig. Bx12.2b**). Using directional drilling, many holes can be drilled from the same platform. The second of these technologies is hydraulic fracturing or, informally, "hydrofracking," which gives drillers the capability to greatly increase permeability in the otherwise impermeable shale.

The combination of increased gas-volume estimates, and of the ability to access the gas by directional drilling and hydrofracturing, has led to a "gas boom" in the northeastern United States called the Marcellus Gas Play. Oil companies have spent billions of dollars to lease the right to obtain gas from large areas of the region, and some local landowners have become millionaires overnight. The boom remains controversial, though, because of questions about the amount of gas that can be recovered and because of environmental concerns. Some residents are worried that chemicals in the solutions used during hydraulic fracturing and drilling may contaminate groundwater and that increased permeability caused by fracturing may release gas into groundwater.

FIGURE Bx12.2 Extracting natural gas from the Marcellus Shale.



(a) Marcellus Shale underlies regions near population centers; this map is an approximation.



(b) By using directional drilling and hydrofracture, gas can be drawn from broad regions. The hole stays within shale for kilometers.

bonded to form complicated molecules. Note that coal and oil do not have the same composition or origin. In contrast to oil, coal forms from plant material (wood, stems, leaves) that once grew in coal swamps, regions that resembled the wetlands and rain forests of modern tropical to semitropical coastal areas (**Fig. 12.6a**). Like oil and gas, coal is a fossil fuel because it stores solar energy that reached Earth long ago.

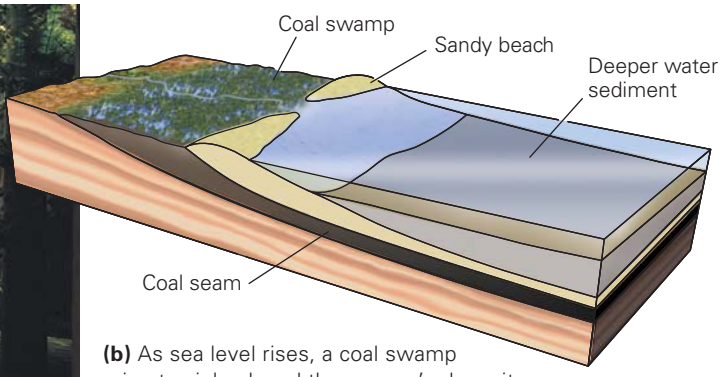
Did you ever wonder . . .
how coal differs from oil?

Significant coal deposits could not form until vascular land plants appeared in the late Silurian Period, about 420 million years ago. The most extensive deposits of coal in the world occur in Carboniferous-age strata (deposited between 286 and 354 million years ago). During the Carboniferous, the continents were assembled in Pangaea, and large areas straddled

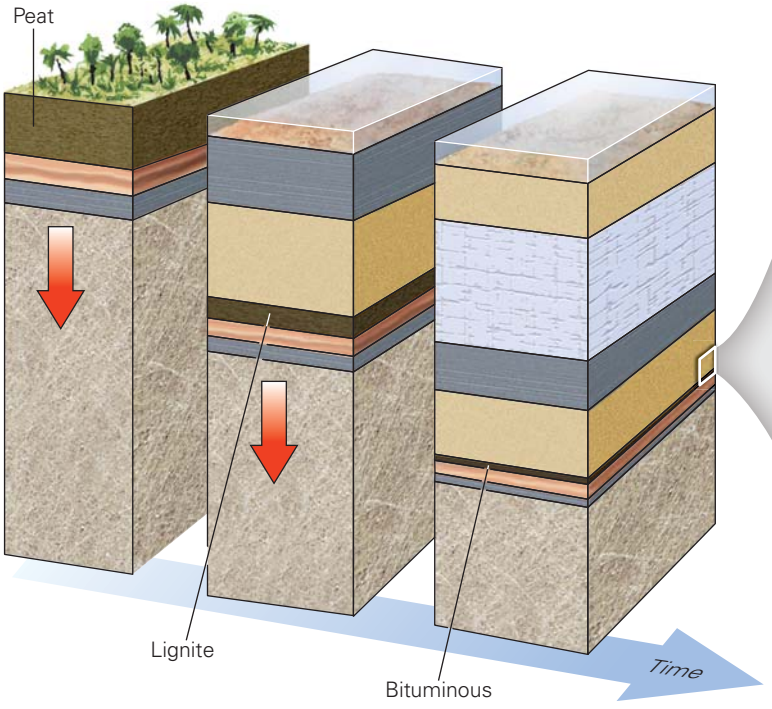
FIGURE 12.6 The formation of coal. Coal forms when plant debris becomes deeply buried.



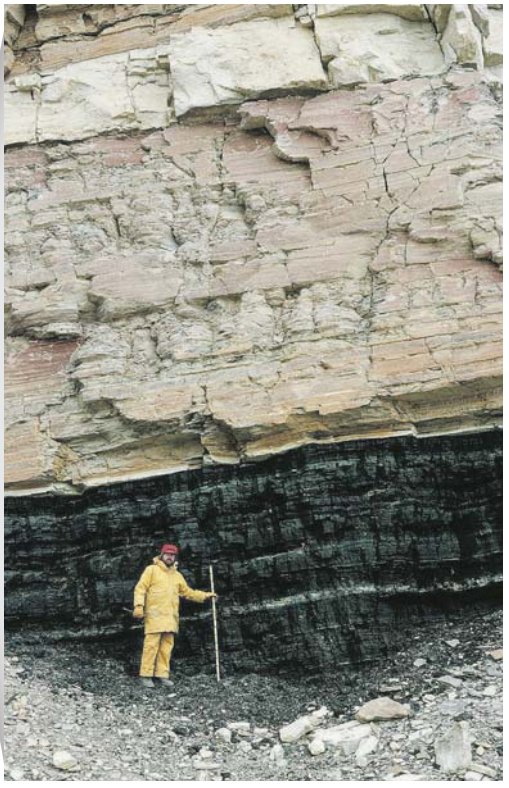
(a) The organic debris that eventually becomes coal comes from plant matter, such as the flora that thrived in Carboniferous swamps.



(b) As sea level rises, a coal swamp migrates inland, and the swamp's deposits eventually are buried by other strata.



(c) A layer of peat accumulates beneath a swamp. Upon burial, the peat becomes lignite. After further burial, the lignite alters to form bituminous coal.



(d) Coal is found in sedimentary beds interlayered with other strata (sandstone, shale, and limestone).

warm tropical regions where vegetation flourished. Also during this time, sea level was so high that large areas of continents were flooded by shallow seas along which vast swamps grew; the plant debris of these swamps, once buried and heated, turned into coal. Not all coal reserves, however, are Carboniferous—during the Cretaceous (144 to 65 Ma), large areas of freshwater coal swamps developed in Wyoming and adjacent states.

Coal commonly occurs in beds, or seams, that may be centimeters to meters thick and may be traceable over very large regions. Broad, continuous coal seams develop when sea level rises slowly relative to the land surface so the coastline, and therefore the coal swamp, migrates slowly inland. During such a transgression (see Chapter 7), the submerged portion of the coal swamp eventually gets buried by layers of other sediments, such as sand and mud. When lithified, the succession turns into beds of sedimentary rock, with the coal occurring as a sedimentary bed, interlayered with sandstone and shale (**Fig. 12.6b**).

The Formation of Coal

How do the remains of plants transform into coal? The vegetation of an ancient swamp must fall and be buried in an oxygen-poor environment, such as stagnant water, so that it can be incorporated in a sedimentary sequence without first decaying by reacting with oxygen and/or by being eaten by microbes or larger organisms. Compaction and partial decay of the vegetation transforms it into **peat**. (Peat, which contains about 50% carbon, itself serves as a fuel in many parts of the world.)

To transform peat into coal, the peat must be buried deeply (4–10 km) by overlying sediment. Such deep burial can happen where the surface of the continent gradually sinks, creating a depression, or sedimentary basin, that can collect sediment. Over time, many kilometers of sediment containing numerous peat layers accumulate. At depth in the pile, the weight of overlying sediment compacts the peat and squeezes out any remaining water. Then, because temperature increases with depth in the Earth, deeply buried peat gradually heats up. Heat accelerates chemical reactions that gradually destroy plant fiber and release elements such as hydrogen, nitrogen, and sulfur in the form of gas. These gases seep out of the reacting peat layer, leaving behind a residue concentrated with carbon. Once the proportion of carbon in the residue exceeds about 50%, the deposit formally becomes coal. With further burial and higher temperatures, chemical reactions allow additional hydrogen, nitrogen, and sulfur to escape, yielding progressively higher concentrations of carbon.

The Classification of Coal

Geologists classify coal according to the concentration of carbon. With increasing burial, peat transforms into a soft, dark-brown coal called *lignite*. At higher temperatures (about 100°–200°C), lignite, in turn, becomes dull, black *bituminous* coal. At still higher temperatures (about 200°–300°C), bituminous coal transforms into shiny, black *anthracite* coal (also called hard coal). The progressive transformation of peat to anthracite coal, which occurs as the coal layer is buried more deeply and becomes warmer, reflects the completeness of chemical reactions that remove water, hydrogen, nitrogen, and sulfur from the organic chemicals of the peat and leave behind carbon (Fig. 12.6c). Thus, lignite contains only about 50% carbon, bituminous about 70%, and anthracite about 90%. As the carbon content of coal increases, we say the **coal rank** increases.

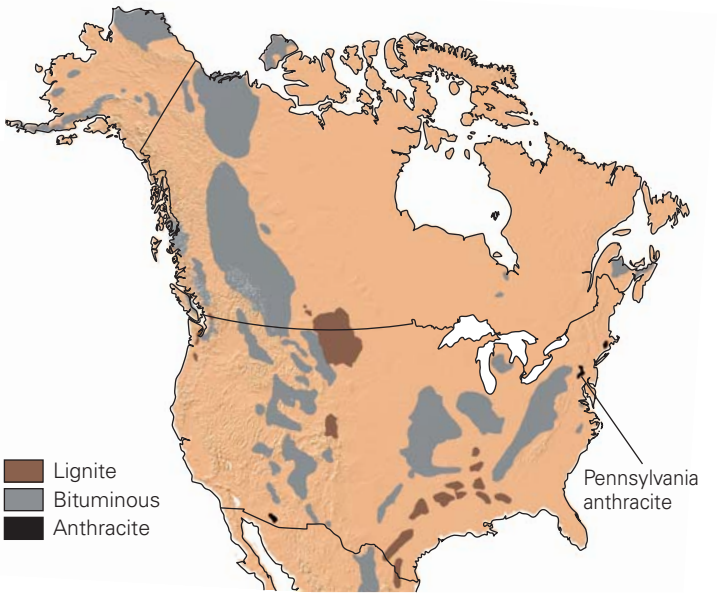
Notably, the formation of anthracite coal requires high temperatures that develop only on the borders of mountain belts, where mountain-building processes can push thick sheets of rock up along thrust faults and over the coal-bearing sediment, so the sediment ends up at depths of 8 to 10 km, where temperatures reach 300°C. Hot groundwater flowing through the rock may also provide enough heat to produce anthracite.

Finding and Mining Coal

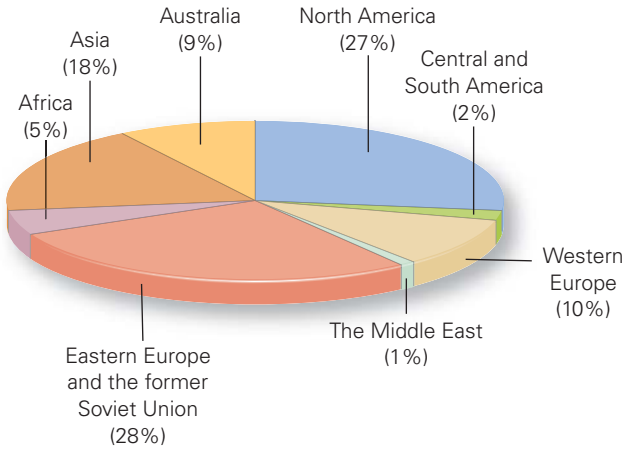
Because the vegetation that eventually becomes coal was initially deposited in a sequence of sediment, coal seams interlayered with other sedimentary rocks (Fig. 12.6d). To find coal, geologists search for sequences of strata that were deposited in tropical to semitropical, shallow-marine to terrestrial environments—the environments in which a swamp could exist. The sedimentary strata of continents contain huge quantities of discovered coal, or **coal reserves** (Fig. 12.7a, b).

The way in which companies mine coal depends on the depth of the coal seam. If the coal seam lies within about 100 m of the ground surface, strip mining proves to be the most economical method. In strip mines, miners use a giant

FIGURE 12.7 The distribution of coal reserves. Vast quantities lie buried in continental sedimentary basins.

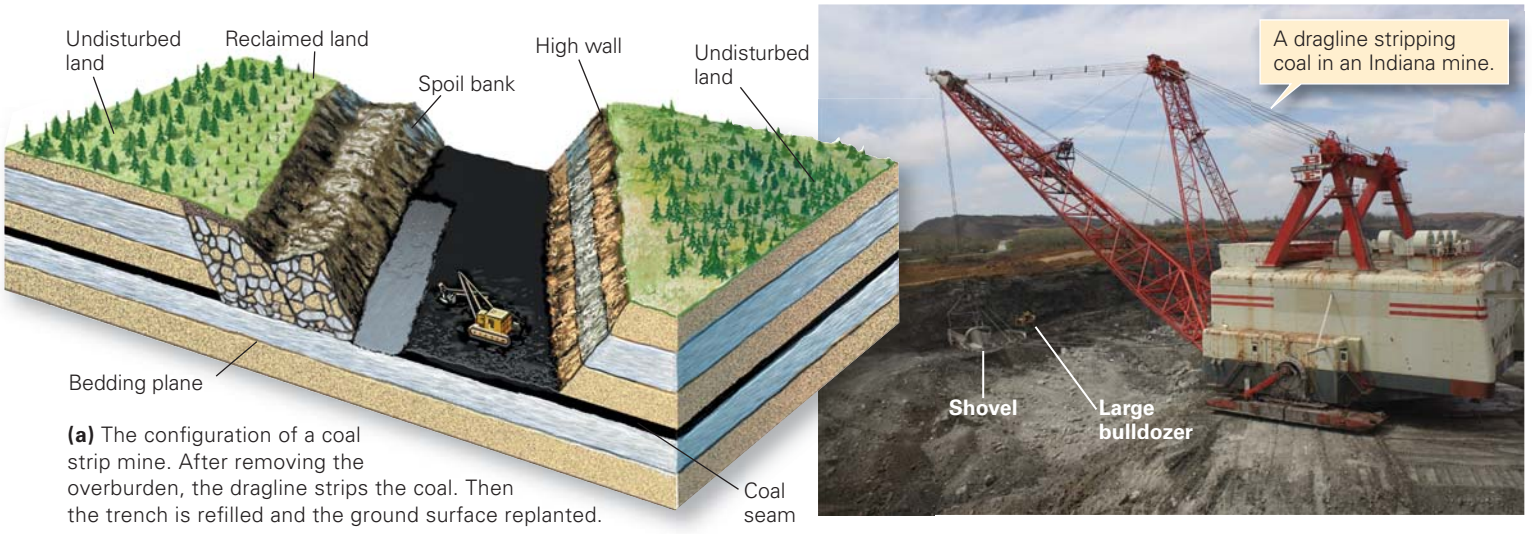


(a) Areas underlain by coal in North America.



(b) Global coal reserves.

FIGURE 12.8 The process of mining coal.



(a) The configuration of a coal strip mine. After removing the overburden, the dragline strips the coal. Then the trench is refilled and the ground surface replanted.



(b) Special machinery grinds into an underground coal seam and dumps coal on a conveyor. This seam is about 2.5 m thick.



(c) Chunks of freshly mined coal await processing at a mine in Indiana.

shovel called a dragline to scrape off soil and layers of sedimentary rock above the coal seam (Fig. 12.8a). Draglines are so big that the shovel could swallow a two-car garage without a trace. Once the dragline has exposed the seam, miners use smaller power shovels to dig out the coal and dump it into trucks or onto a conveyor belt. Before modern environmental awareness took hold, strip mining left huge scars on the landscape. Without topsoil, the rubble and exposed rock of the mining operation remained barren of vegetation. In many contemporary mines, however, the dragline operator separates out and preserves soil. Then, when the coal has been scraped out, the operator fills the hole with the rock that had been stripped to expose the coal and covers the rock back up with the saved soil, on which grass or trees may eventually grow. In hilly areas, however, miners may use a practice called mountain top removal, during which they blast off the top of the mountain and dump the debris into adjacent valleys. This practice can disrupt the landscape permanently.

Deep coal can be obtained only by underground mining. To develop an underground mine, miners dig a shaft down to the depth of the coal seam and then create a maze of tunnels, using huge grinding machines that chew their way into the coal (Fig. 12.8b, c). Underground coal mining can be very dangerous, not only because the sedimentary rocks forming the roof of the mine are weak and can collapse but also because methane gas released by chemical reactions in coal can accumulate in the mine, leading to the danger of a small spark triggering a deadly mine explosion. Unless they breathe through filters, underground miners also risk contracting black lung disease from the inhalation of coal dust.

Gas from Coal

Coalbed Methane As we've noted, the natural process by which coal forms underground yields methane, a type of natural gas. Over time, some of the gas escapes to the atmosphere, but vast amounts remain within the coal in pores or bonded to

coal molecules. Such **coalbed methane**, trapped in strata too deep to be reached by mining, is an energy resource that has become a target for exploration in many regions of the world. Obtaining coalbed methane from deep layers of strata involves drilling, rather than mining. Drillers penetrate a coalbed with a hole and then start pumping out groundwater. As a result of pumping out water, the pressure in the vicinity of the drillhole decreases relative to the surrounding bed. Methane bubbles into the hole and then up to the ground surface, where condensers compress it into tanks for storage.

Coal Gasification Solid coal can be transformed into various gases, as well as solid by-products, *before* burning. The process of producing relatively clean-burning gases from solid coal is called **coal gasification**. Coal gasification involves the following steps. First, pulverized coal is placed in a large container. Then, a mixture of steam and oxygen passes through the coal at high pressure. As a result, the coal heats up to a high temperature but does not ignite; under these conditions, chemical reactions break down and oxidize the molecules in coal to produce flammable gases as well as water and CO_2. Solid ash, as well as sulfur and mercury, concentrate at the bottom of the container and can be removed before the gases are burned.

Underground Coalbed Fires

Coal will burn not only in furnaces but also in surface and subsurface mines, as long as the fire has access to oxygen. Coal mining of the past two centuries has exposed much more coal to the air and has provided many more opportunities for fires to begin; once started, a coalbed fire that progresses underground (sucking in oxygen from joints in overlying rock) may be very difficult or impossible to extinguish.

For the past 50 years, a coalbed fire has progressed under the town of Centralia, Pennsylvania, eventually burning coal seams beneath the town itself. The fire produces toxic fumes that rise through the ground and make the overlying landscape uninhabitable, and it also causes the land surface to collapse and sink. And today, over 100 major coalbed fires are burning in northern China. Recent estimates suggest that 200 million tons of coal burn underground in China every year, an amount equal to approximately 20% of the annual national production of coal in China.

Take-Home Message

Coal forms from the remains of plant material. When buried deeply, this organic material undergoes reactions that concentrate carbon; higher-rank coal contains more carbon. Coal occurs in sedimentary successions and must be mined underground or in open pits.

12.7 Nuclear Power

How Does a Nuclear Power Plant Work?

So far, we have looked at fuels (oil, gas, and coal) that release energy when *chemically* burned. During such burning, a chemical reaction between the fuel and oxygen releases the potential energy stored in the chemical bonds of the fuel. The energy that drives a nuclear power plant comes from a totally different process: the fission, or breaking, of the nuclear bonds that hold protons and neutrons together in the nucleus. Fission splits an atom into smaller pieces, and during this process, a small amount of mass transforms into thermal and electromagnetic energy, as Einstein recognized.

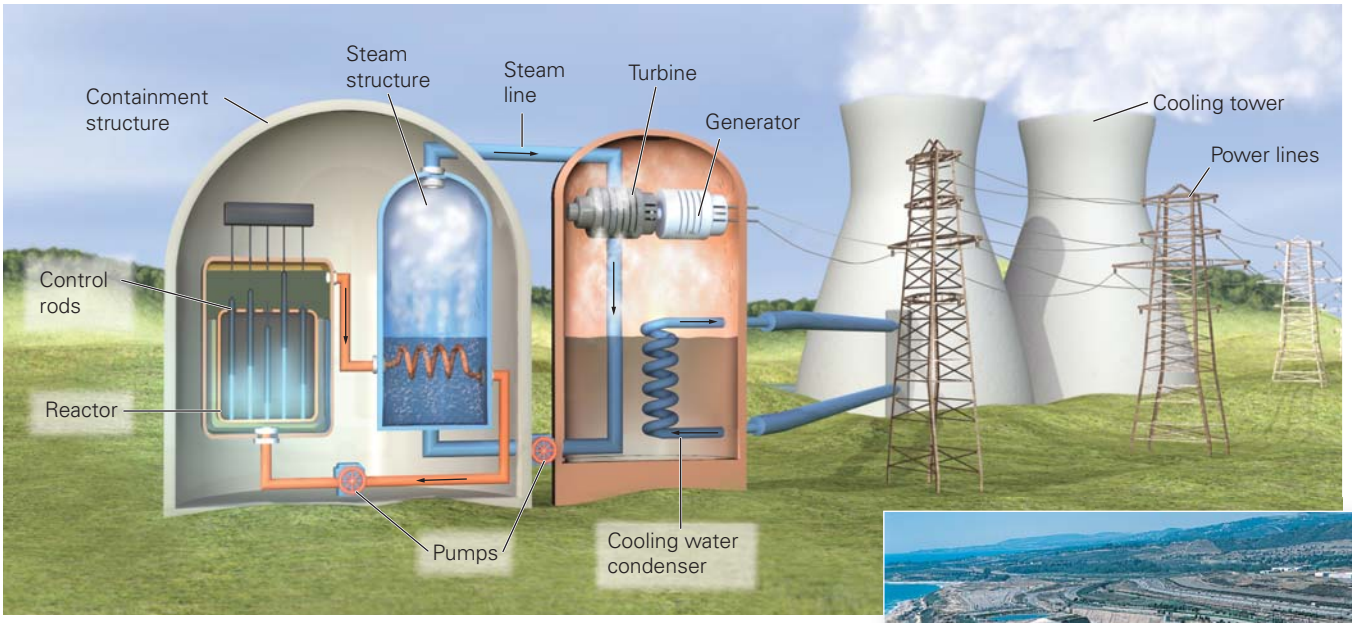
Nuclear power plants were first built to produce electricity during the 1950s. A **nuclear reactor**, the heart of the plant, commonly lies within a shell (containment building) made of reinforced concrete (**Fig. 12.9a, b**). The reactor itself contains nuclear fuel, consisting of pellets of concentrated uranium oxide or a comparable radioactive material that are packed into metal tubes called fuel rods. Fission occurs when a neutron strikes a radioactive atom, causing it to split. For example, radioactive uranium-235 splits into barium-141 and krypton-92, plus three neutrons. The neutrons released during the fission of one atom strike other atoms, thereby triggering more fission in a self-perpetuating process called a **chain reaction** that, overall, produces lots of heat. Pipes carry water close to the heat-generating fuel rods, and the heat transforms the water into high-pressure steam. The pipes then carry this steam to a turbine, where it rotates fan blades; the rotation drives a dynamo that generates electricity. Eventually, the steam goes into cooling towers, where it condenses back into water that can be reused in the plant or returned to the environment.

The Geology of Uranium

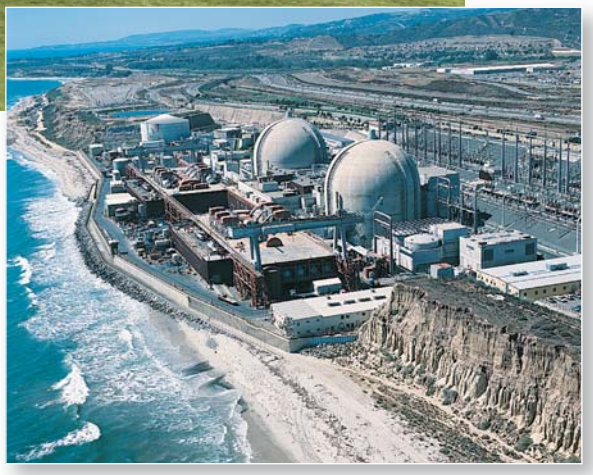
Where does uranium come from? The Earth's radioactive elements, including uranium, probably formed during the explosion of a supernova before the existence of the Solar System. Uranium atoms from this explosion became part of the nebula out of which the Earth grew and thus were incorporated into the planet. They gradually rose into the upper crust, carried in granitic magma.

Even though granite contains uranium, it does not contain very much. But nature has a way of concentrating uranium. Hot water circulating through a pluton after intrusion dissolves the uranium and precipitates it as the mineral pitchblende (UO_2) in veins. Uranium may be further concentrated once plutons, and the associated uranium-rich veins, weather and erode at the ground surface. Sand derived from a weathered pluton washes

FIGURE 12.9 Producing electricity at a nuclear power plant.



(a) In a nuclear power plant, a reactor heats water, which produces high-pressure steam. The steam drives a turbine that, in turn, drives a generator to produce electricity. A condenser transforms the steam back into water.



(b) This nuclear power plant in California has two reactors, each in its own containment building.

down a stream, and as it does so, uranium-rich grains stay behind because they are so heavy, relative to quartz and feldspar grains. Uranium deposits may also form when groundwater percolates through uranium-rich sedimentary rocks; the uranium dissolves in the water and moves with the water to another location, where it precipitates out of solution and fills the pores of the host sedimentary rock.

You can't just mine uranium and put it into a reactor. That's because ^{235}U, the isotope of uranium that serves as the most common fuel for nuclear power plants, accounts for only about 0.7% of naturally occurring uranium; most uranium consists of ^{238}U. Thus, to make a fuel suitable for use in a power plant, the ^{235}U concentration in a mass of natural uranium must be increased by a factor of 2 or 3, an expensive process called enrichment.

Challenges of Using Nuclear Power

Maintaining safety at nuclear power plants requires work. Operators must constantly cool the nuclear fuel with circulating water, and the rate of nuclear fission must be regulated by the insertion of control rods, which absorb neutrons and thus decrease the number of collisions between neutrons and radioactive atoms. If not properly controlled, the fuel would become so hot that it would melt. Such a **meltdown** might cause a steam explosion that could breach the containment building and scatter radioactive debris into the air. In some cases, the water gets so hot that it splits into hydrogen and oxygen gases that can recombine explosively. (Note that a meltdown is *not* the same as an atomic bomb explosion. The fuel of a reactor is not enriched enough for a "critical mass" to exist in which fission reactions happen so quickly that the fuel itself explodes.)

Did you ever wonder . . .
could a nuclear power plant explode like an atomic bomb?

Globally, about 450 nuclear power plants are currently operating. To date, there have been two major disasters in which the reactor buildings were damaged and significant quantities of radiation were released. The most serious nuclear disaster occurred at the power plant in Chernobyl, Ukraine, in April 1986. The fuel pile became too hot, triggering a steam or hydrogen explosion that raised the roof of the containment building and spread fragments of the reactor and its fuel around the plant grounds. Within 6 weeks, 20 people had died from radiation sickness. In 2011, a disaster occurred at the multi-reactor Fukushima power plant along the east coast of northern Japan. This disaster, second only to Chernobyl in terms of the amount of radiation released, occurred when the catastrophic tsunami (giant wave) that followed the magnitude 9.0 Tohoku earthquake knocked out the power providing electricity to pumps that circulated cooling water. As a result, some of the reactors overheated, and they suffered partial meltdowns and hydrogen gas explosions (see Chapter 10).

The nuclear industry also needs to manage **nuclear waste**, the radioactive material produced in a nuclear plant. Some radioactive material decays quickly (in decades to centuries), but some remains dangerous for thousands of years or more. Nuclear waste cannot just be stashed in a warehouse or buried in a town landfill. Some of the waste is hot enough that it needs to be cooled with water. Even cooler waste has the potential to leak radioactive elements into municipal water supplies or nearby lakes or streams. Ideally, waste should be sealed in containers that will last for thousands of years (the time needed for the short-lived radioactive atoms to undergo decay) and stored in a place where it will not come in contact with the environment. Finding an appropriate place is not easy.

Take-Home Message

Controlled fission in reactors produces nuclear power. The fuel consists of uranium or other elements obtained by mining. Reactors run the risk of meltdown, but cannot explode like an atomic bomb. They also yield radioactive waste that is difficult to store.

12.8 Other Energy Sources

Biofuels

In recent years, farmers have begun to produce rapidly growing crops such as corn and sugar cane specifically for the purpose of producing biomass for fuel production. The resulting liquids are called **biofuels**.

The most commonly used biofuel is ethanol, a type of alcohol. Ethanol can substitute for gasoline in car engines. The process of producing ethanol from corn includes the following steps. First, producers grind corn into a fine powder, mix it with water, and cook it to produce a mash of starch. Then, they add an enzyme to the mash, which converts the mash to sugar. The sugar, when mixed with yeast, ferments. Fermentation produces ethanol and CO_2. Finally, the fermented mash is distilled to concentrate the ethanol. Ethanol can be produced directly from sugar extracted from sugar cane without fermentation. More recently, researchers have begun to develop processes that yield ethanol from cellulose, permitting perennial grasses to become a source of liquid fuel, or from algae, which naturally produces fatty chemicals from which hydrocarbons can be produced. Recent technologies have also led to the commercial production of biodiesel, a fuel produced by chemical modification of fats and vegetable oils.

Geothermal Energy

As the name suggests, **geothermal energy** comes from the internal heat of the Earth. Geothermal energy exists because the crust becomes progressively hotter with increasing depth. Where the geothermal gradient is steep (meaning temperature increases rapidly with depth), we find high temperatures at relatively shallow depths. Groundwater absorbs heat from hot rock and itself becomes hot.

Power companies use geothermal energy to produce heat and electricity in several ways. For example, in some places, they simply pump hot groundwater out of the ground and run it through pipes to heat houses and spas. Elsewhere, the groundwater is so hot that when it rises to the Earth's surface and decompresses, it turns to steam. This steam can drive turbines and generate electricity (**Fig. 12.10**). In volcanic areas such as Iceland or New Zealand, geothermal energy provides for a major portion of energy needs. But on a global basis, it doesn't, because few cities lie near geothermal resources.

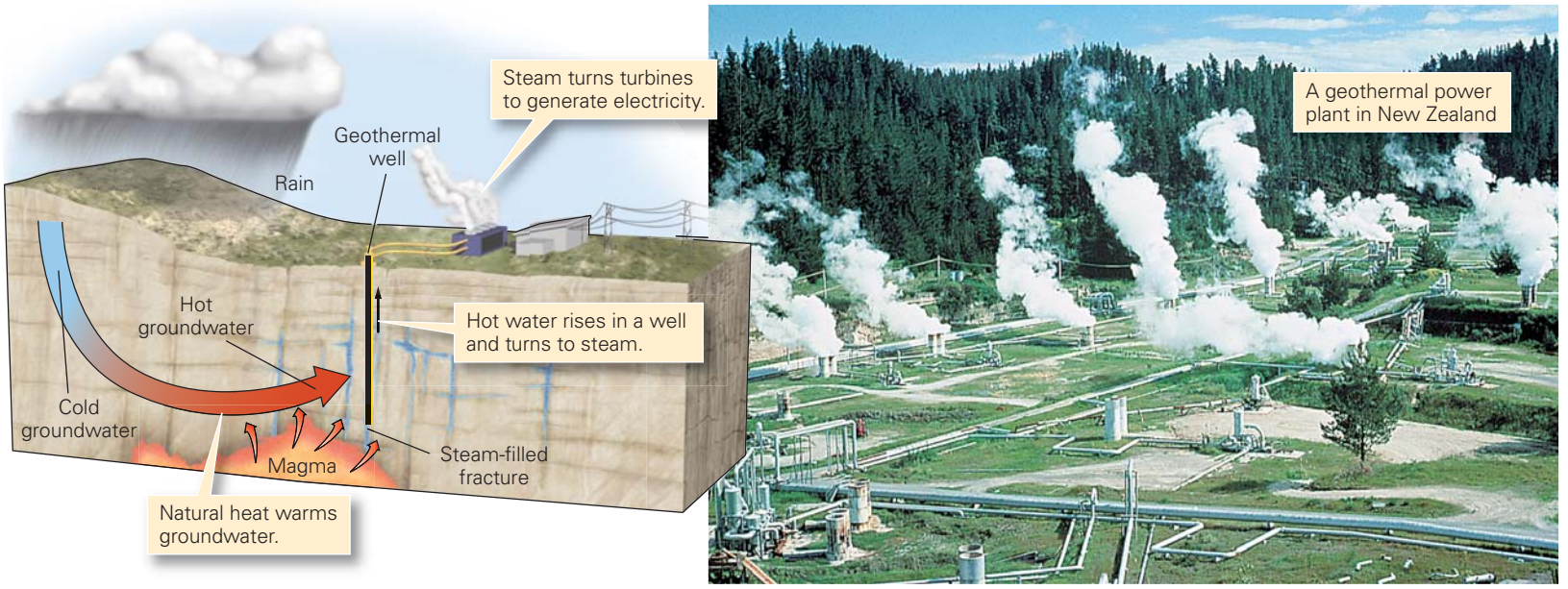
Though geothermal energy from very hot water can be tapped only in special locations, simple geothermal heat pumps can be set up on a household basis just about anywhere. The concept of a geothermal heat pump is simple—the temperature of the ground, at a depth of about six meters, stays roughly the same temperature all year. So, during the winter, cold water from a city water supply can be sent through underground pipes to warm up before being used in the house, and during the summer, warm water from inside the house can be sent through underground pipes to cool down and help remove heat from the house.

Hydroelectric and Wind Power

For millennia, people have used flowing water to produce energy. Waterwheels can provide the power to run mills and factories, so many cities grew up along rivers. In the past century, flowing water has also been used in hydroelectric power plants to produce electricity. In a modern hydroelectric power plant, the potential energy of water is converted to kinetic energy as the water flows from a higher elevation to a lower elevation. The flowing water turns turbine blades placed in a pipe, and the turbine drives an electrical generator. Most hydroelectric plants rely on water from a reservoir held back by a dam. The largest of these is the Three Gorges Dam on the Yangtze River in China (**Fig. 12.11a**).

Hydroelectric energy is clean, in the sense that its production does not release chemical or radioactive pollutants, and it is renewable, in the sense that its production does not consume resources. In addition, the large reservoirs behind the dams of hydroelectric power plants may provide irrigation water, flood control, and recreational opportunities. But the construction of dams and reservoirs may bring unwanted changes to a region, so the benefits of their construction must be weighed against potential harm. Damming a river may flood a spectacular canyon, eliminate exciting rapids, or destroy an ecosystem. Further, reservoirs trap sediment and nutrients, thus disrupting the supply of these materials to downstream floodplains or deltas, a process that may adversely affect agriculture.

FIGURE 12.10 Geothermal power plants utilize hot groundwater. In some cases, the water is so hot that it becomes steam when it rises and undergoes decompression. Most geothermal plants are in volcanic areas.



Not all hydroelectric power generation utilizes flowing river water—engineers have been developing new means to tap **tidal power**, the energy associated with the daily rises and fall of the tides; see Chapter 18. One approach involves building a dam, called a tidal barrage, across the entrance to a bay or estuary (the flooded mouth of a river) in which there are large tides. When the tide rises, water spills into the enclosed area through openings in the dam. When the tide drops, water remains trapped behind the barrage, and then flows back to the sea via a pipe that carries it through a power-generating turbine.

Modern efforts to harness the wind are rapidly developing on a large scale. To produce wind-generated electricity, engineers identify regions, either onshore or just offshore, with steady breezes. In these regions, they build wind farms that consist of numerous towers, each of which holds a wind turbine, a giant fan blade that turns even in a gentle breeze (**Fig. 12.11b**). Some towers are on the order of 100 m (300 ft) tall, with fan blades that are over 40 m (120 ft) long. The largest wind farm currently has close to 200 towers. As with any type of energy source, wind power has some drawbacks. Cluttering the horizon with towers may spoil a beautiful view, and the constant loud hum of the towers can disturb nearby residents. The towers may also be a hazard to migrating birds, and offshore towers may interfere with marine life.

Solar Energy

The Sun drenches the Earth with energy in quantities that dwarf the amounts stored in fossil fuels. Were it possible to harness this energy directly, humanity would have a reliable and totally clean solution for powering modern technology. But using solar energy is not quite so simple because converting light into heat remains quite inefficient.

Let's consider two options for producing solar energy. Household solar collectors consist of a black surface placed beneath a glass plate. The black surface absorbs light that has passed through the glass plate and heats up. The glass does not let the heat escape. When a consumer runs water between the glass and the black surface, the water heats up.

Photovoltaic cells (solar cells), the second option, convert light energy directly to electricity (**Fig. 12.11c**). Most photovoltaic cells consist of two wafers of silicon pressed together. One wafer contains tiny amounts of arsenic, and the other wafer contains tiny amounts of boron. When light strikes the cell, arsenic atoms release electrons that flow over to the boron atoms. If a wire loop connects the back side of one wafer to the back side of the other, this phenomenon produces an electrical current.

Fuel Cells

In a fuel cell, chemical reactions produce electricity directly. As an example, let's consider a hydrogen fuel cell. Hydrogen gas flows through a tube across a platinum anode that has been placed in a water solution containing an electrolyte (a substance that enables the solution to conduct electricity). At the same time, a stream of oxygen gas flows onto a separate platinum cathode that has also been placed into the solution. A wire connects the anode and the cathode to provide an electrical circuit (**Fig. 12.11d**). In this configuration, hydrogen reacts with oxygen to produce water and electricity. Fuel cells are efficient and clean. Their limitation lies in the need for a design that will protect the cells from damage by impact and that will enable them to store hydrogen, an explosive gas, in a safe way.

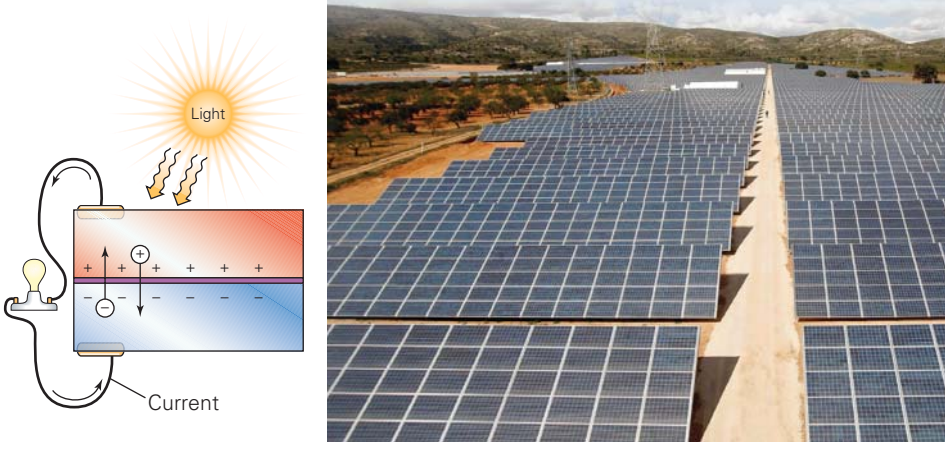
FIGURE 12.11 Alternative energy sources.



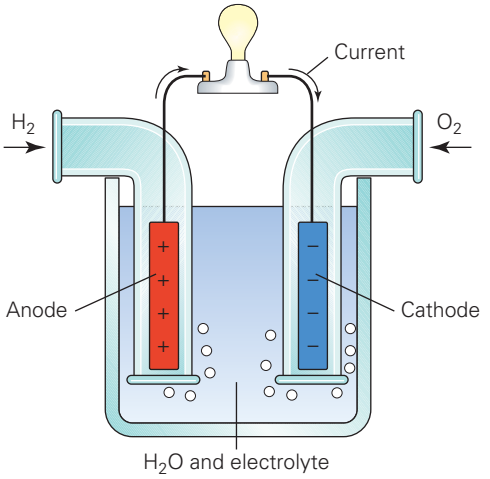
(a) Gravity causes water held back by the Three Gorges Dam to flow through turbines and generate electricity.



(b) A wind farm in southwestern England. The towers are about 50 m high.



(c) A photovoltaic cell produces electricity directly from solar radiation.



(d) A hydrogen fuel cell.

Also, it takes a significant amount of energy from other sources to produce the hydrogen used in fuel cells.

Take-Home Message

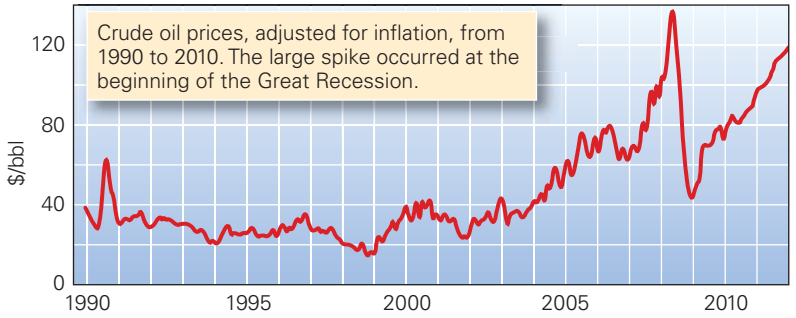
Biomass can be transformed into burnable alcohol and biodiesel. Geothermal energy utilizes hot groundwater that has been warmed by heat from Earth's interior. Flowing water (in rivers or tides), flowing air, solar panels, and fuel cells can also produce energy.

12.9 Energy Choices, Energy Problems

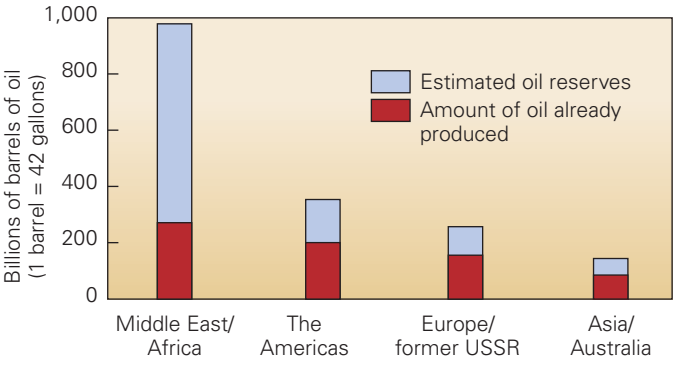
The Age of Oil and the Oil Crunch

Energy usage in industrialized countries grew with dizzying speed through the mid-20th century, and during this time people came to rely increasingly on oil. Eventually, oil supplies within the borders of industrialized countries could no longer match the demand, and these countries began to import more oil than they produced themselves. Through the 1960s, oil prices remained low (about $1.80 a barrel), so this was not a problem. In 1973, however, a complex tangle of politics and war led the Organization of Petroleum Exporting Countries (OPEC) to limit its oil exports. In the United States, fear of an oil shortage turned to panic, and motorists began lining up at gas stations, in many cases waiting for hours to fill their tanks. The price of oil rose to $18 a barrel, and newspaper headlines proclaimed, "Energy Crisis!" Governments in industrialized countries instituted new rules to encourage oil conservation. During the last two decades of the twentieth century, the oil market stabilized. Since 2004, oil prices rose overall, passing the $147/bbl mark in 2008; but the price collapsed in late 2008 when the Great Recession hit. More recently, the price has hovered around

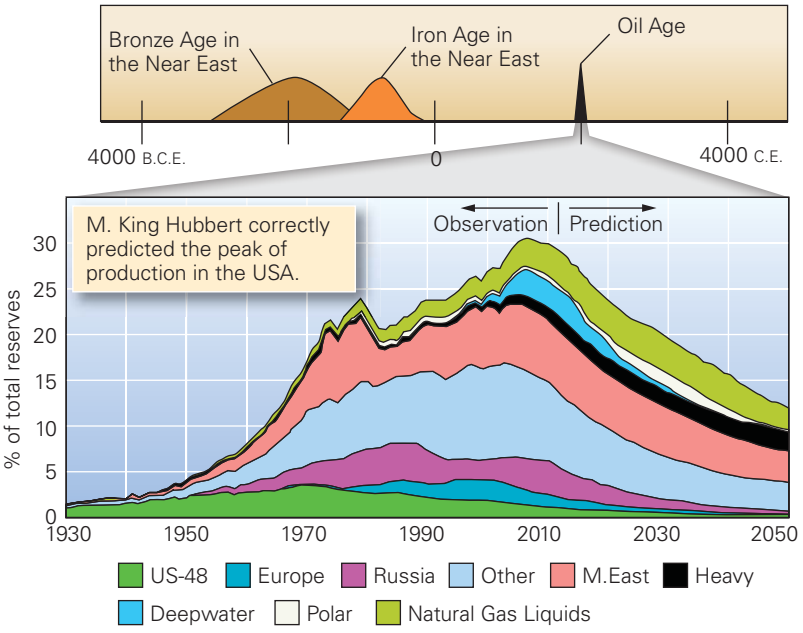
FIGURE 12.12 World energy use, cost and reserves.



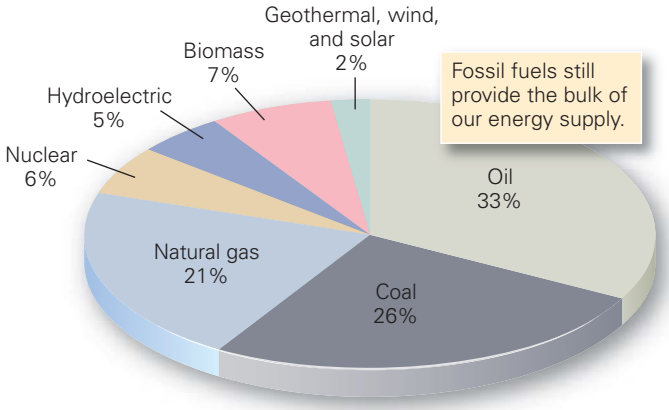
(a) Oil is currently the dominant source of energy worldwide. Recently, prices have been fluctuating dramatically.



(b) Estimated oil reserves worldwide.



(c) The age of oil will have a relatively short duration. The graph depicts changes in oil production over time. The high point is called "Hubbert's Peak."



(d) In the 21st century, a variety of energy sources have come into use globally. The percentages are approximate.

$100/bbl (**Fig. 12.12a**). Will a day come when shortages arise not because of politics or limitations on refining capacity, but because there is no more oil to produce? As highly populous countries such as China and India industrialize, the use of fuels accelerates. To understand the issues involved in predicting the future of energy supplies, we must first classify energy resources. As noted earlier, we call a particular resource *renewable* if nature can replace it within a short time relative to a human life span (in months or, at most, decades). A resource is *nonrenewable* if nature takes a very long time (hundreds to perhaps millions of years) to replenish it. Oil is a nonrenewable resource, in that the rate at which humans consume it far exceeds the rate at which nature replenishes it, so we will inevitably run out of oil. The question is, when?

Historians in the future may refer to our time as the **Oil Age** because so much of our economy depends on oil. How long will the Oil Age last? A reliable answer to this question is hard to come by, because there is not total agreement on the numbers that go into the calculation, especially as the use of unconventional reserves increases, so estimates vary widely. Geologists estimate that we've already used a substantial proportion of our *conventional* reserves, but that there are still about 850 to 1,350 billion barrels of *proven* conventional oil reserves (**Fig. 12.12b**), meaning reserves that have been documented and are still in the ground. Optimistically, there may be an additional 2,000 billion barrels of *unproven* conventional reserves, meaning oil that has not yet been found but might exist. Thus, the world possibly holds between 850 and 3,350 billion barrels of conventional oil. Presently, humanity guzzles oil at a rate of about 31 billion barrels per year. At this rate, conventional oil supplies will last until some time between 2050 and 2150, not too far in the future.

Did you ever wonder . . .
how much longer the world's oil supply will last?

Some geologists argue that the beginning of the end of the Oil Age has begun, because the rate of consumption now

exceeds the rate of discovery and in many regions, the rate of production has already started to decrease. The peak of production for a given reserve is called **Hubbert's Peak**, after the geologist who first emphasized that the production of reserves must decline because oil is a nonrenewable resource. Hubbert's Peak for the United States appears to have been passed in the 1970s. Some researchers argue that the global peak may occur between 2012 and 2014, but this number remains uncertain, and only time will tell. Conservation approaches, such as increasing the gas mileage of cars and increasing the amount of insulation in buildings, could stretch out supplies and make them last decades longer.

Of course, the picture of oil reserves changes significantly if *unconventional* reserves are included in estimates. All told, perhaps 1.5 trillion barrels of oil may be trapped in tar sands, and 3 trillion barrels trapped in oil shale. But wide disagreement remains concerning whether it's fair to include all of these reserves, because a significant proportion would be so difficult and expensive to access that they may never really be an economical energy source.

Even in the most optimistic scenario, including 3,000 billion bbls of conventional oil and perhaps 3,000 billion bbls of accessible unconventional oil, at current rates of consumption, supplies can last for only another 200 years, so the Oil Age will last a total of about 350 years (**Fig. 12.12c**). On a timeline representing the 4,000 years since the construction of the Egyptian pyramids, this looks like a very short blip. We may indeed be living during a unique interval of human history.

Can Other Fossil Fuels Replace Oil?

As true limits to the oil supply approach, societies are looking first at relatively abundant supplies of other conventional fossil fuels, namely natural gas and coal, as sources of energy (**Fig. 12.12d**). Rough estimates suggest that world natural gas reserves may exceed 180 trillion cubic meters, which would provide approximately the same amount of energy as 1.2 trillion barrels of oil. But tapping into this gas supply requires expensive technologies for extraction and transport. Similarly, worldwide coal reserves are estimated to be about 850 trillion tons, which contains approximately the same amount of energy as 11 trillion barrels of oil. But the stated number for coal reserves does not distinguish clearly between accessible (mineable) coal and inaccessible coal, which is too deep to mine. And, as is the case for oil, there are political and environmental consequences to relying on gas or coal.

Environmental Issues of Fossil Fuel Use

Environmental concerns about energy resources begin right at the source. Oil drilling requires substantial equipment, the use of which can damage the land. And as demonstrated by the 2010 Gulf of Mexico offshore well blowout, oil drilling can lead to tragic loss of life and disastrous marine oil spills (**Box 12.3**). Oil spills from pipelines or trucks sink into the subsurface and contaminate groundwater, and oil spills from ships and tankers create slicks that spread over the sea surface and foul the shoreline (**Fig. 12.13a, b**). Coal and uranium mining also scar the land and can lead to the production of acid mine runoff, a dilute solution of sulfuric acid that forms when sulfur-bearing minerals such as pyrite (FeS_2) in mines react with rainwater. The runoff enters streams and kills fish and plants. Collapse of underground coal mines may cause the ground surface to sink.

Numerous air-pollution issues also arise from the burning of fossil fuels, which sends soot, carbon monoxide, sulfur dioxide, nitrous oxide, and unburned hydrocarbons into the air. Coal, for example, commonly contains sulfur, primarily in the form of pyrite, which enters the air as sulfur dioxide

FIGURE 12.13 Marine oil spills. These can come from drilling rigs, or from tankers.



(a) An oil tanker leaking oil on the sea surface.



(b) Oil spills can contaminate the shore, and can be very difficult to clean.

BOX 12.3 CONSIDER THIS . . .

Offshore Drilling and the Deepwater Horizon Disaster

A substantial proportion of the world's oil reserves reside in the sedimentary basins that underlie the continental shelves of passive continental margins. To access such reserves, oil companies must build offshore drilling platforms. In water less than 600 m (2,000 ft) deep, companies position fixed platforms on towers resting on the sea floor. In deeper water, semi-submersible platforms float on huge submerged pontoons (**Fig. Bx12.3a**). With these, oil companies can now access fields lying beneath 3 km (10,000 ft) of water.

North America's largest offshore fields occur in the passive-margin basin that fringes the coast of the Gulf of Mexico. More than 3,500 platforms operate in the Gulf at present, together yielding up to 1.7 million bbl/day.

During both onshore and offshore exploration, drillers worry about the possibility of a **blowout**. A blowout happens when the pressure within a hydrocarbon reserve penetrated by a well exceeds the pressure that drillers had planned for, causing the hydrocarbons (oil and/or gas) to rush up the well in an uncontrolled manner and burst out of the well at the surface in an oil gusher or gas plume. Blowouts are rare because, although fluids below the ground are under great pressure due to the weight of overlying material, engineers fill the hole with drilling mud with a density greater than that of clear water. The weight of drilling mud can counter the pressure of underground hydrocarbons and hold the fluids underground. But if drillers encounter a bed in which pressures are unexpectedly high, or if they remove the mud before the walls of the well have been sealed with a casing (a pipe, cemented in place by concrete) a blowout may happen.

A catastrophic blowout occurred on April 20, 2010, when drillers on the Deepwater Horizon, a huge semi-submersible platform leased by BP, were finishing a 5.5-km-long (18,000 ft) hole in 1.5-km-deep (5,000 ft) water south of Louisiana. Due to a series of errors, the casing was not sufficiently strong when workers began to replace the drilling mud with clear water. Thus the high-pressure, gassy oil in the reservoir that the well had punctured rushed up the drillhole. A backup safety device called a blowout preventer failed, so the gassy oil reached the platform and sprayed 100 m (328 ft) into the sky. Sparks from electronic gear triggered an explosion, and the platform became a fountain of flame and smoke that killed 11 workers. An armada of fireboats could not douse the conflagration (**Fig. Bx12.3b**), and after 36 hours, the still-burning platform tipped over and sank.

Robot submersibles sent to the sea floor to investigate found that the twisted mess of bent and ruptured pipes at the well head was billowing oil and gas. On the order of 50,000 to 62,000 bbl/day of hydrocarbons entered the Gulf's water from the well. Stopping this underwater gusher proved to be an immense challenge, and initial efforts to block the well, or to put a containment dome over the well head, failed. It was not until July 15 that the flow was finally stopped, and not until September 19 that a new relief well intersected the blown well and provided a conduit to pump concrete down to block the original well permanently. All told, about 4.2 million bbl of hydrocarbons contaminated the Gulf from the Deepwater Horizon blowout. The spill was devastating to wetlands, wildlife, and the fishing and tourism industries.

FIGURE Bx12.3 The Deepwater Horizon.



(a) The Deepwater Horizon platform being transported to a drilling site.



(b) Fireboats dousing the burning rig, before the rig sank.

(SO_2) when coal is burned. This gas combines with rainwater to form dilute sulfuric acid (H_2SO_4), or **acid rain**. For this reason, many countries now regulate the amount of sulfur that coal can contain when it is burned. But even if pollutants can be decreased, burning fossil fuels still releases carbon dioxide (CO_2) into the atmosphere. As we discuss in Chapter 19, CO_2 is a greenhouse gas, so a change in the amount of CO_2 in the atmosphere can affect climate. Because of concern about CO_2 production, research efforts are under way to develop techniques to capture CO_2 at power plants, liquefy it, and pump it into reservoir rocks deep underground. This process is called **carbon sequestration**.

Alternative Energy

Can nuclear power or hydroelectric power replace oil? Vast supplies of uranium, the fuel of traditional nuclear plants, remain untapped. Further, nuclear engineers have designed alternative plants, powered by breeder reactors, that essentially produce new fuel. But many people view nuclear plants with concern because of issues pertaining to radiation, accidents, terrorism, and waste storage, and these concerns have slowed the industry. A substantial increase in hydroelectric power production is not likely, as most major rivers have already been dammed, and industrialized countries have little appetite for taming any more. Similarly, the growth of geothermal-energy output seems limited.

Because of the potential problems that might result from relying more on coal, hydroelectric, and nuclear energy, researchers have been increasingly exploring clean energy options (see Fig. 12.12d). One possibility is solar power, and the cost of solar power is steadily decreasing. Unfortunately, technologies for large-scale solar energy do not yet exist. Similarly, we can turn to wind power for relatively small-scale energy production, but covering the landscape with windmills is not appealing, and since wind production varies with wind speed, so it can't provide a steady supply that the present-day energy grid requires. Fusion power may be possible some day, but physicists and engineers have not yet figured out a way to harness it.

Clearly, society will be facing difficult choices in the not-so-distant future about where to obtain energy, and we will need to invest in the research required to discover new alternatives. By 2050, 40% of energy may be from renewable sources. In the near term, conservation can play an important role by diminishing demand for fossil fuels.

Take-Home Message

Oil is a nonrenewable resource and conventional supplies may run out in less than a century—we live in the Oil Age, which may last less than 350 years. Unconventional supplies may last longer, but use of fossil fuel has environmental consequences.

12.10 Introducing Mineral Resources

In June 1845, James Marshall arrived by horse at Sutter's Fort, in central California, to make a new life. Marshall convinced Captain John Sutter to finance the construction of a sawmill in the foothills of the Sierra Nevada Mountains. Marshall's scruffy crew finished the mill by the beginning of 1848. As Marshall stood admiring the new building, he noticed a glimmer of metal in the gravel that littered the bed of the adjacent stream. He picked it up, banged it between two rocks to test its hardness, and shouted, "Boys, by God, I believe I have found a gold mine!" For a short while, Marshall and Sutter managed to keep the discovery secret. But word of the gold soon spread, and within weeks, all the workers at Marshall's mill had disappeared into the mountains to seek their own fortunes. Through that year, gold fever spread throughout California and eventually reached the East Coast. As a result, 1849 brought 40,000 prospectors to California. These "forty-niners," as they were called, had abandoned their friends and relatives on the gamble that they could strike it rich.

Gold is but one of many mineral resources, meaning minerals extracted from the Earth's crust for use by people. Without these resources, industrialized societies could not function. Geologists divide mineral resources into two categories: metallic mineral resources (materials containing gold, copper, aluminum, iron, etc.) and nonmetallic mineral resources (building stone, gravel, sand, gypsum, phosphate, salt, etc.). Below, we look at the nature of mineral resources, the geologic phenomena responsible for their formation, and the ways people mine them. We conclude by considering the sustainability of mineral reserves.

12.11 Metals and Ores

Metal and Its Discovery

Metals are opaque, shiny, smooth solids that can conduct electricity and can be bent, drawn into wire, or hammered into thin sheets. In this regard, they look and behave quite differently from wood, plastic, meat, or rock. This is because, unlike in other substances, the atoms that make up metals are held together by metallic bonds, so electrons can flow from atom to atom fairly easily and atoms can, in effect, slide past each other without breaking apart.

The first metals that people used—copper, silver, and gold—can occur in rock as native metals. Native metals consist only of metal atoms, and thus look and behave like metal.

FIGURE 12.14 Gold occurs as native metal within quartz veins. The quartz breaks up to form sand, leaving nuggets of gold.



Gold nuggets, for example, are chunks of native metal that have eroded free of bedrock (**Fig. 12.14**). Over the ages, people have collected nuggets of native metal from streambeds and pounded them together with stone hammers to make arrowheads, scrapers, and later, coins and jewelry. But if we had to rely solely on native metals as our source of metal, we would have access to only a tiny fraction of our current metal supply. Most of the metal atoms we use today originated as ions bonded to nonmetallic elements in a great variety of minerals that themselves look nothing like metal. Only because of the chance discovery by some prehistoric genius that certain rocks, when heated to high temperatures in fire (a process called smelting), decompose to yield metal plus a nonmetallic residue called slag, do we now have the ability to produce sufficient metal for the needs of industrialized society.

What Is an Ore?

The minerals from which metals can be extracted are called **ore minerals**, or economic minerals. These minerals contain metal in high concentrations and in a form that can be easily extracted. Galena (PbS), for example, is about 50% lead, so we consider it to be an ore mineral of lead (**Fig. 12.15a**). We obtain most of our iron from hematite and magnetite. Copper comes from a variety of minerals, none of which look like copper (**Fig. 12.15b**). Geologists have identified a great variety of ore minerals. Many ore minerals are sulfides, in which the metal occurs in combination with sulfur (S), or oxides, in which the metal occurs in combination with oxygen (O).

To obtain the metals needed for industrialized society, we mine **ore**, rock containing native metals or a concentrated accumulation of ore minerals. To be an ore, rock must not only contain ore minerals, it must also contain a sufficient amount to make the rock worth mining. Iron constitutes only about 6.2% of the continental crust's weight but makes up about 30% to 60% of iron ore. The concentration of a useful metal in an ore determines the **grade** of the ore—the higher the concentration, the higher the grade. Whether or not an ore of a given grade is worth mining depends on the price of metal in the market.

How Do Ore Deposits Form?

Ore minerals do not occur uniformly through rocks of the crust. If they did, we would not be able to extract them economically. Fortunately for humanity, geologic processes concentrate these minerals into accumulations called ore deposits. Simply put, an **ore deposit** is an economically significant occurrence of ore. The various kinds of ore deposits differ from each other in terms of which ore minerals they contain and which geologic conditions led to their formation. Below, we introduce a few examples.

Magmatic deposits. When a magma cools, sulfide ore minerals crystallize early, then, because sulfides tend to be dense,

FIGURE 12.15 Examples of ore minerals.

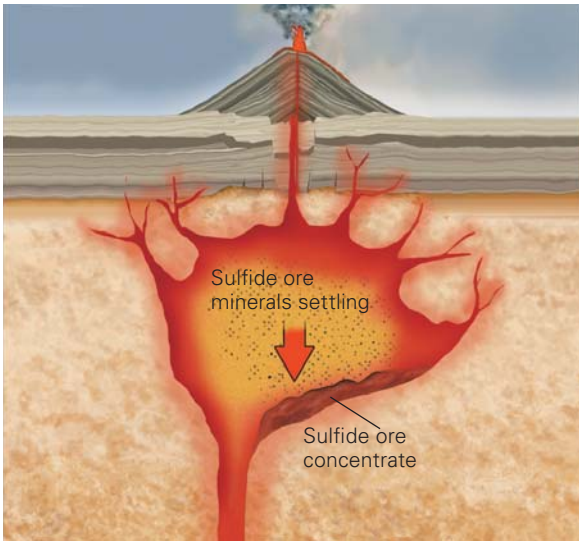


(a) This lead ore, from Missouri, consists of galena (PbS) crystals that grew in dolostone.

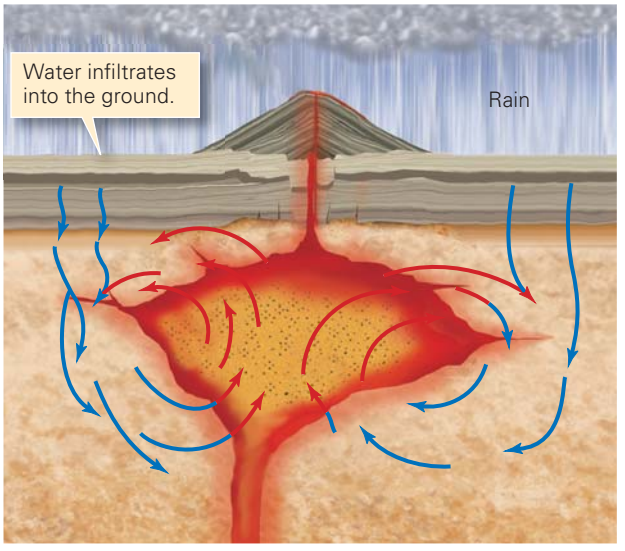


(b) Most copper comes from ore minerals that look nothing like metallic copper. This ore consists of azurite (blue) and malachite (green).

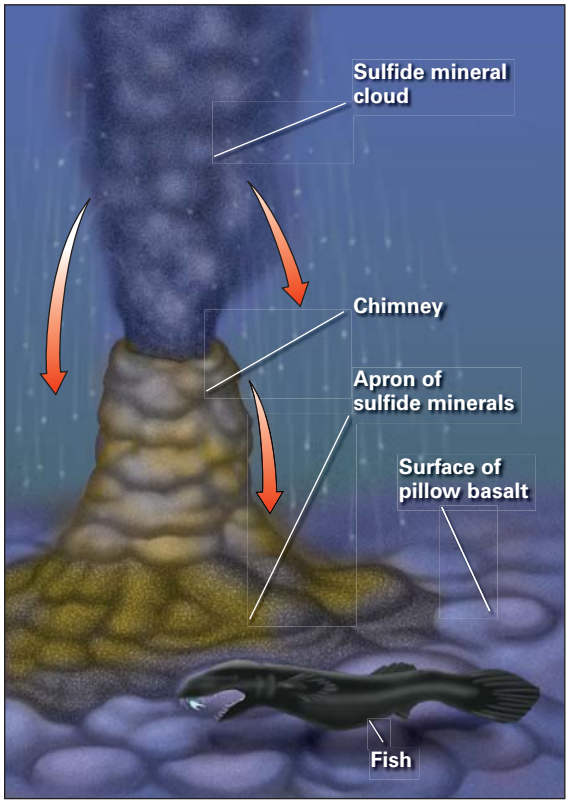
FIGURE 12.16 Various processes that form ore deposits.



(a) Massive-sulfide deposits can form when sulfide ore minerals sink to the bottom of a magma chamber.



(b) Hydrothermal deposits form when water circulating around and through magma dissolves and redistributes metals.



(c) Massive-sulfide deposits also form when ore minerals precipitate around hydrothermal vents (black smokers) along a mid-ocean ridge.

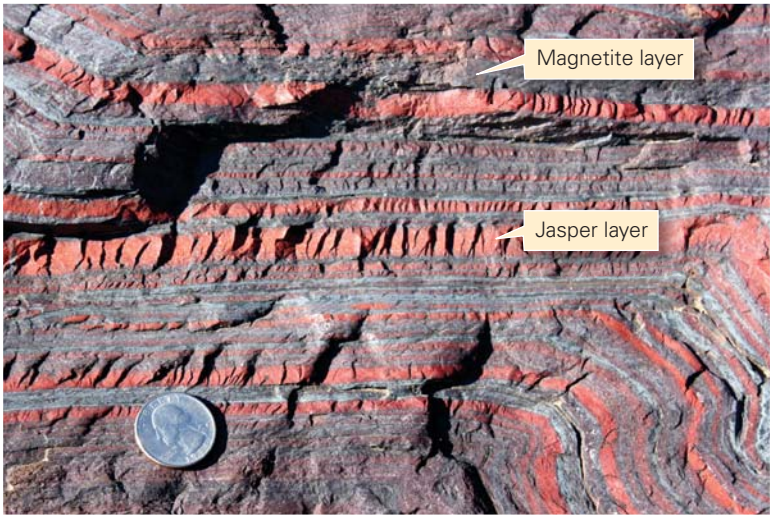
they sink to the bottom of the magma chamber, where they accumulate; this accumulation is a *magmatic deposit*. When the magma freezes solid, the resulting igneous body may contain a concentration of sulfide minerals at its base. Because of their composition, such concentrations are known as "massive-sulfide deposits" (**Fig. 12.16a**).

Hydrothermal deposits. Hydrothermal activity involves the circulation of hot-water solutions through a magma or through the rocks surrounding an igneous intrusion. These fluids dissolve metal ions. When a solution enters a region of lower pressure, lower temperature, different acidity, and/or different availability of oxygen, the metals come out of solution and form ore minerals that precipitate in fractures and pores, creating a *hydrothermal deposit* (**Fig. 12.16b**). Such deposits may form within an igneous intrusion or in surrounding country rock. If the resulting ore minerals disperse through the intrusion, we can also call the deposit a *disseminated deposit*, but if they precipitate to fill cracks in preexisting rock, we can call the deposit a *vein deposit*; veins are mineral-filled cracks.

In recent decades, geologists have discovered that hydrothermal activity at the submarine volcanoes along mid-ocean ridges leads to the eruption of hot water, containing high concentrations of dissolved metal and sulfur, from a vent. When this hot water comes in contact with cold seawater, the dissolved components instantly precipitate as tiny crystals of metal-sulfide minerals (**Fig. 12.16c**). The erupting water, therefore, looks like a black cloud, so the vents are called "black smokers" (see Chapter 2). The minerals in the cloud eventually sink and form a pile of ore minerals around the vent. Since the ore minerals typically are sulfides, the resulting hydrothermal deposits constitute another type of massive-sulfide deposit.

Secondary-enrichment deposits. Sometimes groundwater passes through ore-bearing rock long after the rock first formed. This groundwater dissolves some of the ore minerals and carries the dissolved ions away. When the water eventually flows into a different chemical environment

FIGURE 12.17 A Precambrian banded iron formation from northern Michigan.



(for instance, one with a different amount of oxygen or acid), it precipitates new ore minerals, commonly in concentrations exceeding that of the original deposit. A new ore deposit formed from metals that were dissolved and carried away from a preexisting ore deposit is called a *secondary-enrichment deposit*. Some of these deposits contain spectacularly beautiful copper-bearing carbonate minerals, such as azurite and malachite (see Fig. 12.15).

MVT ores. Rain falling along one margin of a large sedimentary basin may sink into the subsurface and then flow as groundwater along a curving path that takes it first down to the bottom of the basin, and then eventually back up to the opposite margin of the basin, hundreds of kilometers away. At the bottom of the basin, temperatures become high enough that the water dissolves metals. As the water returns to the surface and enters cooler rock, these metals precipitate in ore minerals. Ore deposits formed in this way, containing lead- and zinc-bearing minerals, appear in dolomite beds of the Mississippi Valley region of the United States, and thus have come to be known as Mississippi Valley–type (MVT) ores.

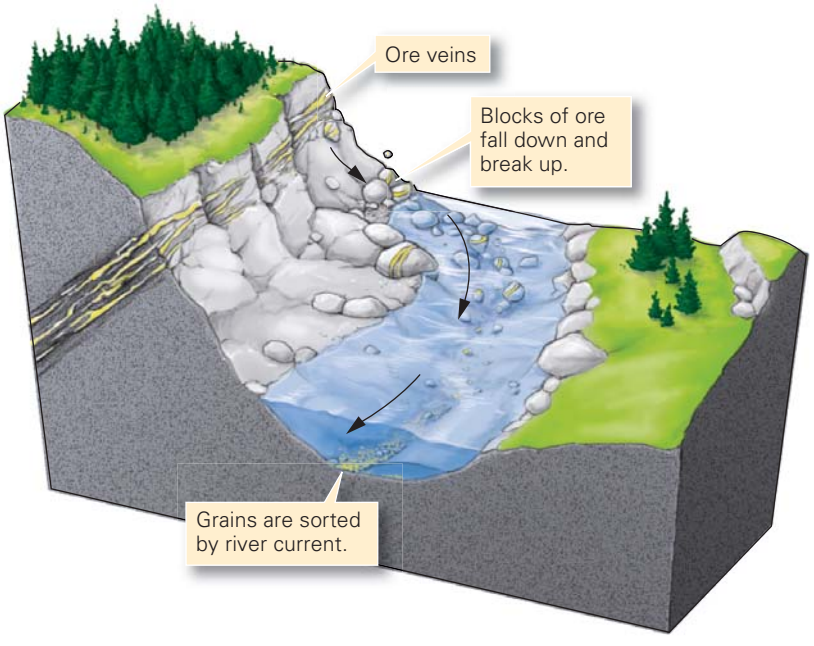
Sedimentary deposits of metals. Some ore minerals accumulate in sedimentary environments under special circumstances. For example, between 2.5 and 1.8 billion years ago, the atmosphere, which previously had contained very little oxygen, gained oxygen because of the evolution of abundant photosynthetic organisms. This change affected the chemistry of seawater so that large quantities of dissolved iron precipitated as iron oxide minerals that settled as sediment on the sea floor. As you learned in Chapter 11, the resulting iron-rich sedimentary deposits are known as a banded iron formation (BIF) (**Fig. 12.17**), because after lithification they consist of alternating beds of gray iron oxide (magnetite or hematite) and red beds of jasper (iron-rich chert).

The chemistry of seawater in some parts of the ocean today leads to the deposition of manganese-oxide minerals on the sea floor. These minerals grow into lumpy accumulations known as manganese nodules. Mining companies have begun to explore technologies for vacuuming up these nodules; geoscientists estimate that the worldwide supply of nodules contains 720 years' worth of copper and 60,000 years' worth of manganese, at current rates of consumption.

Residual mineral deposits. Recall from Interlude B that as rainwater sinks into the Earth, it leaches (dissolves) certain elements and leaves behind others, as part of the process of forming soil. In rainy, tropical environments, the residue left behind in soils after leaching includes concentrations of iron or aluminum. Locally, these metals become so concentrated that the soil itself becomes an ore deposit. We refer to such deposits as *residual mineral deposits*. Most of the aluminum ore mined today comes from bauxite, a residual mineral deposit created by the extreme leaching of rocks (such as granite) containing aluminum-bearing minerals.

Placer deposits. Ore deposits may develop when rocks containing native metals erode, producing a mixture of sand grains and metal flakes or nuggets (pebble-sized fragments). For example, gold accumulates in sand or gravel bars along the course of rivers, for the moving water carries away lighter mineral grains (quartz and feldspar) but can't move the heavy metal grains (gold) so easily. Concentrations of metal grains in stream sediments are a type of placer deposit (**Fig. 12.18**). Panning further concentrates gold flakes or nuggets—swirling water in a pan causes the lighter sand grains to wash away, leaving the gold behind.

FIGURE 12.18 Placer deposits form where erosion produces clasts of native metals. Sorting by the stream concentrates the metals.



Where Are Ore Deposits Found?

The Inca Empire of fifteenth-century Peru boasted elaborate cities and temples, decorated with fantastic masks, jewelry, and sculptures made of gold. Then, around 1532, Spanish ships arrived, led by conquistadors who quipped, "We Spaniards suffer from a disease that only gold can cure." The Incas, already weakened by civil war, were no match for the armor-clad Spaniards with their guns and horses. Within six years, the Inca Empire had vanished, and Spanish ships were transporting Inca treasure back to Spain. Why did the Incas possess so much gold? Or to ask the broader question, what geologic factors control the distribution of ore? Once again, we can find the answer by considering the consequences of plate tectonics.

Several of the ore-deposit types mentioned above occur in association with igneous rocks. As we learned in Chapter 4, igneous activity does not happen randomly around the Earth, but rather concentrates along convergent plate boundaries (specifically, in the overriding plate of a subduction zone), along divergent plate boundaries (along mid-ocean ridges), continental rifts, or hot spots. Thus, magmatic and hydrothermal deposits (and secondary-enrichment deposits derived from these) occur in these geologic settings. Placer deposits are typically found in the sediments eroded from such magmatic or hydrothermal deposits. The Inca gold formed in the Andes along a convergent plate boundary.

Take-Home Message

Ores can be processed economically to produce metals. Ores form by settling from a melt, precipitating from hot water, deposition from currents, interaction with groundwater, and extreme weathering. The distribution of ores can be explained by plate tectonics.

12.12 Ore-Mineral Exploration and Production

Imagine an old prospector of days past clanking through the desert with a worn-out donkey. To find bedrock ore, such prospectors would eye hillsides for a "show," visible evidence on the ground surface. What does a show look like? It may be an outcropping of milky-white quartz veins, or brightly colored stains due to oxidation (rusting) of ore minerals. On finding a possible ore, a prospector would take samples back to town for an assay, a test to determine how much extractable metal the samples contain. If the assay indicated a significant concentration of metal, the prospector might "stake a claim" by literally marking off an area of ground with stakes.

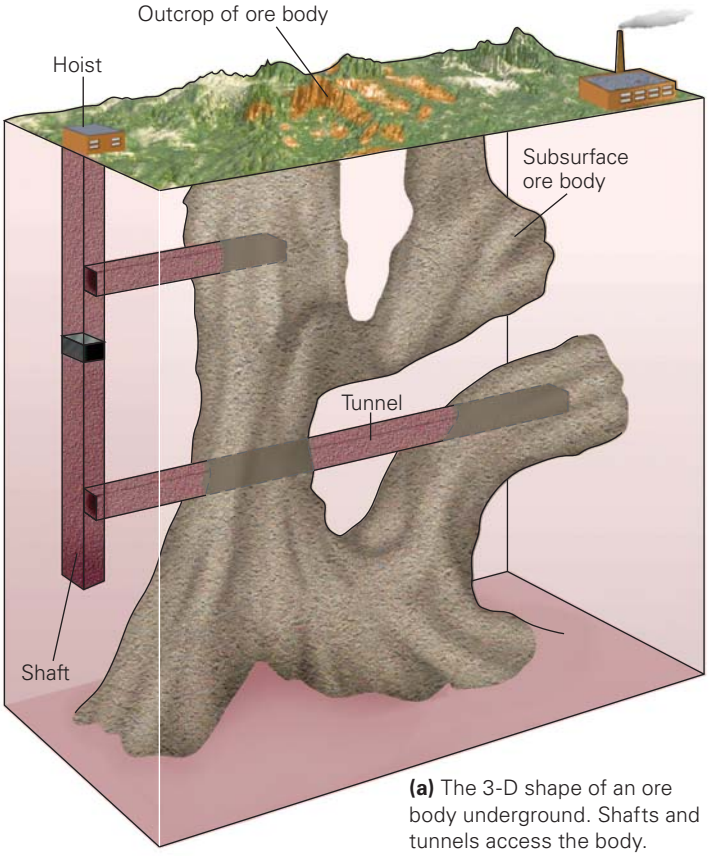
These days, large mining companies employ professional geologists to survey ore-bearing regions systematically. The geologists focus their studies on rocks that developed in settings appropriate for ore formation. Once such a region has been identified, they may measure gravity or magnetic anomalies (see Interlude D), because ore minerals tend to be denser and more magnetic than average rocks (**Fig. 12.19a**). Geologists also sample rocks and soils to test for metal content, and may even analyze plants in the area to detect traces of metals, for plants absorb metals through their roots. Once geologists have identified a possible ore deposit, they drill holes to sample subsurface rock and to determine the ore deposit's shape and extent. Ore-mineral exploration sometimes takes geologists into jungles, deserts, and tundras worldwide.

If calculations indicate that mining an ore deposit will yield a profit, and if environmental concerns can be accommodated, a company builds a mine. Mines can be below or above ground, depending on how close the ore deposit is to the surface. To develop an open-pit mine (**Fig. 12.19b**), workers first drill a series of holes into the solid bedrock and then fill the holes with high explosives. They must space the holes carefully and must set off the charges in a precise sequence, so that the bedrock shatters into appropriate-sized blocks for handling. When the dust settles, large front-end loaders dump the ore into giant ore trucks, which can carry as much as 200 tons of ore in a single load. (In comparison, a loaded cement mixer weighs about 70 tons.) The trucks transport waste rock or "tailings" (rock that doesn't contain ore) to a tailings pile and the ore to a crusher, a giant set of moving steel jaws that smash the ore into small fragments. Workers then separate ore minerals from other minerals and send the ore-mineral concentrate to a processing plant, where it undergoes smelting or treatment with acidic solutions to separate metal atoms from other atoms. Eventually, workers melt the metal and then pour it into molds to make ingots (brick-shaped blocks) for transport to a manufacturing facility.

If the ore deposit lies more than about 100 meters below the Earth's surface, miners must dig an underground mine. To do so, they either bore a tunnel into the side of a mountain (the entrance to the tunnel is called an adit), or they sink a vertical shaft in which they install an elevator. At the level in the crust where the ore body appears, they build a maze of tunnels into the ore by drilling holes into the rock and then blasting. The rock removed must be carried back to the surface. Rock columns between the tunnels hold up the ceiling of the mine.

Miners face danger from mine collapse and rockfalls. In 2010, a collapse trapped 33 miners at a depth of 500 m (~1600 feet) below the ground surface in Chile. They remained underground for 69 days until a wide hole was drilled down to the chamber they were huddled in. One billion viewers watched on TV as the miners were brought up from the hole, one by one.

FIGURE 12.19 Mining ore deposits.



(a) The 3-D shape of an ore body underground. Shafts and tunnels access the body.



(b) Open-pit mining utilizes ore that lies fairly close to the ground surface. The steps help wall stability.

Take-Home Message

Geologists study outcrops and drillholes for ore shows, and make maps of gravity and rock magnetism in order to discover ore deposits. Mining takes place either in open-pit mines or in shafts and tunnels underground.

12.13 Nonmetallic Mineral Resources

So far, this chapter has focused on resources that contain metal. But society uses many non-metallic mineral resources, also known as **industrial minerals**, as well. From the ground, we get the stone used to make roadbeds and buildings, the chemicals for fertilizers, the gypsum in drywall, the salt filling salt shakers, and the sand used to make glass—the list is endless. This section looks at a few of these materials and explains where they come from.

Dimension Stone

The Parthenon, a colossal stone temple rimmed by 46 carved columns, has stood atop a hill overlooking the city of Athens

FIGURE 12.20 Stone production in quarries.



(a) An active quarrying operation in Missouri that produces large blocks of cut dimension stone.



(b) A crushed limestone quarry in Illinois. The stone is sorted by fragment size.

for almost 2,500 years. No wonder—"stone," an architect's word for rock, outlasts nearly all other construction materials. We use stone to make facades, roofs, curbs, steps, countertops, and floors. We value stone for its visual appeal as well as its durability. The names that architects give to various types of stone may differ from the formal rock names that geologists use. For example, architects refer to any polished carbonate rock as "marble," whether or not it has been metamorphosed. Likewise, they refer to any crystalline rocks containing feldspar and/or quartz as "granite," regardless of whether the rock has an igneous or a metamorphic texture, or a felsic or mafic composition.

To obtain intact slabs and blocks of rock—known as **dimension stone** in the trade—for architectural purposes, workers must carefully cut rock out of the walls of quarries (**Fig. 12.20a**). (Note that a quarry provides stone, whereas a mine supplies ore.) To cut stone slabs, quarry operators split rock blocks from bedrock by hammering a series of wedges into the rock, or slice it off bedrock by using a wireline saw, a thermal lance, or a water jet. A wireline saw consists of a loop of braided wire moving between two pulleys. In some cases, as the wire moves along the rock surface, the quarry operator spills abrasive (sand or garnet grains) and water onto the wire. The movement of the wire drags the abrasive along the rock and grinds into it. Alternatively, the quarry operator may use a diamond-coated wire, cooled with pure water. A thermal lance looks like a long blowtorch: a flame of burning diesel fuel, stoked by high-pressure air, pulverizes rock and thereby cuts a slot. More recently, quarry operators have begun to use an abrasive water jet, which squirts out water and abrasives at very high pressure, to cut rock.

Crushed Stone and Concrete

Crushed stone forms the substrate of highways and railroads and serves as the raw material for manufacturing cement, concrete, and asphalt. In crushed-stone quarries (**Fig. 12.20b**), operators use high explosives to break up bedrock into rubble that they then transport by truck to a jaw crusher. This reduces the rubble into usable chunks.

Most of the buildings and highways constructed in the past two centuries consist of bricks attached to each other by mortar, or of walls, floors, columns, and roads made of concrete that has been spread into a layer or poured into a form. Both mortar and concrete start out as a slurry, but when allowed to set, they harden into a hard, rock-like substance. The slurry from which mortar and concrete form consists of "aggregate" (sand and/or gravel) mixed with water and cement. Before mixing, the **cement** in mortar and concrete is a powder that consists of lime (CaO), quartz (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3); typically, lime accounts for 66% of cement, silica for 25%, and the remaining chemicals for about 9%. When cement is mixed with water, the chemicals comprising it dissolve. Mortar and concrete set when these chemicals react and a complex assemblage of new mineral crystals grows and binds together preexisting solid grains—in effect, the "cement" in mortar or concrete serves the same purpose as the "cement" in a sandstone or conglomerate.

Did you ever wonder . . .
how concrete differs from rock?

It appears that the ancient Romans were the first to use cement—they made it from a mixture of volcanic ash and limestone. In the 18th and early 19th centuries, cement was produced by heating specific types of limestone (which happened to contain calcite, clay, and quartz in the correct proportions) in a kiln up to a temperature of about 1450°C; the heating releases CO_2 gas and produces "clinker," chunks consisting of lime and other oxide compounds. Manufacturers crushed the clinker into cement powder and packed it in bags for transport. But limestone with the exact composition necessary to make such "cement" is fairly rare, so most cement used today is **Portland cement**, made by mechanically mixing limestone, sandstone, and shale in just the right proportions, before heating in a kiln to provide the correct chemical makeup. Isaac Johnson, an English engineer, came up with the recipe for Portland cement in 1844; he named it after the town of Portland, England, because he thought that concrete made from it resembled rock exposed there.

Nonmetallic Minerals for Homes and Farms

We use an astounding variety of nonmetallic geologic resources without ever realizing where they come from. Consider the materials in a typical house or apartment. The foundation consists of concrete, made from limestone mixed with sand or gravel. The bricks in the exterior walls originated as clay, formed from the chemical weathering of silicate rocks and perhaps dug from the floodplain of a stream. To make bricks, workers mold wet clay into blocks and then bake it. Baking drives out water and causes metamorphic reactions that recrystallize the clay. The glass used to glaze windows consists largely of silica, formed by first melting and then freezing pure quartz sand from a beach deposit or a sandstone formation. Gypsum board (drywall), used to construct interior walls, comes from a slurry of water and the mineral gypsum sandwiched between sheets of paper. Gypsum ($CaSO_4 \cdot 2H_2O$) occurs in evaporite strata precipitated from seawater or saline lake water. Evaporites provide other useful minerals as well, such as halite, and serve as the source for lithium, a key element in computer and camera batteries.

Modern technological innovations have also greatly increased the demand for the **rare earth elements**, a group of 17 elements including the lanthanides, scandium, and yttrium.

While the names of rare earth elements are unfamiliar to most people, the elements themselves have become essential in the production of lasers, magnets, X-ray tubes, night-vision goggles, camera lenses, and high-tech lamps. Rare earth elements aren't actually that rare, in terms of their abundance relative to other elements in the crust. But localities where ores have a high enough concentration to be mined are rare.

Take-Home Message

Society uses a great variety of nonmetallic geologic materials. These include dimension stone, crushed stone, cement (made from roasted limestone), evaporites (including gypsum), and clay (to make bricks).

12.14 Global Mineral Needs

How Long Will Resources Last?

The average citizen of an industrialized country uses 25 kilograms (kg) of aluminum, 10 kg of copper, and 550 kg of iron and steel in a year's time (Table 12.1). If you combine these figures with the quantities of energy resources and nonmetallic geologic resources a person uses, you get a total of about 15,000 kg (15 metric tons) of resources used per capita each year. To create the supply of the materials used in the United States alone, workers must mine, quarry, or pump 18 billion metric tons per year. By comparison, the Mississippi River transports 190 million metric tons of sediment per year.

TABLE 12.1 Yearly per Capita Usage of Geologic Materials in the United States

4,100 kg	Stone
3,860 kg	Sand and gravel
3,050 kg	Petroleum
2,650 kg	Coal
1,900 kg	Natural gas
550 kg	Iron and steel
360 kg	Cement
220 kg	Clay
200 kg	Salt
140 kg	Phosphate
25 kg	Aluminum
10 kg	Copper
6 kg	Lead
5 kg	Zinc

1 kg = 2.205 pounds

TABLE 12.2 Expected Lifetimes of Currently Known Ore Resources (in years)

Metal	World Resources	U.S. Resources
Iron	120	40
Aluminum	330	2
Copper	65	40
Lead	20	40
Zinc	30	25
Gold	30	20
Platinum	45	1
Nickel	75	less than 1
Cobalt	50	less than 1
Manganese	70	0
Chromium	75	0

Mineral resources, like oil and coal, are nonrenewable resources. Once mined, an ore deposit or a limestone hill disappears forever. Natural geologic processes do not happen fast enough to replace the deposits as quickly as we use them. Geologists have calculated reserves (measured quantities of a commodity) for various mineral deposits just as they have for oil. Based on current definitions of reserves (which depend on today's prices) and rates of consumption, supplies of some metals may run out in only decades to centuries (Table 12.2). But these estimates may change as supplies become depleted and prices rise, making previously uneconomical deposits worth mining. And supplies could increase if geologists discover new reserves or if new ways of mining become available. Further, increased efforts at conservation and recycling can cause a dramatic decrease in rates of consumption and thereby stretch the lifetime of existing reserves.

Ore deposits do not occur everywhere because their formation requires special geologic conditions. As a result, some countries possess vast supplies, whereas others have none. In fact, no single country owns all the mineral resources it needs, so nations must trade with each other to maintain supplies, and global politics inevitably affects prices. Many wars have their roots in competition for mineral reserves, and it is no surprise that the outcomes of some wars have hinged on who controls these reserves.

Mining and the Environment

Mining leaves a big footprint in the Earth System. Some of the gaping holes that open-pit mining creates in the landscape have become so big that astronauts can see them from space. Both open-pit (See for Yourself L) and underground mining yield immense quantities of waste rock, which miners dump in tailings piles. Some tailings piles grow into artificial hills 200 meters high and many kilometers long. Lacking soil, tailings

FIGURE 12.21 Environmental consequences of producing metallic mineral resources.



(a) The orange color in this mine runoff is due to iron and sulfide in the water.



(b) Acidic smelter smoke killed off vegetation near Sudbury, Ontario, in the 1970s. A large tailings pile can be seen in the distance.

piles tend to remain unvegetated for a long time. Mining also exposes ore-bearing rock to the atmosphere, and since many ore minerals are sulfides, they react with rainwater to produce acid mine runoff, which can severely damage vegetation downstream (**Fig. 12.21a**). In many cases, mining companies douse tailings with acidic solutions to leach out more metals; these acids sometimes escape into the environment.

Ore processing tends to release noxious chemicals that can mix with rain and spread over the countryside, damaging life. Before the installation of modern environmental controls, smoke from ore-processing plants caused severe air pollution; plumes of smoke from the old smelters in Sudbury, Ontario, for example, created a wasteland for many kilometers downwind (**Fig. 12.21b**). In recent years, people have made efforts to reclaim mining spoils, and new technologies have been developed to extract metals in ways that are less deleterious to the environment.

Take-Home Message

Mineral resources are nonrenewable, so minerals have limited reserves. Also, reserves are not distributed uniformly around the planet, so all supplies are not accessible to all consumers. Mineral utilization has significant environmental consequences.

ANOTHER VIEW The Bingham open-pit mine near Salt Lake City, Utah is 1.2 km deep and 4 km wide, making it the largest excavation in the world. In this photo, the pit itself is largely hidden by vast tailing piles, the debris left behind once the ore has been extracted. During its century of operation, the mine has yielded about 17 million tons of copper, 700 tons of gold, 6,000 tons of silver, and 400 tons of molybdenum.



CHAPTER 12 REVIEW

Chapter Summary

- Energy resources come in a variety of forms: energy directly from the Sun; energy from tides, flowing water, or wind; energy from chemical reactions; energy from nuclear fission; and geothermal energy from Earth's internal heat.
- Oil and gas are hydrocarbons formed from the organic leftovers of plankton, which settle out and become incorporated in black organic shale. Chemical reactions at elevated temperatures convert the organic matter to kerogen and then oil.
- To form an oil reserve, oil must migrate from a source rock into a reservoir rock. The subsurface configuration of strata that holds oil is called an oil trap.
- Substantial volumes of hydrocarbons also exist in tar sand, gas shale, and oil shale.
- For coal to form, abundant plant debris must be deposited in an oxygen-poor environment. Compaction creates peat that, when buried deeply and heated, transforms into coal.
- Geologists rank coal based on the amount of carbon it contains. Coal occurs in beds, and can be mined by either strip mining or underground mining.
- Nuclear power plants generate energy by using the heat released from the fission of uranium.
- Nuclear reactors must be carefully controlled to avoid overheating or meltdown. The disposal of radioactive nuclear waste can create environmental problems.
- Geothermal energy uses Earth's internal heat to transform groundwater into steam that drives turbines; hydroelectric power uses the potential energy of water; and solar energy uses solar cells to convert sunlight to electricity.
- We now live in the Oil Age, but oil supplies may last for only another century, and use of energy resources has many environmental consequences.
- Industrial societies use many types of minerals, all of which must be extracted from the upper crust.
- Metals come from ore. An ore is a rock containing native metals or ore minerals in sufficient quantities to be worth mining.
- Magmatic ore deposits form when ore minerals settle to the floor of a magma chamber. In hydrothermal deposits, ore minerals precipitate from hot-water solutions. Secondary-enrichment deposits form when groundwater carries metals away from a preexisting deposit. MVT deposits precipitate from groundwater. Sedimentary deposits settle out of water. Residual mineral deposits are the result of severe leaching. Placer deposits develop when metal grains accumulate in sediment.
- Nonmetallic resources include dimension stone, crushed stone, clay, sand, and many other materials. A large proportion of materials in your home have a geological ancestry.
- Mineral resources are nonrenewable. Many are now or may soon be in short supply.

Key Terms

acid rain (p. 375)
biofuel (p. 369)
biomass (p. 354)
blowout (p. 374)
carbon sequestration (p. 375)
cement (p. 381)
chain reaction (p. 367)
coal (p. 362)
coalbed methane (p. 367)
coal gasification (p. 367)
coal rank (p. 365)
coal reserve (p. 365)
dimension stone (p. 381)
directional drilling (p. 360)
distillation column (p. 361)
energy resource (p. 353)
fossil fuel (p. 354)
fuel (p. 354)
geothermal energy (p. 369)
grade (p. 376)
Hubbert's Peak (p. 373)
hydrocarbon (p. 355)
hydrocarbon generation (p. 356)
hydrocarbon reserve (p. 355)
hydrocarbon system (p. 355)
hydrofracturing (p. 361)
industrial mineral (p. 380)
kerogen (p. 356)
meltdown (p. 368)
metal (p. 375)
mineral resource (p. 353)
nuclear reactor (p. 367)
nuclear waste (p. 369)
Oil Age (p. 372)
oil seep (p. 357)
oil shale (pp. 356, 362)
oil window (p. 356)
ore (p. 376)
ore deposit (p. 376)
ore mineral (p. 376)
peat (p. 365)
permeability (p. 356)
photosynthesis (p. 354)
plankton (p. 355)
pore (p. 356)
porosity (p. 356)
Portland cement (p. 381)
rare earth element (p. 381)
reservoir rock (p. 356)
salt dome (p. 359)
seal rock (p. 357)
seismic-reflection profile (p. 358)
shale gas (p. 362)
source rock (p. 355)
tar sand (p. 362)
tidal power (p. 370)
trap (p. 357)

Review Questions

1. What are the fundamental sources of energy?
2. What is the source of the organic material in oil and how is it transformed into oil?
3. What is the oil window, and what happens to oil at temperatures higher than the oil window?
4. How is organic matter trapped to yield an oil reserve?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on the formation of tar sands and coal seams.
- Labeling and matching exercises on identifying energy sources.
- Visual problems addressing our global mineral needs.

5. What are tar sand and oil shale, and how can oil be extracted from them?
6. Where is most of the world's oil found? At present rates of consumption, how long will oil supplies last?
7. How is coal formed, and in what class of rocks is coal considered to be?
8. What determines the rank of coal?
9. Describe the nuclear reactions in a nuclear reactor.
10. Where do uranium deposits form in the Earth's crust?
11. What are some of the drawbacks of nuclear energy?
12. What is geothermal energy? What limits its use?
13. What is the difference between renewable and nonrenewable resources?
14. What is the likely future of hydrocarbon production and use in the 21st century?
15. Why don't we use an average granite as a source for metals?
16. Describe various kinds of economic mineral deposits.
17. What procedures are used to locate and mine mineral resources today?
18. How is stone cut from a quarry?
19. What are the ingredients of concrete and mortar?
20. Will the supply of mineral resources run out? Can a country survive without importing minerals?
21. What are some environmental hazards of mining?
22. Name materials in your home that come from mineral resources.

On Further Thought

23. Do you think it would make sense for an energy company to drill for oil in a locality where beds of anthracite occur in the stratigraphic sequence? Explain your answer.
24. An ore deposit at a location in Arizona has the following characteristics: One portion of the ore deposit is an intrusive igneous rock in which tiny grains of copper sulfide minerals are dispersed among the other minerals of the rock. Another nearby portion of the ore deposit consists of limestone in which malachite fills cavities and pores in the rock. What types of ores are these? Describe the geologic history that led to the formation of these deposits.

SEE FOR YOURSELF L. . . Energy and Mineral Resources

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet L of our **Geotours Workbook**.



Oil field near Lamesa, Texas
Latitude 32°33′18.42″N,
Longitude 101°46′55.39″W

This view, from 8 km, shows a grid of farm fields, 1.6 km or 1 mile wide, within which small roads lead to patches of dirt. Each patch hosts or hosted a pump for extracting oil. These wells are tapping an oil reserve in Permian sandstone reservoirs.

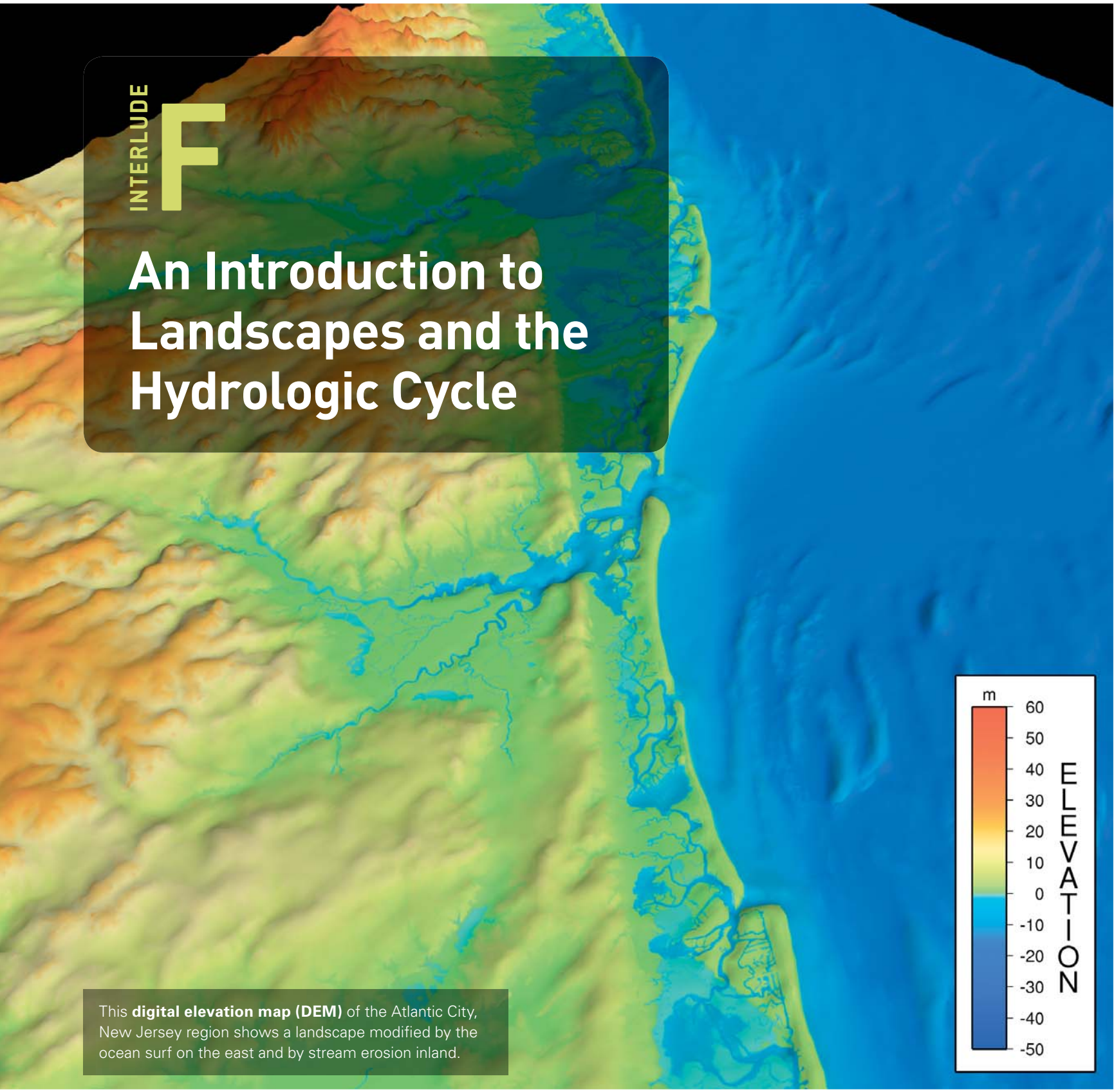


Bingham Copper Mine, Utah
Latitude 40°31′14.66″N,
Longitude 112°9′1.97″W

The gray patch southwest of Salt Lake City, is the largest open-pit mine in the world. Over 17 million tons of copper have been extracted from ore formed when hydrothermal fluids circulated through Cenozoic igneous rock. Zoom in from 20 km to see the pit and tailings piles.

INTERLUDE F

An Introduction to Landscapes and the Hydrologic Cycle



This **digital elevation map (DEM)** of the Atlantic City, New Jersey region shows a landscape modified by the ocean surf on the east and by stream erosion inland.

F.1 Introduction

It's no wonder that artists and writers across the ages have sought inspiration from the **landscape**—the character and shape of the land surface in a region—for landscapes engage the full range of human emotion (Fig. F.1a–d). Geologists, like artists and writers, savor the impression of a dramatic landscape; but on seeing one, they can't help but ask: How did it come to be? And how will it change in the future?

The subject of landscape development and evolution, and the **landforms** (individual shapes such as mesas, valleys, cliffs, and dunes) that constitute it, dominate many of the subsequent chapters in this book. This Interlude, a general introduction to our planet's surface and near-surface realms, characterizes the variety of landscapes, the processes that shape landforms, and the many interrelationships among climate, life, water, rock, and sediment in the Earth System. We will see that water, in both its solid and liquid states, plays a key role in landscape evolution. Thus, we include a focus on the hydrologic cycle, the pathway that water molecules follow as they move from ocean to air to land and back to ocean.

F.2 Shaping the Earth's Surface

If the Earth's surface were totally flat, the great diversity of landscapes that embellish our vistas would not exist. But the surface isn't flat, because a variety of geologic processes cause portions of the surface to move up or down relative to adjacent regions. We refer to the upward movement of the land surface as **uplift**, and the sinking or downward movement of the land surface as **subsidence**.

When uplift or subsidence takes place, the elevation difference does not remain the same forever, because other components of the Earth System kick into action. Material at higher elevations weathers, fractures, and becomes unstable and thus, is susceptible to **downslope movement** (the tumbling or sliding of rock and sediment from higher elevations to lower ones, driven by gravity); moving water, ice, and air cause

FIGURE F.1 Examples of the great variety of landscapes on Earth.



(a) A rock and sand seascape along the coast of Brazil.



(b) The peaks of the Grand Tetons in Wyoming.



(c) Buttes of sandstone in Monument Valley, Arizona.



(d) Steep cliffs in Australia's Blue Mountains.

erosion (the grinding away and removal of material at the Earth's surface); and where moving fluids slow down, **deposition** of sediment takes place. Downslope movement, erosion, and deposition redistribute rock and sediment, ultimately stripping it from higher areas and collecting it in low areas. As a consequence, a great variety of both **erosional landforms** (those carved by erosion) and **depositional landforms** (those built from an accumulation of sediment) can form.

The energy that drives landscape evolution comes from three sources: **internal energy**, the heat within the Earth, which drives the plate motions and mantle plumes that cause displacement of the crust's surface; **external energy**, energy coming to the Earth from the Sun, which warms the atmosphere and ocean; and **gravitational energy**, which pulls rock down slopes at the surface and, along with external energy, causes convection (as currents and winds). Landscape evolution, in fact, reflects a "battle" between tectonic processes such as collision, convergence, and rifting, which *build* **relief**, an elevation difference between two locations (**Box F.1**); and processes such as downslope movement, erosion, and deposition, which *destroy* relief by removing material from high areas and depositing it in low ones. If, in a particular region, the rate of uplift exceeds the rate of erosion, the land surface rises. But if the rate of subsidence exceeds the rate of deposition, the land surface sinks. Without erosion and deposition, high and low areas would have lasted for the entirety of Earth history.

How rapidly do uplift, subsidence, erosion, and deposition take place? The Earth's surface can rise or sink by as much as 3 m during a single major earthquake. But averaged over time, the rates of uplift and subsidence range between 0.01 and 10 mm per year (**Fig. F.2a**). Similarly, erosion can carve out several meters of **substrate**, the material at and just below the ground surface, during a single flood, storm, or landslide (**Fig. F.2b**). And deposition during a single event can produce a layer of debris tens of meters thick in a matter of minutes to days. But, averaged over time, erosional and depositional rates also vary between 0.10 and 10 mm per year. Although these rates seem small, a change in surface elevation of just 0.5 mm (the thickness of a fingernail) per year can yield a net change of 5 km in 10 million years. Uplift can build a mountain range, and erosion can whittle one down to near sea level—it just takes time!

F.3 Factors Controlling Landscape Development

Imagine traveling across a continent. On your journey, you pass plains, swamps, hills, valleys, mesas, and mountains. Some of these features are erosional landforms, in that they result from the breakdown and removal of rock or sediment. They develop where **agents of erosion** such as water, ice, or air carve into the substrate—of these three agents, water has the greatest effect on a global basis. Other features are depositional landforms, in that they result from the deposition of sediment where the medium carrying the sediment evaporates, slows down, or melts. The specific landforms that develop at a given locality, and that together make up the landscape, reflect several factors.

- *Eroding or transporting agent*: Water, ice, and wind all cause erosion and transport sediment. But the shapes of landforms formed by each are different, because of differences in the abilities of these agents to carve into the substrate and to carry debris.
- *Relief*: The elevation difference, or relief, between adjacent places in a landscape determines the height and steepness of slopes. Steepness, in turn, controls the velocity of ice or water flow and determines whether rock or soil stays in place or tumbles downslope.

FIGURE F.2 The processes of uplift, subsidence, erosion, and deposition can be slow or rapid.



(a) Uplifted beach terraces form where the coast is rising relative to sea level. Present-day wave erosion is forming a new terrace and cutting a cliff on the edge of the old one.



(b) So much erosion can take place during a single hurricane that houses built along the beach become undermined.

Topographic Maps and Profiles

We can distinguish one landform from another by its shape—for example, as you will see in succeeding chapters, a river-carved valley simply does not look like a glacially carved valley. Landform shapes are manifested by variations in elevation within a region. Geologists use the term **topography** to refer to such variations.

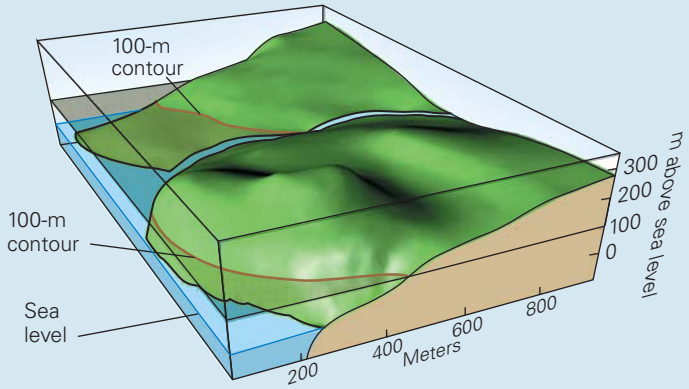
How can we convey information about topography—a three-dimensional feature—on a two-dimensional sheet of paper? Geologists do this by means of a **topographic map**, which uses contour lines to represent variations in elevation (**Fig. BxF.1a, b**). A **contour line** represents an imaginary line on the land surface along which all points have the same elevation. You can picture the contour line as the intersection between the land surface and an imaginary horizontal plane.

We can also represent variations in elevation by means of a topographic profile (**Fig. BxF.1c**). A profile is the trace of the ground surface as it would appear on a vertical plane that sliced into the ground—put another way, it's the shape of the ground surface as viewed from the side.

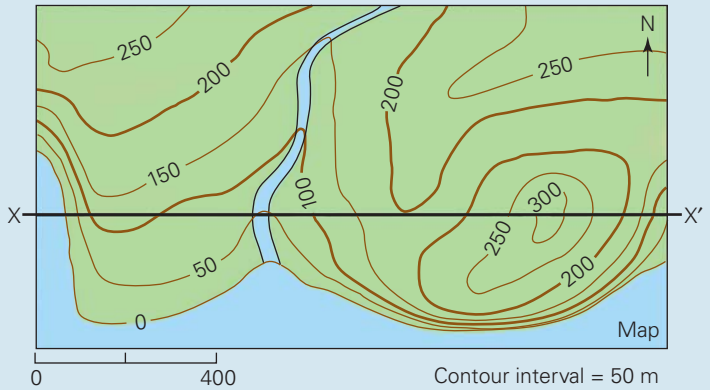
The elevation difference between two adjacent contour lines on a topographical map is called the **contour interval**. For a given topographic map, the contour interval is constant, so the spacing between contour lines represents the steepness of a slope. Specifically, closely spaced contour lines represent a steep slope, whereas widely spaced contour lines represent a gentle slope.

If we add a representation of geologic features under the ground surface, then we have a geologic cross section. In some cases, geologists gain insight into subsurface geology simply by looking at the shape of a landform. For example, a steep cliff in a region of dipping sedimentary strata may indicate the presence of a resistant (difficult to erode) layer; low areas may be underlain with nonresistant (easy to erode) layers (**Fig. BxF.1d, e**).

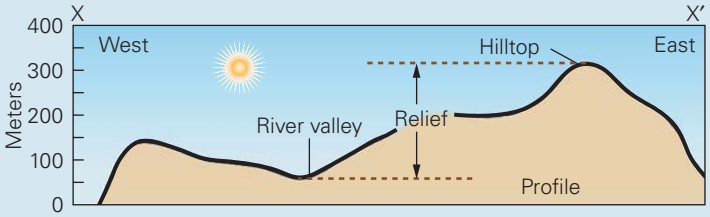
FIGURE BxF.1 Topographic maps and profiles.



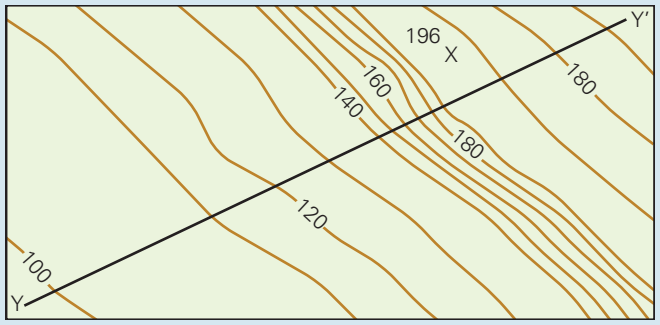
(a) A contour line is the intersection of a horizontal plane with the land surface. This block diagram shows the map area.



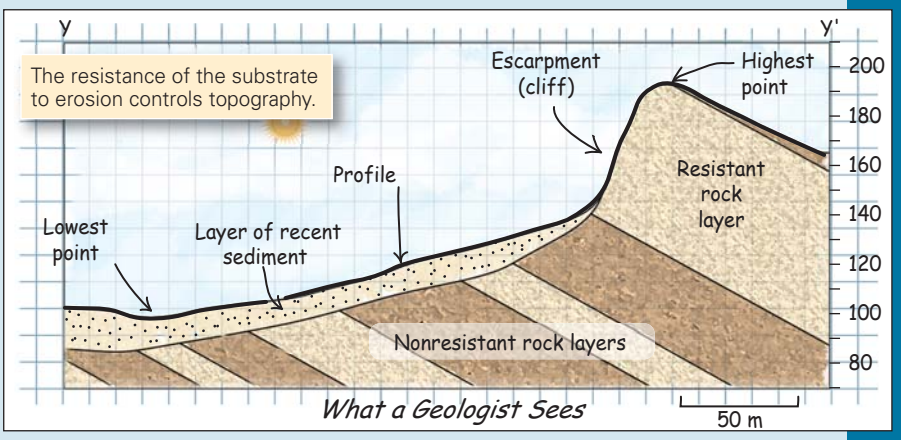
(b) A topographic map depicts the shape of the land surface through the use of contour lines. The difference in elevation between two adjacent lines is the contour interval.



(c) A topographic profile (along section line X–X′) shows the shape of the land surface as seen in a vertical slice.



(d) This topographic map shows a distinct cliff.



(e) Topographic profile along line YY′ **(not to scale)** showing a geologic interpretation of the subsurface.

- *Climate*: The average mean temperature and the volume of precipitation in a region determine whether running water, flowing ice, or wind serves as the main agent of erosion or deposition.
- *Substrate composition*: The material comprising the substrate determines how the substrate responds to erosion. For example, strong rocks can stand up to form steep cliffs, while soft sediment collapses to generate gentle slopes.
- *Life activity*: Some life activity weakens the substrate (by burrowing, wedging, or digesting), while some holds it together (by binding it with roots).
- *Time*: Landscapes evolve through time, in response to continued erosion and/or deposition. For instance, a gully that has just started to form in response to the flow of a stream does not look the same as a deep canyon that develops after the same stream has existed for a long time.

Although water, wind, and ice are responsible for the development of most landscapes, human activities have had an increasingly important impact on the Earth's surface. We have dug pits (mines) where once there were mountains, have built hills (tailings piles and landfills) where once there were valleys, and have made steep slopes gentle and gentle slopes steep (**Fig. F.3a–c**). By constructing concrete walls, we modify the shapes of coastlines, change the courses of rivers, and fill new lakes (reservoirs). In cities, buildings and pavements completely seal the ground and cause water that might once have seeped down into the ground to spill into streams instead, increasing their flow. The area of land covered by pavement or buildings in the United States now exceeds the area of Ohio! And in the country, agriculture, grazing, water usage, and deforestation substantially alter the rates at which natural erosion and deposition take place. For example, agriculture greatly increases the rate of erosion, because for much of the year farm fields have no vegetation cover. Humanity has become a major agent of erosion and deposition.

F.4 The Hydrologic Cycle

Nothing that is can pause or stay—
The moon will wax, the moon will wane,
The mist and cloud will turn to rain,
The rain to mist and cloud again,
Tomorrow be today.

—Henry Wadsworth Longfellow (1807–1882)

As is evident from the discussion above, water in its various forms (liquid, gas, and solid) plays a major role in erosion and deposition on Earth's surface. Our planet's water occupies several distinct reservoirs (**Table F.1**). Atmospheric water occurs as vapor, mist, or ice crystals. Surface water collects in oceans, lakes, streams, puddles, and swamps. Frozen water forms snowfields and glaciers. Subsurface water dampens soil and rock near the surface, or sinks deeper to a realm where it fills underground pores and cracks as **groundwater**. A significant amount of water also resides in living organisms—about 50% to 65% of your body consists of water. Water constantly flows from reservoir to reservoir, and this never-ending passage is called the **hydrologic cycle** (see **Geology at a Glance**, pp. 392–393). Perhaps without realizing it, Longfellow, an American poet fascinated with reincarnation, provided an accurate if somewhat romantic image of the hydrologic cycle.

TABLE F.1 Major Water Reservoirs of the Earth

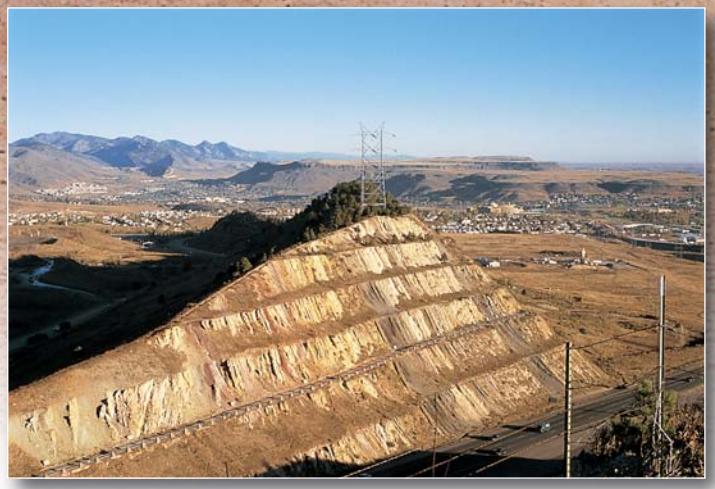
H_2O Reservoir	Volume (km^3)	% of Total Water	% of Fresh Water
Oceans and seas	1,338,000,000	96.5	—
Glaciers, ice caps, snow	24,064,000	2.05	68.7
Saline groundwater	12,870,000	0.76	—
Fresh groundwater	10,500,000	0.94	30.1
Permafrost	300,000	0.022	0.86
Freshwater lakes	91,000	0.007	0.26
Salt lakes	85,400	0.006	—
Soil moisture	16,500	0.001	0.05
Atmosphere	12,900	0.001	0.04
Swamps	11,470	0.0008	0.03
Rivers and streams	2,120	0.0002	0.006
Living organisms	1,120	0.0001	0.003

Source: Data from P. H. Gleick, *Encyclopedia of Climate and Weather* (New York: Oxford University Press, 1996).

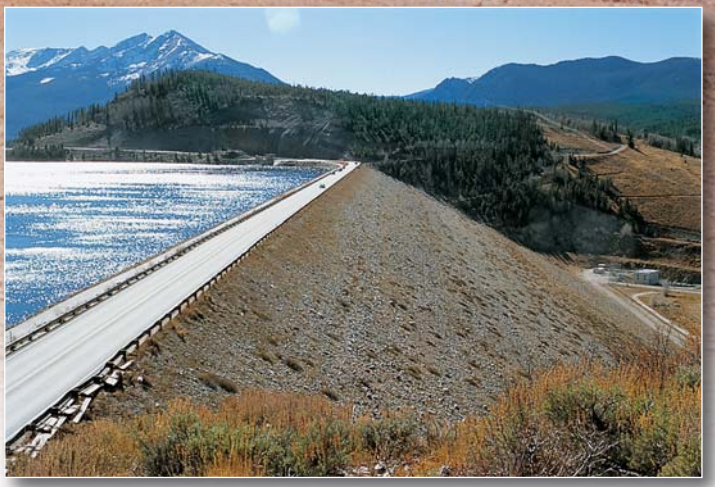
To get a clearer sense of how the hydrologic cycle operates, let's follow the fate of seawater that has just reached the surface of the ocean. Solar radiation heats the water, and the increased thermal energy of the vibrating water molecules allows them to evaporate and drift upward in a gaseous state to become part of the atmosphere. About 30% of the total ocean volume evaporates every year. Atmospheric water vapor moves with the wind to higher elevations, where it cools, undergoes condensation, and rains or snows. About 76% of this water precipitates (falls out of the air) directly back into the ocean. The remainder precipitates onto land. Most of this water becomes trapped temporarily in the soil, or in plants and animals, and soon returns directly to the atmosphere by **evapotranspiration** (the sum of evaporation from bodies of water, evaporation from the ground surface, and release of water from plants and animals). Rainwater that did not become trapped in the soil or in living organisms either enters lakes or rivers and ultimately flows back to the sea as surface water, becomes trapped in glaciers, or sinks deeper into the ground to become groundwater. Groundwater also flows and

FIGURE F.3 Human influence on a geologic scale.

(a) The pyramids of Egypt are human-made hills that rise above the desert sands. They have lasted for thousands of years.



(b) In the process of making highway cuts, engineers cut deep valleys through high ridges. This example borders a highway near Denver.



(c) This stone dam holds back a reservoir in Colorado. Think about how long it would take a glacier to pile up so much sediment.

ultimately returns to the Earth's surface reservoirs. In sum, during the hydrologic cycle, water moves among the ocean, the atmosphere, reservoirs on or below the land, and living organisms.

The *average* length of time that water stays in a particular reservoir during the hydrologic cycle is called the **residence time**. Water in different reservoirs has different residence times. For example, a typical molecule of water remains in the oceans for 4,000 years or less, in lakes and ponds for 10 years or less, in rivers for 2 weeks or less, and in the atmosphere for 10 days or less. Groundwater residence times are highly variable and depend on how deep the groundwater flows. Water can stay underground for anywhere from 2 weeks to 10,000 years before it inevitably moves on to another reservoir.

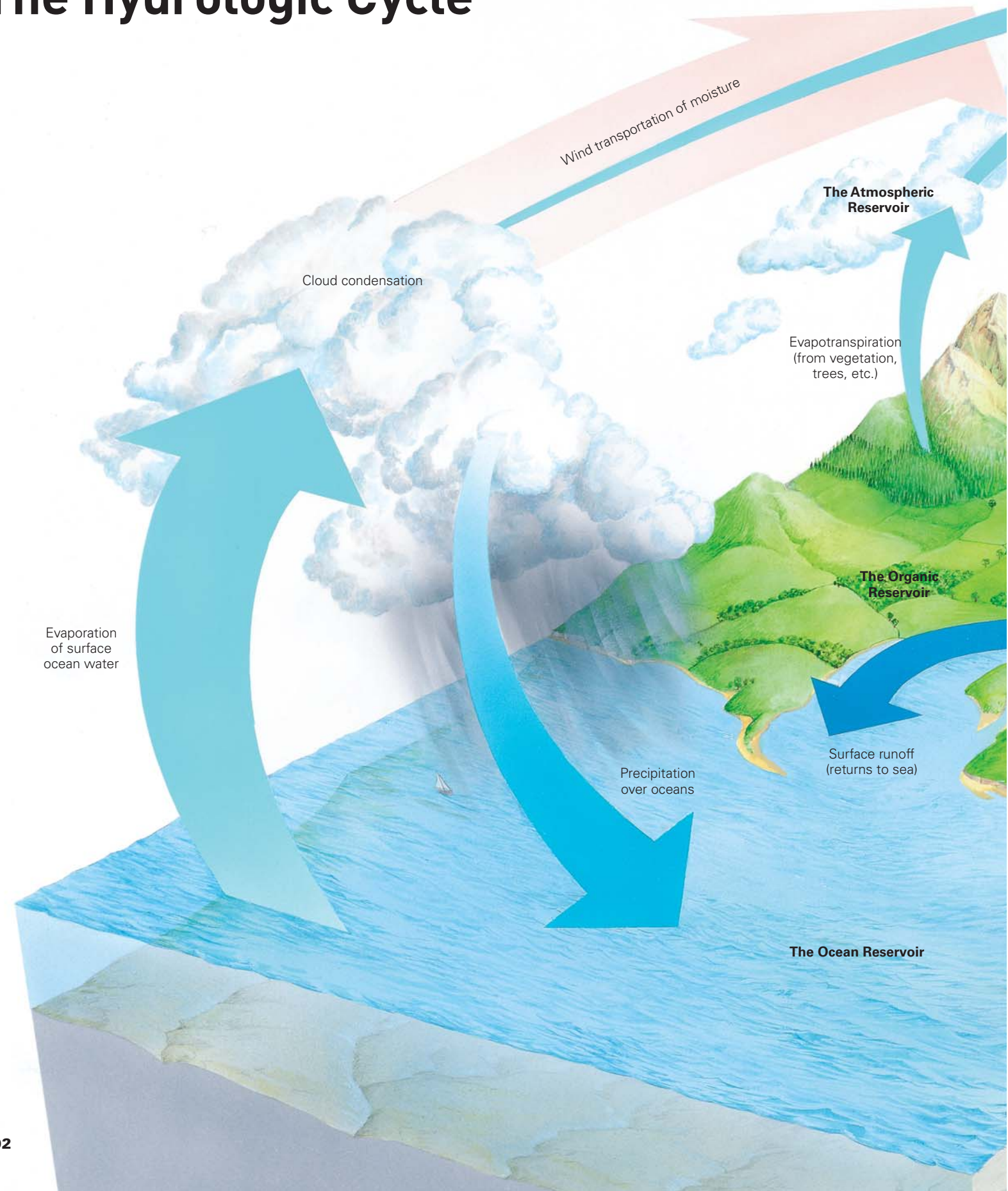
F.5 Landscapes of Other Planets

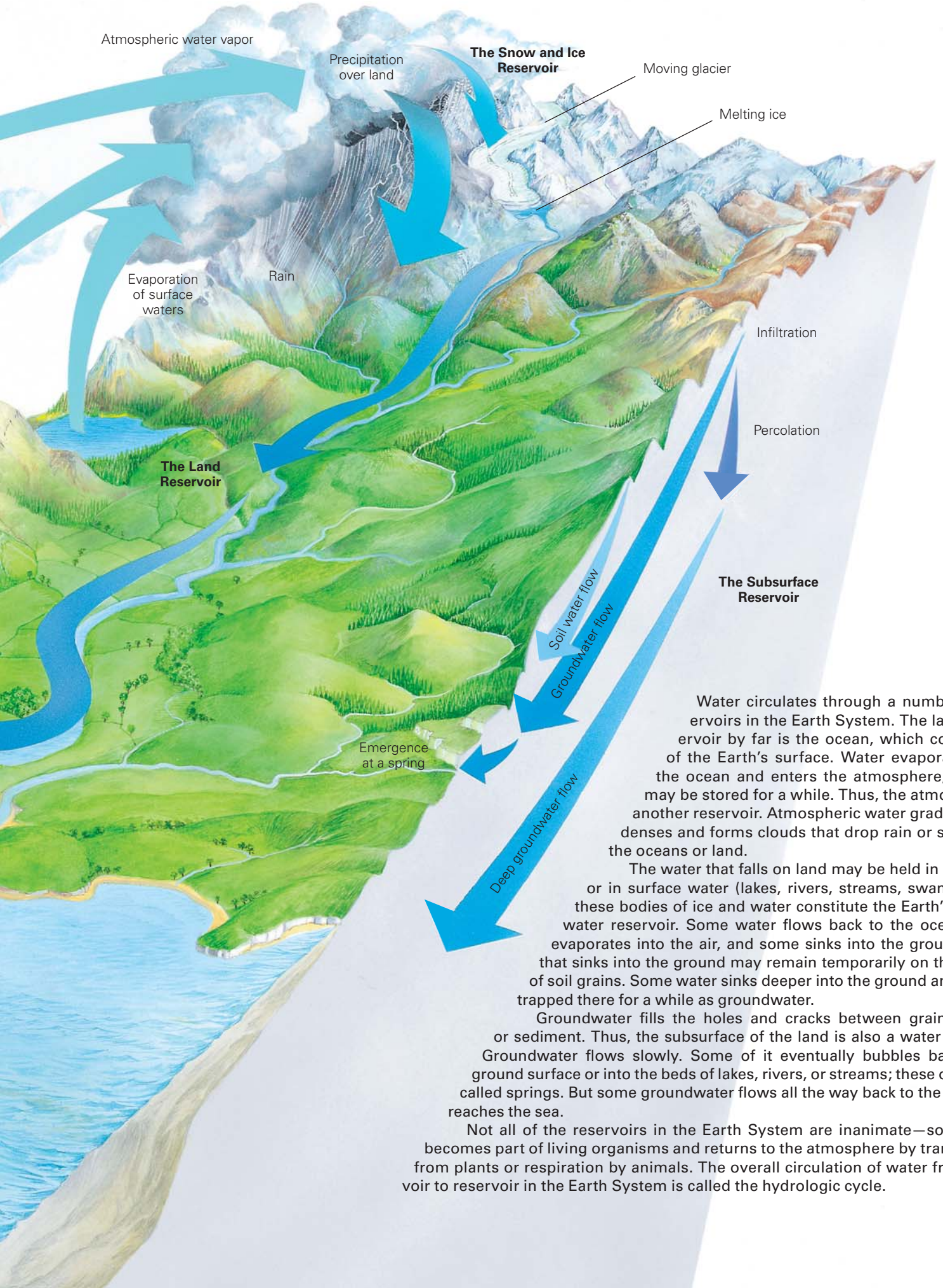
The dynamic, ever-changing landscape of Earth contrasts markedly with those of other terrestrial planets. Each of the terrestrial planets and moons has its own unique surface landscape features, reflecting the interplay between the object's particular tectonic and erosional processes. Let's look at a few examples: the Moon, Mars, and Venus.

Our Moon has a static, pockmarked landscape generated exclusively by meteorite impacts and volcanic activity. Because no plate tectonics occurs on the Moon, no new mountains form; and because no atmosphere or ocean exists, there is no hydrologic cycle and no erosion from rivers, glaciers, or winds. Therefore, the lunar surface has remained largely unchanged for most of its history (**Fig. F.4a**).

Landscapes on Mars differ from those of the Moon because Mars *does* have an atmosphere (though it is much less dense than that of Earth) whose winds generate huge dust storms, some of which obscure nearly the entire surface of the planet for months at a time. The landscapes of Mars also differ from the Moon's because Mars probably once had surface water (**Box F.2**; **Fig. F.4b**). Thus, the Martian surface appears to consist of four kinds of materials: volcanic flows and

The Hydrologic Cycle





Water circulates through a number of reservoirs in the Earth System. The largest reservoir by far is the ocean, which covers 71% of the Earth's surface. Water evaporates from the ocean and enters the atmosphere, where it may be stored for a while. Thus, the atmosphere is another reservoir. Atmospheric water gradually condenses and forms clouds that drop rain or snow onto the oceans or land.

The water that falls on land may be held in glacial ice or in surface water (lakes, rivers, streams, swamps, etc.); these bodies of ice and water constitute the Earth's surface-water reservoir. Some water flows back to the ocean, some evaporates into the air, and some sinks into the ground. Water that sinks into the ground may remain temporarily on the surface of soil grains. Some water sinks deeper into the ground and may be trapped there for a while as groundwater.

Groundwater fills the holes and cracks between grains of rock or sediment. Thus, the subsurface of the land is also a water reservoir. Groundwater flows slowly. Some of it eventually bubbles back to the ground surface or into the beds of lakes, rivers, or streams; these outlets are called springs. But some groundwater flows all the way back to the coast and reaches the sea.

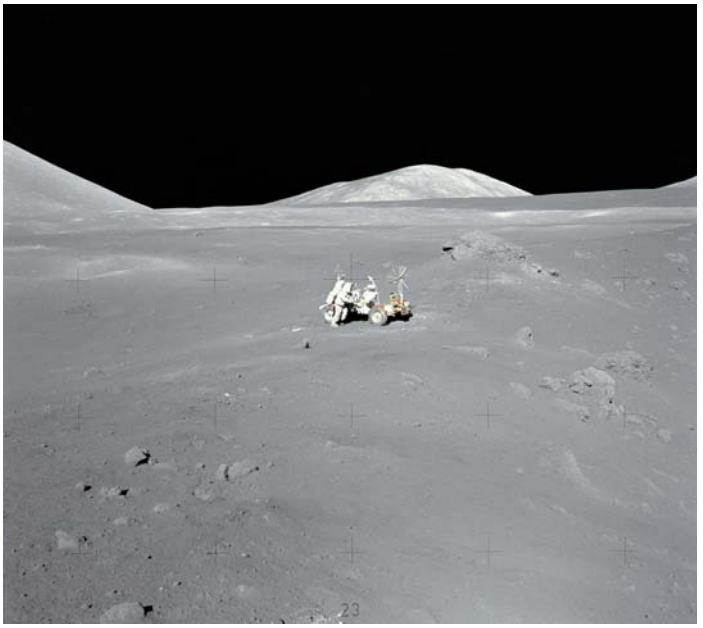
Not all of the reservoirs in the Earth System are inanimate—some water becomes part of living organisms and returns to the atmosphere by transpiration from plants or respiration by animals. The overall circulation of water from reservoir to reservoir in the Earth System is called the hydrologic cycle.

deposits (primarily of basalt), debris from impacts, windblown sediment, and water-laid sediment. There is even evidence that soil-forming processes affected surface materials. Martian winds not only deposit sediment, they also slowly erode impact craters and polish surface rocks.

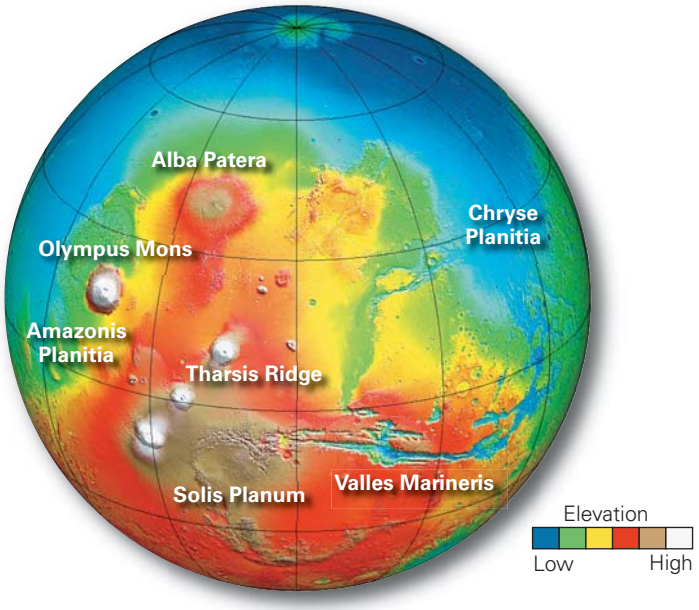
Landscapes on Mars also differ from those on Earth, because Mars does not have plate tectonics. So, unlike Earth, Mars has no mountain belts or volcanic arcs. There was, however, plume activity in the planet's distant past. A plume caused the uplift of a 9-km-high bulge (the Tharsis Ridge) that covers an area comparable to that of North America. Thermal activity also led to the eruption of gargantuan hot-spot volcanoes, such as the 22-km-high Olympus Mons, the highest mountain in the Solar System. Mars also boasts the largest known canyon, the Valles Marineris, a gash over 3,000 km long and 8 km deep. No comparable feature exists on Earth. Because Mars has no vegetation and no longer has rain, its surface does not weather and erode like that of Earth, so it still bears the scars of impact by swarms of meteors earlier in the history of the Solar System, scars that have long since disappeared on Earth. But Martian winds move enough dust to blunt these features, due to deposition of dust and subtle erosion and polishing. Mars does have a hydrologic cycle, of sorts, in that it has ice caps that grow and recede on an annual basis.

Venus is closer to the size of the Earth and may still have operating mantle plumes. Virtually the entire surface of Venus was resurfaced by volcanic eruptions about 300 to 1,600 Ma, making the planet's surface much younger than those of the Moon and Mars. Further, Venus has a dense atmosphere that protects it from impacts by smaller objects. Because there has been relatively little cratering since the resurfacing event, volcanic and tectonic features dominate the landscape of Venus (**Fig. F.4c**). Satellites have used radar to reveal a variety of volcanic constructions (such as shield volcanoes, lava flows, and calderas). Rifting on Venus produced faults, some of which occur in association with volcanic features. Liquid water cannot survive the scalding temperatures of Venus's surface, so no hydrologic cycle operates there and no life exists. Because of the density of the atmosphere, winds are too slow to cause much erosion or deposition.

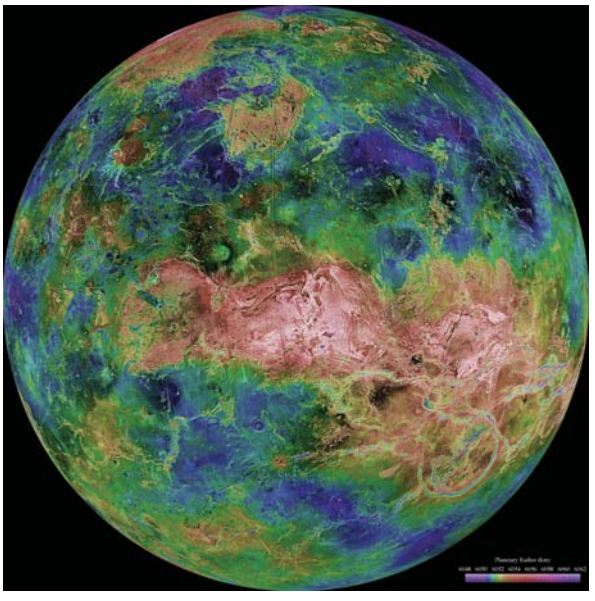
FIGURE F.4 Landscapes of other planets.



(a) A close-up view of the lunar landscape, with the lunar rover and an astronaut for scale.



(b) A digital elevation model depicting the surface of Mars. Note the huge bulge of Tharsis Ridge, the giant Olympus Mons volcano, and the deep Valles Marineris canyon.



(c) A radar image of Venus. A thick blanket of clouds obscures this planet's surface, so it can't be seen through a telescope. Red areas are higher, blue areas lower.

Water on Mars?

In 1877, an Italian astronomer named Giovanni Schiaparelli studied the surface of Mars with a telescope and announced that long, straight *canali* crisscrossed the planet's surface. *Canali* should have been translated into the English word *channel*, but perhaps because of the recent construction of the Suez Canal, newspapers of the day translated the word into the English *canal*, with the implication that the features had been constructed by intelligent beings. An eminent American astronomer began to study the "canals" and suggested that they had been built to carry water from polar ice caps to Martian deserts.

Late-20th-century satellite mapping of Mars showed that the "canals" do not exist—they were simply optical illusions. There are no lakes, oceans, rainstorms, or flowing rivers on the surface of Mars today. The atmosphere of Mars has such low density, and thus exerts so little pressure on the planet's surface, that any liquid water released at the surface would quickly evaporate. Thus Mars has no hydrologic cycle the way the Earth does. But three crucial questions remain: Does liquid water ever form, even for short periods, on the Martian surface today? Did Mars ever have a significant amount of running water or standing water in the past? If the planet once had significant water, where is the water now? The question of the presence of water lies at the heart of an even more basic question: Given that the simplest life as we know it requires water, is there, or was there, life on Mars?

Many planetary geologists believe that the case for liquid water on Mars is quite strong. Much of the evidence comes from comparing landforms on the planet's surface with landforms of known origin on Earth. High-resolution images of Mars reveal a number of landforms that look as if they formed in response to flowing water. Examples include networks of channels resembling river networks on Earth (**Fig. BxF.2a, b**), scour features, deep gullies, and streamlined deposits of sediment.

Studies by the *Odyssey* satellite in 2003, and by Mars rovers (*Spirit* and *Opportunity*) that landed on the planet in 2004, added intriguing new data to the debate. *Odyssey* detected hints that hydrogen, an element in water, exists beneath the surface of the planet over broad regions, and the Mars rovers have documented the existence of hematite and gypsum, minerals that form in the presence of water. The rovers also have found sedimentary deposits that appear to have been deposited in water. The *Phoenix* lander, in 2008, confirmed the existence of water ice by digging into the surface to expose some. Researchers speculate that Mars was much wetter in its past, perhaps billions of years ago. But since the atmosphere became less dense, the water evaporated and now lies hidden underground or trapped in polar ice caps.

FIGURE BxF.2 Water-carved landscapes on Mars, as photographed by satellites orbiting the planet.



(a) An elongate island in a channel, resembling islands that have been shaped by rivers on Earth.



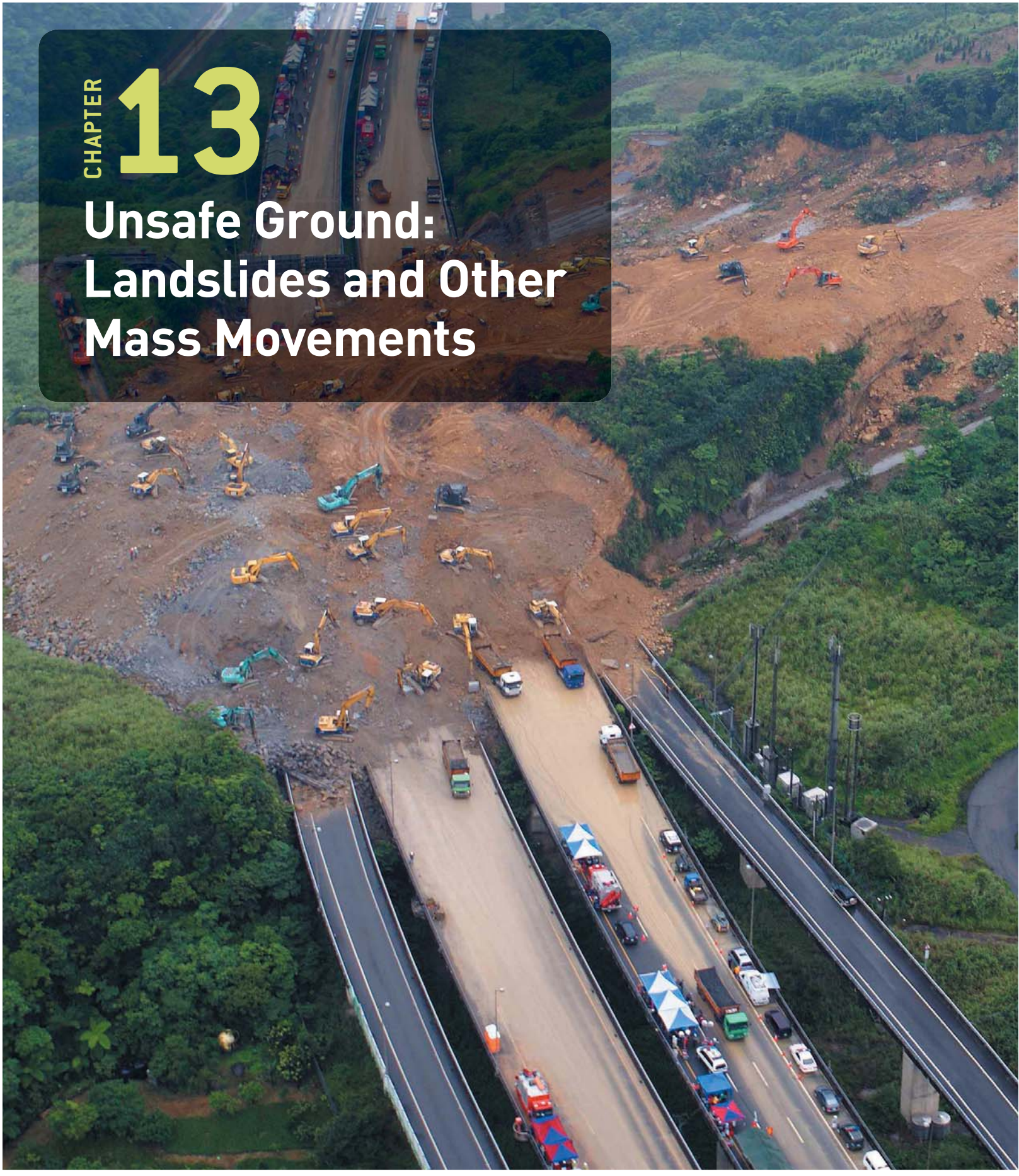
(b) A network of channels resembling channels cut by rivers on Earth.

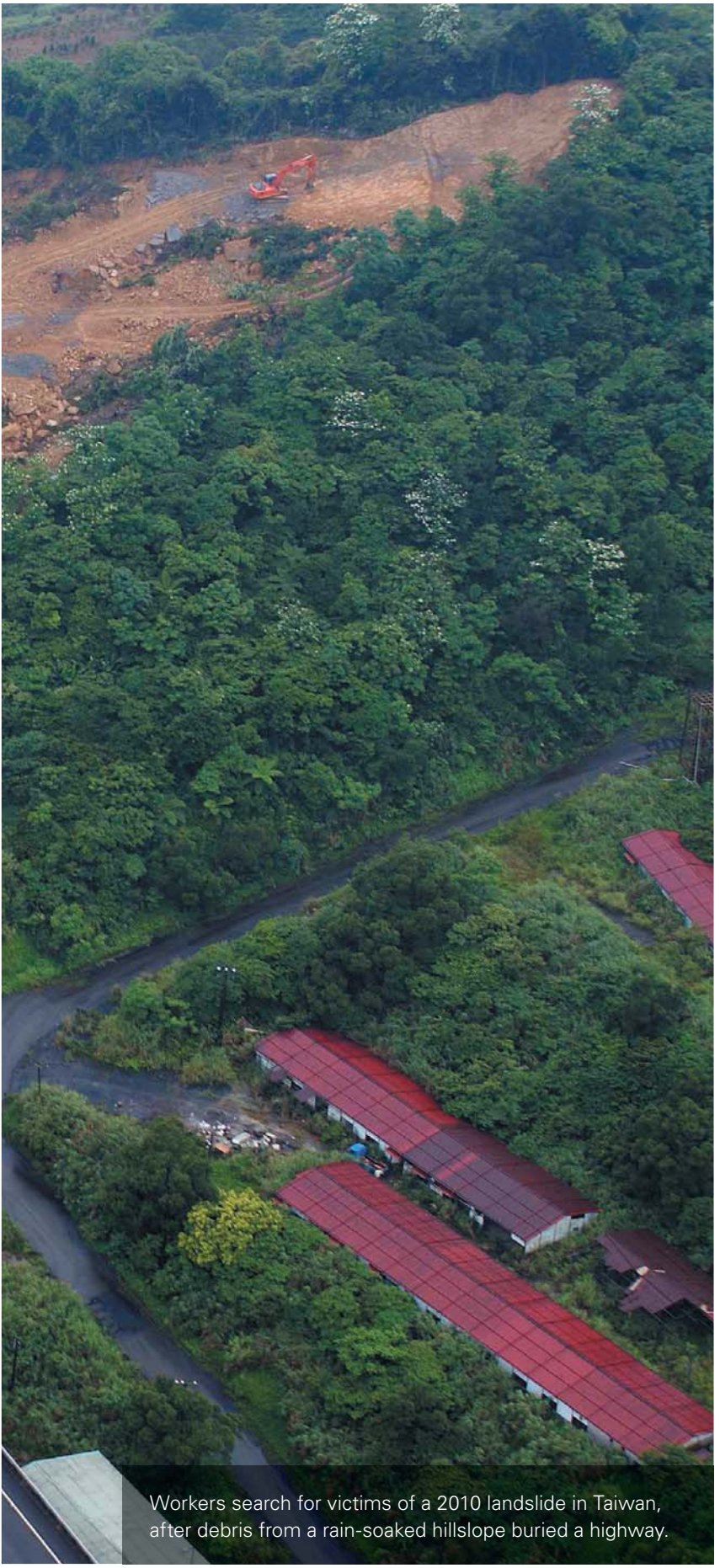
Key Terms

agent of erosion (p. 388)
contour interval (p. 389)
contour line (p. 389)
deposition (p. 388)
depositional landform (p. 388)
digital elevation map (p. 386)
downslope movement (p. 387)
erosion (p. 388)
erosional landform (p. 388)
evapotranspiration (p. 390)
external energy (p. 388)
gravitational energy (p. 388)
groundwater (p. 390)
hydrologic cycle (p. 390)
internal energy (p. 388)
landform (p. 387)
landscape (p. 387)
relief (p. 388)
residence time (p. 391)
subsidence (p. 387)
substrate (p. 388)
topographic map (p. 389)
topography (p. 389)
uplift (p. 387)

CHAPTER 13

Unsafe Ground: Landslides and Other Mass Movements





Workers search for victims of a 2010 landslide in Taiwan, after debris from a rain-soaked hillslope buried a highway.

Chapter Objectives

By the end of this chapter, you should know . . .

- the characteristics and consequences of different types of mass movements (landslides).
- factors that determine whether a slope is stable or unstable.
- events that can trigger a mass-movement event.
- how landslide hazards can be identified, evaluated, and in some cases prevented.

13.1 Introduction

It was Sunday, May 31, 1970, a market day, and thousands of people had crammed into the Andean town of Yungay, Peru, to shop. Suddenly they felt the jolt of an earthquake, strong enough to topple some masonry houses. But worse was yet to come. This earthquake also broke an 800-m-wide ice slab off the end of a glacier at the top of Nevado Huascarán, a nearby 6.6-km-high mountain peak. As it tumbled down over 3.7 km, the ice disintegrated into a chaotic avalanche of chunks traveling at speeds of over 300 km per hour. Near the base of the mountain, most of the avalanche channeled into a valley and thickened into a churning cloud as high as a ten-story building, ripping up rocks and soil along the way. Frictional heating transformed the ice into water, which mixed with rock and dust to produce 50 million cubic meters of a muddy slurry viscous enough to carry boulders larger than houses. This mass, sometimes floating on a compressed air cushion that allowed it to pass without disturbing the grass below, traveled over 14.5 km in less than four minutes.

At the mouth of the valley, most of the debris overran the village of Ranrahirca before coming to rest and creating a dam that blocked the Santa River. But some shot up the sides of the valley and became airborne for several seconds, flying over the ridge bordering Yungay. As the town's inhabitants and visitors stumbled out of earthquake-damaged buildings, they heard a deafening roar and looked up to see a wall of debris burst above the nearby ridge. The debris engulfed the town and buried it. Only the top of the church and a few palm trees remained visible to show where Yungay once lay (**Fig. 13.1a, b**). Today, the site is a grassy meadow with a hummocky (irregular and lumpy) surface, spotted with crosses left by relatives mourning the 18,000 people entombed by the debris.

People often assume that the ground beneath them is *terra firma*, a solid foundation on which they can build their lives. But the catastrophe at Yungay says otherwise. Much of the Earth's surface is unstable and capable of moving downslope, due to the pull of gravity, in seconds to weeks. Geologists refer to the downslope transport of rock, regolith (soil, sediment, and debris), snow, and ice as **mass movement**, or mass wasting. Like earthquakes, volcanic eruptions, storms, and floods, mass movements are a type of **natural hazard**, meaning a natural feature of the environment that can cause damage to living organisms and to buildings. Unfortunately, mass movement becomes more of a threat every year, because as the world's population grows, cities expand into areas of unsafe ground. Mass movement also plays a critical role in the rock cycle, as the first step in the transportation of sediment, and in the evolution of landscapes, as the most rapid means of modifying the shapes of slopes.

In this chapter, we look at the types, causes, and consequences of mass movement (both on land and under the sea), and the precautions society can take to protect people and property from its dangers. You might want to consider this information when selecting a site for your home or when voting on land-use propositions for your community.

13.2 Types of Mass Movement

Most people refer to any mass movement of rock and/or regolith down a slope as a *landslide*. Geologists and engineers, however, find it useful to distinguish among different kinds of landslides based on four features: (1) the type of material involved (rock or regolith); (2) the velocity of movement (slow, intermediate, or fast); (3) the character of the moving mass (coherent, chaotic, or slurry); and (4) the environment in which the movement takes place (subaerial or submarine). Below, we examine mass movements that occur on land roughly in order from slow to very fast (**See for Yourself M**).

Creep and Solifluction

Creep (also known as soil creep) refers to the slow, gradual downslope movement of regolith on a slope. Creep happens when regolith alternately expands and contracts in response to freezing and thawing, wetting and drying, or warming and cooling. To see how the process of creep works, let's focus on the consequences of seasonal freezing and thawing. In the winter, when water freezes, the regolith expands, and particles move outward, perpendicular to the slope. During the spring thaw, water becomes liquid again, and gravity makes the particles sink vertically and thus migrate downslope slightly (**Fig. 13.2a, b**). You can't see creep by staring at a hillslope because it occurs too slowly, but over a period of years, creep causes trees, fences, gravestones, walls, and foundations built on a hillside to tilt downslope. Notably, trees that continue to grow after they have been tilted display a pronounced curvature at their base (**Fig. 13.2c**).

In Arctic or high-elevation regions, regolith freezes solid to great depth during the winter. In the brief summer thaw, only the uppermost 1 to 3 m of the ground thaws. Since meltwater cannot sink into the permanently frozen ground, or permafrost, the melted layer becomes soggy and weak and flows slowly downslope in overlapping sheets. Geologists refer to this kind of creep as **solifluction** (**Fig. 13.2d**).

FIGURE 13.1 The May 1970 Yungay landslide disaster in Peru.

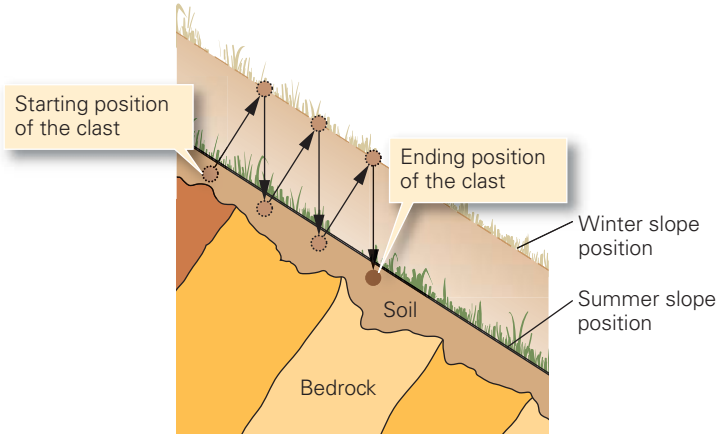


(a) Before the landslide, the town of Yungay perched on a hill near the ice-covered mountain Nevado Huascarán.

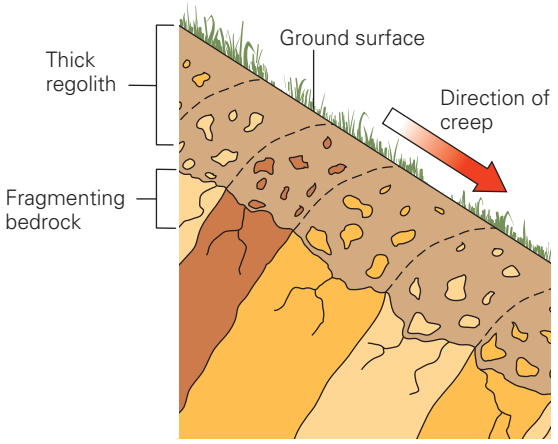


(b) The landslide completely buried the town beneath debris. A landslide scar is visible on the mountain in the distance.

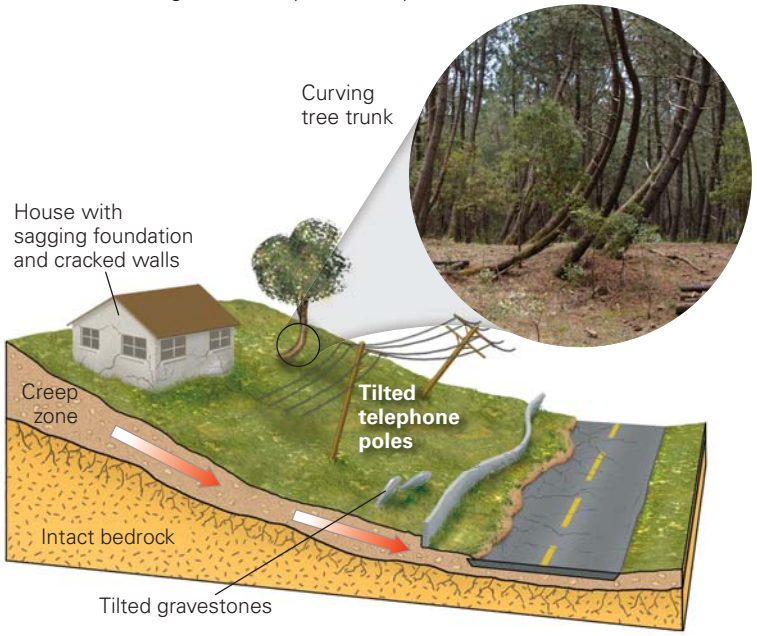
FIGURE 13.2 The process and consequences of slow mass movements (creep and solifluction).



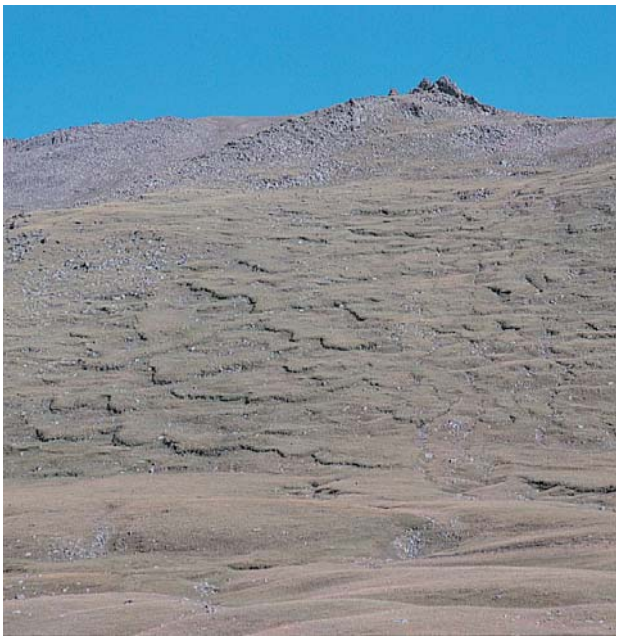
(a) Creep due to freezing and thawing: The clast rises perpendicular to the ground during freezing, and sinks vertically during thawing. After 3 years, it migrates to the position shown.



(b) As rock layers weather and break up, the resulting debris creeps downslope.



(c) Soil creep causes walls to bend and crack, building foundations to sink, trees to bend, and power poles and gravestones to tilt.



(d) Solifluction on a hillslope in the tundra.

Slumping

During the summer of 2011 after weeks of drenching rains, a 1.5-km-wide portion of a slope began to move down and out into the floor of Keene Valley, New York. The mass moved at only centimeters to tens of centimeters per day, but even at this slow rate, the accumulated displacement destroyed several expensive homes. The boundary between the moving mass and the unmoving land upslope evolved into a 5-m-high escarpment.

Geologists refer to such relatively slow-moving mass-movement events, during which moving rock and/or regolith does not disintegrate but rather stays somewhat coherent, as a **slump**, and they refer to the moving mass itself as a slump block (Fig. 13.3a–d). A slump block slides on a **failure surface**. Some failure surfaces are planar, but commonly they curve and resemble a spoon lying concave side up. The exposed upslope edge of a failure surface forms a **head scarp**, a new cliff face. Geologists refer to the downslope end of a slump block as the block's "toe." On a hillslope, the toe can move up and over the pre-existing land surface to form a curving ridge, but along sea coasts or river banks, the toe ends up in the water, where it eventually washes away. In some cases, the upslope and downslope ends of a slump block break into a series of discrete slices, each separated from its neighbor by a small sliding surface (Fig. 13.3e). Slumps come in all sizes, from only a few meters across to tens of kilometers across. They move at speeds from millimeters per day to tens of meters per minute.

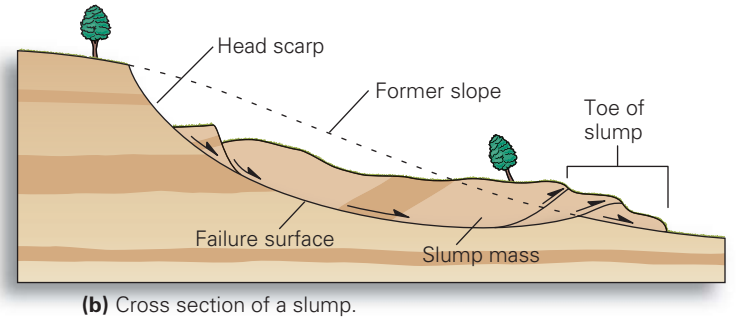
Mudflows, Debris Flows, and Lahars

Rio de Janeiro, Brazil, originally occupied only the flat-lands bordering beautiful crescent beaches that had formed

FIGURE 13.3 The process of slumping on a hillslope. Note the scarps that form at the head of the slump.



(a) A head scarp on the hillslope.



(b) Cross section of a slump.



(c) Slumping dumped sediment into this river in Costa Rica.



(d) A slump beginning to form along a highway in Utah.



(e) A 1-km-wide slump buried a highway and blocked a river in the Cascade Mountains of Washington in 2009.

between steep hills along the shore. But in recent decades, the population has grown so much that, in many places, densely populated communities of makeshift shacks cover the steep slopes. These communities, which have inadequate storm drains, were built on the thick regolith that resulted from long-term weathering of bedrock in Brazil's tropical climate. In 2011, particularly heavy rains saturated the regolith north of Rio, which turned into a viscous slurry of mud, resembling wet concrete, that flowed downslope. Whole communities disappeared overnight, replaced by a hummocky muddle of mud and debris. And at the base of the cliffs, the flowing mud knocked over and buried buildings of all sizes. Similar mass movements ripped away forests in nearby hills (**Fig. 13.4a**). Geologists refer to a moving slurry of mud as a **mudflow** or mudslide, and a slurry consisting of a mixture of mud and larger, pebble- to boulder-sized fragments as a **debris flow** or debris slide (**Fig. 13.4b**).

The speed at which mud or debris moves depends on the slope angle and on the water content. Flows move faster if they contain more water and are less viscous, and if they move on

FIGURE 13.4 Examples of mudflows and lahars.



(a) Mudslides of 2011 stripped away forests on hillslopes in Brazil.



(b) A recent debris flow in Utah. Note the chaotic mixture of rock chunks and mud.



(c) The aftermath of a lahar that flowed down the side of Mt. St. Helens following an eruption in 1982.

steeper slopes. On a gentle slope, drier mudflows move like molasses; but on a steep slope, low-viscosity, very wet mud may move at over 100 km per hour. Because mudflows and debris flows have greater viscosity than clear water, they can carry large rock chunks as well as houses and cars. They typically follow channels downslope and at the base of the slope they spread out into a broad lobe (**Box 13.1**).

Particularly devastating mudflows spill down the river valleys bordering volcanoes. These mudflows, known as **lahars**, consist of a mixture of volcanic ash and water from the snow and ice that melts in a volcano's heat or from heavy rains (**Fig. 13.4c**; see Chapter 5). One of the most destructive lahars occurred on November 13, 1985, in the Andes Mountains in Colombia. That night, a major eruption melted a volcano's thick snowcap, creating hot water that mixed with ash. A scalding lahar rushed down river valleys and swept over the nearby town of Armero while most inhabitants were asleep. Of the 25,000 residents, 20,000 perished.

Rockslides and Debris Slides

In the early 1960s, engineers built a huge new dam across a river on the northern side of Monte Toc, in the Italian Alps, to create a reservoir for generating electricity. This dam, the Vaiont Dam, was an engineering marvel, a concrete wall rising 260 m (as high as an 85-story skyscraper) above the valley floor (**Fig. 13.5a**). Unfortunately, the dam's builders did not recognize the hazard posed by nearby Monte Toc. The side of Monte Toc facing the reservoir was underlain with limestone beds interlayered with weak shale beds. These beds dipped parallel to the surface of the mountain and curved under the reservoir (**Fig. 13.5b**). As the reservoir filled, the flank of the mountain cracked, shook, and rumbled. Local residents began to call Monte Toc *la montagna che cammina* (the mountain that walks).

After several days of rain, Monte Toc began to rumble so much that on October 9, 1963, engineers lowered the water level in the reservoir. They thought the wet ground might slump a little into the reservoir, with minor consequences, so no one ordered the evacuation of the town of Longarone, a few kilometers down the valley. Unfortunately, the engineers underestimated the problem. At 10:30 that evening, a huge chunk of Monte Toc—600 million tons of rock—detached from the mountain and slid downslope into the reservoir. Some debris rocketed up the opposite wall of the valley to a height of 260 m above the original reservoir level. The displaced water of the reservoir spilled over the top of the dam and rushed down into the valley below. When the flood had passed, nothing of Longarone and its 1,500 inhabitants remained. Though the dam itself still stands, it holds back only debris and has never provided any electricity.

Geologists refer to such a sudden movement of rock and debris down a nonvertical slope as a **rockslide** if the mass consists only of rock or as a **debris slide** if it consists mostly of regolith. Once a slide has taken place, it leaves a scar on the slope and forms a debris pile at the base of the slope. Slides happen when bedrock and/or regolith detaches from a slope, slips rapidly downhill on a failure surface, and breaks

BOX 13.1 CONSIDER THIS . . .

What Goes Up Must Come Down

Along the coast of California, waves slowly erode the land and produce low, flat areas called wave-cut benches (see Chapter 15). While this happens, tectonic motions slowly raise the land surface. When uplifted, these benches form small plateaus, or terraces. One such terrace lies at an elevation of 180 m above sea level, about 500 m east of the present-day beach at La Conchita; the west face of this terrace is a cliff-like bluff (**Fig. Bx13.1a**). Repeated slip along the San Andreas plate boundary has broken up the bedrock of the area, and fragments have weathered substantially, so the substrate of the terrace and bluff consists of weak clay and debris.

Relatively little vegetation covers the bluff or the terrace above. Rain that falls on the face of the bluff drains away quickly via a network of small, temporary streams. But the water falling on the terrace infiltrates into the ground, sinks down, and saturates clay and debris meters below the surface of the bluff, turning into very weak mud. When this happens, the weight of surface material causes the bluff to give way, and a mass of mud and debris flows downslope at rates of up to 10 m per second.

If the region of La Conchita were uninhabited, such mass wasting would just be part of the natural process of landscape evolution—gravity brings down land that had been raised by tectonic activity. But when downslope movements take place in La Conchita, it makes headlines, because on the modern wave-cut bench between the shore and the base of the bluff, developers built a community housing 350 people. In 1995, a mud and debris flow overwhelmed 9 houses at the base of the bluff. An even more devastating flow happened in 2005, burying 13 houses, damaging 23, and killing 10 people (**Fig. Bx13.1b, c**). These events have sent a clear message about the importance of reading the landscape before planning construction.

FIGURE Bx13.1 The 2005 La Conchita mudslide along the coast of California.



(a) A housing development was built in a narrow strip between the beach and steep cliffs.

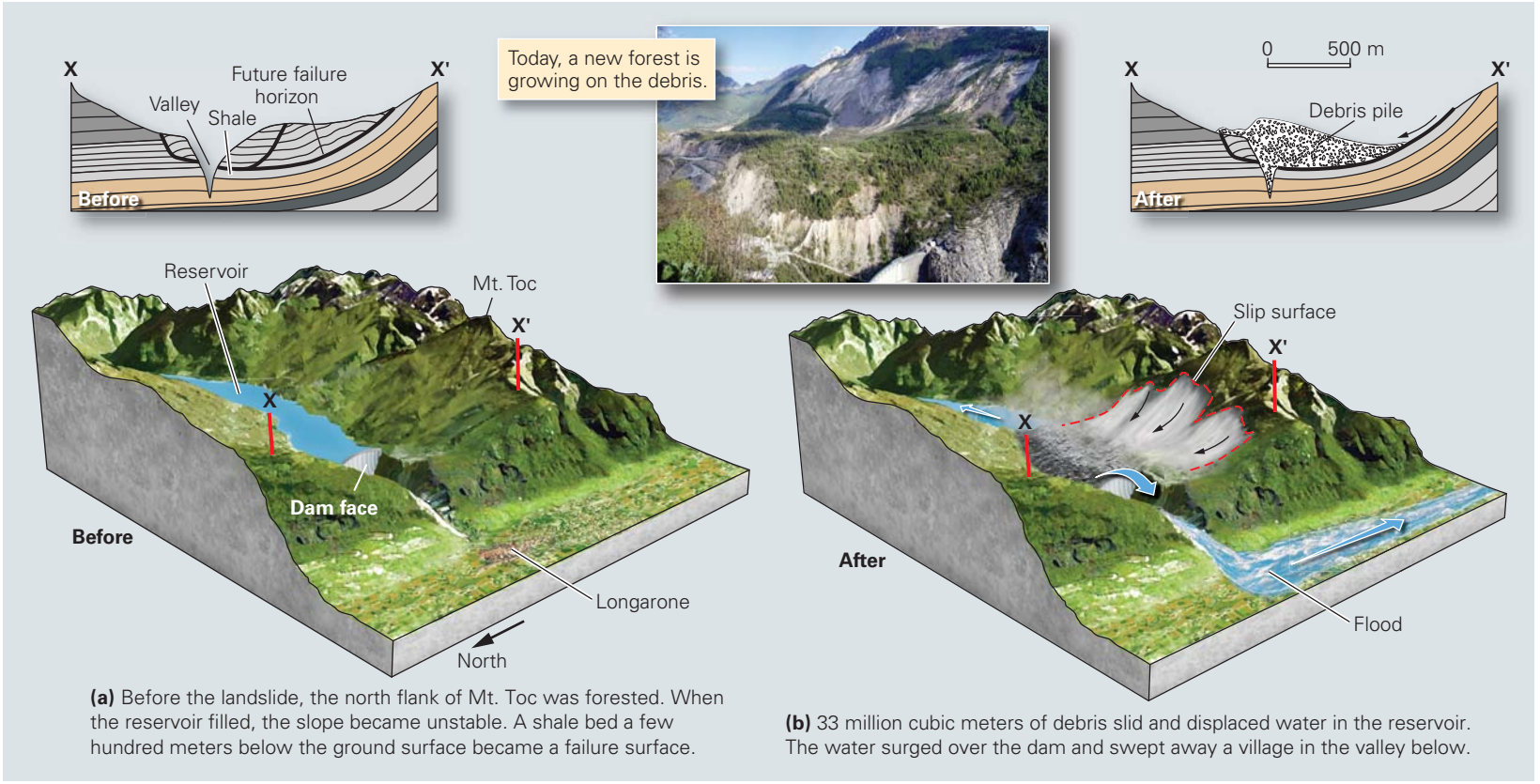


(c) Rescuers at the toe of the mudslide.



(b) During heavy rains, the slope gave way and heavy mud flowed down, burying houses and taking several lives.

FIGURE 13.5 The Vaiont Dam disaster—a catastrophic landslide that displaced the water in a reservoir with rock debris.



(a) Before the landslide, the north flank of Mt. Toc was forested. When the reservoir filled, the slope became unstable. A shale bed a few hundred meters below the ground surface became a failure surface.

(b) 33 million cubic meters of debris slid and displaced water in the reservoir. The water surged over the dam and swept away a village in the valley below.

up into a chaotic jumble. Slides may move at speeds of up to 300 km per hour; they are particularly fast when a cushion of air gets trapped beneath, so there is virtually no friction between the slide and its substrate, and the mass moves like a hovercraft. Rockslides and debris slides sometimes have enough momentum to climb the opposite side of the valley into which they fell. Slides, like slumps, come at a variety of scales.

Avalanches

In the winter of 1999, an unusual weather system passed over the Austrian Alps. First it snowed. Then the temperature warmed and the snow began to melt. But then the weather turned cold again, and the melted snow froze into a hard, icy crust. This cold snap ushered in a blizzard that blanketed the ice crust with tens of centimeters (1–2 ft) of new snow. With the frozen snow layer underneath acting as a failure surface, 200,000 tons of new snow began to slide down the mountain. As it accelerated, the mass transformed into a **snow avalanche**, a chaotic jumble of snow surging downslope. At the bottom of the slope, the avalanche overran a ski resort, crushing and carrying away buildings, cars, and trees, and killing over 30 people. It took searchers and their specially trained dogs many days to find buried survivors and victims under the 5- to 20-m-thick pile of snow that the avalanche deposited (Fig. 13.6a).

What triggers snow avalanches? Some happen when a cornice, a large drift of snow that builds up on the lee side of a windy mountain summit, suddenly gives way and falls onto slopes below, where it knocks free additional snow. Others happen when a broad slab of snow on a moderate slope detaches from its substrate along an icy failure surface. *Wet* avalanches move as a slurry of solid and liquid water, whereas *dry* avalanches tumble as a cloud of powder (Fig. 13.6b).

Rockfalls and Debris Falls

Rockfalls and **debris falls**, as their names suggest, occur when a mass free-falls from a cliff (Fig. 13.7a, b). Commonly, rockfalls happen when a body of rock separates from a cliff face along a joint. Friction and collision with other rocks may bring some blocks to a halt before they reach the bottom of the slope; these blocks pile up to form a **talus**, a sloping apron of rocks along the base of the cliff. Debris that has fallen a long way can reach speeds of 300 km per hour and may have so much momentum that it keeps moving as an avalanche-like cloud of fragments mixed with air when it reaches the base of a cliff. Large, fast rockfalls push the air in front of them, creating a short blast of hurricane-like wind. For example, the wind in front of a 1996 rockfall in Yosemite National Park flattened over 2,000 trees.

Did you ever wonder . . .
why highway engineers erect "falling rock" signs?

Small rockfalls happen fairly frequently along steep highway roadcuts, leading to the posting of "falling-rock zone" signs. Such rockfalls commonly take place soon after construction because blasting and excavation leave loose

rocks on the slope above the road. But rockfalls may continue long after construction, for mechanical and chemical weathering weakens slopes over time (see Interlude B). In fact, in temperate climates, rockfalls are common in the spring, after winter ice, which may cause frost wedging, melts.

FIGURE 13.6 Examples of avalanches.



(a) Aftermath of a 1999 avalanche in the Austrian Alps. Masses of snow buried several homes.



(b) A dry-snow avalanche in Alaska. It's a turbulent cloud.

Submarine Mass Movements

So far, we've focused on mass movements that occur subaerially, for these are the ones we can see most easily and that affect us the most. But mass wasting also happens underwater. Geologists distinguish three types of submarine mass movements, according to whether the mass remains coherent or disintegrates as it moves. In *submarine slumps*, semi-coherent blocks slip downslope on weak detachments. In some cases, the layers constituting the blocks become contorted as they move, like a tablecloth that has slid off a table. In submarine *debris flows*, the moving mass breaks apart to form a slurry containing larger clasts (pebbles to boulders) suspended in a mud matrix. And in *turbidity currents*, sediment disperses in water to create a turbulent cloud of

FIGURE 13.7 Examples of rockfalls.



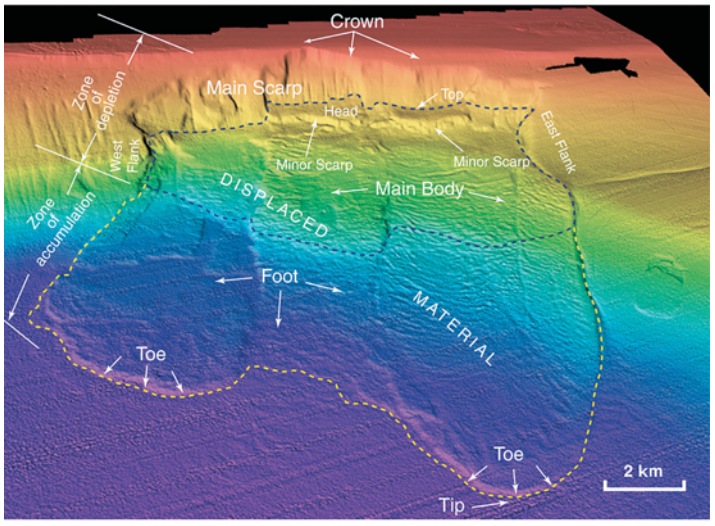
(a) Successive rockfalls have littered the base of this sandstone cliff with boulders. Note the talus at the base of the cliff.



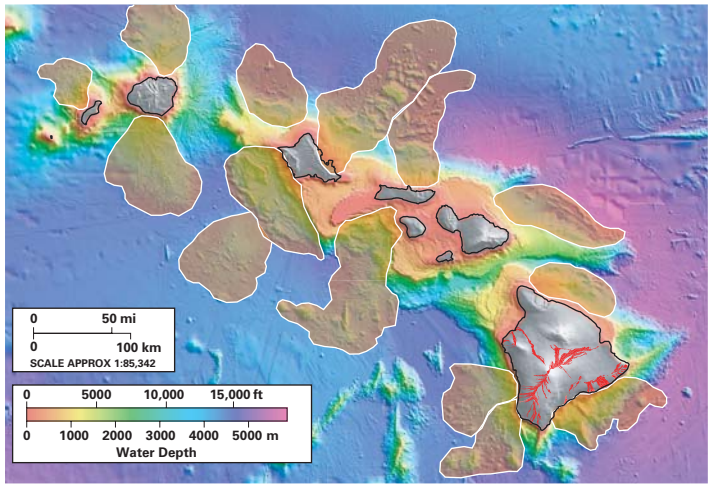
(b) A large rockslide buried a portion of the forest bordering a lake in the Uinta Mountains, Utah.



(a) A laboratory model of a turbidity current. The cloud is entirely underwater and consists of fine clay suspended in water.



(b) A digital bathymetric map of a slip along the coast of California. The parts of the slump are labeled.



(c) A bathymetric map of the area around Hawaii shows several huge slumps, shaded in tan. The islands are grey.

FIGURE 13.8 Examples of huge submarine slumps and debris flows.

suspended sediment that rushes downslope like an underwater avalanche (Fig. 13.8a).

In recent years, geologists have used satellites as well as sonar to map out the extent of submarine landslides. The shapes of slumps and landslide deposits stand out on the resulting new generation of high-resolution sea-floor maps (Fig. 13.8b). Geologists have found that submarine slopes bordering both hot-spot volcanoes and active plate boundaries are scalloped by many immense slumps, because tectonic activity frequently jars these areas with earthquakes that set masses of material in motion. Debris from countless slumps over millions of years has substantially modified the flanks of the Hawaiian Islands (Fig. 13.8c). Significantly, passive-margin coasts are not immune to slumping, and immense slumps have been mapped along the coasts of the Atlantic Ocean.

Since a submarine slump can develop fairly quickly, and since its movement can displace a large area of the sea floor, it can trigger a tsunami. A huge slump called the Storegga Slide occurred west of Norway, along the Atlantic passive margin, thousands of years ago. The area affected by the slump is about 100 km wide, and the slump debris traveled underwater for over 600 km. Tsunamis generated by the slump may have wiped out Stone-Age villages all around the coast of the North Sea.

Take-Home Message

Mass movements differ from one another based on speed and character. Creep, slumping, and solifluction are slow. Mudflows and debris flows move faster, and avalanches and rockfalls move the fastest. Movements occur on land and underwater.

13.3 Why Do Mass Movements Occur?

We've seen that mass movements travel at a range of different velocities, from slow (creep) to faster (slumps, mudflows and debris flows, and rockslides and debris slides) to fastest (snow avalanches, and rock and debris falls—see Geology at a Glance, pp. 408–409). The velocity depends on the steepness of the slope and the water or air content of the mass. For these movements to take place, the stage must be set by the following phenomena: fracturing and weathering, which weaken materials at Earth's surface so that they cannot hold up against the pull of gravity; and the development of relief, which provides slopes down which masses move.

Weakening the Substrate by Fragmentation and Weathering

If the Earth's surface were covered by intact (unbroken) rock, mass movements would be of little concern, for intact rock has great strength and could form stalwart mountain faces that would rarely tumble. But the rock of the Earth's upper crust has been fractured by jointing and faulting (Fig. 13.9), and in many locations the surface has a cover of regolith resulting from the weathering of rock. Regolith and fractured rock are much weaker than intact rock and can indeed collapse in

FIGURE 13.9 Jointing broke up this thick sandstone bed along a cliff in Utah. Blocks of sandstone break free along joints and tumble downslope.



response to gravitational pull. Thus jointing, faulting, and weathering ultimately make mass movements possible.

Why are regolith and fractured rocks weaker than intact bedrock? The answer comes from looking at the strength of the attachments holding materials together. A mass of intact bedrock is relatively strong because the chemical bonds within its interlocking grains, or within the cements between grains, can't be broken easily. A mass of loose rocks or of regolith, in contrast, is relatively weak because the grains are held together only by friction, electrostatic attraction, and/or surface tension of water. All of these forces combined are weaker than chemical bonds holding together the atoms in the minerals of intact rock. To picture this contrast, think about how much easier it is to bust up a sand castle (whose strength comes primarily from the surface tension of water films on the sand grains) than it is to bust up a granite sculpture of a castle.

Slope Stability

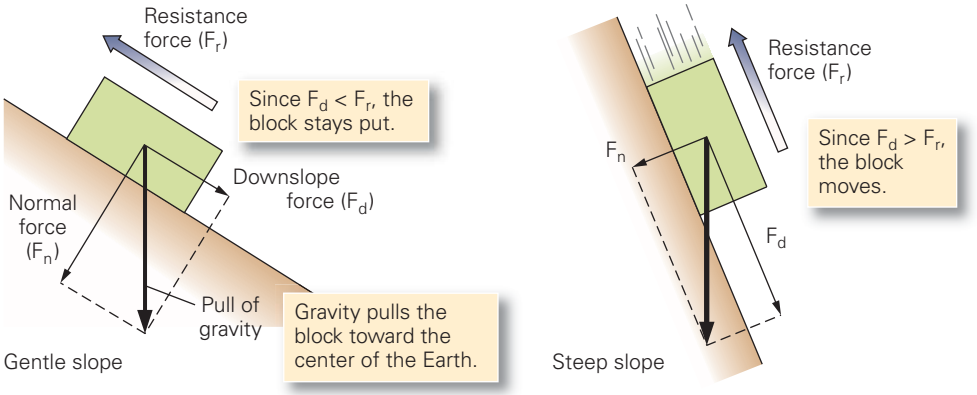
Mass movements do not take place on all slopes, and even on slopes where such movements are possible, they occur only occasionally. Geologists distinguish between *stable* slopes, on which sliding is unlikely, and *unstable* slopes, on which sliding will likely happen. When material starts moving on an unstable slope, we say that *slope failure* has occurred. Whether a slope fails or not depends on the balance between two forces—the downslope force, caused by gravity, and the resistance force, which inhibits sliding. If the downslope force exceeds the resistance force, the slope fails and mass movement results.

Let's examine this phenomenon more closely by imagining a block sitting on a slope. We can represent the gravitational attraction between this block and the Earth by an arrow (a vector) that points straight down, toward the Earth's center of gravity. This arrow can be separated into two components—the downslope force parallel to the slope and the normal force perpendicular to the slope. We can symbolize the resistance force by an arrow pointing uphill. If the downslope force is larger than the resistance force, then the block moves; otherwise, it stays in place (**Fig. 13.10a, b**). Note that for a given mass, downslope forces are greater on steeper slopes.

What produces a resistance force? As we saw above, chemical bonds in mineral crystals or cement hold intact rock in place, friction holds an unattached block in place, electrical charges and friction hold dry regolith in place, and surface tension holds wet regolith in place. Because of resistance force, granular debris tends to pile up to produce the steepest slope it can without collapsing. The angle of this slope is called the **angle of repose**, and for most dry, unconsolidated materials (such as dry sand) it typically has a value of between 30° and 37°. The angle depends partly on the shape and size of grains, which determine the amount of friction across grain boundaries. For example, steeper angles of repose (up to 45°) tend to form on slopes composed of large, irregularly shaped grains (**Fig. 13.11**).

In many locations, the resistance force is less than might be expected because a weak surface exists at some depth below ground level. If downslope movement begins on the weak surface, we can say that the weak surface has become a failure surface. Geologists recognize several different kinds of weak surfaces that are likely to become failure surfaces (**Fig. 13.12a–c**). These include wet clay layers; wet, unconsolidated sand layers; joints; weak bedding planes (shale beds and evaporite beds are particularly weak); and metamorphic foliation planes. Weak surfaces that dip parallel to the land surface slope are particularly likely to fail. An example of such failure occurred in Madison Canyon, southwestern Montana, on August 17, 1959.

FIGURE 13.10 Forces that trigger downslope movement.



(a) Gravity can be divided into a normal force and a downslope force. If the resistance force, caused by friction, is greater than the downslope force, the block does not move.

(b) If the slope angle increases, the downslope force due to gravity increases. If the downslope force becomes greater than the resistance force, the block starts to move.

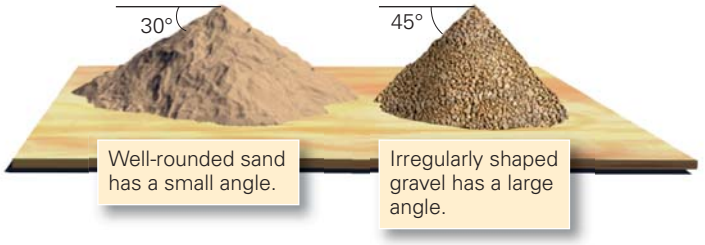


FIGURE 13.11 The angle of repose is the steepest slope that a pile of unconsolidated sediment can have and remain stable. The angle depends on the shape and size of grains.

That day, vibrations from a strong earthquake jarred the region. Metamorphic rock with a strong foliation that could serve as weak surfaces formed the bedrock of the canyon's southern wall. When the ground vibrated, rock detached along a foliation plane and tumbled downslope. Unfortunately, 28 campers lay sleeping on the valley floor. They were probably awakened by the hurricane-like winds blasting in front of the moving mass, but seconds later were buried under 45 m of rubble.

Fingers on the Trigger: What Causes Slope Failure?

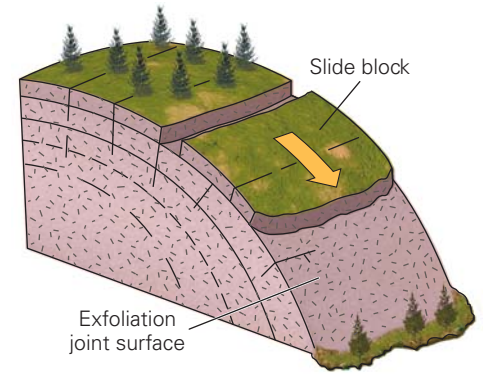
What triggers an individual mass-wasting event? In other words, what causes the balance of forces to change so that the downslope force exceeds the resistance force, and a slope suddenly fails? Here, we look at various phenomena—natural and human-made—that trigger slope failure.

Shocks, vibrations, and liquefaction. Earthquake tremors, storms, the passing of large trucks, or blasting in construction sites may cause a mass that was on the verge of moving actually to start moving. For example, an earthquake-triggered slide dumped debris into Lituya Bay, in southeastern Alaska, in 1958. The debris displaced the water in the bay, creating a 300-m-high (1,200 ft) splash that washed forests off the slopes bordering the bay and carried fishing boats anchored in the bay many kilometers out to sea. The vibrations of an earthquake break bonds that hold a mass in place and/or cause the mass and the slope to separate slightly, thereby decreasing friction. As a consequence, the resistance force decreases, and the downslope force sets the mass in motion. Shaking can also cause **liquefaction** of wet sediment by either increasing water pressure in spaces between grains so that the grains are pushed apart, or by breaking the cohesion between the grains.

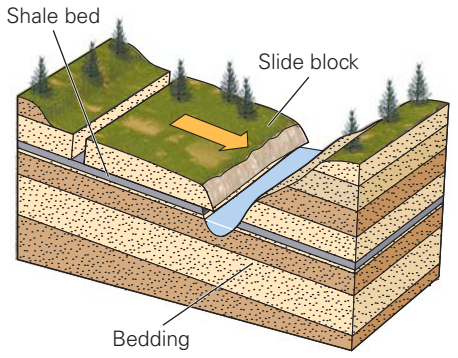
Changing slope loads, steepness, and support. As we have seen, the stability of a slope at a given time depends on the balance between the downslope force and the resistance force. Factors that change one or the other of these forces can lead to failure. Examples include changes in slope loads, failure-surface strength, slope steepness, and the support provided by material at the base of the slope.

Slope loads change when the weight of the material above a potential failure plane changes. If the load increases, due to construction of buildings on top of a slope or due to saturation of regolith with water due to heavy rains, the downslope force increases and may exceed the resistance force. Seepage of water into the ground may also weaken underground failure surfaces, further decreasing resistance force. An example of such failure triggered the largest observed landslide in U.S. history, the Gros Ventre Slide, which took place in 1925 on the flank of Sheep Mountain, near Jackson Hole, Wyoming (Fig. 13.13). Almost 40 million cubic meters of rock, as well as the overlying soil and forest, detached from the side of the mountain and slid 600 m downslope, filling a valley and forming a 75-m-high natural dam across the Gros Ventre River.

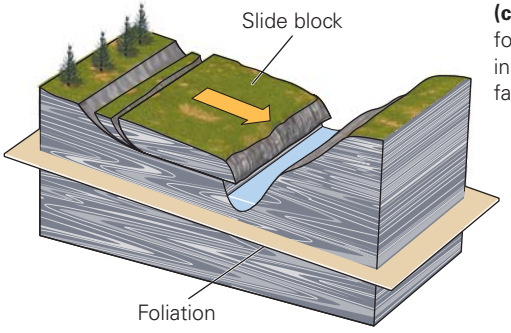
Removing support at the base of a slope due to river or wave erosion or to construction efforts plays a major role in triggering many slope failures. In effect, the material at the base of a slope acts like a dam holding back the material farther up the slope.



(a) Exfoliation joints form parallel to slope surfaces in granite and become failure surfaces.



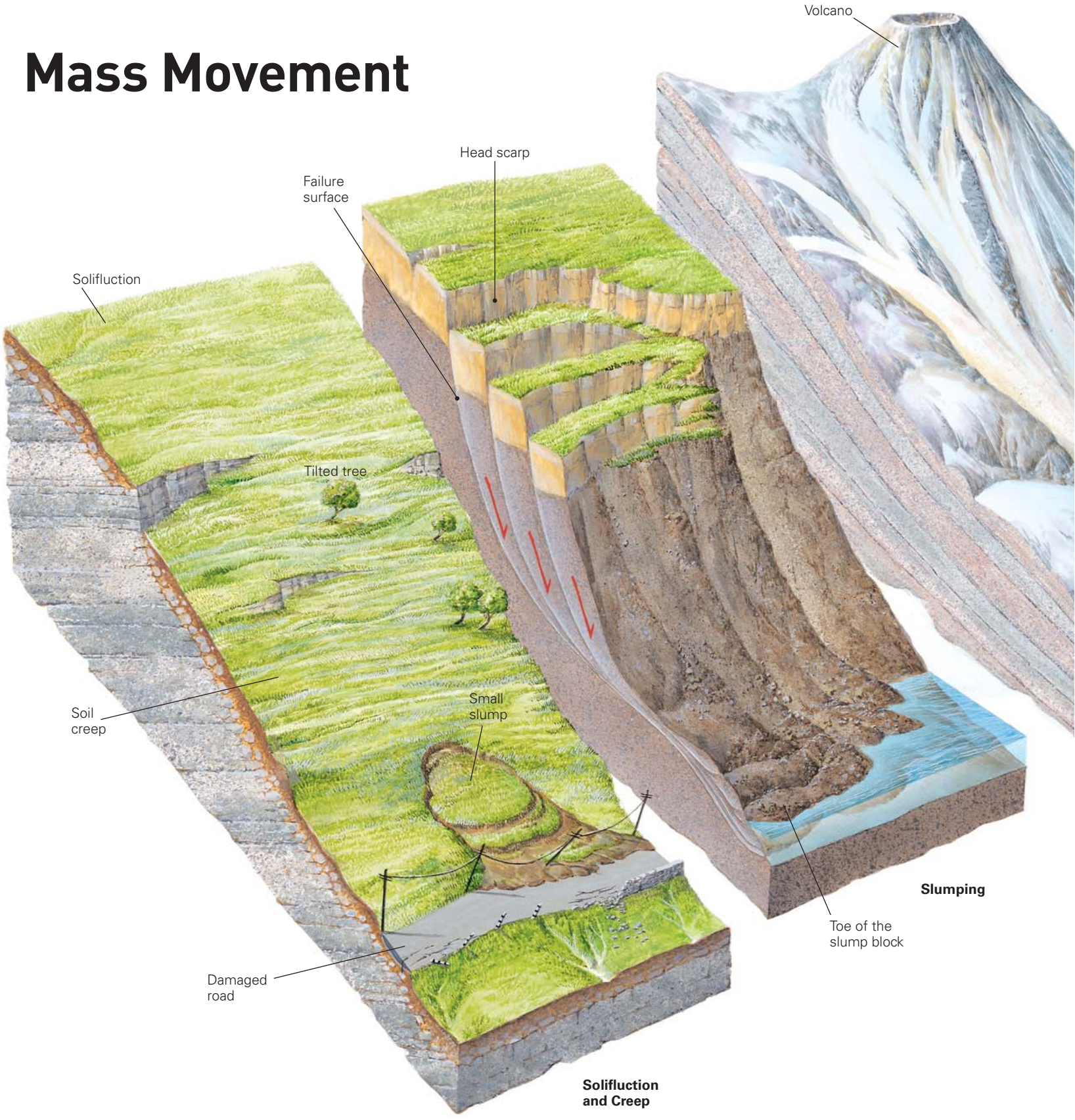
(b) In sedimentary rock, bedding planes (particularly in weak shale) become failure surfaces.



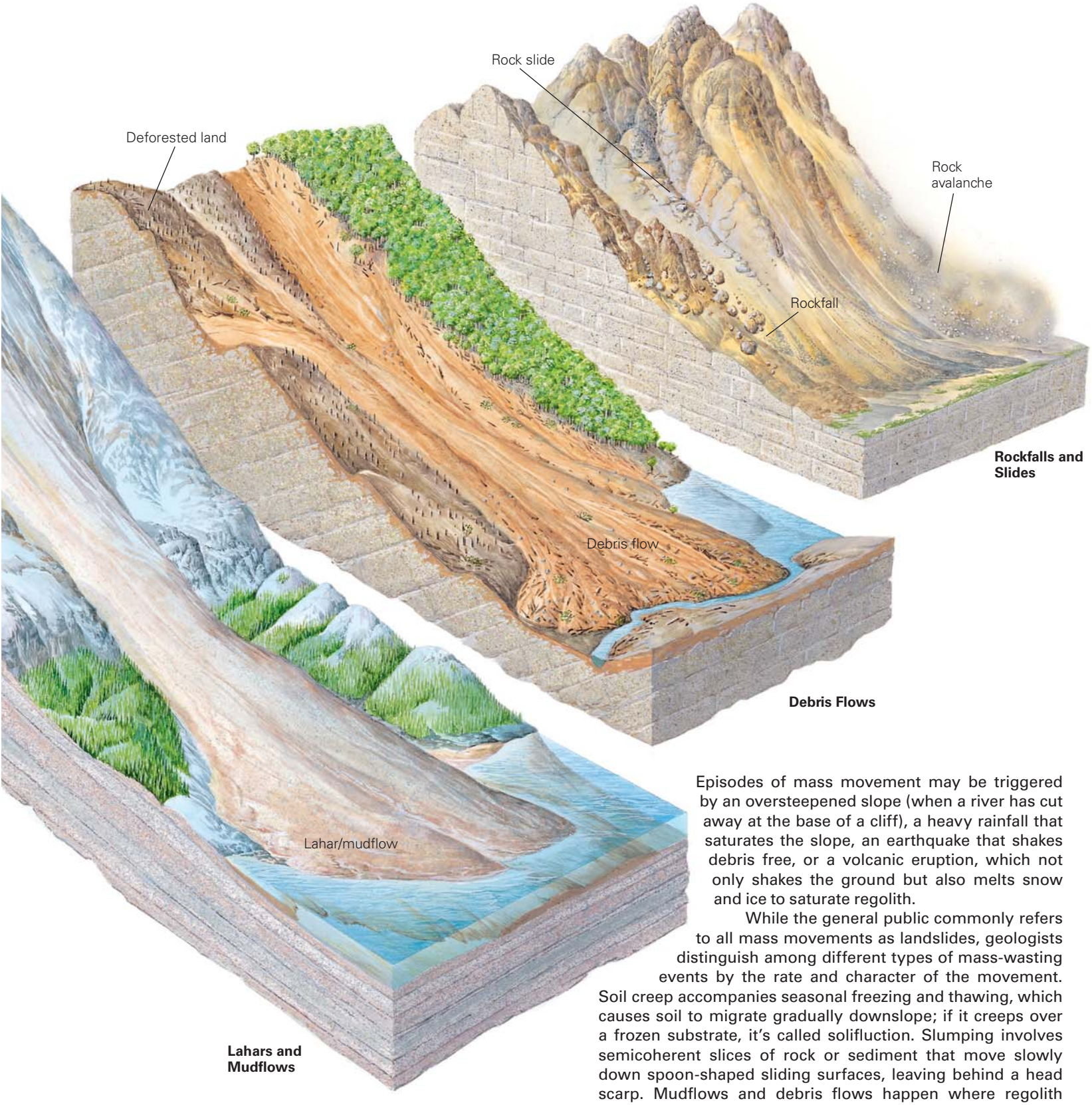
(c) In metamorphic rock, foliation planes (particularly in mica-rich schist) become failure surfaces.

FIGURE 13.12 Different kinds of weak surfaces can become failure surfaces.

Mass Movement



In Earth's gravity field, what goes up must come down—sometimes with disastrous consequences. Rock and regolith are not infinitely strong, so every now and then slopes or cliffs give way in response to gravity, and materials slide, tumble, or career downslope. This downslope movement, called mass movement, or mass wasting, is the first step in the process of erosion and sediment formation. The resulting debris may eventually be carried away by water, ice, or wind.



The kind of mass wasting that takes place at a given location reflects the composition of the slope (is it composed of weak soil, loose rock, or hard rock containing joints?), the steepness of the slope, and the climate (is the slope wet or dry, frozen or unfrozen?). Stronger rocks can hold up steep cliffs, but with time, rock breaks free along joints and tumbles or slides down weak surfaces. Coherent regolith may slowly slide down slopes, whereas water-saturated regolith may flow rapidly. Episodes of mass movement may be triggered by an oversteepened slope (when a river has cut away at the base of a cliff), a heavy rainfall that saturates the slope, an earthquake that shakes debris free, or a volcanic eruption, which not only shakes the ground but also melts snow and ice to saturate regolith.

While the general public commonly refers to all mass movements as landslides, geologists distinguish among different types of mass-wasting events by the rate and character of the movement. Soil creep accompanies seasonal freezing and thawing, which causes soil to migrate gradually downslope; if it creeps over a frozen substrate, it's called solifluction. Slumping involves semicoherent slices of rock or sediment that move slowly down spoon-shaped sliding surfaces, leaving behind a head scarp. Mudflows and debris flows happen where regolith has become saturated with water and moves downslope as a slurry. When volcanoes erupt and melt ice and snow at their summit, or if heavy rains fall during an eruption, water mixes with ash, creating a fast-moving lahar. Steep, rocky cliffs may suddenly give way in rockfalls. If the rock breaks up into a cloud of debris that rushes downslope at high velocity, it is a rock avalanche. Snow avalanches are similar, but the debris consists only of snow.

In some cases, erosion by a river or by waves eats into the base of a cliff and produces an overhang. When such **undercutting** has occurred, rock making up the overhang eventually breaks away from the slope and falls (Fig. 13.14a, b).

Changing the slope strength. The stability of a slope depends on the strength of the material constituting it. If the material weakens with time, the slope becomes weaker and eventually collapses. Three factors influence the strength of slopes:

(1) *Weathering*: With time, chemical weathering produces weaker minerals, and physical weathering breaks rocks apart. Thus, a formerly intact rock composed of strong minerals is transformed into a weaker rock or into regolith.

(2) *Vegetation cover*: In the case of slopes underlain by regolith, vegetation tends to strengthen the slope because the roots hold otherwise unconsolidated grains together. Also, plants absorb water from the ground, thus keeping it from turning into slippery mud. The removal of vegetation therefore has the net result of making slopes more susceptible to downslope mass movement. Deforestation in tropical rainforests, similarly, leads to catastrophic mass wasting of the forest's substrate.

(3) *Water content*: Water affects materials comprising slopes in many ways. Surface tension, due to the film of water on grain surfaces, may help hold regolith together. But if the water content increases, water pressure may push grains apart so that regolith liquefies and can begin to flow. Water infiltration may make weak surfaces underground more slippery, or may push surfaces apart and decrease friction. Some kinds of clays absorb water and expand, causing the ground surface to rise and, as a consequence, break up.

FIGURE 13.13 Stages leading to the 1925 Gros Ventre Slide in Wyoming.

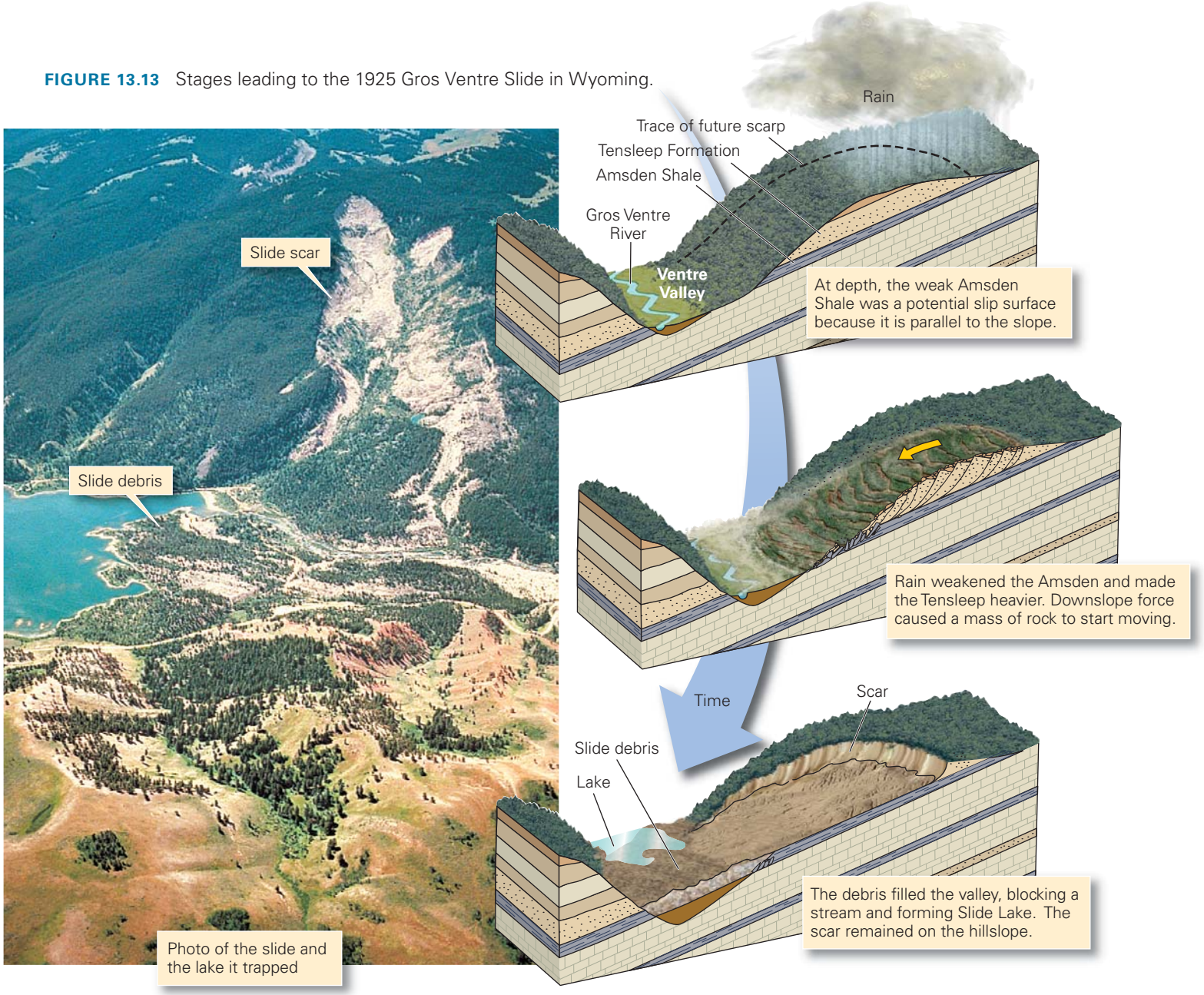
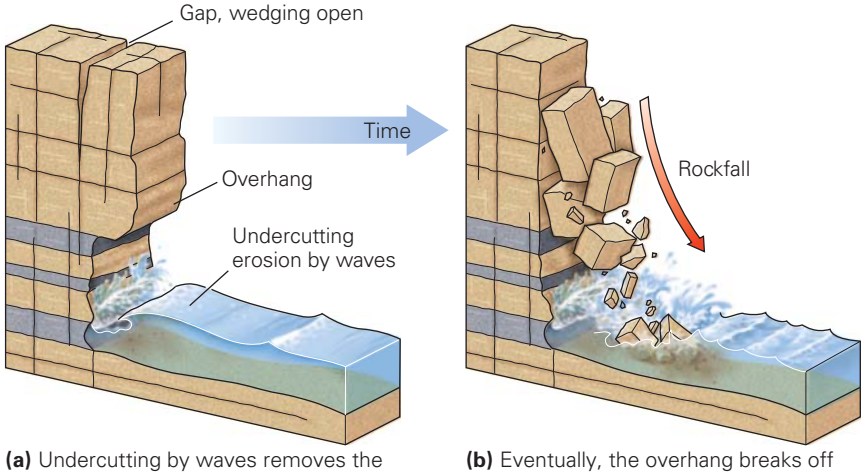


FIGURE 13.14 Undercutting and collapse of a sea cliff.



(a) Undercutting by waves removes the support beneath an overhang.

(b) Eventually, the overhang breaks off along joints, and a rockfall takes place.

13.4 How Can We Protect Against Mass-Movement Disasters?

Identifying Regions at Risk

Clearly, landslides, mudflows, and slumps are natural hazards we cannot ignore. Too many of us live in regions where mass wasting has the potential to kill people and destroy property. In many cases, the best solution is avoidance: don't build, live, or work in an area where mass movement can take place. But avoidance is possible only if we know where the hazards are.

To pinpoint dangerous regions, geologists look for landforms known to result from mass movements, for where these movements have happened in the past, they might happen again in the future. Features such as slump head scarps, swaths of forest in which trees have been tilted, piles of loose debris at the base of hills, and hummocky land surfaces all indicate recent mass wasting.

Take-Home Message

Weathering and fragmentation weaken slope materials and make them more susceptible to mass movement. Failure occurs when downslope pull exceeds resistance force due to shocks, changing slope angles and strength, changing water content, and changing slope support.

FIGURE 13.15 Surface features warn that a large slump is beginning to develop. Cracks that appear at the head scarp may drain water and kill trees. Power-line poles tilt and the lines become tight. Fences, roads, and houses on the slump begin to crack.

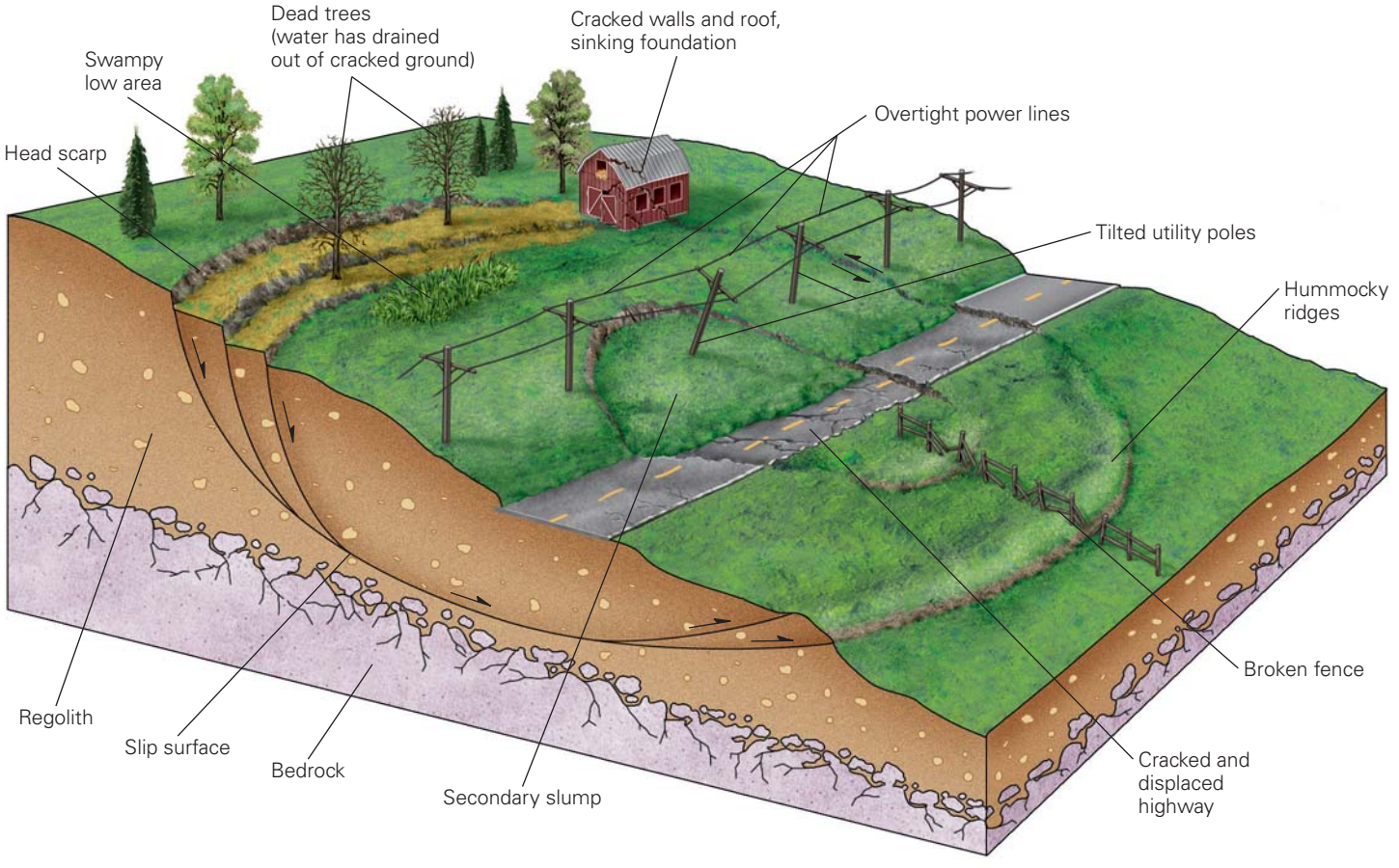


FIGURE 13.16 A landslide hazard map of the Seattle area.



In some cases, geologists may also be able to detect regions that are *beginning to move* (Fig. 13.15). For example, roads, buildings, and pipes begin to crack over unstable ground. Power lines may be too tight or too loose because the poles to which they are attached move together or apart. Visible cracks form on the ground at the potential head of a slump, and the ground may bulge up at the toe of the slump. In some cases, subsurface cracks may drain the water from an area and kill off vegetation, whereas in other areas land may sink and form a swamp. Slow movements cause trees to develop pronounced curves at their base. More recently, new extremely precise surveying technologies have permitted geologists to detect the beginnings of mass movements that may not yet have visibly affected the land surface.

Even if there is no evidence of recent movement, a danger may still exist: just because a steep slope hasn't collapsed in the recent past doesn't mean it won't in the future. In recent years, geologists have begun to identify such potential hazards by using computer programs that evaluate factors that trigger mass wasting. These factors include the following: slope steepness; strength of substrate; degree of water saturation; orientation of bedding, joints, or foliation relative to the slope; nature of vegetation cover; potential for heavy rains; potential for undercutting to occur; and likelihood of earthquakes. From such hazard-assessment studies, geologists compile **landslide-potential maps**, which rank regions according to the likelihood that a mass movement will occur (Fig. 13.16). In any case, common sense suggests that you should avoid building on or below particularly dangerous slide-prone slopes.

Preventing Mass Movements

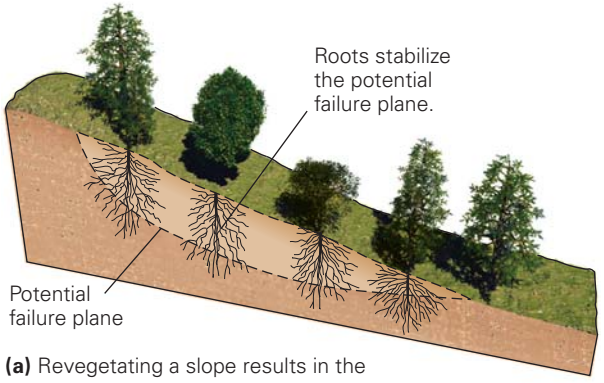
In areas where a hazard exists, people can take certain steps to remedy the problem and stabilize the slope (Fig. 13.17a–h).

- *Revegetation*: Stability in deforested areas will be greatly enhanced if land owners replant the region with vegetation that sends down deep roots and binds regolith together.
- *Regrading*: An oversteepened slope can be regraded or terraced so that it does not exceed the angle of repose.
- *Reducing subsurface water*: Because water weakens material beneath a slope and adds weight to the slope, an unstable situation may be remedied either by improving drainage so that water does not enter the subsurface in the first place, or by removing water from the ground.
- *Preventing undercutting*: In places where a river undercuts a cliff face, engineers can divert the river. Similarly, along coastal regions they may build an offshore breakwater or pile riprap (loose boulders or concrete) along the beach to absorb wave energy before it strikes the cliff face.
- *Constructing safety structures*: In some cases, the best way to prevent mass wasting is to build a structure that stabilizes a potentially unstable slope or protects a region downslope from debris if a mass movement does occur. For example, civil engineers can build retaining walls or bolt loose slabs of rock to more coherent masses in the substrate in order to stabilize highway embankments. The danger from rockfalls can be decreased by covering a roadcut with chain link fencing or by spraying roadcuts with concrete. Highways at the base of an avalanche-prone slope can be covered by an avalanche shed, whose roof keeps debris off the road.
- *Controlled blasting of unstable slopes*: When it is clear that unstable ground or snow threatens a particular region, the best solution may be to blast the unstable ground or snow loose at a time when its movement can do no harm.

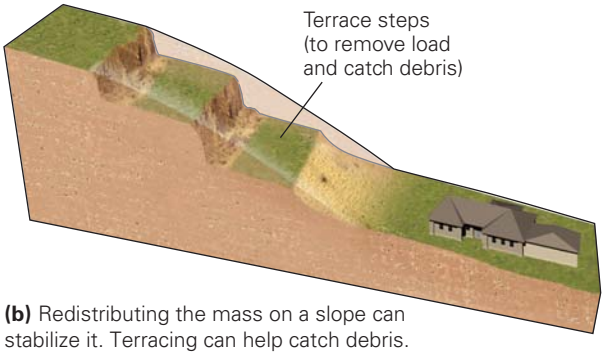
Take-Home Message

Various features of the landscape may help geologists to identify unstable slopes and estimate risk. Systematic study allows production of landslide-potential maps. Engineers use a variety of techniques to stabilize slopes.

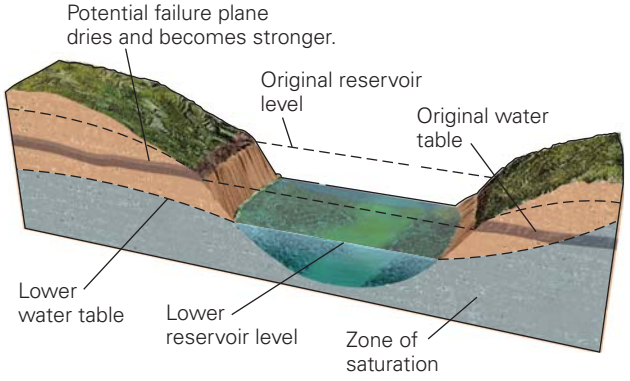
FIGURE 13.17 A variety of remedial steps can stabilize unstable ground.



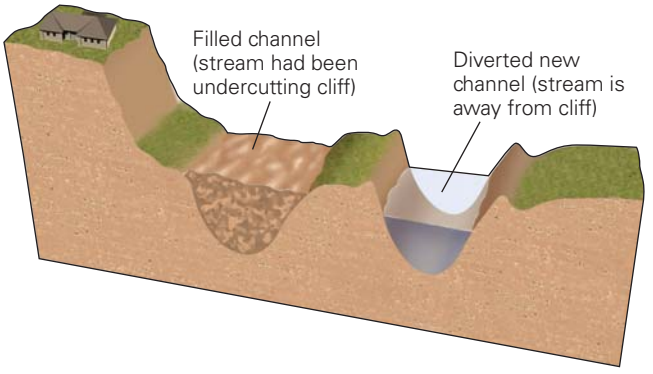
(a) Revegetating a slope results in the growth of roots that can hold a slope together.



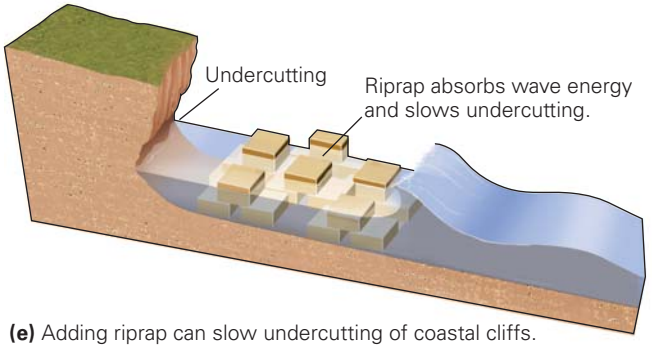
(b) Redistributing the mass on a slope can stabilize it. Terracing can help catch debris.



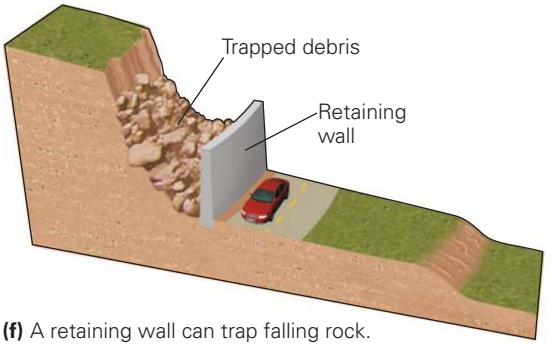
(c) Lowering the level of the water table can strengthen a potential failure surface.



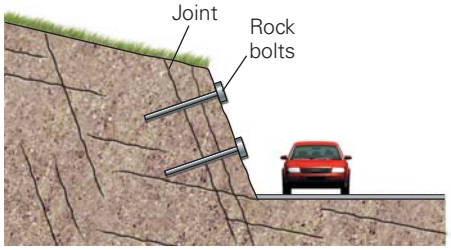
(d) Relocating a river channel can prevent undercutting.



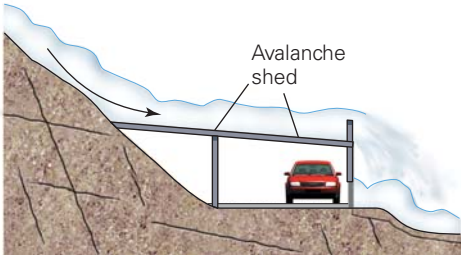
(e) Adding riprap can slow undercutting of coastal cliffs.



(f) A retaining wall can trap falling rock.



(g) Bolting or screening a cliff face can hold loose rocks in place.



(h) An avalanche shed diverts debris or snow over a roadway.

CHAPTER 13 REVIEW

Chapter Summary

- Rock or regolith on unstable slopes has the potential to move downslope under the influence of gravity. This process, called mass movement, or mass wasting, plays an important role in the erosion of hills and mountains.
- Slow mass movement, caused by the freezing and thawing of regolith, is called creep. In places where slopes are underlain with permafrost, solifluction causes a melted layer of regolith to flow down slopes. During slumping, a semicoherent mass of material moves down a spoon-shaped failure surface. Mudflows and debris flows occur where regolith has become saturated with water and moves downslope as a slurry.
- Rock and debris slides move very rapidly down a slope; the rock or debris breaks apart and tumbles. During avalanches, snow or debris mixes with air and moves downslope as a turbulent cloud. And in a debris fall or rockfall, the material free-falls down a vertical cliff.
- Large mass movements can take place on underwater slopes. Some generate tsunamis.
- Intact, fresh rock is usually too strong to undergo mass movement. Thus, for mass movement to be possible, rock must be weakened by fracturing or weathering.
- Unstable slopes start to move when the downslope force exceeds the resistance force that holds material in place. The steepest angle at which a slope of unconsolidated material can remain without collapsing is the angle of repose.
- Downslope movement can be triggered by shocks and vibrations, changes in the steepness of a slope, removal of support from the base of the slope, changes in the strength of a slope, deforestation, weathering, or heavy rain.
- Geologists can sometimes detect unstable ground before it begins to move, and they produce landslide-potential maps to identify areas susceptible to mass movement.
- Engineers can help prevent mass movements by using a variety of techniques to stabilize slopes.

Key Terms

angle of repose (p. 406)
creep (p. 398)
debris fall (p. 403)
debris flow (debris slide) (pp. 400, 401)
failure surface (p. 399)
head scarp (p. 399)
lahar (p. 401)
landslide-potential map (p. 412)
liquefaction (p. 407)
mass movement (wasting) (p. 398)
mudflow (mudslide) (p. 400)
natural hazard (p. 398)
rockfall (p. 403)
rockslide (p. 401)
slump (p. 399)
snow avalanche (p. 403)
solifluction (p. 398)
talus (p. 403)
undercutting (p. 410)

Review Questions

1. What factors do geologists use to distinguish among various types of mass movements?
2. Explain how soil creep operates.
3. Identify the key differences between a slump, a debris flow, a lahar, an avalanche, a rockslide, and a rockfall.
4. Why is intact bedrock stronger than fractured bedrock? Why is it stronger than regolith?
5. Explain the difference between a stable and an unstable slope. What factors determine the angle of repose of a material? What features are likely to serve as failure surfaces?
6. Discuss the variety of phenomena that can cause a stable slope to become so unstable that it fails.
7. How can ground shaking cause fairly solid layers of sand or mud to become weak slurries capable of flowing?
8. Discuss the role of vegetation and water in slope stability. Why can fires and deforestation lead to slope failure?
9. What factors do geologists take into account when producing a landslide-potential map, and how can geologists detect the beginning of mass movement in an area?
10. What steps can people take to avoid landslide disasters?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on the identification of mass movements.
- Animation-based exercises on debris flows and cliff retreat.
- Questions that help students understand the concept of slope stability.

On Further Thought

11. Imagine that you have been asked by the World Bank to determine whether it makes sense to build a dam in a steep-sided, east-west-trending valley in a small central Asian nation. The local government has lobbied for the dam because the climate of the country has gradually been getting drier, and the farms of the area are running out of water. The World Bank is considering making a loan to finance construction of the dam, a process that would employ thousands of now-jobless people. Initial investigation shows that the rock of the valley wall consists of schist containing a strong foliation that dips toward the valley and is parallel to the slope of the valley wall. Outcrop studies reveal that abundant fractures occur in the schist along the valley floor; the surface of most fractures are coated with slickensides. Moderate earthquakes have rattled the region. What would you advise the bank? Explain the hazards and what might happen if the reservoir were filled.

SEE FOR YOURSELF M. . . Mass Movements

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet M of our **Geotours Workbook**.



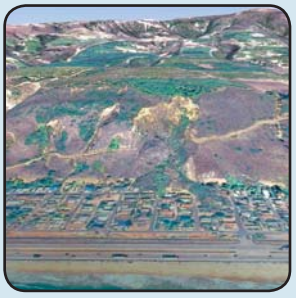
Portuguese Bend, California
Latitude 33°44′46.94″N,
Longitude 118°22′7.83″W

As seen from 7 km, housing covers much of the land in southern California, but not on a 3.5-km-wide spoon-shaped depression at Portuguese Bend slump. In the 1950s, developers built on the hummocky land, but water infiltration weakened a failure surface and reactivatied the slump, destroying 150 houses.



Canyonlands, Utah
Latitude 38°29′50.07″N,
Longitude 110°0′15.63″W

As seen from 5 km, the Green River has carved a deep valley through horizontal layers of strata. Shale forms the slopes, and sandstone forms the top ledge. Erosion of the shale undercuts the sandstone, which breaks away at joints and tumbles downslope to build a talus pile.



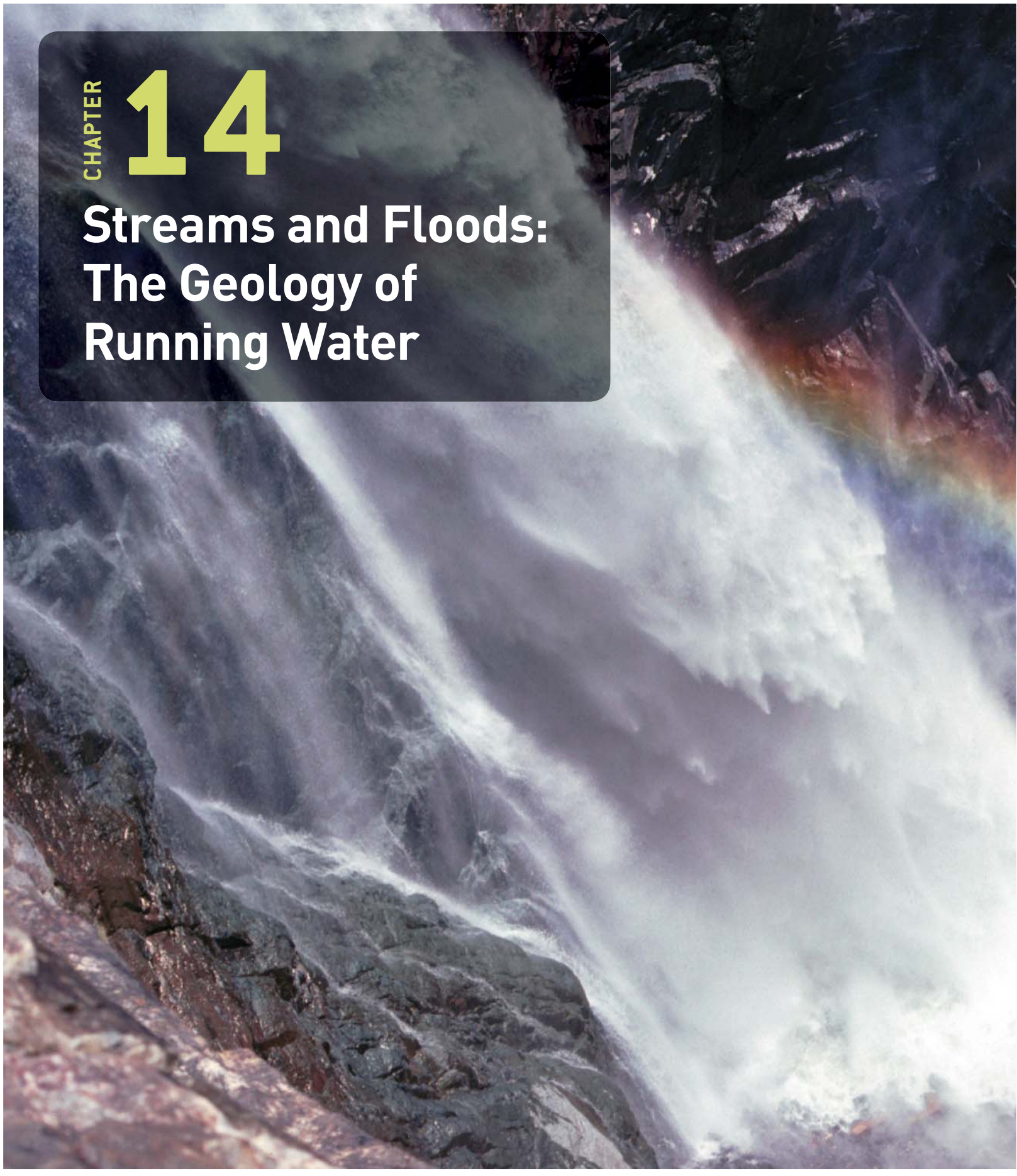
La Conchita Mudslide, California
Latitude 34°21′50.29″N,
Longitude 119°26′46.85″W

Tectonic activity has uplifted the coast of California to form a terrace bordered on the ocean side by a steep escarpment. Looking NE from 250 m, you can see a mudflow that overran houses built at the base of the escarpment. Note the head scarp.



Debris Fall, Yungay, Peru
Latitude 9°7′21.42″S,
Longitude 77°39′44.86″W

Looking NE from 6.4 km, you can see the steep, glaciated face of Nevado Huascarán. In 1970, a debris fall from the mountain rushed down the valley in the foreground and buried the landscape. More recent, smaller debris flows have accumulated on top of the larger one.



CHAPTER 14

Streams and Floods: The Geology of Running Water



Some of the water that falls on land drains downslope in streams. Where slopes become very steep, the water tumbles through the air as a waterfall, as seen here in the San Juan Mountains, Colorado.

Chapter Objectives

By the end of this chapter you should know . . .

- what streams and drainage networks are, and how they form and evolve.
- how to describe stream flow and erosion, and how streams transport and deposit sediment.
- how streams change from headwaters to mouth.
- how erosional and depositional landscapes formed by streams evolve over time.
- the nature and causes of flooding, and the steps that people take to protect against flooding.
- the environmental issues that pertain to streams.

As many fresh streams meet in one salt sea, as many lines close in the dial's center, so may a thousand actions, once afoot, end in one purpose.

—William Shakespeare (1564–1616)

14.1 Introduction

By the 1880s, Johnstown, built along the Conemaugh River in scenic western Pennsylvania, had become a significant industrial town. Recognizing the attraction of the surrounding hills as a summer retreat, speculators built a mud-and-gravel dam across the river, upstream of Johnstown, to trap a pleasant reservoir of cool water. A group of industrialists and bankers bought the reservoir and established the exclusive South Fork Hunting and Fishing Club. Unfortunately, the dam had been poorly designed, setting the stage for a monumental tragedy. On May 31, 1889, torrential rain drenched Pennsylvania, and the reservoir filled until water began to flow over the dam. Despite frantic attempts to strengthen the dam, the soggy structure abruptly collapsed, and the reservoir emptied into the Conemaugh River Valley. A 20-m-high wall of water roared downstream and slammed into Johnstown, transforming bridges and buildings into twisted wreckage (**Fig. 14.1**). When the water subsided, 2,300 people were dead, and Johnstown became the focus of national sympathy. It took years for the town to recover, and many residents simply picked up and left.

The unlucky inhabitants of Johnstown had experienced the immense power of **running water**, water that flows down the surface of sloping land in response to the pull of gravity. Geologists use

FIGURE 14.1 In 1889 raging waters destroyed Johnstown.



the term **stream** for any body of running water that flows along a **channel**, an elongate depression or trough. (In everyday English, we also refer to large streams as rivers and medium-sized ones as creeks or brooks.) Streams drain water from the landscape and carry it into lakes or to the sea, much as culverts drain water from a parking lot. In the process, streams erode the landscape and transport sediment and debris to sites of deposition. Generally, a stream stays within the confines of its channel, but when the supply of water entering a stream exceeds the channel's capacity, water spills out and covers the surrounding land, thereby causing a **flood**, such as the one that washed away Johnstown.

Earth is the only planet in the Solar System that currently hosts flowing streams. In this chapter, we examine how streams operate in the Earth System. First, we learn about the origin of running water and about the architecture of streams and stream networks. Then we look at the process of stream erosion and deposition and at the landscapes that form in response to these processes. Finally, we consider the nature and consequences of flooding.

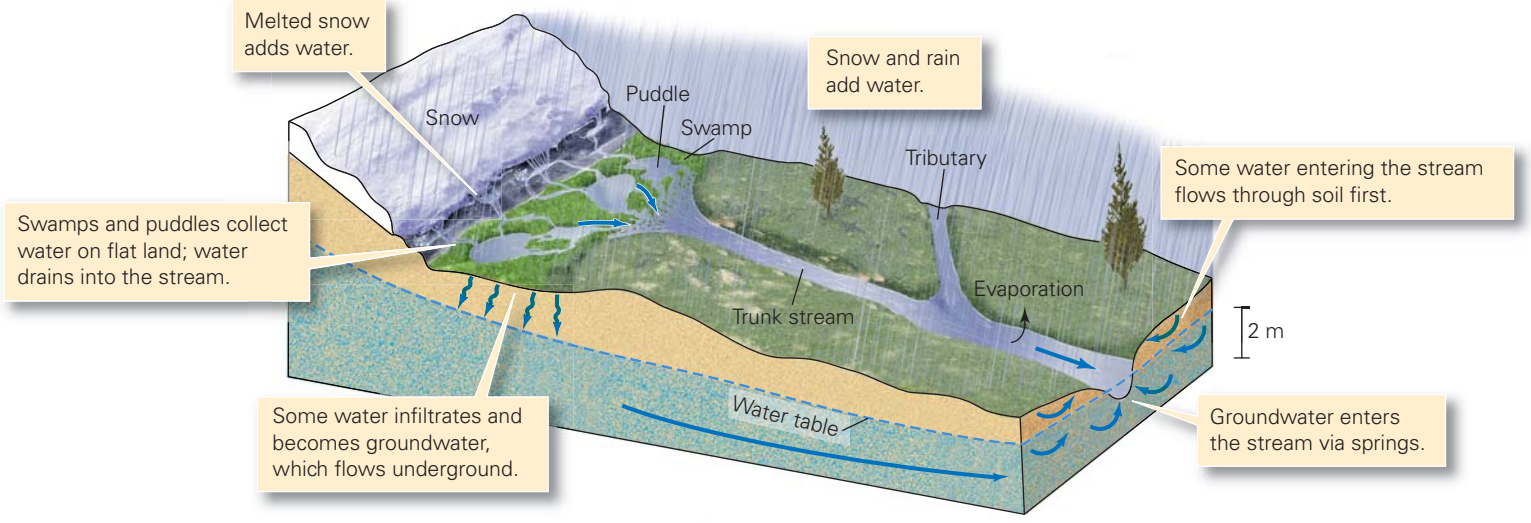
14.2 Draining the Land

Forming Streams and Drainage Networks

Where does the water in a stream come from? Recall that water enters the hydrologic cycle by evaporating from the Earth's surface and rising into the atmosphere (see Interlude F). After a relatively short residence time, atmospheric water condenses and falls back to the Earth's surface as rain or snow that accumulates in various reservoirs. Some rain or snow remains on the land as surface water (in puddles, swamps, lakes, snowfields, and glaciers), some flows downslope as a thin film called **sheetwash**, and some sinks into the ground, where it either becomes trapped in soil (as soil moisture) or descends below the water table to become groundwater. (As we discuss further in Chapter 16, the *water table* is the level below which groundwater fills all the pores and cracks in subsurface rock or sediment. Above the water table, air partially or entirely fills the pores and cracks.) Streams can receive input of water from all of these reservoirs (**Fig. 14.2**). Specifically, gravity pulls surface water (including meltwater) downhill into stream channels, the pressure exerted by the weight of new rainfall squeezes existing soil moisture back out of the ground, and groundwater seeps out of the channel walls into the channel, if the floor of the channel lies below the water table.

Running water collects in stream channels, because a channel is lower than the surrounding area and gravity

FIGURE 14.2 Excess surface water (runoff) comes from rain, melting ice or snow, and groundwater springs. On flat ground, water accumulates in puddles or swamps, but on slopes, it flows downslope in streams.



always moves material from higher to lower elevation. How does a stream channel form in the first place? The process of channel formation begins when sheetwash starts flowing downslope. Like any flowing fluid, sheetwash erodes its substrate (the material it flows over). The efficiency of such erosion depends on the velocity of the flow—faster flows erode more rapidly. In nature, the ground is not perfectly planar, not all substrate has the same resistance to erosion, and the amount of vegetation that covers and protects the ground varies with location. Thus, the velocity of sheetwash also varies with location. Where the flow happens to be a bit faster, or the substrate is a little weaker, erosion scours (digs) a channel. Since the channel is lower than the surrounding ground, sheetwash in adjacent areas starts to head toward it. With time, the extra flow deepens the channel relative to its surroundings, a process called **downcutting**, and a stream forms.

As its flow increases, a stream channel begins to lengthen at its origin, a process called **headward erosion** (Fig. 14.3). Headward erosion occurs for two reasons. First, it happens when the surface flow converging at the entrance to a channel has sufficient erosive power to downcut. Second, it happens at locations where groundwater seeps out of the ground and enters the entrance to the stream channel. Such seepage, called "groundwater sapping," gradually weakens and undermines the soil or rock just upstream of the channel's endpoint until the material collapses into the channel; the collapsed debris eventually washes away during a flood. Each increment of collapse makes the channel longer.

As downcutting deepens the main channel, the surrounding land surfaces start to slope toward the channel. Thus, new side channels, or **tributaries**, begin to form, and these flow into the main channel. Eventually, an array of linked streams evolves, with the smaller tributaries flowing into a *trunk stream*. The array of interconnecting streams together constitute the **drainage network**. Like transportation networks of roads, drainage networks of streams reach into all corners of a region, providing conduits for the removal of runoff.

The configuration of tributaries and trunk streams defines the map pattern of a drainage network. This pattern depends on the shape of the landscape and the composition of the substrate. Geologists recognize several types of networks on the basis of the network's map pattern (Fig. 14.4).

- *Dendritic*: When rivers flow over a fairly uniform substrate with a fairly uniform initial slope, they develop a dendritic network, which looks like the pattern of branches connecting to the trunk of a deciduous tree.
- *Radial*: Drainage networks forming on the surface of a cone-shaped mountain flow outward from the mountain peak, like spokes on a wheel. Such a pattern defines a radial network.
- *Rectangular*: In places where a rectangular grid of fractures (vertical joints) breaks up the ground, channels form along the preexisting fractures, and streams join each other at right angles, creating a rectangular network.
- *Trellis*: In places where a drainage network develops across a landscape of parallel valleys and ridges, major tributaries flow down a valley and join a trunk stream that cuts across the ridges. The resulting map pattern resembles a garden trellis, so the arrangement of streams constitutes a trellis network.
- *Parallel*: On a uniform slope, several streams with parallel courses develop simultaneously. The group comprises a parallel network.

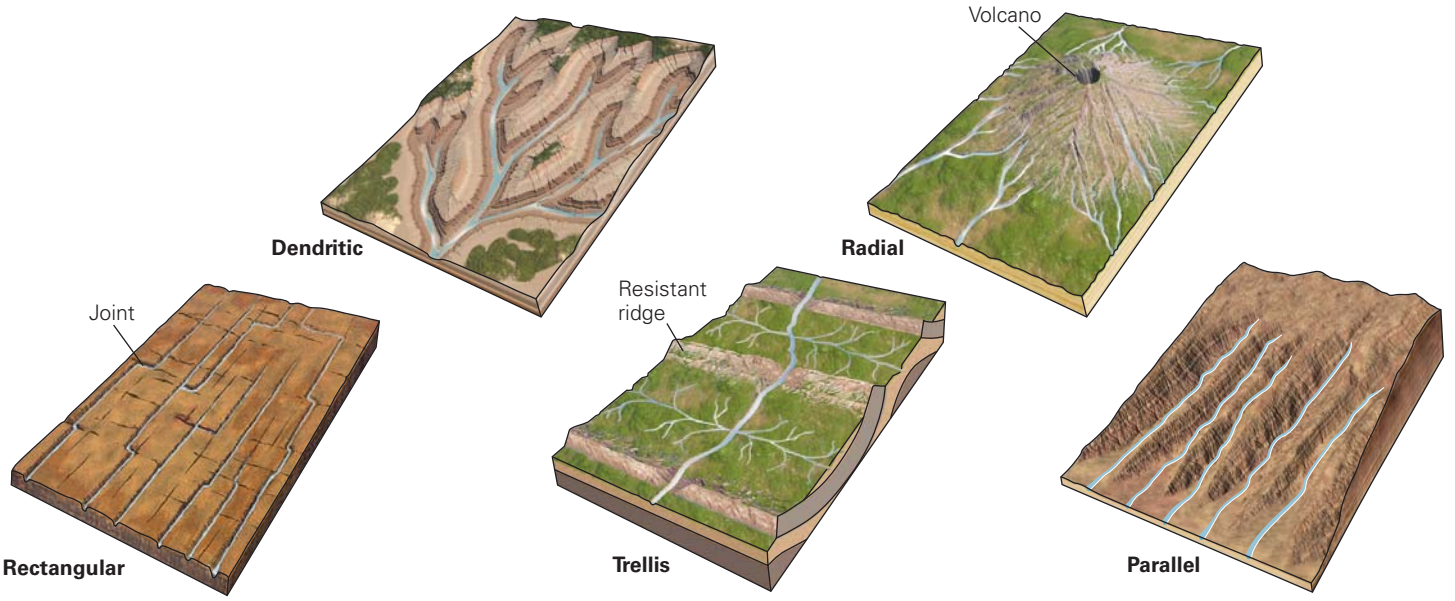
FIGURE 14.3 An example of headward erosion. The main stream flows in a deep valley. Side streams are cutting into the bordering plateau.



Drainage Basins and Divides

A drainage network collects water from a broad region, variously called a drainage basin, catchment, or **watershed**, and feeds it into the trunk stream, which carries the water away. The highland, or ridge, that separates one watershed from another is a **drainage divide** (Fig. 14.5a, b). A continental divide separates drainage that flows into one ocean from drainage that flows into another. For example, if you straddle the continental divide where it runs along the crest of the Rocky Mountains in the western United States, and pour a cup of water out of each hand, the water in one hand flows to the Atlantic, and the water in the other flows to the Pacific. Three

FIGURE 14.4 Block diagrams illustrating five types of drainage networks.

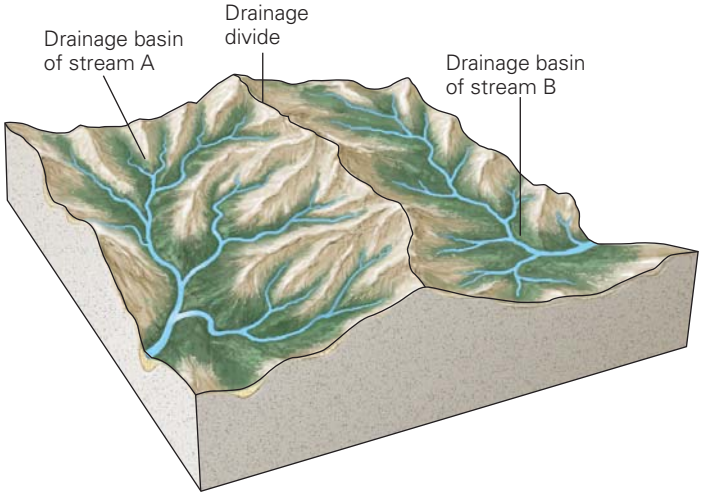


divides bound part of the Mississippi drainage basin, which drains the interior of the United States.

Streams That Last, Streams That Don't

Permanent streams flow all year long, whereas **ephemeral streams** flow only for part of the year. Some ephemeral streams flow only for tens of minutes to a few hours, following a heavy rain. Most permanent streams exist where the floor (or bed) of the stream channel lies *below* the water table (**Fig. 14.6a**; see Chapter 16). In these streams, which occur in humid or temperate climates, water comes not only from upstream or from surface runoff, but also from springs through which groundwater seeps. If the bed of a stream lies *above* the water table, then the stream can be permanent only when the rate at which water arrives from upstream exceeds the rate at which water infiltrates into the ground below. For example, the downstream

FIGURE 14.5 Drainage divides and basins.

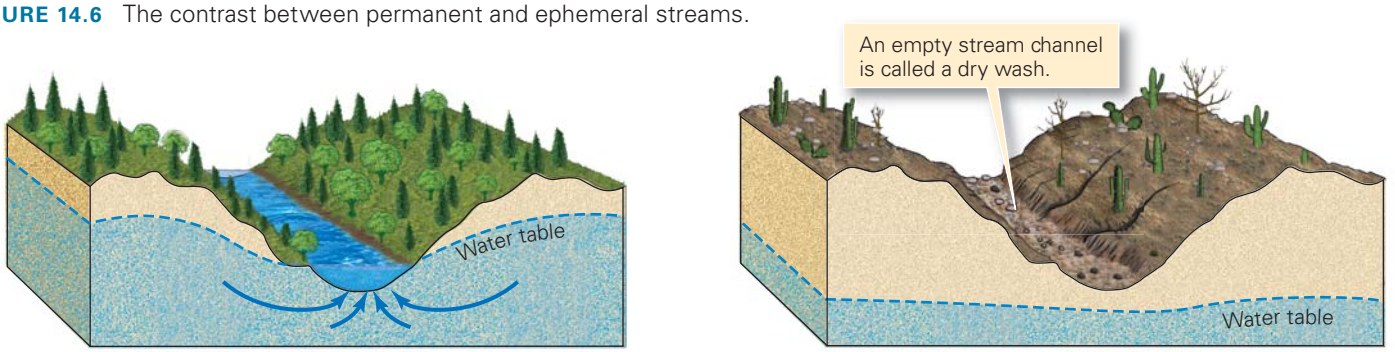


(a) A drainage divide is a relatively high ridge that separates two drainage basins.



(b) The major drainage basins of North America.

FIGURE 14.6 The contrast between permanent and ephemeral streams.



(a) The floor of a permanent stream in a temperate climate lies below the water table. Springs add water from below, so the stream contains water even between rains.

(b) The channel of an ephemeral stream lies above the water table, so the stream flows only when water enters the stream faster than it can infiltrate into the ground.

portion of the Colorado River in the dry Sonoran Desert of Arizona flows all year, because enough water enters it from the river's wet headwaters upstream in Colorado; hardly any water enters the stream from the desert itself.

Streams that do not have a sufficient upstream source, and whose beds lie above the water table, are ephemeral, because the water that fills a channel due to a heavy rain or a spring thaw eventually sinks into the ground and/or evaporates, and the stream dries up (**Fig. 14.6b**). Streams whose watersheds lie entirely within an arid region tend to be ephemeral. The dry bed of an ephemeral stream is variously called a dry wash, an arroyo, or a wadi.

Take-Home Message

Stream channels form by downcutting and lengthen by headward erosion. They carry water from sheetwash, lakes, springs, and melting snow or ice. Drainage networks carry water from a watershed to the sea. They have a variety of different geometries.

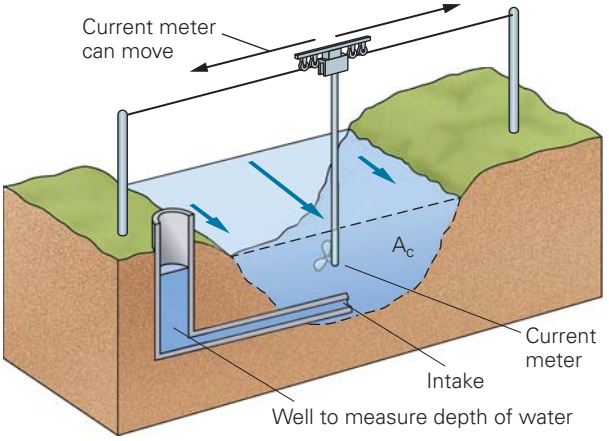
14.3 Describing Flow in Streams: Discharge and Turbulence

Imagine two streams—a larger one in which water flows slowly, and a smaller one in which water flows rapidly. Which stream carries more water? The answer is not obvious. To answer this question completely, geologists must calculate the streams' discharge. Technically speaking, we define **discharge** as the volume of water passing through a cross section of the stream in a given time. We can calculate stream discharge by using a simple formula: $D = A_c \times v_a$. In this formula, A_c is the area of the stream, as measured in an imaginary plane perpendicular to the stream flow, and v_a is the *average* velocity at which water moves in the downstream direction. For example, if a stream has a cross-sectional area of 100 m^2, and the water in the stream flows at an average velocity of 0.2 m/s, then discharge = 100 m^2 × 0.2 m/s = 20 m^3/s. Note that the discharge ends up being specified in units of volume per second. Stream discharge can be determined at a *stream-gauging station*, where instruments measure the velocity and depth of the water at several points across the stream (**Fig. 14.7a**).

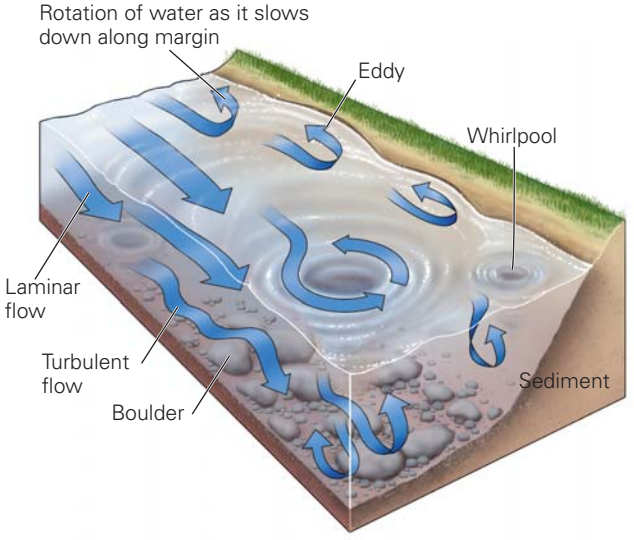
A stream's average discharge reflects the size of its drainage basin and the climate. The Amazon River drains a huge rainforest and has the largest average discharge in the world—about 200,000 m^3/s, or 15% of the total amount of runoff on Earth. In contrast, the "mighty" Mississippi's discharge is only 17,000 m^3/s. The discharge of a given stream varies along its length. For example, discharge in a temperate region increases in the downstream direction, because each tributary that enters the stream adds more water, whereas the discharge in an arid region decreases downstream, as progressively more water seeps into the ground or evaporates. Human activity can affect discharge—for example, if people divert the river's water for irrigation, the river's discharge decreases downstream. Finally, the discharge at a given location can vary with time: in a temperate climate, a stream's discharge during the spring may be double or triple the amount during a dry summer, and a flood may increase the discharge to more than a hundred times normal.

The average velocity of stream water (v_a) can be difficult to calculate because the water doesn't all travel at the same velocity, for two reasons. First, friction along the sides and floor of the stream slows the flow. Thus, water near the channel walls or the streambed (the floor of the stream) moves more slowly than water in the middle of the flow (Fig. 14.7a). In fact, the fastest-moving part of the stream lies near the surface in the center of the channel. Second, *turbulence*—the twisting, swirling motion of a fluid—can create eddies in which water curves and flows upstream or circles in place (**Fig. 14.7b**). Turbulence develops because the shearing motion of one water volume against its neighbor causes the neighbor to spin, and because obstacles, such as boulders, deflect water flow.

FIGURE 14.7 Flow velocity and turbulence in streams.



(a) At a stream-gauging station, geologists measure the cross-sectional area (A_c), the depth, and the average velocity of the stream. Velocity is slower near the banks.



(b) In detail, flow is turbulent. Turbulence can make measuring velocity difficult.

Take-Home Message

Stream discharge, the amount of water passing through a cross section of the stream in a given time, depends on such factors as watershed area and climate. Water velocity varies across a stream, and tends to be turbulent, so calculating average velocity is complicated.

14.4 The Work of Running Water

How Do Streams Erode?

The energy that makes running water move comes from gravity. As water flows downslope from a higher to a lower elevation, the gravitational potential energy stored in water transforms into kinetic energy. About 3% of this energy goes into the work of eroding the walls and beds of stream channels. Running water causes erosion in four ways:

- *Scouring*: Running water can remove loose fragments of sediment, a process called scouring.
- *Breaking and lifting*: In some cases, the push of flowing water can break chunks of solid rock off the channel floor or walls. In addition, the flow of a current over a clast can cause the clast to rise, or lift off the substrate.
- *Abrasion*: Clean water has little erosive effect, but sediment-laden water acts like sandpaper and grinds or rasps away at the channel floor and walls, a process called abrasion. In places where turbulence produces long-lived whirlpools, abrasion by sand or gravel carves a bowl-shaped depression, called a *pothole*, into the floor of the stream (**Fig. 14.8a, b**).
- *Dissolution*: Running water dissolves soluble minerals as it passes, and carries the minerals away in solution.

The efficiency of erosion depends on the velocity and volume of water and on its sediment content. A large volume of fast-moving, turbulent, sandy water causes more erosion than does a trickle of quiet, clear water. Thus, most erosion takes place during floods, when a stream carries a large volume of fast-moving, sediment-laden water.

How Do Streams Transport Sediment?

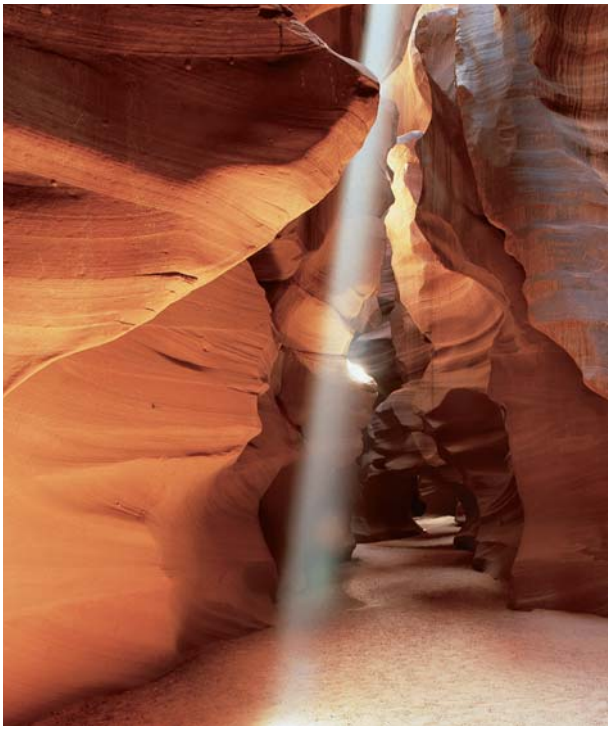
The Mississippi River received the nickname "Big Muddy" for a reason—its water can become chocolate brown because of all the clay and silt it carries. Geologists refer to the total volume of sediment carried by a stream as its sediment load. The sediment load consists of three components (**Fig. 14.8c**):

- *Dissolved load*: Running water dissolves soluble minerals in the sediment or rock that it flows over, and groundwater seeping into a stream brings dissolved minerals with it. The ions of these dissolved minerals constitute a stream's dissolved load.
- *Suspended load*: The suspended load of a stream usually consists of tiny solid grains (silt or clay size) that swirl along with the water without settling to the floor of the channel.
- *Bed load*: The **bed load** of a stream consists of large particles (such as sand, pebbles, or cobbles) that bounce or roll along the stream floor. Bed-load movement commonly involves **saltation**. During saltation, a multitude of grains bounce along in the direction of flow, within a zone that extends up from the surface of the streambed for a distance of several centimeters to several tens of centimeters. Each saltating grain in this zone follows a curved trajectory up through the water and then back down to the bed. When it strikes the bed, it knocks other grains upward, and thus supplies grains to the saltation zone.

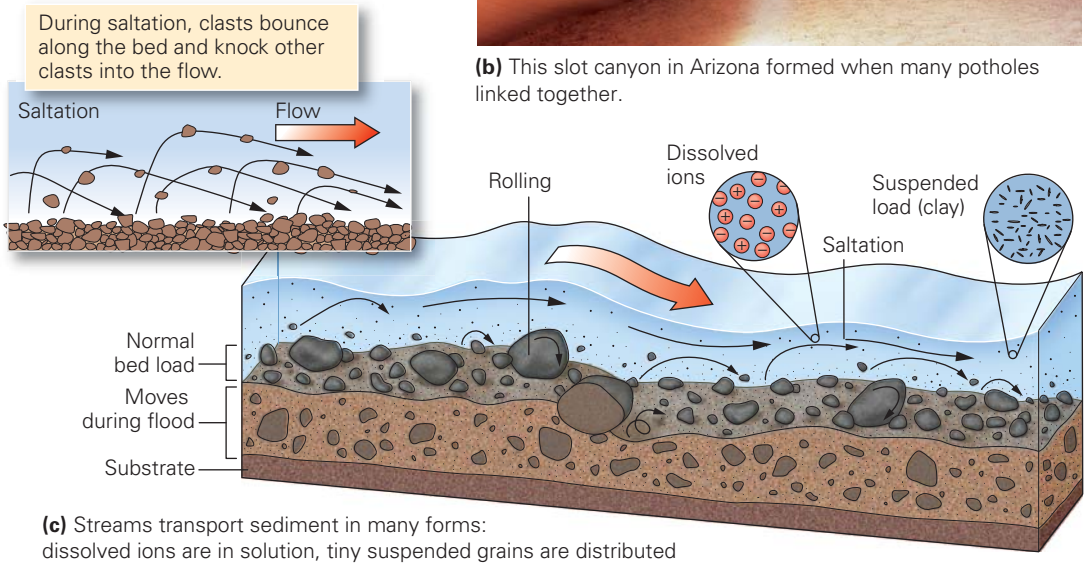
FIGURE 14.8 Erosion and transportation in streams.



(a) Two potholes in the bed of a stream near Ithaca, New York.



(b) This slot canyon in Arizona formed when many potholes linked together.



(c) Streams transport sediment in many forms: dissolved ions are in solution, tiny suspended grains are distributed through the water, and the bed load slides, rolls, and/or undergoes saltation.

When describing a stream's ability to carry sediment, geologists specify its competence and capacity. The **competence** of a stream refers to the maximum particle size it carries; a stream with high competence can carry large particles, whereas one with low competence can carry only small particles. Competence depends on water velocity. Thus, a fast-moving, turbulent stream has greater competence (it can carry bigger particles) than a slow-moving stream, and a stream in flood has greater competence than a stream with normal flow. In fact, the huge boulders that litter the bed of a mountain creek move only during floods. The **capacity** of a stream refers to the total quantity of sediment it can carry. A stream's capacity depends on its competence and discharge. So a large river has more capacity than a small creek.

Depositional Processes

A raging torrent of water can carry coarse and fine sediment—the finer clasts rush along with the water as suspended load, whereas the coarser clasts may bounce and tumble as bed load. If the flow velocity decreases, either because the slope of the streambed becomes shallower or because the channel broadens out and friction between the bed and the water increases, then the competence of the stream decreases and sediment settles out. The size of the clasts that settle at a particular locality depends on the decrease in flow velocity at the locality. For example, if the stream slows by a small amount, only large clasts settle; if the stream slows by a greater amount, medium-sized clasts settle; and if the stream slows almost to a standstill, the fine grains settle. Because of this process of *sediment sorting*, stream deposits tend to be segregated by size—gravel accumulates in one location and mud in another.

Geologists refer to sediments transported by a stream as **fluvial deposits** (from the Latin *fluvius*, meaning river) or **alluvium**. Fluvial deposits may accumulate along the stream bed in elongate mounds, called **bars** (Fig. 14.9a, b). In cases where the stream channel makes a broad curve, water slows along the inner edge of a curve, so a crescent-shaped **point bar** bordering the shoreline of the inner curve develops. During floods, a stream may overtop the banks of its channel and spread out over its **floodplain**, a broad flat area bordering the stream. Friction slows the water on the floodplain, so a sheet of silt and mud settles out to comprise floodplain deposits. Where a stream empties at its mouth into a standing body of water, the water slows and a wedge of sediment, called a **delta**, accumulates (Fig. 14.9c). We will discuss floodplains and deltas in more detail later in this chapter.

FIGURE 14.9 Sediment, carried and deposited by streams. The clast size depends on stream velocity.



(a) Gravel in a streambed of a mountain stream in Denali National Park, Alaska. The large clasts were carried during floods.



(b) Point bars of mud deposited along a gentle, slowly moving stream in Brazil.



(c) An air photo shows a muddy river emptying into the Black Sea. Currents along the shore are carrying the sediment away.

Take-Home Message

Streams erode by scouring, breaking and lifting, abrasion, and dissolution. They carry sediment as dissolved, suspended, or bed loads. Competence, the ability to carry sediment, depends on flow velocity. Where the velocity decreases, sediment settles out.

14.5 How Do Streams Change Along Their Length?

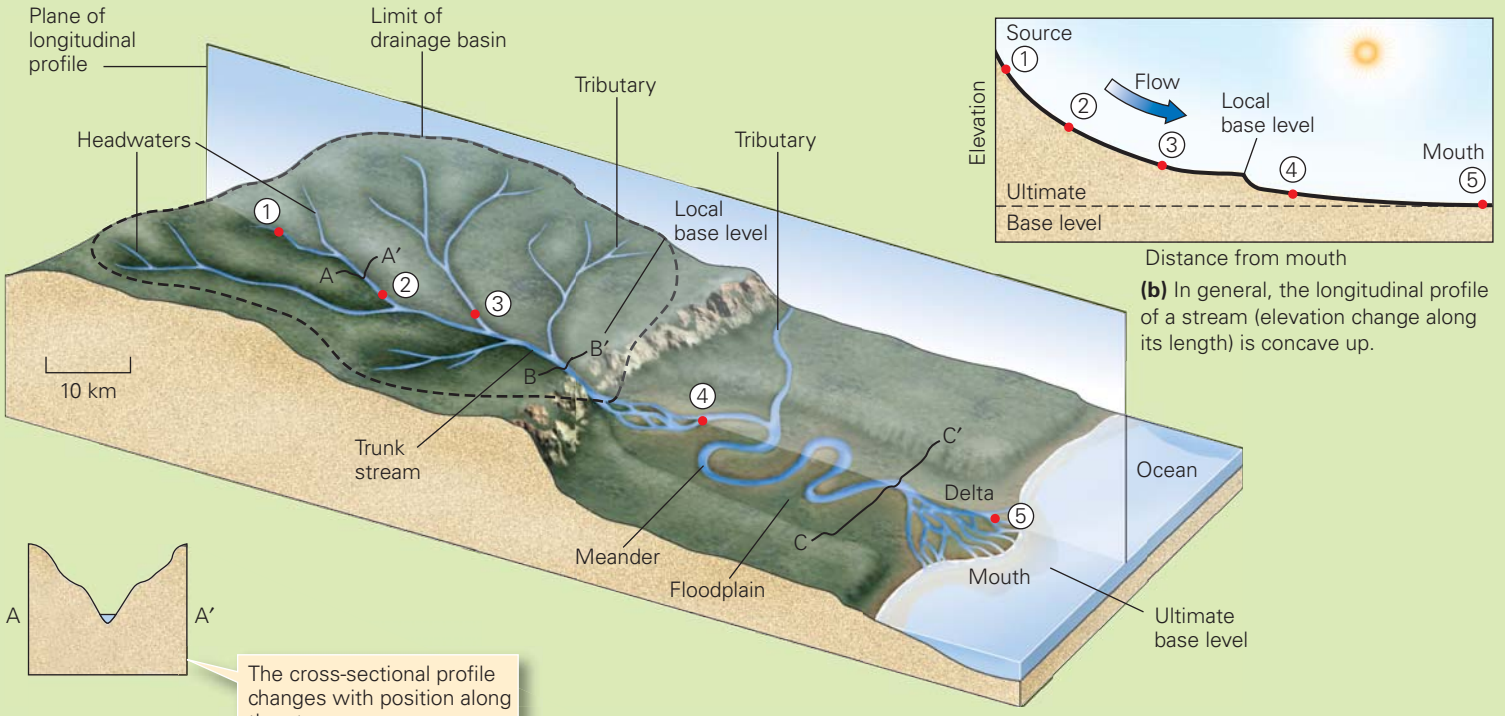
Longitudinal Profiles

In 1803, under President Thomas Jefferson's leadership, the United States bought the Louisiana Territory, a vast tract of land encompassing the western half of the Mississippi drainage basin. At the time, the geography of the territory was a mystery. To fill the blank on the map, Jefferson asked Meriwether Lewis and William Clark to lead a voyage of exploration across the Louisiana Territory to the Pacific.

Lewis and Clark, along with about 40 men, began their expedition at the mouth of the Missouri River, where it joins the Mississippi. At this juncture, the Missouri is a wide, languid stream of muddy water. The group found that along the Missouri's downstream *reach* (an interval along the length of a stream), the river's channel was deep and the water easily navigable. But the farther upstream they went, the more difficult their voyage became, for the **stream gradient** (the slope of the stream channel) became progressively steeper, and the stream's discharge diminished. When Lewis and Clark reached the site of what is now Bismarck, North Dakota, they had to abandon their original boats and haul smaller vessels up reaches where turbulent water plunges over a steep, bouldery bed, and occasionally they had to carry their boats around waterfalls, where water free-falls through the air. When they reached what is now southwestern Montana, they abandoned these boats as well and trudged along the stream valley on foot or on horseback, struggling up steep gradients until they reached the continental divide.

If Lewis and Clark had been able to plot a graph showing their elevation above sea level relative to their distance from the river's mouth, they would have found that the **longitudinal profile** of the Missouri, a cross-sectional image showing the variation in the river's elevation along its length, is roughly a concave-up curve (**Fig. 14.10a, b**). This curve illustrates that, typically, a stream's gradient is steeper near its headwaters (source) than near its mouth. Near its headwaters, an

FIGURE 14.10 Drainage basins, and the change in character of a stream along its longitudinal profile.



(b) In general, the longitudinal profile of a stream (elevation change along its length) is concave up.

(a) A drainage network collects water from a broad drainage basin, or watershed, via numerous tributaries. These carry water to a trunk stream and eventually to a standing body of water. Points 1 to 5 refer to locations along the longitudinal profile (inset).

idealized stream flows down deep valleys or canyons, whereas near its mouth, it flows over nearly horizontal plains. Real longitudinal profiles are not perfectly smooth curves, but rather display little plateaus and steps, representing interruptions by lakes or waterfalls.

The Concept of a Base Level

The lowest elevation a stream channel's surface can reach at a locality is the **base level** of the stream. A *local* base level is one that occurs at a location upstream of a drainage network's mouth, and the *ultimate* base level (that is, the lowest possible elevation along the stream's longitudinal profile) is sea level. The surface of a trunk stream cannot be lower than sea level, for if it were, the stream would have to flow upslope to enter the sea. The base level limits the depth to which a stream can downcut its channel.

Lakes or reservoirs can act as local base levels along a stream. A ledge of resistant rock can also act as a local base level, for the stream level cannot drop below the ledge until the ledge erodes away. Finally, where a tributary joins a larger stream, the surface of the larger stream acts as the base level for the tributary. Local base levels do not last forever, because running water eventually removes the obstructions that create them.

Take-Home Message

Streams have steeper regional gradients toward their sources, and gentler gradients near their mouths, so longitudinal profiles tend to be concave up. A stream's mouth cannot be lower than its base level. Sea level is the ultimate base level for drainage networks.

14.6 Streams and Their Deposits in the Landscape

Valleys and Canyons

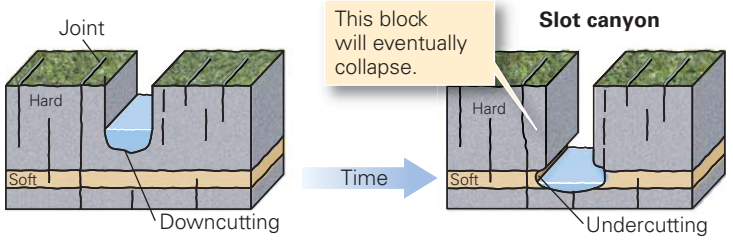
About 17 million years ago, a large block of crust, the region now known as the Colorado Plateau (located in Arizona, Utah, Colorado, and New Mexico), began to rise. Before the rise, the Colorado River had been flowing over a plain not far above sea level, causing little erosion. But as the land uplifted, the river began to downcut. Eventually, its channel lay as much as 1.6 km below the surface of the plateau at the base of a steep-walled gash now known as the Grand Canyon. The formation of the Grand Canyon illustrates a general phenomenon.

In regions where the land surface lies well above the base level, a stream can carve a deep trough, much deeper than the channel itself. If the walls of the trough slope gently, the landform is a *valley*, but if they slope steeply, the landform is a *canyon*.

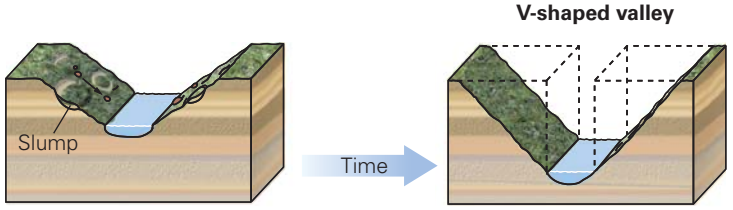
Whether stream erosion produces a valley or a canyon depends on the rate at which downcutting occurs relative to the rate at which mass wasting causes the walls on either side of the stream to collapse. In places where a stream downcuts through its substrate faster than the walls of the stream collapse, erosion creates a slot (steep-walled) canyon. Such canyons typically form in hard rock, which can hold up steep cliffs for a long time (Fig. 14.11a). In places where the walls collapse as fast as the stream downcuts, landslides and slumps gradually cause the slope of the walls to approach the angle of repose. When this happens, the stream channel lies at the floor of a valley whose cross-sectional shape resembles the letter V (Fig. 14.11b); this landform is called a **V-shaped valley**. Where the walls of the stream consist of alternating layers of hard and soft rock, the walls develop a stair-step shape such as that of the Grand Canyon (Fig. 14.11c).

In places where active downcutting occurs, the valley floor remains relatively clear of sediment, for the stream—especially when it floods—carries away sediment that has fallen or slumped into the channel from the stream walls. But if the stream's base level rises, its discharge decreases, or its sediment load increases, the valley floor fills with sediment, creating an alluvium-filled valley (Fig. 14.12a). The surface of the alluvium becomes a broad floodplain. If the stream's base level later drops again and/or the discharge increases, the stream will start to cut down into its own alluvium, a process that generates **stream terraces** bordering the present floodplain (Fig. 14.12b).

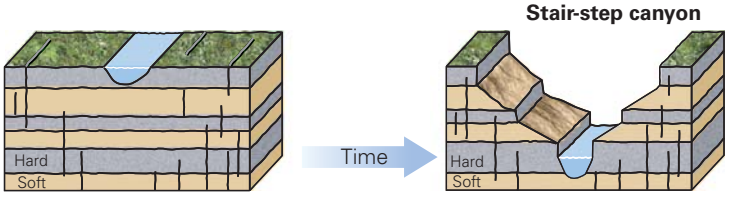
FIGURE 14.11 The shape of a canyon or valley depends on the resistance of its walls to erosion slumping.



(a) If downcutting by the stream happens faster than mass wasting on the walls, a slot canyon forms. The canyon widens as the stream undercuts the walls.

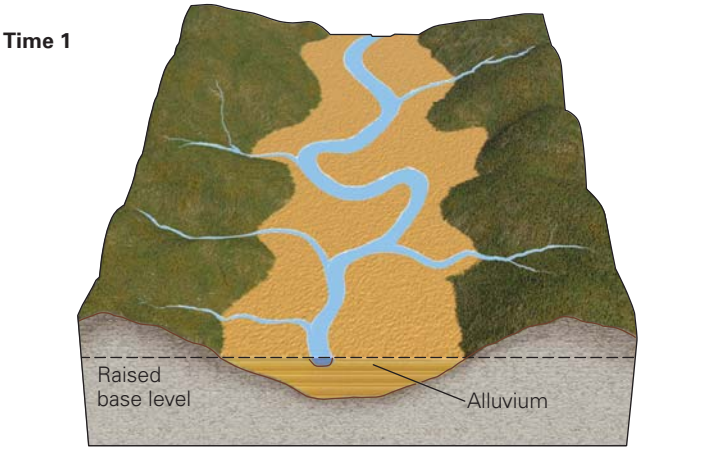


(b) If mass wasting takes place as fast as downcutting occurs, a V-shaped valley develops.

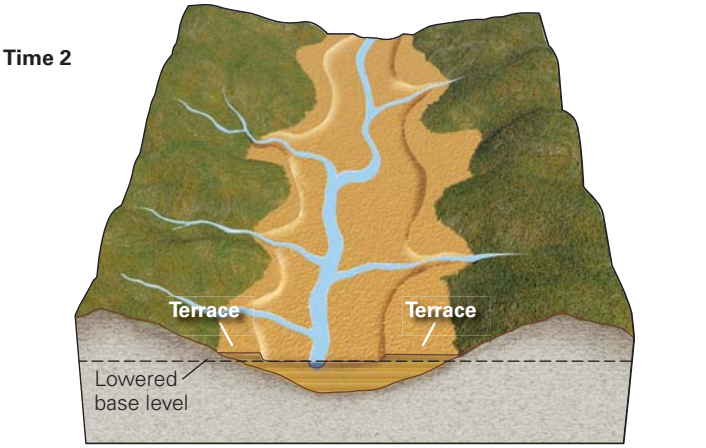


(c) Downcutting through alternating hard and soft layers produces a stair-step canyon.

FIGURE 14.12 The evolution of alluvium-filled stream valleys and the development of terraces.



(a) A rise in the base level or a decrease in discharge causes the valley to fill with alluvium.



(b) Later, if the base level falls or the discharge increases, the stream downcuts through the alluvium and a new, lower floodplain develops. The remnants of the original alluvial plain remain as a pair of terraces.

Rapids and Waterfalls

When Lewis and Clark forged a path up the Missouri River, they came to reaches that could not be navigated by boat because of **rapids**, particularly turbulent water with a rough surface (Fig. 14.13a). Rapids form where water flows over steps or large clasts in the channel floor, where the channel abruptly narrows, or where its gradient abruptly changes. The turbulence in rapids produces eddies, waves, and whirlpools that roil and churn the water surface, in the process creating whitewater, a mixture of bubbles and water. Modern-day whitewater rafters thrill to the unpredictable movement of rapids.

A **waterfall** forms where the gradient of a stream becomes so steep that some or all of the water literally free-falls above the streambed (Fig. 14.13b). The energy of falling water may scour a depression, called a plunge pool, at the base of the waterfall. Though a waterfall may appear to be a permanent feature of the landscape, all waterfalls eventually disappear because headward erosion slowly eats back the resistant ledge. We can see a classic example of headward erosion at Niagara Falls. As water flows from Lake Erie to Lake Ontario, it drops over a 55-m-high ledge of resistant Silurian dolostone, which overlies a weak shale. Erosion of the shale leads to undercutting of the dolostone. Gradually, the overhang of dolostone becomes unstable and collapses, with the result that the waterfall migrates upstream. Before the industrial age, the edge of Niagara Falls cut upstream at an average rate of 1 m per year; but since then, the diversion of water from the Niagara River into a hydroelectric power station has decreased the rate of headward erosion to half that (Fig. 14.14a, b).

Alluvial Fans and Braided Streams

Where a fast-moving stream abruptly emerges from a mountain canyon into an open plain at the range front, the water that was once confined to a narrow channel spreads out over a broad surface. As a consequence, the water slows and drops its sedimentary load, forming a sloping apron of sediment (sand, gravel, and cobbles) called an **alluvial fan** (Fig. 14.15a). The stream then divides into a series of small channels that spread out over the fan. During particularly strong floods, the water contains so much sediment that it becomes a debris flow that spreads over and smooths out the fan's surface.

In some localities, streams carry abundant coarse sediment during floods but cannot carry this sediment during normal flow. Thus, during normal flow, the sediment settles out and chokes the channel. As a consequence, the stream divides into numerous strands weaving back and forth between elongate bars of gravel and sand. The result is a **braided stream**—the name emphasizes that the streams entwine like strands of hair in a braid (Fig. 14.15b).

FIGURE 14.13 Examples of rapids and waterfalls.



(a) These rapids in the Grand Canyon formed when a flood from a side canyon dumped debris into the channel of the Colorado River.

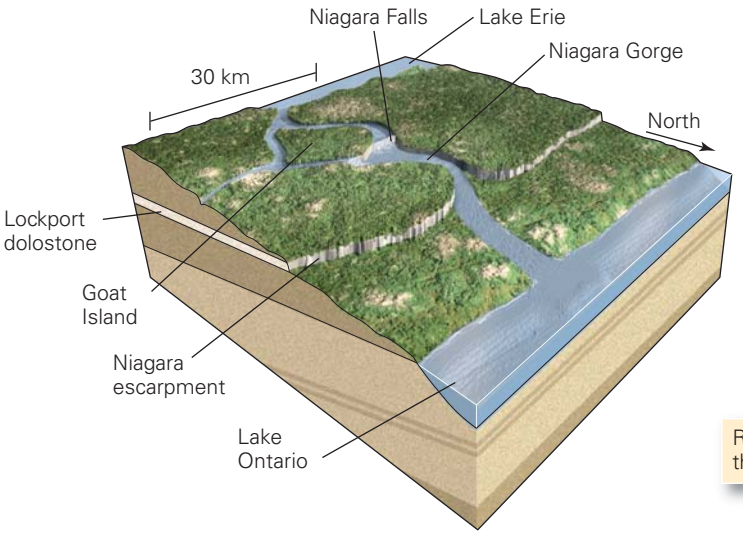


(b) Iguaçu Falls, at the Brazil-Argentina border, spills across layers of basalt. The basalt acts as a resistant ledge.

Meandering Streams and Their Floodplains

A riverboat cruising along the lower reaches of the Mississippi River cannot sail in a straight line, for the river channel winds back and forth in a series of snake-like curves called **meanders** (Fig. 14.16a). In fact, the boat has to go 500 km along the river channel to travel 100 km as the crow flies.

FIGURE 14.14 The formation of Niagara Falls, at the border between Ontario, Canada, and New York State. The falls tumble over the Lockport Dolomite, a relatively strong rock layer.



(a) Niagara Falls lies where water spills over the Niagara escarpment.



(b) The American Falls, a part of Niagara Falls.

How do meanders evolve? Even if a stream starts out with a straight channel, natural variations in the water depth and associated friction cause the fastest-moving current to swing back and forth. The water erodes the side of the stream more effectively where it flows faster, so it begins to cut away faster on the outer arc of the curve. Thus, each curve begins to migrate sideways and grow more pronounced until it becomes a meander (Fig. 14.16b). On the outside edge of a meander, erosion continues to eat away at the channel wall, forming a cut bank. On the inside edge, water slows down so that its competence decreases and sediment accumulates, forming a wedge-shaped deposit called a point bar, as noted earlier. With continued erosion, a meander may curve through more than 180°, so that the cut bank at the meander's entrance approaches the cut bank at its end, leaving a *meander neck*, a narrow isthmus of land separating the portions of the meander. When erosion eats through a meander neck, a straight reach called a *cutoff* develops. The meander that has been cut off is called an **oxbow lake** if it remains filled with water, or an *abandoned meander* if it dries out (Fig. 14.16c). Streams that develop many meanders are known, not surprisingly, as meandering streams. The course of a meandering stream naturally

FIGURE 14.15 Examples of depositional landforms produced from stream sediment.

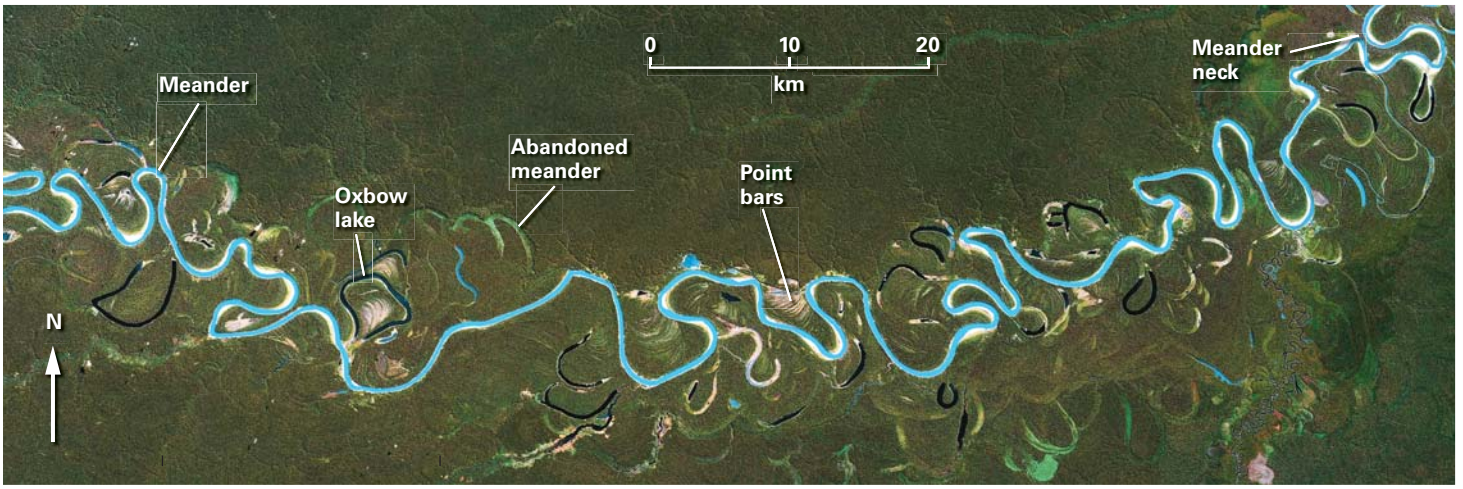


(a) An alluvial fan in Death Valley, California, consists of sand, gravel, and debris flows. The curving black line is a road.

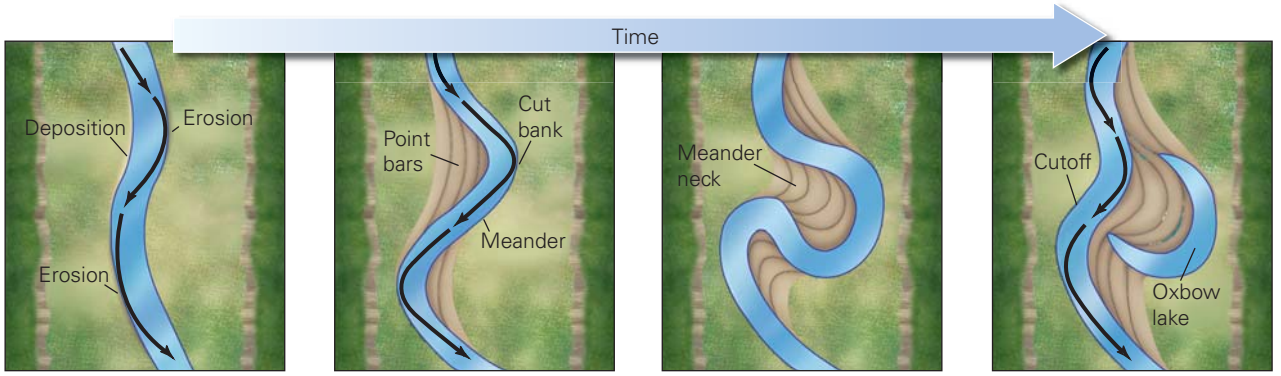


(b) A braided stream, carrying meltwater from a glacier near Denali, Alaska, deposits elongate bars of gravel.

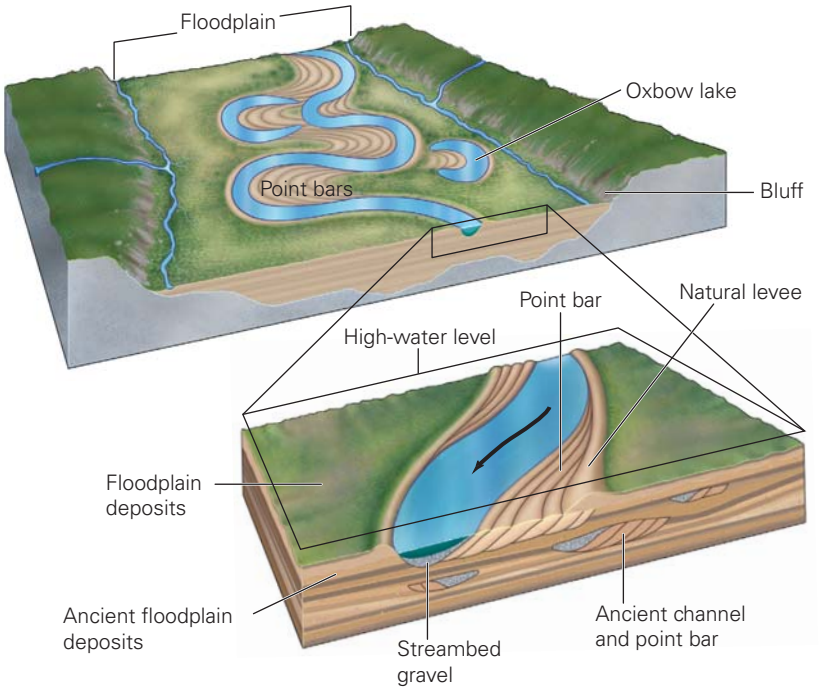
FIGURE 14.16 The character and evolution of meandering streams and floodplains.



(a) A meandering stream in Brazil, as viewed from space. Note the oxbows, cutoffs, and abandoned meanders.



(b) Meanders evolve because erosion occurs faster on the outer bank of a curve, and deposition takes place on the inner curve. Eventually, a cutoff isolates an oxbow lake.



(c) Landforms along meandering streams include natural levees, point bars, and floodplains. Older deposits record the position of ancient channels and floodplains.

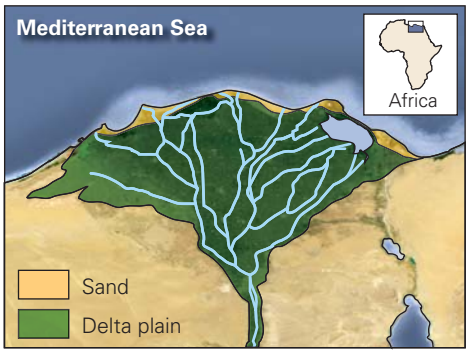


(d) The flat land of this flood plain hosts farm fields. Trees delineate the channel.

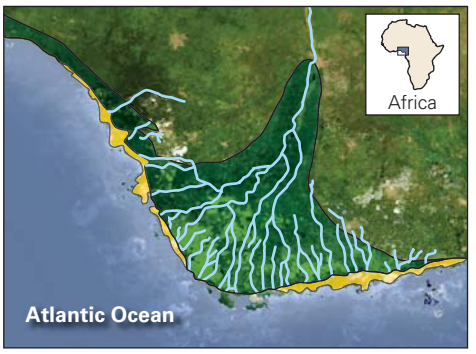
changes over time, on a time scale of years to centuries, as new meanders grow and old ones are cut off and abandoned.

Most meandering stream channels cover only a relatively small portion of a broad, gently sloping **floodplain** (Fig. 14.16d). Floodplains, as we noted earlier, are so named because during a flood, water overtops the edge of the stream channel and spreads out over the floodplain. In many cases, a floodplain terminates at its sides along a bluff, or escarpment; large floods may cover the entire floodplain from bluff to bluff. As the water rises above the channel walls and starts to spread out, over the floodplain, friction slows down the flow. This slowdown decreases the competence of the running water, so sediment settles out along the edge of the channel. Over time, the accumulation of this sediment creates a pair of low ridges, called **natural levees**, on either side of the stream. Natural levees may grow so large that the floor of the channel may become higher than the surface of the floodplain.

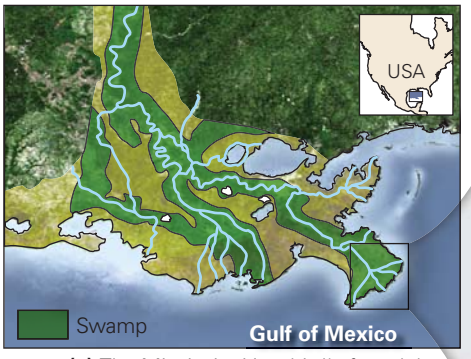
FIGURE 14.17 Delta shape varies depending on current activity, waves, and vegetation.



(a) The Nile is a Δ-shaped delta.



(b) The Niger is an arc-like delta.



(c) The Mississippi is a bird's-foot delta.



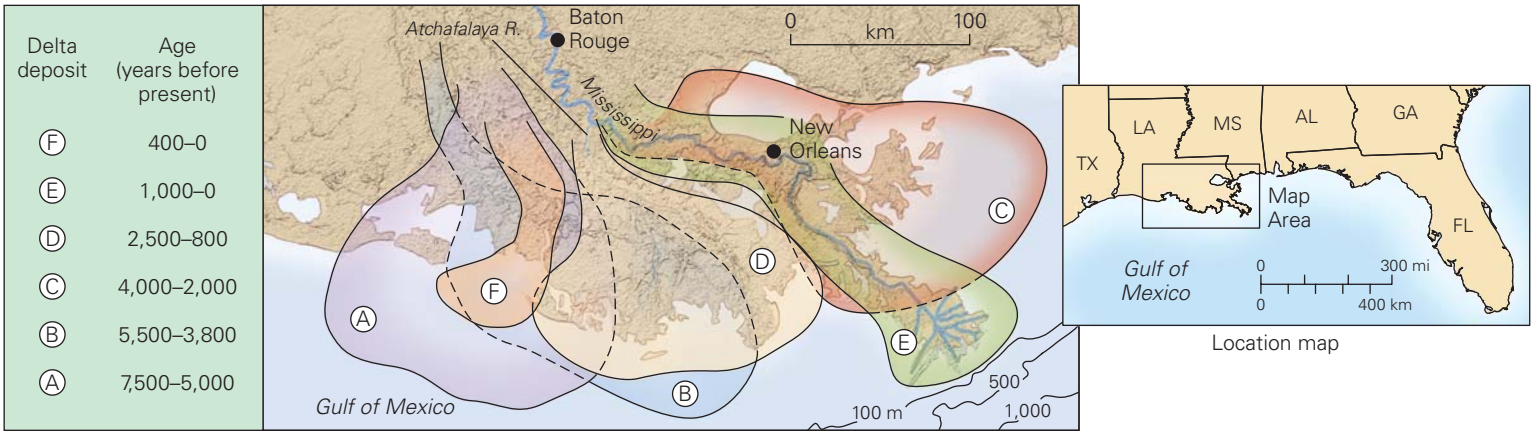
Deltas: Deposition at the Mouth of a Stream

Along most of its length, only a narrow floodplain—covered by green, irrigated farm fields—borders the Nile River in Egypt. But at its mouth, the trunk stream of the Nile divides into a fan of smaller streams, called **distributaries**, and the area of green agricultural lands broadens into a triangular patch. The Greek historian Herodotus noted that this triangular patch resembles the shape of the Greek letter delta (Δ), and so the region became known as the Nile Delta. Deltas develop where the running water of a stream enters standing water, the current slows, the stream loses competence, and sediment settles out. This can happen in either a lake or the sea (see Chapter 6).

Geologists refer to any wedge of sediment formed at a river mouth as a delta, even though relatively few have the triangular shape of the Nile Delta (Fig. 14.17a–c). Some deltas curve smoothly outward, whereas others consist of many elongate lobes formed at different times. Bird's-foot deltas, so-named because they resemble the scrawny toes of a bird, develop where several distributaries extend far out into relatively calm water; the end of the Mississippi's active channel ends in a bird's-foot delta (Fig. 14.17a–c). The existence of several overlapping deltas indicates that the main course of the river in the delta has shifted on several occasions. These shifts occur when a toe builds so far out into the sea that the slope of the stream becomes too gentle to allow the river to flow. At this point, the river overflows a natural levee upstream and begins to flow in a new direction, an event called an *avulsion*. The distinct lobes of the Mississippi Delta suggest that avulsions have happened several times during the past 9,000 years (Fig. 14.18). New Orleans, built along one of the Mississippi's distributaries, may eventually lose its riverfront, for a break in a levee upstream of the city could divert the Mississippi into the Atchafalaya River channel.

The shape of a delta depends on many factors. Deltas that form where the strength of the river current exceeds that of ocean currents have a bird's-foot shape, since the sediment can be carried far offshore. In contrast, deltas that form where the ocean currents are strong have a Δ shape, for the ocean currents redistribute sediment in bars running parallel to the shore. And in places where waves and currents are strong enough to remove sediment as fast as it arrives, a river has no delta at all.

FIGURE 14.18 A map showing ancient lobes of the Mississippi Delta. A major flood could divert water from the Mississippi into the channel of the Atchafalaya.



With time, the sediment of a larger delta compacts, and the weight of the delta pushes down the crust below. As a consequence, the surface of a delta slowly sinks. Distributaries can provide sediment that fills the resulting space so that the delta's surface remains at or just above sea level, forming a broad, flat area called a *delta plain*. But if people build up artificial levees to constrain the river to its channel, sediment gets carried directly to the seaward edge of the delta and the delta's interior "starves" (does not receive sediment). When this happens, the delta's surface drops below sea level. Because of this process, much of New Orleans lies below sea level (see Chapter 15).

Take-Home Message

Erosion carves valleys and canyons, with shapes that depend on the balance between slope-collapse and downcutting rates. Streams choked with sediment become braided; those following snake-like paths are meandering. Deltas build into standing water.

14.7 The Evolution of Drainage

Beveling Topography

Imagine a place where continental collision uplifts a region; the landscape will evolve (Fig. 14.19a). At first, rivers have steep gradients, flow over many rapids and waterfalls, and cut deep valleys. But with time, rugged mountains become low, rounded hills; once-deep, narrow valleys broaden into wide floodplains with more gradual gradients. As more time passes, even the low hills are beveled down, becoming small mounds or even disappearing altogether. (Some geologists have referred to the resulting landscape as a peneplain, from the Latin *paene*, which means almost; it lies at an elevation close to that of a stream's base level.)

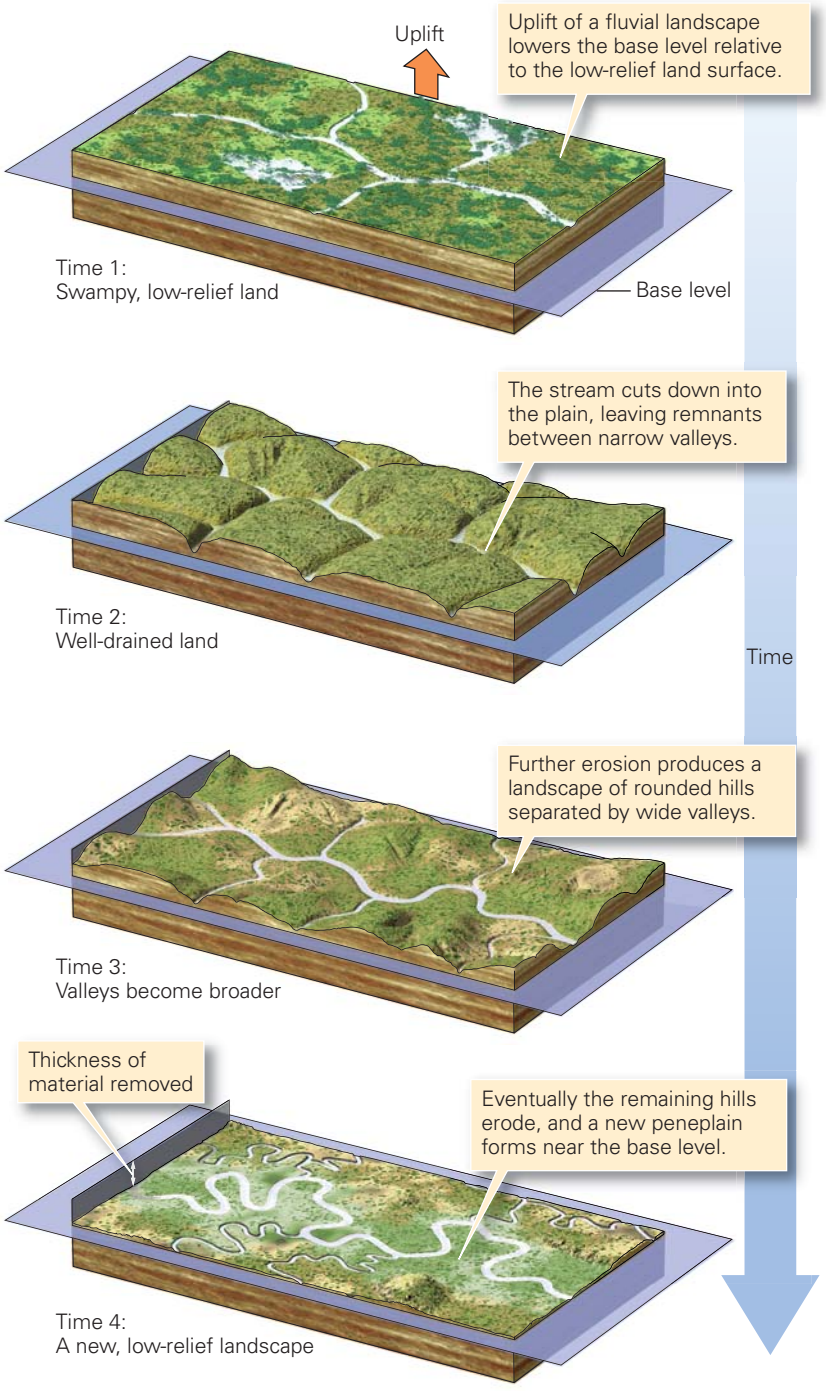
Though the above model makes intuitive sense, it is an oversimplification. Plate tectonics can uplift the land again, and/or global sea-level rise or fall can change the base level, so in reality peneplains rarely develop before downcutting begins again. **Stream rejuvenation** occurs when a stream starts to downcut into a land surface whose elevation lies near the stream's base level. Rejuvenation can be triggered by several phenomena, such as: a drop in base level, as happens when sea level falls; an uplift event that causes the land to rise relative to the base level; or an increase in stream discharge that makes the stream more able to erode and transport sediment. As we've seen, rejuvenation can lead to formation of stream terraces in alluvium. In cases where rejuvenation causes a stream to erode deeply into the land, a new canyon or valley will develop. If the rejuvenated stream had a meandering course, downcutting produces incised meanders (Fig. 14.19b).

Stream Piracy and Drainage Reversal

Stream piracy sounds like pretty violent stuff. In reality, it's just a natural process that happens when headward erosion by one stream causes the stream to intersect the course of another stream. When this happens, the pirate stream "captures" the water of the stream that it has intersected, so that the water of the captured stream starts to flow down the pirate stream. Because of piracy, the channel of the captured stream, downstream of the point of capture, dries up (Fig. 14.20a, b). In some cases, stream capture changes a "water gap" (a stream-carved notch through a ridge) into a dry "wind gap." In 1775, Daniel Boone, the legendary pioneer, led settlers through the Cumberland Gap, a wind gap in the Appalachians, to new homesteads in western Kentucky.

The pattern of stream flow in an area can also be altered, over time, on a continental scale. For example, when South America and Africa were adjacent to each other in Pangaea,

FIGURE 14.19 Fluvial landscapes evolve over time.



(a) When the base level drops, streams downcut and a hilly landscape develops. The relief, however, eventually erodes away.



(b) The "goosenecks" of the San Juan River, Utah, are incised meanders.

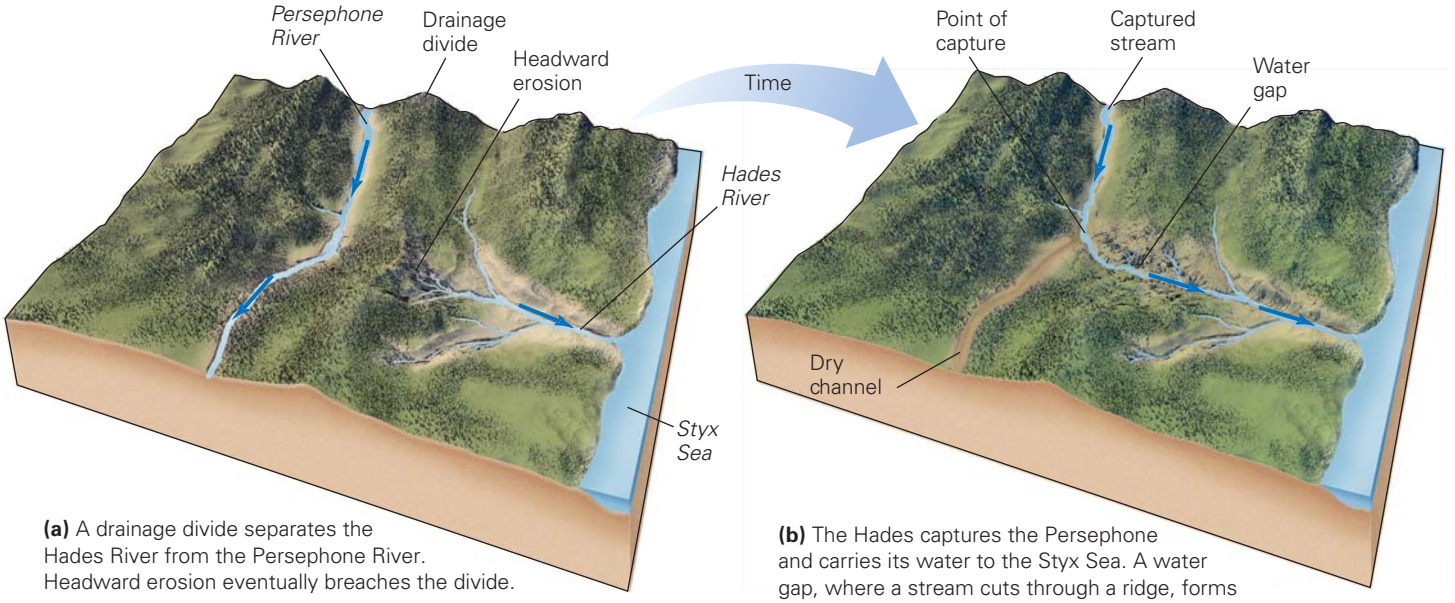
a highland existed along the boundary between the two continents, and the main drainage network of northern South America flowed westward. Later, when South America rifted away from Africa, a convergent plate boundary developed along the western margin of South America, causing the Andes Mountains to rise. The uplift of the Andes caused a **drainage reversal**, in that the overall slope direction of the drainage network became the opposite of what it once had been. As a consequence, westward flow became impossible, and the eastward-flowing Amazon drainage network developed.

Superposed and Antecedent Streams

The structure and topography of the landscape do not always appear to control the path, or course, of a stream. For example, imagine a stream that carves a deep canyon straight across a strong mountain ridge—why didn't the stream find a way around the ridge? We distinguish two types of streams that cut across resistant topographic highs:

- *Superposed streams*: Imagine a region in which streams start to flow over horizontal beds of strata that unconformably overlie folded strata. When the streams eventually erode down through the unconformity and start to downcut into the folded strata, they maintain their earlier course, ignoring the structure of the folded strata. Geologists call such streams **superposed streams**, because their preexisting geometry has been laid down on underlying rock structure (**Fig. 14.21a, b**).
- *Antecedent streams*: In some cases, tectonic activity (such as subduction or collision) causes a mountain range to rise up beneath an already established stream. If the stream downcuts as fast as the range rises, it can maintain its course and will cut right across the range. Geologists call such streams **antecedent streams** (from the Greek *ante*, meaning before) to emphasize that they existed before the range uplifted. Note that if the range rises faster than the

FIGURE 14.20 The concept of stream capture or "piracy."



(a) A drainage divide separates the Hades River from the Persephone River. Headward erosion eventually breaches the divide.

(b) The Hades captures the Persephone and carries its water to the Styx Sea. A water gap, where a stream cuts through a ridge, forms and the former Persephone channel becomes a dry canyon.

stream downcuts, the new highlands divert (change) the stream's course so that it flows parallel to the range face (Fig. 14.22a–c).

Take-Home Message

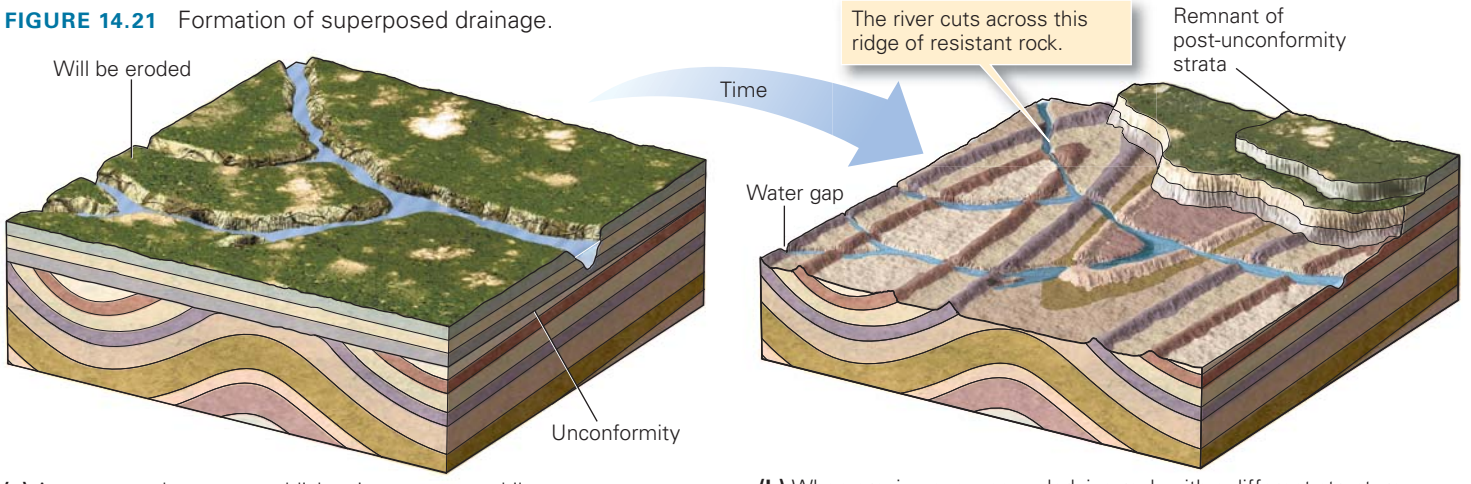
Stream-carved landscapes evolve over time as gradients diminish and ridges between valleys erode away. Superposed streams attain their shape before cutting down into rock structure, whereas antecedent streams cut while the land beneath them uplifts.

14.8 Raging Waters

The Inevitable Catastrophe

Up to now, this chapter has focused on the process of drainage formation and evolution and on the variety of landscape features formed by streams (see **Geology at a Glance**, pp. 438–439). Now we turn our attention to the havoc that a stream can cause when flooding takes place. Floods can be catastrophic—they can strip land of forests and buildings, they can bury land in clay and silt, and they can submerge cities. A **flood** occurs when the volume of water flowing down a stream exceeds the

FIGURE 14.21 Formation of superposed drainage.



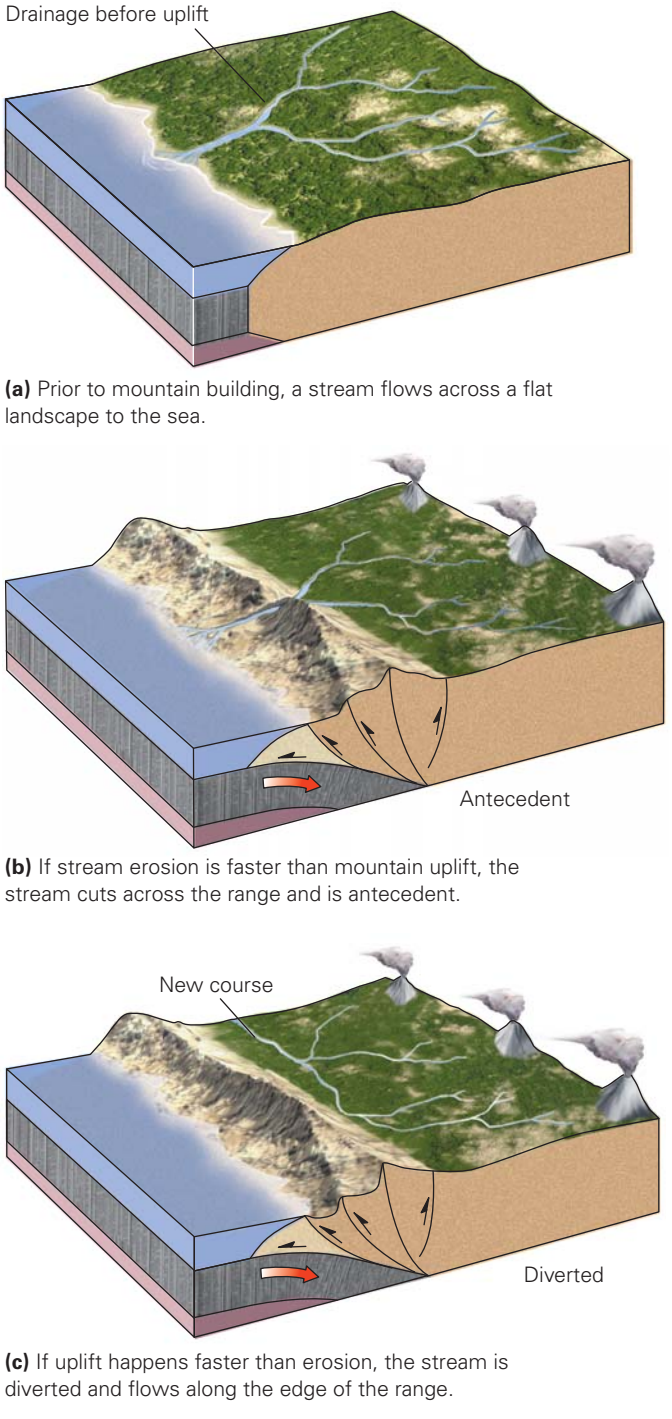
(a) A superposed stream establishes its geometry while flowing over a uniform substrate above an unconformity.

(b) When erosion exposes underlying rock with a different structure, the river is superposed on the structure. As a result, it cuts across resistant ridges instead of flowing around them.

volume of the stream channel, so water rises out of the normal channel and spreads out over a floodplain or delta plain, or fills a canyon to a greater depth than normal.

Floods happen (1) during abrupt, heavy rains, when water falls on the ground faster than it can infiltrate and thus becomes surface runoff; (2) after a long period of continuous rain, when the ground has become saturated with water and can hold no more; (3) when heavy snows from the previous winter melt rapidly in response to a sudden hot spell; or (4) when a dam holding back a lake or reservoir, or a levee or retaining wall holding back a river or canal, suddenly collapses and releases the water that it held back.

FIGURE 14.22 Development of antecedent and diverted streams.



(a) Prior to mountain building, a stream flows across a flat landscape to the sea.

(b) If stream erosion is faster than mountain uplift, the stream cuts across the range and is antecedent.

(c) If uplift happens faster than erosion, the stream is diverted and flows along the edge of the range.

Geologists find it convenient to divide floods into two general categories. Floods that occur during a "wet season," when rainfall is heavy or when winter snows start to melt, are called **seasonal floods**. Floods of this type typically take place in tropical regions during monsoons, and in temperate regions during the spring when storms drench the land frequently and/or a heavy winter snowpack melts. When seasonal floods submerge floodplains, they produce *floodplain floods*, and when they submerge delta plains they produce *delta-plain floods* (**Fig. 14.23a–c**).

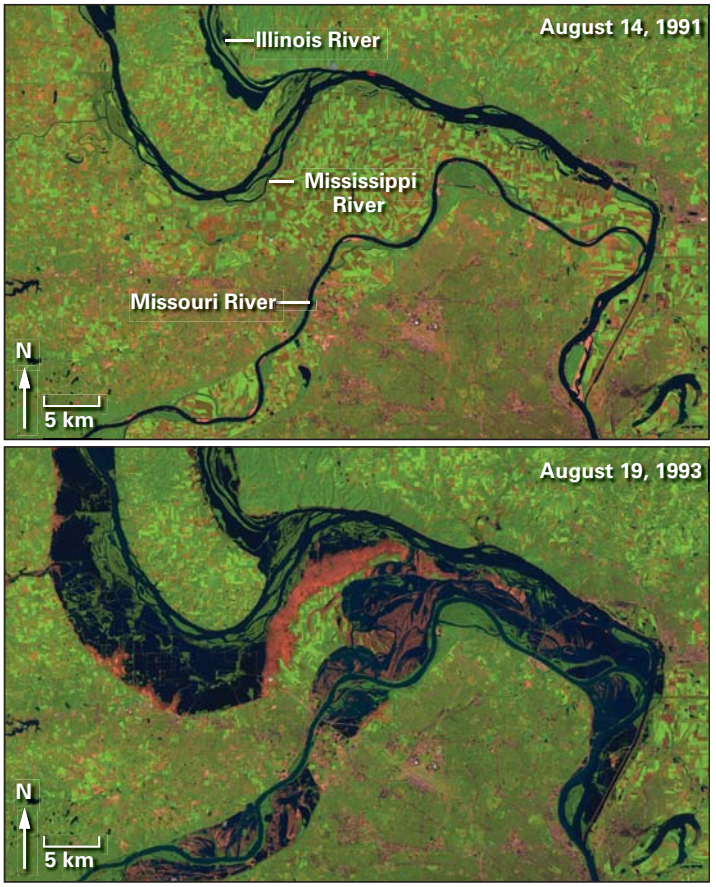
Events during which the floodwaters rise so fast that it may be impossible to escape from the path of the water are called **flash floods** (**Fig. 14.24a, b**). These happen during unusually intense rainfall or as a result of a dam collapse (as in the 1889 Johnstown flood) or levee failure. During a flash flood, a canyon or valley may fill to a level many meters above normal. In some cases, a wall of water may slam downstream with great force, leaving devastation in its wake, but the floodwaters subside after a short time. Flash floods can be particularly unexpected in arid or semiarid climates, where isolated thundershowers may suddenly fill the channel of an otherwise dry wash, whose unvegetated ground allows runoff to reach the channel faster. Such a flood may even affect areas downstream that had not received a drop of rain.

Case Study: A Seasonal Flood

In the spring of 1993, the jet stream, the high-altitude (10–15 km high) wind current that strongly affects weather systems, drifted southward. For weeks, the jet stream's cool, dry air formed an invisible wall that trapped warm, moist air from the Gulf of Mexico over the central United States. When this air rose to higher elevations, it cooled, and the water it held condensed and fell as rain, rain, and more rain. In fact, almost a whole year's supply of rain fell in just that spring—some regions received 400% more than usual. Because the rain fell over such a short period, the ground became saturated and could no longer absorb additional water, so the excess entered the region's streams, which carried it into the Missouri and Mississippi rivers. Eventually, the water in these rivers rose above the height of levees or broke through levees, and spread out over the floodplain. By July, parts of nine states were underwater (see Fig. 14.23a).

The roiling, muddy flood uprooted trees, cars, and even coffins (which floated up from inundated graveyards). All barge traffic along the Mississippi came to a halt, bridges

FIGURE 14.23 Examples of seasonal floodplain flooding.



(a) Satellite photos (before and during) show the extent of flooding during the 1993 Mississippi River flood.



(b) Great Falls, Montana, was submerged by floodwaters in 1975.



(c) In 2007, contaminated floodwaters spread disease in Indonesia.

and roads were undermined and washed away, and towns along the river were submerged. For example, in Davenport, Iowa, the riverfront district and baseball stadium were covered with 4 m (14 ft) of water. In Des Moines, Iowa, 250,000 residents lost their supply of drinking water when floodwaters contaminated the municipal water supply with raw sewage and chemical fertilizers. Rowboats replaced cars as the favored mode of transportation in towns where only the rooftops remained visible. In St. Louis, Missouri, the river crested 14 m (47 ft) above flood stage.

For 79 days, the flooding continued. When the water finally subsided, it left behind a thick layer of sediment, filling living rooms and kitchens in floodplain towns and burying crops in floodplain fields. In the end, more than 40,000 square km of the floodplain had been submerged, 50 people died, at least 55,000 homes were destroyed, and countless acres of crops were buried. Officials estimated that the flood caused over $12 billion in damage. Comparable flooding happened again in the spring of 2011, in the Mississippi and Missouri drainage basins.

Case Study: A Flash Flood

On a typical sunny day in the Front Range of the Rocky Mountains, north of Denver, Colorado, the Big Thompson River seems quite harmless. Clear water, dripping from melting ice and snow higher in the mountains, flows down its course through a narrow canyon, frothing over and around boulders. In places, vacation cabins, campgrounds, and motels line the river. The landscape seems immutable, but as is the case with so many geologic features, permanence is an illusion.

On July 31, 1976, easterly winds blew warm, moist air from the Great Plains toward the Rocky Mountain front. As this air rose over the mountains, towering thunderheads built up, and at 7:00 P.M. rain began to fall. It poured, in quantities that even old-timers couldn't recall. In a little over an hour, 19 cm (7.5 inches) of rain drenched the watershed of the Big

FIGURE 14.24 Flash floods can occur after torrential rains.



(a) A flash flood in a desert region of Israel has washed over a highway forcing the evacuation of truckers.



(b) During the 1976 Big Thompson River flash flood, this house was carried off its foundation and dropped on a bridge.

Thompson River. The river's discharge grew to more than four times the maximum recorded at any time during the previous century. The river rose quickly, in places reaching depths several meters above normal. Turbulent water swirled down the canyon at up to 8 m per second and churned up so much sand and mud that it became a viscous slurry. Slides of rock and soil tumbled down the steep slopes bordering the river and fed the torrent with even more sediment. The water undercut house foundations and washed the houses away, along with their inhabitants (see Fig 14.24b). Roads and bridges disappeared, and boulders that had stood like landmarks for generations bounced along in the torrent like beach balls, striking and shattering other rocks along the way. Cars drifted downstream until they finally wrapped like foil around obstacles. When the flood subsided, the canyon had changed forever, and 144 people had lost their lives.

Living with Floods

Flood Control Mark Twain once wrote of the Mississippi that we "cannot tame that lawless stream, cannot curb it or confine it, cannot say to it, 'go here or go there,' and make it obey." Was Twain right? Since ancient times, people have attempted to control courses of rivers so as to prevent undesired flooding. In the 20th century, flood-control efforts intensified as the population living along rivers increased. For example, since the passage of the 1927 Mississippi River Flood Control Act (drafted after a disastrous flood took place that year), the U.S. Army Corps of Engineers has labored to control the Mississippi. First, engineers built about 300 dams along the river's tributaries so that excess runoff could be stored in the reservoirs and later be released slowly. Second, they built **artificial levees** of sand and mud, and built concrete flood walls to increase the channel's volume. Artificial levees and flood walls isolate a discrete area of the floodplain (**Fig. 14.25a–c**).

Although the Corps' strategy worked for floods up to a certain size, it was insufficient to handle the 1993 and 2011 floods when reservoirs filled to capacity, and additional runoff headed downstream. The river rose until it spilled over the tops of some levees and undermined others. "Undermining" occurs when rising water levels increase the water pressure on the river side of the levee, forcing water through sand under the levee. In susceptible areas, water begins to spurt out of the ground on the dry side of the levee, thereby washing away the levee's support. The levee finally becomes so weak that it collapses, and water fills in the area behind it. In some cases, the Corps of Engineers intentionally dynamites levees along a relatively unpopulated reach of the river upstream of a vulnerable town. This diverts water out onto a portion of the floodplain where the

water will do less damage, and prevents the floodwaters from overtopping levees close to the town.

Another solution to flooding in some localities may involve restoration of wetland areas along rivers, for wetlands can absorb significant quantities of floodwater. Also, where appropriate, planners may prohibit construction within designated land areas adjacent to the channel, so that floodwater can fill these areas without causing expensive damage. The existence of such areas, which are known as **floodways**, effectively increases the volume of water that the river can carry and thus helps prevent the water level from rising too high.

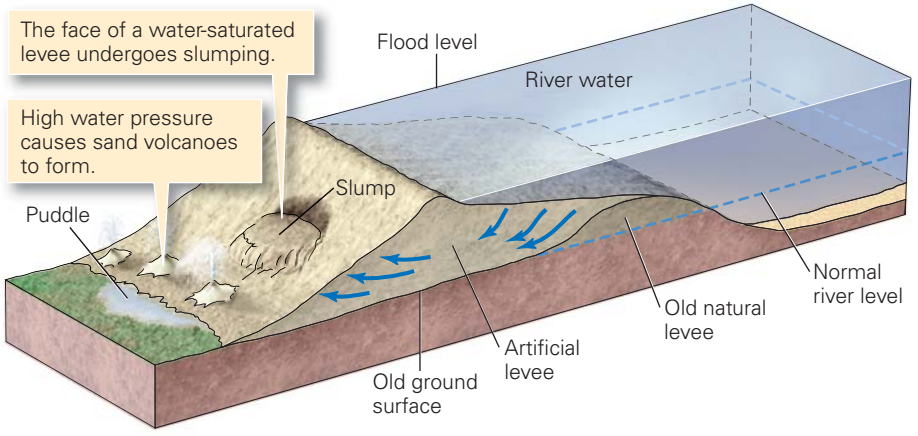
Evaluating Flooding Hazard When making decisions about investing in flood-control measures, mortgages, or insurance, planners need a basis for defining the hazard or risk posed by flooding. If floodwaters submerge a locality every year, a bank officer would be ill advised to approve a loan that would promote building there. But if floodwaters submerge the locality very rarely, then the loan may be worth the risk. Geologists characterize the risk of flooding in two ways. The **annual probability** of flooding indicates the likelihood that a flood of a given size or larger will happen at a specified locality during any given year. For example, if we say that a flood of a given size has an annual probability of 1%, then we mean there is a 1 in 100 chance that a flood of at least this size will happen in any given year. The **recurrence interval** of a flood of a given size is defined as the *average* number of years between successive floods of at least this size. For example, if a flood of a given size happens once in 100 years, *on average*, then it is assigned a recurrence interval of 100 years and is called a "100-year-flood." Note that annual probability and recurrence interval are related:

Did you ever wonder . . .
what do newscasters mean by a "100-year flood"?

$$\text{annual probability} = \frac{1}{\text{recurrence interval}}$$

For example, the annual probability of a 50-year-flood is 1/50, which can also be written as 0.02 or 2%.

FIGURE 14.25 Holding back rivers to prevent floods.



(a) Engineers build artificial levees to keep floodwater in the channel. Levees weaken and may fail when infiltrated by water.



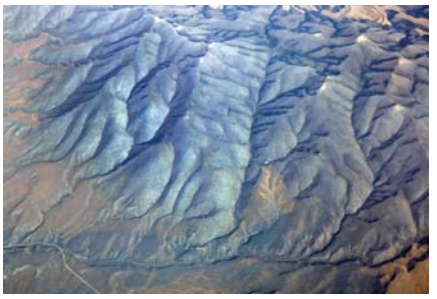
(b) At a levee breach, water flows from the river to the floodplain.



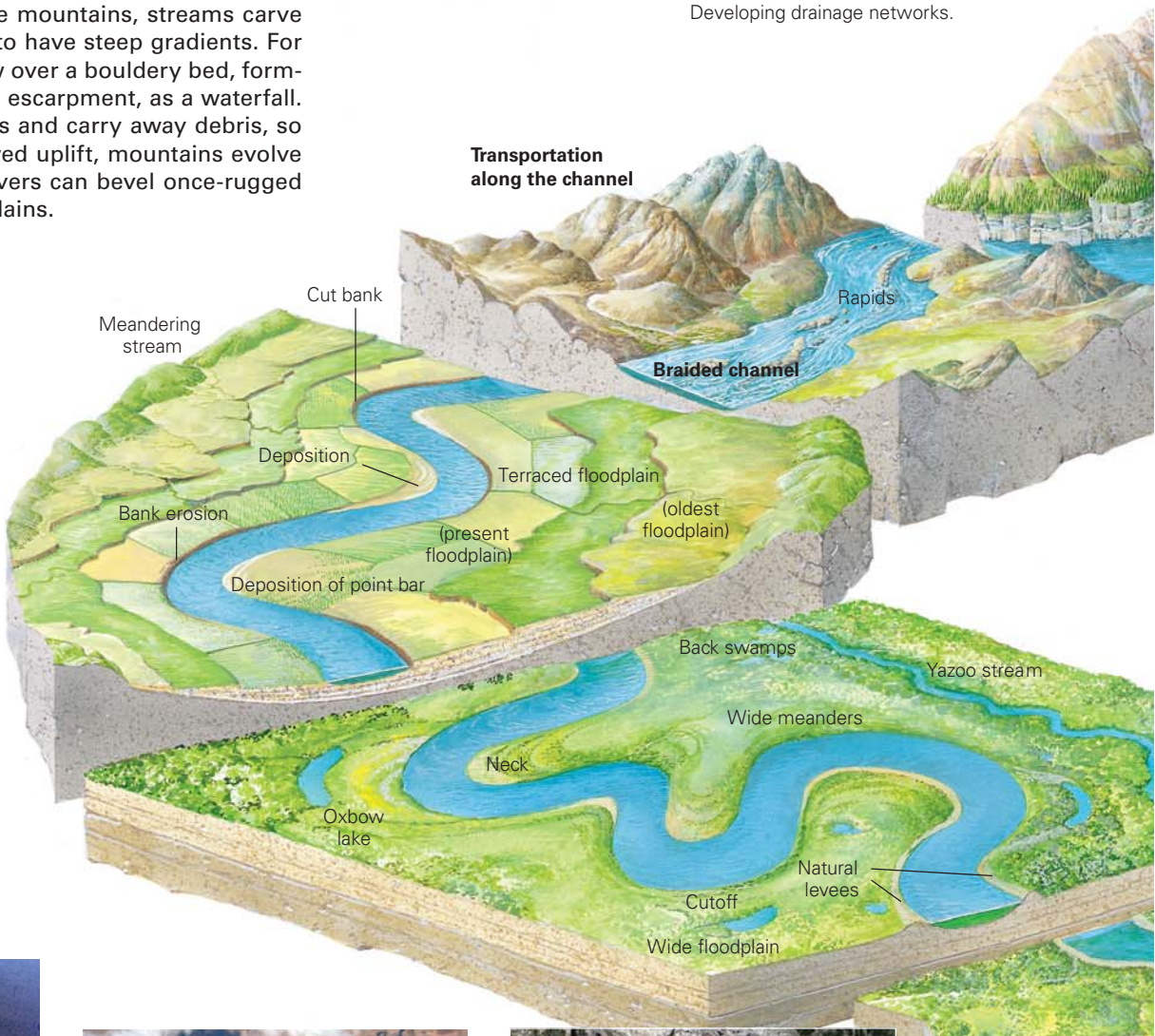
(c) A concrete floodwall at Cape Girardeau, Missouri. When floods threaten, a crane drops a gate into the slot to hold out the river.

River Systems

Rivers, or streams, drain the landscape of surface runoff. Typically, an array of connected streams called a drainage network develops, consisting of a trunk stream into which numerous tributaries flow. The land drained is the network's watershed. A stream starts from a source, or headwaters. Some headwaters are in the mountains, collecting water from rainfall or from melting ice and snow. In the mountains, streams carve deep, V-shaped valleys and tend to have steep gradients. For part of its course, a river may flow over a bouldery bed, forming rapids, and it may drop off an escarpment, as a waterfall. Rivers gradually erode landscapes and carry away debris, so after a while, if there is no renewed uplift, mountains evolve into gentle hills. Through time, rivers can bevel once-rugged mountain ranges into nearly flat plains.



Developing drainage networks.





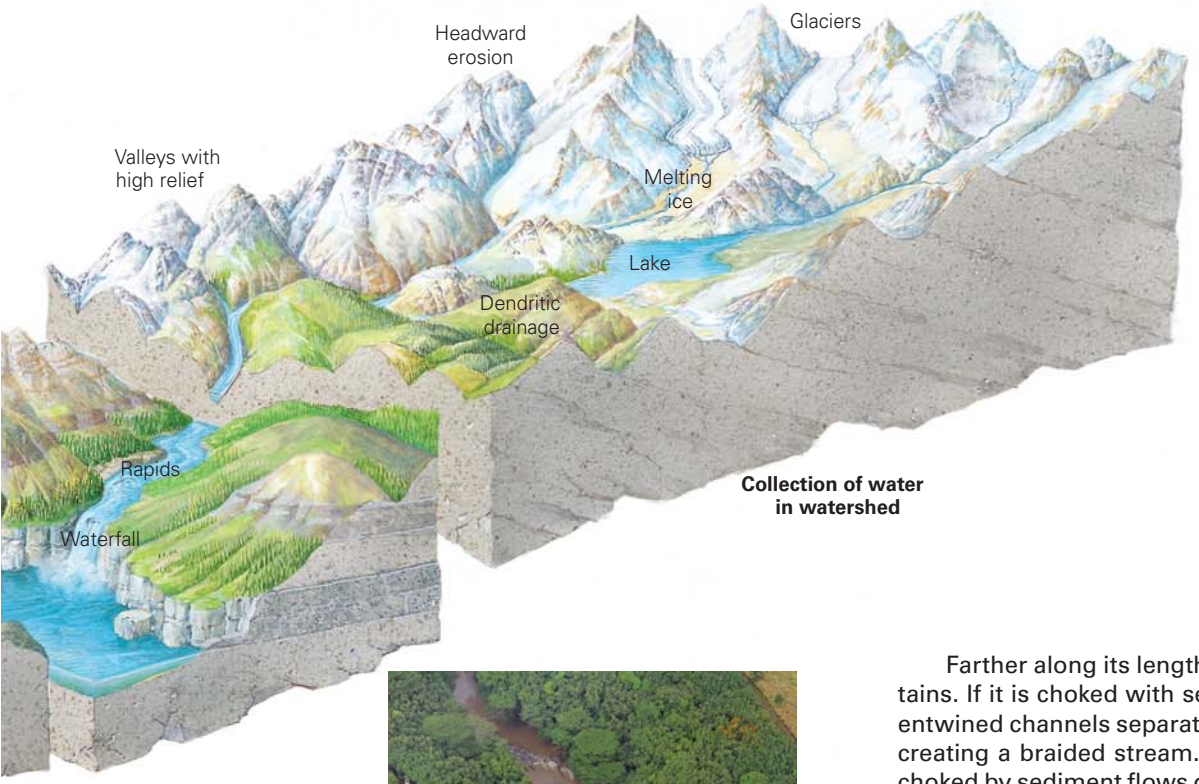
Point bars forming on inner curves.



Meanders, abandoned meanders, and cutoffs.



A small delta in a mountain lake.



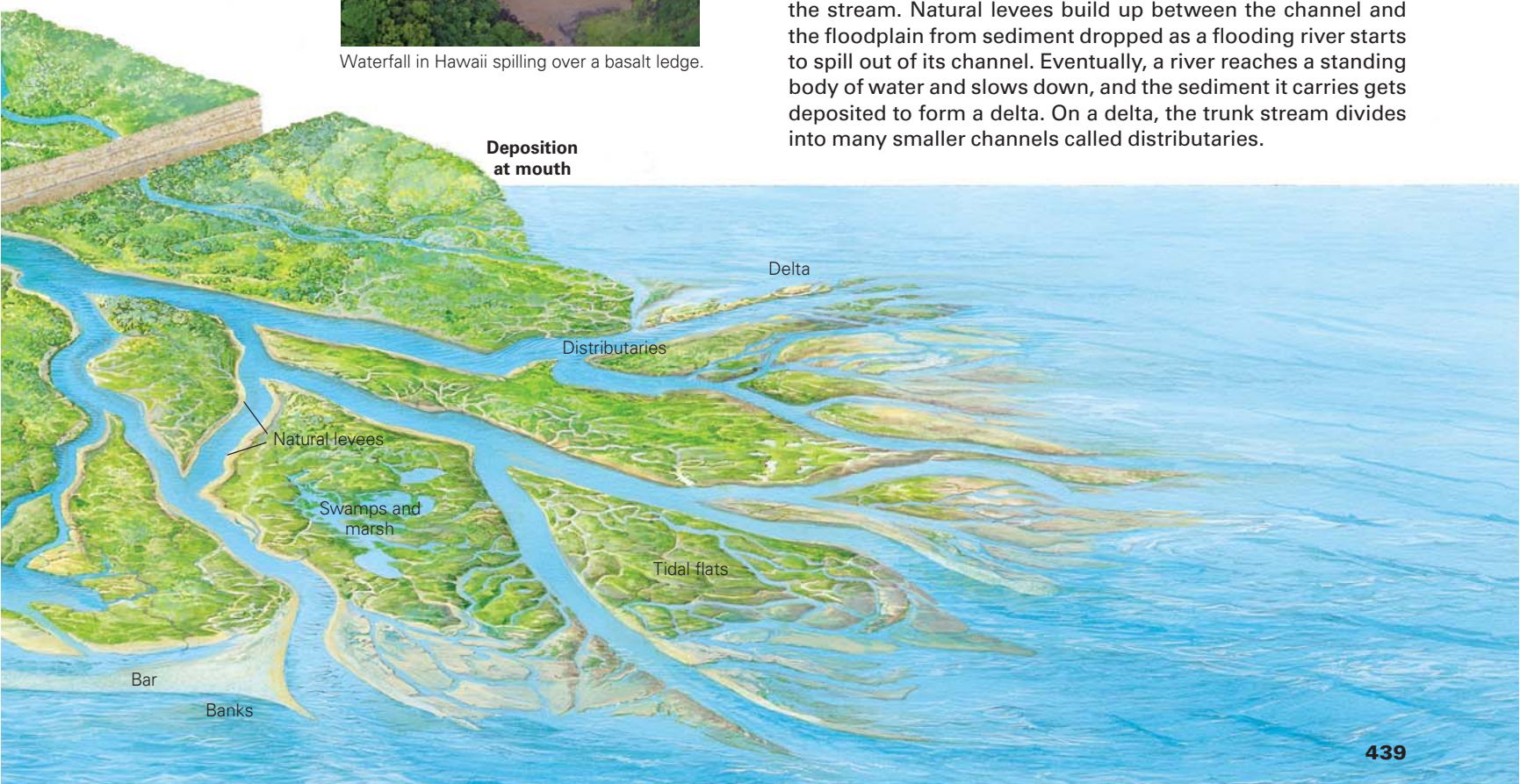


Streams contribute to carving mountains.



Waterfall in Hawaii spilling over a basalt ledge.

Farther along its length, the river emerges from the mountains. If it is choked with sediment, it may split into numerous entwined channels separated from one another by gravel bars, creating a braided stream. Where a stream that has not been choked by sediment flows over flat ground, it becomes a meandering stream, winding back and forth in snake-like curves called meanders. The current flows faster on the outer arc of a curve, so erosion takes place there, whereas the current flows more slowly on the inner arc, where it drops sediment. Because of erosion and deposition, a meandering stream changes shape over time. Occasionally, a meander may be cut off, leaving a curving lake called an oxbow lake. A broad floodplain, covered with water only during floods, may develop on either side of the stream. Natural levees build up between the channel and the floodplain from sediment dropped as a flooding river starts to spill out of its channel. Eventually, a river reaches a standing body of water and slows down, and the sediment it carries gets deposited to form a delta. On a delta, the trunk stream divides into many smaller channels called distributaries.



Unfortunately, some people are misled by the meaning of recurrence interval, and think that they do not face future flooding hazard if they buy a home within an area just after a 100-year flood has occurred. Their confidence comes from making the incorrect assumption that because such flooding just happened, it can't happen again until "long after I'm gone." They may regret their decision because two 100-year floods can occur in consecutive years or even in the same year (alternatively, the interval between such floods could be, say, 210 years).

The recurrence interval for a flood along a particular river reflects the size of a flood. For example, the discharge of a 100-year flood is larger than that of a 2-year flood, because the 100-year event happens less frequently (**Fig. 14.26a**). To define this relationship, geologists construct graphs that plot flood discharge on the vertical axis against recurrence interval on the horizontal axis (**Fig. 14.26b**).

Knowing the discharge during a flood of a specified annual probability, and knowing the shape of the river channel and the elevation of the land bordering the river, hydrologists can predict the extent of land that will be submerged by such a flood. Such data, in turn, permit hydrologists to produce **flood-hazard maps**. In the United States, the Federal Emergency Management Agency (FEMA) produces maps that show the 1% annual probability (100-year) flood area and the 0.2% annual probability (500-year) flood risk zones (**Fig. 14.26c**).

Take-Home Message

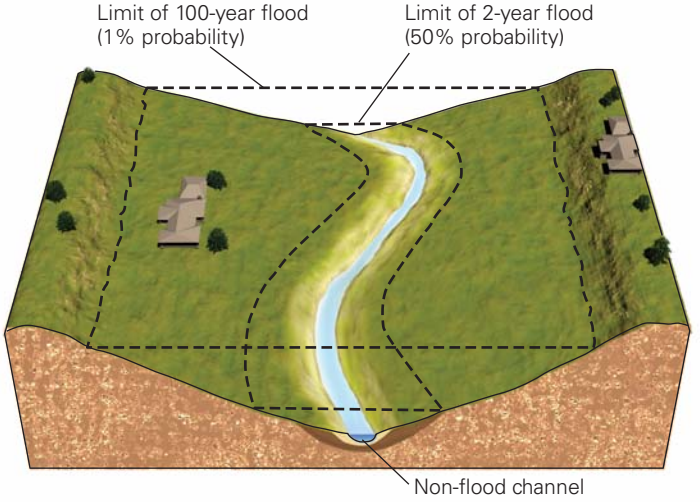
Seasonal floods submerge floodplains and delta plains at certain times of the year. Flash floods are sudden and short-lived. We can specify the probability that a certain size of flood will happen in a given year, but flood-control efforts meet with mixed success.

14.9 Vanishing Rivers

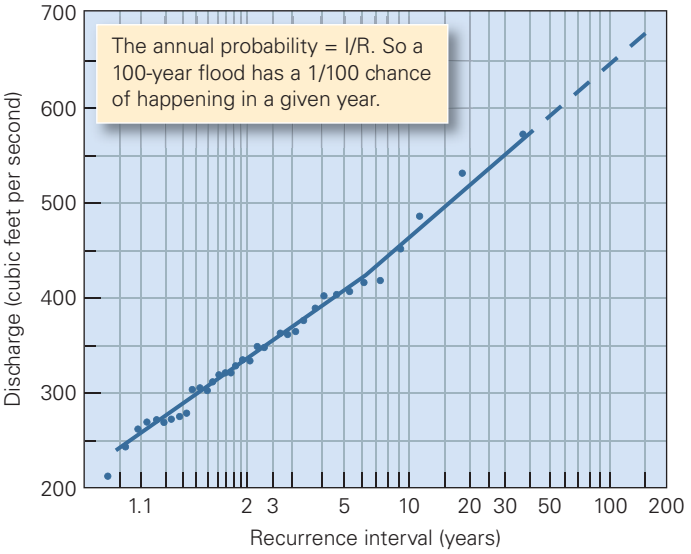
As *Homo sapiens* evolved from hunter-gatherers into farmers, areas along rivers became attractive places to settle. Rivers serve as avenues for transportation and are sources of food, irrigation water, drinking water, power, recreation, and (unfortunately) waste disposal. Further, their floodplains provide particularly fertile soil for fields, replenished annually by seasonal floods. Considering the multitudinous resources that rivers provide, it's no coincidence that ancient cultures developed in river valleys and on floodplains. Nevertheless, over time, humans have increasingly tended to abuse or overuse the Earth's rivers. Here we note four pressing environmental issues pertaining to rivers.

- *Pollution:* The capacity of some rivers to carry pollutants has long been exceeded, transforming them into deadly cesspools. Pollutants include raw sewage and storm drainage from urban areas, spilled oil, toxic chemicals from industrial sites, floating garbage, excess fertilizer, and animal waste. Some pollutants directly poison aquatic life, some feed algae blooms that strip water of its oxygen, and some settle out to be buried along with sediments.
- *Dam Construction:* In 1950, there were about 5,000 large (over 15 m high) dams worldwide, but today there are over 38,000. Damming rivers has both positive and negative results. Reservoirs provide irrigation water and hydroelectric power, and they trap some floodwaters and create popular recreation areas. But in some locations their construction destroys "wild rivers" (the whitewater streams of hilly and mountainous areas) and alters the ecosystem of a drainage network by forming barriers to migrating fish, by decreasing the nutrient supply to organisms downstream, by removing the source of sediment for the delta, and by eliminating seasonal floods that replenish nutrients in the landscape.
- *Overuse of Water:* Because of growing populations, our thirst for river water continues to increase, but the supply of water does not. The use of water has grown especially in response to the "green revolution" of the 1960s, during which huge new tracts of land came under irrigation. Today, 65% of the water taken out of rivers is used for agriculture, 25% for industry, and 9% for drinking. As a result, in some places human activity consumes the entire volume of a river's water, so that the channel contains little more than a saline trickle, if that, at its mouth. For example, except during unusually wet years, the Colorado River's channel contains almost no water where it crosses the Mexican border, for huge pipes and canals carry the water instead to Phoenix and Los Angeles (**Fig. 14.27**).
- *Effects of Urbanization and Agriculture on Streams:* When it rains in a naturally vegetated region, or in an agricultural region, much of the water that falls from the sky either soaks into the ground or gets absorbed by plants. Some of the soil moisture or groundwater eventually seeps into a nearby stream, but the remainder flows elsewhere underground. As a result, the amount of water that reaches nearby streams after a storm is less than the total amount of precipitation, and a significant lag occurs between the time when the water falls and when the stream's discharge increases. Urbanization changes both the volume of water reaching the stream and the length of the time lag, because when developers

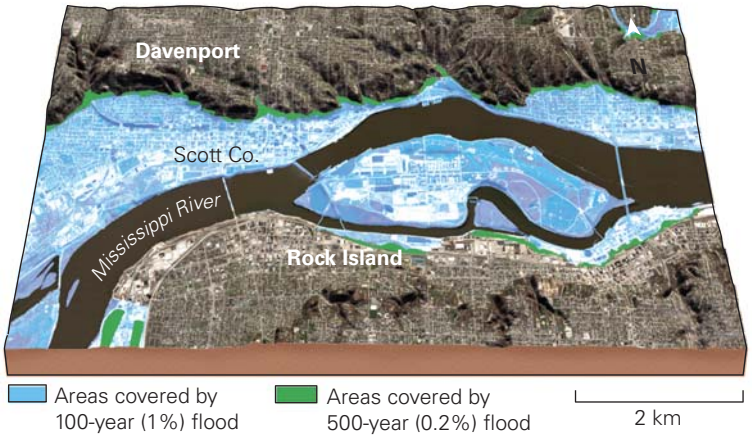
FIGURE 14.26 The conceptual relationship between flood size and probability.



(a) A 100-year flood covers a larger area than a 2-year flood and occurs less frequently.



(b) A flood-frequency graph shows the relationship between the recurrence interval and the discharge for an idealized river.



(c) A flood-hazard map shows areas likely to be flooded. Here, near Rock Island, Illinois, even large floods are confined to the floodplain.

FIGURE 14.27 The Central Arizona Project canal shunts water from the Colorado River to Phoenix.



transform fields and forests into parking lots, roads, and buildings, a layer of impermeable concrete and asphalt prevents rainfall from infiltrating, and the amount of living biomass is smaller. Storm sewers and streets divert water directly to streams, so not only does the volume of water entering the streams increase, but also the rate at which the volume changes increases.

Although we tend to think of farmland as "vegetated land," it actually has less plant cover than does natural grassland or forest. That's because the land surface between the crop rows remains bare during the growing season, and after harvest, entire fields become a broad expanse of exposed soil. Sheetwash flowing across the unprotected land surface erodes and carries with it significant volumes of sediment. Thus, a river's sediment load increases significantly when farms replace forests nearby.

Take-Home Message

People have greatly modified streams by constructing dams and levees, by discarding pollutants into the water, and by modifying discharge.

Chapter Summary

- Streams are bodies of water that flow down channels and drain the land surface. They grow by downcutting and headward erosion. Streams carry water out of a drainage basin; a drainage divide separates two adjacent catchments. Drainage networks consist of many tributaries that flow into a trunk stream.
- Permanent streams exist where the water table lies above the bed of the channel or when large amounts of water enter the channel from upstream. Where the water table lies below the channel bed, streams are ephemeral.
- The discharge of a stream is the total volume of water passing a point along the bank in a second. Most streams are turbulent, meaning that their water swirls in complex patterns.
- Streams erode the landscape by scouring, lifting, abrading, and dissolving. The resulting sediment provides dissolved loads, suspended loads, and bed loads. The total quantity of sediment carried by a stream is its capacity. Capacity differs from competence, the maximum particle size a stream can carry. When stream water slows, it deposits alluvium.
- The longitudinal profile of a stream is concave up. Typically, a stream has a steeper gradient at its headwaters than near its mouth.
- Streams cut valleys or canyons, depending on the rate of downcutting relative to the rate at which the slopes on either side of the stream undergo mass wasting. The amount of downcutting is limited by the base level. Where a stream flows down steep gradients and has a bed littered with large rocks, rapids develop, and where a stream plunges off a vertical face, a waterfall forms.
- A meandering stream wanders back and forth across a floodplain. It erodes its outer bank and deposits a point bar on the inner bank. Eventually, a meander may be cut off and turn into an oxbow lake. Natural levees form on either side of the river channel. Braided streams consist of many entwined channels.
- Where streams or rivers flow into standing water, they deposit deltas. Different deltas have different shapes.
- Fluvial erosion can bevel landscapes to a nearly flat plain. If the base level drops or the land surface rises, stream rejuvenation causes the stream to start downcutting. The headward erosion of one stream may capture the flow of another.
- If an increase in rainfall or spring melting causes more water to enter a stream than the channel can hold, a flood results. Some floods are seasonal and submerge floodplains or delta plains. Flash floods happen very rapidly. Officials try to prevent floods by building reservoirs and levees.
- Rivers are becoming a vanishing resource because of pollution, damming, and overuse of water.

Key Terms

alluvial fan (p. 427)
alluvium (p. 423)
annual probability (p. 437)
antecedent stream (p. 432)
artificial levee (p. 436)
bar (p. 423)
base level (p. 425)
bed load (p. 422)
braided stream (p. 427)
capacity (p. 423)
channel (p. 418)
competence (p. 423)
delta (p. 423)
discharge (p. 421)
distributary (p. 430)
downcutting (p. 419)
drainage divide (p. 419)
drainage network (p. 419)
drainage reversal (p. 432)
ephemeral stream (p. 420)
flash flood (p. 434)
flood (pp. 418, 433)
flood-hazard map (p. 440)
floodplain (pp. 423, 430)
floodway (p. 437)
fluvial deposit (p. 423)
headward erosion (p. 419)
longitudinal profile (p. 424)
meander (p. 427)
natural levee (p. 430)
oxbow lake (p. 428)
permanent stream (p. 420)
point bar (p. 423)
rapids (p. 427)
recurrence interval (p. 437)
running water (p. 417)
saltation (p. 422)
seasonal flood (p. 434)
sheetwash (p. 418)
stream (p. 418)
stream gradient (p. 424)
stream piracy (p. 431)
Stream rejuvenation (p. 431)
stream terrace (p. 426)
superposed stream (p. 432)
tributary (p. 419)
V-shaped valley (p. 426)
waterfall (p. 427)
watershed (p. 419)

Review Questions

1. What role do streams serve during the hydrologic cycle?
2. Describe the four different types of drainage networks.
3. Distinguish between permanent and ephemeral streams.
4. How does discharge vary according to the stream's length, and how does weather affect discharge?
5. Why is *average* downstream velocity always less than maximum downstream velocity?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on drainage networks, erosion, and river landscapes.
- Problems that help students learn how to calculate discharge.
- A video exercise that demonstrates sediment transport.

6. Describe how streams erode the Earth's surface.
7. What are three components of sediment load in a stream?
8. Distinguish between a stream's competence and capacity.
9. Describe how the character of a drainage network changes, along its length, from headwaters to mouth.
10. What is the difference between a *local* base level and the ultimate base level of a stream?
11. How does a braided stream differ from a meandering stream? What is a floodplain?
12. Describe how meanders form, develop, are cut off, and then are abandoned.
13. Describe how deltas grow and develop. How do they differ from alluvial fans?
14. How does a stream-eroded landscape evolve over time?
15. What is stream piracy? What causes a drainage reversal?
16. How are superposed and antecedent drainages similar?
17. What is the difference between a seasonal flood and a floodplain flood?
18. What activities tend to increase flood risk and damage?
19. What is the recurrence interval of a flood, and how is it related to the annual probability?
20. How have humans abused and overused the resource of running water?

On Further Thought

21. Records indicate that flood crests for a given amount of discharge along the Mississippi River have been getting *higher* since 1927, when a system of levees began to block off portions of the floodplain. Why?

SEE FOR YOURSELF N. . . Stream Landscapes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet N of our **Geotours Workbook**.



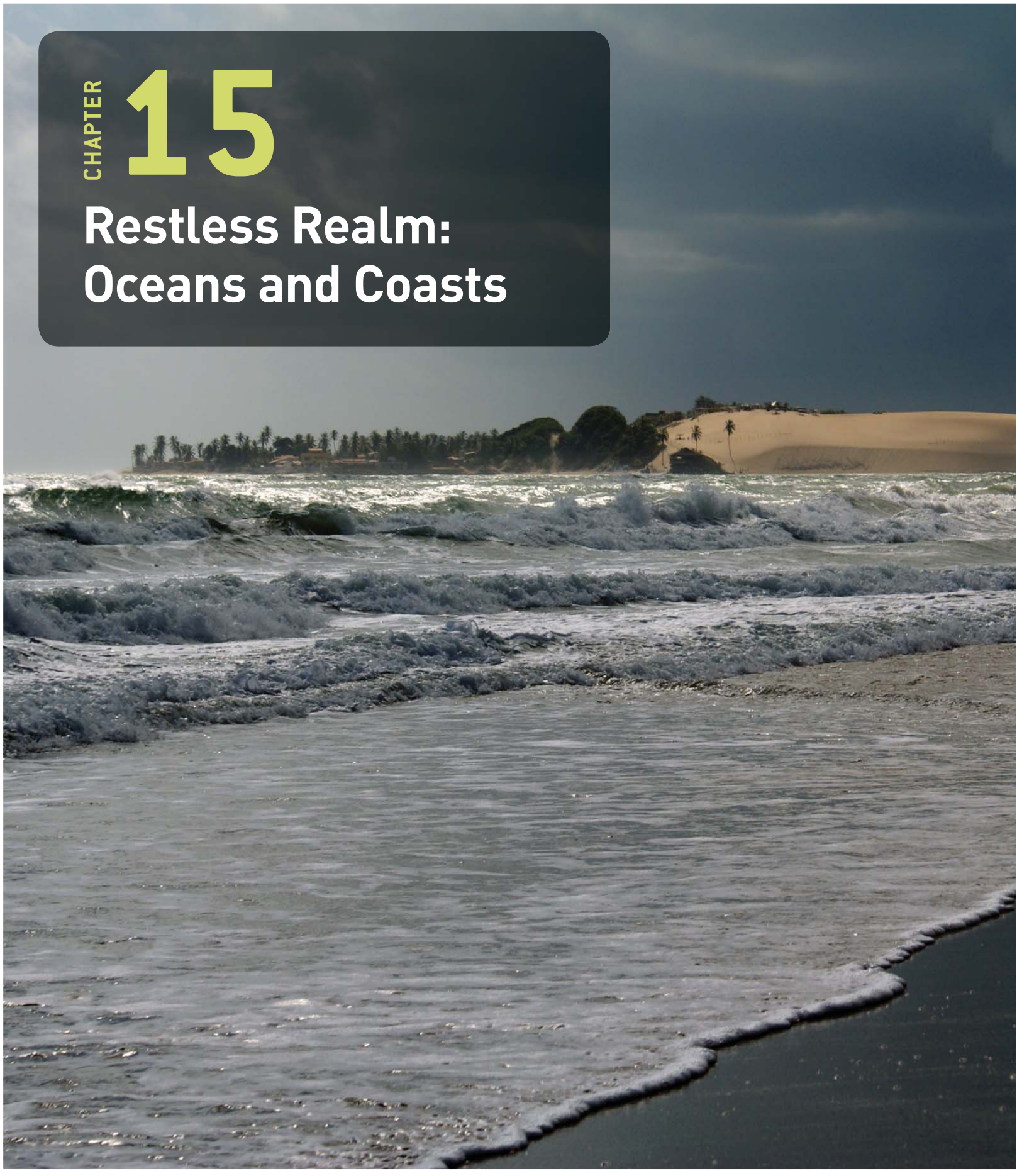
River-cut gorge in the Himalayas
Latitude 28°9′41.82″N,
Longitude 85°23′1.04″E

This NE oblique view, from 6 km, looks upstream along a deep gorge, about 50 km north of Katmandu. The gorge was cut by rivers flowing out of the Himalaya Mountains. Note that, in the upper reaches of a river, it has a steep gradient and can downcut substantially. If you position your view to look straight upstream, you'll note that the valley has a V-shape in profile.



Headward erosion, Utah
Latitude 38°17′58.16″N,
Longitude 109°50′18.76″W

In the desert areas of Utah, from 8 km, you can see intermittent tributaries flow down tributary canyons into the Colorado River in Canyonlands National Park. The tributaries cut horizontal strata. You can see a steep escarpment at the head of each tributary canyon. Groundwater sapping at this locality causes collapse of debris into the canyon, resulting in the headward erosion of the tributaries.



CHAPTER 15

Restless Realm: Oceans and Coasts



As storm clouds build, frothing waves round and sort sand on a beach near Natal, Brazil. The wind can blow the sand into huge dunes near the shore. The oceans and their fringes are constantly changing.

Chapter Objectives

By the end of this chapter, you should know . . .

- how tectonic processes produce bathymetric features of the sea floor.
- the nature and causes of surface and deep currents.
- the behavior and cause of tides.
- why waves form and how they behave.
- how a great variety of different coastal landforms develop and evolve.
- how changes in sea level, wave erosion, and human activities affect the coast.

"The three great elemental sounds in nature are the sound of rain, the sound of wind in a primeval wood, and the sound of the outer ocean on a beach."

—Henry Beston (American naturalist, 1888–1968)

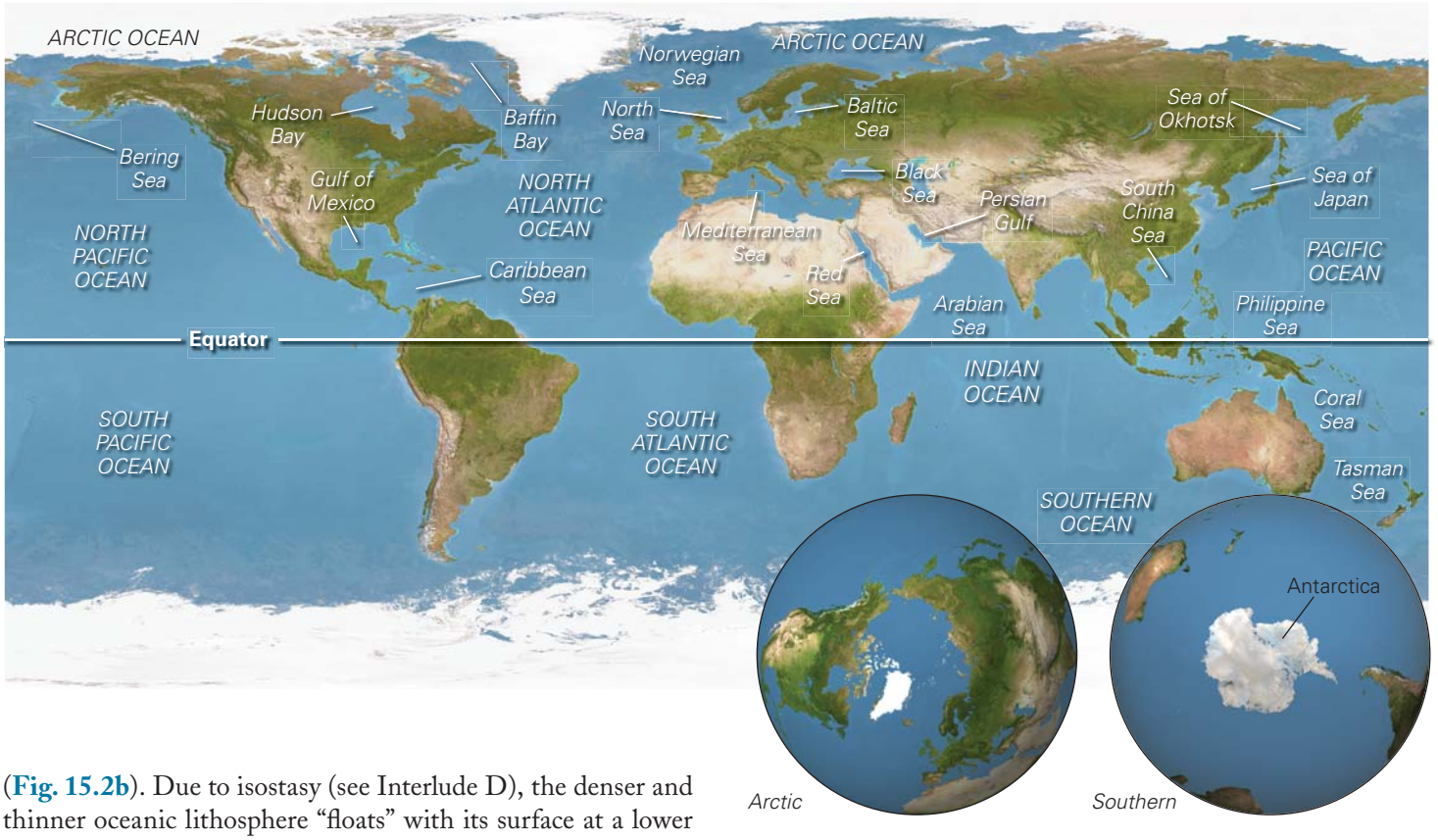
15.1 Introduction

When seen from space, Earth glows blue, for the ocean covers 70.8% of its surface (**Fig. 15.1**). The ocean provides the basis for life, tempers Earth's climate, and spawns its storms. It is a vast reservoir for water and chemicals that cycle into the atmosphere and crust, and for sediment washed off the continents. In this chapter, we first learn the fundamental geologic characteristics of ocean basins, the nature of seawater, and the pattern of ocean circulation. Then we focus on the landforms that develop along the **coast**, the region where the land meets the sea. Finally, we consider the hazards of coastal areas and how people confront them.

15.2 Landscapes Beneath the Sea

If the surface of the lithosphere were completely smooth, an ocean would surround the Earth as a uniform, 2.5-km-deep layer. But because about 30% of this planet's surface is dry land, most seawater resides in distinct ocean basins (**Fig. 15.2a**). The distinction between land and sea exists because continental and oceanic lithosphere differ markedly from one another in terms of composition and thickness

FIGURE 15.1 The oceans of the world. The Pacific is the largest, covering almost half the planet. The Arctic region is an ocean covered by a thin coating of ice, whereas the Antarctic region is a continent surrounded by an ocean.



(**Fig. 15.2b**). Due to isostasy (see Interlude D), the denser and thinner oceanic lithosphere "floats" with its surface at a lower elevation, relative to that of the relatively buoyant, thicker continental lithosphere. On the present-day map of the world, cartographers divide the global ocean into several major parts (oceans and seas), with somewhat arbitrary boundaries and significantly different volumes (see Fig. 15.1).

Have you ever wondered what the ocean floor would look like if all the water evaporated? Marine geologists can now provide a clear image of the ocean's **bathymetry**, or variation in depth (**See for Yourself O**). These measurements were first obtained by using a plumb line (a weight at the end of a cable). Then, in the 20th century, sonar measurements (made by bouncing sound waves off the ocean floor) became available. Today, satellites survey the ocean. Such studies indicate that the ocean contains bathymetric provinces, distinguished from each other by their water depth. Let's now examine each of these provinces.

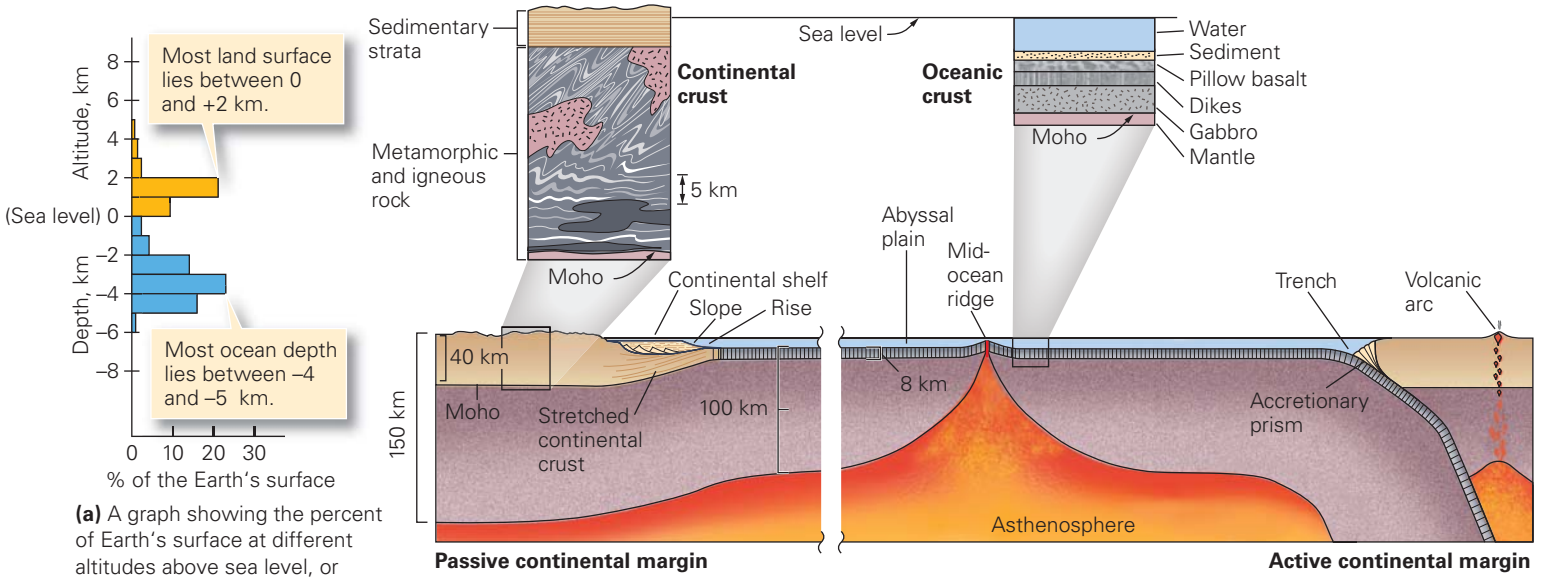
Continental Shelves, Slopes, and Rises

Imagine you're in a submersible cruising just above the floor of the western half of the North Atlantic. If you start at the shoreline of North America and head east, you will cross the 200- to 500-km-wide **continental shelf**, a relatively shallow portion of the ocean that fringes the continent. Water depth over the continental shelf does not exceed 500 m. At its eastern edge, the continental shelf merges with the continental slope, which descends to depths of nearly 4 km. From about 4 km down to about 4.5 km, a province called the continental rise, the slope angle decreases until at 4.5 km deep, you find yourself above a vast, nearly horizontal surface, the **abyssal plain**.

Broad continental shelves, like that of eastern North America, form along *passive continental margins*, margins that are not plate boundaries and thus lack seismicity (**Fig. 15.3a**; see Chapter 2). Passive margins originate after rifting breaks a continent in two. When rifting stops and sea-floor spreading begins, the stretched lithosphere at the boundary between the ocean and continent gradually cools and sinks. Sand and mud that washed off the continent, along with the shells of marine creatures that grow on the sea floor or settle from the water above, bury the sinking crust, slowly producing a pile of sediment up to 20 km thick.

If you were to take your submersible to the western coast of South America and cruise out into the Pacific, you would find a very different continental margin. After crossing a narrow continental shelf, the sea floor drops down to a depth of over 8 km. South America does not have a broad continental shelf because it is an *active continental margin*, a margin that coincides with a plate boundary and thus hosts many earthquakes (**Fig. 15.3b**). In the case of South America, the edge of the Pacific Ocean is a convergent plate

FIGURE 15.2 Contrasts between continental lithosphere and oceanic lithosphere.



(a) A graph showing the percent of Earth's surface at different altitudes above sea level, or depth below sea level.

(b) The crustal portion of continental lithosphere differs markedly from that of oceanic lithosphere.

boundary. The narrow shelf along a convergent plate boundary forms where an apron of sediment eroding from the continent spreads out over the top of an accretionary prism, the pile of sediment and basalt scraped off the downgoing subducting plate.

At many locations, relatively narrow and deep valleys called **submarine canyons** downcut into continental shelves and slopes (Fig. 15.3c). Some submarine canyons start offshore of major rivers, and for good reason: rivers cut into the continental shelf at times when sea level was low and the shelf was exposed. But river erosion cannot explain the total depth of these canyons—some slice almost 1,000 m down into the continental margin, far deeper than the maximum sea-level change. Much of the erosion of submarine canyons results from the flow of turbidity currents, submarine avalanches of sediment mixed with water (see Chapter 6).

The Bathymetry of Oceanic Plate Boundaries

Sea-floor spreading at a divergent boundary yields a mid-ocean ridge, a 2-km-high submarine mountain belt. Because crust stretches and breaks as sea-floor spreading continues, the axis of a ridge may be bordered by escarpments, a result of normal faulting. Oceanic transform faults, strike-slip faults along which one plate shears sideways past another, typically link segments of mid-ocean ridges (see Chapter 2). Transforms are delineated by fracture zones, narrow belts of steep escarpments, and broken-up rock. These fracture zones can be traced into the oceanic plate away from the ridge axis where they are not seismically active but still form the boundary between plates of different ages.

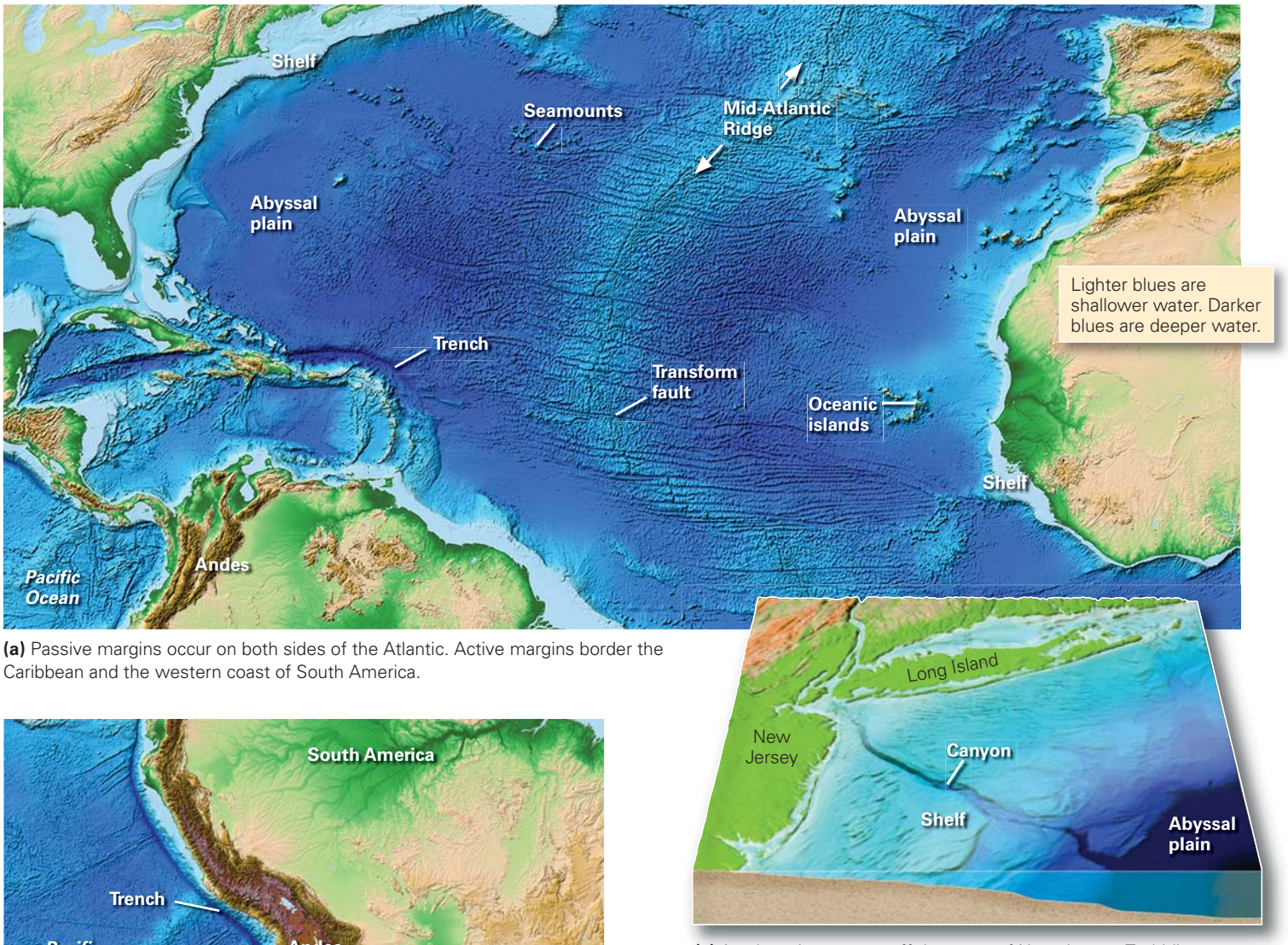
Subduction at convergent boundaries yields a trench, a deep, elongate trough bordering a volcanic arc. Some trenches reach depths of over 8 km—the deepest point in the ocean, –11,035 m, lies in the Mariana Trench of the western Pacific. Only three people have descended to the floor of the Mariana Trench—two in 1960 and the third in 2012. Some trenches border continents as we described earlier; others border island arcs, which are curving chains of active volcanic islands.

Abyssal Plains and Seamounts

As oceanic crust ages and moves away from the axis of the mid-ocean ridge, two changes take place. First, the lithosphere cools, and as it does so, its surface sinks. Second, a blanket of sediment gradually accumulates and covers the basalt of the oceanic crust. This blanket consists mostly of microscopic plankton shells and fine flakes of clay, which slowly fall like snow from the ocean water and settle on the sea floor. Because the ocean crust gets progressively older away from the ridge axis, sediment thickness increases away from the ridge axis.

In dozens of locations around the world, hot-spot eruptions on oceanic lithosphere produced volcanoes. Presently active oceanic hot-spot volcanoes, as well as the remnants of extinct ones, rise above sea level as oceanic islands; those that lie below

FIGURE 15.3 Bathymetric features of the seafloor. The maps are produced by computer using measurements from satellites or submersibles.



(a) Passive margins occur on both sides of the Atlantic. Active margins border the Caribbean and the western coast of South America.

(b) The western coast of South America is an active continental margin.

(c) A submarine canyon off the coast of New Jersey. Turbidity currents in submarine canyons carry sediment to the abyssal plain.

sea level are called **seamounts**. Particularly voluminous eruptions have produced broader buildups of basalt that are known as submarine plateaus.

Take-Home Message

Ocean basins exist because oceanic and continental lithosphere differ. Sea-floor bathymetric features (ridges, trenches, and fracture zones) reflect plate-tectonic processes. Abyssal plains overlie old lithosphere, and continental shelves overlie passive-margin basins.

15.3 Ocean Water and Currents

Composition and Temperature

If you've ever had a chance to swim in the ocean, you may have noticed that you float much more easily in ocean water than you do in freshwater. That's because ocean water contains an average of 3.5% dissolved salt; in contrast, typical freshwater contains less than 0.02% salt. The dissolved ions fit between water molecules without changing the volume of the water, so adding salt to water increases the water's density, and you float higher in a denser liquid.

There's so much salt in the ocean that if all the water suddenly evaporated, a 60-m-thick layer of salt would coat the ocean floor. This layer would consist of about 75% halite (NaCl) with lesser amounts of gypsum ($CaSO_4 \cdot H_2O$), anhydrite

($CaSO_4$), and other salts. Oceanographers refer to the concentration of salt in water as **salinity**. Although ocean salinity averages 3.5%, measurements from around the world demonstrate that salinity varies with location, ranging from about 1.0% to about 4.1%. Salinity reflects the balance between the addition of freshwater by rivers or rain and the removal of freshwater by evaporation, for when seawater evaporates, salt stays behind; salinity also depends on water temperature, for warmer water can hold more salt in solution than can cold water.

When the *Titanic* sank after striking an iceberg in the North Atlantic, most of the unlucky passengers and crew who jumped or fell into the sea died within minutes because the seawater temperature at the site of the tragedy approached freezing, and cold water removes heat from a body very rapidly. Yet swimmers can play for hours in the Caribbean, where sea-surface temperatures reach 28°C (83°F). Though the *average* global sea-surface temperature hovers around 17°C, it ranges between freezing near the poles to almost 35°C in restricted tropical seas. The correlation of average temperature with latitude exists because the intensity of solar radiation varies with latitude.

Water temperature in the ocean varies markedly with depth. Waters warmed by the Sun are less dense and tend to remain at the surface. An abrupt **thermocline**—below which water temperatures decrease sharply, reaching near freezing at the sea floor—appears at a depth of about 300 m in the tropics. There is no pronounced thermocline in polar seas, since surface waters there are already so cold.

Currents: Rivers in the Sea

Since first setting sail on the open ocean, people have known that the water of the ocean does not stand still, but rather flows or circulates at velocities of up to several kilometers per hour in fairly well-defined streams called **currents**. Oceanographic studies demonstrate that circulation in the sea occurs at two levels: *surface* currents affect the upper hundred meters of water, and *deep* currents keep the remainder of the water column in motion.

Surface currents occur in all the world's oceans (Fig. 15.4). They result from interaction between the sea surface and the wind—as moving air molecules shear across the surface of the water, the friction between air and water drags the water along with it. The Earth's rotation, however, generates the **Coriolis effect** (Box 15.1), a phenomenon that causes surface currents in the northern hemisphere to veer

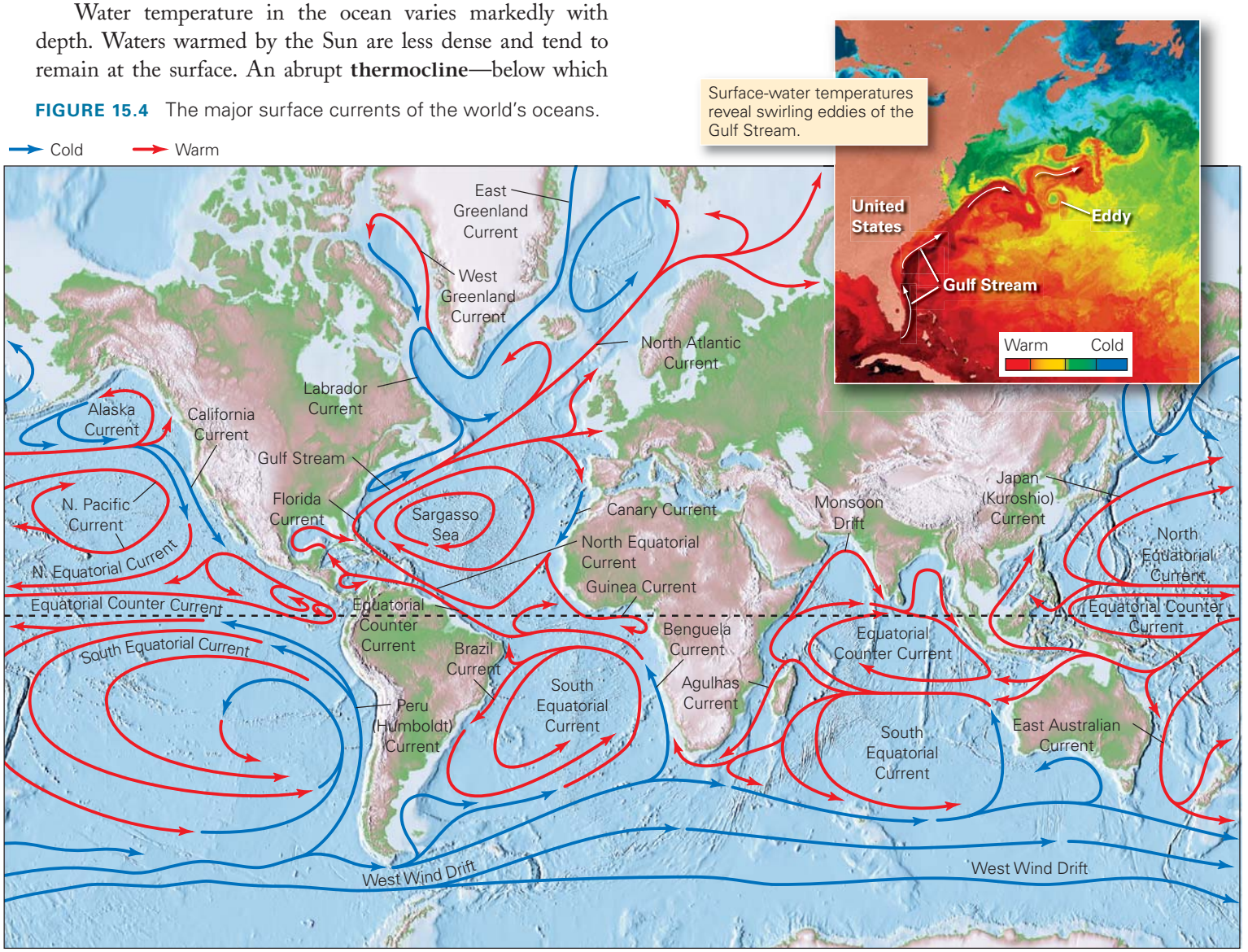


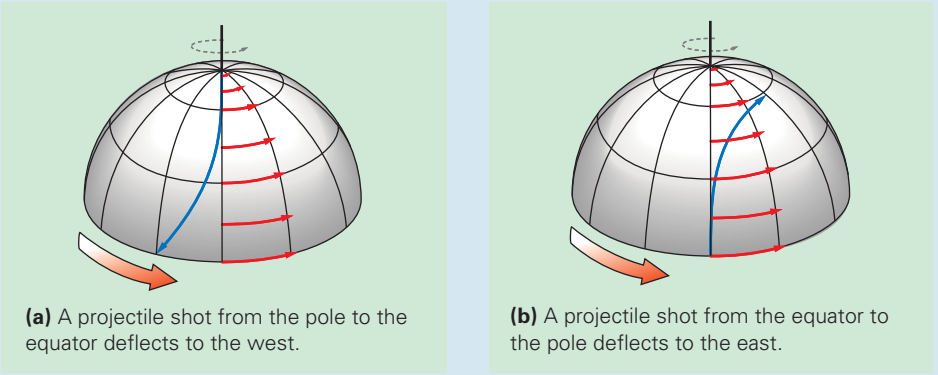
FIGURE 15.4 The major surface currents of the world's oceans.

BOX 15.1 CONSIDER THIS . . .

The Coriolis Effect

Imagine that you have a huge cannon—aim it due south and fire a projectile from the North Pole to a target on the equator (**Fig. Bx15.1a**). If the Earth were standing still, the shot would follow a line of longitude. But the Earth isn't standing still. It rotates counterclockwise around its "axis" (an imaginary line that passes through the planet's center and its geographic poles). To an observer in space, an object at the pole doesn't move at all as the Earth spins because it is sitting on the axis, but an object at the equator moves at about 1,665 km/h (1,035 mph). Because of this difference, the target on the equator will have moved by the time the projectile reaches it. In fact, to an observer standing on the Earth and moving with it, the projectile follows a curving trajectory. The same phenomenon happens if you place the cannon on the equator and fire the projectile due north (**Fig. Bx15.1b**)—the projectile's path curves because the projectile moves eastwards progressively faster than the land beneath while moving north. (The same phenomenon, of course, happens in the southern hemisphere, but in reverse.) This behavior is called the Coriolis effect, after the French engineer who, in 1835, described its consequences. Because of the Coriolis effect, north-flowing currents in the northern hemisphere deflect to the east, and south-flowing currents deflect to the west.

FIGURE Bx15.1 The Coriolis effect occurs because the velocity of a point at the equator, in the direction of the Earth's spin, is greater than that of a point near the pole.



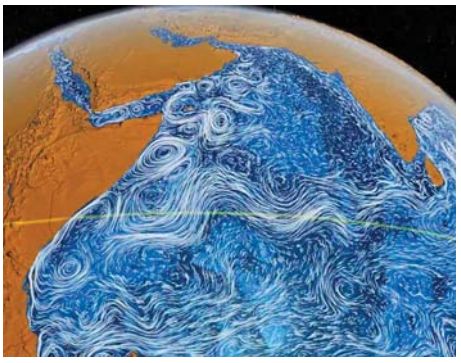
(a) A projectile shot from the pole to the equator deflects to the west.

(b) A projectile shot from the equator to the pole deflects to the east.

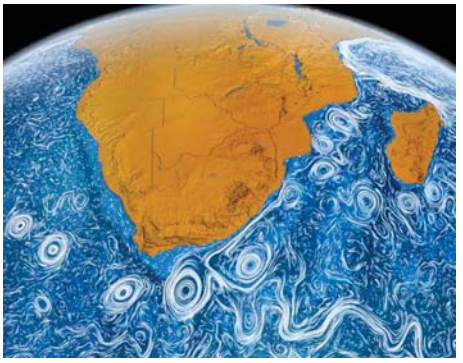
toward the right and surface currents in the southern hemisphere to veer toward the left of the average wind direction. Across the width of an ocean, the Coriolis effect causes surface currents to make a complete loop, known as a **gyre**. Surface water may become trapped for a long time in the center of the gyre, where currents hardly exist, so these regions tend to accumulate floating plastics, sludge, and seaweed. The "Sargasso Sea," named for a kind of floating seaweed, lies at the center of the North Atlantic gyre, and the "Great Pacific Garbage Patch," an accumulation of floating plastic and trash, lies at the center of the North Pacific gyre. Figure 15.4 is a simplification of currents—interactions of currents with coastlines create chains of eddies, in which water circulates in small loops (**Fig. 15.5a–c**).

Surface water and deeper water in the ocean exchange at a number of locations. Specifically, in *downwelling* zones, surface water sinks, and in *upwelling* zones, deeper water rises. Downwelling and upwelling occur for a number of reasons. For example, in places where winds blow surface water shoreward, an oversupply of water develops along the coast, so surface

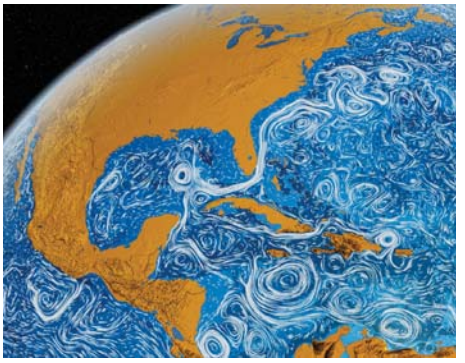
FIGURE 15.5 The complexity of the ocean's currents. An animation by NASA, based on data collected over a two-year period, shows the details of eddies and swirls in the ocean, and emphasizes that currents interact with the coasts.



(a) Western Indian Ocean.

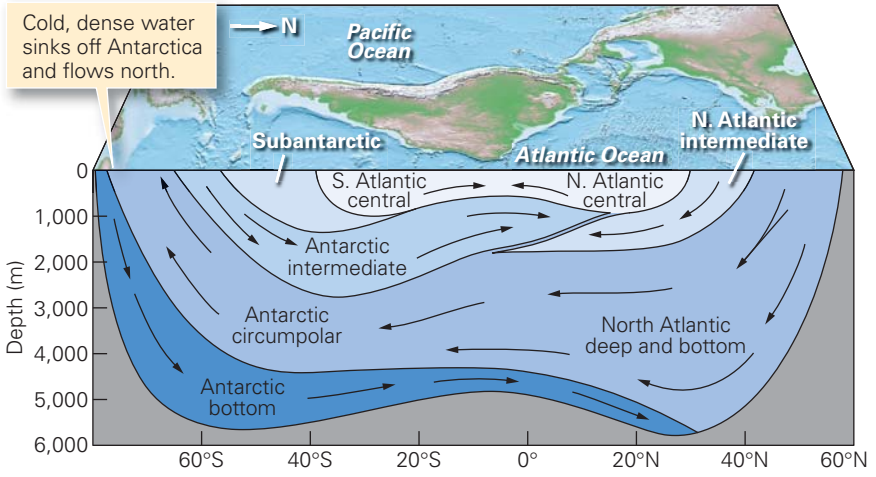


(b) Southern Ocean, south of Africa

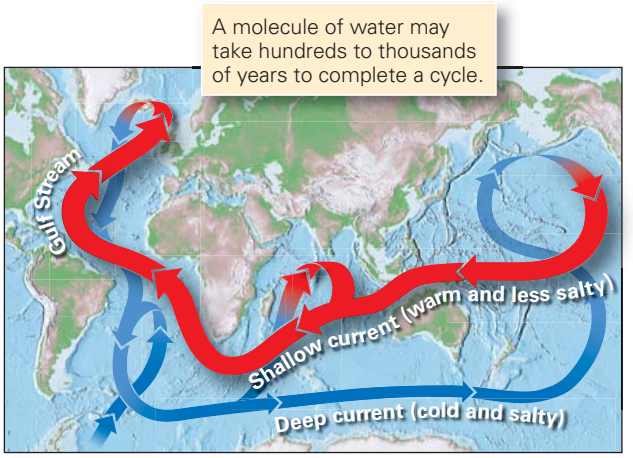


(c) Western North Atlantic, and Caribbean.

FIGURE 15.6 Global-scale upwelling and downwelling of ocean water.



(a) Due to variations in density, the oceans are stratified into distinct water masses.



(b) Thermohaline circulation results in a global-scale "conveyor belt" that circulates water throughout the entire ocean system. The ocean mixes entirely in a 1,500-year period.

water must sink to make room. And where winds blow surface water away from the shore, a deficit of water develops along the coast, so deeper water must rise to fill the gap. Upwelling of deeper water also occurs near the equator, where winds blow steadily from east to west, because the Coriolis effect deflects surface currents to the right in the northern hemisphere and to the left in the southern hemisphere, thereby leading to the development of a water deficit along the equator. The resulting rise of cool, nutrient-rich water fosters an abundance of life in equatorial water.

Contrasts in water density, caused by differences in temperature and salinity, can also drive upwelling and downwelling. We refer to the rising and sinking of water driven by such density contrasts as **thermohaline circulation**. During thermohaline circulation, denser (cold and/or saltier) water sinks, whereas water that is less dense (warm and/or less salty) rises. As a result, the cold water in polar regions sinks and flows back along the bottom of the ocean toward the equator. This process divides the ocean vertically into a number of distinct water masses, which mix only very slowly with one another. In the Atlantic Ocean, for example, the Antarctic Bottom Water sinks along the coast of Antarctica, and the North Atlantic Deep Water sinks in the north polar region (Fig. 15.6a). The combination of surface currents and thermohaline circulation, like a conveyor belt, moves water and heat among the various ocean basins and moderates global climate (Fig. 15.6b).

Take-Home Message

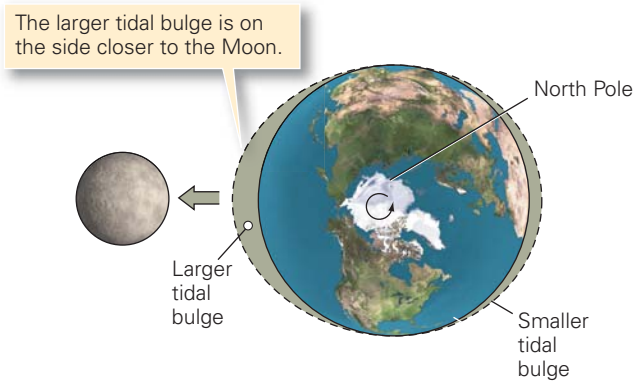
Ocean salinity and temperature vary with depth and location. The wind drives surface currents, forming large gyres. Upwelling and downwelling develop due to wind-driven water surplus or deficit, or due to density variations related to temperature and salinity.

15.4 Tides

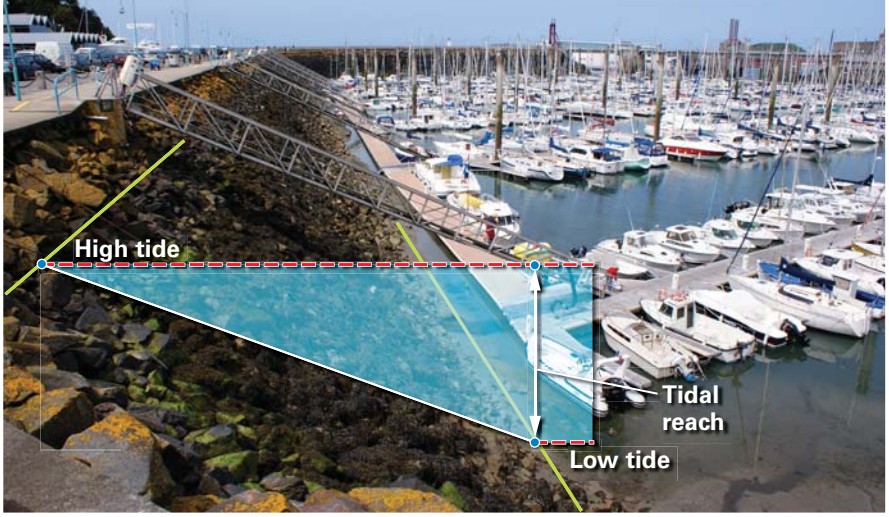
A ship captain hoping to set sail from a port must pay close attention to the **tide**, the generally twice daily rise and fall of sea level. At high tide, the harbor's water is deep enough that the ship can easily float over obstacles, but at low tide, the water may be so shallow that the ship could run aground. Tides develop in response to the *tide-generating force*, which in simple terms is due in part to the gravitational attraction of the Sun and Moon, and in part to centrifugal force produced by the revolution of the Earth-Moon System around its center of mass. The tide-generating force results in two tidal bulges in the oceans on opposite sides of our planet (Fig. 15.7a). Of these, the larger one occurs on the side of the Earth closer to the Moon, for the Moon's gravitational pull is stronger than that of other contributors to the tide-generating force. When a location lies under a tidal bulge, it experiences a high tide, and when it underlies a depression between two bulges, it experiences a low tide. If the Earth's surface were smooth and completely submerged beneath the oceans, each point on the surface would experience two high tides and two low tides per day, as the Earth spins relative to the tidal bulges. But the complex shape of the sea floor near the shore means that the specific timing and magnitude of tides can vary along a coast. Specifically, the **tidal reach**, meaning the elevation difference between sea level at high tide and low tide, can range from less than a meter to several meters. The largest tidal reach on Earth, 16.8 m (54.6 ft), occurs in the Bay of Fundy on the Atlantic coast of Canada.

The manifestation of tides along a shore depends not only on the tidal reach, but on the slope of the shore. Along a vertical cliff, the intertidal zone (the region of shore submerged at high tide and exposed at low tide) appears as a ring of stained,

FIGURE 15.7 Ocean tides and their manifestation.



(a) Tides develop as the Earth spins relative to the two tidal bulges.



(b) The tidal reach is the vertical distance between low tide and high tide. This photo of a French harbor was taken at low tide.



(c) Mont Saint-Michel, off the western coast of France, is an island at high tide.



(d) At low tide, muddy tidal flats surround Mont Saint-Michel.

barnacle- and seaweed-encrusted rock. Where the coast has a gentle slope, the shoreline (meaning the boundary between land and sea) moves substantially inland during a rising tide, and seaward during a falling tide (Fig. 15.7b). Vast muddy tidal flats may be exposed during low tide (Fig. 15.7c, d). Tidal flats can be hazardous for people who head out across the mud flats in search of shellfish, for the rising tide can trap them offshore.

Take-Home Message

Gravitational attraction by the Moon and Sun, as well as centrifugal force in the Earth-Moon System, cause two tidal bulges that move around the Earth. Because of the twice daily rise and fall of tides, intertidal regions are alternately submerged and exposed.

15.5 Wave Action

Wind-driven waves make the ocean surface a restless, ever-changing vista. They develop because of the shear between the molecules of air in the wind and the molecules of water at the surface of the sea. Molecules of water within a wave moving across the open ocean don't move great distances horizontally but rather move in a circle. The diameter of the circle is largest for molecules at the surface, where it equals the wave height (the vertical distance from crest to trough) of the wave. With increasing depth, though, the diameter of the circle decreases until, at a depth equal to about half the wavelength (the horizontal distance between two wave troughs or two wave crests), there is no wave movement at all (Fig. 15.8a). Submarines traveling below this **wave base** cruise through smooth water, while ships toss about above.

The character of waves in the open ocean depends on the strength of the wind (how fast the air moves) and on the fetch of the wind (the distance over which it blows). When the wind first begins to blow, it creates ripples in the water surface, pointed waves whose height and wavelength are small. With continued blowing over a long fetch, swells, larger waves with wave heights of 2 to 10 m and wavelengths of 40 to 500 m, begin to build. Hurricane wave heights may grow to over 35 m. Swells may travel for thousands of kilometers across the ocean, well beyond the region where they formed.

The constructive interference of waves (meaning the additive effect that happens when two wave crests cross each other), the interaction of waves and currents, and the focusing of wave energy due to the shape of the sea floor can lead to the growth of **rogue waves**, defined as waves that are two to five times the size of most of the large waves passing a locality in a given time interval. Rogue waves have swamped the decks of ocean liners.

Did you ever wonder . . .
why the breakers that surfers love form near the shore?

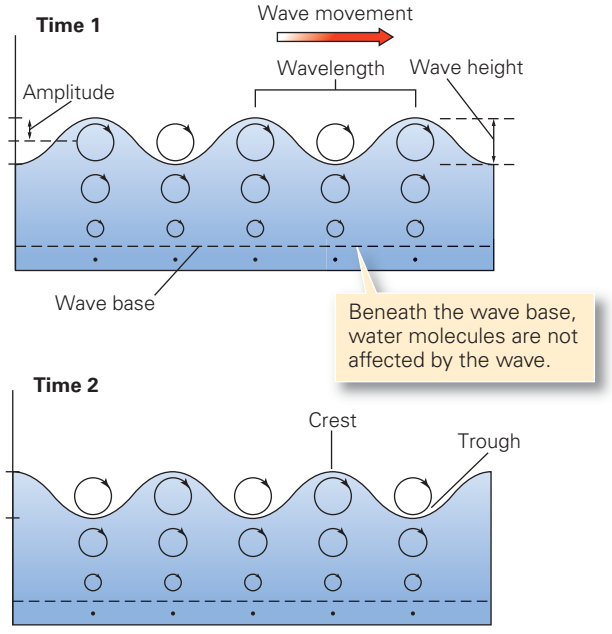
Waves have no effect on the ocean floor, as long as the floor lies below the wave base. However, near the shore, where the wave base just touches the floor, it causes a slight back-and-forth motion of sediment. Closer to shore, as the water gets shallower, friction between the wave and the sea floor slows the deeper part of the wave, and the motion in the wave becomes more elliptical (Fig. 15.8b). Eventually, water at the top of the wave curves over the base, and the wave becomes a breaker, ready for surfers to ride. Breakers crash onto the shore in the surf zone, sending a surge of water up the beach. This upward surge, or **swash**, continues until friction brings motion to a halt. Then gravity draws the water back down the beach as **backwash**.

Waves may make a large angle with the shoreline as they're coming in, but they bend as they approach the shore, a phenomenon called **wave refraction**; right at the shore, wave crests generally make less than a 5° angle with the shoreline (Fig. 15.9a, b). To understand why this happens, imagine a wave approaching the shore so that its crest initially makes an angle of 45° with the shoreline. The end of the wave closer to the shore touches bottom first and slows down because of friction, whereas the end farther offshore continues to move at its original velocity, swinging the whole wave around so that it becomes more parallel with the shoreline.

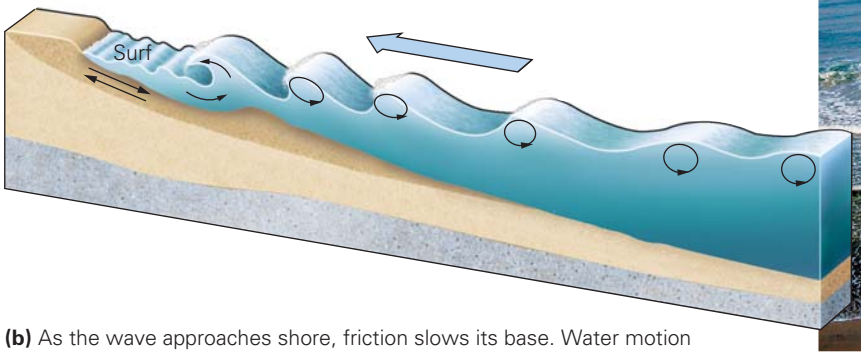
Although wave refraction decreases the angle at which waves move close to shore, it does not necessarily eliminate the angle. Where waves do arrive at the shore obliquely, water in the nearshore region has a component of motion that trends parallel to the shore. This **longshore current** causes swimmers floating in the water just offshore to drift gradually in a direction parallel to the beach. And where waves roll onto the shore at an angle, sediment in the surf follows a sawtooth pattern of movement that results in a gradual *net* transport of beach sediment parallel to the beach—such movement of sediment is called **longshore drift** (or beach drift). This sawtooth pattern happens because the swash of a wave moves perpendicular to the wave crest, so an oblique wave carries sediment diagonally up the beach, but the backwash must flow straight down the slope of the beach due to gravity.

Waves pile water up on the shore incessantly. As the excess water moves back to the sea, it may localize into a strong seaward flow perpendicular to the beach called a rip current. Rip

FIGURE 15.8 Ocean waves build in response to the shear of wind blowing over the water surface.



(a) Within a deep-ocean wave, water molecules follow a circular path. The radius of the circle decreases with depth. Note that the wave height is twice the amplitude.



(b) As the wave approaches shore, friction slows its base. Water motion in the wave becomes more elliptical, and the wave becomes a breaker.



currents are the cause of many drownings every year along beaches, because they can carry unsuspecting swimmers far away from the beach.

Take-Home Message

The friction of the wind against the sea surface causes waves to form. Within a wave, water moves in a circle; the amount of motion decreases with depth. Near shore, water piles up into breakers that refract when they approach the shore, causing longshore drift.

15.6 Where Land Meets Sea: Coastal Landforms

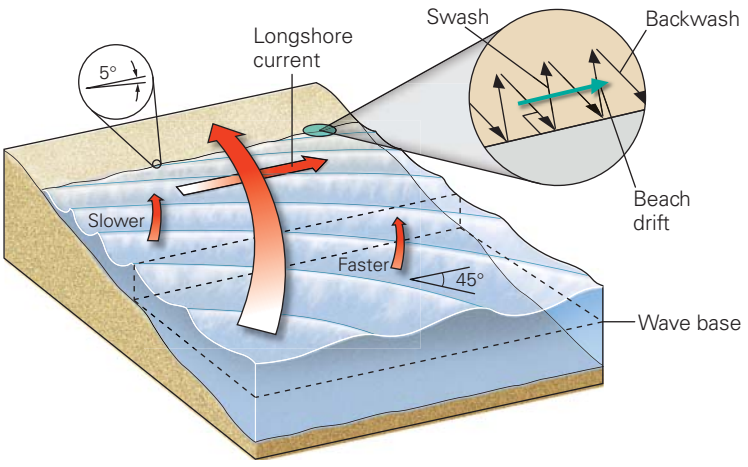
Tourists along the Amalfi coast of Italy thrill to the sound of waves crashing on rocky shores. But in the Virgin Islands sunbathers can find seemingly endless white sand beaches, and along the Mississippi delta, vast swamps border the sea. Large, dome-like mountains rise directly from the sea in Rio de Janeiro, Brazil, but a 100-m-high vertical cliff marks the boundary between the Nullarbor Plain of southern Australia and the Great Southern Ocean. As these examples illustrate, **coasts**, the belts of land bordering the sea, vary dramatically in terms of topography and associated landforms.

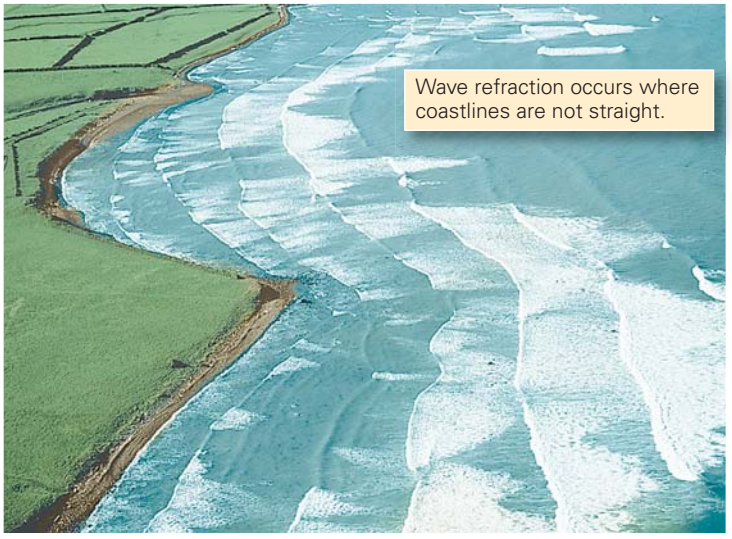
Beaches and Tidal Flats

For millions of vacationers, the ideal holiday includes a trip to a **beach**, a gently sloping fringe of sediment along the shore. Some beaches consist of pebbles or boulders, whereas others consist of sand grains (Fig. 15.10a, b). This is no accident, for waves winnow out finer sediment like silt and clay and carry it to quieter water, where it settles. Storm waves, which can smash cobbles against one another with enough force to shatter them, have little effect on sand, for sand grains can't collide with enough energy to crack. Thus, cobble beaches exist only where nearby cliffs supply large rock fragments.

Did you ever wonder . . .
why beautiful sandy beaches don't form along all coasts?

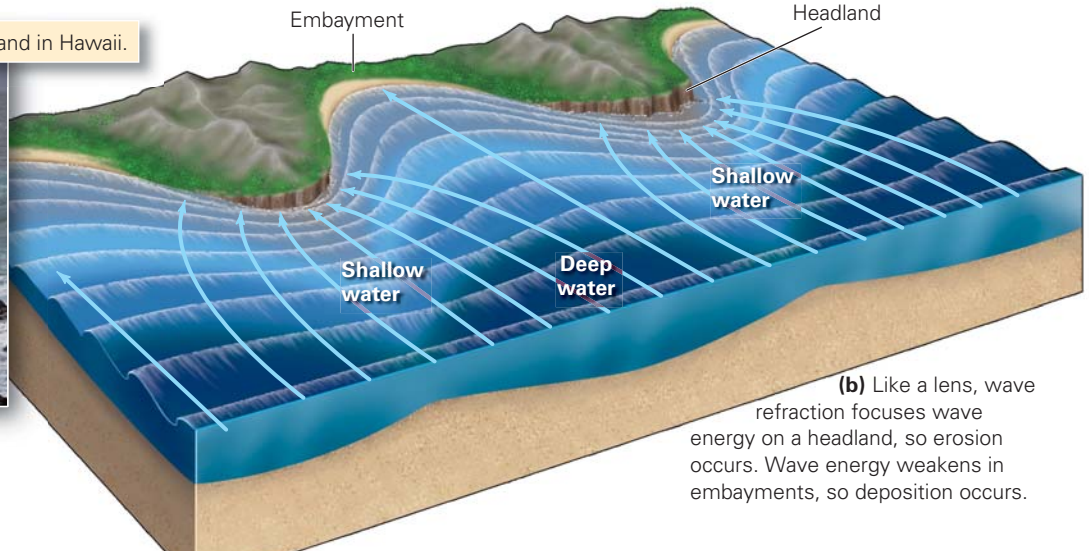
FIGURE 15.9 Wave refraction and its consequences along the shore.





(a) Wave refraction occurs when waves approach the shore at an angle. If the wave reaches the beach at an angle, it causes a longshore current and beach drift of sand.





(b) Like a lens, wave refraction focuses wave energy on a headland, so erosion occurs. Wave energy weakens in embayments, so deposition occurs.

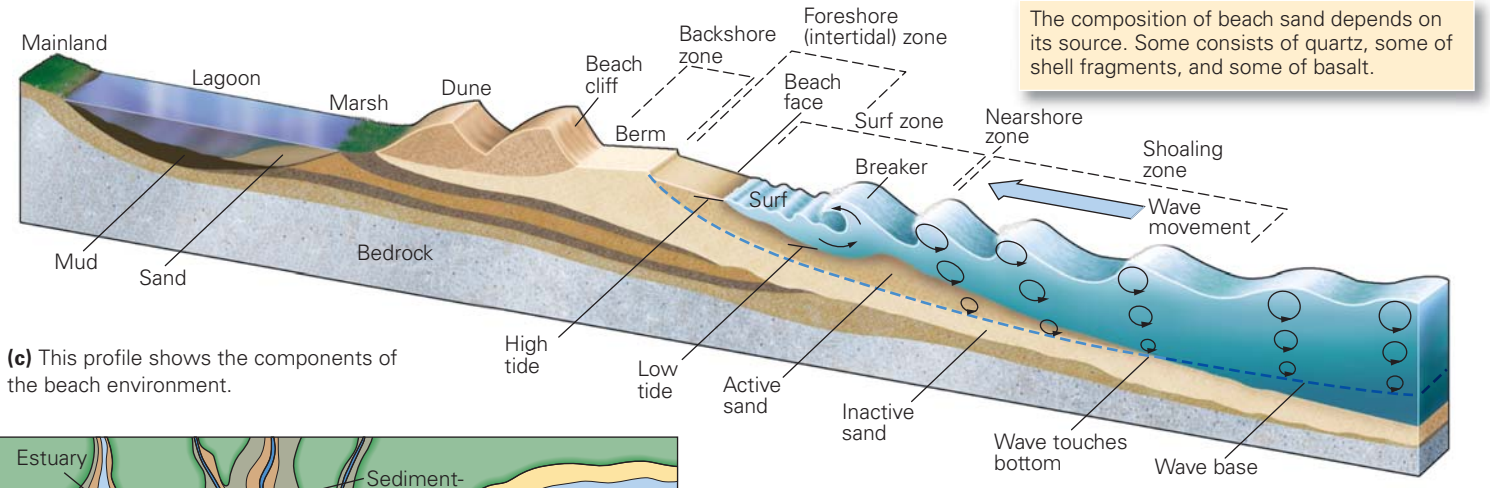
FIGURE 15.10 Characteristics of beaches, barrier islands, and tidal flats.



(a) A gravel beach along the Olympic Peninsula, Washington. The clasts were derived from erosion of adjacent cliffs.

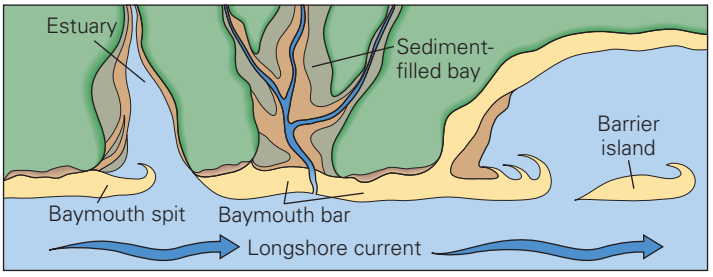


(b) A sand beach on the western coast of Puerto Rico. Wave action has carried away finer sediment.

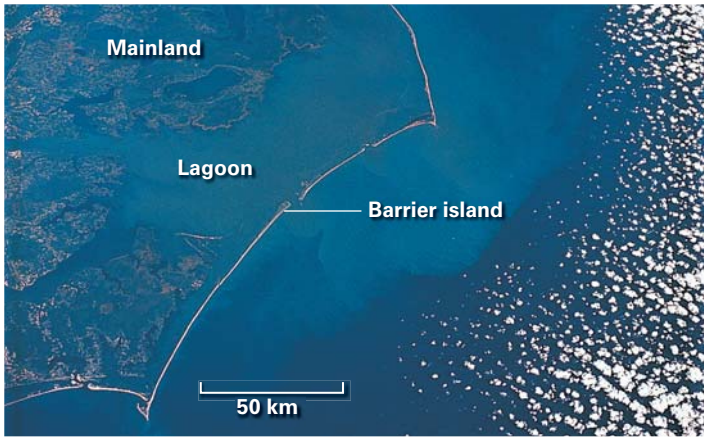


The composition of beach sand depends on its source. Some consists of quartz, some of shell fragments, and some of basalt.

(c) This profile shows the components of the beach environment.



(d) Beach drift can generate sand spits and baymouth bars. Sedimentation eventually fills in the region behind a baymouth bar.



(e) A satellite image showing barrier islands off the coast of North Carolina.



(f) At low tide, boats at anchor rest in the mud of a tidal flat along the coast of Wales.

The composition of sand varies from beach to beach, because different sands come from different sources. Sands derived from the weathering and erosion of silicic-to-intermediate rocks consist mainly of quartz; other minerals in these rocks chemically weather to form clay, which washes away in waves. Beaches made from the erosion of limestone, or of coral reefs and shells, consist of carbonate sand, including masses of sand-sized chips of shells. And beaches derived from the erosion of basalt boast black sand, made of tiny basalt grains.

A *beach profile*, a cross section drawn perpendicular to the shore, illustrates the shape of a beach (**Fig. 15.10c**). Starting from the sea and moving landward, a beach consists of a foreshore zone, or intertidal zone, across which the tide rises and falls. The beach face, a steeper, concave-up part of the foreshore zone, forms where the swash of the waves actively scours the sand. The backshore zone extends from a small step, cut by high-tide swash to the front of the dunes or cliffs that lie farther inshore. The backshore zone includes one or more berms, horizontal to landward-sloping terraces that receive sediment only during a storm.

Geologists commonly refer to beaches as "rivers of sand," to emphasize that beach sand moves along the coast over time—it is not a permanent substrate. Wave action at the shore moves an active sand layer on the sea floor on a daily basis. Inactive sand, buried below this layer, moves only during severe storms or not at all. Longshore drift, discussed earlier, can transport sand hundreds of kilometers along a coast in a matter of centuries. Where the coastline indents landward, beach drift stretches beaches out into open water to create a **sand spit**. Some sand spits grow across the opening of a bay, to form a baymouth bar (**Fig. 15.10d**).

The scouring action of waves sometimes piles sand up in a narrow ridge away from the shore called an **offshore bar**, which parallels the shoreline. In regions with an abundant sand supply, offshore bars rise above the mean high-water level and become **barrier islands** (**Fig. 15.10e**), and the water between a barrier island and the mainland becomes a quiet-water **lagoon**, a body of shallow seawater separated from the open ocean. Though developers have covered some barrier islands with expensive resorts, in the time frame of centuries to millennia, barrier islands are temporary features and may wash away in a storm.

Tidal flats, regions of clay and silt exposed or nearly exposed at low tide but totally submerged at high tide, develop in regions protected from strong wave action (**Fig. 15.10f**). They are typically found along the margins of lagoons or on shores protected by barrier islands. Here, sediments accumulate to form thick, sticky layers.

Rocky Coasts

More than one ship has met its end, smashed and splintered in the spray and thunderous surf of a rocky coast, where bedrock cliffs rise directly from the sea. Lacking the protection of a beach, rocky coasts feel the full impact of ocean breakers. The water pressure generated during the impact of a breaker can pick up boulders and smash them together until they shatter, and it can squeeze air into cracks, creating enough force to push rocks apart. Further, because of its turbulence, the water hitting a cliff face carries suspended sand and thus can abrade the cliff. The combined effects of shattering, wedging, and abrading, together called wave erosion, gradually undercut a cliff face and make a **wave-cut notch** (**Fig. 15.11a**). Undercutting continues until the overhang becomes unstable and breaks away at a joint, creating a pile of rubble at the base of the cliff that waves immediately attack and break up. In this process, wave erosion cuts away at a rocky coast, so that the cliff gradually migrates inland. Such cliff retreat may leave behind a **wave-cut bench**, or *platform*, that becomes visible at low tide (**Fig. 15.11b**).

Other processes besides wave erosion break up the rocks along coasts. For example, salt spray coats the cliff face above the waves and infiltrates into pores. When the water evaporates, salt crystals grow and push apart the grains, thereby weakening the rock. Biological processes also contribute to erosion, for plants and animals in the intertidal zone bore into the rocks and gradually break them up.

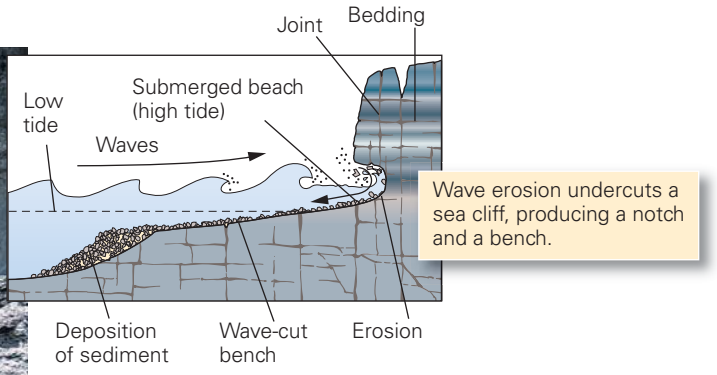
Many rocky coasts are irregular with headlands protruding into the sea and embayments set back from the sea. Wave energy focuses on headlands and disperses in embayments, a result of wave refraction. The resulting erosion removes debris at headlands, and sediment accumulates in embayments (**Fig. 15.11c**). In some cases, a headland erodes in stages (**Fig. 15.11d**). Because of refraction, waves curve and attack the sides of a headland, slowly eating through it to create a sea arch connected to the mainland by a narrow bridge. Eventually the arch collapses, leaving isolated **sea stacks** just offshore (Fig. 15.11d). Once formed, a sea stack protects the adjacent shore from waves. Therefore, sand may collect in the lee of the stack, slowly building a tombolo, a narrow ridge of sand that links the sea stack to the mainland.

Estuaries

Along some coastlines, a relative rise in sea level causes the sea to flood river valleys that merge with the coast, resulting in **estuaries**, where seawater and river water mix. You can recognize an estuary on a map by the dendritic pattern of its river-carved coastline (**Fig. 15.12**). Oceanic and fluvial waters interact in two ways within an estuary. In quiet estuaries, protected from wave action or river turbulence, the water becomes stratified, with denser oceanic saltwater flowing upstream as a wedge beneath less-dense fluvial freshwater. In turbulent estuaries, oceanic and fluvial water combine to create nutrient-rich brackish water with a salinity between that of oceans and rivers. Estuaries are complex ecosystems inhabited by unique species of shrimp, clams, oysters, worms, and fish that can tolerate large changes in salinity.

FIGURE 15.11 Erosion landforms of rocky shorelines.

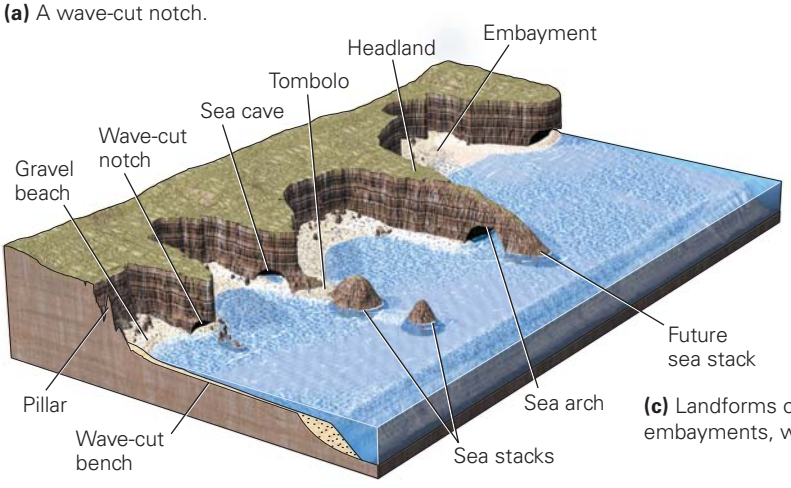




(a) A wave-cut notch.



(b) A wave-cut bench at the foot of the cliffs at Etretat, France.



(c) Landforms of a rocky shore. Beaches collect in embayments, whereas erosion concentrates at headlands.

(d) Coastal erosion along Australia's southern coast produced a sea arch (left). Eventually, the bridge will collapse, and only sea stacks will remain (right). These two are among several that together are known locally as the Twelve Apostles.





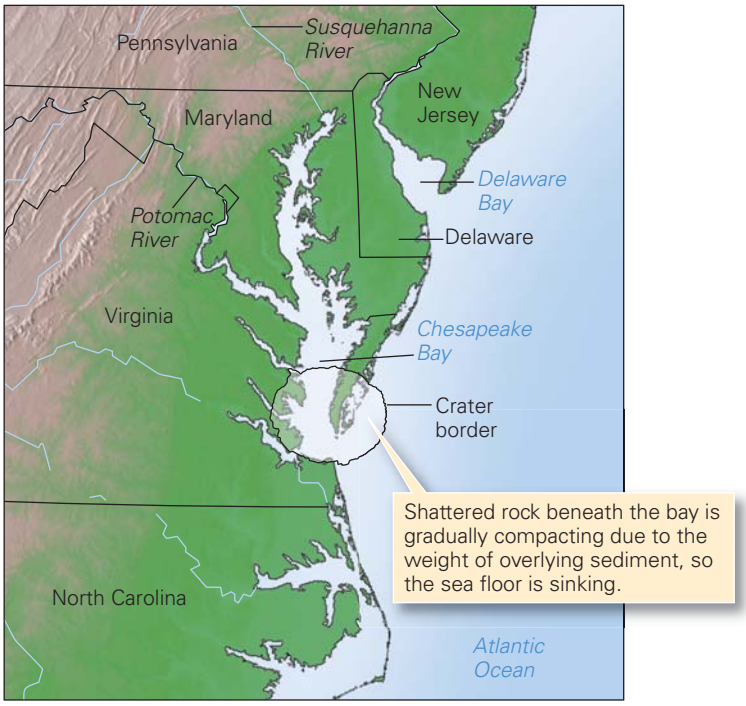
Fjords

During the last ice age, glaciers carved deep valleys in coastal mountain ranges. When the ice age came to a close, the glaciers melted away, leaving deep, U-shaped valleys (see Chapter 18). The water stored in the glaciers, along with the water within the vast ice sheets that covered continents during the ice age, flowed back into the sea and caused sea level to rise. The rising sea filled the deep valleys, creating **fjords**, or flooded glacial valleys. Coastal fjords are fingers of the sea surrounded by mountains; because of their deep-blue water and steep walls of polished rock, they are distinctively beautiful (Fig. 15.13).

Coastal Wetlands

A flat-lying coastal area that floods during high tide and drains during low tide, but does not get pummeled by intense waves, can host salt-resistant plants and evolve into a **coastal**

FIGURE 15.12 The Chesapeake Bay estuary formed when the sea flooded river valleys. The region is sinking relative to other coast areas because it overlies a buried meteor crater.



wetland. Wetland-dominated shorelines are sometimes called "organic coasts." Researchers distinguish among different types of coastal wetlands based on the plants they host. Examples include swamps (dominated by trees), marshes (dominated by grasses; **Fig. 15.14a**), and bogs (dominated by moss and shrubs). So many marine species spawn in wetlands that as a whole, wetlands account for 10% to 30% of marine organic productivity.

In tropical or semitropical climates (between 30° north and 30° south of the equator), mangrove trees may become the dominant plant in swamps (**Fig. 15.14b**). Some mangrove species form a broad network of roots above the water surface, making the plant look like an octopus standing on its tentacles, and some send up small protrusions from roots that rise above the water and allow the plant to breathe. Dense mangrove swamps counter the effects of stormy weather and thus prevent coastal erosion.

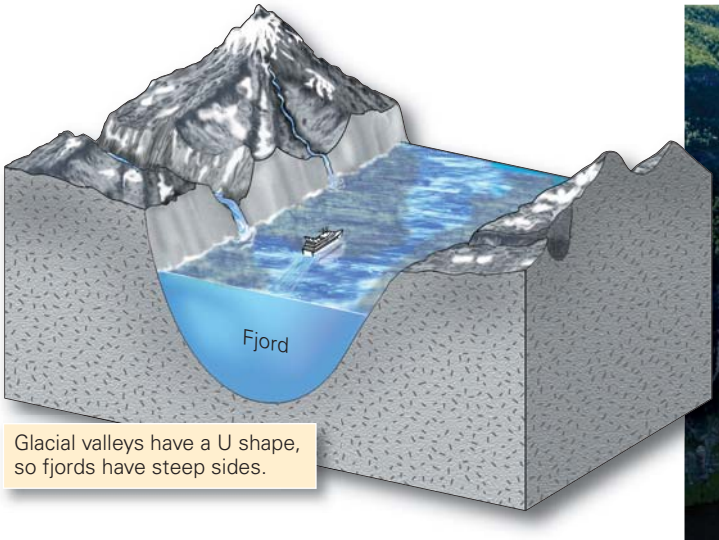
Coral Reefs

Along the azure coasts of Hawaii, visitors swim through colorful growths of living coral. Some corals look like brains, others like elk antlers, still others like delicate fans (**Fig. 15.15a**). Sea anemones, sponges, and clams grow on and around the coral. Though at first glance coral looks like a plant, it is actually a colony of tiny invertebrates related to jellyfish. An individual coral animal, or polyp, has a tube-like body with a head of tentacles.

Coral polyps secrete calcite shells, which gradually build into a mound of solid limestone whose top surface lies from just below the low-tide level down to a depth of about 60 m. At any given time, only the surface of the mound lives—the mound's interior consists of shells from previous generations of coral. The realm of shallow water underlain by coral mounds, associated organisms, and debris comprises a **coral reef**. Reefs absorb wave energy and thus serve as a living buffer zone that protects coasts from erosion. Corals need clear, well-lit, warm (18°–30°C) water with normal oceanic salinity, so coral reefs grow only along clean coasts at latitudes of less than about 30° (**Fig. 15.15b**).

Marine geologists distinguish three different kinds of coral reef, on the basis of their geometry (**Fig. 15.15c**). A fringing reef forms directly along the coast, a barrier reef develops offshore, and an atoll makes a circular ring surrounding a lagoon. As Charles Darwin first recognized back in 1859, coral reefs associated with islands in the Pacific start out as fringing reefs

FIGURE 15.13 Fjord landscapes form where relative sea-level rise drowns glacially carved valleys.



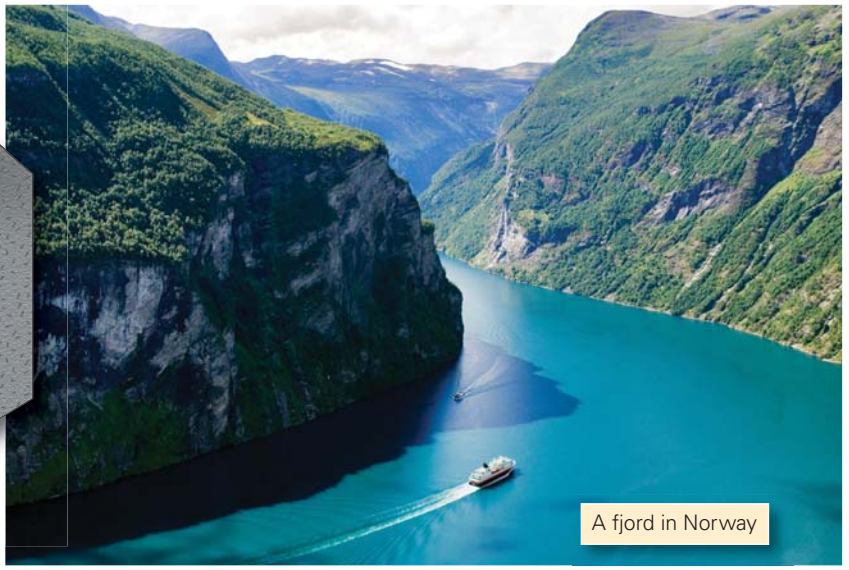


FIGURE 15.14 Examples of coastal wetlands.



(a) A salt marsh along the coast of Cape Cod.



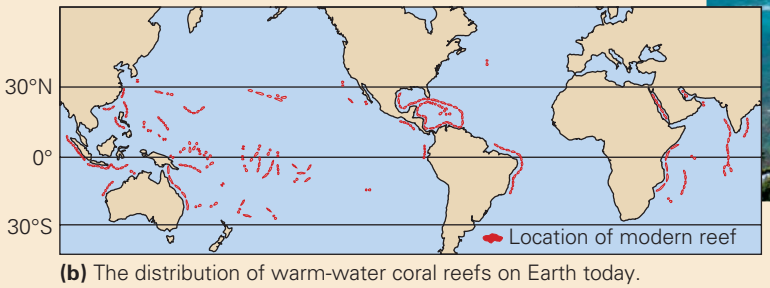
(b) A mangrove swamp in northeastern Brazil.

FIGURE 15.15 The character and evolution of coral reefs.

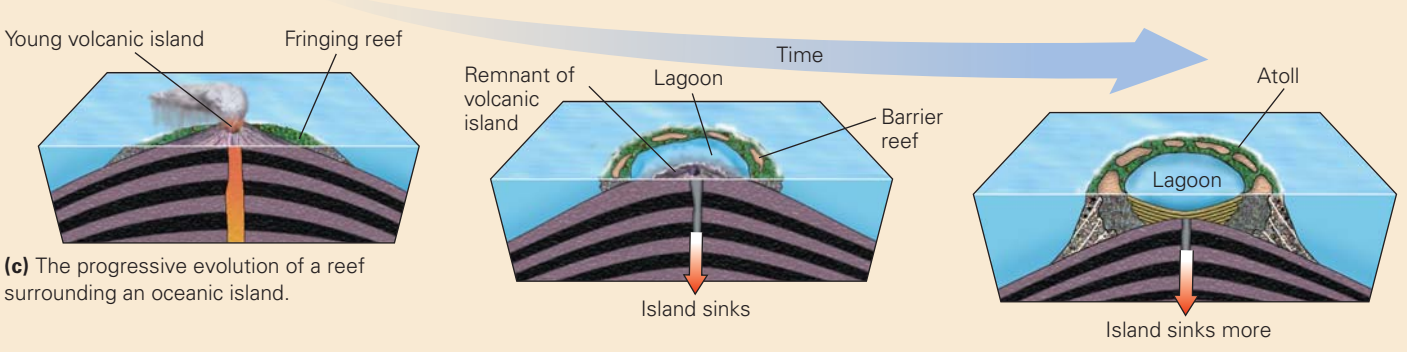


(a) The surface of this Hawaiian coral reef protects the shore from wave erosion. The underwater view emphasizes that a reef hosts a great variety of organisms.





(b) The distribution of warm-water coral reefs on Earth today.



(c) The progressive evolution of a reef surrounding an oceanic island.

and then later become barrier reefs and finally atolls. This progression reflects the continued growth of the reef as the island around which it formed gradually sinks. Eventually, the reef itself sinks too far below sea level to remain alive and becomes the cap of a flat-topped seamount known as a guyot.

Take-Home Message

Beaches form from wave-washed sediment; waves may build bars, and beach drift may produce spits. Rocky coasts evolve due to wave erosion, fjords are submerged glacial valleys, and estuaries are submerged river valleys. Some coasts host wetlands and reefs.

15.7 Causes of Coastal Variability

Plate Tectonic Setting

The tectonic setting of a coast plays a role in determining whether the coast has steep-sided mountain slopes or a broad plain that borders the sea (see **Geology at a Glance**, pp. 462–463). Along an active margin, compression squeezes the crust and pushes it up, creating mountains like the Andes along the western coast of South America. Along a passive margin, the cooling and sinking of the lithosphere may create a broad *coastal plain*, a flatland that merges with the continental shelf, as exists along the Gulf Coast and southeastern Atlantic coast of the United States.

Not all passive margins have coastal plains. The coastal areas of some passive margins were uplifted during the rifting event that preceded establishment of the passive margin. For example, highlands formed during rifting border the Red Sea and portions of the Brazilian and southern African coasts. Highlands also rise along the east coast of Australia.

Relative Sea-Level Changes

Sea level, relative to the land surface, changes during geologic time. Some changes develop due to vertical movement of the land. These may reflect plate-tectonic processes or the addition or removal of a load (such as a glacier) on the crust. Local changes in sea level may reflect human activity—when people pump out groundwater or oil, for example, the pores between grains in the sediment beneath the ground collapse, and the land surface sinks (see Chapter 16). Some relative sea-level changes, however, are due to a *global* rise or fall of the ocean surface. Such *eustatic sea-level changes* may reflect changes in the volume of mid-ocean ridges. An increase in the number or width of ridges, for example, displaces water and causes sea level to rise. Eustatic sea-level changes may also reflect changes in the volume of glaciers, for glaciers store water on land (**Fig. 15.16**). As glaciers grow, sea level falls, and as glaciers shrink, sea level rises.

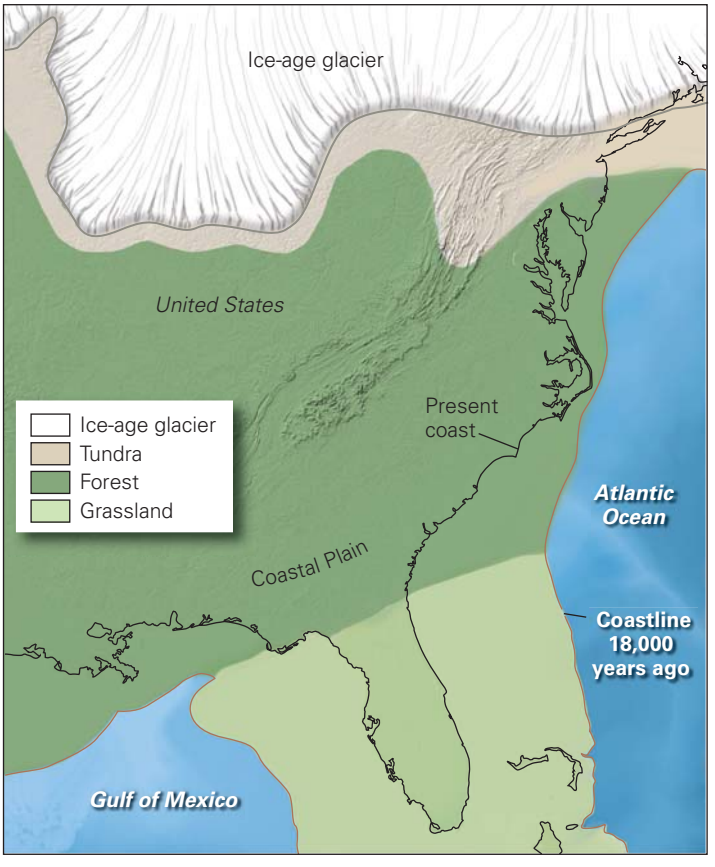
Geologists refer to coasts where the land is rising or rose relative to sea level as **emergent coasts**. At emergent coasts, steep slopes typically border the shore. A series of step-like terraces form along some emergent coasts (**Fig. 15.17a**). These terraces reflect episodic changes in relative sea level and/or ground uplift. Those coasts at which the land sinks relative to sea level become **submergent coasts** (**Fig. 15.17b**). At submergent coasts, landforms include estuaries and fjords that developed when the rising sea flooded coastal valleys.

Sediment Supply and Climate

The quantity and character of sediment supplied to a shore affects its character. That is, coastlines where the sea washes sediment away faster than it can be supplied (erosional coasts) recede landward and may become rocky, whereas coastlines that receive more sediment than erodes away (accretionary coasts) grow seaward and develop broad beaches.

Climate also affects the character of a coast. Shores that enjoy generally calm weather erode less rapidly than those constantly subjected to ravaging storms. A sediment supply large enough

FIGURE 15.16 Because of sea-level drop during the ice age, there was more dry land.



to generate an accretionary coast in a calm environment may be insufficient to prevent the development of an erosional coast in a stormy environment. The climate also affects biological activity along coasts. For example, in the warm water of tropical climates, mangrove swamps flourish along the shore, and coral reefs form offshore. The reefs may build into a broad carbonate platform such as appears in the Bahamas today. In cooler climates, salt marshes develop, whereas in arctic regions, the coast may be a stark environment of lichen-covered rock and barren sediment.

Take-Home Message

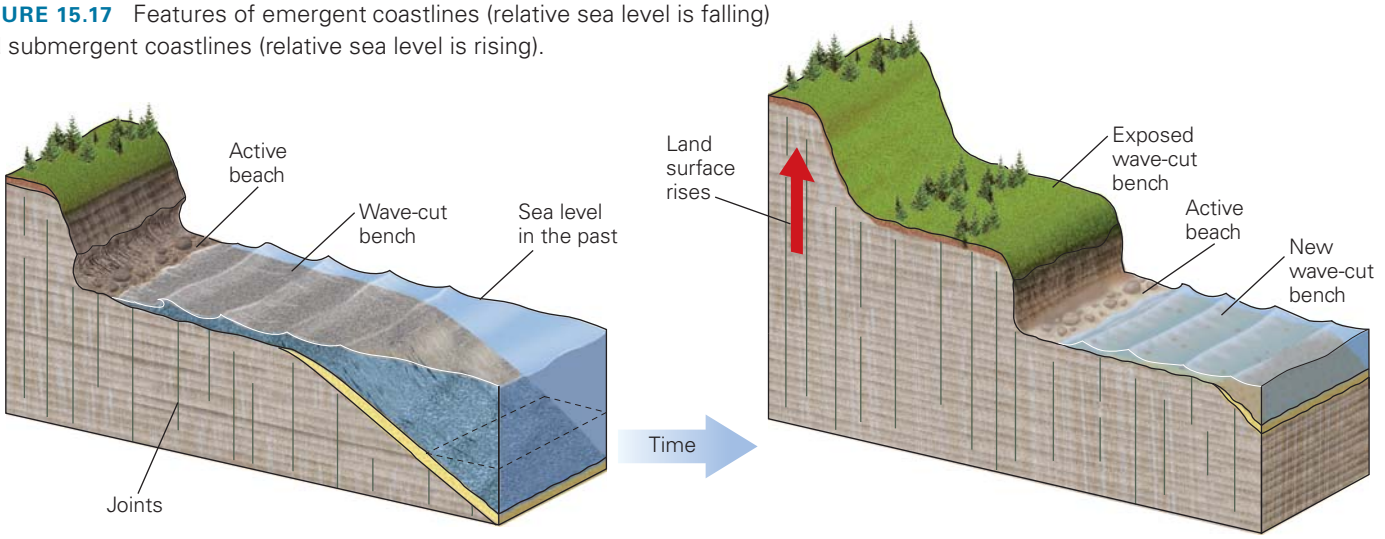
Tectonic activity and sediment supply influence the character of a coastline. At an emergent coast, land is rising relative to sea level, whereas at a submergent coast, it is sinking. Changing mid-ocean ridge and glacial volumes affect global sea level.

15.8 Coastal Problems and Solutions

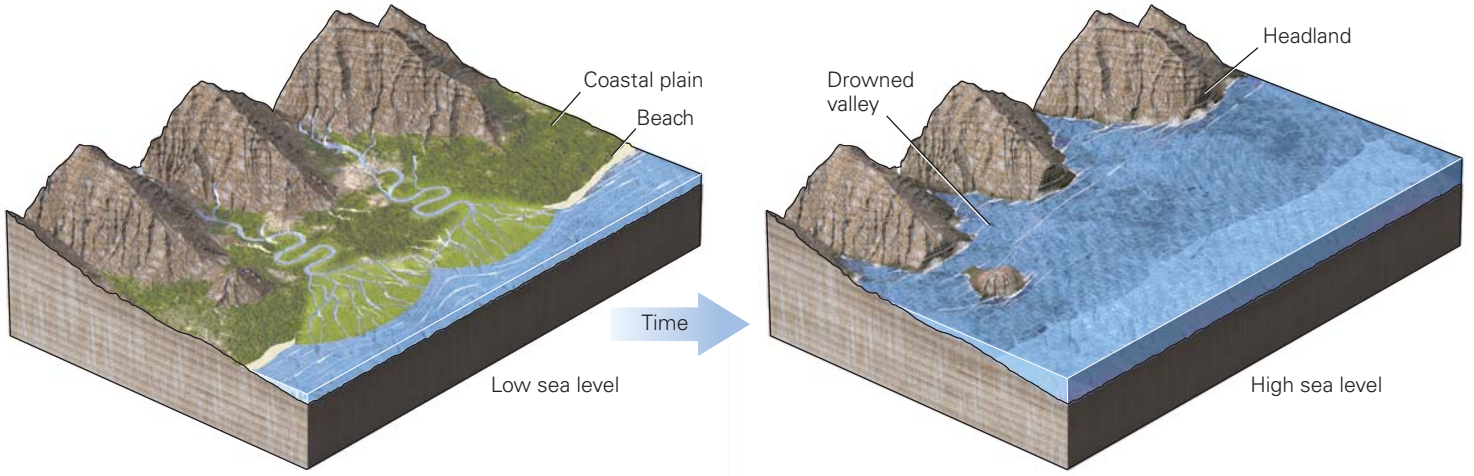
Contemporary Sea-Level Changes

People tend to view a shoreline as a permanent entity. But in fact, shorelines are ephemeral geologic features. On a time scale of hundreds to thousands of years, a shoreline moves inland or seaward depending on whether relative sea level rises or falls or whether sediment supply increases or decreases. In places where sea level is rising today, shoreline towns will eventually be submerged. For example, the Persian Gulf now covers about twice the area that it did 4,000 years ago. And if present rates of sea-level rise along the East Coast of the United States continue, major coastal cities such as Washington, New York, Miami, and Philadelphia may be inundated within the next millennium (Fig. 15.18).

FIGURE 15.17 Features of emergent coastlines (relative sea level is falling) and submergent coastlines (relative sea level is rising).



(a) *Emergent coasts*: Wave erosion produces a wave-cut bench along an emergent ooast. As the land rises, the bench becomes a terrace, and a new wave-cut bench forms.



(b) *Submergent coasts*: A coast before sea level rises. Rivers drain valleys and deposit sediment on a coastal plain. As a submergent coast forms, sea level rises and floods the valleys, and waves erode the headlands.

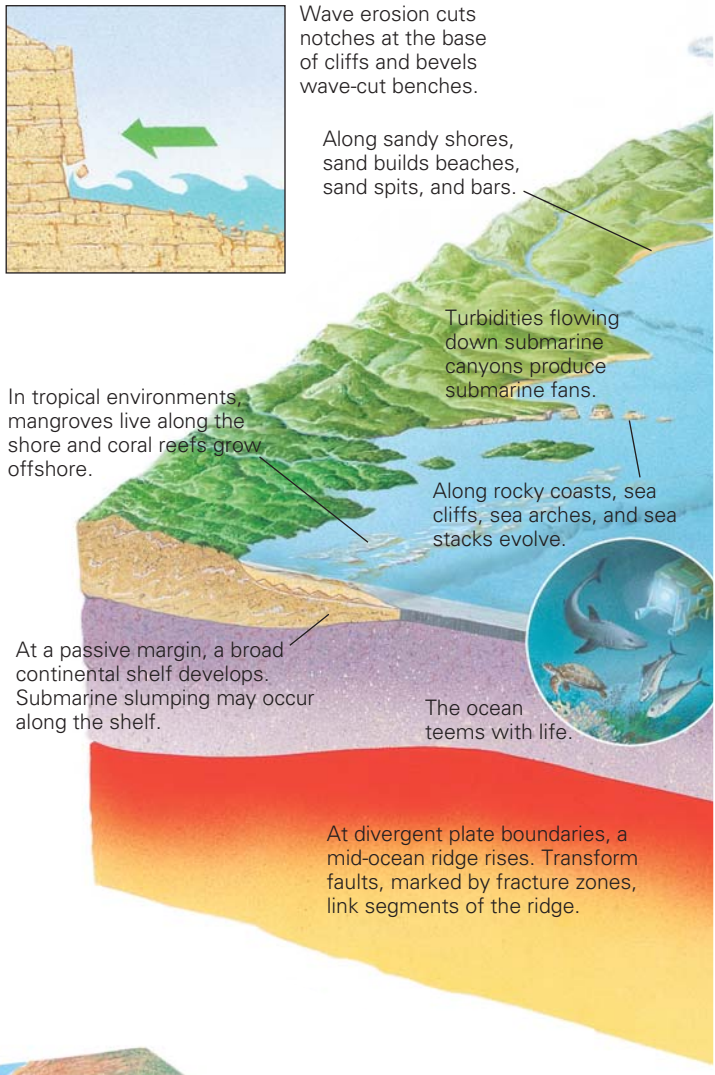
Oceans and Coasts

The oceans of the world host a diverse array of environments and landscapes, illustrating the complexity of the Earth System. Tectonic processes and surface processes working alone or in tandem generate unique features beneath the sea and along its coasts.

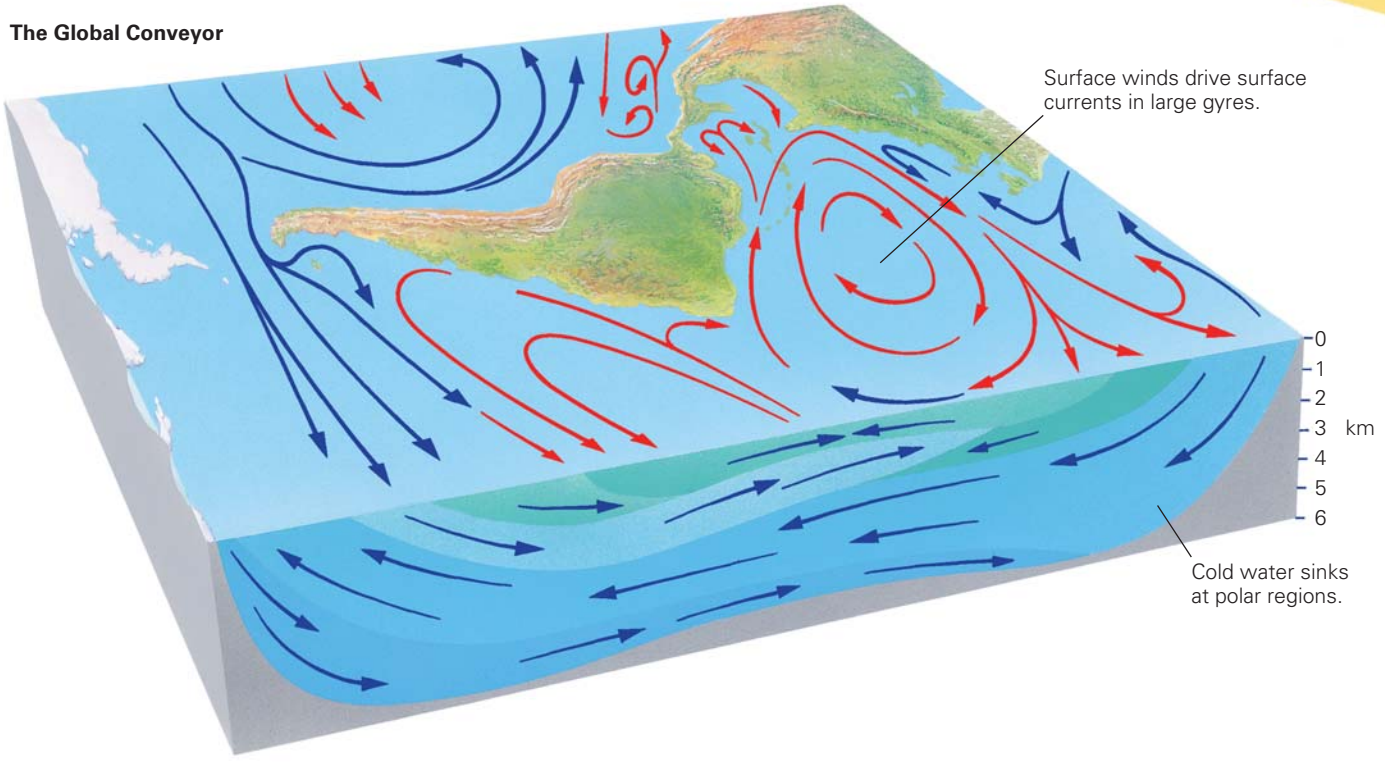
The major structures of the ocean floor are the result of plate-tectonic activity. For example, mid-ocean ridges define divergent boundaries, fracture zones form along transform faults, and trenches mark subduction zones. Oceanic islands, seamounts, and plateaus build above hot spots. Along passive continental margins, broad continental shelves develop, locally incised by submarine canyons, as sediment buries stretched continental lithosphere. Along convergent margins, accretionary prisms and volcanic arcs grow.

Within the ocean, currents circulate water due to regional variations in both water salinity and temperature (factors that control density) and to the traction between wind and the water surface. Tides cause sea level to rise and fall, and wind builds waves that churn the sea surface, erode shorelines, and transport sediment.

Coastal landscapes reflect variations in sediment supply, relative sea-level rise or fall, and climate. For example, where the supply of sediment is low and the landscape is rising relative to sea level, rocky shores with dramatic cliffs and sea stacks may evolve. Where sediment is abundant, sandy beaches and bars develop. Regions where glaciers carved deep valleys now feature spectacular fjords. Protected coastal areas, especially those in warm climates, host unique coastal ecosystems inhabited by grasses, mangroves, and/or corals. Corals may contribute to growth of broad reefs along the shore. Human activities can significantly affect coastal landscape.



The Global Conveyor



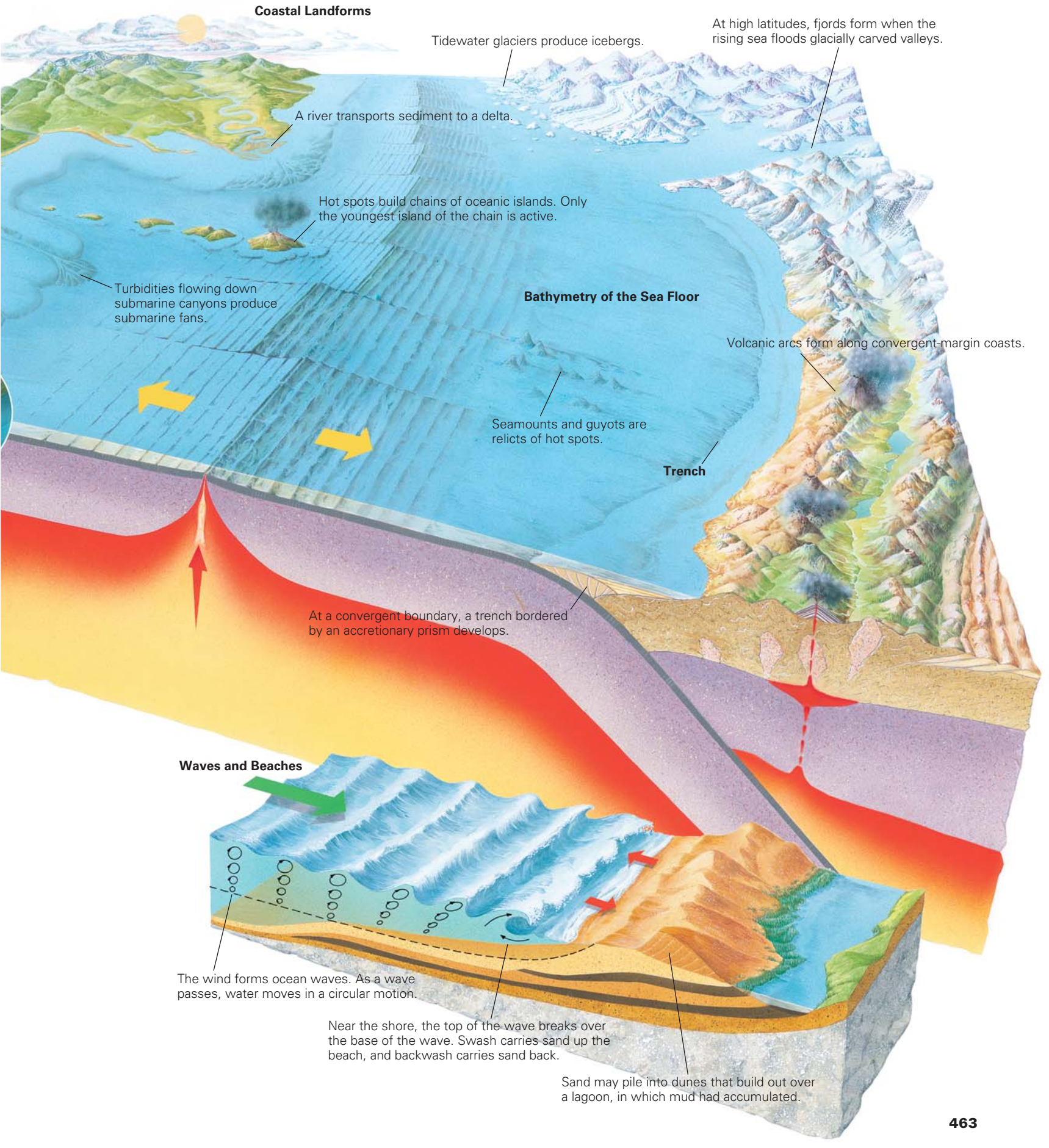

Coastal Landforms
Tidewater glaciers produce icebergs.
At high latitudes, fjords form when the rising sea floods glacially carved valleys.
A river transports sediment to a delta.
Hot spots build chains of oceanic islands. Only the youngest island of the chain is active.
Turbidities flowing down submarine canyons produce submarine fans.
Bathymetry of the Sea Floor
Volcanic arcs form along convergent-margin coasts.
Seamounts and guyots are relicts of hot spots.
Trench
At a convergent boundary, a trench bordered by an accretionary prism develops.
Waves and Beaches
The wind forms ocean waves. As a wave passes, water moves in a circular motion.
Near the shore, the top of the wave breaks over the base of the wave. Swash carries sand up the beach, and backwash carries sand back.
Sand may pile into dunes that build out over a lagoon, in which mud had accumulated.

FIGURE 15.18 Future sea-level rise, due to melting of polar ice, would flood many coastal cities.



FIGURE 15.19 Examples of beach erosion.



(a) When Hurricane Ike hit Galveston, Texas, in September 2008, many beachfront homes were washed away.

Beach Destruction—Beach Protection?

In a matter of hours, a storm—especially a hurricane—can radically alter a landscape that took centuries or millennia to form. The backwash of storm waves sweeps vast quantities of sand seaward, leaving the beach a skeleton of its former self. The surf submerges barrier islands and shifts them toward the lagoon. Waves and wind together rip out mangrove swamps and salt marshes and break up coral reefs, thereby destroying the organic buffer that can protect a coast, leaving it vulnerable to erosion for years to come. Of course, major storms also destroy human constructions: erosion undermines shoreside buildings, causing them to collapse into the sea; wave impacts smash buildings to bits; and the storm surge—very high water levels created when storm winds push water toward the shore—floats buildings off their foundations (**Fig. 15.19a, b**).

But even less-dramatic events, such as the loss of river sediment, a gradual rise in sea level, a change in the shape of a shoreline, or the destruction of coastal vegetation, can alter the balance between sediment accumulation and sediment removal on a beach, leading to beach erosion. In some places, beaches retreat landward at rates of 1 to 2 m per year.

In many parts of the world, beachfront property has great value; but if a hotel loses its beach sand, it probably won't stay in business. Similarly, a harbor can't function if its mouth gets blocked by sediment. Thus property owners often construct artificial barriers to alter the natural movement of sand along the coast, sometimes with undesirable results. For example, beach-front property owners may build groins, concrete or stone walls protruding perpendicular to the shore, to prevent beach drift from removing sand (**Fig. 15.20a**). Sand accumulates on the updrift side of the groin, forming a long triangular wedge, but sand erodes

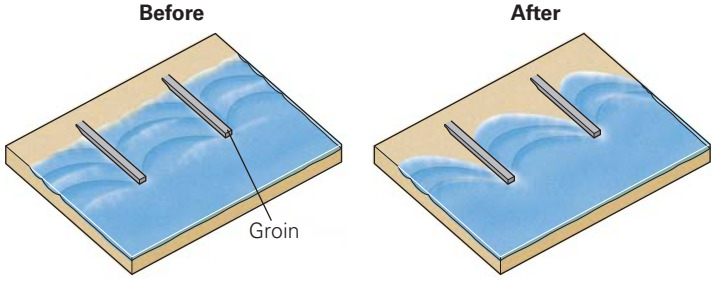


(b) Wave erosion has completely removed the beach, and has started to erode a beach cliff, along the coast of Cape Cod.

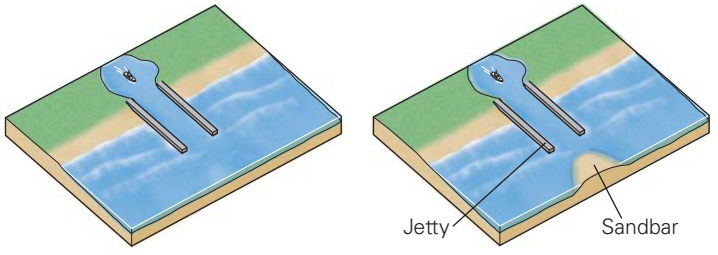
away on the downdrift side. Needless to say, the property owner on the downdrift side doesn't appreciate this process. Harbor engineers may build a pair of walls called jetties to protect the entrance to a harbor (Fig. 15.20b). But jetties erected at the mouth of a river channel effectively extend the river into deeper water and thus may lead to the deposition of an offshore sandbar. Engineers may also build an offshore wall called a breakwater, parallel or at an angle to the beach, to prevent the full force of waves from reaching a harbor. With time, however, sand builds up in the lee of the breakwater and the beach grows seaward, clogging the harbor (Fig. 15.20c). To protect expensive shoreside construction, people build seawalls out of riprap (large stone or concrete blocks) or reinforced concrete on the landward side of the beach (Fig. 15.20d), but during a storm, these can be undermined.

In some places, people have given up trying to decrease the rate of beach erosion and instead have worked to increase the rate of sediment supply. To do this, they pump sand from farther offshore, or truck in sand from elsewhere to replenish a beach. This procedure, called beach nourishment, can be hugely expensive and at best provides only a temporary fix, for the backwash and beach drift that removed the sand in the first place continue unabated as long as the wind blows and the waves break.

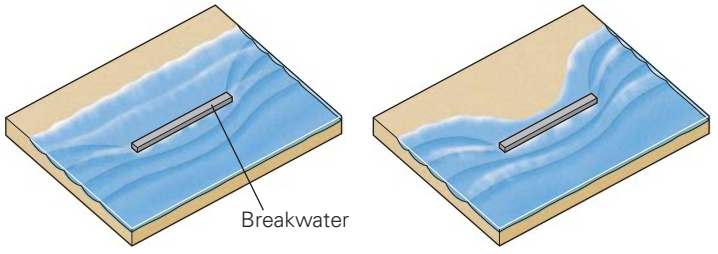
FIGURE 15.20 Techniques used to preserve beaches.



(a) The construction of groins may produce a sawtooth beach.



(b) Jetties extend a river farther into the sea, but may cause a sandbar to form at the end of the channel.



(c) A beach may grow seaward behind a breakwater.

Destruction of Wetlands and Reefs

Bad cases of beach pollution create headlines. Because of beach drift, garbage dumped in the sea in an urban area may drift along the shore and be deposited on a tourist beach far from its point of introduction. Oil spills, from ships that flush their bilges or from tankers that have run aground or foundered in stormy seas, or from offshore well leaks, have contaminated shorelines at several places around the world.

The influx of nutrients, from sewage and agricultural runoff, into coastal waters can create dead zones along coasts. A *dead zone* is a region in which water contains so little oxygen that fish and other organisms within it die. Dead zones form when the concentration of nutrients rises enough to stimulate an algae bloom, for overnight respiration by algae depletes dissolved oxygen in the water, and the eventual death and decay of plankton depletes oxygen even more. One of the world's largest dead zones occurs in the Gulf of Mexico, offshore of the Mississippi River's mouth.

Coastal wetlands and coral reefs are particularly susceptible to changes in the environment, and many of them have been destroyed in recent decades. Their loss both increases a coast's vulnerability to erosion and, because they provide spawning grounds for marine organisms, disrupts the global food chain. Destruction of wetlands and reefs happens for many reasons. Wetlands have been filled or drained to be converted to farmland, housing developments, resorts, or garbage dumps. Reefs have been destroyed by boat anchors, dredging, the activities of divers, dynamite explosions intended to kill fish, and quarrying operations intended to obtain construction materials. Chemicals and particulates entering coastal water from urban, industrial, and agricultural areas can cause havoc in wetlands and reefs, for these materials cloud water and/or trigger algal blooms, killing filter-feeding organisms. Toxic chemicals in



(d) Riprap will slow erosion of a parking lot along a California beach.

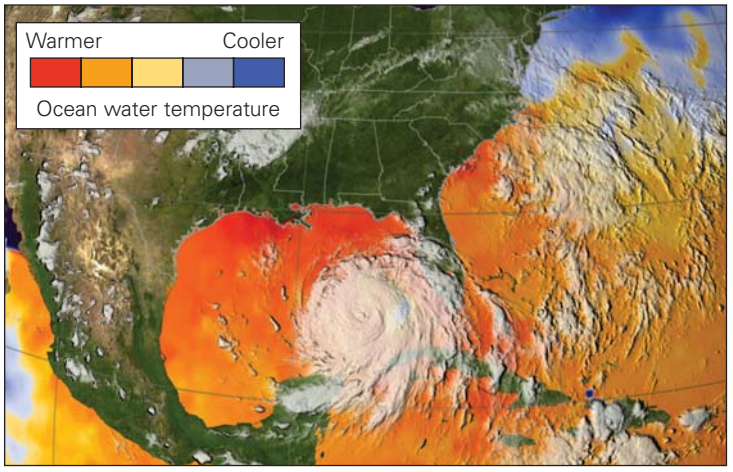
such runoff can also poison plankton and burrowing organisms and, therefore, other organisms progressively up the food chain.

Global climate change also impacts the health of organic coasts (see Chapter 19). For example, transformation of once vegetated regions into deserts means that the amount of dust carried by winds from the land to the sea has increased. This dust can interfere with coral respiration and can bring dangerous viruses. A global increase in seawater temperature may be contributing to *reef bleaching*, the loss of coral color due to the death of the algae that live in coral polyps. The statistics of wetland and reef destruction worldwide are frightening—ecologists estimate that between 20% and 70% of wetlands have already been destroyed, and along some coasts, 90% of reefs have died.

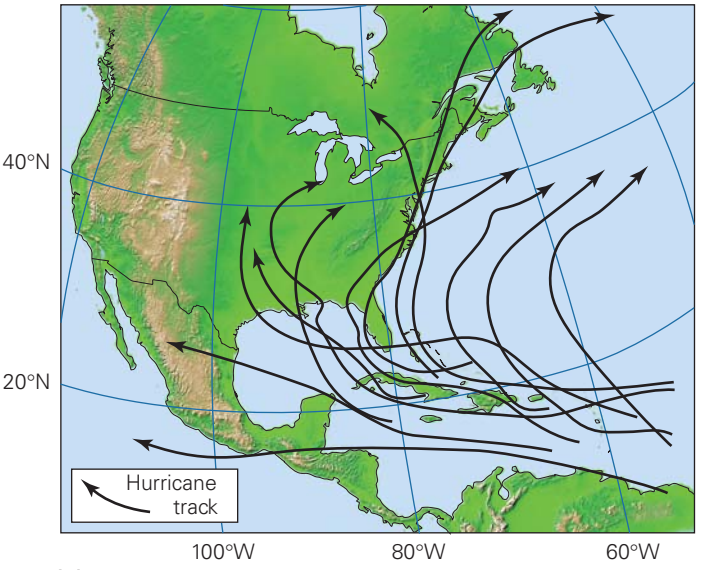
Hurricanes—A Coastal Calamity

Global-scale convection of the atmosphere, influenced by the Coriolis effect, causes currents of warm air to flow steadily from east to west in tropical latitudes. As the air flows over the ocean, it absorbs moisture. Because air becomes less dense as it gets warmer, tropical air eventually begins to rise like a balloon. As the air rises, it cools, and the water vapor it contains condenses to form clouds (mists of very tiny water droplets). If the air contains sufficient moisture, the clouds grow into a cluster of large thunderstorms, which consolidate to form a single, very large storm. Because of the Coriolis effect, this large storm evolves into a rotating swirl called a tropical disturbance. If the disturbance remains over warm ocean water, as can happen in late summer and early fall, rising warm moist air

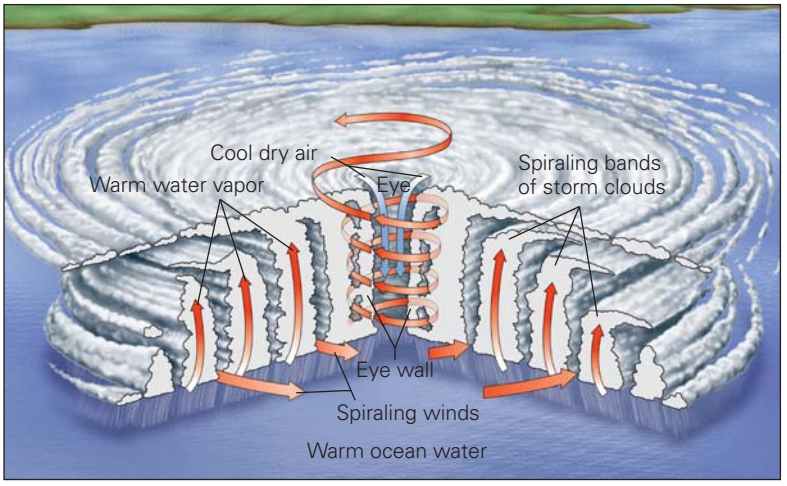
FIGURE 15.21 Characteristics and paths of hurricanes in the western North Atlantic.



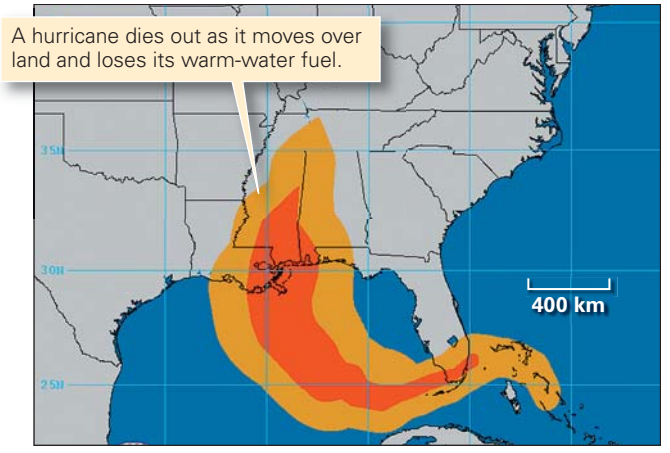
(a) A 2005 satellite photograph of Hurricane Katrina entering the Gulf of Mexico, where very warm waters fed the storm.



(b) Tracks of several Atlantic hurricanes show how most drift westward, then northward.



(c) In this cutaway drawing, we can see the spirals of clouds, the eye, and the eye wall of a hurricane. Dry air descends in the eye.



(d) A wind-swath map of Hurricane Katrina. Red areas represent hurricane winds; orange areas represent tropical-storm winds.

continues to feed the storm, fostering more growth. Eventually a spiral of rapidly circulating clouds forms, and the tropical disturbance becomes a tropical depression. Additional nourishment causes the tropical depression to spin even faster and grow broader, until it becomes a tropical storm and receives a name. If a tropical storm becomes powerful enough, it becomes a tropical cyclone. Formally defined, a *tropical cyclone* is a huge rotating storm, which forms in tropical latitudes, and in which winds exceed 119 km per hour (74 mph). It resembles a giant counterclockwise spiral of clouds—300 to 1,500 km (930 miles) wide—when viewed from space (**Fig. 15.21a**). Such a storm is called a **hurricane** in the Atlantic and eastern Pacific, a typhoon in the western Pacific, and simply a cyclone around Australia and in the Indian Ocean.

Atlantic hurricanes generally form in the ocean to the east of the Caribbean Sea, though some form in the Caribbean itself. They first drift westward at speeds of up to 60 km per hour (37 mph). They may eventually turn north and head into the North Atlantic or into the interior of North America, where they die when they run out of a supply of warm water (**Fig. 15.21b**). Weather researchers classify the strength of hurricanes using the Saffir-Simpson scale, which runs from 1 to 5; somewhat different scales are used for typhoons and cyclones. On the Saffir-Simpson scale, a Category 5 hurricane has sustained winds of ≥250 km/hr (≥156 mph). The highest wind speed ever recorded during a hurricane was in excess of 300 km/hr.

A typical hurricane (or typhoon or cyclone) consists of several spiral arms extending inward to a central zone of relative calm known as the hurricane's *eye* (**Fig. 15.21c**). A rotating vertical cylinder of clouds, the eye wall, surrounds the eye. Winds spiral toward the eye, so like an ice skater who spins faster when she brings her arms inward, the winds accelerate toward the interior of the storm and are fastest along the eye wall. Thus, hurricane-force winds affect a belt that is only 15% to 35% as wide as the whole storm (**Fig. 15.21d**). On the side of the eye where winds blow in the same direction as the whole storm is moving, the ground speed of winds is greatest, because the storm's overall speed adds to the rotational motion.

Hurricanes pose extreme danger in the open ocean, because their winds cause huge waves to build, and thus have led to the foundering of countless ships. They also cause havoc in coastal regions, and even inland, though they die out rapidly after moving onshore. The coastal damage happens for several reasons:

- *Wind*: Winds of weaker hurricanes tear off branches and smash windows. Stronger hurricanes uproot trees, rip off roofs, and collapse walls.
- *Waves*: Winds shearing across the sea surface during a hurricane generate huge waves. In the open ocean, these waves can capsize ships. Near shore, waves batter and erode beaches, rip boats from moorings, and destroy coastal property.
- *Storm surge*: Rising air in a hurricane causes a region of extremely low air pressure beneath. This decrease in pressure causes the surface of the sea to bulge upward over an area with a diameter of 60 to 80 km. Sustained winds blowing in an onshore direction build this bulge even higher. When the hurricane reaches the coast, the bulge of water, or storm surge, swamps the land. If the bulge hits the land at high tide, the sea surface will be especially high and will affect a broader area.
- *Rain, stream flooding, and landslides*: Rain drenches the Earth's surface beneath a hurricane. In places, half a meter or more of rain falls in a single day. Rain causes streams to flood, even far inland, and can trigger landslides.
- *Disruption of social structure*: When the storm passes, the hazard is not over. By disrupting transportation and communication networks, breaking water mains, and washing away sewage-treatment plants, hurricane damage creates severe obstacles to search and rescue, and can lead to the spread of disease, fire, and looting.

Nearly all hurricanes that reach the coast cause death and destruction, but some are truly catastrophic. Storm surge from a 1970 cyclone making landfall on the low-lying delta lands of Bangladesh led to an estimated 500,000 deaths. In 1992, Hurricane Andrew leveled extensive areas of southern Florida, causing over $30 billion in damage and leaving 250,000 people homeless. Hurricane Katrina, in 2005, stands as the most destructive hurricane to strike the United States. Let's look at this storm's history.

Hurricane Katrina

Tropical Storm Katrina came into existence over the Bahamas and headed west. Just before landfall in southeastern Florida, winds strengthened and the storm became Hurricane Katrina. This hurricane sliced across the southern tip of Florida, causing several deaths and millions of dollars in damage. It then entered the Gulf of Mexico and passed directly over the Loop Current, an eddy of summer-heated water from the Caribbean that had entered the Gulf of Mexico. Water in the Loop Current reaches temperatures of 32°C (90°F), and thus stoked the storm, injecting it with a burst of energy sufficient for the storm to morph into a Category 5 monster whose swath of hurricane-force winds reached a width of 325 km (200 miles). When it entered the central Gulf of Mexico, Katrina turned north and began to bear down on the Louisiana-Mississippi coast. The eye of the storm passed just east of New Orleans, and then across the coast of Mississippi. Storm surges broke records, in places rising 7.5 m (25 feet) above sea level, and they washed coastal communities off the

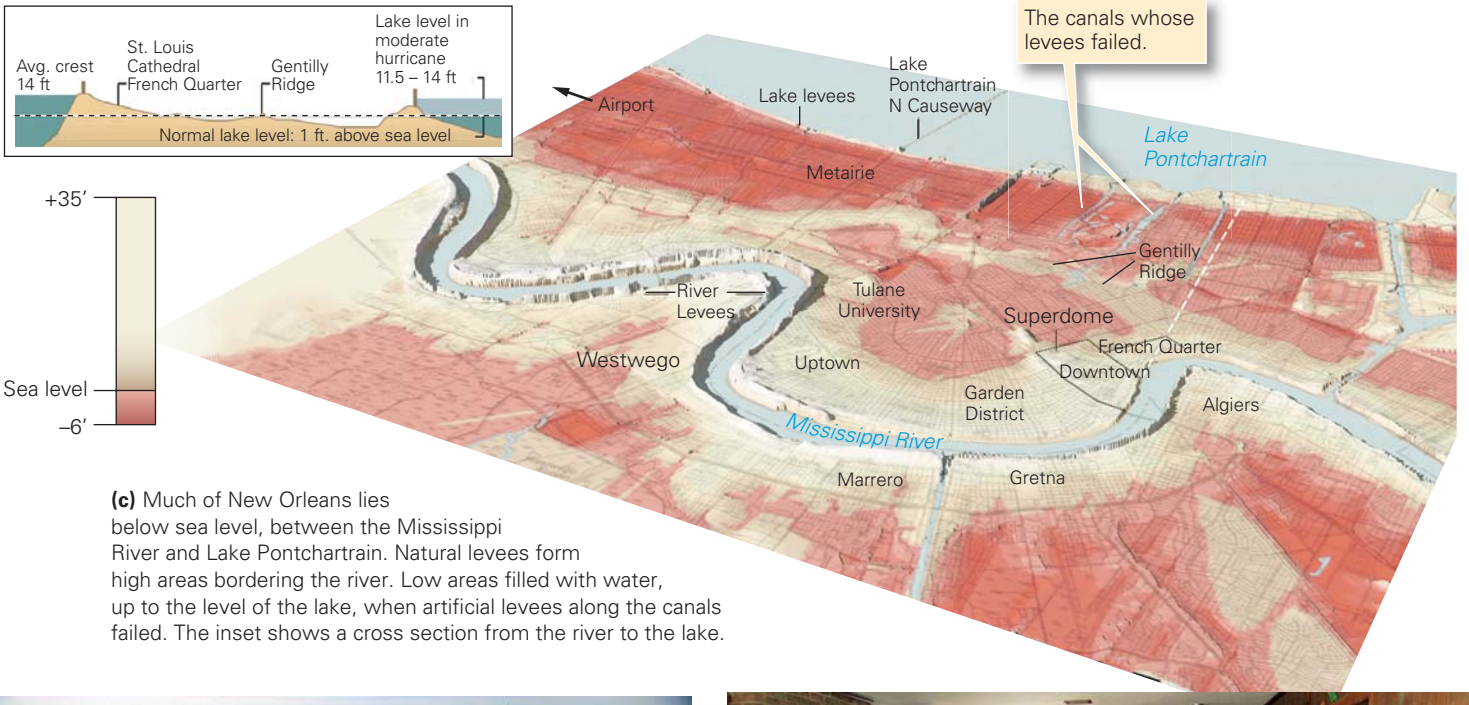
FIGURE 15.22 The devastation of coastal areas by Hurricane Katrina.



(a) Surge from the storm destroyed homes along the Alabama coast.



(b) Officials survey the storm damage.



(c) Much of New Orleans lies below sea level, between the Mississippi River and Lake Pontchartrain. Natural levees form high areas bordering the river. Low areas filled with water, up to the level of the lake, when artificial levees along the canals failed. The inset shows a cross section from the river to the lake.



(d) Water flowing across the levees bordering the 17th Street Canal after the hurricane had passed.



(e) The flooded interior of a New Orleans home.

map along a broad swath of the Gulf Coast (Fig. 15.22a, b). In addition to the devastating wind and surge damage, Katrina led to the drowning of New Orleans.

To understand what happened to New Orleans, we must consider the city's geologic history. New Orleans grew on the Mississippi Delta, between the banks of the Mississippi River on the south and Lake Pontchartrain (actually a bay of the Gulf of Mexico) on the north. The older parts of the town grew up on the relatively high land of the Mississippi's natural levee. Younger parts of the city, however, spread out over the topographically lower delta plain. As decades passed, people modified the surrounding delta landscape by draining wetlands, by constructing artificial levees that confined the Mississippi River, and by extracting groundwater. Sediment beneath the delta compacted, and the delta's surface has been starved of new sediment, so large areas of the delta sank below sea level. Today, most of New Orleans lies in a bowl-shaped depression as much as 2 m (7 feet) below sea level—the hazard implicit in this situation had been recognized for years (Fig. 15.22c).

The winds of Hurricane Katrina ripped off roofs, toppled trees, smashed windows, and triggered the collapse of weaker buildings, but their direct consequences were not catastrophic. However, when the winds blew storm surge into Lake Pontchartrain, its water level rose beyond most expectations and pressed against the system of artificial levees and flood walls that had been built to protect New Orleans. Hours after the hurricane eye had passed, the high water of Lake Pontchartrain found a weakness along the floodwall bordering a drainage canal and pushed out a section. Breaks eventually formed in a few other locations as well. So, a day after the hurricane was over, New Orleans began to flood. As the water line climbed the walls of houses, brick by brick, residents fled first upstairs, then to their attics, and finally to their roofs. Water spread across the city until the bowl of New Orleans filled to the same level as Lake Pontchartrain, submerging 80% of the city (Fig. 15.22d)

Floodwaters washed some houses away and filled others with debris (Fig. 15.22e). The disaster took on national significance, as the trapped population sweltered without food, drinking water, or adequate shelter. With no communications, no hospitals, and few police, the city almost descended into anarchy. It took days for outside relief to reach the city, and by then, many had died and parts of New Orleans, a cultural landmark and major port, had become uninhabitable.

Take-Home Message

Coastal landscapes can be impacted by human activities or climate change. Beaches and bars erode, pollution destroys wetlands, and hurricanes ravage the landscape. People try to protect beaches by constructing barriers or replenishing sand, but this can lead to other problems.



ANOTHER VIEW The Great Barrier Reef forms shoals off the coast of northeastern Australia. It is the largest reef on Earth.

CHAPTER 15 REVIEW

Chapter Summary

- The landscape of the sea floor depends on the character of the underlying crust. Wide continental shelves form over passive-margin basins. Continental shelves are cut by submarine canyons. Abyssal plains develop on old, cool oceanic lithosphere. Seamounts form above hot spots.
- The salinity, temperature, and density of seawater vary with location and depth.
- Water in the oceans circulates in currents. Surface currents are driven by the wind and are deflected by the Coriolis effect. The vertical upwelling and downwelling of water create deep currents. Some of this movement is thermohaline circulation.
- Tides—the daily rise and fall of sea level—are caused by a tide-generating force. The largest contribution to this force comes from the gravitational pull of the Moon.
- Waves are caused by friction where the wind shears across the surface of the ocean. Water particles follow a circular motion in a vertical plane as a wave passes. Waves refract (bend) when they approach the shore because of frictional drag with the sea floor.
- Sand on beaches moves with the swash and backwash of waves. If there is a longshore current, the sand gradually moves along the beach and may build spits.
- At rocky coasts, waves grind away at rocks, yielding such features as wave-cut benches and sea stacks. Some shores are wetlands, where marshes or mangrove swamps grow. Coral reefs grow along coasts in warm, clear water.
- The differences in coasts reflect their tectonic setting, whether sea level is rising or falling, sediment supply, and climate.
- To protect beach property, people build groins, jetties, breakwaters, and seawalls.
- Human activities have led to the pollution of coasts. Reef bleaching has become dangerously widespread.
- Hurricanes produce winds of between 119 and 300 km per hour. The force of the winds, along with storm surge and heavy rains, can destroy coastal areas.

Key Terms

abyssal plain (p. 446)
backwash (p. 453)
barrier island (p. 456)
bathymetry (p. 446)
beach (p. 454)
coast (pp. 445, 454)
coastal wetland (p. 457–458)
continental shelf (p. 446)
coral reef (p. 458)
Coriolis effect (p. 449)
current (p. 449)
emergent coast (p. 460)
estuary (p. 456)
fjord (p. 457)
gyre (p. 450)
hurricane (p. 467)
lagoon (p. 456)
longshore current (p. 453)
longshore drift (p. 453)
offshore bar (p. 456)
rogue wave (p. 453)
salinity (p. 449)
sand spit (p. 456)
seamount (p. 448)
sea stack (p. 456)
submarine canyon (p. 447)
submergent coast (p. 460)
swash (p. 453)
thermocline (p. 449)
thermohaline circulation (p. 451)
tidal reach (p. 451)
tide (p. 451)
wave base (p. 452)
wave-cut bench (p. 456)
wave-cut notch (p. 456)
wave refraction (p. 453)

Review Questions

1. How much of the Earth's surface is covered by oceans? What proportion of the world's population lives near a coast?
2. How does the lithosphere beneath a passive margin differ from that beneath an abyssal plain?
3. How do the shelf and slope of an *active* continental margin differ from those of a *passive* margin?
4. Where does the salt in the ocean come from? How do the salinity and temperature in the ocean vary?
5. What factors control the direction of surface currents in the ocean? What is the Coriolis effect, and how does it affect oceanic circulation? Explain thermohaline circulation.
6. What causes the tides? Why do the range and reach of tides vary with location?
7. Describe the motion of water molecules in a wave. How does wave refraction cause longshore currents?
8. Describe the components of a beach profile. How does beach sand migrate as a result of longshore currents?
9. Describe how rocky coasts evolve.
10. What is an estuary? Why is it such a delicate ecosystem? What is the difference between an estuary and a fjord?
11. Discuss the different types of coastal wetlands. Describe the different kinds of reefs, and how a reef surrounding an oceanic island changes with time.

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- An animation-based exercise on longshore drift.
- A video-based exercise showing sea surface currents and temperature.
- A What a Geologist Sees exercise that helps students calculate wave base depth.

12. How do plate tectonics, sea-level changes, sediment supply, and climate change affect the shape of a coastline? Explain the difference between emergent and submergent coasts.
13. In what ways do people try to modify or "stabilize" coasts? How do the actions of people threaten coastal areas?
14. Where do hurricanes form, and how can they affect coasts?

On Further Thought

15. In 1789, the crew of the HMS *Bounty* mutinied. Near Tonga, in the Friendly Islands (approximately 20°S and 175°W), the crew forced the ship's commanding officer, Lieutenant Bligh, along with those crewmen who remained loyal to Bligh, into a rowboat and set them adrift in the Pacific Ocean. The castaways, amazingly, survived; 47 days later, they landed at Timor (near Sumatra), 6,700 km to the west. Why did they end up where they did?

SEE FOR YOURSELF 0. . . Oceans and Coastlines

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet 0 of our **Geotours Workbook**.



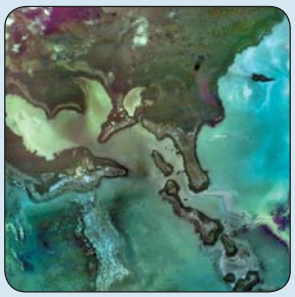
Coral Reefs, Pacific
Latitude 16°47′26.92″S,
Longitude 150°58′1.27″W

From 20 km, you can see the fringing reef of Huahine. Waves break on the outer edge of the reef, coral buildups lie beneath the surface, and sand partially fills the lagoon. The island itself represents the subsiding remnants of a hot-spot volcano.



Groins of Chicago's shore
Latitude 41°54′59.76″N,
Longitude 87°37′36.41″W

From 2 km elevation, you see the sandy beaches that fringe the coastline of Lake Michigan. Waves strike the shore obliquely. As a result, beach drift carries sand southwards. The city constructed a series of groins, in an attempt to prevent beach erosion.



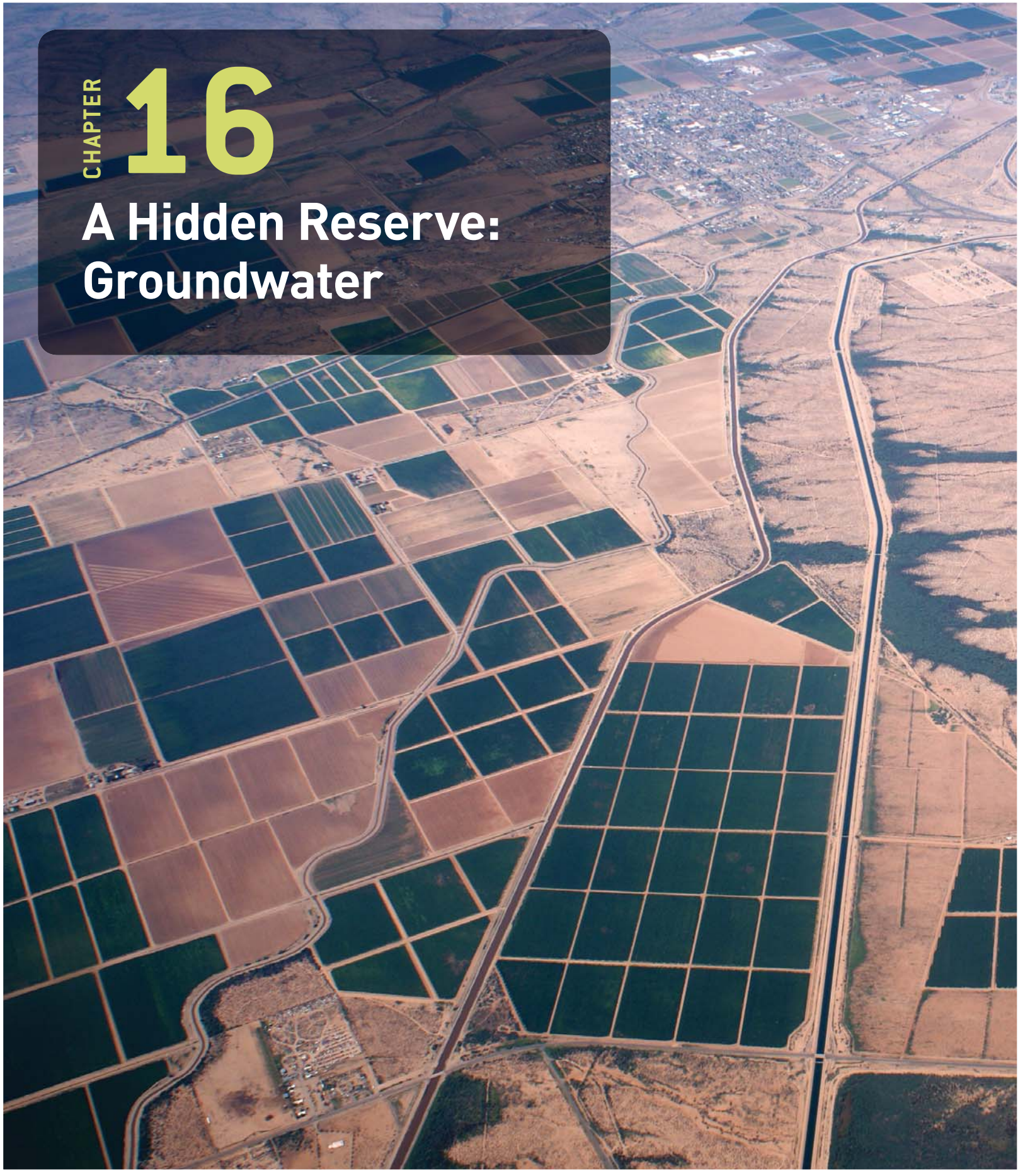
Organic Coast, Florida
Latitude 28°8′51.24″N,
Longitude 80°42′32.53″W

Along Florida's southern coast, thickets of mangroves (viewed from 8 km) line the shore and separate swamps from the sea. The roots of these trees protect the coast from wave erosion.



Fjords of Norway
Latitude 60°53′56.09″N,
Longitude 5°12′31.84″E

During the last ice age, glaciers carved deep, steep-sided valleys into the mountains of western Norway. When the glaciers melted and sea level rose, the valleys filled with water, forming the fjords we can now see from 80 km.



CHAPTER 16

A Hidden Reserve: Groundwater



The land that is now a checkerboard of fields near Phoenix, Arizona, once looked like the desert on the right. Groundwater, along with water brought from a river by the canal, keeps the fields green.

Chapter Objectives

By the end of this chapter, you should know . . .

- what groundwater is, where it comes from, and the factors controlling its flow.
- the difference between porosity and permeability.
- the difference between aquifers and aquitards, and the nature of the water table.
- the various types of wells and springs that provide access to groundwater.
- how hot springs and geysers originate.
- how groundwater supplies can be damaged or depleted, and how to address these problems.
- how caves and karst landscapes originate and evolve.

When the rain falls and enters the earth, when a pearl drops into the depth of the sea, you can dive in the sea and find the pearl, you can dig in the earth and find the water.

—Mei Yao-ch'en (Chinese poet, 1002–1060)

16.1 Introduction

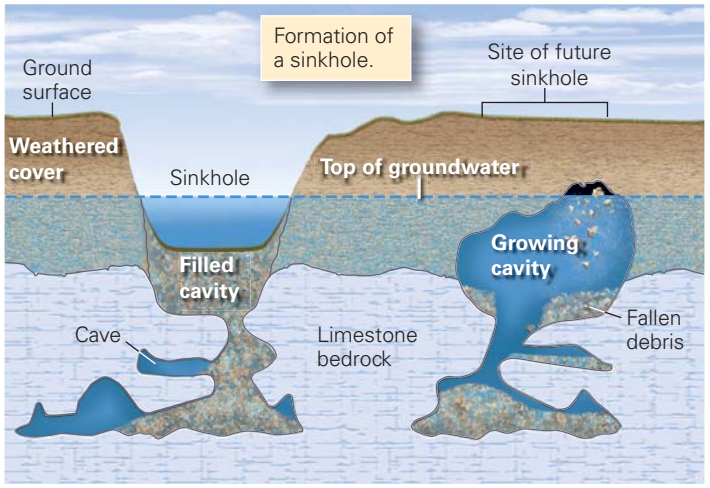
Imagine Mae Rose Owens's surprise when, on May 8, 1981, she looked out her window and discovered that a large sycamore tree in the backyard of her Winter Park, Florida, home had suddenly disappeared. It wasn't a particularly windy day, so the tree hadn't blown over—it had just vanished! When Owens went outside to investigate, she found that more than the tree had disappeared. Her whole backyard had become a deep, gaping pit. The pit continued to grow for a few days until finally it swallowed Owens's house and six other buildings, as well as the municipal swimming pool, part of a road, and several expensive Porsches in a car dealer's lot (**Fig. 16.1a**).

What had happened in Winter Park? The bedrock beneath the town consists of limestone, a fairly soluble rock. Water had gradually dissolved the limestone, carving open rooms, or caverns, underground. On May 8, the roof of a cavern underneath Owens's backyard began to collapse, forming a circular depression called a **sinkhole** (**Fig. 16.1b**). The sycamore tree and the rest of the neighborhood simply dropped down into the sinkhole. It would have taken too much effort to fill in the sinkhole with soil, so the community allowed it to fill with water, and now it's a circular lake, the centerpiece of a pleasant municipal park.

FIGURE 16.1 Development of sinkholes in central Florida.



(a) The Winter Park sinkhole, as seen from a helicopter.



(b) As overburden slowly washes into underlying caves, a cavity forms. When the roof of this cavity collapses, a sinkhole forms (not to scale).



(c) An airplane view of Florida sinkholes that have become lakes.

Similar lakes appear throughout central Florida (**Fig. 16.1c**), and elsewhere worldwide.

The Winter Park sinkhole is one of the more dramatic reminders that significant quantities of water reside underground. This water, which occupies the cracks and other openings in between the solid components of rock or sediments, or occurs in underground lakes or streams, is called **groundwater**. Though we can easily see Earth's surface water (in lakes, rivers, streams, marshes, glaciers, and oceans) and atmospheric water (in clouds and rain), groundwater lies hidden beneath the surface. Nevertheless, groundwater accounts for about two-thirds of the Earth's freshwater resources used by homes, agriculture, and industry. In this chapter, we examine where subsurface water comes from, how it flows, and how it interacts with rock and sediment.

16.2 Where Does Groundwater Reside?

The Underground Reservoir

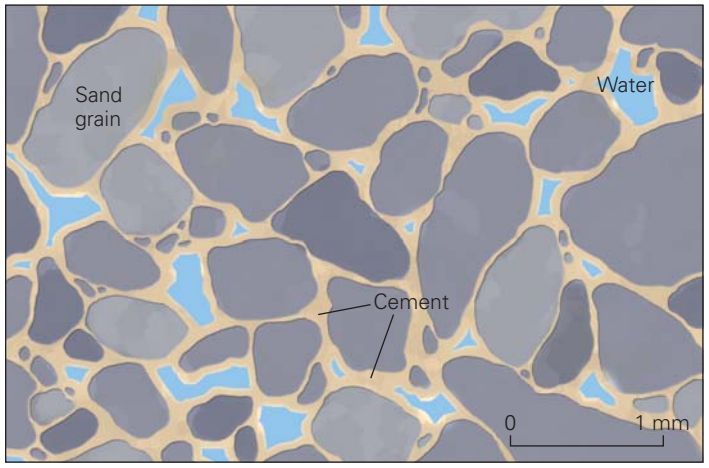
As we saw in Interlude F, water moves among various reservoirs during the *hydrologic cycle*. Of the water that falls on land, some evaporates directly back into the atmosphere, some gets trapped in glaciers, and some becomes runoff that enters a network of streams and lakes that drains to the sea. The remainder sinks or percolates downward, by a process called infiltration, into the ground. In effect, the upper part of the crust behaves like a giant sponge that can soak up water.

Of the water that does infiltrate, some descends only into the soil and wets the surfaces of grains and organic material making up the soil. This water, called **soil moisture**, later evaporates back into the atmosphere or gets sucked up by the roots of plants and transpires back into the atmosphere. But some water sinks deeper into sediment or rock, and along with water trapped in rock at the time the rock formed, makes up groundwater. Groundwater slowly flows underground for anywhere from a few months to tens of thousands of years before returning to the surface to pass once again into other reservoirs of the hydrologic cycle.

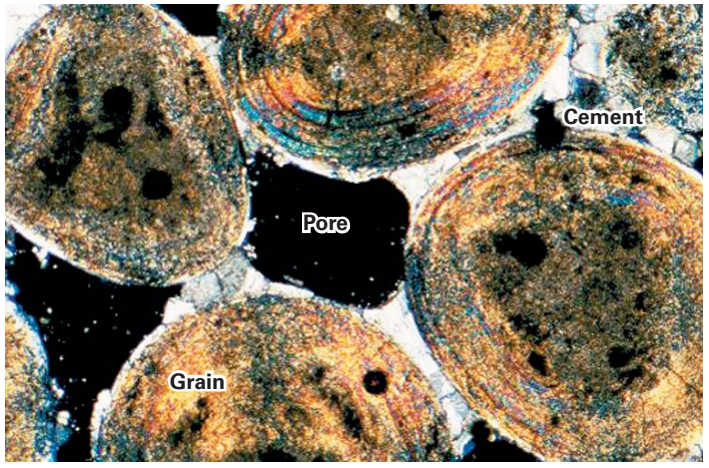
Porosity: Open Space in Rock and Regolith

Contrary to popular belief, only a small proportion of underground water occurs in caves. Most groundwater resides in relatively small open spaces between grains of sediment or between grains of seemingly solid rock, or within cracks of various sizes. The term **pore** refers to any open space within a volume of sediment, or within a body of rock, and the term **porosity** refers to the total amount of open space within a material, specified as a percentage. For example, if we say that a block of rock has 30% porosity, then 30% of the block consists of pores. Geologists distinguish between two basic kinds of porosity—primary and secondary.

FIGURE 16.2 Porosity is the open space in rock or sediment, whereas permeability is the degree to which the pores are connected.



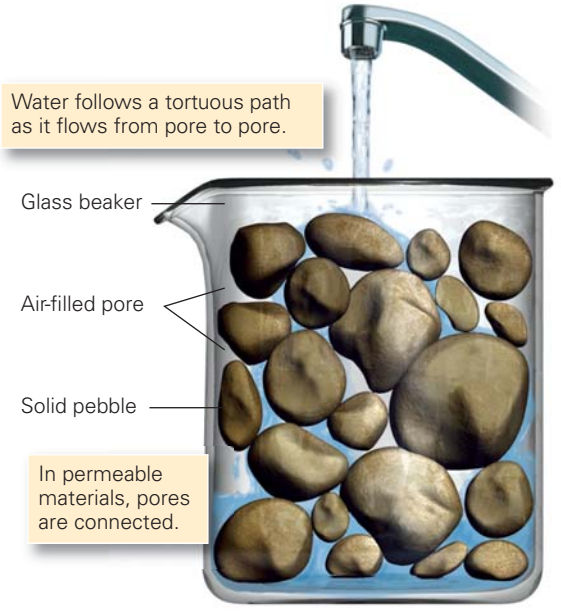
(a) Isolated pores in a sandstone occur in the spaces between grains. Water or air can fill pores.



(b) A photograph of a thin section shows tiny pores in a limestone. Here, the grains consist of calcite spheres, and the cement of calcite crystals.



(c) Limestone outcrop on the coast of Ireland contains abundant fractures that provide secondary porosity.



(d) Gravel contains pore space, because clasts don't fit together tightly. The connection of pores produces permeability.

Primary porosity develops during sediment deposition and during rock formation (**Fig. 16.2a,b**). It includes the pores between clastic grains that exist because the grains don't fit together tightly during deposition. Secondary porosity refers to new pore space produced in rocks some time after the rock first formed. For example, when rocks fracture, the opposing walls of the fracture do not fit together tightly, so narrow spaces remain in between. Thus, joints and faults may provide secondary porosity for water (**Fig. 16.2c**). As groundwater passes through rock, it may dissolve and remove some minerals, creating solution cavities that also provide secondary porosity.

Permeability: The Ease of Flow

If solid rock completely surrounds a pore, the water in the pore cannot flow to another location. For groundwater to flow, pores must be linked by conduits (openings). The ability of a material to allow fluids to pass through an interconnected network of pores is a characteristic known as **permeability**. Groundwater flows easily through a material, such as loose gravel, that has *high permeability*. In gravel, the water is able to pass quickly from pore to pore, so if you pour water into a gravel-filled jar, it will trickle down to the bottom of the jar, where it displaces air and fills the pores (**Fig. 16.2d**). In tightly packed sediments or in rock, the water flows more slowly because it follows a tortuous path through tiny conduits. Water flows slowly or not at all through an *impermeable material*. Put another way,

an impermeable material has low permeability or even no permeability. The permeability of a material depends on several factors:

- *Number of available conduits*: As the number of conduits increases, permeability increases.
- *Size of the conduits*: More fluids can travel through wider conduits than through narrower ones.
- *Straightness of the conduits*: Water flows more rapidly through straight conduits than it does through crooked ones.

Note that the factors that control permeability in rock or sediment resemble those that control the ease with which traffic moves through a city. Traffic can flow quickly through cities with many straight, multilane boulevards, whereas it flows slowly through cities with only a few narrow, crooked streets. Porosity and permeability are *not* the same feature. A material whose pores are isolated from each other can have high porosity but low permeability.

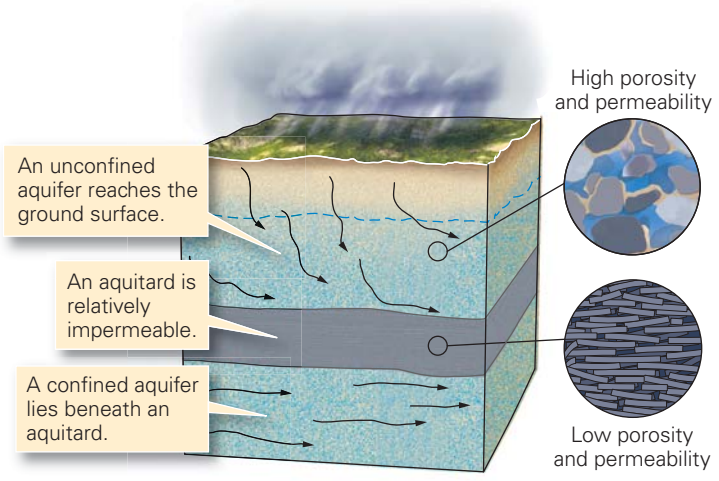
Aquifers and Aquitards

With the concept of permeability in mind, hydrogeologists distinguish between an **aquifer**, sediment or rock with high permeability and porosity, and an **aquitard**, sediment or rock that does not transmit water easily and therefore retards the motion of water. An aquifer that is not overlain by an aquitard is an *unconfined aquifer*. Water can infiltrate down into an unconfined aquifer from the Earth's surface, and groundwater can rise to reach the Earth's surface from an unconfined aquifer. An aquifer that is overlain by an aquitard is a *confined aquifer*—its water is isolated from the ground surface (Fig. 16.3a).

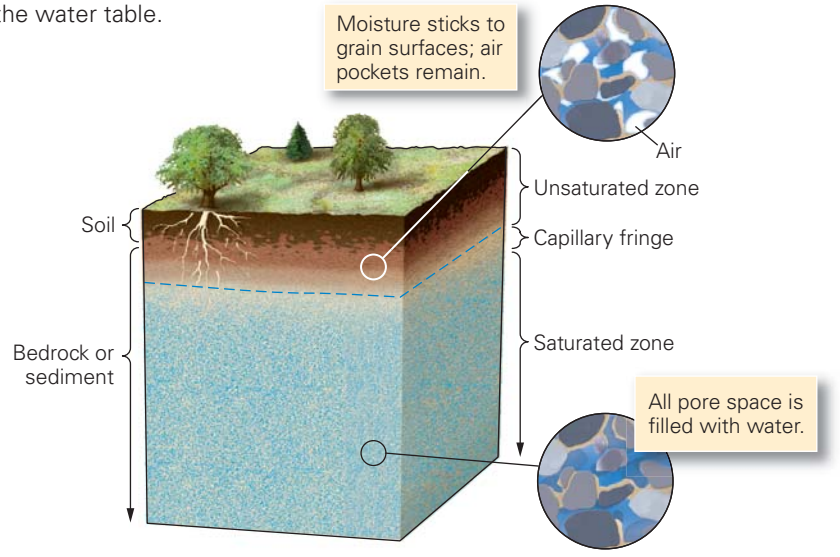
The Water Table

Infiltrating water can enter permeable sediment and bedrock by percolating along cracks and through conduits connecting pores. Nearer the ground surface, water only partially fills pores, leaving some space that remains filled with air (Fig. 16.3b). The region

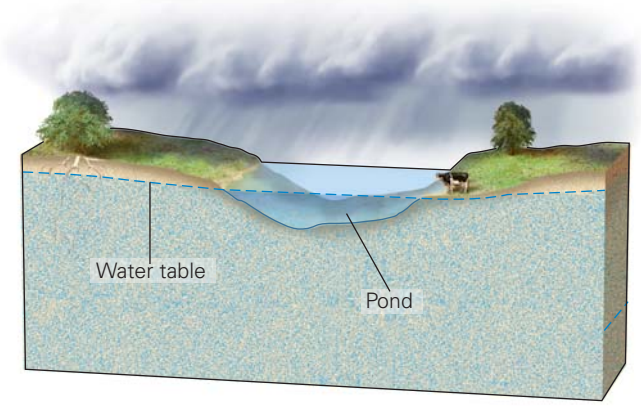
FIGURE 16.3 Water in the ground—aquifers, aquitards, and the water table.



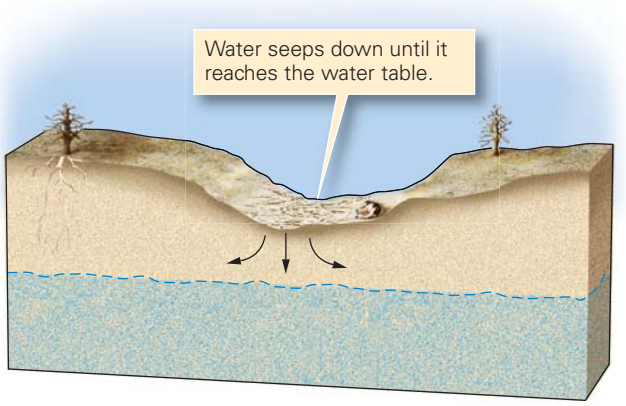
(a) An aquifer is a high-porosity, high-permeability rock. Some aquifers are unconfined, and some are confined.



(b) The water table is the top of the groundwater reservoir in the subsurface. It separates the unsaturated (vadose) zone above from the unsaturated zone below. A capillary fringe forms at the boundary.



(c) Where the water table lies close to the ground surface, ponds remain filled—the water table is the surface of the pond.



(d) In dry regions, the water table sinks deep below the surface. Water that collects temporarily in low areas sinks into the subsurface.

of the subsurface in which water only partially fills pores is called the *unsaturated zone*. Deeper down, water completely fills, or saturates, the pores. This region is the *saturated zone*. In a strict sense, geologists use the term "groundwater" specifically for subsurface water in the saturated zone, where water completely fills pores.

The term **water table** refers to the horizon that separates the unsaturated zone above from the saturated zone below. Typically, surface tension, the electrostatic attraction of water molecules to each other and to mineral surfaces, causes water to seep up from the water table (just as water rises in a thin straw), filling pores in the **capillary fringe**, a thin layer at the base of the unsaturated zone. Note that the water table forms the top boundary of groundwater in an unconfined aquifer.

The depth of the water table in the subsurface varies greatly with location. In some places, the water table defines the surface of a permanent stream, lake, or marsh, and thus effectively lies above the ground level (Fig. 16.3c). Elsewhere, the water table lies hidden below the ground surface. In humid regions, it typically lies within a few meters of the surface, whereas in arid regions, it may lie hundreds of meters below the surface. Rainfall rates affect the water table depth in a given locality (Fig. 16.3d)—the water table drops during the dry season and rises during the wet season. Streams or ponds that hold water during the wet season may, therefore, dry up during the dry season because their water infiltrates into the ground below.

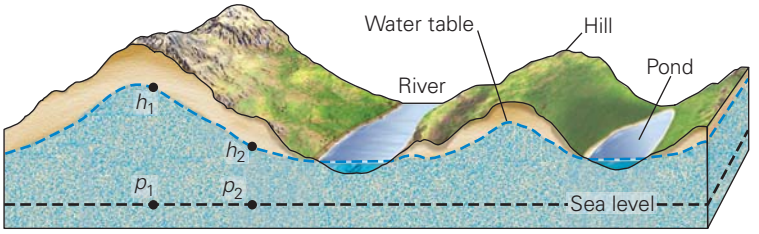
Topography of the Water Table

In hilly regions, if the subsurface has relatively low permeability, the water table is not a planar surface. Rather, its shape mimics, in a subdued way, the shape of the overlying topography (Fig. 16.4a). This means that the water table lies at a higher elevation beneath hills than it does beneath valleys. But the relief (the vertical distance between the highest and lowest elevations) of the water table is not as great as that of the overlying land, so the surface of the water table tends to be smoother than that of the landscape.

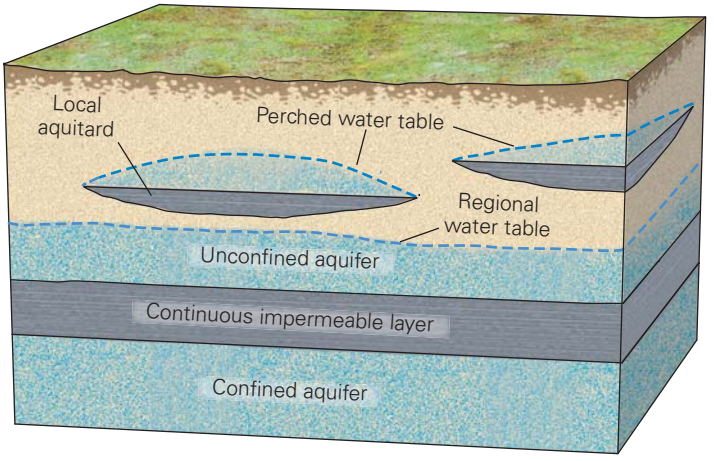
At first thought, it may seem surprising that the elevation of the water table varies as a consequence of ground-surface topography. After all, when you pour a bucket of water into a pond, the surface of the pond immediately adjusts to remain horizontal. The elevation of the water table varies because groundwater moves so slowly through rock and sediment that it cannot quickly assume a horizontal surface. When rain falls on a hill and water infiltrates down to the water table, the water table rises a little. When it doesn't rain, the water table sinks slowly, but so slowly that when rain falls again, the water table rises before it has had time to sink very far.

In some locations, lens-shaped layers of impermeable rock (such as shale) may lie within a thick aquifer. A mound of groundwater accumulates above such aquitard lenses. The result is a **perched water table**, a groundwater top surface that lies above the regional water table because the underlying lens of impermeable rock or sediment prevents the groundwater from sinking down to the regional water table (Fig. 16.4b).

FIGURE 16.4 Factors that influence the position of the water table.



(a) The shape of a water table beneath hilly topography. Point h_1 on the water table is higher than Point h_2, relative to a reference elevation (sea level). The pressure at p_1 is, therefore, more than the pressure at p_2.



(b) A perched water table occurs where a mound of groundwater becomes trapped above a localized aquitard that lies above the regional water table.

Take-Home Message

Most underground water fills pores and cracks in rock or sediment. Porosity refers to the total amount of open space within a material, whereas permeability indicates the degree to which pores connect. Aquifers have high porosity and permeability; aquitards don't.

16.3 Groundwater Flow

What happens to groundwater over time? Does it just sit, unmoving, like the water in a stagnant puddle, or does it flow and eventually find its way back to the surface? Countless measurements confirm that groundwater enjoys the latter fate—groundwater indeed flows, and in some cases it moves great distances underground. Let's examine factors that drive groundwater flow.

In the unsaturated zone—the region between the ground surface and the water table—water percolates straight down,

like the water passing through a drip coffee maker, for this water moves only in response to the downward pull of gravity. But in the zone of saturation—the region below the water table—water flow is more complex, for in addition to the downward pull of gravity, water responds to differences in pressure. Pressure can cause groundwater to flow sideways, or even upward. (If you've ever watched water spray from a fountain, you've seen pressure pushing water upward.) Thus, to understand the nature of groundwater flow, we must first understand the origin of pressure in groundwater. For simplicity, we'll consider only the case of groundwater in an unconfined aquifer.

Pressure in groundwater at a specific point underground is caused by the weight of all the overlying water from that point up to the water table. (The weight of overlying rock does not contribute to the pressure exerted on groundwater, for the contact points between mineral grains bear the rock's weight.) Thus, a point at a greater depth below the water table feels more pressure than does a point at lesser depth. If the water table is horizontal, the pressure acting on an imaginary horizontal reference plane at a specified depth below the water table is the same everywhere. But if the water table is not horizontal, as shown in Figure 16.4a, the pressure at points on a horizontal reference plane at depth changes with location. For example, the pressure acting at point p_1, which lies below the hill in Figure 16.4a, is greater than the pressure acting at point p_2, which lies below the valley, even though both p_1 and p_2 are at the same elevation.

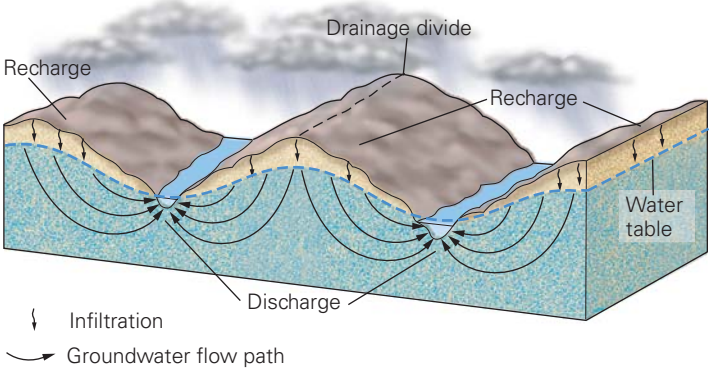
Both the elevation of a volume of groundwater and the pressure within the water provide energy that, if given the chance, will cause the water to flow. Physicists refer to such stored energy as *potential energy*. The potential energy available to drive the flow of a given volume of groundwater at a location is called the **hydraulic head**. To measure the hydraulic head at a point in an aquifer, hydrogeologists drill a vertical hole down to the point and then insert a pipe in the hole. The height above a reference elevation (for example, sea level) to which water rises in the pipe represents the hydraulic head—water rises higher in the pipe where the head is higher. As a rule, *groundwater flows from regions where it has higher hydraulic head to regions where it has lower hydraulic head*. This statement generally implies that groundwater regionally flows from locations where the water table is higher to locations where the water table is lower.

Hydrogeologists have calculated how hydraulic head changes with location underground, by taking into account both the effect of gravity and the effect of pressure. These calculations reveal that groundwater flows along concave-up curved paths, as illustrated in cross section (**Fig. 16.5a, b**). These curved paths eventually take groundwater from regions where the water table is high (under a hill) to regions where the water table is low (below a valley), but because of flow-path shape, some groundwater may flow deep down into the crust along the first part of its path and then may flow back up, toward the ground surface, along the final part of its path. The location where water enters the ground (where the flow direction has a downward trajectory) is called the **recharge area**, and the location where groundwater flows back up to the surface is called the **discharge area** (see Fig. 16.5a).

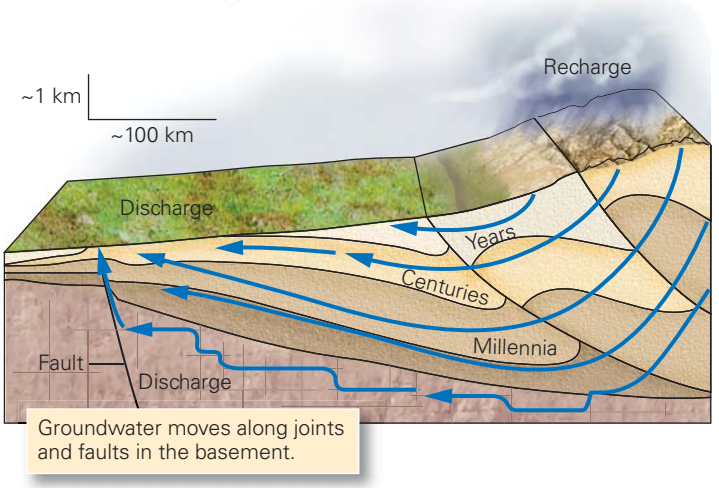
Flowing water in an ocean current moves at up to 3 km per hour, and water in a steep river channel can reach speeds of up to 30 km per hour. In contrast, groundwater moves at less than a snail's pace, between 0.01 and 1.4 m per day (about 4 to 500 m per year). Groundwater moves much more slowly than surface water, for two reasons. First, groundwater moves by percolating through a complex, crooked network of tiny conduits, so it must travel a much greater distance than it would if it could follow a straight path. Second, friction between groundwater and conduit walls slows down the water flow.

Simplistically, the velocity of groundwater flow depends on the slope of the water table and the permeability of the material through which the groundwater is flowing. Thus,

FIGURE 16.5 The flow of groundwater.



(a) Groundwater flows from recharge areas to discharge areas. Typically, the flow follows curving paths.



(b) The large hydraulic head resulting from uplift of a mountain belt may drive groundwater hundreds of kilometers, across regional sedimentary basins. Deeper flow paths take longer.

CONSIDER THIS . . .

BOX 16.1

Darcy's Law for Groundwater Flow

The rate at which groundwater flows at a given location depends on the permeability of the material containing the groundwater; groundwater flows faster in a more permeable material than it does in a less permeable material. The rate also depends on the **hydraulic gradient**, the change in hydraulic head per unit of distance between two locations, as measured along the flow path.

To calculate the hydraulic gradient, we divide the difference in hydraulic head between two points by the distance between the two points as measured along the flow path. This can be written as a formula:

$$\text{hydraulic gradient} = \frac{h_1 - h_2}{j}$$

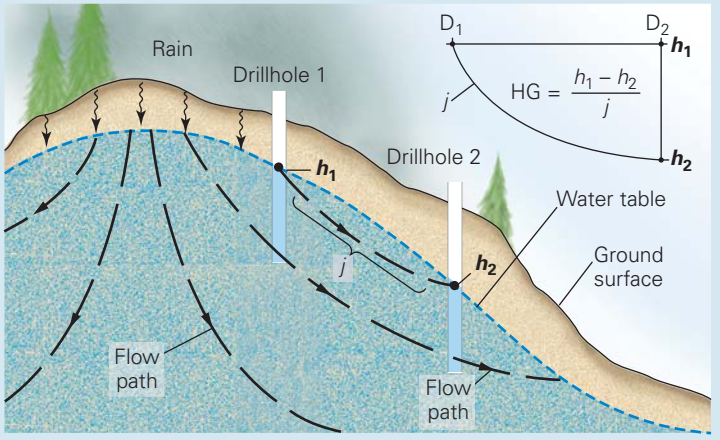
where $h_1 - h_2$ is the difference in head (given in meters or feet, because head can be represented as an elevation) between two points along the water table, and j is the distance between the two points as measured along the flow path (**Fig. Bx16.1**). A hydraulic gradient exists anywhere that the water table has a slope. Typically, the slope of the water table is so small that the path length is almost the same as the horizontal distance between two points. So, in general, the hydraulic gradient is roughly equivalent to the slope of the water table.

In 1856, a French engineer named Henry Darcy carried out a series of experiments designed to characterize factors that control the velocity at which groundwater flows between two locations (1 and 2), each of which has a different hydraulic head (h_1 and h_2). Darcy represented the velocity of flow by a quantity called the discharge (Q), meaning the volume of water passing through an imaginary vertical plane perpendicular to the groundwater's flow path in a given time. He found that the discharge depends on the the hydraulic head ($h_1 - h_2$); the area (A) of the imaginary plane through which the groundwater is passing; and a number called the hydraulic conductivity (K). The hydraulic conductivity represents the ease with which a fluid can flow through a material. This, in turn, depends on many factors (such as the viscosity and density of the fluid), but mostly it reflects the permeability of the material. The relationship that Darcy discovered, now known as **Darcy's law**, can be written in the form of an equation as:

$$Q = \frac{KA(h_1 - h_2)}{j}$$

The equation states that if the hydraulic gradient increases, discharge increases, and that as conductivity increases, discharge increases. Put in simpler terms, the flow rate of groundwater increases as the permeability increases and as the slope of the water table gets steeper.

FIGURE Bx16.1 The level to which water rises in a drillhole is the hydraulic head (h). The hydraulic gradient (HG) is the difference in head divided by the length of the flow path.



groundwater flows faster through high-permeability rocks than it does through low-permeability rocks, and it flows faster in regions where the water table has a steep slope than it does in regions where the water table has a gentle slope. For example, groundwater flows relatively slowly (~2 m per year) through a low-permeability aquifer under the Great Plains, but flows relatively quickly (~30 m per year) through a high-permeability aquifer under a steep hillslope. In detail, hydrogeologists use Darcy's Law to determine flow rates at a location (**Box 16.1**).

Take-Home Message

Gravity and pressure cause groundwater to flow slowly from recharge to discharge areas. In essence, the rate of flow depends on the water table's slope and on permeability. Groundwater can follow curving flow paths that take it deep into the crust.

16.4 Tapping Groundwater Supplies

We can obtain groundwater at wells or springs. **Wells** are holes that people dig or drill to obtain water. **Springs** are natural outlets from which groundwater flows. Wells and springs provide welcome sources of water but must be treated with care if they are to last.

Wells

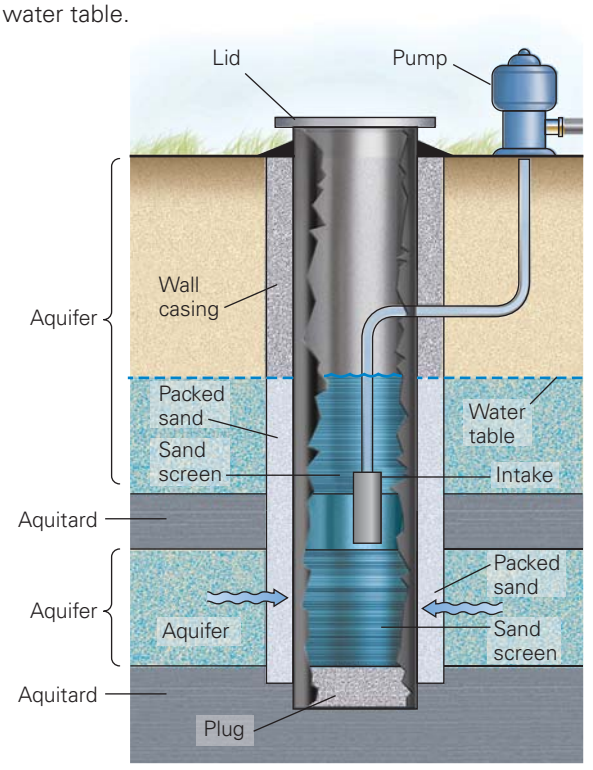
In an **ordinary well**, the base of the well penetrates an aquifer below the water table (Fig. 16.6a). Water from the pore space in the aquifer seeps into the well and fills it to the level of the water table. Drilling into an aquitard, or into rock that lies above the water table, will not supply water, and thus yields a *dry well*. Some ordinary wells are seasonal and function only during the rainy season, when the water table rises. During the dry season, the water table lies below the base of the well, so the well is dry.

To obtain water from an ordinary well, you either pull water up in a bucket or pump the water out. As long as the rate at which groundwater fills the well exceeds the rate at which water is removed, the level of the water table near the well remains about the same. However, if users pump water out of the well too fast, then the water table sinks down around the well, in a process called *drawdown*, so that the water table becomes a downward-pointing, cone-shaped surface called a **cone of depression** (Fig. 16.6b, c). Drawdown by a deep well may cause shallower wells that have been drilled nearby to run dry.

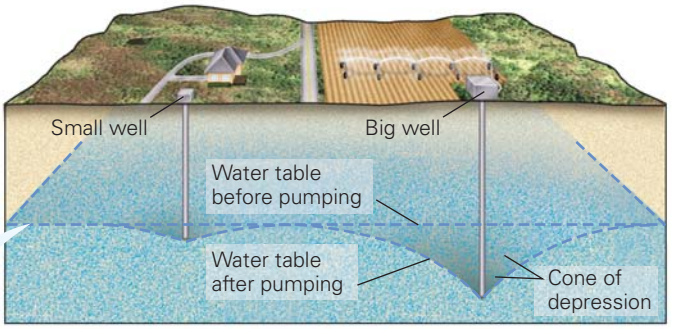
An **artesian well**, named for the province of Artois in France, penetrates confined aquifers in which water is under enough pressure to rise on its own to a level above the surface of the aquifer. If this level lies below the ground surface, the well is a *nonflowing* artesian well. But if the level lies above the ground surface, the well is a *flowing* artesian well, and water actively fountains out of the ground (Fig. 16.7a). Artesian wells occur in special situations where a confined aquifer lies beneath a sloping aquitard.

We can understand why artesian wells exist if we look first at the configuration of a city water supply (Fig. 16.7b). Water companies pump water into a high tank that has a significant hydraulic head relative to the surrounding areas. If the water were connected by a water main to a series of vertical pipes, pressure caused by the elevation of the water in the high tank would make the water rise in the pipes until it reached an imaginary surface, called a *potentiometric surface*, that lies above the ground. This pressure drives water through water mains to household water systems without requiring pumps. In an artesian system, water enters a tilted, confined aquifer that

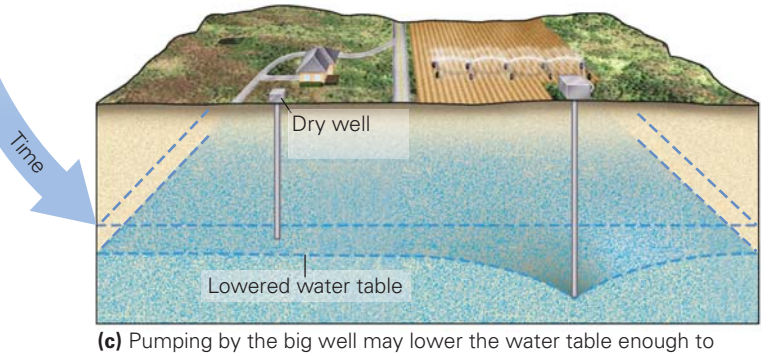
FIGURE 16.6 Pumping groundwater at a normal well affects the water table.



(a) A modern ordinary well sucks up water with an electric pump. The packed sand filters the water.



(b) If groundwater is extracted faster than it can be replaced, a cone of depression forms around the well.



(c) Pumping by the big well may lower the water table enough to cause the nearby small well to go dry.

intersects the ground in the hills of a high-elevation recharge area (Fig. 16.7c). The confined groundwater flows down to the adjacent plains, which lie at a lower elevation. The potentiometric surface to which the water would rise, were it not confined, lies above this aquifer. Pressure in the confined aquifer pushes water up a well.

Springs

Many towns were founded next to springs, places where groundwater naturally flows or seeps onto the Earth's surface, for springs can provide fresh, clear water for drinking or irrigation, without the expense of drilling or digging. Some springs spill water onto dry land. Others bubble up through the bed of a stream or lake. Springs form under a variety of conditions:

- Where the ground surface intersects the water table in a discharge area (Fig. 16.8a); such springs typically occur in valley floors, where they may add water to lakes or streams.
- Where flowing groundwater collides with a steep, impermeable barrier, and pressure pushes it up to the ground along the barrier (Fig. 16.8b).
- Where a perched water table intersects the surface of a hill (Fig. 16.8c).
- Where downward-percolating water runs into a relatively impermeable layer and migrates along the top surface of the layer to a hillslope (Fig. 16.8d).
- Where a network of interconnected fractures channels groundwater to the surface of a hill (Fig. 16.8e).
- Where the ground surface intersects a natural fracture (joint) that taps a confined aquifer in which the pressure is sufficient to drive the water to the surface; such an occurrence is an **artesian spring**.

Springs can provide water in regions that would otherwise be uninhabitable. For example, oases in deserts may develop around a spring. An **oasis** is a wet area, where plants can grow, in an otherwise bone-dry region.

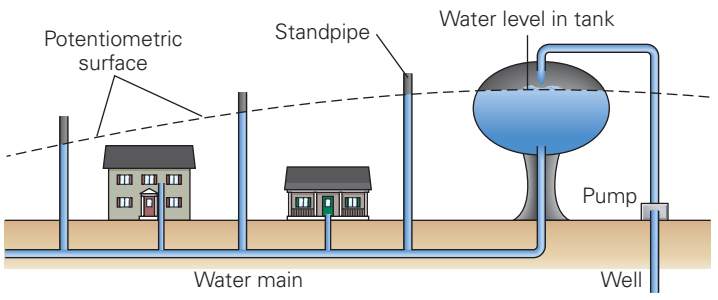
Take-Home Message

Groundwater can be obtained at wells (built by people) and springs (natural outlets). In ordinary wells, water must be lifted to the surface, but in artesian wells and springs, it rises due to its hydraulic head. Pumping of groundwater lowers the water table.

FIGURE 16.7 Artesian wells, where water rises from the aquifer without pumping.



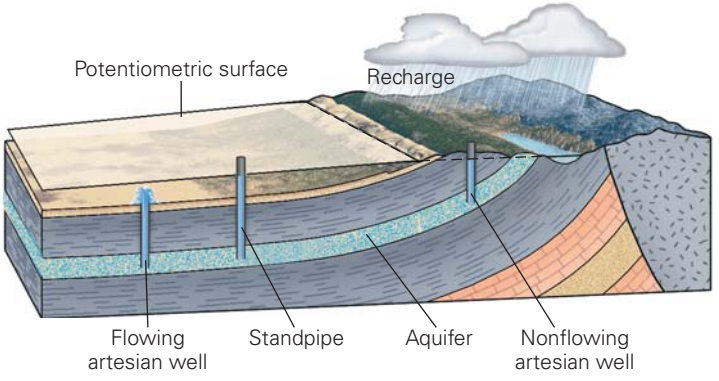
(a) A flowing artesian well in a Missouri field.



(b) The configuration of a city water supply. Water rises in vertical pipes up to the level of the potentiometric surface.

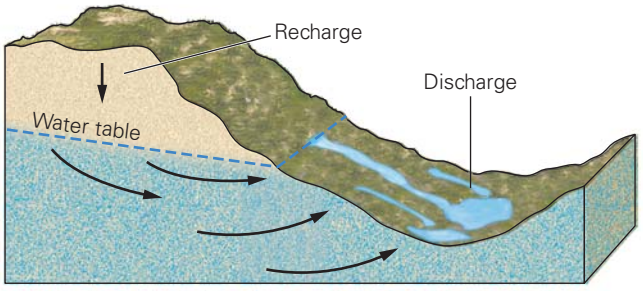
16.5 Hot Springs and Geysers

Hot springs, springs that emit water ranging in temperature from about 30° to 104°C, are found in two geologic settings. First, they occur where very deep groundwater, heated in warm bedrock at depth, flows up to the ground surface. This water brings heat with it as it rises. Such hot springs form in places where faults or fractures provide a high-permeability conduit for deep water, or where the water emitted in a discharge region followed a trajectory that first carried it deep into the crust. Second, hot springs develop in **geothermal regions**, places where volcanism currently takes place or has

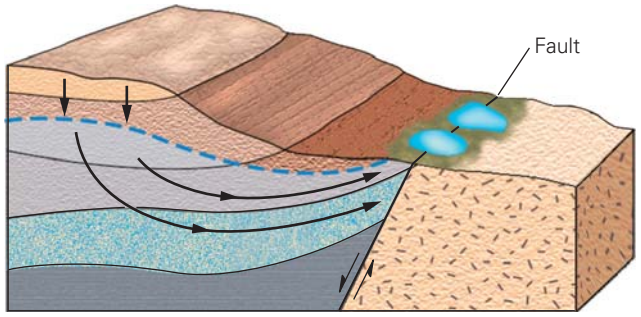


(c) The configuration of a regional artesian system.

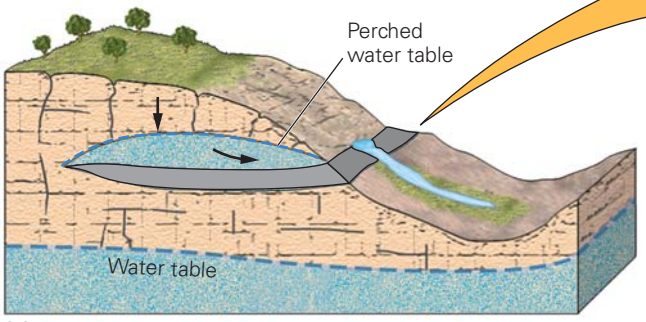
FIGURE 16.8 Geological settings in which springs form.



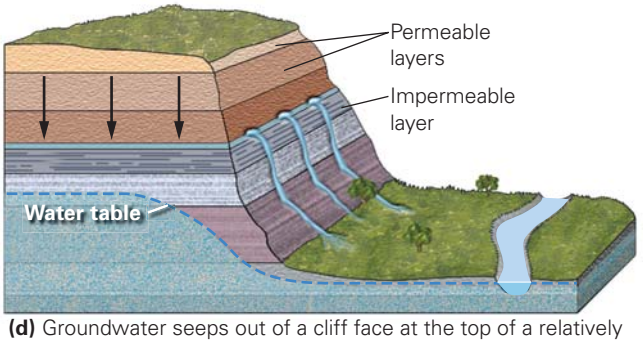
(a) Groundwater reaches the ground surface in a discharge zone.



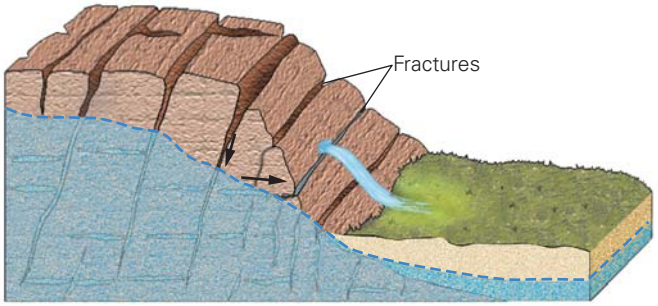
(b) Where groundwater reaches an impermeable barrier, it rises.



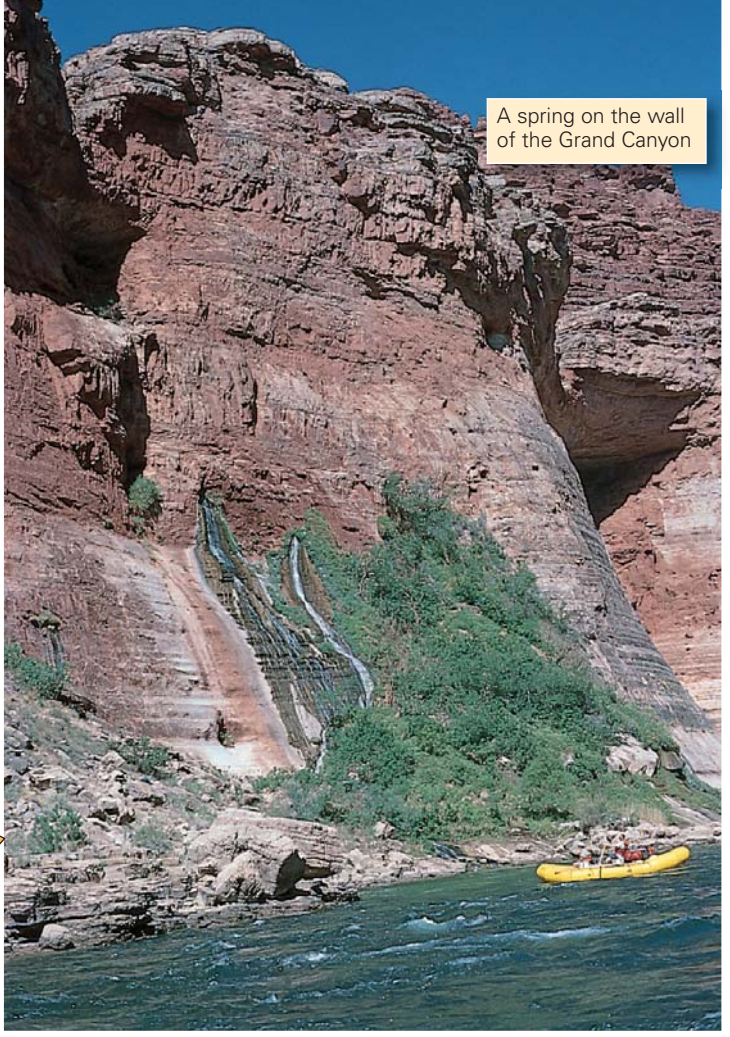
(c) Groundwater seeps where a perched water table intersects a slope.



(d) Groundwater seeps out of a cliff face at the top of a relatively impermeable bed.



(e) A network of interconnected fractures channels water to the surface of a hill.

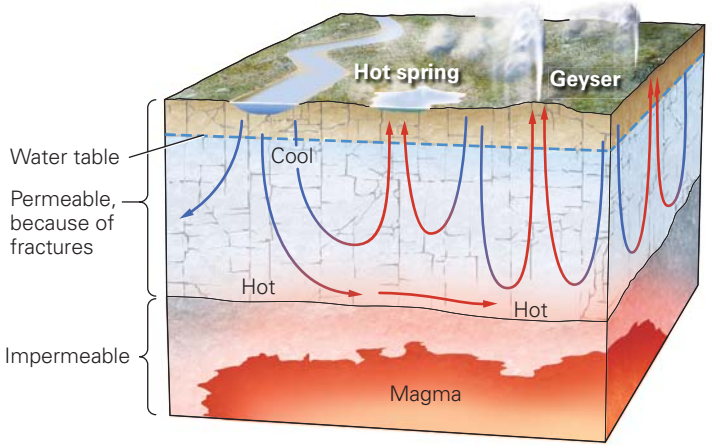

A spring on the wall of the Grand Canyon

occurred recently, so that magma and/or very hot rock resides close to the Earth's surface (**Fig. 16.9a**). Hot groundwater dissolves minerals from rock that it passes through because water becomes a more effective solvent when hot, so people use the water emitted at hot springs as relaxing mineral baths (**Fig. 16.9b**). Natural pools of geothermal water may become brightly colored—the gaudy greens, blues, and oranges of these pools come from thermophyllic (heat-loving) bacteria and archaea that thrive in hot water and metabolize the sulfur-containing minerals dissolved in the groundwater (**Fig. 16.9c**).

Numerous distinctive geologic features form in geothermal regions as a result of the eruption of hot water. In places where the hot water rises into soils rich in volcanic ash and clay, a viscous slurry forms and fills bubbling mud pots. Bubbles of steam rising through the slurry cause it to splatter about in goopy drops. Where geothermal waters spill out of natural springs and then cool, dissolved minerals in the water precipitate, forming colorful mounds or terraces of travertine and other chemical sedimentary rocks (**Fig. 16.9d**).

Under special circumstances, geothermal water emerges from the ground in a **geyser** (from the Icelandic spring, Geysir, and the word for gush), a fountain of steam and hot water that erupts episodically from a vent in the ground (**Fig. 16.9e**). To understand why a geyser erupts, we first need a picture of its underground plumbing. Beneath a geyser lies a network of irregular fractures in very hot rock; groundwater sinks and fills these fractures. Heat transfers from the rock to the groundwater and makes the water's

FIGURE 16.9 Geothermal waters and examples of their manifestation in the landscape.



(a) Geysers and hot springs occur where groundwater, heated at depth, rises to the surface.



(b) Hot springs in Iceland, warmed by magma below, attract tourists from around the world.



(c) Colorful bacteria- and archaea-laden pools, Yellowstone National Park, Wyoming.



(d) Terraces of minerals precipitated at Mammoth Hot Springs, Yellowstone.



(e) The Old Faithful geyser, in Yellowstone, erupts predictably.

temperature rise. Since the boiling point of water (the temperature at which water vaporizes) increases with increasing pressure, hot groundwater at depth can remain in liquid form even if its temperature has become greater than the boiling point of water at the Earth's surface. When such "superheated" groundwater begins to rise through a conduit toward the surface, pressure in it decreases until eventually some of the water transforms into steam. The resulting expansion causes water higher up to spill out of the conduit at the ground surface. When this spill happens, pressure in the conduit, from the weight of overlying water, suddenly decreases. A sudden drop in pressure causes the superhot water at depth to turn into steam instantly, and this steam quickly rises, ejecting all the water and steam above it out of the conduit in a geyser eruption. Once the conduit empties, the eruption ceases, and the conduit fills once again with water that gradually heats up, starting the eruptive cycle all over again.

Take-Home Message

In geothermal regions, or in localities where discharged groundwater followed a flow path deep into the crust, hot springs appear. Geysers develop under special circumstances where pressure builds up sufficiently to eject water and steam forcefully.

16.6 Groundwater Problems

Since prehistoric times, groundwater has been an important resource that people have relied on for drinking, irrigation, and industry. Groundwater feeds the lushness of desert oases in the Sahara, the amber grain in the North American high plains, and the growing cities of sunny arid regions.

Though groundwater accounts for about 95% of the liquid freshwater on the planet, accessible groundwater cannot be replenished quickly, and this leads to shortages. Groundwater contamination is also a growing tragedy. Such pollution, caused when toxic wastes and other impurities infiltrate down to the water table, may be invisible to us but may ruin a water supply for generations to come. In this section, we'll take a look at problems associated with the use of groundwater supplies.

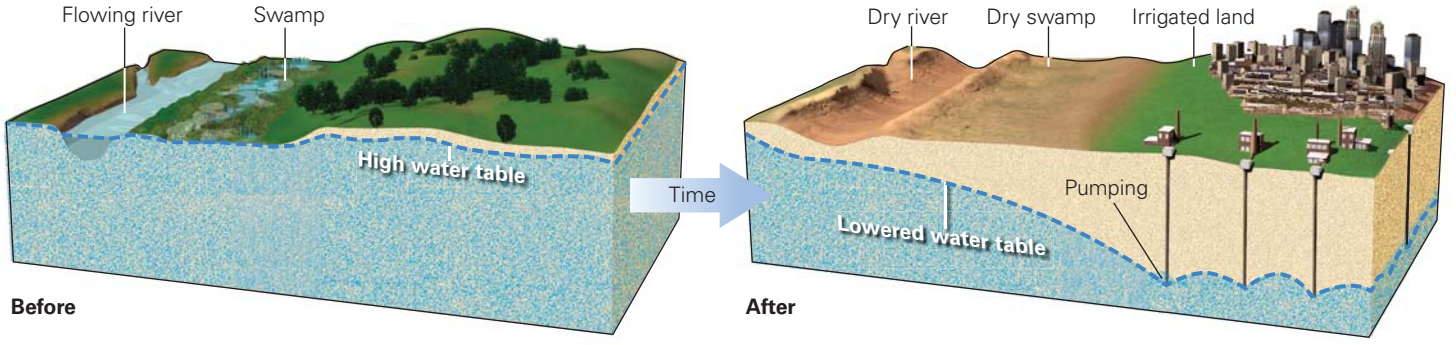
Depletion of Groundwater Supplies

Is groundwater a renewable resource? In a time frame of 10,000 years, the answer is yes, for the hydrologic cycle will eventually resupply depleted reserves. But in a time frame of 100 to 1,000 years—the span of a human lifetime or a civilization—groundwater in many regions may be a *nonrenewable* resource. By pumping water out of the ground at a rate faster than nature replaces it, people are effectively "mining" the groundwater supply. In fact, in portions of the desert Sunbelt region of the United States, supplies of young groundwater have already been exhausted, and deep wells now extract 10,000-year-old groundwater. Some of this ancient water has been in rock so long that it has become too mineralized to be usable. A number of other problems accompany the depletion of groundwater.

- *Lowering the water table*: When we extract groundwater from wells at a rate faster than it can be resupplied by nature, the water table drops. First, a cone of depression forms locally around the well; then the water table gradually becomes lower in a broad region. As a consequence, existing wells, springs, and rivers, and swamps dry up (Fig. 16.10a, b). To continue tapping into the water supply, we must drill progressively deeper.

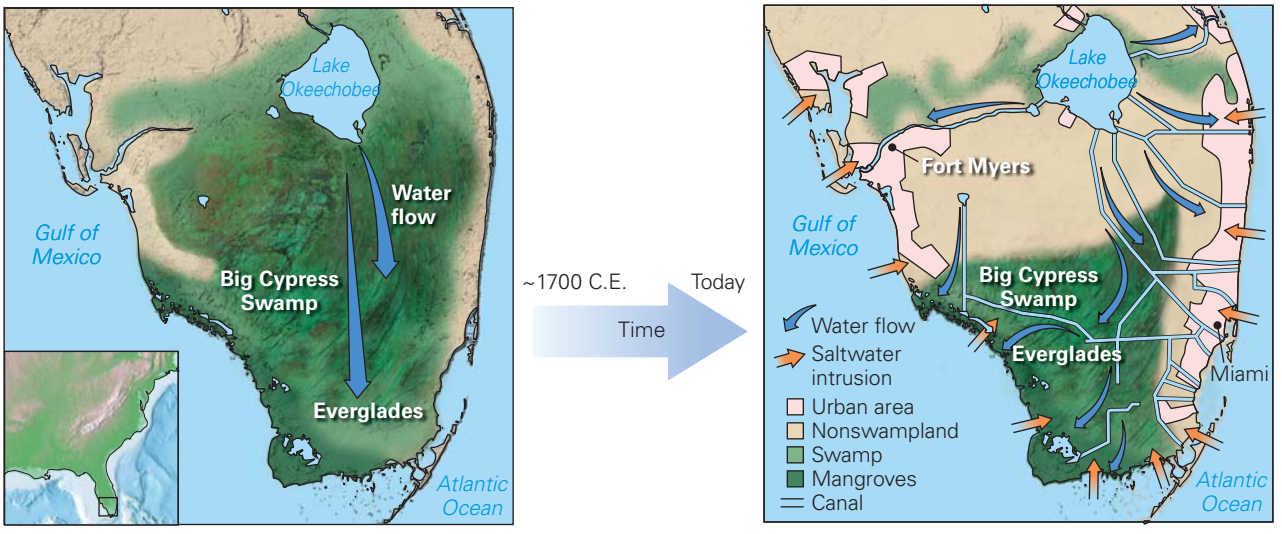
  Notably, the water table can also drop when people divert surface water from the recharge area. Such a problem has developed in the Everglades of southern Florida, a huge swamp where, before the expansion of Miami and the development of agriculture, the water table lay at the ground surface (Fig. 16.10c, d). Diversion of water from the Everglades'

FIGURE 16.10 Effects of human modification of the water table.



(a) Before humans start pumping groundwater, the water table is high. A swamp and permanent stream exist.

(b) Pumping for consumers in a nearby city causes the water table to sink in, so the swamp dries up.



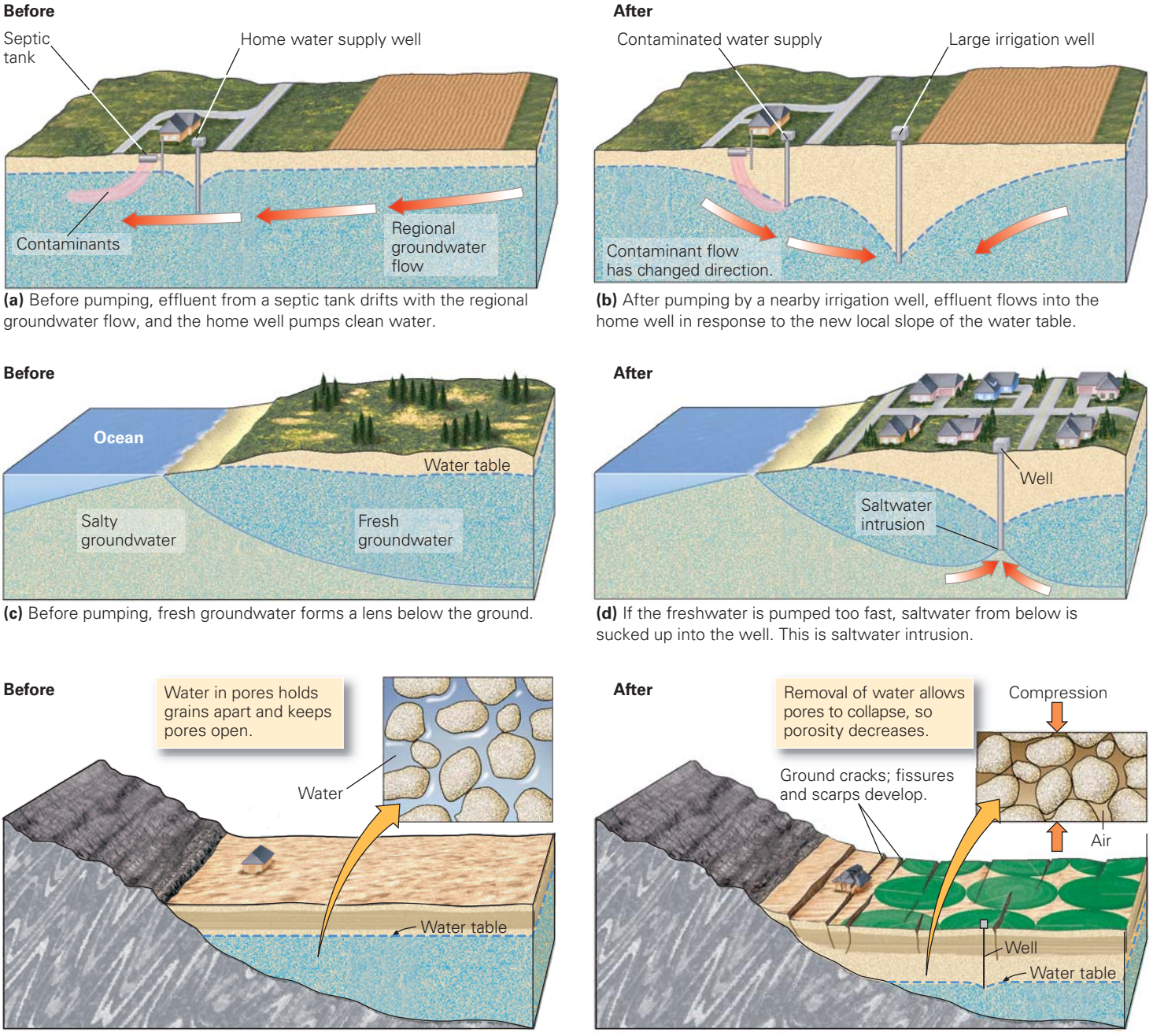
(c) The Florida Everglades before the advent of urban growth and intensive agriculture.

(d) Channelization and urbanization have removed water from recharge areas, disrupting flow paths.

recharge area into canals has significantly lowered the water table, causing parts of the Everglades to dry up.

- *Reversing the flow direction of groundwater*: The cone of depression that develops around a well creates a local slope to the water table. The resulting hydraulic gradient may be large enough to reverse the flow direction of nearby groundwater (**Fig. 16.11a, b**). Such reversals can allow contaminants, seeping out of a septic tank, to contaminate the well.
- *Saline intrusion*: In coastal areas, fresh groundwater lies in a layer above saline (salty) water that entered the aquifer from the adjacent ocean (**Fig. 16.11c, d**). Because fresh water is less dense than saline water, it floats above the saline water. If people pump water out of a well too quickly, the boundary between the saline water and the fresh groundwater rises. And if this boundary rises above the base of the well, then the well will start to yield useless saline water. Geologists refer to this phenomenon as saline intrusion.
- *Pore collapse and land subsidence*: When groundwater fills the pore space of a rock or sediment, it holds the grains apart, for water cannot be compressed. The extraction of water from a pore eliminates the support holding the grains apart, because the air that replaces the water *can* be compressed. As a result,

FIGURE 16.11 Some causes of groundwater problems.



(a) Before pumping, effluent from a septic tank drifts with the regional groundwater flow, and the home well pumps clean water.

(b) After pumping by a nearby irrigation well, effluent flows into the home well in response to the new local slope of the water table.

(c) Before pumping, fresh groundwater forms a lens below the ground.

(d) If the freshwater is pumped too fast, saltwater from below is sucked up into the well. This is saltwater intrusion.

(e) When intensive irrigation removes groundwater, pore space in an aquifer collapses.

(f) As a result, the land surface sinks, leading to the formation of ground fissures and causing houses to crack.

the grains pack more closely together. Such **pore collapse** permanently decreases the porosity and permeability of a rock, and thus lessens its value as an aquifer (Fig. 16.11e, f).

Pore collapse also decreases the volume of the aquifer, with the result that the ground above the aquifer sinks. Such land subsidence may cause fissures at the surface to develop and the ground to tilt. Buildings constructed over regions undergoing land subsidence may themselves tilt, or their foundations may crack. In the San Joaquin Valley of California, the land surface subsided by 9 m between 1925 and 1975, because water was removed to irrigate farm fields.

Natural Groundwater Quality

Much of the world's groundwater is crystal clear, and pure enough to drink right out of the ground. Rocks and sediment are natural filters capable of removing suspended solids—these solids get trapped in tiny pores or stick to the surfaces of clay flakes. In fact, the commercial distribution of bottled groundwater ("spring water") has become a major business worldwide. But dissolved chemicals, and in some cases methane, may make some natural groundwater unusable. For example, groundwater that has passed through salt-containing strata may become salty and unsuitable for irrigation or drinking. Groundwater that has passed through limestone or dolomite contains dissolved calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions; this water, called **hard water**, can be a problem because carbonate minerals precipitate from it to form "scale" that clogs pipes. Also, washing with hard water can be difficult because soap won't develop a lather. Groundwater that has passed through iron-bearing rocks may contain dissolved iron oxide that precipitates to form rusty stains. Some groundwater contains dissolved hydrogen sulfide, which comes out of solution when the groundwater rises to the surface; hydrogen sulfide is a poisonous gas that has a rotten-egg smell. In recent years, concern has grown about arsenic, a highly toxic chemical that enters groundwater when arsenic-bearing minerals dissolve in groundwater.

Did you ever wonder . . .
where does bottled "spring water" come from?

Human-Caused Groundwater Contamination

As we've noted, some contaminants in groundwater occur naturally. But in recent decades, contaminants have increasingly been introduced into aquifers because of human activity (Fig. 16.12a). These contaminants include agricultural waste (pesticides, fertilizers, and animal sewage), industrial waste (dangerous organic and inorganic chemicals), effluent from "sanitary" landfills and septic tanks (including bacteria and viruses), petroleum products and other chemicals that do not dissolve in water, radioactive waste (from weapons manufacture, power plants, and hospitals), and acids leached from sulfide minerals in coal and metal mines. The cloud of contaminated groundwater that moves away from the source of contamination is called a **contaminant plume** (Fig. 16.12b).

The best way to avoid such **groundwater contamination** is to prevent contaminants from entering groundwater in the first place. This can be done by placing contaminants in sealed containers or on impermeable bedrock so that they are isolated from aquifers. If such a site is not available, the storage area should be lined with plastic or with a thick layer of clay, for the clay not only acts as an aquitard, but it can bond to contaminants. Fortunately, in some cases, natural processes can clean up groundwater contamination. Chemicals may be absorbed by clay, oxygen in the water may oxidize the chemicals, and bacteria in the water may metabolize the chemicals, thereby turning them into harmless substances.

Where contaminants do make it into an aquifer, environmental engineers drill test wells to determine which way and how fast the contaminant plume is flowing; once they know the flow path, they can close wells in the path to prevent consumption of contaminated water. Engineers may attempt to clean the groundwater by drilling a series of extraction wells to pump it out of the ground. If the contaminated water does not rise fast enough, engineers drill injection wells to force clean water or steam into the ground beneath the contaminant plume (Fig. 16.12c). The injected fluids then push the contaminated water up into the extraction wells.

More recently, environmental engineers have begun exploring techniques of **bioremediation**: injecting oxygen and nutrients into a contaminated aquifer to foster growth of bacteria that can react with and break down molecules of contaminants. Needless to say, cleaning techniques are expensive and generally only partially effective.

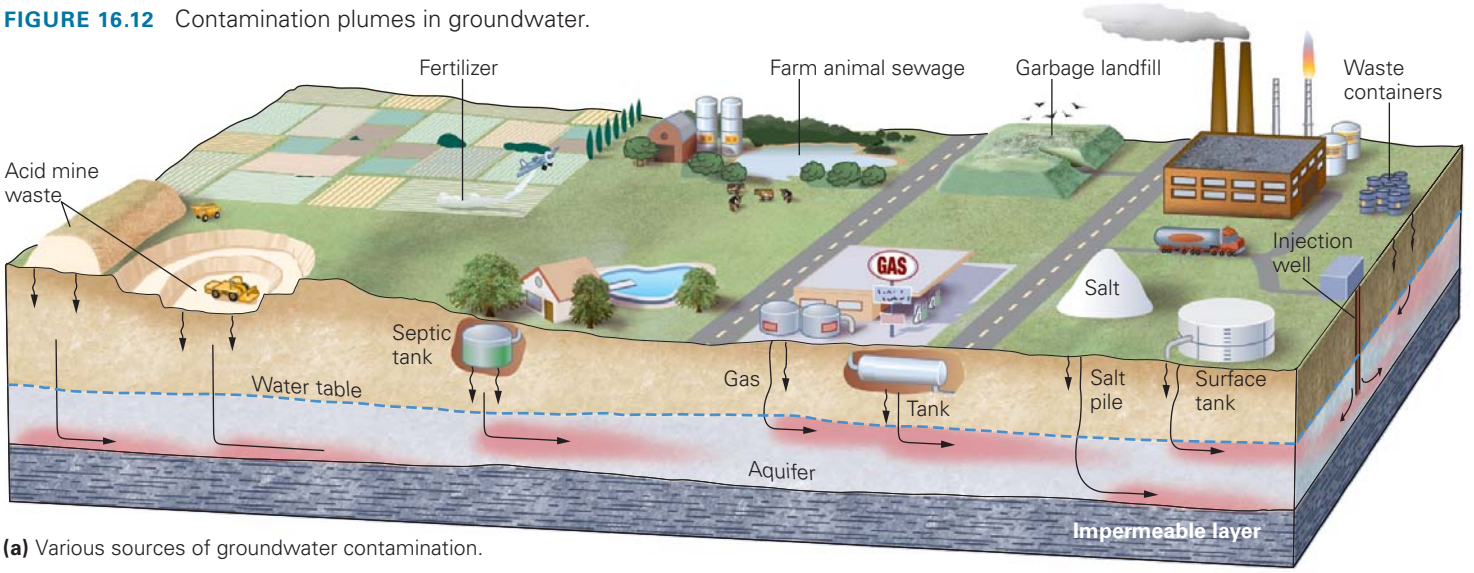
Unwanted Effects of Rising Water Tables

We've seen the negative consequences of sinking water tables, but what happens when the water table rises? Is that necessarily good? Sometimes, but not always. If the water table rises above the level of a house's basement, water seeps through the foundation and floods the basement floor. Catastrophic damage occurs when a rising water table weakens the base of a hillslope or a failure surface underground triggers landslides and slumps.

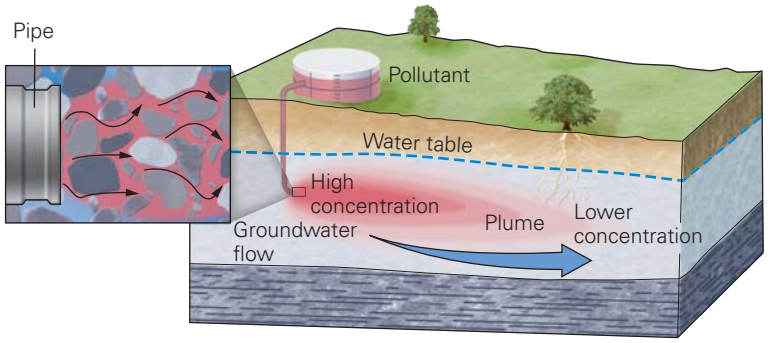
Take-Home Message

Groundwater usage can cause problems. Too much pumping lowers the water table, causing land subsidence and/or saltwater intrusion. Contamination can ruin a groundwater supply, for remediation of groundwater is extremely expensive.

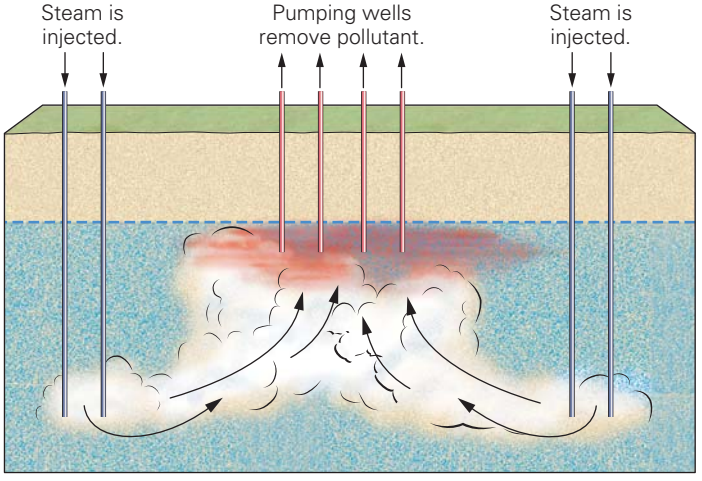
FIGURE 16.12 Contamination plumes in groundwater.



(a) Various sources of groundwater contamination.



(b) A contaminant plume as seen in cross section. The darker the color, the greater the concentration of contaminant.



(c) Steam injected beneath the contamination drives the contaminated water upward in the aquifer, where pumping wells remove it.

16.7 Caves and Karst

The Development of Caves

In 1799, as legend has it, a hunter by the name of Houchins was tracking a bear through the woods of Kentucky when the bear suddenly disappeared on a hillslope. Baffled, Houchins plunged through the brambles trying to sight his prey. Suddenly he felt a draft of surprisingly cool air flowing down the slope from uphill. Now curious, Houchins climbed up the hill and found a dark portal into the hillslope beneath a ledge of rocks. Bear tracks were all around—was the creature inside? He returned later with a lantern and cautiously stepped into the passageway. After walking a short distance, he found himself in a large, underground room. Houchins had discovered Mammoth Cave, an immense network of natural tunnels and subterranean chambers—a walk through the entire network would extend for 630 km!

Most large cave networks develop in limestone bedrock because limestone dissolves relatively easily in corrosive groundwater. Generally, the corrosive component in groundwater is dilute carbonic acid (H_2CO_3), which forms when water absorbs carbon dioxide (CO_2) from materials, such as soil, that it has passed through. When carbonic acid comes in contact with calcite ($CaCO_3$) in limestone, it reacts to produce HCO_3^{1-} and Ca^{2+} ions, which then dissolve.

Did you ever wonder . . .
why do huge underground caverns form?

In recent years, geologists have discovered that about 5% of limestone caves around the world form due to reactions with sulfuric-acid-bearing water—Carlsbad Caverns in New Mexico serves as an example. Such caves form where limestone overlies strata containing oil, because microbes can convert the sulfur in the oil to hydrogen sulfide gas, which rises and reacts with oxygen to produce sulfuric acid, which in turn eats into limestone and reacts to produce gypsum and CO_2 gas.

Geologists debate about the depth at which limestone cave networks form. Some limestone dissolves above the water

table, but it appears that most cave formation takes place in limestone that lies just below the water table, for in this interval the acidity of the groundwater remains high, the mixture of groundwater and newly added rainwater is not yet saturated with dissolved ions, and groundwater flow is fastest. The association between cave formation and the water table helps explain why openings in a cave network align along the same horizontal plane.

The Character of Cave Networks

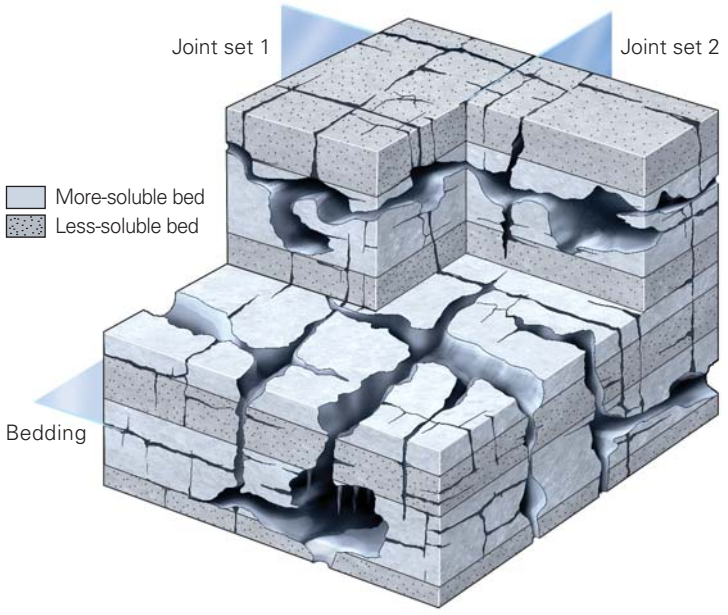
As we have noted, caves in limestone usually occur as part of a network. Cave networks include rooms, or chambers, which are large, open spaces sometimes with cathedral-like ceilings, and tunnel-shaped or slot-shaped passages. (See **Geology at a Glance**, pp. 490–491.) Some chambers may host underground lakes, and some passageways may serve as conduits for underground streams. The shape of the cave network reflects variations in permeability and in the composition of the rock from which the caves formed. Larger open spaces developed where the limestone was most soluble and where groundwater flow was fastest. Thus, in a sequence of strata, caves develop preferentially in the more soluble limestone beds. Passages in cave networks typically follow preexisting joints, for the joints provide secondary porosity along which groundwater can flow faster (**Fig. 16.13a**). Because joints commonly occur in orthogonal systems (consisting of two sets of joints oriented at right angles to each other; see Chapter 9), passages may form a grid.

Precipitation and the Formation of Speleothems

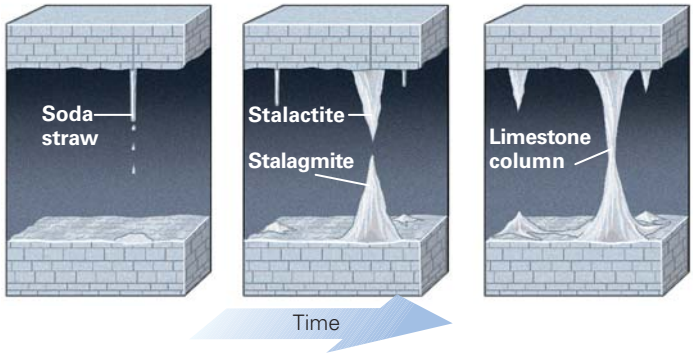
When the water table drops below the level of a cave, the cave becomes an open space filled with air. In places where downward-percolating groundwater containing dissolved calcite emerges from the rock above the cave and drips from the ceiling, the surface of the cave gradually changes. As soon as this water reenters the air, it evaporates a little and releases some of its dissolved carbon dioxide. As a result, calcium carbonate (limestone) precipitates out of the water and produces a type of travertine. The various intricately shaped formations that grow in caves by the accumulation of dripstone are called **speleothems**.

Cave explorers (spelunkers) and geologists have developed a detailed nomenclature for different kinds of speleothems (**Fig. 16.13b**). Where water drips from the ceiling of the cave, the precipitated limestone builds *dripstone*. Initially, calcite precipitates around the outside of the drip, forming a delicate, hollow tube called a soda straw. But eventually, the soda straw fills up, and water migrates down the margin of the cone to form a more massive, solid icicle-like cone called a **stalactite**. Where the drips hit the floor, the resulting precipitate builds an upward-pointing cone called a **stalagmite**.

FIGURE 16.13 Development of karst, dripstone, and flowstone.



(a) Joints act as conduits for water in cave networks. Caves and passageways follow joints, and preferentially form in more-soluble beds.



(b) The evolution of dripstone.



(c) Flowstone on the wall of a cave in Vietnam.

If the process of dripstone formation in a cave continues long enough, stalagmites merge with overlying stalactites to create travertine columns. In some cases, groundwater flows along the surface of a wall and precipitates to produce drape-like sheets of travertine called *flowstone* (Fig. 16.13c). The travertine of caves tends to be translucent and, when lit from behind, glows with an eerie amber light.

The Formation of Karst Landscapes

Limestone bedrock underlies most of the Kras Plateau in Slovenia, along the east coast of the Adriatic Sea. The name *kras*, which means rocky ground, is apt because this region includes abundant rock exposures (Fig. 16.14a). Geologists refer to regions such as the Kras Plateau, where surface landforms develop when limestone bedrock dissolves both at the surface and in underlying cave networks, as **karst landscapes** or karst terrains—from the Germanized version of kras (See for Yourself P).

Karst landscapes typically display a number of distinct landforms. Perhaps the most widespread are sinkholes (see Fig. 16.1), circular depressions that form either when the ground collapses into an underground cave below (as we discussed early in this chapter) or when surface bedrock dissolves in acidic water on the floor of a bog or pond. Not all of the caves or passageways beneath a karst landscape have collapsed, and this situation leads to unusual drainage patterns. Specifically, where surface streams intersect cracks (joints) or holes that link to caverns or passageways below, the water cascades downward into the subsurface and disappears (Fig. 16.14b). Such **disappearing streams** may flow through passageways underground and reemerge from a cave entrance downstream. In cases where the ground collapses over a long, joint-controlled passage, sinkholes may be elongate and canyon-like. Remnants of cave roofs remain as natural bridges. Ridges or walls between adjacent sinkholes tend to be steep-sided. Over time, the walls erode, leaving only jagged, isolated spires—a karst landscape dominated by such spires is called tower karst. The surreal collection of pinnacles constituting the tower karst landscape in the Guilin region of China inspired generations of artists who portray them on scroll paintings (Fig. 16.15).

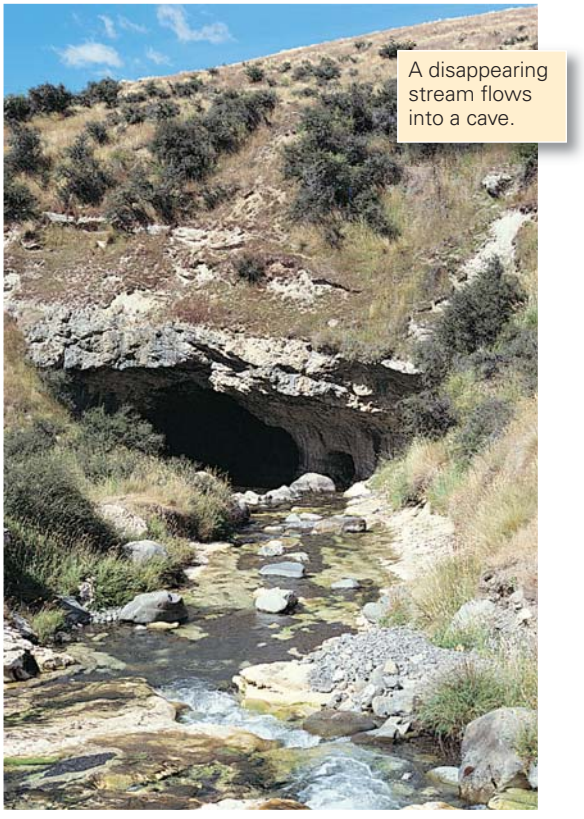
Karst landscapes form in a series of stages (Fig. 16.16a–c).

- *The establishment of a water table in limestone*: The story of a karst landscape begins after the formation of a thick interval of limestone in which the water table lies underground.
- *The formation of a cave network*: Once the water table has been established, dissolution begins and a cave network develops.
- *A drop in the water table*: If the water table later becomes lower, either because of a decrease in rainfall or because nearby rivers downcut and drain the region, newly formed caves dry out. Downward-percolating water emerges from the roofs of the caves; dripstone and flowstone precipitate.
- *Roof collapse*: If rocks fall off the roof of a cave for a long time, the roof eventually collapses. Such collapse creates sinkholes and troughs, leaving behind hills, ridges, and natural bridges.

FIGURE 16.14 Features of karst landscapes.



(a) Karst terrains typically have a rough, rocky surface.

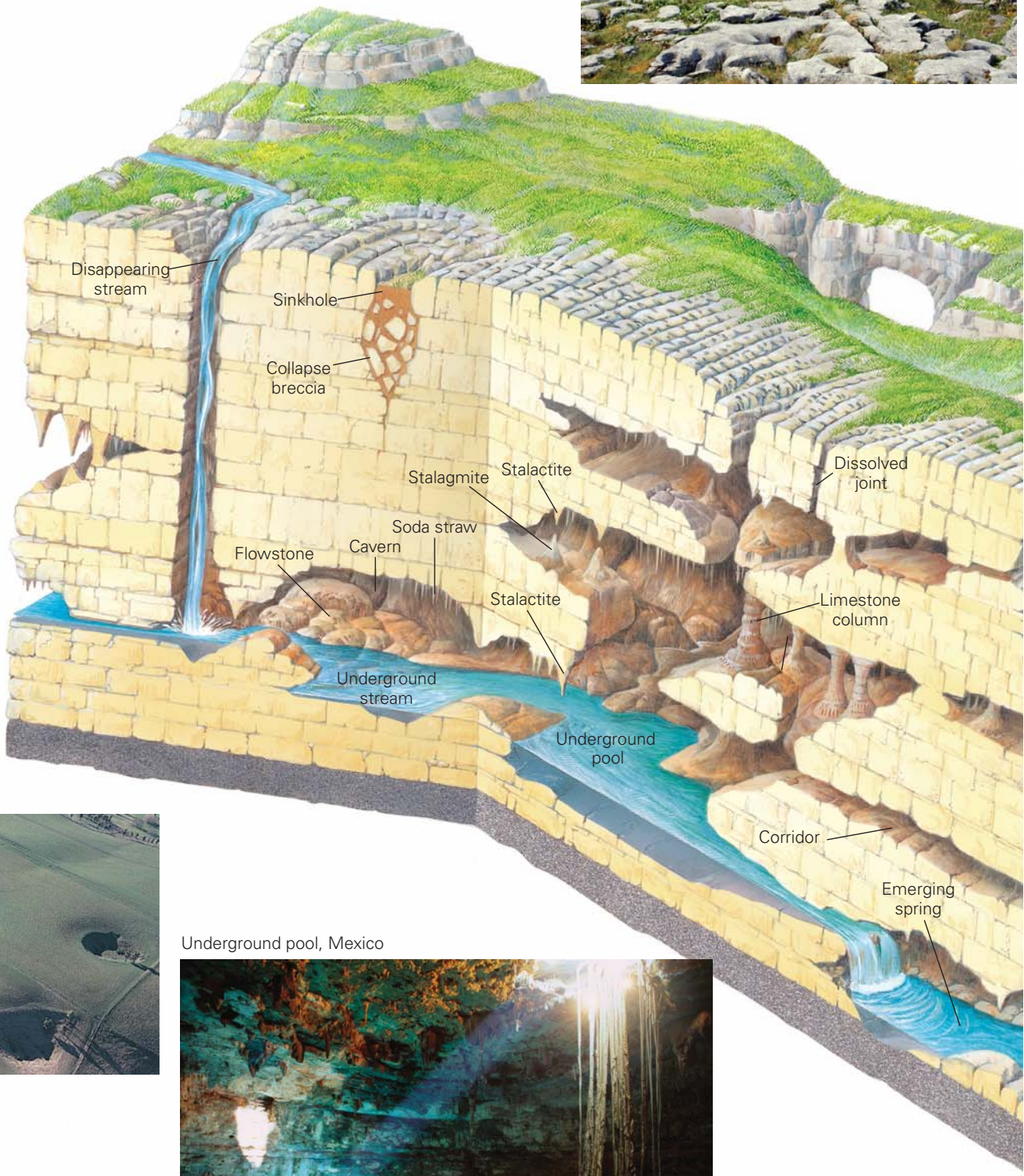


(b) Water may flow underground in a karst terrain.

Caves and Karst Landscapes

Limestone pavement, Ireland





Sinkholes



Underground pool, Mexico

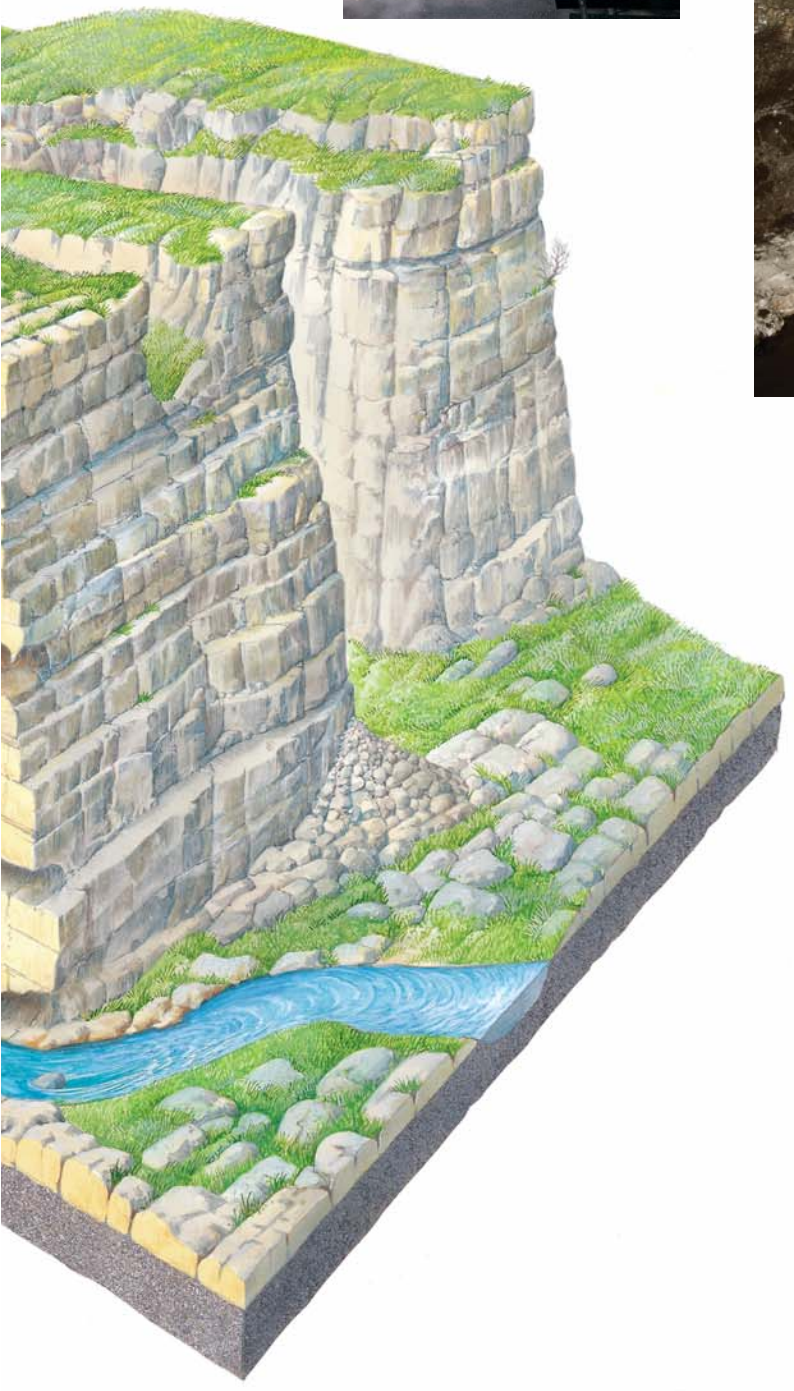


Natural Bridge, Virginia



Spelunker crawling in a cave





Limestone is soluble in acidic water. Much of the water that falls to the ground as rain, or seeps through the ground as groundwater, tends to be acidic, so in regions of the Earth where bedrock consists of limestone, we find signs of dissolution. Underground openings that develop by dissolution are called caves or caverns. Some of these may be large, open rooms, whereas others are long, narrow passages. Underground lakes and streams may cover the floor. A cave's location depends on the orientation of bedding and joints, for these features localize the flow of groundwater.

Caves originally form at or near the water table. As the water table drops, caves empty of most water and become filled with air. In many locations, groundwater drips from the ceiling of a cave or flows along its walls. As the water evaporates and loses its acidity, new calcite precipitates. Over time, this calcite builds into cave formations, or speleothems, such as stalactites, stalagmites, columns, and flowstone.

Distinctive landscapes, called karst landscapes, develop at the Earth's surface over limestone bedrock. In such regions, the ground may be rough where rock has dissolved along joints; where the roofs of caves collapse, sinkholes develop. If a surface stream flows into a cave network, we say that the stream is "disappearing." The water from such streams may reemerge elsewhere as a spring. In some places, the collapse of subsurface openings leaves behind natural bridges.

FIGURE 16.15 Tower karst forms a spectacular landscape in southern China.

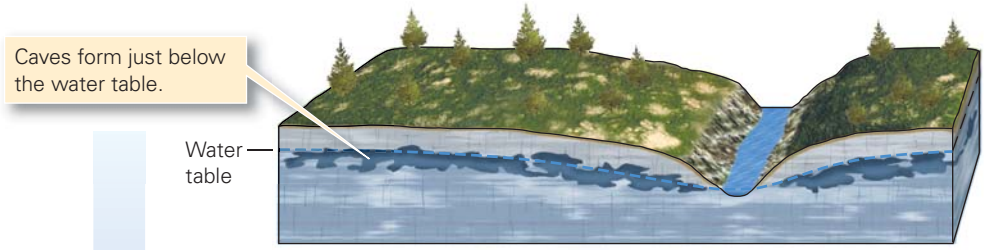


Chinese artists painted scrolls depicting forested towers of karst.

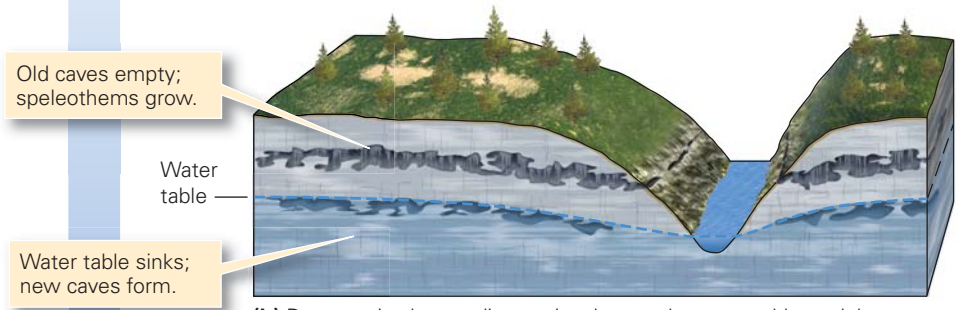


The landscape is treeless today, a consequence of industrialization policies in the 1950s.

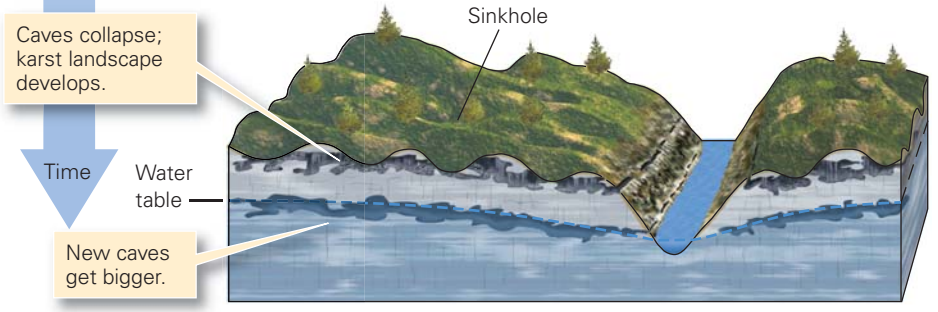
FIGURE 16.16 The progressive formation of caves and a karst landscape.



(a) Dissolution takes place near the water table in an uplifted sequence of limestone.



(b) Downcutting by an adjacent river lowers the water table, and the caves empty. Speleothems grow.



(c) After roof collapse, the landscape becomes pockmarked with sinkholes.

Life in Caves

Despite their lack of light, caves are not sterile, lifeless environments. Caves that are open to the air provide a refuge for bats as well as for various insects and spiders. Similarly, fish and crustaceans enter caves where streams flow in or out. Species living in caves have evolved some unusual characteristics. For example, cave fish lose their pigment and in some cases their eyes. Recently, explorers discovered caves in Mexico in which warm, mineral-rich groundwater currently flows. Colonies of bacteria metabolize sulfur-containing minerals in this water and create thick mats of living ooze in the complete darkness of the cave. Long gobs of this bacteria slowly drip from the ceiling. Because of the mucus-like texture of these drips, they have come to be known as "snotites".

Take-Home Message

Reaction with natural acids dissolves limestone underground to form caverns. Most dissolution takes place near the water table. If the water table sinks, dripping of water in caves can produce speleothems. Collapse of a cavern network produces karst terrain.



ANOTHER VIEW Swamps are swamps because the land surface lies just below the water table. The bald cypress trees of this swamp in southern Illinois have adapted to life in soggy ground. During dry seasons, the water table sinks below the ground surface and the land dries out.

CHAPTER 16 REVIEW

Chapter Summary

- During the hydrologic cycle, water infiltrates the ground and fills the pores and cracks in rock and sediment. This subsurface water is called groundwater. The amount of open space in rock or sediment is its porosity; and the ease with which water can flow through is its permeability.
- Aquifers are relatively permeable, and aquitards are relatively impermeable.
- The water table is the surface in the ground above which pores contain mostly air, and below which pores are filled with water. The shape of a water table is a subdued imitation of the shape of the overlying land surface.
- Groundwater flows wherever the water table has a hydraulic gradient, and moves from recharge areas to discharge areas. The velocity of flow depends on permeability and the hydraulic gradient.
- Groundwater contains dissolved ions, which may come out of solution to form the cement in clastic rocks and veins.
- Groundwater can be extracted in wells. An ordinary well penetrates below the water table, but in an artesian well, water rises on its own. Pumping water out of a well too fast causes drawdown, yielding a cone of depression. At a spring, groundwater exits the ground on its own.
- Hot springs and geysers release hot water to the Earth's surface. This water may have been heated by residing very deep in the crust, or by the proximity of a magma chamber.
- Groundwater is a precious resource, used for municipal water supplies, industry, and agriculture. In recent years, some regions have lost their groundwater supply because of overuse or contamination.
- When limestone dissolves just below the water table, underground caves develop. Soluble beds and joints determine the location and orientation of caves. If the water table drops, caves empty out. Limestone then precipitates out of water dripping from cave roofs, and creates speleothems.
- Regions where abundant caves have collapsed to form sinkholes are called karst landscapes. These terrains can contain sinkholes, natural bridges, and disappearing streams.

Key Terms

aquifer (p. 476)
aquitard (aquiclude) (p. 476)
artesian spring (p. 481)
artesian well (p. 480)
bioremediation (p. 486)
capillary fringe (p. 477)
cone of depression (p. 480)
contaminant plume (p. 486)
Darcy's law (p. 479)
disappearing stream (p. 489)
discharge area (p. 478)
geothermal region (p. 481)
geyser (p. 482)
groundwater (p. 474)
groundwater contamination (p. 486)
hard water (p. 486)
hot spring (p. 481)
hydraulic gradient (p. 479)
hydraulic head (p. 478)
karst landscape (p. 489)
oasis (p. 481)
ordinary well (p. 480)
perched water table (p. 477)
permeability (p. 475)
pore (p. 474)
porosity (p. 474)
recharge area (p. 478)
sinkhole (p. 473)
soil moisture (p. 474)
speleothem (p. 488)
spring (p. 480)
stalactite (p. 488)
stalagmite (p. 488)
water table (p. 477)
well (p. 480)

Review Questions

1. How do porosity and permeability differ? Give examples of substances with high porosity but low permeability.
2. What is a water table, and what factors affect the level of the water table? What factors affect the flow direction of the water below the water table?
3. How does the rate of groundwater flow compare with that of moving ocean water or river currents?
4. What factors control the rate of groundwater flow?
5. How does the chemical composition of groundwater change with time? What is "hard water"?
6. How does excessive pumping affect the local water table?
7. How is an artesian well different from an ordinary well?
8. Why do natural springs form?
9. Explain why hot springs form and why geysers erupt.

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Visual problems on water tables, aquifers, and aquitards.
- A labeling exercise on karst landscapes.
- A What a Geologist Sees exercise on identifying sources of groundwater contamination.

10. Is groundwater a renewable or nonrenewable resource?
11. Describe some of the ways in which human activities can adversely affect the water table.
12. What are some sources of groundwater contamination? How can contamination be prevented?
13. Describe the process leading to the formation of caves and the speleothems within caves.
14. Describe the various features of a karst landscape, and explain how they evolve.

On Further Thought

15. The population of Desert Paradise (a fictitious town in the southwestern United States) has been doubling every seven years. Most of the new inhabitants are "snowbirds," people escaping the cold winters of more northerly latitudes. There are no permanent streams or lakes anywhere near DP. In fact, the only standing water in the town occurs in the ponds of golf courses. The water in these ponds needs to be replenished almost constantly, for without supplementing it, the water seeps into the ground quickly and the ponds dry up. The golf courses and yards of the suburban-style developments all have lawns of green grass. DP has been growing on a flat, gravel-filled basin between two small mountain ranges. Where does the water supply of DP come from? What do you predict will happen to the water table of the area in coming years, and how might the land surface change as a consequence? Is there a policy that you might suggest to the residents of DP that could slow the process of change?

SEE FOR YOURSELF P. . . **Groundwater and Karst Landscapes**

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet P of our **Geotours Workbook**.



Sinkholes in Central Florida
Latitude 28°37′50.59″N,
Longitude 81°23′13.60″W

Several sinkholes, that range from about 100 to 800 m across can be seen from an elevation of 20 km. These lie within suburban developments. Since the water table lies very close to the surface, the sinkholes have filled with water and are now lakes.

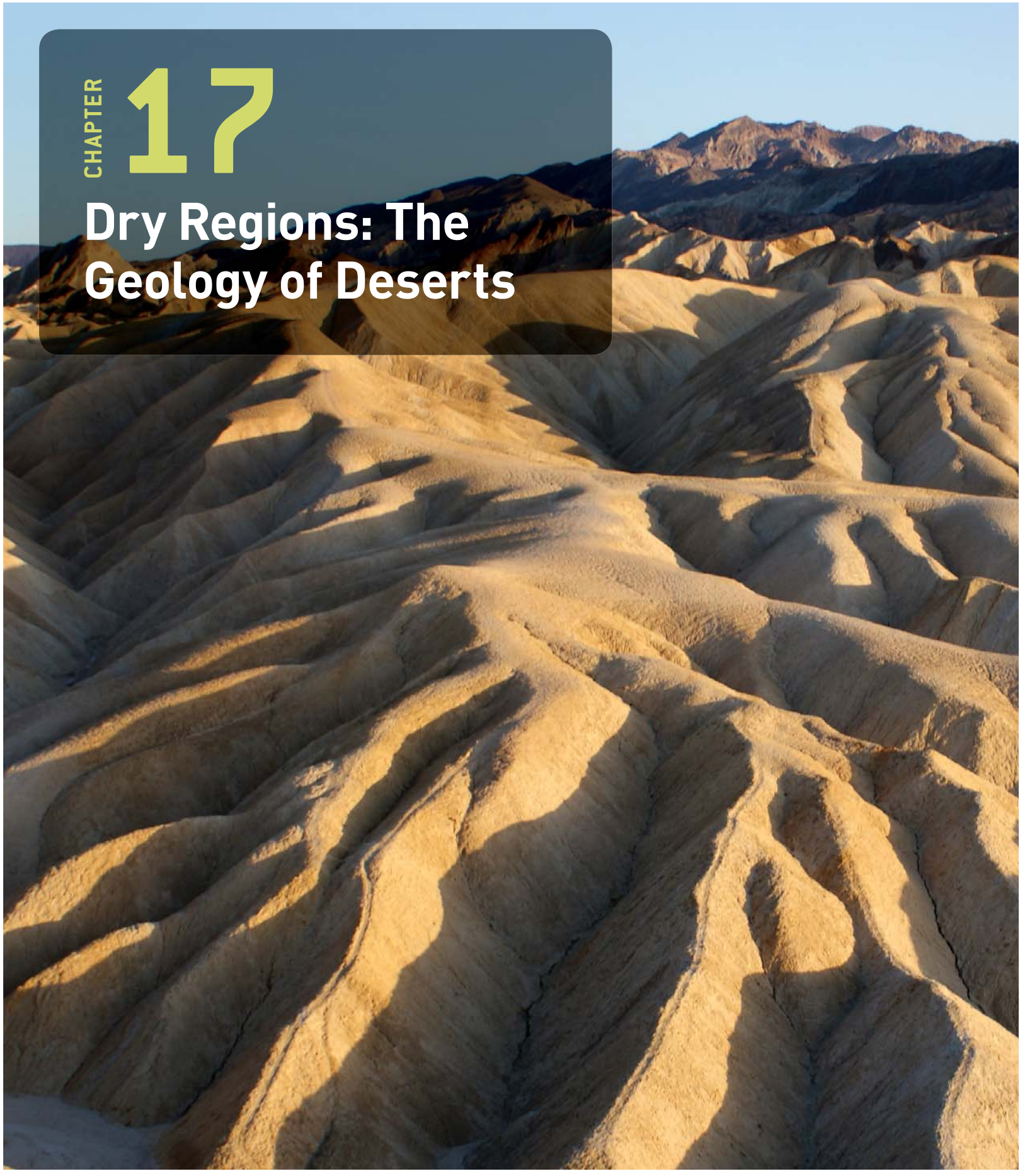


Karst landscape in Puerto Rico
Latitude 18°23′53.04″N,
Longitude 66°25′49.43″W

From an elevation of 7 km, we see a karst terrain in central Puerto Rico. Each of the rounded depressions is a sinkhole. Ridges of limestone separate adjacent sinkholes.

CHAPTER 17

Dry Regions: The Geology of Deserts





At Zabriskie Point, near Death Valley, it's too dry for vegetation to grow. So, during infrequent storms, the soft, tan rock erodes quickly.

Chapter Objectives

By the end of this chapter, you should know . . .

- why certain regions of the land have been classified as deserts, and what factors cause these regions to have arid climates.
- how weathering and erosional processes in deserts differ from those in temperate lands.
- the distinctive landforms and landscapes of deserts.
- how certain species of plants and animals survive desert climates, and how human activity may transform vegetated regions into deserts.

The bare hills are cut out with sharp gorges, and over their stone skeletons scanty earth clings. . . . A white light beat down, dispelling the last tract of shadow, and above hung the burnished shield of hard, pitiless sky.

—Clarence King (1842–1901; first director of the U.S. Geological Society, describing a desert)

17.1 Introduction

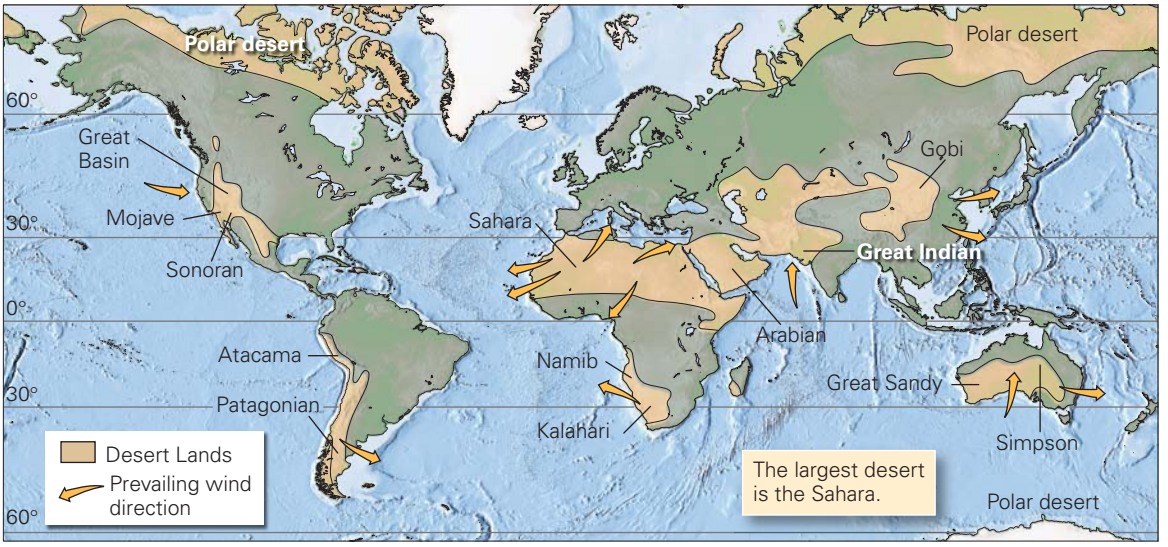
For generations, nomadic traders have saddled camels to traverse the Sahara Desert in northern Africa (**Fig. 17.1a**). The Sahara, the world's largest desert, receives so little rainfall that it has hardly any surface water or vegetation. So camels must be able to walk for up to 3 weeks without drinking or eating. They can survive these journeys because they sweat relatively little; they have the ability to metabolize their own body fat to produce new water; and they can withstand severe dehydration.

The survival challenges faced by a camel emphasize that deserts are lands of extremes—extreme dryness, heat, cold, and, in some places, beauty. Desert vistas include everything from sand seas to sagebrush plains, cactus-covered hills to endless stony pavements. Although less populated than other regions on Earth, deserts cover about 25% of the land surface, and thus constitute an important component of the Earth System (**Fig. 17.1b**). In this chapter, we take a look at the desert landscape. We learn why deserts occur where they do, and how erosion and deposition shape their surface. We conclude by exploring life in the desert and by examining the problem of desertification, the gradual transformation of temperate lands into desert.

FIGURE 17.1 Deserts and their hardy inhabitants.



(a) Camels can survive the harsh desert conditions of the Arabian Desert.



(b) The global distribution of deserts. Arid regions cover 25% of the land surface.

17.2 The Nature and Locations of Deserts

What Is a Desert?

Formally defined, a **desert** is a region that is so arid (dry) that it supports vegetation on no more than 15% of its surface. In general, desert conditions exist where less than 25 cm of rain falls per year, on average. Because of the lack of water, deserts contain no permanent streams, except for those that bring water in from temperate regions elsewhere.

Note that the definition of a desert depends on a region's aridity, not on its temperature. Geologists, therefore, distinguish between cold deserts, where temperatures generally stay below about 20°C for the year, and hot deserts, where summer daytime temperatures exceed 35°C. Cold deserts exist at high latitudes where the Sun's rays strike the Earth obliquely and thus don't provide much energy, at high elevations where the air is too thin to hold much heat, or in lands adjacent to cold oceans, where the cold water absorbs heat from the air above. Hot deserts develop at low latitudes where the Sun's rays strike the desert at a high angle, at low elevations where dense air can hold a lot of heat, and in regions distant from the cooling effect of cold ocean currents. The hottest recorded temperatures on Earth occur in low-latitude, low-elevation deserts—58°C (136°F) in Libya and 57°C (133°F) in Death Valley, California.

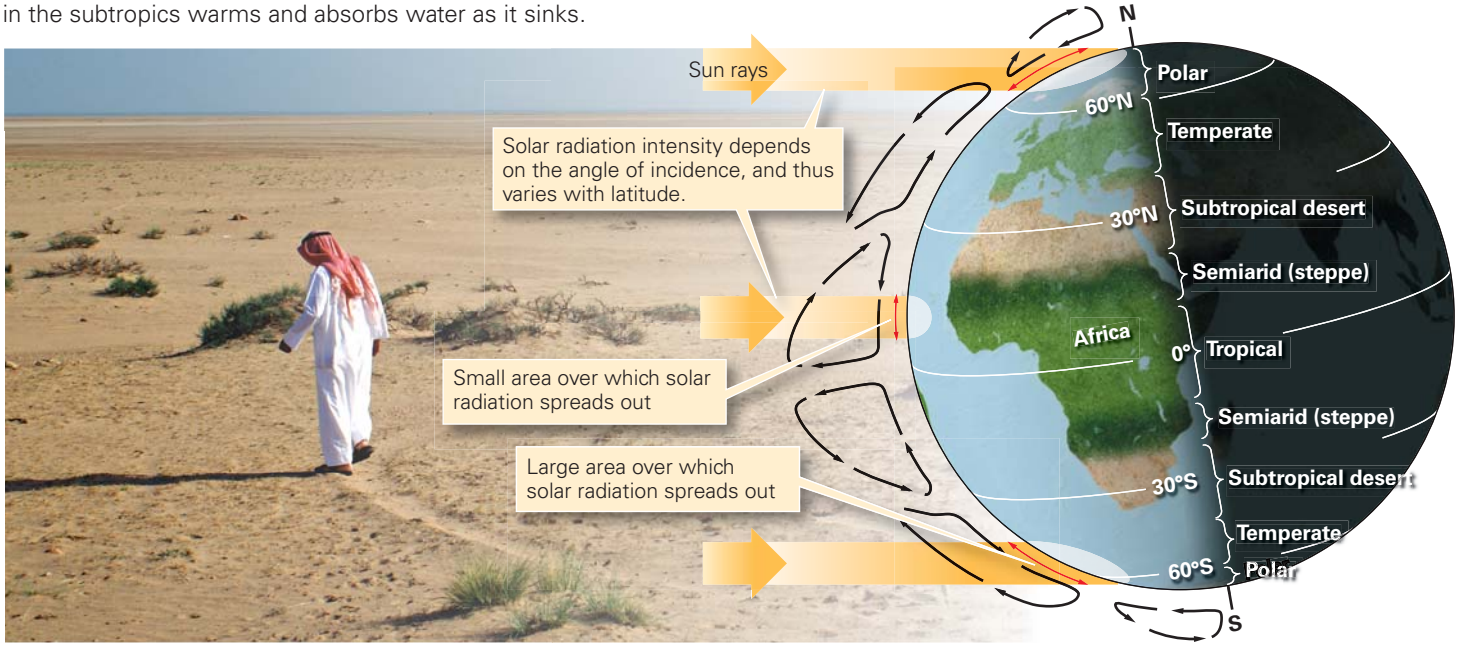
Did you ever wonder . . .
how hot can it become in a desert?

Types of Deserts

Each desert on Earth has unique characteristics of landscape and vegetation that distinguish it from others. Geologists group deserts into five different classes, based on the environment in which the desert forms (Fig. 17.2).

- *Subtropical deserts*: Subtropical deserts (such as the Sahara, Arabian, Kalahari, and Australian) form because of the regional pattern of air circulation in the atmosphere. At the equator, the air becomes warm and humid, for sunlight is intense and water rapidly evaporates from the ocean. The hot, moisture-laden air rises to great heights above the equator. As this air rises, it expands and cools, and can no longer hold so much moisture. Water condenses and falls in downpours that feed the lushness of the equatorial rain forest. The now-dry air high in the troposphere spreads laterally north or south. When this air reaches latitudes of 20° to 30°, a region called the subtropics, it has become cold and dense enough to sink. Because the air is dry, no clouds form, and intense solar radiation strikes the Earth's surface. The sinking, dry air becomes denser and heats up, soaking up any moisture present. In the regions swept by this hot air on its journey back to the equator, evaporation rates greatly exceed rainfall rates, so the land becomes parched.
- *Deserts formed in rain shadows*: As air flows over the sea toward a coastal mountain range, the air must rise (Fig. 17.3). As the air rises, it expands and cools. The water it contains condenses and falls as rain on the seaward flank of the mountains, nourishing a coastal rain forest. When the air finally reaches the inland side of the mountains, it has lost all its moisture and can no longer provide rain. As a consequence, a **rain shadow** forms, and the land beneath the rain shadow becomes a desert. A rain-shadow desert can be found east of the Cascade Mountains in the state of Washington.

FIGURE 17.2 Subtropical deserts form because the air that convectively flows downward in the subtropics warms and absorbs water as it sinks.



- *Coastal deserts formed along cold ocean currents*: Cold ocean water cools the overlying air by absorbing heat, thereby decreasing the capacity of the air to hold moisture. For example, the cold Humboldt Current, which carries water northward from Antarctica to the western coast of South America, cools the air that blows east, over the coast. The air is so dry when it reaches the coast that rain rarely falls on the coastal areas of Chile and Peru. As a result, this region hosts a desert landscape, including one of the driest deserts in the world, the Atacama (**Fig. 17.4a, b**). Portions of this narrow desert received no rain at all between 1570 and 1971.
- *Deserts formed in the interiors of continents*: As air masses move across a continent, they lose moisture by dropping rain, even in the absence of a coastal mountain range. Thus, when an air mass reaches the interior of a broad continent, it has become so dry that the land beneath becomes arid. The largest present-day example of such a continental-interior desert, the Gobi, lies in central Asia.
- *Deserts of the polar regions*: So little precipitation falls in Earth's polar regions (north of the Arctic Circle and south of the Antarctic Circle) that these areas are, in fact, arid. Polar regions are dry, in part, for the same reason that the subtropics are dry (the global pattern of air circulation means that the air flowing over these regions is dry), and in part, for the same reason that coastal areas along cold currents are dry (cold air holds little moisture).

Different regions of the land surface have become deserts at different times in the Earth's history, because plate movements change the latitude of landmasses, the position of landmasses relative to the coast, and the proximity of landmasses to a mountain range. Because of plate tectonics, some regions that were deserts in the past are temperate or tropical regions now, and vice versa.

Take-Home Message

Deserts are so arid that they host only very sparse vegetation. They occur in several settings: subtropical dry climates, rain shadows, coasts bordered by cold currents, continental interiors, and polar regions.

FIGURE 17.3 The formation of a rain-shadow desert. Moist air rises and drops rain on the coastal side of the range. By the time the air has crossed the mountains, it is dry.

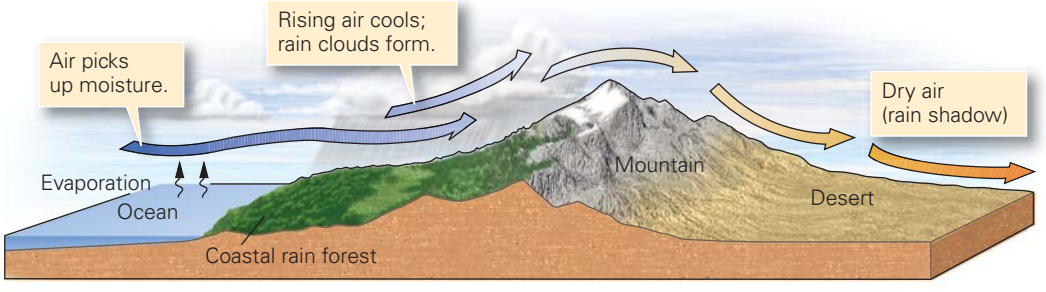
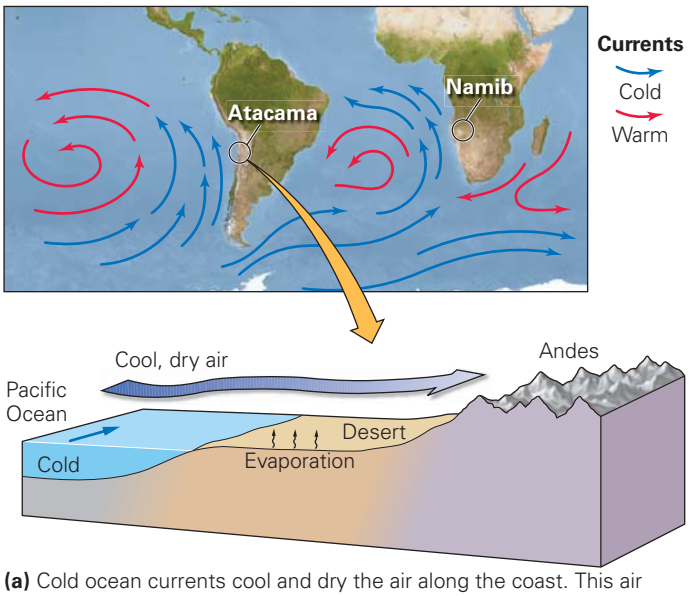


FIGURE 17.4 The formation of a coastal desert.



(a) Cold ocean currents cool and dry the air along the coast. This air absorbs moisture from adjacent coastal land.



(b) The Atacama Desert is the driest place on Earth.

17.3 Weathering and Erosional Processes in Deserts

Without the protection of foliage to catch rainfall and slow the wind, and without roots to hold regolith in place, rain and wind can attack and erode the land surface of deserts and soil tends to be sparse. The result, as we have noted, is that hillslopes are typically bare, and plains can be covered with stony debris or drifting sand.

Arid Weathering and Desert Soil Formation

In the desert, as in temperate climates, physical weathering happens primarily when joints (natural fractures) split rock into pieces. Joint-bounded blocks eventually break free of bedrock and tumble down slopes, fragmenting into smaller pieces as they fall. In temperate climates, thick soil develops and covers bedrock. In deserts, however, bedrock commonly remains exposed, forming rugged, rocky escarpments.

Chemical weathering happens more slowly in deserts than in temperate or tropical climates, because less water is available to react with rock. Still, rain or dew provides enough moisture for some weathering to occur. This water seeps into rock and leaches (dissolves and carries away) calcite, quartz, and various salts. Leaching effectively rots the rock by transforming it into a poorly cemented aggregate. Over time, the rock will crumble and form a pile of unconsolidated sediment, susceptible to transport by water or wind.

Although enough rain falls in deserts to leach chemicals out of sediment and rock, there is not enough rain to carry the chemicals away entirely. So they precipitate to form calcite and other minerals in regolith beneath the surface. The new minerals may bind clasts together to form a rock-like material called *calcrete*.

Shiny **desert varnish**, a dark, rusty brown coating of iron oxide, manganese oxide, and clay, may cover the surface of rocks in deserts (Fig. 17.5a). Desert varnish was once thought to form when water from rain or dew seeped into a rock, dissolved iron and magnesium ions, and carried the ions back to the surface of the rock by capillary action. More recent studies, however, suggest that desert varnish is not necessarily derived from the rock it coats. Instead, the iron and manganese in the varnish may come from dust that settles on the surface of the rock, for in the presence of moisture, microorganisms (bacteria and archaea) can extract iron and manganese from the dust and transform it into oxide minerals. Such varnish won't form in humid climates, because rain washes away the dust.

Desert varnish takes a long time to form. In fact, the thickness of a desert varnish layer provides an approximate estimate of how long a rock has been exposed at the ground surface. In past centuries, Native Americans used desert-varnished rock as a medium for art: by chipping away the varnish to reveal the underlying lighter-colored rock, they were able to create figures or symbols on a dark background. The resulting drawings are called **petroglyphs**.

Because of the lack of plant cover in deserts, variations in bedrock and soil color visually stand out. Slight variations in the concentration of iron, or in the degree of iron oxidation, in adjacent beds result in spectacular color bands in rock layers and the thin soils derived from them. The Painted Desert of northern Arizona earned its name from the brilliant and varied hues of oxidized iron in the region's shale bedrock (Fig. 17.5b).

Water Erosion

Although rain rarely falls in deserts, when it does come, it can radically alter a landscape in a matter of minutes. Since deserts

FIGURE 17.5 Soil formation and chemical weathering in deserts.



(a) Native Americans chiseled this petroglyph of a snake into desert varnish on a Utah boulder.



(b) The red hues of the Painted Desert in Arizona are due to the oxidation of iron in the rock.

lack plant cover, rainfall, sheetwash, and stream flow are all extremely effective agents of erosion. It may seem surprising, but water generally causes more erosion than does the wind in most deserts (**Fig. 17.6a**).

Water erosion begins with the impacts of raindrops, which eject sediment from the ground into the air. On a hill, the ejected sediment lands downslope. The ground quickly becomes saturated with water during a heavy rain, so water starts flowing across the surface, carrying the loose sediment with it. Within minutes after a heavy downpour begins, dry stream channels fill with a turbulent mixture of water and sediment, which rushes downstream as a flash flood. When the rain stops, the water sinks into the stream bed's gravel and disappears—such streams are called intermittent, or ephemeral streams (see Chapter 14). Because of the relatively high viscosity of the water (owing to its load of suspended sediment) and the velocity and turbulence of the flow, flash floods in deserts cause intense erosion. Dry stream channels in desert regions of southwestern North America are called **dry washes**, or **arroyos**, and in the Middle East and North Africa they are called wadis (**Fig. 17.6b**).

Wind Erosion

In temperate and humid regions, plant cover protects the ground surface from the wind, but in deserts, the wind has direct access to the ground. Wind, just like flowing water, can carry sediment both as suspended load and as surface load.

FIGURE 17.6 Evidence of erosion by running water in deserts.



(a) These hills in the desert near Las Vegas, Nevada, are bone dry, but their shape indicates erosion by water. Note the numerous stream channels.

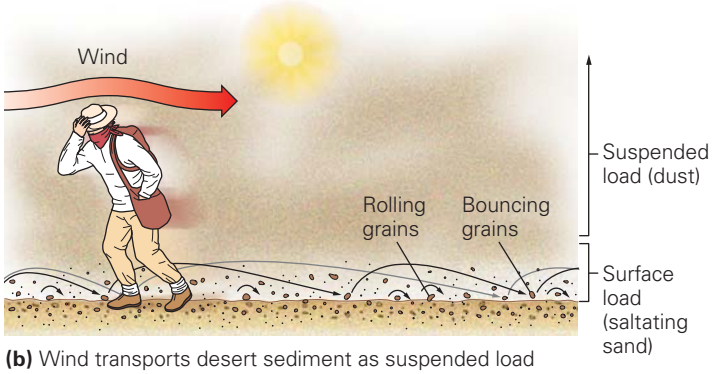


(b) Gravel and sand are left behind on the floor of a dry wash after a flash flood in Death Valley. Erosion by the water is cutting a channel.

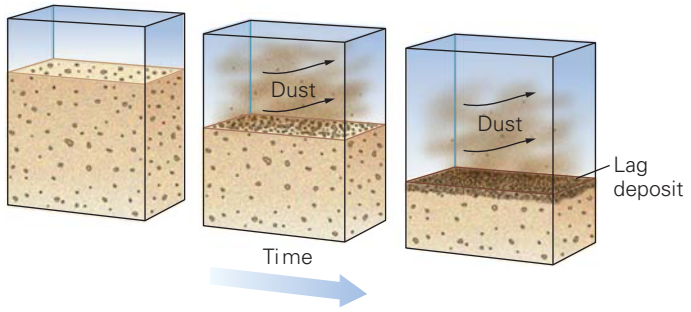
FIGURE 17.7 Sediment transport by wind in deserts.



(a) A huge dust storm approaching Phoenix, Arizona.



(b) Wind transports desert sediment as suspended load and surface load.



(c) A lag deposit develops when wind blows away finer sediment, leaving behind a layer of coarser grains.

Suspended load (fine-grained sediment such as dust and silt held in suspension) stays in the air for a long time and moves with it. The suspended sediment can be carried so high into the atmosphere (up to several kilometers above the Earth's surface) and so far downwind (tens to thousands of kilometers) that it may move completely out of its source region. Particularly strong winds can generate a dramatic **dust storm**, or haboob, that can be 100 km long and 1.5 km high (Fig. 17.7a). A dust storm, as it approaches, looks like a roiling, opaque wave. A particularly large one engulfed Phoenix, Arizona, in 2011, and shut down the airport. Dust storms are fairly common in the Sahara and Arabian Deserts, where they are known as haboobs.

Surface loads, or bed loads, start moving only in moderate to strong winds, for such winds can roll and bounce sand grains along the ground, a process called **saltation**. Saltation begins when turbulence caused by wind shearing along the ground surface lifts sand grains. The grains move downwind, following an asymmetric, arch-like trajectory. Eventually, they return to the ground, where they strike other sand grains, causing the new grains to bounce up and drift or roll downwind. The collisions between sand grains make the grains rounded and frosted. Saltating grains generally rise no more than 0.5 m, but where sand bounces on bedrock the grains may rise 2 m.

The size of clasts that wind can carry depends on the wind velocity. Wind, therefore, does an effective job of sorting sediment, sending dust-sized particles skyward and sand-sized particles bouncing along the ground, while pebbles and larger grains remain behind. In some cases, wind carries away so much fine sediment that pebbles and cobbles become concentrated at the ground surface (Fig. 17.7b, c). An accumulation of coarser sediment left behind when fine-grained sediment blows away is called a **lag deposit**.

Just as sandblasting cleans the grime off the surface of a building, windblown sand and dust grind away at surfaces in the desert. Over long periods of time, such wind abrasion creates smooth faces, or facets, on pebbles, cobbles, and boulders. If a rock rolls or tips relative to the prevailing wind direction after it has been faceted on one side, or if the wind shifts direction, a new facet with a different orientation forms, and the two facets join at a sharp edge. Rocks whose surface has been faceted by the wind are faceted rocks, or **ventifacts** (Fig. 17.8). Wind abrasion also gradually polishes and bevels down irregularities

FIGURE 17.8 The progressive development of a ventifact.

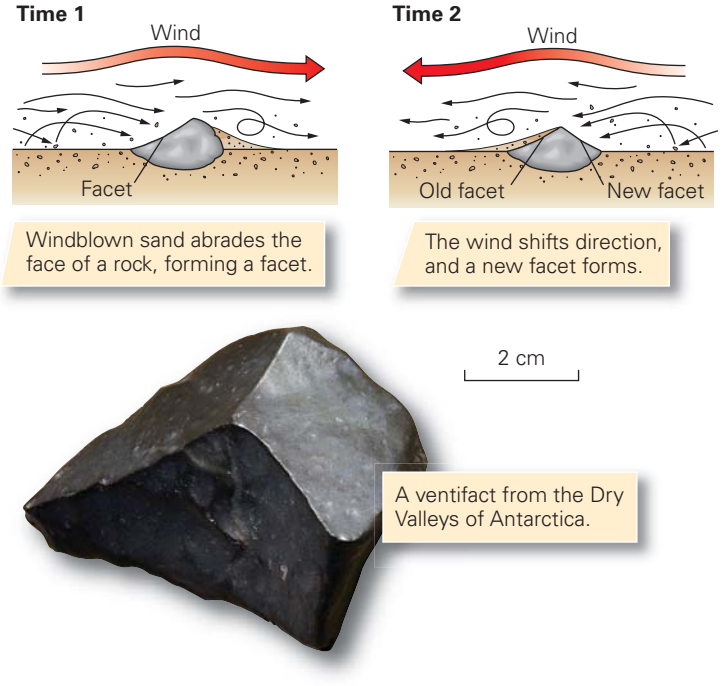


FIGURE 17.9 Wind erosion in Death Valley has left bushes perched on mounds; roots keep soil from blowing away.



on a desert pavement and polishes the surfaces of desert-varnished outcrops, giving them a reflective sheen.

Over time, in regions where the substrate consists of soft sediment, wind picks up and removes so much sediment that the land surface becomes lower. The process of lowering the land surface by wind erosion is called **deflation**. Shrubs can stabilize a small patch of sediment with their roots, so after deflation a forlorn shrub with its residual pedestal of soil stands isolated above a lowered ground surface (Fig. 17.9). In some places, the shape of the land surface twists the wind into a turbulent vortex that causes enough deflation to scour a deep, bowl-like depression called a blowout.

Take-Home Message

Physical weathering dominates in deserts. Soils are thin, and desert varnish may coat rock surfaces. Water causes most erosion and sediment transport but rarely flows, so stream channels are dry washes. Wind transports sediment and carves ventifacts.

17.4 Deposition in Deserts

We've seen that erosion relentlessly eats away at bedrock and sediment in deserts. Where does the debris go? Below, we examine the various desert settings in which sediment accumulates.

Talus Aprons

Over time, joint-bounded blocks of rock break off ledges and cliffs on the sides of hills. Under the influence of gravity, the resulting debris tumbles downslope and accumulates as **talus**, a pile of debris at the base of a hill. Talus can survive for a long time in desert climates, so we typically see aprons of talus fringing the bases of cliffs in deserts (Fig. 17.10a).

Alluvial Fans

Flash floods can carry sediment downstream in a steep-walled canyon. In some cases, the water contains so much sediment that it is best called a debris flow (see Chapter 13). When the turbulent water flows out into a plain at the mouth of a canyon, it spreads out over a broader surface and slows. As a consequence, sediment in the water settles out. The channel that emerges from the mountains tends to subdivide into a number of subchannels or distributaries that diverge outward. The network of distributaries spreads the sediment, or alluvium, out into a broad **alluvial fan**, a wedge- or apron-shaped pile of sediment (Fig. 17.10b). Alluvial fans emerging from adjacent valleys may merge and overlap along the front of a

FIGURE 17.10 Production and transportation of debris and sediment in deserts.

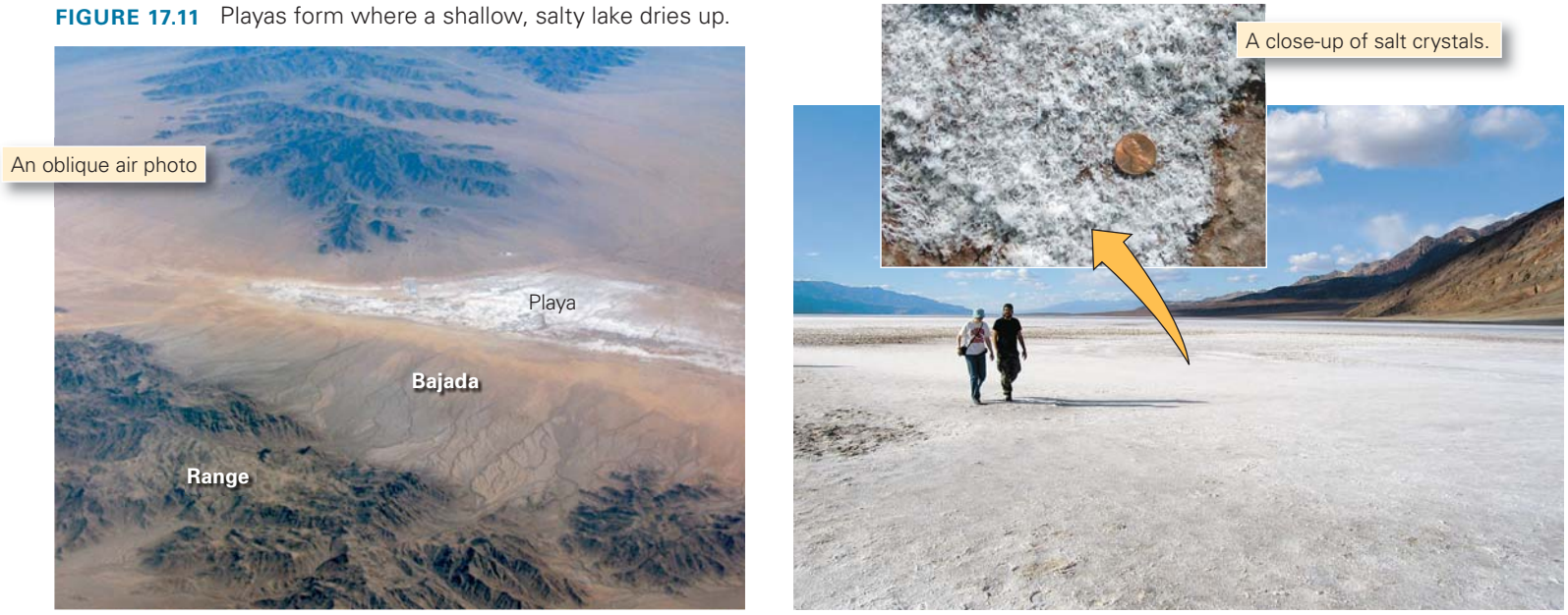


(a) This talus apron along the base of a desert cliff formed from rocks that broke off and tumbled down the cliff.



(b) Sediment in this alluvial fan in Death Valley was carried by flash floods. The fan forms at the mountain front where water slows.

FIGURE 17.11 Playas form where a shallow, salty lake dries up.



(a) This playa in southern California formed at the base of a bajada.

(b) White salt crystals encrust the floor of a playa in Death Valley.

mountain range, producing an elongate wedge of sediment called a bajada. Over long periods, the sediment of bajadas can fill in adjacent valleys to depths of several kilometers.

Playas and Salt Lakes

Water from a flash flood occasionally reaches the center of an alluvium-filled basin. But if the supply of water is relatively small, the water quickly sinks into the permeable alluvium without accumulating as a standing body. During a particularly large storm or an unusually wet spring, however, a temporary lake may develop over the low part of a basin. During drier times, such desert lakes evaporate entirely, leaving behind a dry, flat, exposed lake bed known as a **playa** (Fig. 17.11a, b). Over time, a smooth crust of clay and various salts (halite, gypsum, borax, and other minerals) accumulates on the surface of playas.

Where sufficient water flows into a desert basin, it creates a permanent lake. If the basin is an interior basin, with no outlet to allow water to flow out, the lake becomes very salty, because although its water escapes by evaporation in the desert sun, its salt cannot. The Great Salt Lake, in Utah, exemplifies this process. Even though the streams feeding the lake are fresh enough to drink, their water contains trace amounts of dissolved salt ions. Because the lake has no outlet, these ions have become concentrated in the lake over time, making it even saltier than the ocean.

Deposition from the Wind

As mentioned earlier, wind carries two kinds of sediment loads—a suspended load of dust-sized particles and a surface load of sand. Much of the dust is carried out of the desert and accumulates elsewhere. Sand, however, cannot travel far, and accumulates within the desert in piles called **dunes**, ranging in size from less than a meter to over 300 m high. In favorable locations, dunes accumulate to form vast "sand seas." We'll look at dunes in more detail later in this chapter.

Take-Home Message

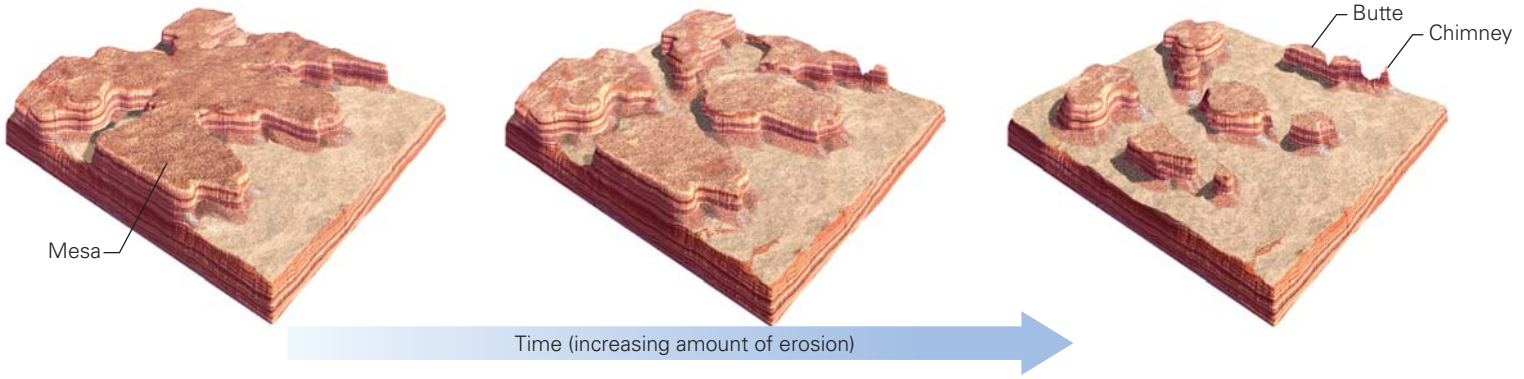
Sediment carried by water and wind in deserts accumulates in a variety of landforms. Alluvial fans form at the outlets of canyons, playas form where water temporarily collects in basins, and dunes form where large amounts of sand are available.

17.5 Desert Landscapes and Life

The popular media commonly portray deserts as endless vistas of sand, punctuated by the occasional palm-studded oasis. In reality, not all desert landscapes are buried by sand. Some deserts are vast, rocky plains; others sport a stubble of cacti and other hardy desert plants; and still others display intricate rock formations that look like medieval castles (See for Yourself Q). Explorers of the Sahara, for example, traditionally distinguished among hamada (barren, rocky highlands), reg (vast, stony plains), and erg (sand seas in which large dunes form).

Did you ever wonder . . .
are all deserts completely covered by sand?

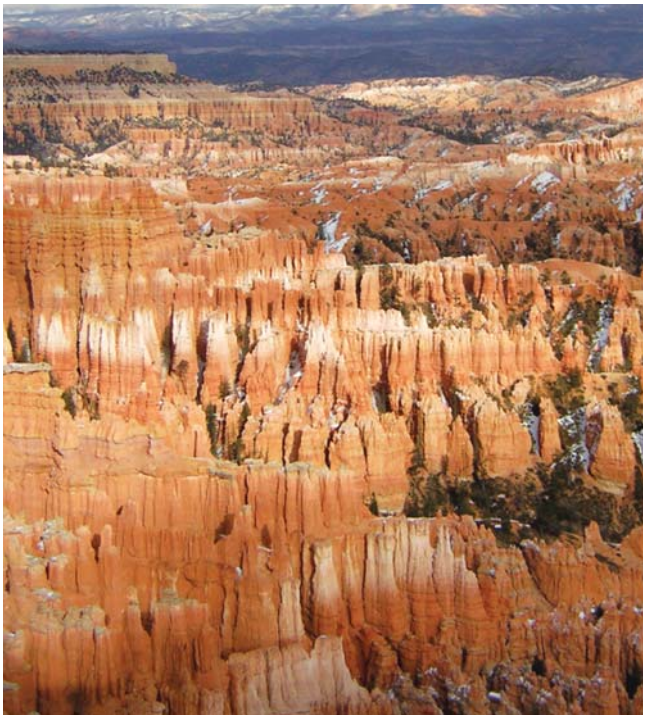
FIGURE 17.12 Mesas and buttes form in deserts as cliffs retreat over time.



(a) Because of cliff retreat, a once-continuous layer of rock evolves into a series of isolated remnants. If the bedding is horizontal, the resulting landforms have flat tops.



(b) Buttes and mesas tower above the floor of Monument Valley, Arizona.



(c) Erosion produced many chimneys in Bryce Canyon, Utah. These features are locally known as "hoodoos."

In this section, we'll see how the erosional and depositional processes described above lead to the formation of such contrasting landscapes.

Rocky Cliffs and Mesas

In hilly desert regions, the lack of soil exposes rocky ridges and cliffs. As noted earlier, cliffs erode when rocks split away along joints. When this happens, the cliff face steps back into the land but retains roughly the same form. The process, commonly referred to as **cliff retreat**, or scarp retreat, occurs in fits and starts. A cliff may remain unchanged for decades or centuries, and then suddenly a block of rock falls off and crumbles into rubble at the foot of the cliff. Cliffs exposing alternating layers of strata with contrasting strength develop a step-like shape; strong layers (sandstone or limestone) become vertical cliffs, and weak layers (shale) become rubble-covered slopes.

With continued erosion and cliff retreat, a plateau of rock slowly evolves into a cluster of isolated hills, ridges, or columns. Flat-lying strata or flat-lying layers of volcanic rocks erode to make flat-topped hills, which go by different names depending on their size. Large examples (with a top surface area of several square km) are **mesas**, from the Spanish word for table. Medium-sized examples are **buttes** (**Fig. 17.12a, b**), and small examples, whose height greatly exceeds their top surface area, are **chimneys** (**Fig. 17.12c**).

Natural arches form when erosion along joints leaves narrow walls of rock. When the lower part of the wall erodes while the upper part remains, an arch results. (See **Geology at a Glance**, pp. 510–511.)

In places where bedding dips at an angle, an asymmetric ridge called a *cuesta* develops. A joint-controlled cliff forms the steep front side of a cuesta, and the tilted top surface of a resistant bed forms the gradual slope on the backside (**Fig. 17.13a**). If the bedding dip is steep to near vertical, a narrow symmetrical ridge, called a *hogback*, forms.

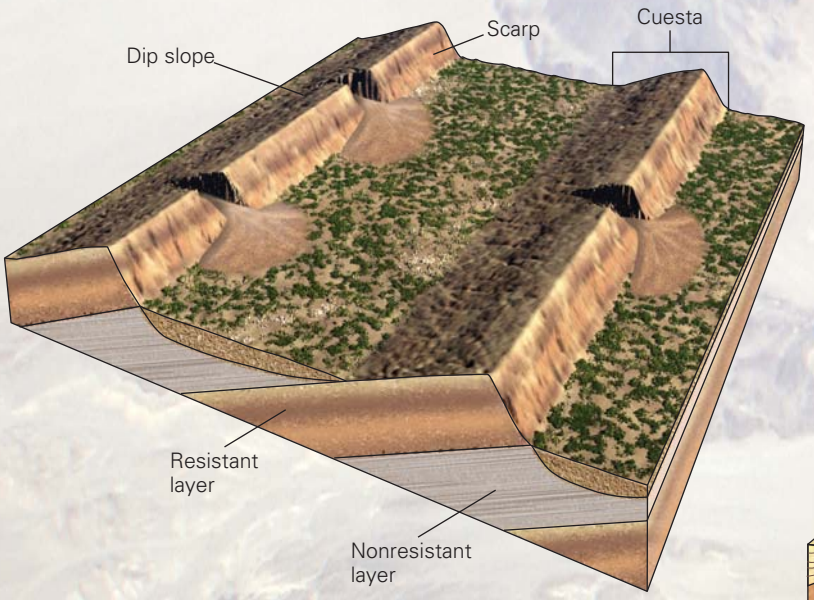
After a long period of erosion, all that may remain of a once broad region of uplifted land is a relatively small island of rock, surrounded by alluvium-filled basins. Geologists refer to such islands of rock by the German word **inselberg** (island mountain; **Fig. 17.13b**). Depending on the rock type or the orientation of stratification in the rock, and on rates of erosion,

inselbergs may be sharp-crested, plateau-like, or loaf-shaped (steep sides and a rounded crest). Inselbergs with a loaf geometry, as exemplified by Uluru (Ayers Rock) in central Australia (Fig. 17.13c), are also known as bornhardts.

Desert Pavement

In many locations, the desert surface resembles a tile mosaic in that it consists of separate stones that fit together tightly, forming a fairly smooth surface layer above a soil composed of silt and clay. Such natural mosaics constitute **desert pavement** (Fig. 17.14a, b). Typically, desert varnish coats the top surfaces of the stones forming desert pavement. Recently, researchers have suggested that pavements form when windblown dust slowly sifts down onto the stones and then washes down between the stones. In this model, the pavement is "born at the surface," meaning that the stones forming the pavement were never buried, but have been progressively lifted up as soil collects and builds up beneath (Fig. 17.14c). Over time, the rocks at the surface crack, perhaps due to differential heating by the desert sun. Sheetwash, during downpours, may wash away fine sediment between fragments, and when soils dry and shrink between storms, the clasts settle together, locking into a stable, jigsaw-like arrangement.

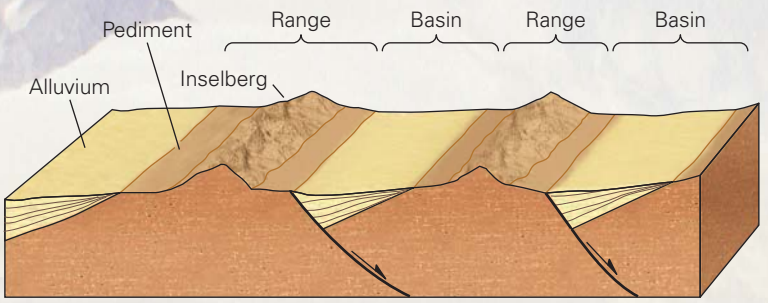
FIGURE 17.13 The formation of cuestas and inselbergs, due to erosion and deposition in deserts.



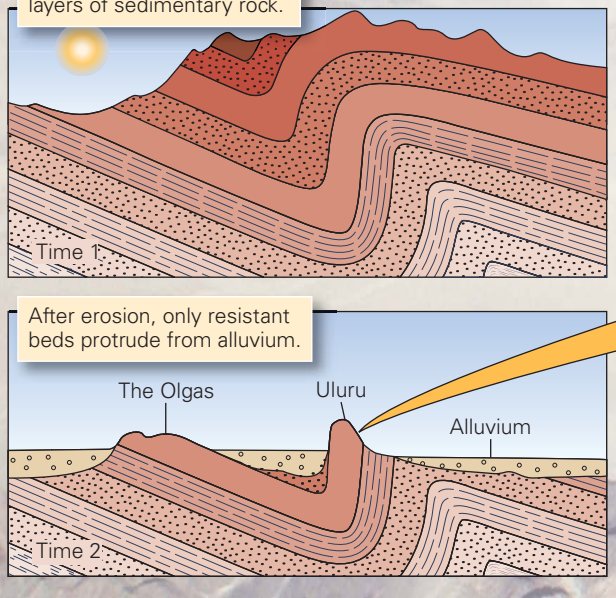
(a) Asymmetric ridges called cuestas develop where strata in a region are not horizontal.



An inselberg protruding from alluvium in California.



(b) Inselbergs are small islands of rock surrounded by pediments. Alluvium gradually covers the pediments.



(c) Uluru (Ayers Rock) in central Australia is an inselberg. The red sandstone beds comprising it are the eroded remnant of the vertical limb of a large syncline. Alluvium buried the surrounding bedrock.



Stony Plains and Pediments

The coarse sediment eroded from desert mountains and ridges washes into adjacent lowlands and builds out to form gently sloping alluvial fans. The surfaces of these gravelly piles are strewn with pebbles, cobbles, and boulders, and are dissected by dry washes (wadis or arroyos). Portions of these stony plains may evolve into desert pavements.

When travelers began trudging through the desert of the southwestern United States during the 19th century, they found that in many locations the wheels of their wagons were rolling over flat or gently sloping bedrock surfaces. These bedrock surfaces extended outward like ramps from the steep cliffs of a mountain range on one side, to the alluvium-filled valleys on the other (see Fig. 17.13b). Geologists now refer to such surfaces as **pediments**. Pediments develop when sheetwash during floods carries sediment away from the mountain front, during mountain-front retreat. The moving sediment grinds away the bedrock that it tumbles over.

Seas of Sand: The Nature of Dunes

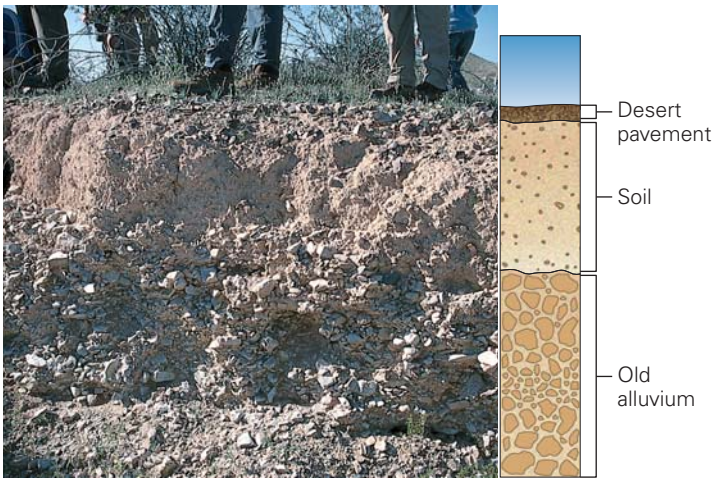
A **sand dune** is a pile of sand deposited by a moving current. Dunes in deserts may start to form where sand becomes trapped on the windward side of an obstacle, such as a rock or a shrub. Gradually, the sand builds downwind into the lee of the obstacle. Dunes display a variety of shapes and sizes, depending on the character of the wind and the sand supply (Fig. 17.15a). Where the sand is relatively scarce and the wind blows steadily in one direction, beautiful crescents called *barchan dunes* develop, with the tips of the crescents pointing downwind. If the wind shifts direction frequently, a group of crescents pointing in different directions overlap one another, creating a constantly changing *star dune*. Where enough sand accumulates to bury the ground surface completely, and only moderate winds blow, sand piles into simple, wave-like shapes called *transverse dunes*. The crests of transverse dunes lie perpendicular to the wind direction. Strong winds may break through transverse dunes and change them into *parabolic dunes* whose ends point in the upwind direction. Finally, if there is abundant sand and a strong, steady wind, the sand streams into *longitudinal dunes*, whose axis lies parallel to the wind direction.

In a sand dune, sand saltates up the windward side of the dune, blows over the crest of the dune, and then settles on the steeper, lee face of the dune. The slope of this face attains the angle of repose, the slope angle of a freestanding

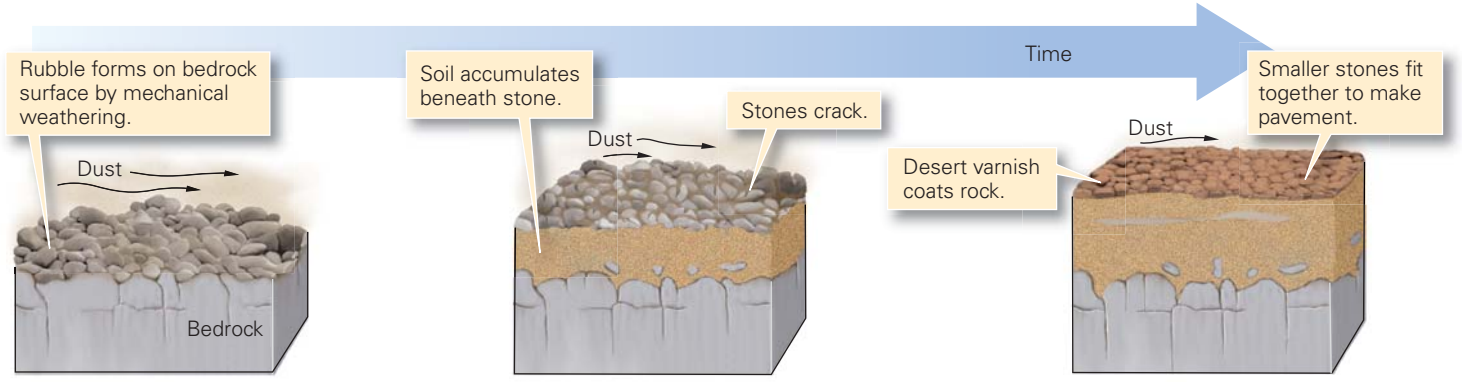
FIGURE 17.14 Desert pavement, and a hypothesis for how it forms by building up a soil from below.



(a) A well-developed desert pavement in the Sonoran Desert, Arizona.



(b) Students standing at the edge of a trench cut into desert pavement. Note the soil between the pavement and the underlying alluvium.



(c) Desert pavement forms in stages. First, loose pebbles and cobbles collect at the surface. Dust settles among the stones and builds up a soil layer below. The stones eventually crack into smaller pieces and settle to form a mosaic-like pavement.

pile of sand. As sand collects on this surface, it eventually becomes unstable and slides down the slope, so geologists refer to the lee side of a dune as the *slip face*. As more and more sand accumulates on the slip face, the crest of the dune migrates downwind, and former slip faces become preserved inside the dune. In cross section, these slip faces appear as cross beds (Fig. 17.15b, c).

Take-Home Message

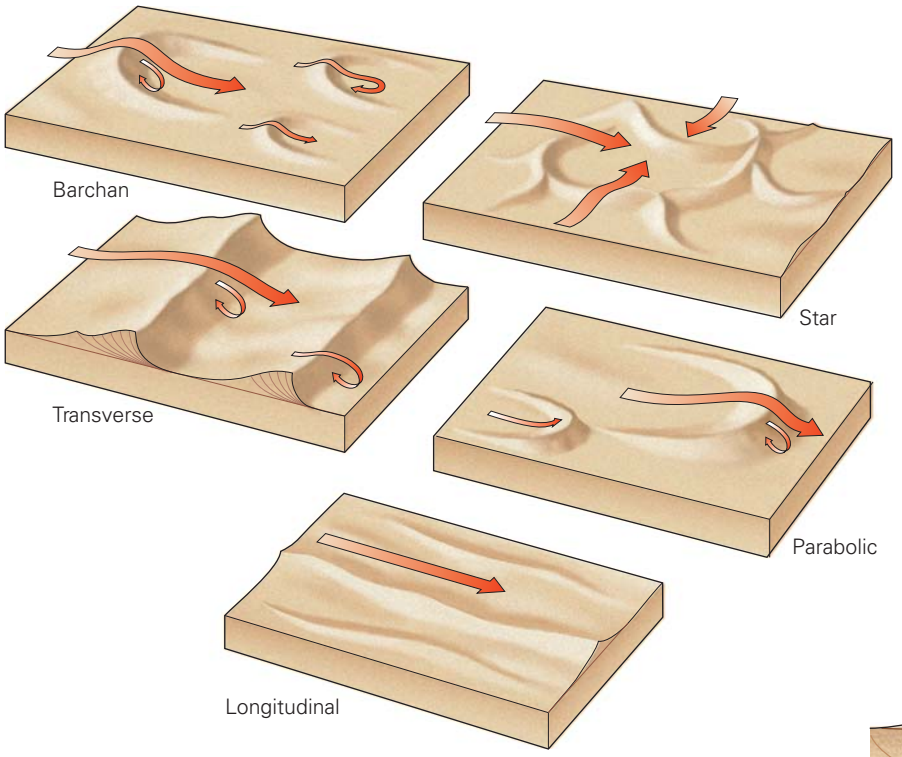
Erosion of thick layers of horizontal sedimentary rock in deserts yields buttes and mesas; erosion of tilted layers forms cuestas. Stony plains develop if finer sediment blows or washes away; some become desert pavements. Sandy areas contain many types of dunes.

17.6 Desert Problems

Natural droughts (periods of unusually low rainfall), overpopulation, overgrazing, careless agricultural practices, and diversion of water supplies have transformed semiarid grasslands into deserts in a matter of years to decades. The consequences of such **desertification** have, for example, devastated the Sahel, the belt of semiarid grassland that fringes the southern margin of the Sahara. In the past, the Sahel provided sufficient vegetation to support a small population of nomadic people and animals. But during the second half of the 20th century, large numbers of people migrated into the Sahel to escape overcrowding in central Africa. The immigrants began farming and maintained large herds of cattle and goats. As a consequence, plowing and overgrazing removed soil-preserving grass and caused the soil to dry out. In addition, the trampling of animal hooves compacted the ground so it could no longer soak up water. In the 1960s and again in the 1980s, a series of natural droughts hit the region, bringing catastrophe (Fig. 17.16a, b). Wind erosion stripped off the remaining topsoil. Without vegetation, the air grew drier, and the semiarid grassland of the Sahel became desert and its inhabitants endured a terrible famine.

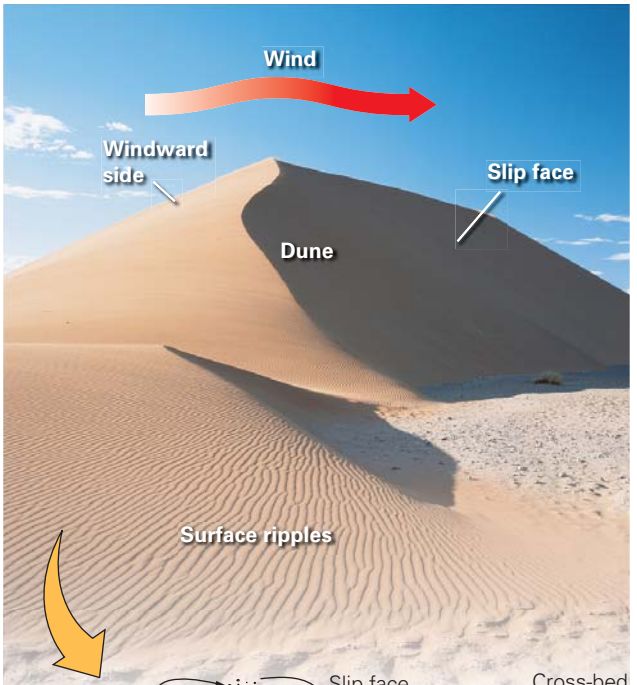
Desertification does not happen only in less industrialized nations. People in the western Great Plains of the United States and Canada suffered from the problem beginning in 1933, the fourth year of the Great Depression. Banks had failed, workers had lost their jobs, the stock market had crashed, and hardship burdened all. No one needed yet another disaster—but that year, even nature turned hostile. All through the fall, so little rain fell in the plains of Texas and Oklahoma that the region's grasslands and croplands browned and withered, and the topsoil turned to powdery dust. Then, on November 12

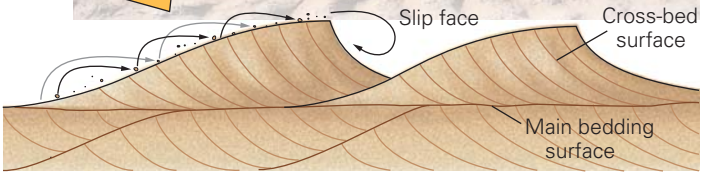
FIGURE 17.15 The types of sand dunes and the cross beds within them.



(a) The various kinds of sand dunes. Shapes depend on the sand supply and the wind character.

(b) The shape of a sand dune depends on the wind direction. Small ripples may form on the dune surface.





(c) Cross bedding inside a dune. Note that a cross bed is a buried slip face.

FIGURE 17.16 Desertification is happening in parts of Africa.



(a) The Sahel is the semi arid land along the southern edge of the Sahara. Large parts have undergone desertification.



(b) Drought in the Sahel has brought deadly consequences. Here, residents seek water from a dwindling pond.

and 13, strong storms blew eastward across the plains. Without vegetation to protect the ground, the wind stripped off the topsoil and sent it skyward to form rolling black clouds that literally blotted out the sun. People caught in the resulting dust storm found themselves gasping for breath. When the dust finally settled, it had buried houses and roads under huge drifts, and dirtied every nook and cranny. The dust blew east as far as New England, where it turned the snow brown. What had once been a rich farmland in the southwestern plains turned into a wasteland that soon acquired a nickname, the Dust Bowl. And it stayed this way for years.

Why did the fertile soils of the southern Great Plains suddenly dry up? The causes were complex; some were natural and some were human-induced. Typically, the region has a semiarid climate in which only thin soil develops. But the plains were settled in the 1880s and 1890s, which were unusually wet years. Not realizing its true character, far more people moved into the region than it could sustain, and the land was farmed too intensively. Plowing destroyed the fragile grassland root systems that held the thin soil in place. And when the drought of the 1930s came, it brought catastrophe.

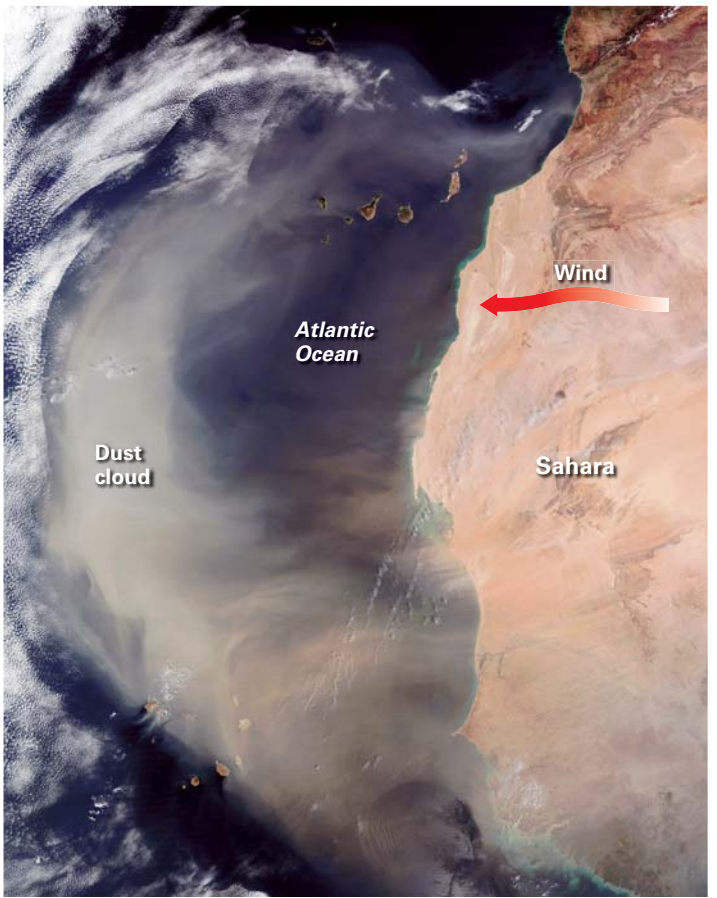
Desertification has an additional dangerous side effect—global transmission of chemicals and pathogens by blowing dust. As desert areas expand in response to desertification, and as desert pavement gets disrupted, windblown dust becomes more of a problem. Dust blown off the Sahara can traverse the Atlantic and settle over the Caribbean (**Fig. 17.17**). Geologists are concerned that this dust, along with the fungi, toxic chemicals, and microbes that it carries, may infect corals with disease or in some other way inhibit their life processes. Thus, windblown dust can contribute to the destruction of coral reefs.

The Dust Bowl of the 1930s and the fate of the Sahel in Africa remind us how fragile the Earth's green blanket of vegetation really is. Global climate changes can shift climatic belts sufficiently to transform agricultural regions into deserts. Unfortunately, if the current trends in climate change continue, present-day agricultural belts could someday become new Saharas.

Take-Home Message

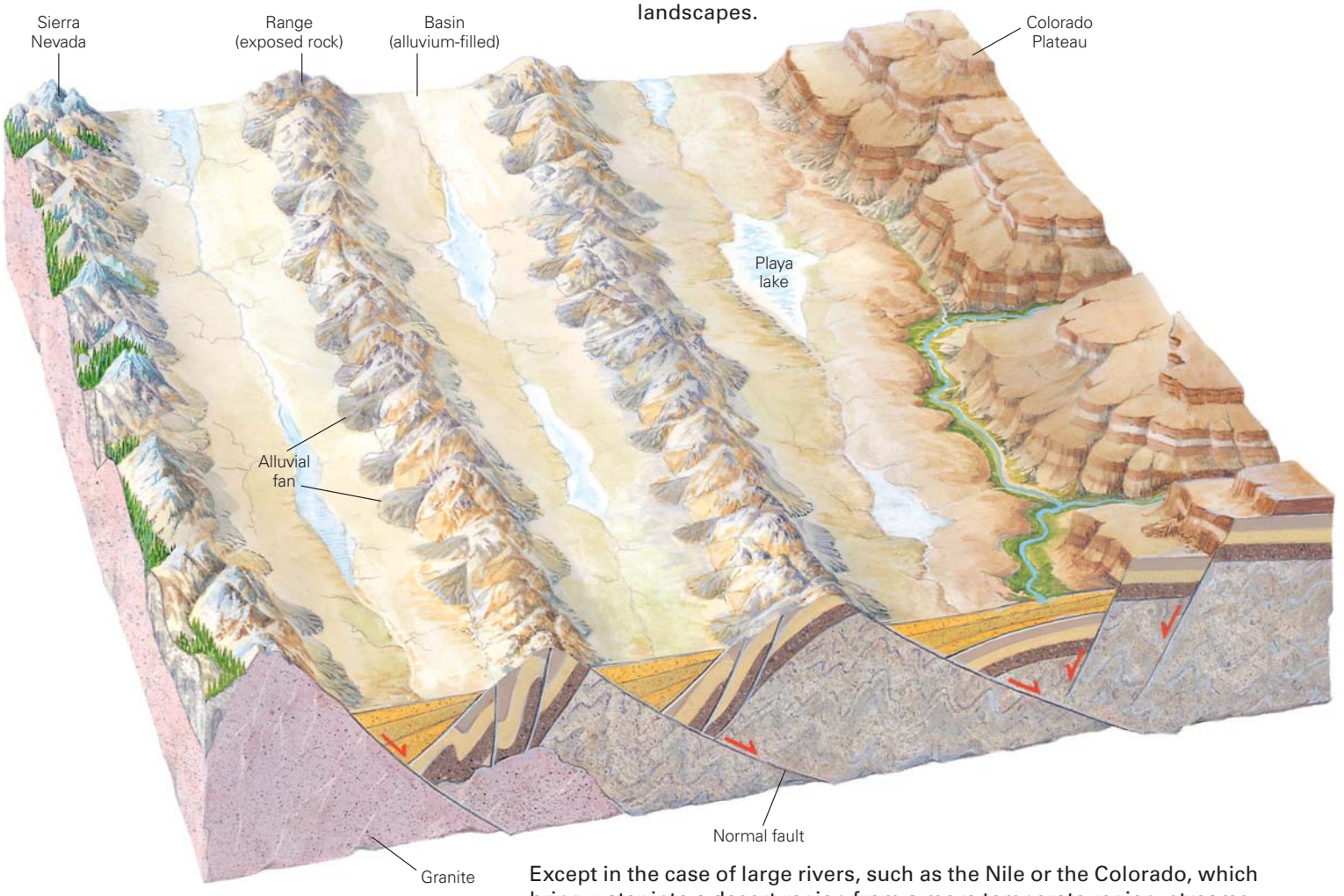
Desert populations have been burgeoning, so water supplies are problematic. In lands bordering deserts, droughts and population pressures have led to desertification, the transformation of vegetated land into desert. Dust storms can destroy topsoil.

FIGURE 17.17 In this satellite image, a huge dust cloud that originated in the Sahara blows across the Atlantic.

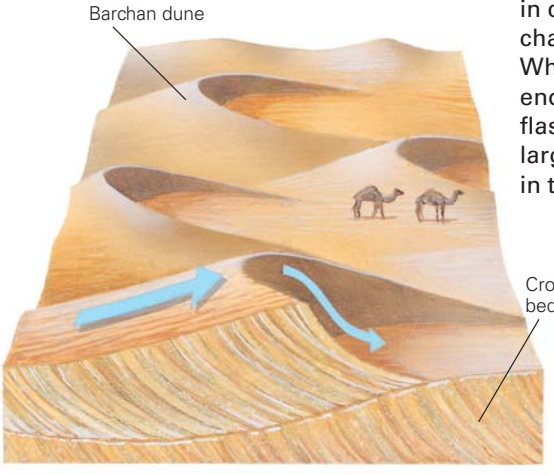


The Desert Realm

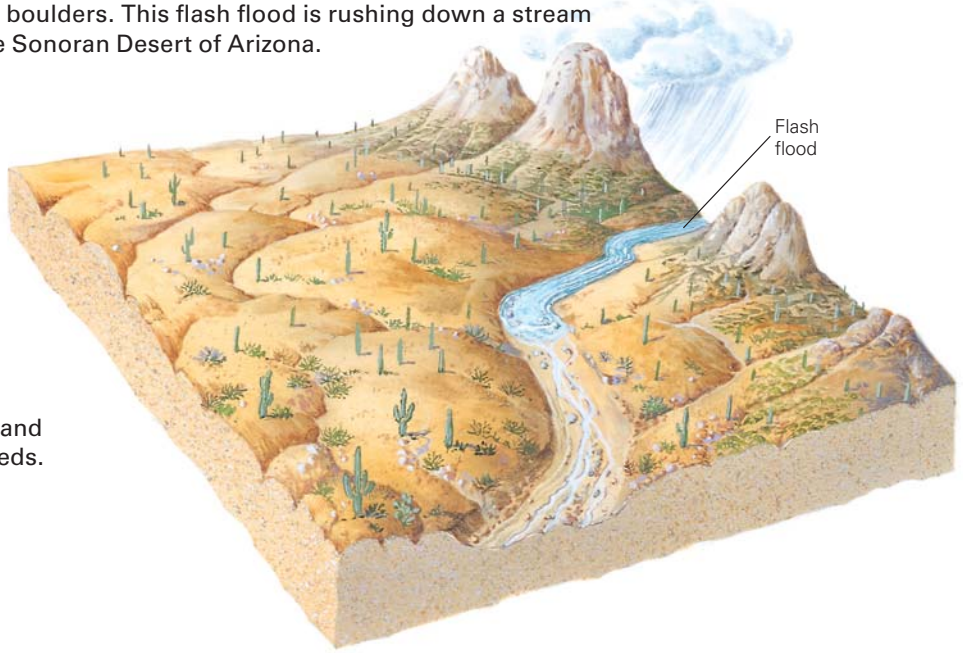
The desert of the Basin and Range Province in Utah, Nevada, and Arizona consists of alternating basins (grabens or half-grabens) separated by narrow ranges (tilted fault blocks). The Sierra Nevada, underlain largely by granite, borders the western edge of the province, while the Colorado Plateau, underlain by flat-lying sedimentary strata, borders the eastern edge. The overall climate of the region is dry. Because of the great variety of elevations and rock types, the region hosts different desert landscapes.

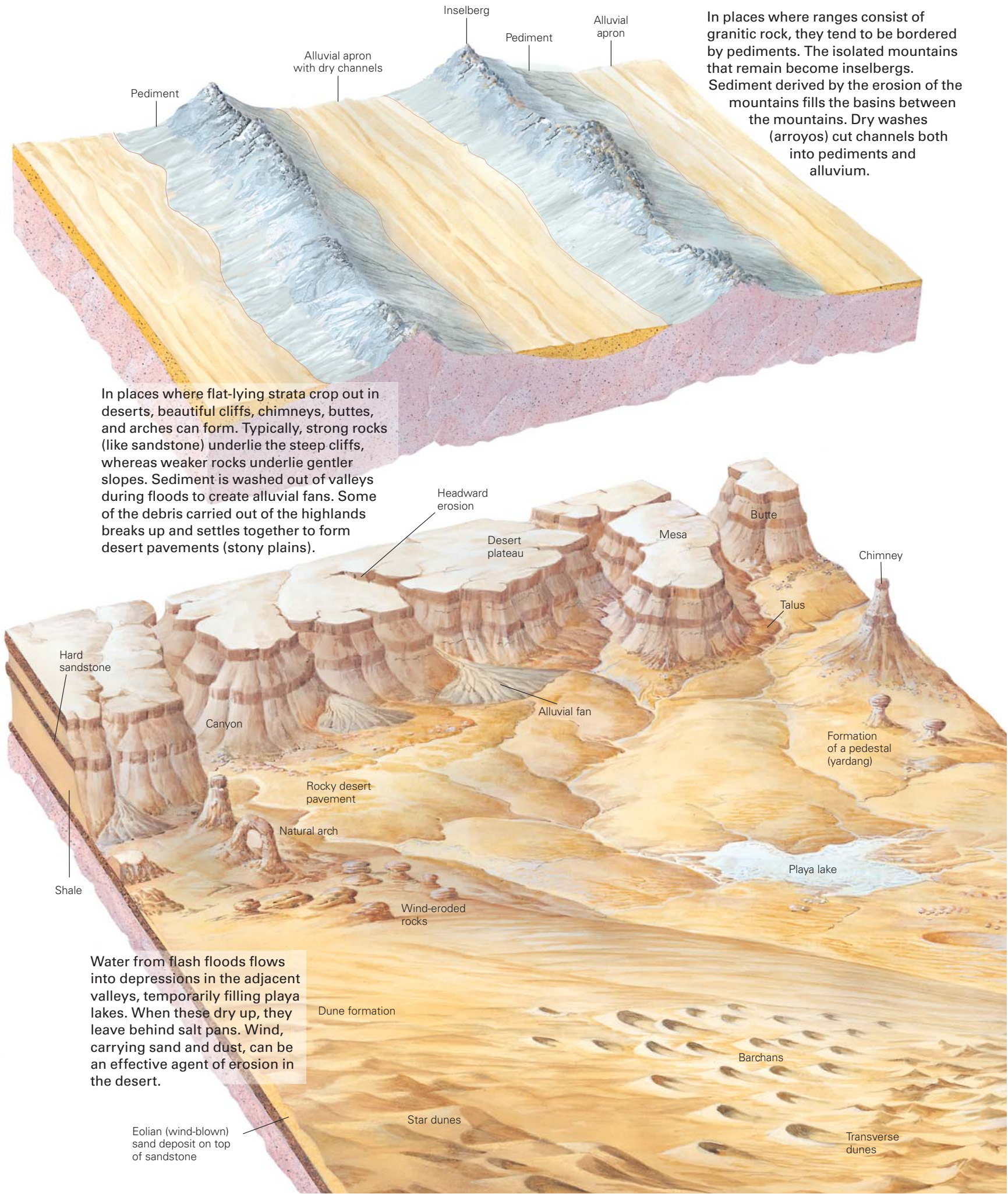


Except in the case of large rivers, such as the Nile or the Colorado, which bring water into a desert region from a more temperate region, streams in deserts fill with water only after heavy rains. At other times, the stream channels are dry. These channels are called dry washes, arroyos, or wadis. When there is a heavy rain, water cannot be absorbed into the ground fast enough, so runoff enters dry washes and fills them very quickly, creating a flash flood. The turbulent, muddy water of a flash flood can transport even large boulders. This flash flood is rushing down a stream in the Sonoran Desert of Arizona.



Where there is a large supply of sand, a variety of sand dunes develop. The geometry of a particular sand dune (such as barchan, longitudinal, or star) depends on the sand supply and the wind. Inside sand dunes, we find cross beds.




Inselberg
Pediment
Alluvial apron
Alluvial apron with dry channels
Pediment
In places where ranges consist of granitic rock, they tend to be bordered by pediments. The isolated mountains that remain become inselbergs. Sediment derived by the erosion of the mountains fills the basins between the mountains. Dry washes (arroyos) cut channels both into pediments and alluvium.
In places where flat-lying strata crop out in deserts, beautiful cliffs, chimneys, buttes, and arches can form. Typically, strong rocks (like sandstone) underlie the steep cliffs, whereas weaker rocks underlie gentler slopes. Sediment is washed out of valleys during floods to create alluvial fans. Some of the debris carried out of the highlands breaks up and settles together to form desert pavements (stony plains).
Headward erosion
Desert plateau
Mesa
Butte
Chimney
Talus
Hard sandstone
Canyon
Alluvial fan
Formation of a pedestal (yardang)
Rocky desert pavement
Natural arch
Shale
Playa lake
Wind-eroded rocks
Water from flash floods flows into depressions in the adjacent valleys, temporarily filling playa lakes. When these dry up, they leave behind salt pans. Wind, carrying sand and dust, can be an effective agent of erosion in the desert.
Dune formation
Barchans
Star dunes
Eolian (wind-blown) sand deposit on top of sandstone
Transverse dunes

CHAPTER 17 REVIEW

Chapter Summary

- Deserts generally receive less than 25 cm of rain per year. Vegetation covers less than 15% of their surface.
- Subtropical deserts form between latitudes of 20° and 30°, rain-shadow deserts are found on the inland side of mountain ranges, coastal deserts are located on the land adjacent to cold ocean currents, continental-interior deserts exist in landlocked regions far from the ocean, and polar deserts form at high latitudes.
- Physical weathering in deserts produces rocky debris. Chemical weathering happens slowly; it produces ions that precipitate as new minerals below the surface.
- Water causes significant erosion in deserts, mostly during heavy downpours. Flash floods carry large quantities of sediments down ephemeral streams. When rain stops, streams dry up, leaving steep-sided dry washes.
- Wind picks up dust and silt as suspended load, and it causes sand to saltate. Where wind blows away finer sediment, a lag deposit remains. Windblown sediment abrades the ground, creating a variety of features such as ventifacts.
- Desert pavements are mosaics of varnished stones armoring the surface of the ground.
- Talus aprons form when rock fragments accumulate at the base of a slope. Alluvial fans form at a mountain front where water in ephemeral streams deposits sediment. When temporary desert lakes dry up, they leave playas.
- In some desert landscapes, erosion causes cliff retreat, eventually resulting in the formation of mesas, buttes, and inselbergs. Pediments of nearly flat or gently sloping bedrock surround some inselbergs.
- Where sand is abundant, the wind builds it into dunes. Common types include barchan, star, transverse, parabolic, and longitudinal (seif) dunes.
- Changing climates and land abuse may cause desertification, the transformation of semiarid land into deserts. Windblown dust, sometimes carrying microbes and toxins, may waft from deserts across oceans.

Key Terms

alluvial fan (p. 503)
arroyo (p. 501)
butte (p. 505)
chimney (p. 505)
cliff retreat (p. 505)
deflation (p. 502)
desert (p. 498)
desertification (p. 508)
desert pavement (p. 506)
desert varnish (p. 500)
dry wash (p. 501)
dune (p. 504)
dust storm (p. 502)
inselberg (p. 505)
lag deposit (p. 502)
mesa (p. 505)
pediment (p. 507)
petroglyph (p. 500)
playa (p. 504)
rain shadow (p. 498)
saltation (p. 502)
sand dune (p. 507)
surface load (p. 502)
suspended load (p. 502)
talus (p. 503)
ventifact (p. 502)

Review Questions

1. What factors determine whether a region can be classified as a desert?
2. Explain why deserts form.
3. Have today's deserts always been deserts? (*Hint*: Keep in mind the consequences of plate tectonics.)
4. How do weathering processes in deserts differ from those in temperate or humid climates?
5. Describe how water modifies the landscape of a desert. Be sure to discuss both erosional and depositional landforms.
6. Explain the ways in which desert winds transport sediment.
7. Explain how the following features form: (a) desert varnish; (b) desert pavement; (c) ventifacts.
8. Describe the process of formation of alluvial fans, bajadas, and playas.
9. Describe the process of cliff (scarp) retreat and the landforms that result from it.
10. What are the various types of sand dunes? What factors determine which type of dune develops at a particular location?
11. What is the process of desertification, and what causes it? How can desertification in Africa affect the Caribbean?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- A What a Geologist Sees exercise that illustrates erosion in deserts.
- An exercise based on a time-lapse video of a developing alluvial fan.
- A video exercise on the process of desertification.

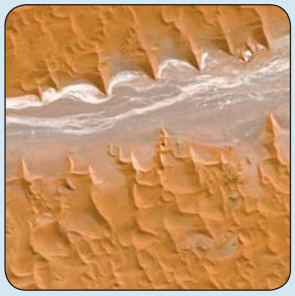
On Further Thought

12. You are working for an international nongovernmental organization (NGO) and have been charged with the task of providing recommendations to an African nation that wishes to slow or halt the process of desertification within its borders. What are your recommendations?

13. The Namib Desert lies to the north and west of the Kalahari Desert, in southern Africa. The reason that the former region is a desert is not the same as the reason that the latter is a desert. Explain this statement.

SEE FOR YOURSELF Q. . . Desert Landscapes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet Q of our **Geotours Workbook**.



Namib Desert, Namibia
Latitude 24°44′27.80″S,
Longitude 15°27′58.92″E

From 20 km, you can see the orange sand of huge dunes bordering a dry wash in western Africa. Zoom in and you'll recognize the slip face of dunes. A road in the wash provides scale.



Uluru, Australia
Latitude 25°20′47.64″S,
Longitude 131°2′28.96″E

Viewed from 5 km, the red sandstone of Uluru (Ayers Rock), a bornhardt, rises above the stony plains of the central Australian desert. The NW-trending diagonal lines are traces of vertical bedding in the sandstone.



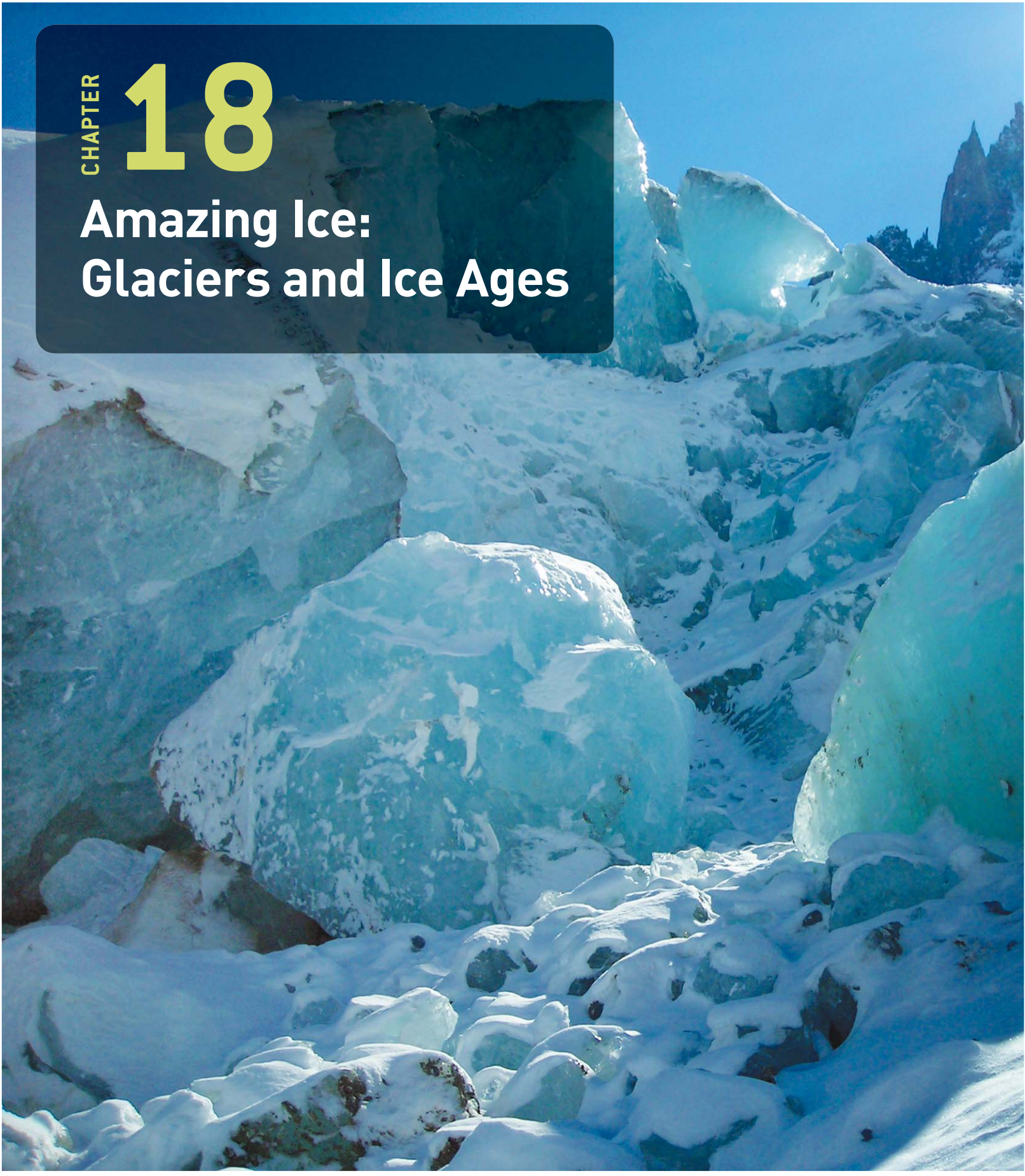
Death Valley, California
Latitude 36°12′42.34″N,
Longitude 116°48′25.43″W

From 35 km, you can see many desert landforms in Death Valley, a narrow basin whose floor lies below sea level. The white patch is a playa. A bajada forms the slope between the playa and the mountains to the west. Small alluvial fans spill into the basin on the east.



Sahara Desert, Egypt
Latitude 25°41′49.34″N,
Longitude 32°40′38.76″E

The green stripe is the Nile Valley near Luxor. Except for the land that can be irrigated with river water, the desert hosts no vegetation. Flash floods carve the intricate canyons in nearby hills but do not provide enough water to sustain life. The Nile brings water in from wetter lands to the south.



CHAPTER 18

Amazing Ice: Glaciers and Ice Ages



The blue ice of a glacier in the French Alps has played a role in carving the surrounding mountains. Ice like this covered vast areas of land during the ice age.

Chapter Objectives

By the end of this chapter you should know . . .

- how glacial ice forms and flows, and how to categorize various kinds of glaciers.
- how glaciers advance and retreat, and how their flow erodes the landscape.
- how to recognize sedimentary deposits and associated landforms left by glaciers.
- that glaciers covered large areas of continents and that sea level dropped during ice ages.
- why ice ages happen, and why glaciations during an ice age happen periodically.

I seemed to vow to myself that some day I would go to the region of ice and snow and go on and on till I came to one of the poles of the earth.

—Ernest Shackleton
(British polar explorer, 1874–1922)

18.1 Introduction

There's nothing like a good mystery, and one of the most puzzling in the annals of geology came to light in northern Europe early in the 19th century. When farmers of the region prepared their land for spring planting, they occasionally broke their plows by running them into boulders buried randomly through otherwise fine-grained sediment. Many of these boulders did not consist of local bedrock, but rather came from outcrops hundreds of kilometers away. Because the boulders had apparently traveled so far, they came to be known as **erratics** (from the Latin *errare*, to wander).

The mystery of the wandering boulders became a subject of great interest to early 19th-century geologists, who realized that such deposits of extremely *unsorted* sediment (sediment that contains a variety of clast sizes) could not be examples of typical stream alluvium, for running water sorts sediment by size. Most attributed the deposits to a vast flood that they imagined had been powerful enough to spread a slurry of boulders, sand, and mud across the continent. In 1837, however, a young Swiss geologist named Louis Agassiz proposed a radically different interpretation. Agassiz often hiked among **glaciers** (slowly flowing masses of ice that survive the summer melt) in the Alps near his home. He observed that glacial ice could carry enormous boulders as well as sand and mud, because ice is solid and has enough strength to support the weight of rock. Agassiz realized that, because solid ice

does not sort sediment as it flows, glaciers leave behind unsorted sediment when they melt. On the basis of these observations, he proposed that the mysterious sediment and erratics of Europe were deposits left by ice sheets, vast glaciers that had once covered much of the continent (**Fig. 18.1**). In Agassiz's mind, Europe had once been in the grip of an **ice age**, a time when the climate was significantly colder and glaciers grew.

Agassiz's radical proposal faced intense criticism for the next two decades, but by the late 1850s, most doubters had changed their minds, and the geological community concluded that the notion that Europe once had Arctic-like climates was correct. Later in life, Agassiz traveled to the United States and documented many glacier-related features in North America's landscape, proving that an ice age had affected vast areas of the planet. Glaciers cover only about 10% of the land on Earth today, but during the most recent ice age, which ended only about 11,000 years ago, as much as 30% of continental land surface had a coating of ice. New York City, Montreal, and many of the great cities of Europe now occupy land that once lay beneath hundreds of meters to a few kilometers of ice.

The work of Louis Agassiz brought the subject of glaciers and ice ages into the realm of geologic study and led people to recognize that major climate changes happen in Earth history. In this chapter, after considering the nature of ice, we see how glaciers form, why they move, and how they modify landscapes by erosion and deposition. A substantial portion of the chapter concerns the most recent ice age, known as the Pleistocene Ice Age, for its impact on the landscape can still be seen today. But we briefly introduce ice ages that happened earlier in Earth history too. We conclude by considering hypotheses put forth to explain why ice ages happen.

18.2 Ice and the Nature of Glaciers

What Is Ice?

Ice consists of solid water, formed when liquid water cools below its freezing point. We can apply concepts introduced in our earlier discussions of rocks and minerals to distinguish among various occurrences of ice. For example, we can think of a single ice crystal as a mineral specimen, for it is a naturally occurring, inorganic solid, with a definite chemical composition (H_2O) and a regular crystal structure. Ice crystals have a hexagonal form, so snowflakes grow into six-pointed stars (**Fig. 18.2a**). We can picture a layer of fresh snow as a layer of sediment, and a layer of snow that has been compacted so that the grains stick together as a layer of sedimentary rock (**Fig. 18.2b**). We can also think of the ice that appears on the surface of a pond as an igneous rock, for it forms when molten ice (liquid water) solidifies. Glacial ice, in effect, is a metamorphic rock. It develops when preexisting ice recrystallizes in the solid state, meaning that the molecules in solid water rearrange to form new crystals (**Fig. 18.2c**).

FIGURE 18.1 Agassiz envisioned that the northern continents were covered by ice sheets similar to Antarctica's today.



How a Glacier Forms

In order for a glacier to form, three conditions must be met. First, the local climate must be cold enough that winter snow does not melt entirely away during the summer. Second, there must be sufficient snowfall for a large amount of snow to accumulate. And third, the slope of the surface on which the snow accumulates must be gentle enough that the snow does not slide away in avalanches, and must be protected enough that the snow doesn't blow away.

Glaciers develop in polar regions because, even though relatively little snow falls today, temperatures remain so cold that most ice and snow survive all year. Glaciers develop in mountains, even at low latitudes, because temperature decreases with elevation; at high elevations, the mean temperature stays cold enough for ice and snow to survive all year. Since the temperature of a region depends on latitude, the specific elevation at which mountain glaciers form also depends on latitude. In Earth's present-day climate, glaciers form only at elevations above 5 km at the equator, but can flow down to sea level at latitudes of between 60° and 90°.

The transformation of snow to glacier ice takes place as younger snow progressively buries older snow. Freshly fallen snow consists of delicate hexagonal crystals with sharp points. The crystals do not fit together tightly, so fresh snow contains about 90% air. With time, the points of the snowflakes become blunt because they either sublimate (evaporate directly into vapor) or melt, and the snow packs more tightly. As snow becomes buried, the weight of the overlying snow increases pressure, which causes remaining points of contact between snowflakes to melt. Gradually, the snow transforms into a packed granular material called firn, which contains only about 25% air (**Fig. 18.2d**). Melting of firn grains at contact points produces water that crystallizes in the spaces between grains until eventually the firn transforms into a solid mass of glacial ice composed of interlocking ice crystals. Such glacial ice, which

FIGURE 18.2 The nature of ice and the formation of glaciers. Snow falls like sediment and metamorphoses to ice when buried.



(a) The hexagonal shape of snowflakes. No two are alike.

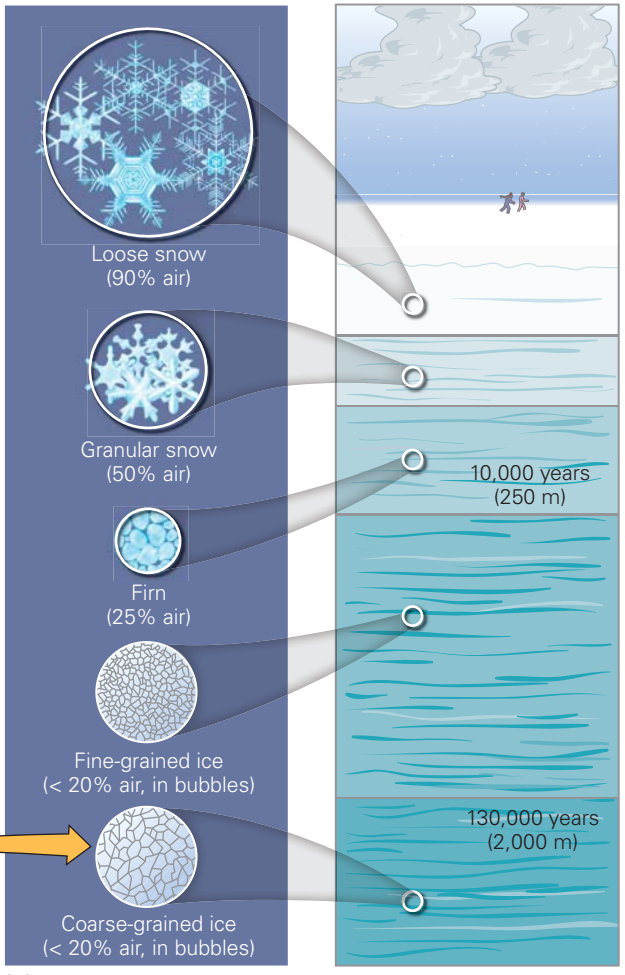




(b) Layers of snow accumulate. They recrystallize to become ice.



(c) Glacial ice is blue. As revealed by a microscope, the ice has coarse grains and contains air bubbles.



(d) Snow compacts and melts to form firn, which recrystallizes into ice. Crystal size increases with depth.

may still contain up to 20% air trapped in bubbles, tends to absorb red light and thus has a bluish color. The transformation of fresh snow to glacier ice can take as little as tens of years in regions with abundant snowfall, or as long as thousands of years in regions with little snowfall.

Categories of Glaciers

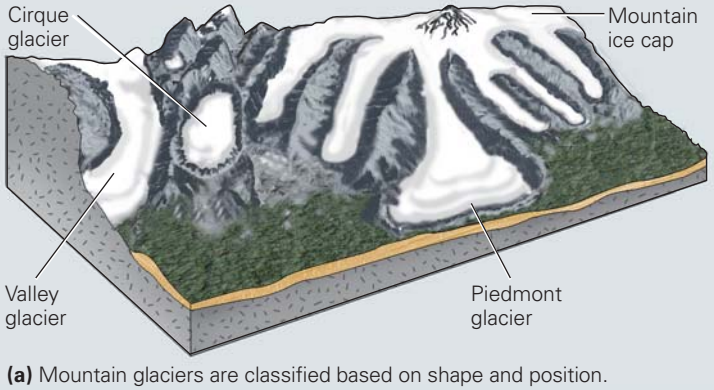
Glaciers are streams or sheets of recrystallized ice that stay frozen all year long and flow under the influence of gravity. Today, they highlight coastal and mountain scenery in Alaska, the Cordillera of western North America, the Alps of Europe, the Southern Alps of New Zealand, the Himalayas of Asia, and the Andes of South America, and they cover most of Greenland and Antarctica (**See for Yourself R**). Geologists distinguish between two main categories: mountain glaciers and continental glaciers.

Mountain glaciers (also called alpine glaciers) exist in or adjacent to mountainous regions (**Fig. 18.3a**). Topographical features of the mountains control their shape; overall, mountain glaciers flow from higher elevations to lower elevations. Mountain glaciers include *cirque glaciers*, which fill bowl-shaped depressions, or *cirques*, on the flank of a mountain; *valley glaciers*, rivers of ice that flow down valleys; mountain *ice caps*, mounds of ice that submerge peaks and ridges at the crest of a mountain range; and *piedmont glaciers*, fans or lobes of ice that form where a valley glacier emerges from a valley and spreads out into the adjacent plain (**Fig. 18.3b–d**). Mountain glaciers range in size from a few hundred meters to a few hundred kilometers long.

Continental glaciers are vast ice sheets that spread over thousands of square kilometers of continental crust. Continental glaciers now exist only on Antarctica and Greenland (**Fig. 18.4a, b**). Antarctica is a continent, so the ice beneath the South Pole rests mostly on solid ground. Locally, however, lakes of liquid water exist at the base of continental glaciers. In 2012, Russian geologists drilled into one of these lakes, Lake Vostock, 3.7 km below the surface of the Antarctic ice sheet. Continental glaciers flow outward from their thickest point (up to 3.5 km thick) and thin toward their margins, where they may be only a few hundred meters thick.

Geologists also find it valuable to distinguish between types of glaciers on the basis of the thermal conditions in which the glaciers exist. **Temperate glaciers** occur in regions where atmospheric temperatures become warm enough for the glacial ice to

FIGURE 18.3 A great variety of glaciers form in mountainous areas.



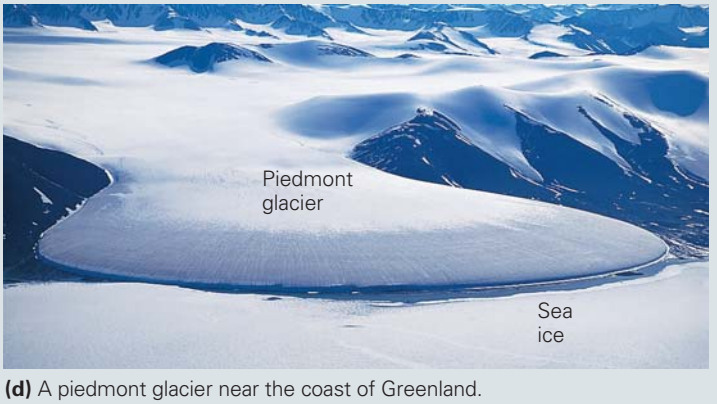
(a) Mountain glaciers are classified based on shape and position.



(b) A valley glacier and cirque glaciers in Switzerland.

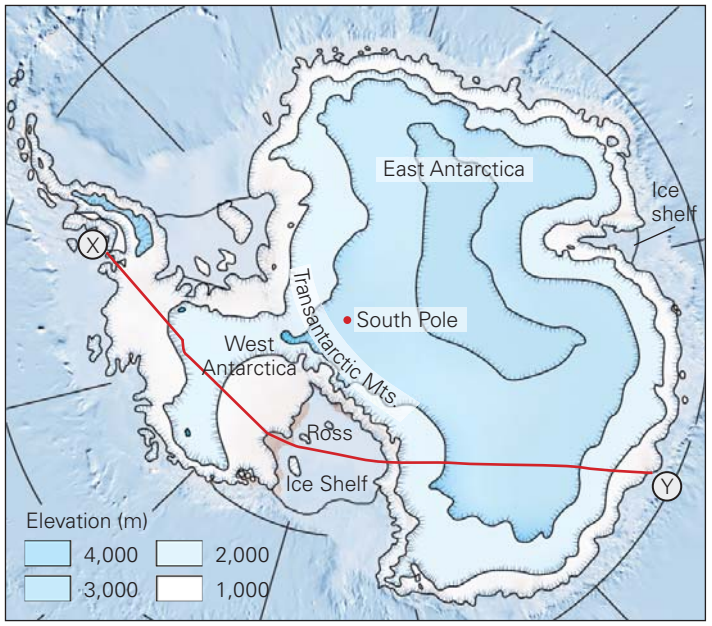


(c) Valley glaciers draining a mountain ice cap in Alaska.

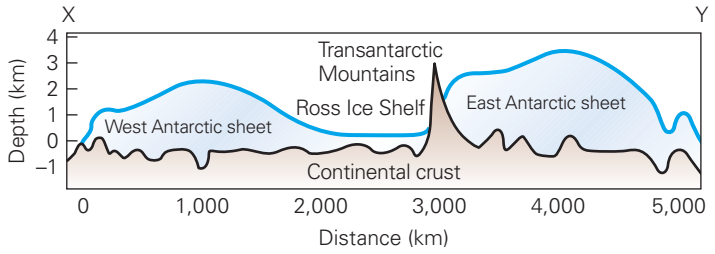


(d) A piedmont glacier near the coast of Greenland.

FIGURE 18.4 Antarctica is an ice-covered continent.



(a) A contour map of the Antarctic ice sheet. Valley glaciers carry ice from the ice sheet of East Antarctica down to the Ross Ice Shelf.



(b) A cross section X to Y of the Antarctic ice sheet. The Transantarctic Mountains separate East Antarctica from West Antarctica.

be at or near its melting temperature during part or all of the year. **Polar glaciers** occur in regions where atmospheric temperatures stay so cold all year long that the glacial ice remains below melting temperature throughout the year. Of note, Earth is not alone in hosting polar glaciers—Mars has them too (**Box 18.1**).

The Movement of Glacial Ice

How do glaciers move? Let's consider the two mechanisms that allow glaciers to move—plastic deformation and basal sliding. At conditions found below depths of about 60 m in a glacier, ice deforms by *plastic deformation*, meaning that the

CONSIDER THIS . . . BOX 18.1

Polar Ice Caps on Mars

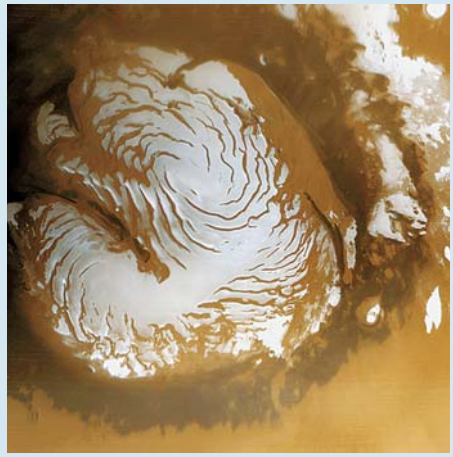
Mars has white polar ice caps that change in area with the season, suggesting that they partially melt and then refreeze (**Fig. Bx18.1a, b**). The question of what the ice caps consist of remained a puzzle until fairly recently. It now appears that the Martian ice caps consist mostly of water (H_2O) ice mixed with a small amount of dust. The ice caps attain a maximum thickness of 3 km. During the winter, atmospheric carbon dioxide freezes and covers the north polar cap with a 1-m-thick layer of frozen CO_2 (dry ice). During the summer, this layer melts away. The south polar cap has a dry-ice blanket that is 8 m thick and doesn't melt away entirely in the summer. The difference between the north and south poles may reflect elevation, for the south pole is 6 km higher and therefore remains colder.

High-resolution photographs reveal that distinctive canyons, up to 10 km wide and 1 km deep, spiral outward from the center of the north polar ice cap. Why did this pattern form? Recent calculations suggest that if the ice sublimates (transforms into gas) on the sunny side of a crack and refreezes on the shady side, the crack will migrate sideways over time. If the cracks migrate more slowly closer to the pole, where it's colder, than they do farther away, they will naturally evolve into spirals.

FIGURE Bx18.1 The ice caps of Mars.



(a) During the winter, the ice caps expand to lower latitudes.



(b) A close-up of the northern polar cap in summer.

grains within it change shape very slowly, and new grains grow while old ones disappear. We can picture such changes to be a consequence of the rearrangement of water molecules within ice grains. If ice is warm enough for thin water films to form along grain boundaries, plastic deformation may also involve the microscopic slip of ice grains past their neighbors along the water films. In cases where significant quantities of meltwater accumulate at the base of a glacier, forming a layer either of liquid or of slurry-like wet sediment, glaciers can move by *basal sliding*. During this process, the liquid water or water-saturated slurry layer holds the glacial ice above bedrock and thereby decreases friction; effectively, the glacier glides along on a wet cushion.

Did you ever wonder . . .
how a glacier moves?

As we noted earlier, plastic deformation takes place only at depths of greater than about 60 m in a glacier—above this depth, known as the brittle–plastic transition, ice is too brittle to flow. As a glacier overall undergoes movement, its upper 60 m of ice deforms predominantly by cracking. A crack that develops by brittle deformation of a glacier is called a **crevasse** (Fig. 18.5). In large glaciers, crevasses can be hundreds of meters long, and they can open up to form open gashes up to 15 m across.

Why do glaciers move? Ultimately, because the pull of gravity is strong enough to make ice flow (Fig. 18.6a, b). A glacier flows in the direction in which its top surface slopes. Thus, valley glaciers flow down their valleys, and continental ice sheets spread outward from their thickest point. To picture the movement of a continental ice sheet, imagine pouring honey on a tabletop. The honey spreads out until the puddle reaches an even thickness. In the case of a continental ice sheet, a thick pile of ice builds up, and gravity causes the top of the pile to push down on the ice at the base. Eventually, the basal ice can no longer support the weight of the overlying ice and begins to deform plastically. When this happens, the basal ice starts squeezing out to the side, carrying the overlying ice with it. The greater the volume of ice that builds up, the wider the ice sheet can become.

Glaciers generally flow at rates of between 10 and 300 m per year. Not all parts of a glacier move at the same rate. For example, friction between rock and ice slows a glacier, so the center of a valley glacier moves faster than its margins, and the top of a glacier moves faster than its base (Fig. 18.7a, b). If water builds up beneath a valley glacier to the point where it lifts the glacier off its substrate, basal sliding starts and the glacier undergoes a *glacial surge*. During surges, glaciers have been clocked at speeds of 10 to 110 m per day! Sudden surges may generate ice quakes, whose seismic vibrations travel through the glacier and through the rock below.

Glacial Advance and Retreat

Glaciers resemble bank accounts: snowfall accumulates and adds to the account, while **ablation**—the removal of ice by sublimation (the evaporation of ice into water vapor), melting (the transformation of ice into liquid water, which flows away), and calving (the breaking off of chunks of ice)—subtracts from the account. Snowfall adds to the glacier in

FIGURE 18.5 Crevasses form in the upper layer of a glacier, in which the ice is brittle. Commonly, cracking takes place where the glacier bends while flowing over steps or ridges in its substrate.

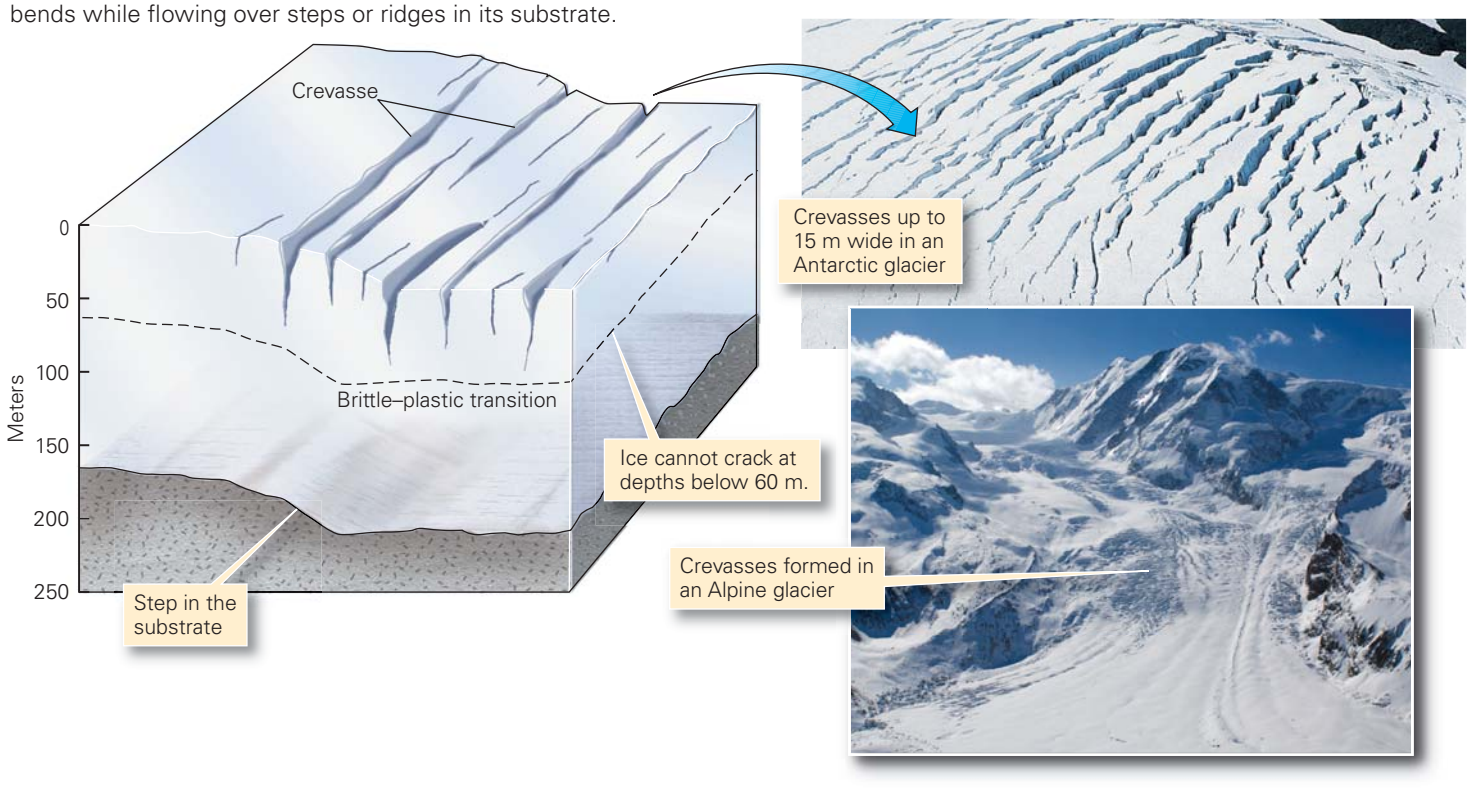


FIGURE 18.6 Forces that drive the movement of glaciers.

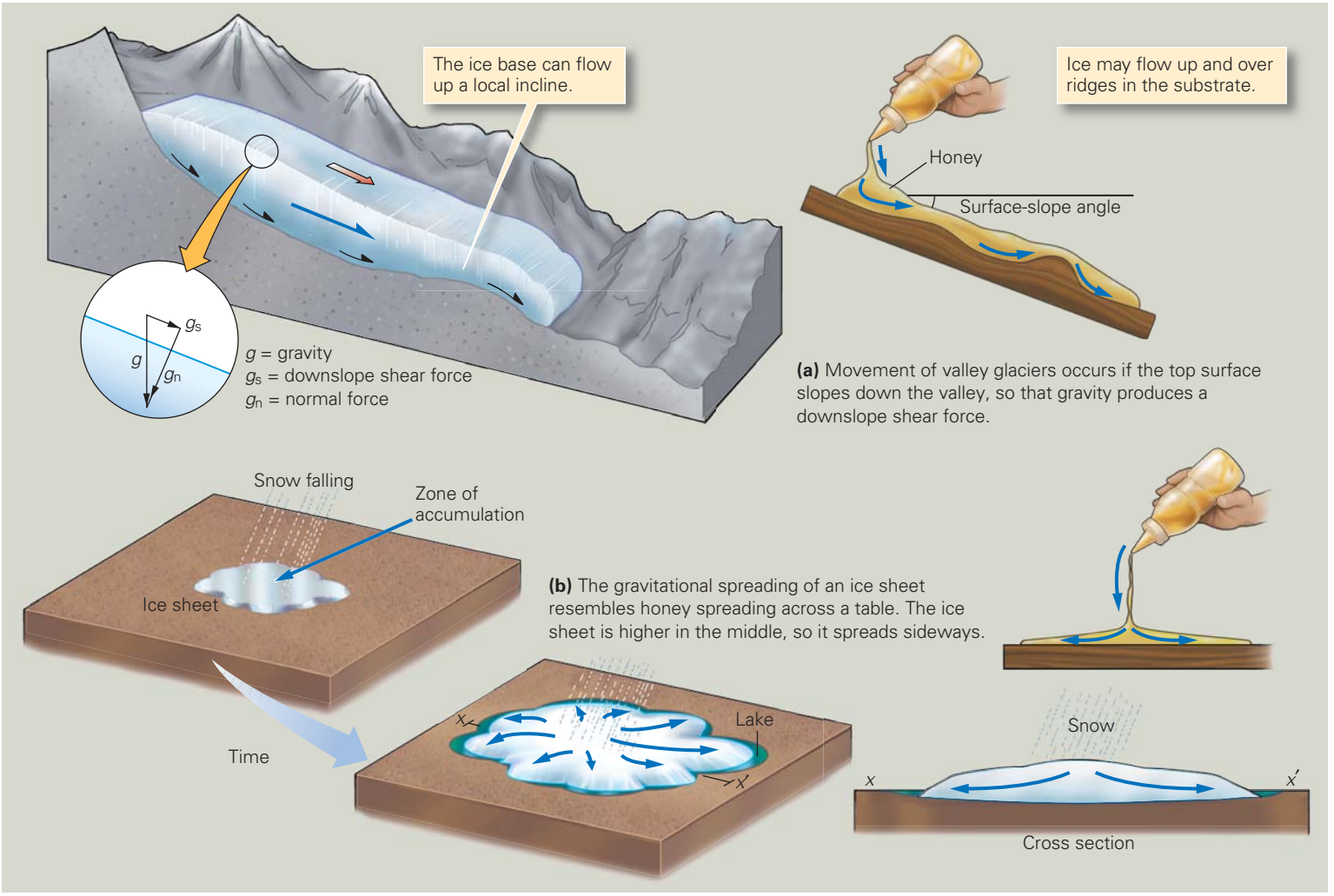
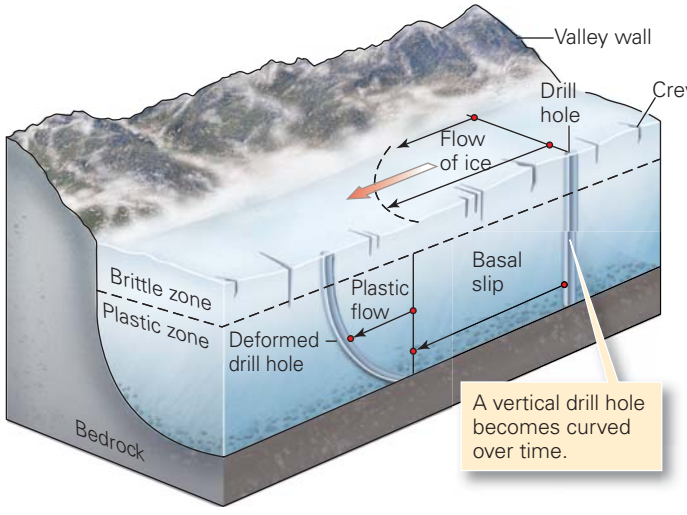
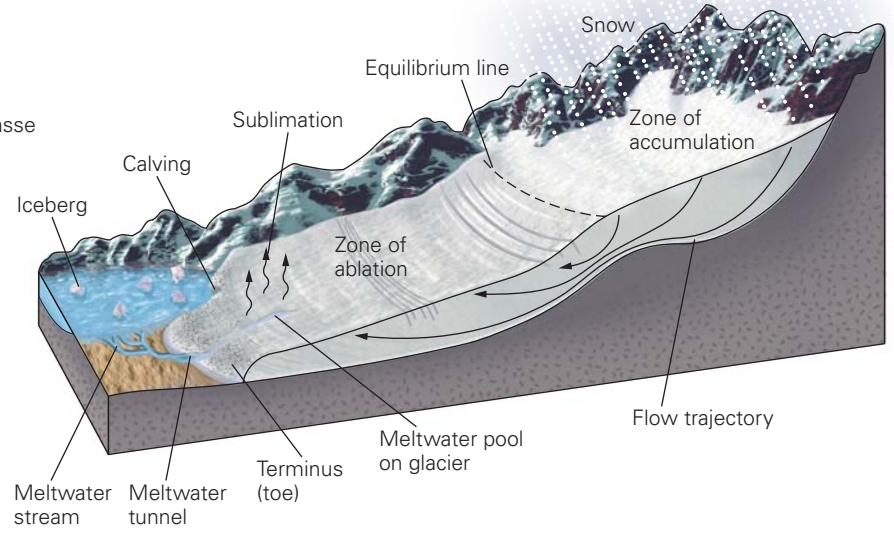


FIGURE 18.7 Flow velocities vary with location in a glacier. Overall, ice flows from the zone of accumulation to the toe.



(a) Different parts of a glacier flow at different velocities, due to friction with the substrate. The top and center regions flow fastest.



(b) The equilibrium line separates the zone of accumulation from the zone of ablation. As indicated by arrows, ice flows down in the zone of accumulation and up in the zone of ablation.

the **zone of accumulation**, whereas ablation subtracts in the **zone of ablation**; the boundary between these two zones is the **equilibrium line**.

The leading edge or margin of a glacier is called its *toe*, or terminus (Fig. 18.8a). If the rate at which ice builds up in the zone of accumulation exceeds the rate at which ablation occurs below the equilibrium line, then the toe moves forward into previously unglaciated regions. Such a change is called a *glacial advance* (Fig. 18.8b). In mountain glaciers, the position of a toe moves downslope during an advance, and in continental glaciers, the toe moves outward, away from the glacier's origin. If the rate of ablation below the equilibrium line equals the rate of accumulation, then the position of the toe remains fixed. But if the rate of ablation exceeds the rate of accumulation, then the position of the toe moves back toward the origin of the glacier; such a change is called a *glacial retreat* (Fig. 18.8c). During a mountain glacier's retreat, the position of the toe moves upslope. It's important to realize that when a glacier retreats, it's only the *position* of the toe that moves back toward the origin, for ice continues to flow toward the toe. Glacial ice cannot flow back toward the glacier's origin.

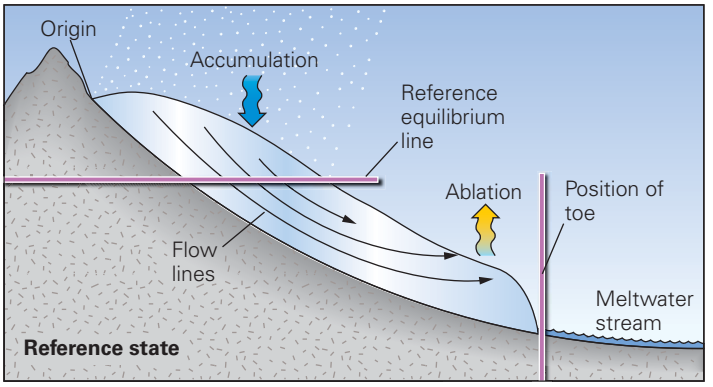
One final point before we leave the subject of glacial flow: beneath the zone of accumulation, a volume of ice gradually moves down toward the base of the glacier as new ice accumulates above it, whereas beneath the zone of ablation, a volume of ice gradually moves up toward the surface of the glacier, as overlying ice ablates. Thus, as a glacier flows, ice volumes follow curved trajectories (see Fig. 18.8a–c). For this reason, rocks picked up by ice at the base of the glacier may slowly move to the surface.

Ice in the Sea

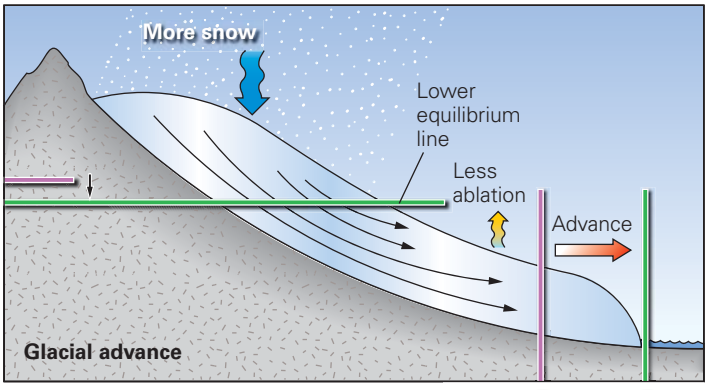
On the moonless night of April 14, 1912, the great ocean liner *Titanic* struck a large iceberg in the frigid North Atlantic. Lookouts had seen the ghostly mass of frozen water only minutes earlier and had alerted the ship's pilot, but the ship had been unable to turn fast enough to avoid disaster. The force of the blow split the steel hull, allowing water to gush in. Less than 3 hours later, the ship disappeared beneath the surface, and 1,500 people perished.

Where do icebergs, such as the one responsible for the *Titanic*'s demise, originate? In high latitudes, mountain glaciers and continental ice sheets flow down to the sea, and they either stop at the shore or flow into the sea. Glaciers whose terminus lies in the water are called **tidewater glaciers**. Valley glaciers may protrude farther into the ocean to become ice tongues. Continental glaciers entering the sea become broad, flat sheets known as **ice shelves**. In shallow water, glacial ice remains grounded (Fig. 18.9a). But where the water becomes deep enough, the ice floats with four-fifths of the ice below the water's surface. At the boundary between glacier and ocean, blocks of ice calve off and tumble into the water with an impressive splash. If a free-floating chunk rises 6 m above the water and is at least 15 m long, it is formally called an **iceberg**. Since four-fifths of the ice lies below the surface of the sea, the base of a large iceberg may actually be a few hundred meters below the surface (Fig. 18.9 b, c).

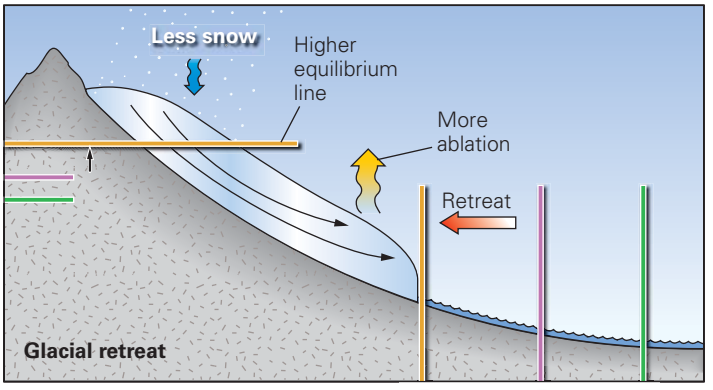
FIGURE 18.8 Glacial advance and retreat.



(a) The position of the toe represents a balance between addition by accumulation and loss by ablation.

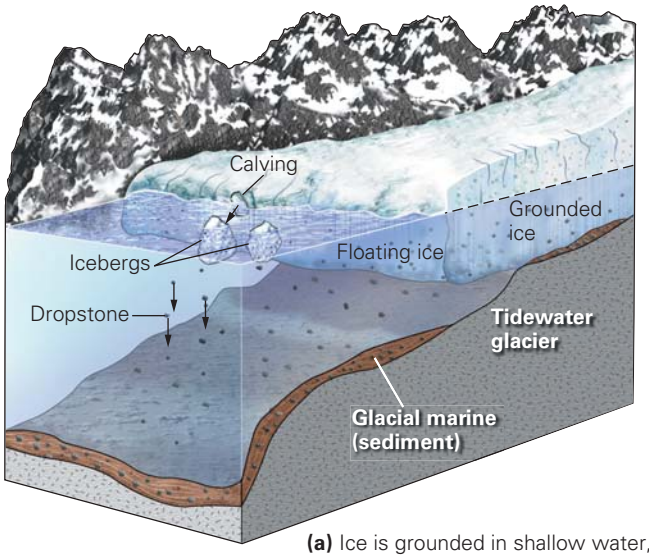


(b) If accumulation exceeds ablation, the glacier advances, the toe moves farther from the origin, and the ice thickens.



(c) If ablation exceeds accumulation, the glacier retreats and thins. The toe moves back, even though ice continues to flow toward the toe.

FIGURE 18.9 Ice shelves, tidewater glaciers, and sea ice—the nature of coastal areas in glacial regions.



(a) Ice is grounded in shallow water, but floats in deep water.

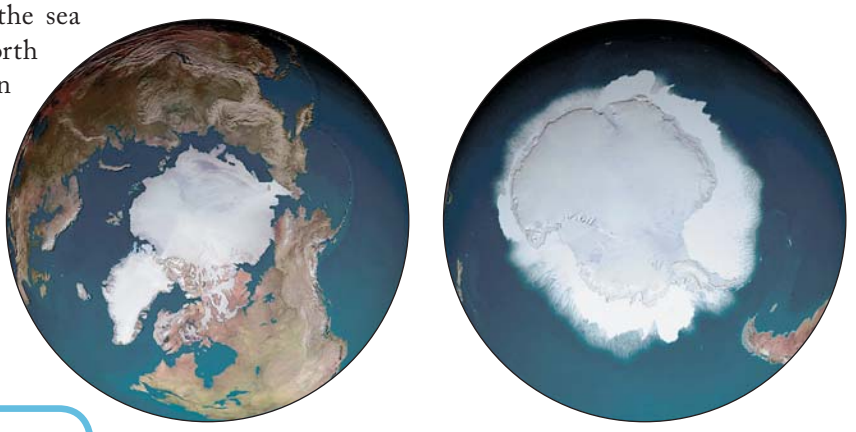


(b) This artist's rendition of an iceberg emphasizes that most of the ice is underwater.



(c) In summer, some of the sea ice of Antarctica breaks up to form tabular icebergs.

Not all ice floating in the sea originates as glaciers on land. In polar climates, the surface of the sea itself freezes, forming **sea ice** (Fig. 18.9d). The north polar ice cap of the Earth consists of sea ice, formed on the surface of the Arctic Ocean. Some sea ice, such as that covering the interior of the Arctic Ocean, floats freely; but some protrudes outward from the shore. Vast areas of ice shelves and of sea ice have been disintegrating in recent years. For example, ice-free openings develop in the Arctic Ocean sea ice during the summers, and the area of the ice shelf in Antarctica has been decreasing rapidly.



(d) Sea ice covers most of the Arctic ocean (left) and surrounds Antarctica (right).

Take-Home Message

Glaciers form when buried snow lasts all year and turns to ice. Mountain glaciers form at high elevation and flow downslope. Ice sheets form in high latitudes and spread over continents. The balance of accumulation to ablation controls glacial advance or retreat. In polar regions, sea ice covers large areas.

18.3 Carving and Carrying by Ice

Glacial Erosion and Its Products

During the last ice age, valley glaciers cut deep, steep-sided valleys into the Sierra Nevada mountains of California. In the process, some granite domes were cut in half, leaving a rounded surface on one side and a steep cliff on the other. Half Dome, in Yosemite National Park, formed in this way (Fig. 18.10a); its steep cliff has challenged many rock climbers. Such glacial erosion also produces the knife-edge ridges and pointed spires of high mountains (Fig. 18.10b) and broad expanses where rock outcrops have been stripped of overlying sediment and polished smooth (Fig. 18.10c). In many localities, the rock surface visible today is the same rock surface once in contact with ice. In some places, subsequent rockfalls and river erosion have substantially modified the surface.

As glaciers flow, clasts embedded in the ice act like the teeth of a giant rasp and grind away the substrate. This process, glacial abrasion, produces long gouges, grooves, or scratches called **glacial striations** (Fig. 18.10d). Striations range from 1 cm to 1 m across and may be tens of centimeters to tens of meters long. As you might expect, striations run parallel to the

FIGURE 18.10 Products of glacial erosion. Ice is a very aggressive agent of erosion.



(a) Half Dome, in Yosemite National Park, California.



(b) The sharp peaks of the Alps were carved, in part, by the action of ice.



(c) Glacially polished outcrop in Central Park, New York City.



(d) Glacial striations in Victoria, British Columbia.

flow direction of the ice. Rasping by embedded sand yields shiny **glacially polished surfaces**.

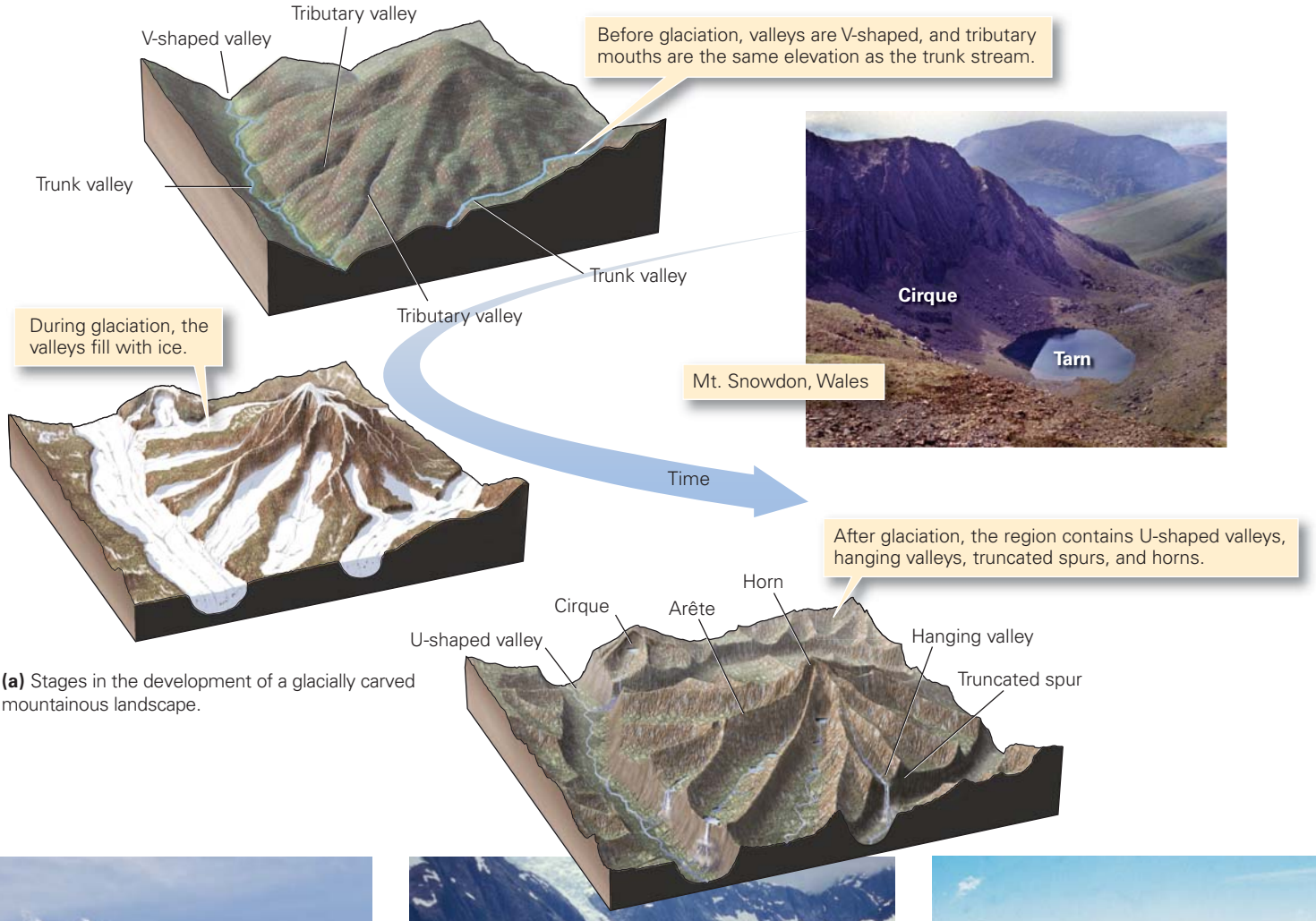
Glaciers pick up fragments of their substrate in several ways. During *glacial incorporation*, ice surrounds debris so the debris starts to move with the ice. During *glacial plucking* (or glacial quarrying), a glacier breaks off fragments of bedrock. Plucking occurs when ice freezes around rock that has just started to separate from its substrate, so that movement of the ice can lift off pieces of the rock. At the toe of a glacier, ice may actually bulldoze sediment and trees slightly before flowing over them.

Let's now look more closely at the erosional features associated with a mountain glacier (**Fig. 18.11a**). Freezing and thawing during the fall and spring help fracture the rock bordering the head of the glacier (the ice edge high in the mountains). This rock falls on the ice or gets picked up at the base of the ice, and moves downslope with the glacier. As a consequence, a bowl-shaped depression, or **cirque**, develops on the side of the mountain. If the ice later melts, a lake called a **tarn** may form at the base of the cirque. The shape of a cirque may be maintained or even amplified by rockfalls after the glacier is gone. An **arête** (French for ridge), a residual knife-edge ridge of rock, separates two adjacent cirques. A pointed mountain peak surrounded by at least three cirques is called a **horn**. The Matterhorn, a peak in Switzerland, is a particularly beautiful example of a horn; each of its four faces is a cirque (**Fig. 18.11b**).

Glacial erosion severely modifies the shape of a valley. To see how, compare a river-eroded valley with a glacially eroded valley. If you look along the length of a river in unglaciated mountains, you'll see that it typically flows down a V-shaped valley, with the river channel forming the point of the V. The V develops because river erosion occurs only in the channel, and mass wasting causes the valley slopes to approach the angle of repose. But if you look down the length of a glacially eroded valley, you'll see that it resembles a U, with steep walls. A **U-shaped valley** (**Fig. 18.11c**) forms because the combined processes of glacial abrasion and plucking not only lower the floor of the valley but also bevel its sides.

Glacial erosion in mountains also modifies the intersections between tributaries and the trunk valley. In a river system, the trunk stream serves as the local base level for tributaries (see Chapter 14), so the mouths of the tributary valleys lie at the *same* elevation as the trunk valley. The ridges (spurs) between valleys taper to a point when they join the trunk valley floor. During glaciation, tributary glaciers flow down side valleys into a trunk glacier. But the trunk glacier cuts the floor of its valley down to a depth that far exceeds the depth cut by the tributary glaciers. Thus, when the glaciers melt away, the mouths of the tributary valleys perch at a higher elevation than the floor of the trunk valley. Such side valleys are called **hanging valleys**. The water in a post-glacial stream that flows down a hanging valley cascades over a spectacular waterfall to reach the post-glacial trunk stream

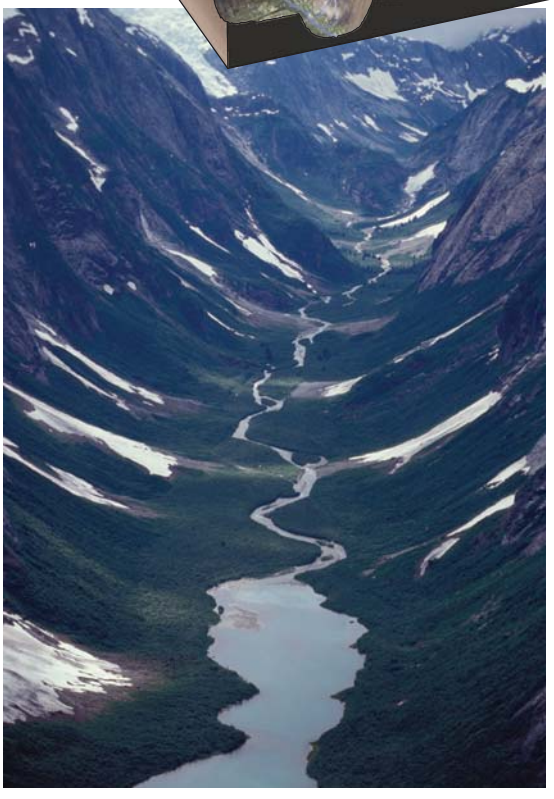
FIGURE 18.11 Landscape features formed by the glacial erosion of a mountainous landscape.



(a) Stages in the development of a glacially carved mountainous landscape.



(b) The Matterhorn in Switzerland. The first ascent was in 1865.



(c) A U-shaped glacial valley in the Tongass National Forest, Alaska.



(d) A waterfall spilling out of a U-shaped hanging valley in the Sierra Nevada.

(Fig. 18.11d). As they erode, trunk glaciers also chop off the ends of spurs (ridges) between valleys, to produce truncated spurs.

Now let's look at the erosional features produced by continental ice sheets. To a large extent, these depend on the nature of the pre-glacial landscape. Where an ice sheet spreads over a region of low relief, such as the Canadian Shield, glacial erosion creates a vast region of polished, flat, striated surfaces. Where an ice sheet spreads over a hilly area, it deepens valleys and smooths hills. Glacially eroded hills may end up being elongate in the direction of flow and may be asymmetric, for glacial rasping smoothes and bevels the upstream part of the hill, creating a gentle slope, whereas glacial plucking eats away at the downstream part, making a steep slope. Ultimately, the hill's profile may resemble that of a sheep lying in a meadow—such a hill is called a **roche moutonnée**, from the French for sheep rock (Fig. 18.12a, b).

Fjords: Submerged Glacial Valleys

As noted earlier, where a valley glacier meets the sea, the glacier's base remains in contact with the ground until the water depth exceeds about four-fifths of the glacier's thickness, at which point the glacier floats. Thus, glaciers can carve U-shaped valleys even below sea level. In addition, during an ice age, water extracted from the sea becomes locked in the ice sheets on land, so sea level drops significantly. Therefore, the floors of valleys cut by coastal glaciers during the Pleistocene Ice Age were cut much deeper than present sea level. Today, the sea has flooded these deep valleys, producing **fjords** (see Chapter 15). In the spectacular fjord-land regions along the coasts of Norway, New Zealand, Chile, and Alaska, the walls of submerged U-shaped valleys rise straight from the sea as vertical cliffs up to 1,000 m high (Fig. 18.13). Fjords also develop where an inland glacial valley fills to become a lake.

Take-Home Message

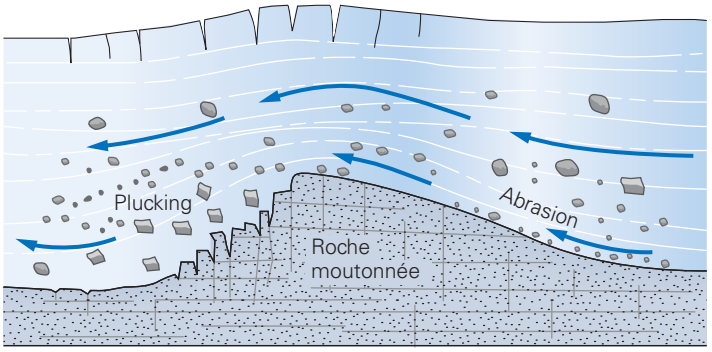
A glacier scrapes up and plucks rock from its substrate, and carries debris that falls on its surface. Glacial erosion polishes and scratches rock and carves distinctive landforms, such as U-shaped valleys and cirques. Since ice is solid, moving ice does not sort sediment.

18.4 Deposition Associated with Glaciation

The Glacial Conveyor

Glaciers can carry sediment of any size and, like a conveyor belt, transport it in the direction of flow (that is, toward the toe; Fig. 18.14a). The sediment load either falls onto the surface of the glacier from bordering cliffs or gets plucked and lifted from

FIGURE 18.12 A roche moutonnée is an asymmetric bedrock hill shaped by the flow of glacial ice.



(a) Abrasion rasps the upstream side, and plucking carries away fracture-bounded blocks on the downstream side.

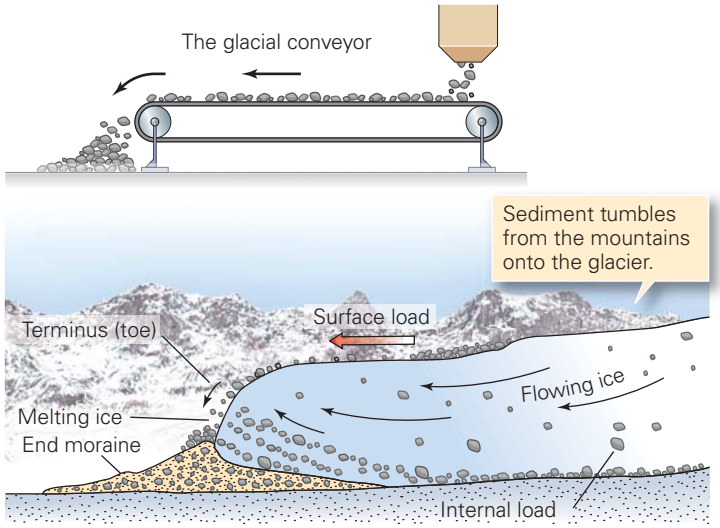


(b) An example of a roche moutonnée in the Sierra Nevada. The glacier flowed from right to left.

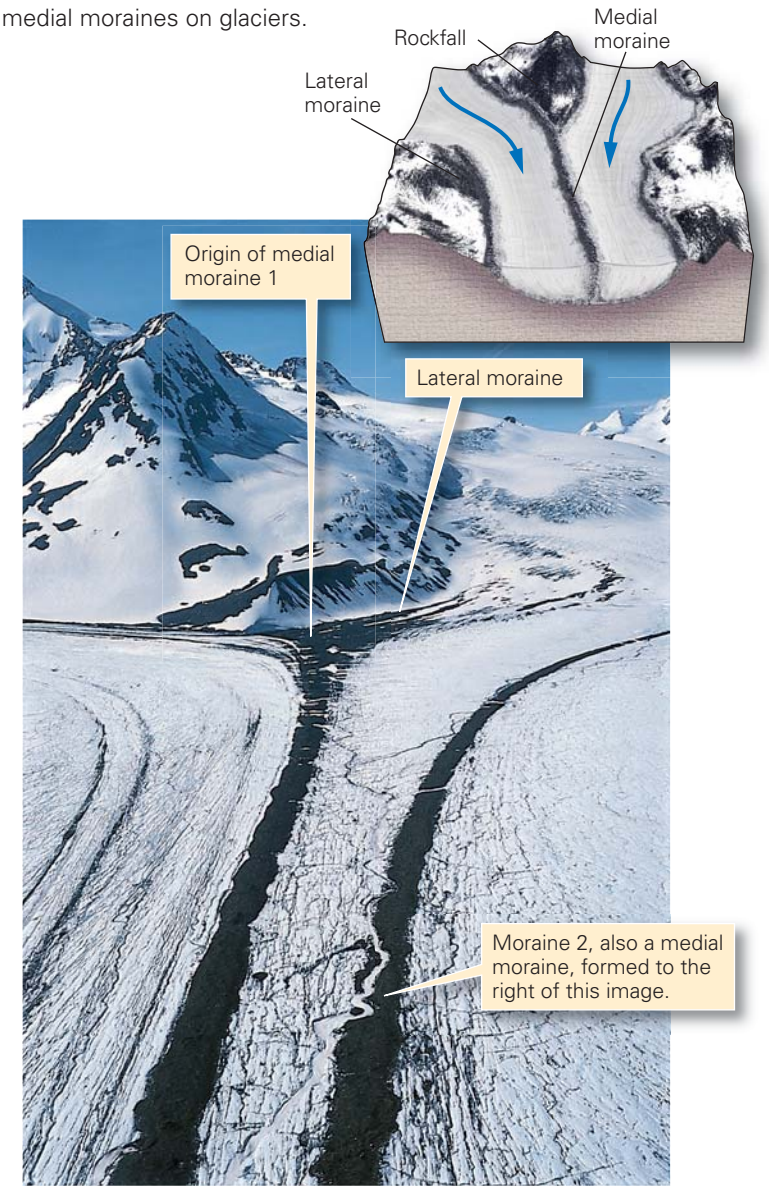
FIGURE 18.13 One of the many spectacular fjords of Norway. The water is an arm of the sea that fills a glacially carved valley. Tourists are standing on Pulpit Rock (Prekestolen).



FIGURE 18.14 The glacial conveyor and the formation of lateral and medial moraines on glaciers.



(a) Sediment falls on a glacier from bordering mountains and gets plucked up from below. Glaciers are like conveyor belts, moving sediment toward the toe of the glacier.



(b) A medial moraine forms where lateral moraines of two valley glaciers merge.

the substrate and incorporated into the moving ice. Geologists refer to a pile of debris carried by or left by glaciers as a **moraine**. Sediment dropped on the glacier's surface moves with the ice and becomes a stripe of debris. Stripes formed along the side edges of the glacier are *lateral moraines*. When a glacier melts, lateral moraines lie stranded along the side of the glacially carved valley, like bathtub rings. Where two valley glaciers merge, the debris constituting two lateral moraines merges to become a *medial moraine*, running as a stripe down the interior of the composite glacier (Fig. 18.14b). Trunk glaciers created by the merging of many tributary glaciers contain several medial moraines. Sediment transported to a glacier's toe by the glacial conveyor accumulates in a pile at the toe and builds up to form an *end moraine*.

Types of Glacial Sedimentary Deposits

Several different types of sediment can be deposited in glacial environments; all of these types together constitute **glacial drift**. The term dates from pre-Agassiz studies of glacial deposits, when geologists thought that the sediment had "drifted" into place during an immense flood. Specifically, glacial drift includes the following:

- *Till*: Sediment transported by ice and deposited beneath, at the side, or at the toe of a glacier is called **glacial till**. Glacial till is unsorted because the solid ice of glaciers can carry clasts of all sizes (Fig. 18.15a).
- *Erratics*: Glacial erratics (Fig. 18.15b) are cobbles and boulders that have been dropped by a glacier. Some lie within or on till piles, and others rest on glacially polished surfaces.
- *Glacial marine*: Where a sediment-laden glacier flows into the sea, icebergs calve off the toe and raft clasts out to sea. As the icebergs melt, they drop the clasts. Sediment consisting of ice-rafted clasts mixed with marine sediment makes up glacial marine.
- *Glacial outwash*: Till deposited by a glacier at its toe may be picked up and transported by meltwater streams that sort the sediment. The clasts are deposited by a braided stream network to form a broad area of gravel and sandbars called an outwash plain. This sediment is known as **glacial outwash** (Fig. 18.15c).
- *Loess*: When the warmer air above ice-free land beyond the toe of a glacier rises, the cold, denser air from above the glacier rushes in to take its place. A strong wind, called katabatic wind, therefore blows at the margin of a glacier. This wind picks up fine clay and silt and transports it away from the glacier's toe. Where the winds die down, the sediment settles and forms a thick layer. This sediment, called **loess**, sticks together because of the electrical charges on clay flakes. Thus, steep escarpments can develop by erosion of loess deposits (Fig. 18.15d).

FIGURE 18.15 Sedimentation processes and products associated with glaciation. Glacial sediment is distinctive.



(a) This glacial till in Ireland is unsorted, because ice can carry sediment of all sizes.



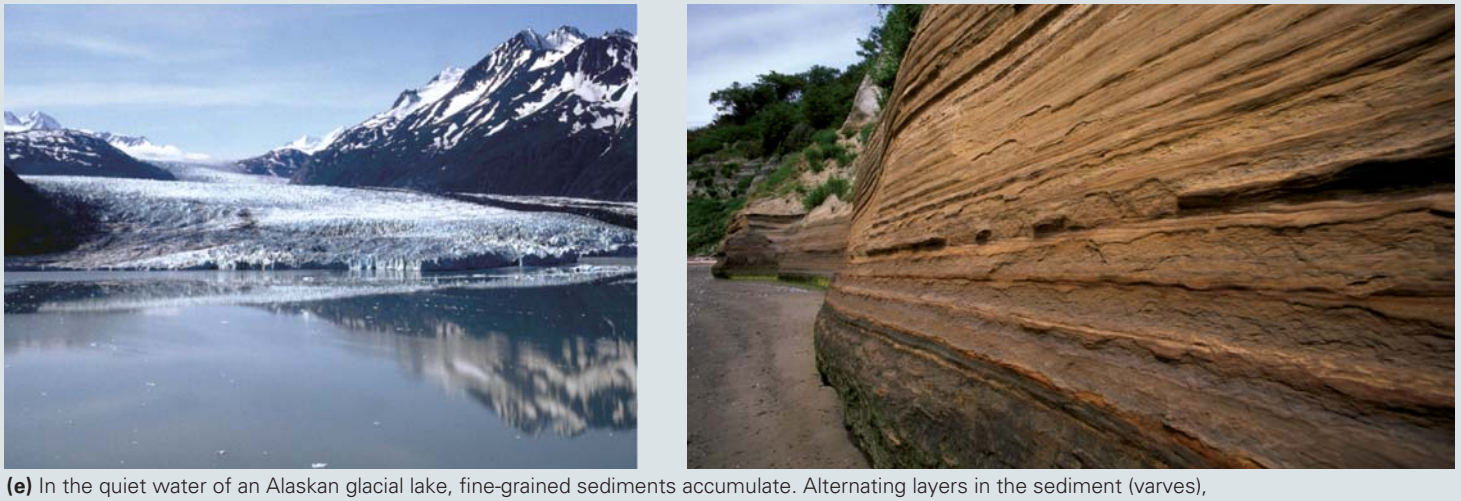
(b) Glacial erratics resting on a glacially polished surface in Wyoming.



(c) Braided streams choked with glacial outwash in Alaska. The streams carry away finer sediment and leave the gravel behind.

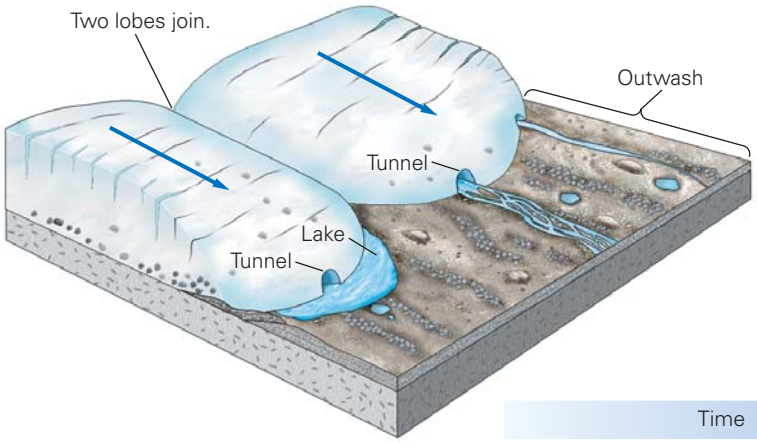


(d) Thick loess deposits underlie parts of the prairie in Illinois.

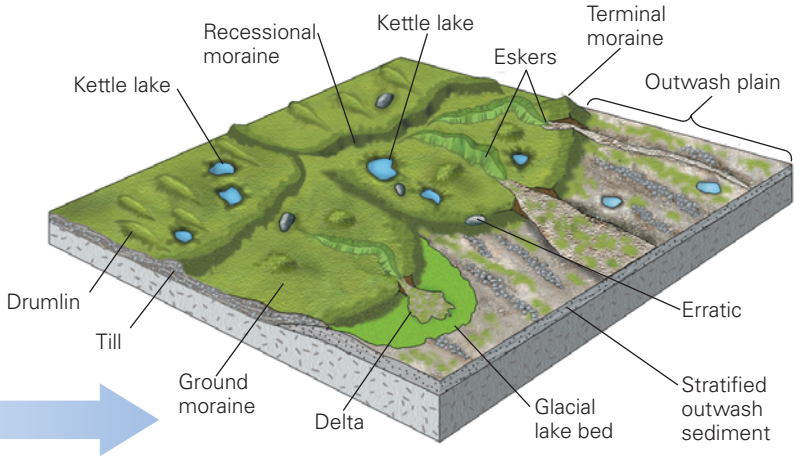


(e) In the quiet water of an Alaskan glacial lake, fine-grained sediments accumulate. Alternating layers in the sediment (varves), now exposed in an outcrop near Puget Sound, Washington, reflect seasonal changes.

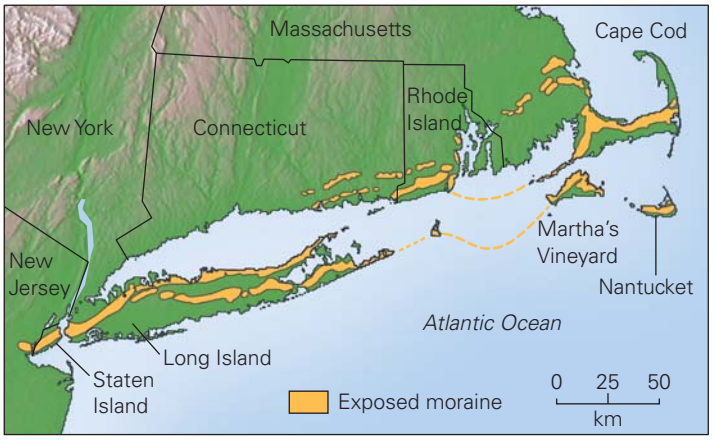
FIGURE 18.16 The formation of depositional landforms associated with continental glaciation.



(a) The ice in continental glaciers flows toward the toe; sediment accumulates at the base and at the toe of the ice sheet.



(b) Several distinct depositional landforms form during glaciation; some developed under the ice and some at the toe.



(c) Cape Cod, Long Island, and other landforms in the northeastern United States formed at the end of the continental ice sheet.

› *Glacial lake-bed sediment*: Streams transport fine clasts, including rock flour, away from the glacial front. This sediment eventually settles in meltwater lakes, forming a layer of glacial lake-bed sediment that commonly contains varves. A *varve* is a pair of thin layers deposited during a single year. One layer consists of silt brought in during spring floods and the other of clay deposited in winter when the lake's surface freezes over and the water is still (**Fig. 18.15e**).

Depositional Landforms of Glacial Environments

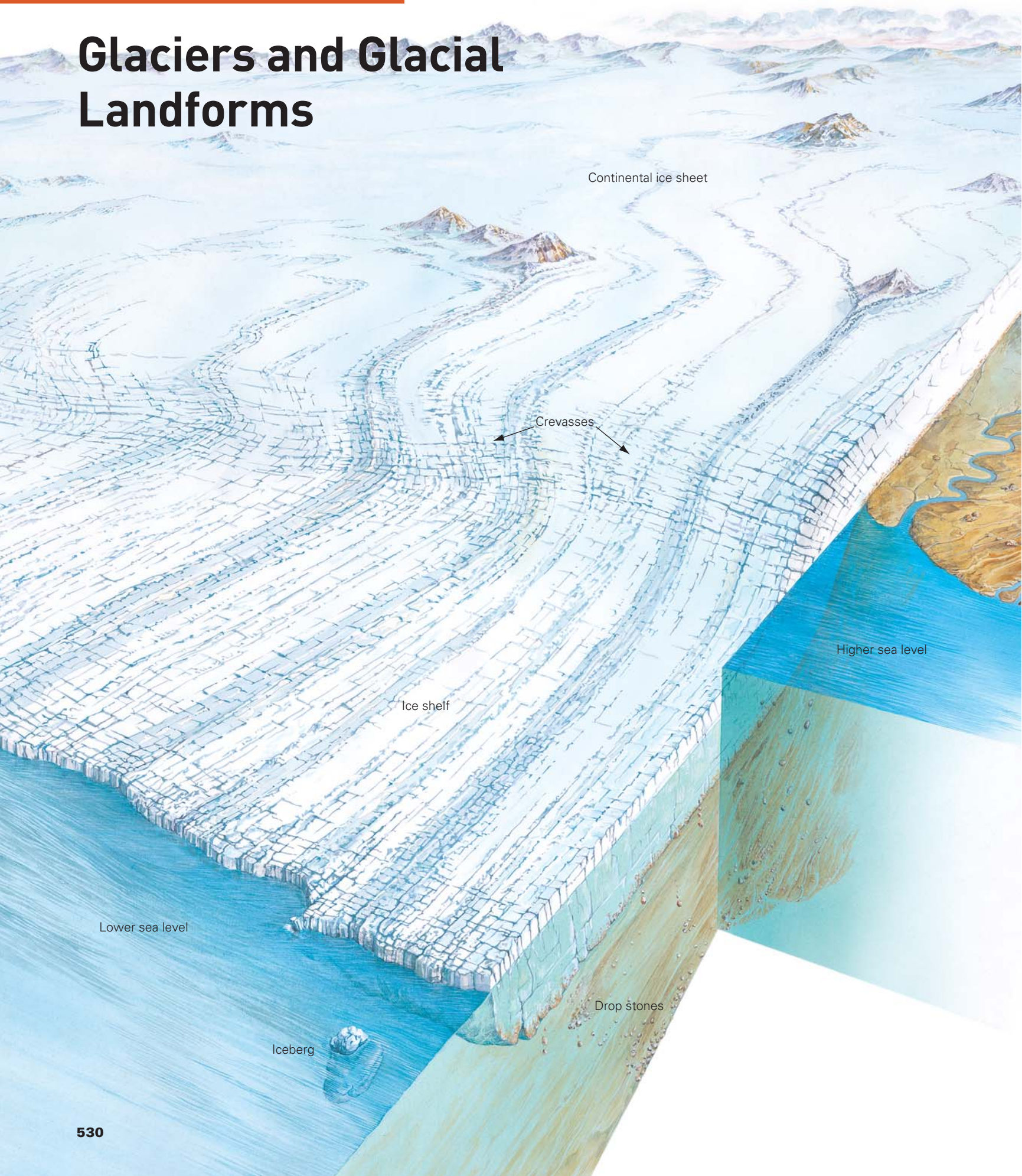
Picture a group of hunters, dressed in reindeer skin, gazing southward from the crest of an ice cliff at the toe of a continental glacier in what is now southern Canada. It's about 12,000 years ago, and the glacier has been receding for at least a millennium. The hunters would have been able to see a variety of landscape features, some formed by glacial erosion and some by deposition, due to moving ice and meltwater (**Geology at a Glance,** pp. 530–531). We've already described erosional features, so now let's focus on the depositional features of the landscape (**Fig. 18.16a, b**).

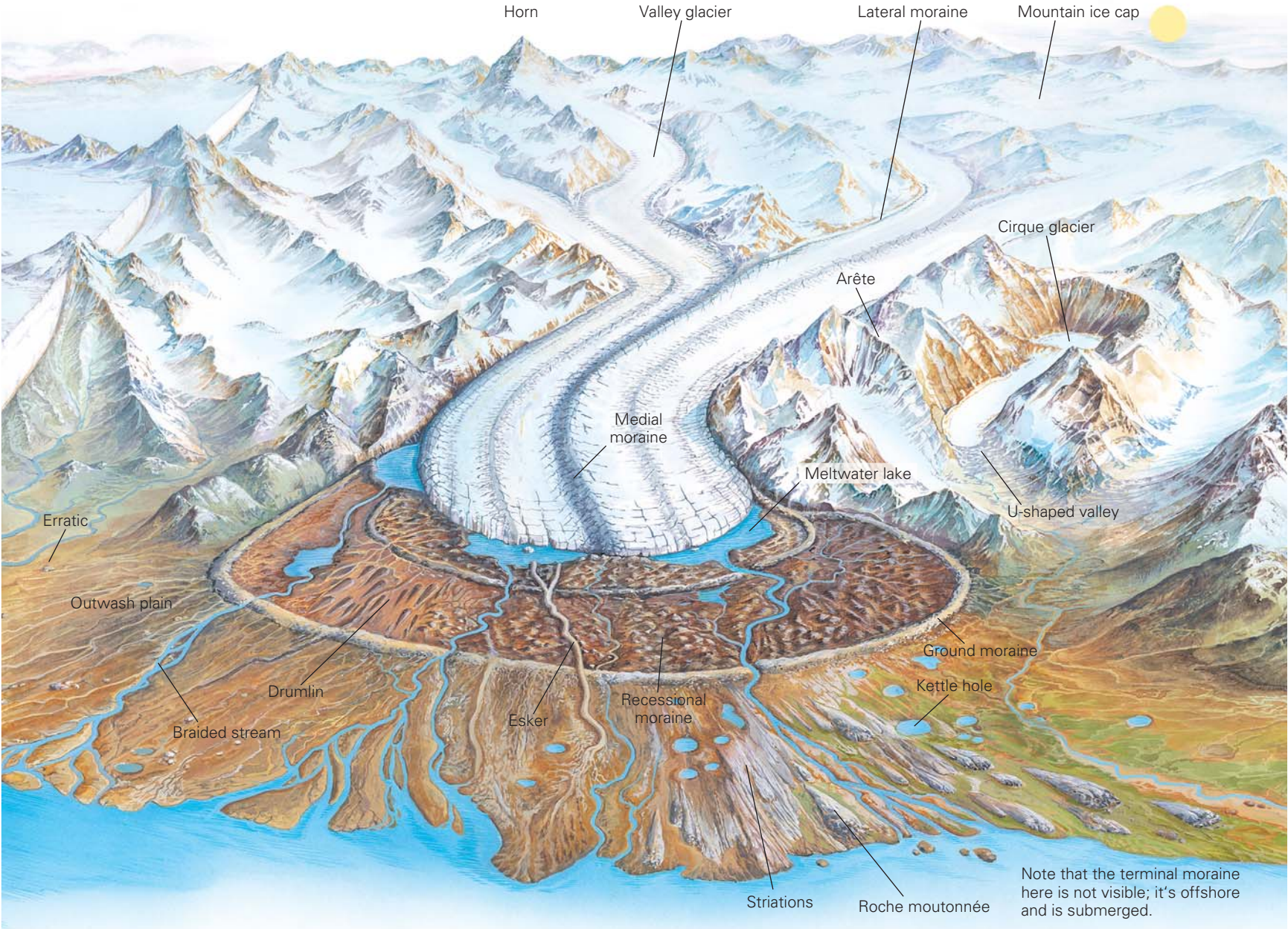
From their vantage point, the hunters would probably have seen a few curving, hummocky ridges of sediment in the region between the glacier's toe and the horizon. Each of these ridges is an *end moraine*, formed when the position of the glacier's toe remained in the same location for a while. Ice keeps flowing to the toe, and like a giant conveyor belt, transports sediment to the toe. As the ice melts, this sediment accumulates to form a pile of till, and this pile comprises the end moraine. Geologists refer to the end moraine at the farthest limit of glaciation as the *terminal moraine*. In the northeastern United States, a large terminal moraine built up during the Pleistocene Ice Age—this ridge of sediment now underlies Long Island, New York, and Cape Cod, Massachusetts (**Fig. 18.16c**). When a glacier starts receding, it may stall several times—the end moraines that form when a glacier stalls while receding are known as *recessional moraines*. The hummocky layer of till between end moraines is known as lodgment till or *ground moraine*. Since this till was deposited by moving ice, clasts within it may be aligned and scratched.

The hummocky surface of a moraine reflects both variations in the amount of sediment supplied by the ice and the development of kettle holes. A **kettle hole** is a roughly circular depression made when a block of ice that calved off the toe of a glacier became buried by till. When the block eventually melts, it leaves behind a depression (**Fig. 18.17a, b**). Geologists refer to a land surface spotted with many kettle holes separated by rounded hills or ridges of sediment as "knob-and-kettle topography" (**Fig. 18.17c**).

In some locations, glacial ice flow molds underlying till into an elongate hill known as a **drumlin** (from the Gaelic word for small hill or ridge). Drumlins commonly occur in swarms, and tend to be about 50 m high. Their long axis trends parallel to the flow direction of the glacier. Notably, drumlins taper in the direction of flow—a drumlin's upstream end is steeper than its downstream end (**Fig. 18.17d, e**).

Glaciers and Glacial Landforms





Glaciers are rivers or sheets of ice that stay frozen all year and slowly flow. Continental glaciers, vast sheets of ice up to a few kilometers thick, covered extensive areas of land during times when Earth had a colder climate. Continental glaciers form when snow accumulates at high latitudes, then, when buried deeply enough, packs together and recrystallizes to make glacial ice. Ice, though solid, is weak, and thus ice sheets spread over the landscape like syrup over a pancake. At the peak of the last ice age, ice sheets covered almost all of Canada, much of the United States, northern Europe, and parts of Russia.

The upper part of a sheet is brittle and may crack to form crevasses. Because ice sheets store so much of the Earth's water, sea level becomes lower during an ice age. When a glacier reaches the sea, it becomes an ice shelf. Rock that the glacier has plucked up along the way is carried out to sea with the ice; when the ice melts, the rocks fall to the sea floor as dropstones. At the edge of the shelf, icebergs calve off and float away.

A second class of glaciers, called mountain or alpine glaciers, exist in mountainous areas because snow can last all year at high elevations. During an ice age, mountain glaciers grow and flow out onto the land surface beyond the mountain front. The glacier at the right has started to recede after formerly advancing and covering more of the land. Glacial recession may happen when the climate warms, so ice melts away faster at the toe (terminus) of the glacier than it can be added at the source. In front of the glacier, you can find consequences of glacial erosion such as striations on bedrock and roches moutonnées.

When the glacier pauses, till (unsorted glacial sediment) accumulates to form an end moraine. Meltwater lakes gather at the toe, and streams carry sediment and deposit it as glacial outwash. Sediment that accumulates in ice tunnels, exposed when the glacier melts, make up sinuous ridges called eskers. Even when the toe remains fixed in position for a while, the ice continues to flow, and thus molds underlying sediment into drumlins. Ice blocks buried in till melt to form kettle holes. (Though the examples shown here were left after the melting away of a piedmont glacier, most actually form during continental glaciation.)

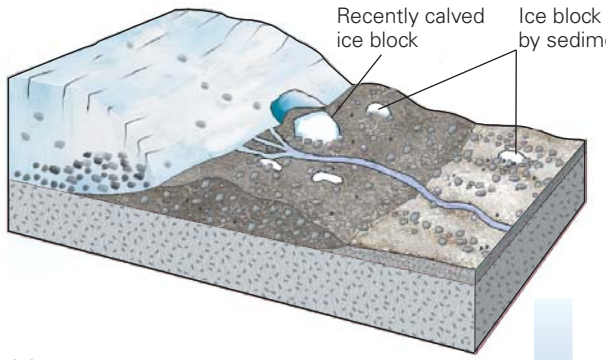
In the mountains, glaciers fill valleys or form ice caps. Sediment falling from the mountains creates lateral and medial moraines. Glaciers carve distinct landforms in the mountains, such as cirques, arêtes, horns, and U-shaped valleys.

As we've noted, not all of the sediment—or "drift"—associated with glacial landscapes was deposited directly by ice, for meltwater also carries and deposits sediment. Water-transported sediment, in contrast to till, tends to be sorted and stratified. Sediment deposited in meltwater tunnels beneath a glacier itself may remain as a sinuous ridge, known as an **esker**, when the glacier melts away (Fig. 18.18a, b). Braided meltwater streams that flow beyond the end of a glacier deposit layers of sand and gravel that underlie *glacial outwash plains*. Meltwater may collect in a lake adjacent to the glacier's toe, to form an *ice-margin lake*. Additional lakes and swamps may form in low areas on the ground moraine. Sediments deposited in eskers and glacial outwash plains serve as important sources of sand and gravel for construction, and the fine sediment of former glacial lake beds evolves into fertile soil for agriculture.

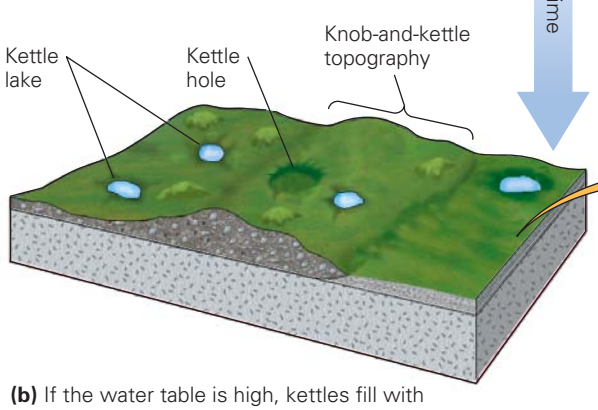
Take-Home Message

When ice melts, it deposits unsorted till. Meltwater streams and wind transport sort the sediment to form outwash-plain gravels and loess deposits, respectively. Deposition by glaciers produces distinctive landforms, such as moraines, eskers, and kettle holes.

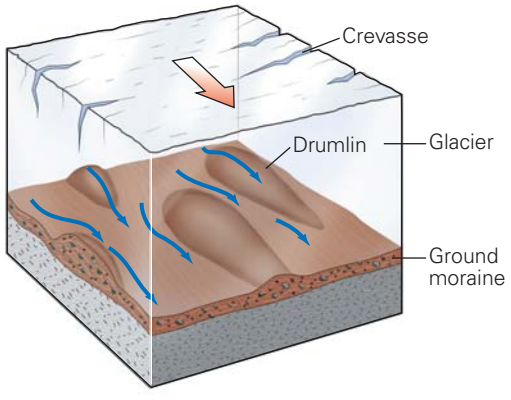
FIGURE 18.17 Knob-and-kettle topography and drumlins characterize some areas that were once glaciated.



(a) Ice blocks calve off glaciers and become buried by sediment. When the ice melts, a kettle forms.



(b) If the water table is high, kettles fill with water and turn into roughly circular lakes.



(d) The formation of a drumlin beneath a glacier.

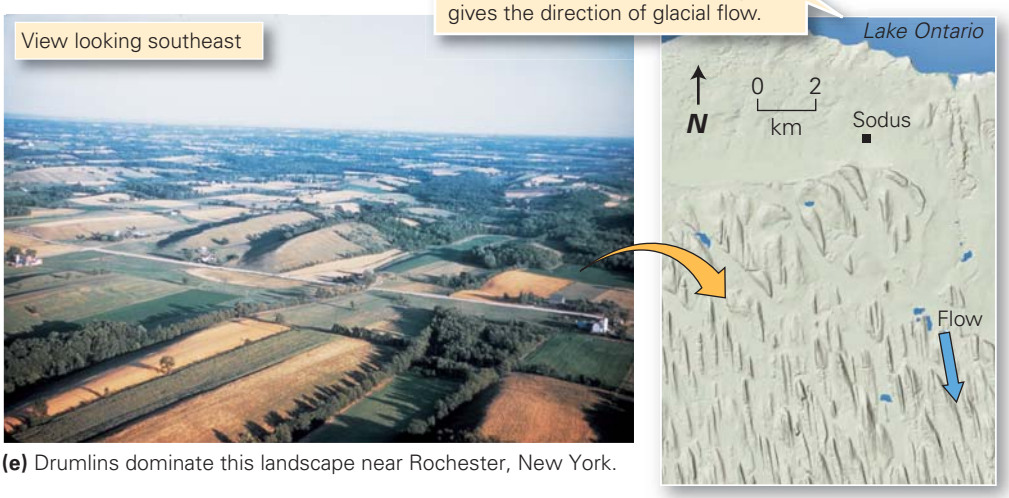
18.5 Other Consequences of Continental Glaciation

Ice Loading and Glacial Rebound

When a large ice sheet (more than 50 km in diameter) grows on a continent, its weight causes the surface of the lithosphere to sink. In other words, ice loading causes **glacial subsidence**.

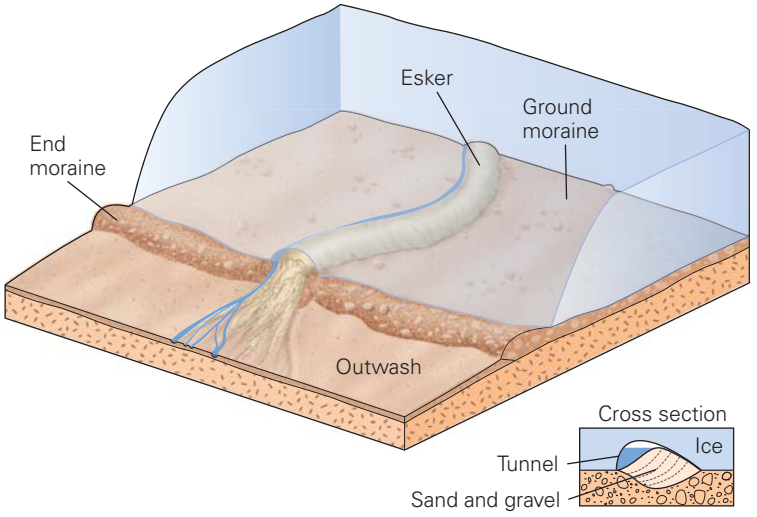


(c) Knob-and-kettle topography make the surface of this moraine in Yellowstone Park, Wyoming, very hummocky.



(e) Drumlins dominate this landscape near Rochester, New York.

FIGURE 18.18 Eskers are snake-like ridges of sand and gravel that form when sediment fills meltwater tunnels at the base of a glacier.



(a) At the time of formation, an esker develops beneath an ice sheet. In cross section (inset), wedges of sand accumulate in the tunnel.



(b) An example of an esker in an area once glaciated, but now farmed.

Lithosphere, the relatively rigid outer shell of the Earth, can sink because the underlying asthenosphere is soft enough to flow slowly out of the way (Fig. 18.19). Because of ice loading, much of Antarctica and Greenland now lie below sea level (see Fig. 18.4), so if their ice were *instantly* to melt away, these continents would be flooded by a shallow sea.

What happens when continental ice sheets do melt away? Gradually, the surface of the underlying continent rises back up, by a process called **glacial rebound**, and the asthenosphere flows back underneath to fill the space. This process doesn't take place instantly, the asthenosphere flows so slowly (at rates of a few millimeters per year) that it takes thousands of years for ice-depressed continents to rebound. Thus, glacial rebound is still taking place in some regions that were covered by ice during the Pleistocene Ice Age.

Sea-Level Changes: The Glacial Reservoir

More of the Earth's surface and near-surface freshwater resides in glacial ice than in any other reservoir. During the Pleistocene Ice Age, glaciers covered almost three times as much land area so they held significantly more water than they do today. In effect, water from the ocean reservoir transferred to the glacial reservoir and remained trapped on land. As a consequence, sea level dropped by as much as 100 m, and extensive areas of continental shelves became exposed as the coastline migrated seaward (Fig. 18.20a–c). People and animals populated the exposed coastal plains. The drop in sea level also created land bridges across the Bering Strait between North America and northeastern Asia, providing convenient migration routes for prehistoric humans.

Ice Dams, Drainage Reversals, and Lakes

When ice freezes over a sewer opening in a street, neither meltwater nor rain can enter the drain, and the street floods. Ice sheets play a similar role in glaciated regions. The ice may block the course of a river, leading to the formation of a lake. In addition, the weight of a glacier changes the tilt of the land surface and therefore the gradients of streams, and glacial sediment may fill preexisting valleys. In sum, continental glaciation modifies or destroys preexisting drainage networks. While the glacier exists, streams find different routes and carve out new valleys; by the time the glacier melts away, these new streams have become so well established that old river courses may remain abandoned.

Meltwater Floods

Subsidence of the land surface at the toe of a glacier locally led to the growth of large ice-margin lakes. Inevitably, the ice dams that held back these lakes melted and broke. In a matter of hours to days, the contents of the lakes drained, creating immense floodwaters that stripped the land of soil and left behind huge ripple marks. For example, glacial Lake Missoula, in Montana, filled when glaciers advanced and blocked the outlet of a large valley. When the glaciers retreated, the ice dam broke, releasing immense torrents—the Great Missoula Flood—that scoured eastern Washington, creating a barren, soil-free landscape called the channeled scablands.

FIGURE 18.19 The concept of subsidence and rebound, due to continental glaciation and deglaciation. (Not to scale.)

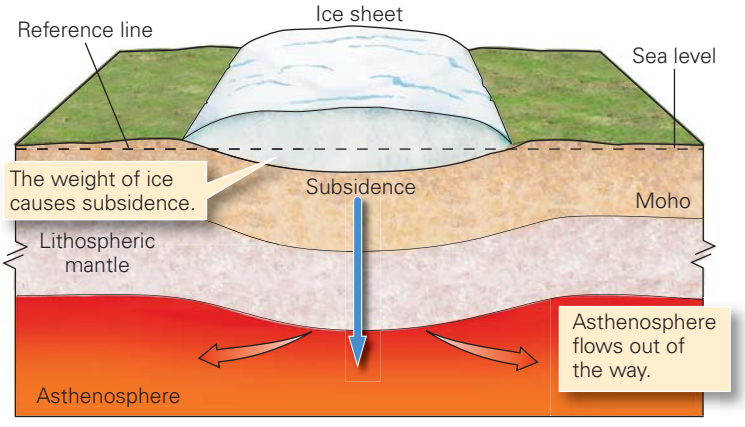
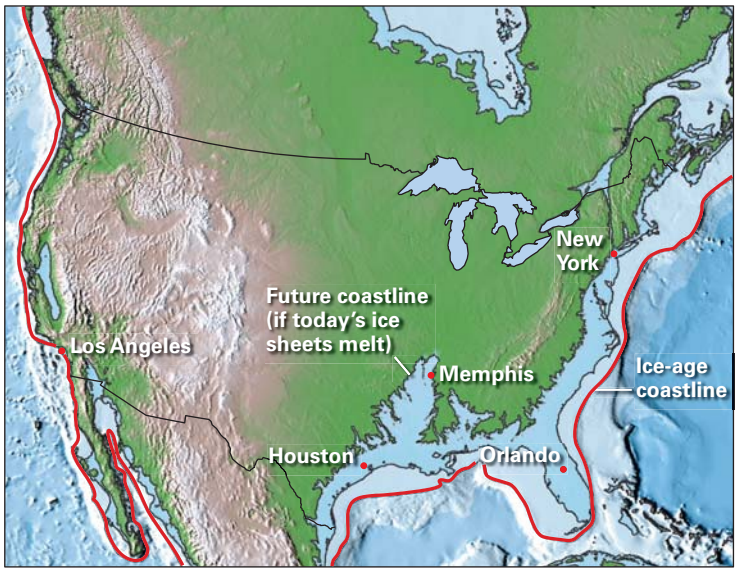


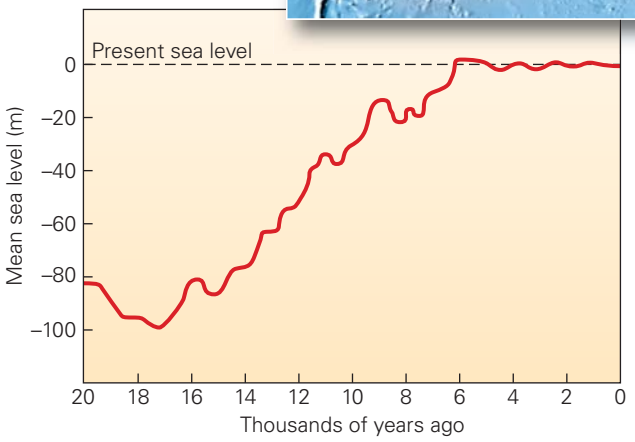
FIGURE 18.20 The link between sea level and global glaciation: glaciers store water so when glaciers grow, sea level falls, and when glaciers melt, sea level rises.



(a) The red line shows the coastline during the last ice age; much of the continental shelf was dry. If present-day ice sheets melt, coastal lands will flood.



(b) Prehistoric people migrated across the Bering Strait land bridge.



(c) Sea-level rise between 17,000 and 7,000 B.C.E. was due to the melting of ice-age glaciers.

The largest known ice-margin lake covered portions of Manitoba and Ontario, in south-central Canada, and North Dakota and Minnesota in the United States (**Fig. 18.21a**). This body of water, Glacial Lake Agassiz, existed between 11,700 and 9,000 years ago, a time during which the most recent phase of the last ice age came to a close and the continental glacier retreated north. At its largest, the lake covered over 250,000 square km (100,000 square miles), an area greater than that of all the present Great Lakes combined. The sudden release of water from Lake Agassiz may have led to a sea-level rise of 1 to 3 m during a single year.

Pluvial Features

During the Pleistocene Ice Age, the climate in regions to the south of continental glaciers was wetter than it is today. Fed by enhanced rainfall, lakes accumulated in low-lying land at a great distance from the ice front. Many such **pluvial lakes** (from the Latin *pluvia*, rain) flooded interior basins of the Basin and Range Province in Utah and Nevada (**Fig. 18.21b**). The largest pluvial lake, Lake Bonneville, covered almost a third of western Utah. When this lake suddenly drained after a natural dam holding it back broke, it left a bathtub ring of shoreline rimming the mountains near Salt Lake City. Today's Great Salt Lake is but a small remnant of Lake Bonneville.

Periglacial Environments

In polar latitudes today, and in regions adjacent to the fronts of continental glaciers during the last ice age, the mean annual temperature stays low enough (below –5°C) that soil moisture and groundwater freeze and, except in the upper few meters, stay solid all year. Such permanently frozen ground is called **permafrost**. Regions with widespread permafrost that do not have a cover of snow or ice are called *periglacial environments* (the Greek *peri* means around, or encircling; periglacial environments appear around the edges of glacial environments; **Fig. 18.22a**).

The upper few meters of permafrost may melt during the summer months, only to refreeze again when winter comes. As a consequence of the freeze-thaw process, the ground of some permafrost areas splits into pentagonal or hexagonal shapes, creating a landscape called **patterned ground** (**Fig. 18.22b**).

Permafrost presents a unique challenge to people who live in polar regions or who work to extract resources from these regions. For example, heat from a building may warm and melt underlying permafrost, creating a mire into which the building settles. For this reason, buildings in permafrost regions must be placed on stilts, so that cold air can circulate beneath them to keep the ground frozen.

Take-Home Message

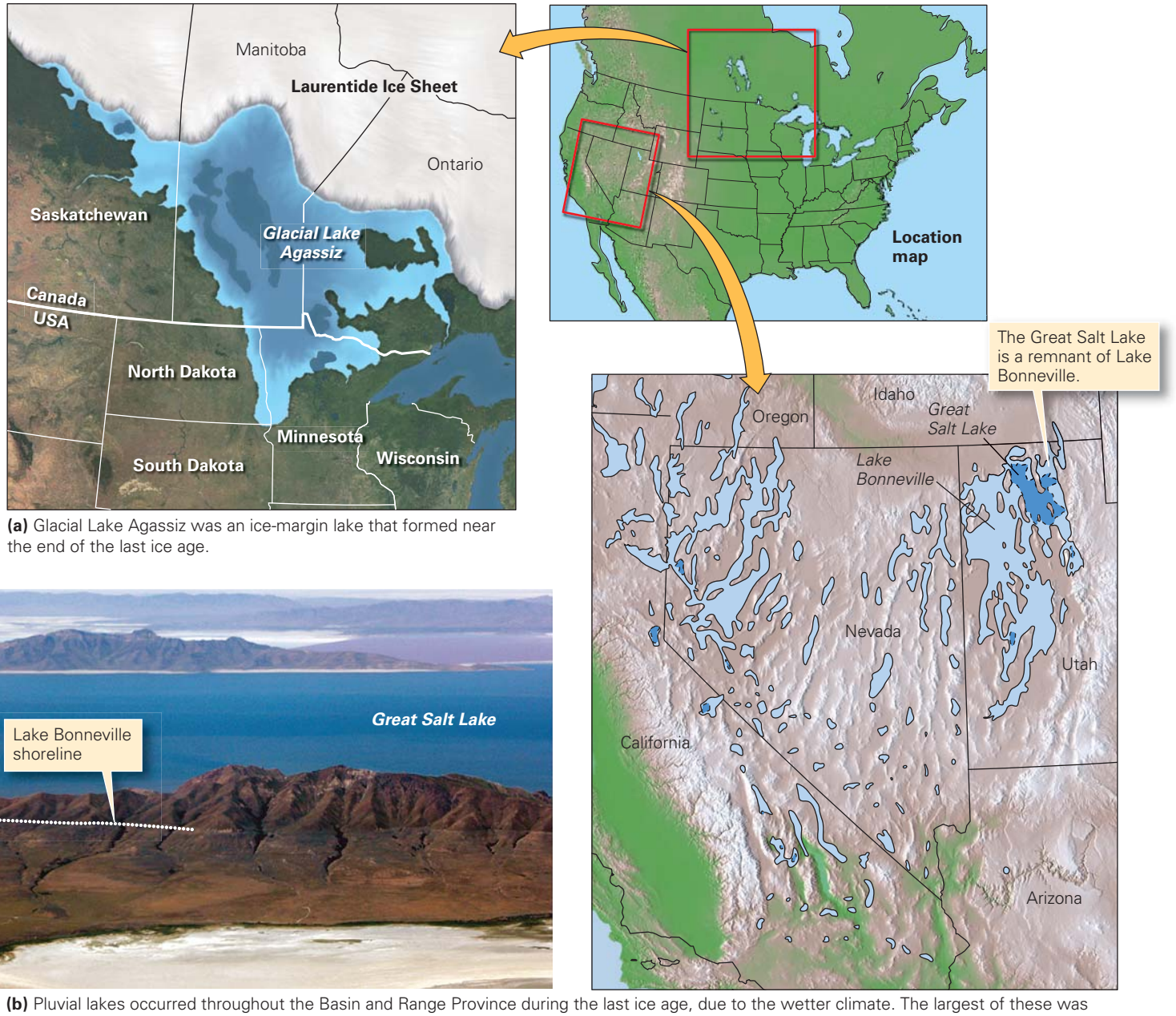
The weight of a continental ice sheet can cause the ground surface to subside, and melting leads to rebound. Continental ice sheets store water, so glacial growth or melting affects sea level. The land beyond an ice sheet may be covered with permafrost or pluvial lakes.

18.6 The Pleistocene Ice Age

The Pleistocene Glaciers

Today, most of the land surface in New York City lies hidden beneath concrete and steel, but in Central Park it's still possible to see land in a seminatural state. If you stroll through the park,

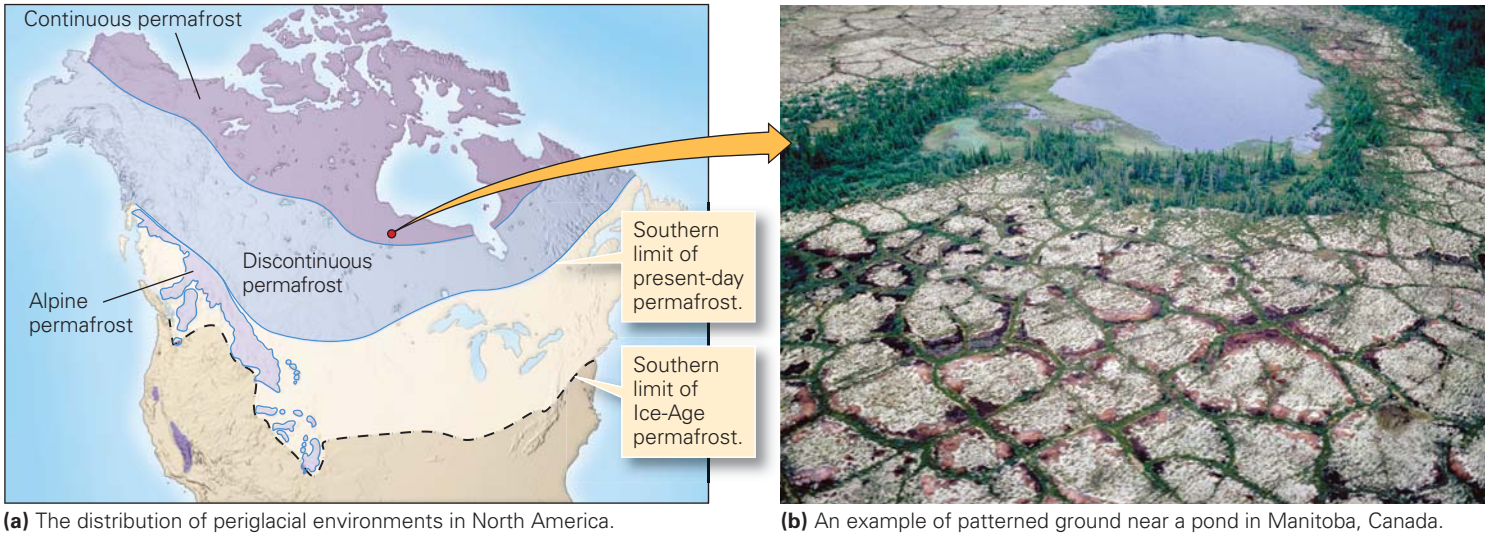
FIGURE 18.21 Ice-age lakes in North America.



(a) Glacial Lake Agassiz was an ice-margin lake that formed near the end of the last ice age.

(b) Pluvial lakes occurred throughout the Basin and Range Province during the last ice age, due to the wetter climate. The largest of these was Lake Bonneville. Subtle horizontal terraces define the remnants of beaches, now over 100 m above the present level of the Great Salt Lake.

FIGURE 18.22 Periglacial regions are not ice covered but do include substantial areas of permafrost.



(a) The distribution of periglacial environments in North America.

(b) An example of patterned ground near a pond in Manitoba, Canada.

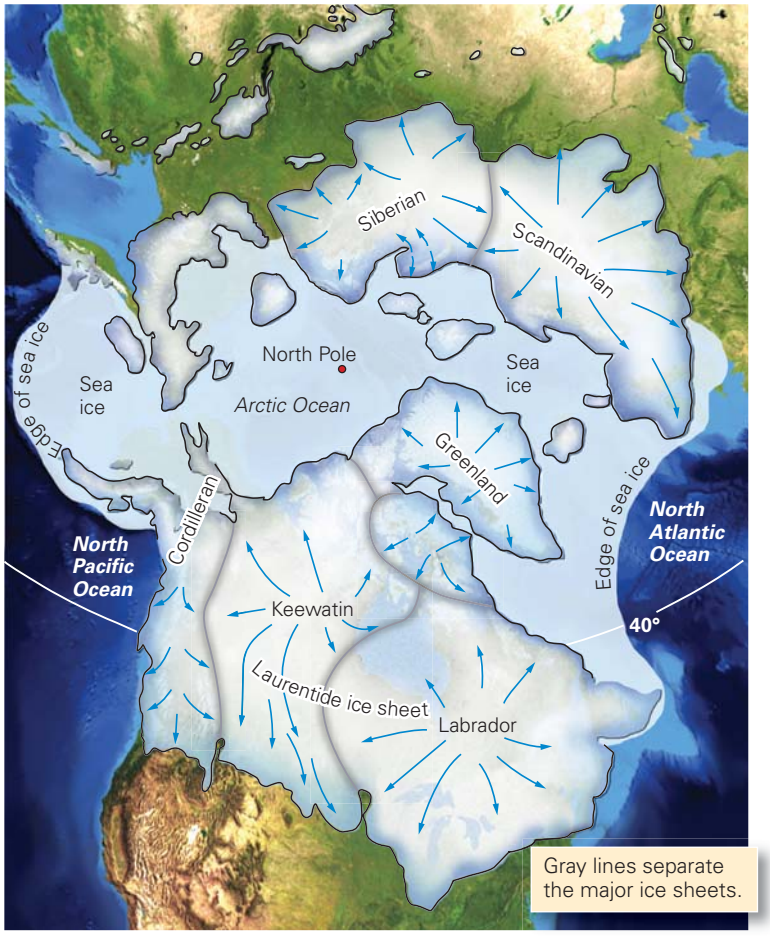
you'll find that the top surfaces of outcrops are smooth and polished, and in places have been grooved and scratched. Here and there, glacial erratics rest on the bedrock. You are seeing evidence that an ice sheet once scraped along this now-urban ground. Geologists estimate that the ice sheet that overrode the New York City area may have been 250 m thick, enough to bury a 75-story building.

The fact that glaciated landscapes still decorate the surface of the Earth means that the last ice age occurred fairly recently during Earth's history. Otherwise, the landscape features would have been either eroded away or buried. The ice age responsible for the glaciated landscapes of North America, Europe, and Asia happened mostly during the Pleistocene Epoch, which began about 2.6 Ma (see Chapter 11), so as we've noted earlier, it is commonly known as the Pleistocene Ice Age.

Based on studying patterns of glacial striations and of the sources of erratics, geologists have developed an approximate idea of where the great Pleistocene ice sheets originated, and the directions in which the ice sheets flowed. In North America, major ice sheets appear to have initiated in at least three locations (**Fig. 18.23**). The Labrador ice sheet formed over northeastern Canada, the Keewatin ice sheet originated in northwestern Canada, and the Baffin ice sheet formed over Baffin Bay. These sheets, together with one or more smaller ones, merged to form the giant *Laurentide ice sheet* that covered all of Canada east of the Rocky Mountains, and spread southward over the northern portion of the United States. The Cordilleran ice sheet, which originated in the mountains of western Canada, spread westward to the Pacific coast and eastward until it merged with the Laurentide ice sheet. Other ice sheets formed in Greenland, Scandinavia, northern Russia, and Siberia.

In addition to continental ice sheets, sea ice in the northern hemisphere expanded to cover all of the Arctic Ocean and parts of the North Atlantic during the Pleistocene. Sea ice surrounded Iceland and approached Scotland and also fringed most of western Canada and southeastern Alaska.

FIGURE 18.23 Pleistocene ice sheets of the northern hemisphere.



Life and Climate in the Pleistocene World

During the Pleistocene Ice Age, all climatic belts shifted southward (**Fig. 18.24a, b**). Geologists can document this shift by examining fossil pollen, which can survive for thousands of years if preserved in the sediment of bogs.

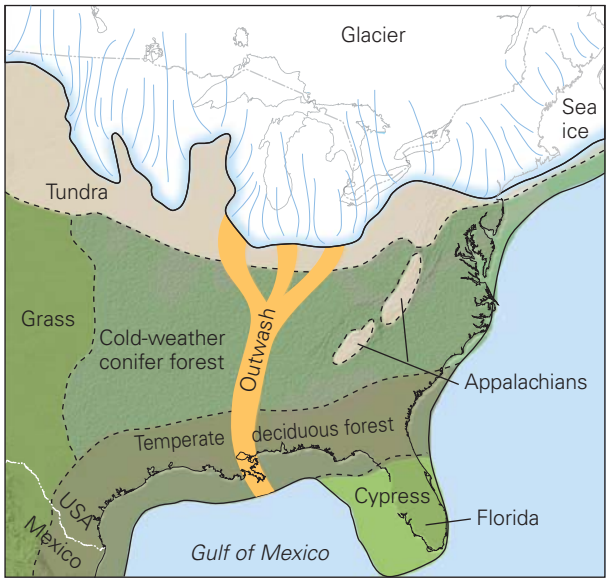
Fossils also tell us that numerous species of now-extinct large mammals inhabited the Pleistocene world (**Fig. 18.24c**). Giant mammoths and mastodons, relatives of the elephant, along with woolly rhinos, musk oxen, reindeer, giant ground sloths, bison, lions, saber-toothed cats, giant cave bears, and hyenas wandered forests and tundra in North America. Early human-like species were already foraging in the woods by the beginning of the Pleistocene Epoch, and by the end modern *Homo sapiens* lived on every continent except Antarctica, and had discovered fire and invented tools.

Timing of the Pleistocene Ice Age

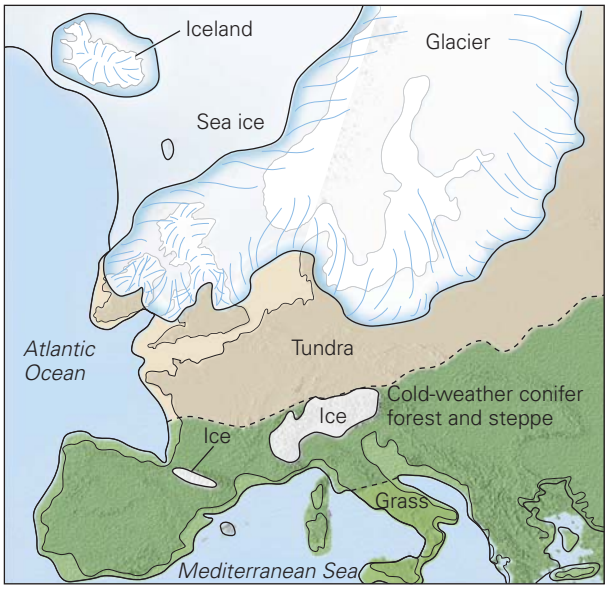
Louis Agassiz assumed that only one ice age had affected the planet. But close examination of the stratigraphy of glacial deposits on land revealed that paleosols (ancient soil preserved in the stratigraphic record), as well as beds containing fossils of warmer-weather animals and plants, lay between distinct layers of glacial sediment. This observation suggested that between episodes of glacial deposition, glaciers receded and temperate climates prevailed. In the second half of the 20th century, when modern methods for dating geological materials became available, the difference in ages between the different layers of glacial sediment could be confirmed. Clearly, glaciers advanced and then retreated more than once during the Pleistocene. Times during which the glaciers grew and covered substantial areas of the continents are called glacial periods, or glaciations, and times between glacial periods are called interglacial periods, or **interglacials**.

Using the on-land sedimentary record, geologists recognized five Pleistocene glaciations in Europe and, traditionally, four in the midwestern United States (Wisconsinan, Illinoian, Kansan, and Nebraskan, named after the southernmost states in which their till was deposited; **Fig. 18.25**).

FIGURE 18.24 Climate belts during the Pleistocene.



(a) Tundra covered parts of the United States, and southern states had forests like those of New England's today.



(b) Regions of Europe that support large populations today would have been barren tundra during the Pleistocene.



(c) Cold-adapted, now-extinct, large mammals roamed regions that are now temperate.

Since the mid-1980s, geologists no longer recognize Nebraskan and Kansan; they are lumped together as "pre-Illinoian."

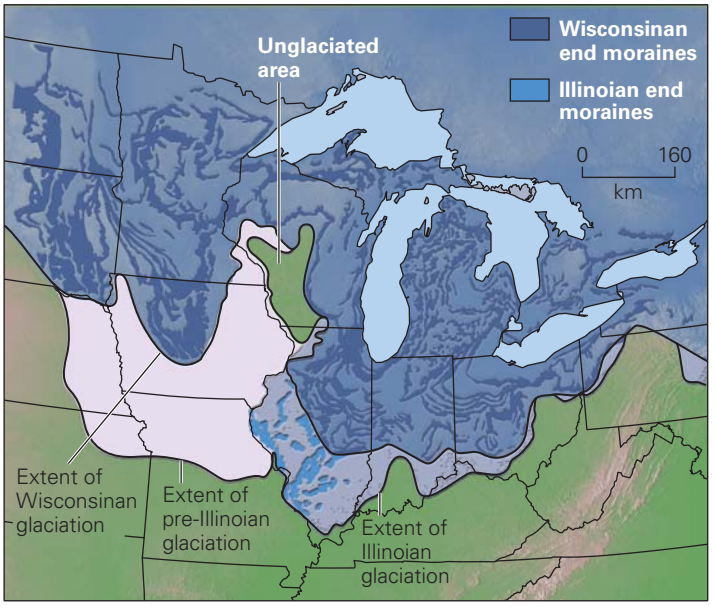
The chronology of glaciations was turned on its head in the 1960s, when geologists began to study submarine sediment. They found that some layers contained glacially transported grains, while others did not. Similarly, they found that at a given location, some layers contained fossils of cold-water plankton and other fossils of warm-water plankton. Researchers found that in sediment of the last 2.6 million years, there is evidence for 20 to 30 glaciations during the Pleistocene Epoch. The traditionally recognized glaciations of Europe and the United States might represent only the largest of these.

Geologists refined their conclusions about the frequency of Pleistocene glaciations by examining the isotopic composition of fossil shells. Shells of many plankton species consist of calcite ($CaCO_3$). The oxygen in the shells includes two isotopes, a heavier one (^{18}O) and a lighter one (^{16}O). The ratio of these isotopes tells us about the water temperature in which the plankton grew; this is because as water gets colder, plankton incorporate a higher proportion of ^{18}O into their shells. The isotope record confirms that 20 to 30 of these events occurred during the last 2.6 million years (**Fig. 18.26a**).

Older Ice Ages during Earth History

So far, we've focused on the Pleistocene Ice Age because of its importance in developing Earth's present landscape. Was this the only ice age during Earth history, or do ice ages happen frequently? To answer such questions, geologists study the stratigraphic record and search for ancient glacial deposits that have hardened into rock. These deposits, called tillites, consist of larger clasts distributed throughout a matrix of sandstone and mudstone. In many cases, tillites are deposited on glacially polished surfaces.

FIGURE 18.25 Pleistocene glacial deposits in the north-central United States. Curving moraines reflect the shape of glacial lobes.



By using the stratigraphic principles described in Chapter 10, geologists have determined that tillites were deposited during the Late Paleozoic; these are the deposits Alfred Wegener studied when he argued in favor of continental drift (Fig. 18.26b). Tillites were also deposited between 850 and 630 Ma (at the end of the Proterozoic Eon), about 2.4 to 2.1 Ga (near the beginning of the Proterozoic), and perhaps about 2.9 Ga (in the Archean Eon). Strata deposited at other times in Earth history do not contain tillites. Thus, it appears that glacial advances and retreats have not occurred steadily throughout Earth history, but rather are restricted to specific time intervals, or ice ages, of which there were four or five: Pleistocene, Permian, late Proterozoic, early Proterozoic, and perhaps Archean.

Did you ever wonder . . .
how many ice ages have happened during Earth history?

Of particular note, some tillites of the late Proterozoic event were deposited at equatorial latitudes, suggesting that, for at least a short time, the continents worldwide were largely glaciated, and the sea may have been covered worldwide by ice. Geologists refer to the ice-encrusted planet as **snowball Earth**.

Take-Home Message

During the Pleistocene (2.6 Ma to 11 Ka), ice sheets advanced and retreated many times; the record on land is less complete than that in marine strata. Ice ages also happened earlier in Earth history; in the Proterozoic, ice may have covered all of "snowball Earth."

18.7 The Causes of Ice Ages

Ice ages occur only during restricted intervals of Earth history, hundreds of millions of years apart. But within an ice age, glaciers advance and retreat with a frequency measured in tens of thousands to hundreds of thousands of years. Thus, there must be both long-term and short-term controls on glaciation.

Long-Term Causes

Plate tectonics exercises some long-term control over glaciation for several reasons. First, continental drift due to plate tectonics determines the distribution of continents relative to the equator and, therefore, the amount of solar heat that the land receives. Second, the distribution of continents relative to upwelling and downwelling zones of the mantle may influence overall land elevation. Finally, global climate can be affected by heat redistributed by oceanic currents—growth of island arcs and drift of continents can influence the configuration of currents and determine whether high-latitude regions can become cold enough to host ice-sheet formation.

The concentration of carbon dioxide in the atmosphere also determines whether an ice age can occur. Carbon dioxide is a greenhouse gas—it traps infrared radiation rising from the Earth—so if the concentration of CO_2 increases, the atmosphere becomes warmer. Ice sheets cannot form during periods when the atmosphere has a relatively high concentration of CO_2, even if other factors favor glaciation. But what might cause long-term changes in CO_2 concentration? Possibilities include changes in the number of marine organisms that extract CO_2 to make shells; changes in the amount of chemical weathering on land (determined by the abundance of mountain ranges) for weathering absorbs CO_2; and changes in the amount of volcanic activity. Major stages in evolution may also affect CO_2 concentration. For example, the appearance of coal swamps at the end of the Paleozoic may have removed CO_2, for plants incorporate CO_2, thus triggering glaciations of Pangaea.

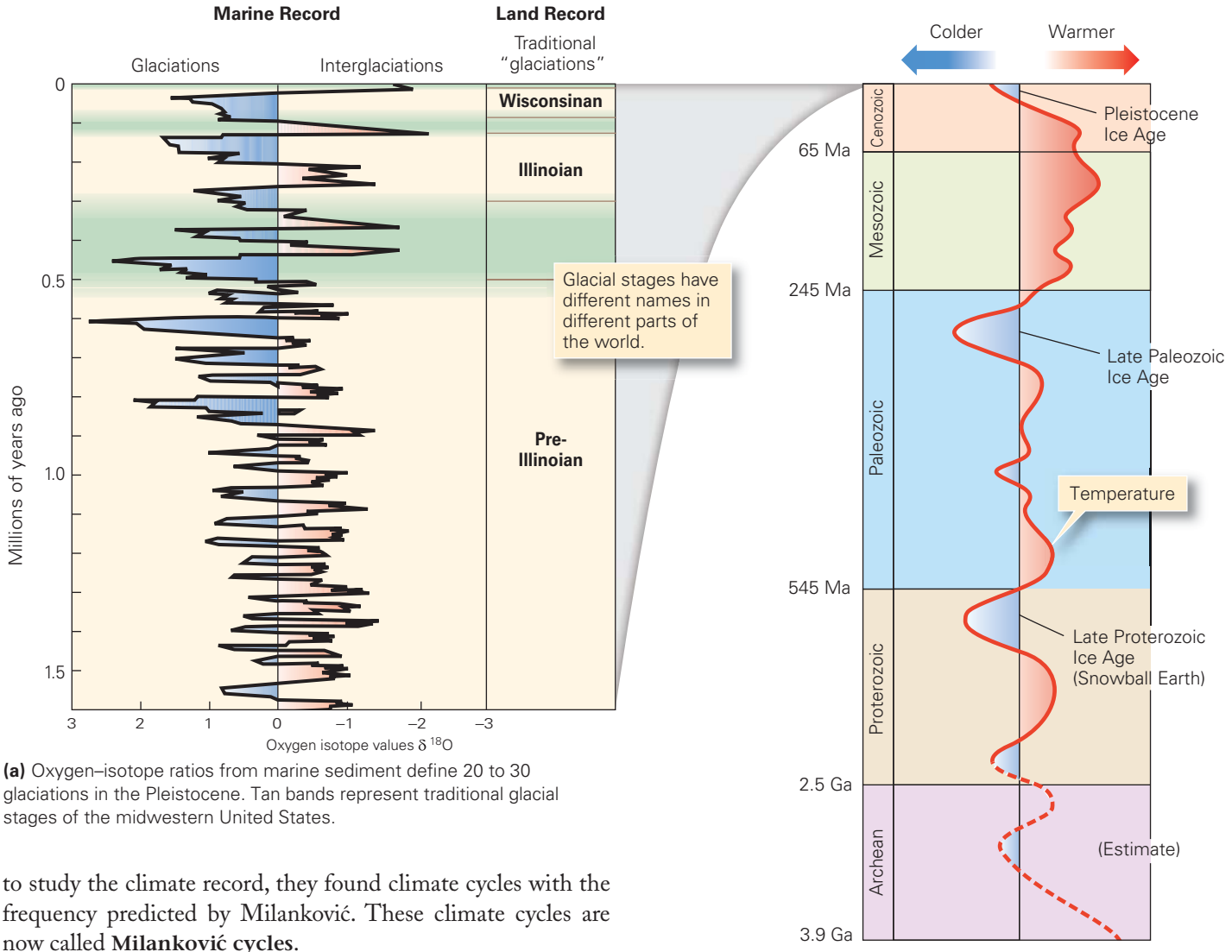
Short-Term Causes

Now we've seen how the stage could be set for an ice age to occur, but why do glaciers advance and retreat periodically *during* an ice age? In 1920, Milutin Milanković, a Serbian astronomer and geophysicist, came up with an explanation. Milanković studied how the Earth's orbit changes shape and how its axis changes orientation through time, and he calculated the frequency of these changes. In particular, he evaluated three aspects of Earth's movement around the Sun.

- *Orbital shape*: Milanković showed that the Earth's orbit gradually changes from a more circular shape (low eccentricity) to a more elliptical shape (high eccentricity) over a time period of around 100,000 years (Fig. 18.27a).
- *Tilt of Earth's axis*: We have seasons because the Earth's axis is not perpendicular to the plane of its orbit. Milanković calculated that over time, the tilt angle varies between 22.5° and 24.5°, with a frequency of 41,000 years (Fig. 18.27b).
- *Precession of Earth's axis*: If you've ever set a top spinning, you've probably noticed that its axis gradually traces a conical path. This motion, or wobble, is called precession (Fig. 18.27c). Milanković determined that the Earth's axis wobbles over the course of about 23,000 years. Precession determines the relationship between the timing of the seasons and the position of Earth along its orbit around the Sun.

Milanković showed that precession, along with variations in orbital eccentricity and tilt, combine to affect the total annual amount of insolation (exposure to the Sun's rays) and the seasonal distribution of insolation that the Earth receives at the mid- to high-latitude regions (such as 65°N) by as much as 25%. For example, such regions receive more insolation when the Earth's axis is almost perpendicular to its orbital plane than when its axis is greatly tilted. According to Milanković, glaciers tend to advance during times of cool summers at 65°N, which occur periodically (Fig. 18.27d). When geologists began

FIGURE 18.26 The timing of glaciations. Ice ages have occurred at several times in the geologic past.



(a) Oxygen–isotope ratios from marine sediment define 20 to 30 glaciations in the Pleistocene. Tan bands represent traditional glacial stages of the midwestern United States.

(b) The Pleistocene is not the only ice-age time in Earth history. Glacial events happened in colder intervals of earlier eras, too.

to study the climate record, they found climate cycles with the frequency predicted by Milanković. These climate cycles are now called **Milanković cycles**.

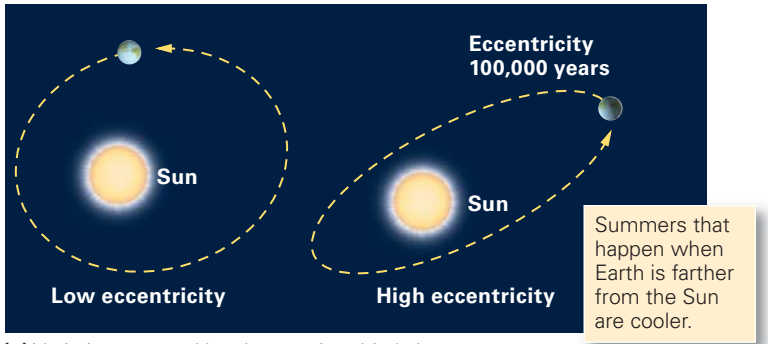
Milanković cycles, however, cannot be the whole story. Geologists suggest that several other factors may come into play in order to trigger a glacial advance.

- *Solar variability*: Changes in the radiation output of the Sun could affect the amount of energy the Earth receives.
- *A changing albedo*: When snow remains on land throughout the year, or clouds form in the sky, the albedo (reflectivity) of the Earth increases, so Earth's surface reflects incoming sunlight and thus becomes even cooler.
- *Interrupting the global heat conveyor*: As the climate cools, evaporation rates from the sea decrease, so seawater does not become as salty. Decreasing salinity might stop the system of thermohaline currents that brings warm water to high latitudes (see Chapter 15). Thus, the high latitudes become even colder than they would otherwise.
- *Biological processes that change CO_2 concentration*: As we have noted, biological processes may have amplified climate changes by altering the concentration of carbon dioxide in the atmosphere.

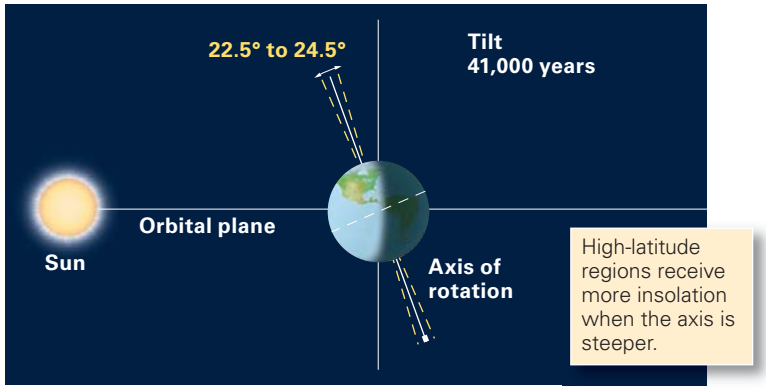
A Model for Pleistocene-Ice-Age History

Long-term cooling in the Cenozoic Era. Taking all of the above causes into account, we can now propose a scenario for the events that led to the Pleistocene glacial advances. Our story begins in the Eocene Epoch, about 55 Ma (Fig. 18.28). At that time, climates were warm and balmy not only in the tropics, but even above the Arctic Circle. Near the end of the Middle Eocene about 40 Ma, the climate began to cool. This long-term climate change may have been caused, in part, by change in the pattern of atmospheric circulation that happened when India collided with Asia. Specifically, the uplift of the Himalayas and Tibet diverted winds in a way that cooled the climate. Further, this uplift exposed more rock to chemical weathering, perhaps leading to extraction of CO_2 from the atmosphere. The formation of the circum-Antarctic current and the isolation of Antarctica also happened about this time. Studies show that this event could have cooled the global ocean.

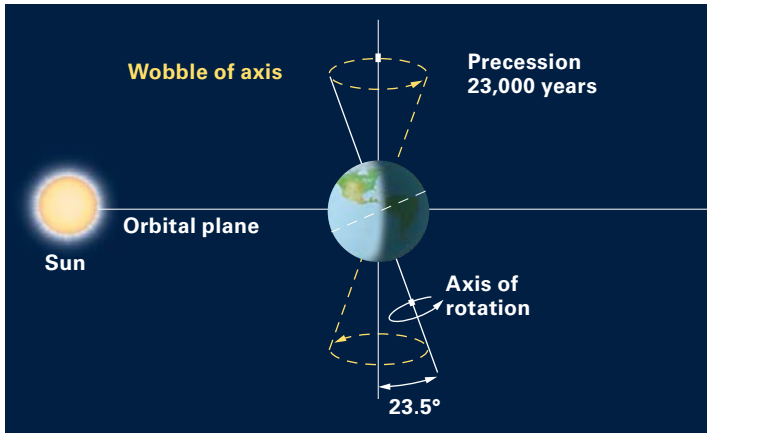
FIGURE 18.27 Milanković cycles influence the amount of insolation received at high latitudes.



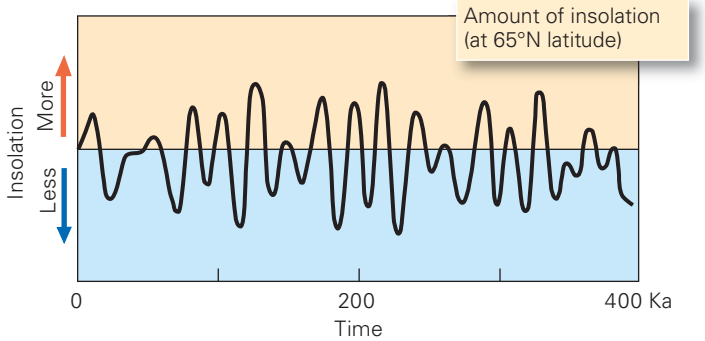
(a) Variations caused by changes in orbital shape.



(b) Variations caused by changes in axis tilt.



(c) Variations caused by the precession of Earth's axis.



(d) Combining the effects of eccentricity, tilt, and precession produces distinct periods of more or less insolation.

So far, we've examined hypotheses that explain long-term cooling since about 40 Ma, but what caused the sudden beginning of the Laurentide ice sheet growth at about 2.6 Ma? This event may coincide with other plate-tectonic events. For example, the closing of the gap between North and South America by the growth of the Isthmus of Panama separated the waters of the Caribbean from those of the tropical Pacific for the first time, and when this happened, warm currents that previously flowed out of the Caribbean into the Pacific were blocked and diverted northward to merge with the Gulf Stream. This current transfers warm water from the Caribbean, up the Atlantic Coast of North America, and ultimately to the British Isles. As the warm water moves up the Atlantic Coast, it generates warm, moisture-laden air that provides a source for the snow that falls over New England, eastern Canada, and Greenland. In other words, the Arctic has long been cold enough for ice caps, but it wasn't until the Gulf Stream was diverted northward by the growth of Panama, that there was sufficient moisture to serve as a source for the abundant snow needed for glacial growth.

Short-term advances and retreats in the Pleistocene Epoch. Once the Earth's climate had cooled overall, short-term climate changes due to Milanković cycles led to periodic advances and retreats of the glaciers. To understand how, let's look at a possible case history of a single advance and retreat of the Laurentide ice sheet. (Note that such models remain the subject of vigorous debate.)

- *Stage 1*: During the overall cooler climates of the late Cenozoic Era, the Earth reaches a point in the Milanković cycle when the average mean temperature in temperate latitudes drops. Not all of winter's snow melts away during the summer in northern Canada. The snow reflects sunlight, so the region grows still colder and even more snow accumulates as evaporation off the Gulf Stream provides moisture. Finally, the snow at the base of the pile turns to ice, and the ice begins to spread outward under its own weight. A new continental glacier has been born.
- *Stage 2*: The ice sheet continues to grow as more snow piles up in the zone of accumulation, and the atmosphere continues

FIGURE 18.28 Until recently, Earth's atmosphere has been gradually cooling, overall, since the Cretaceous.

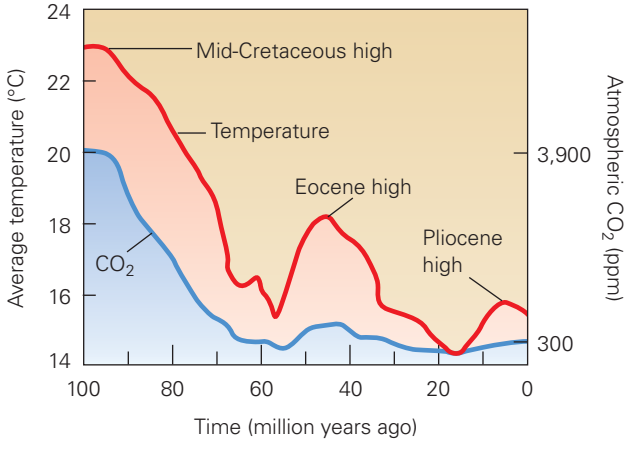
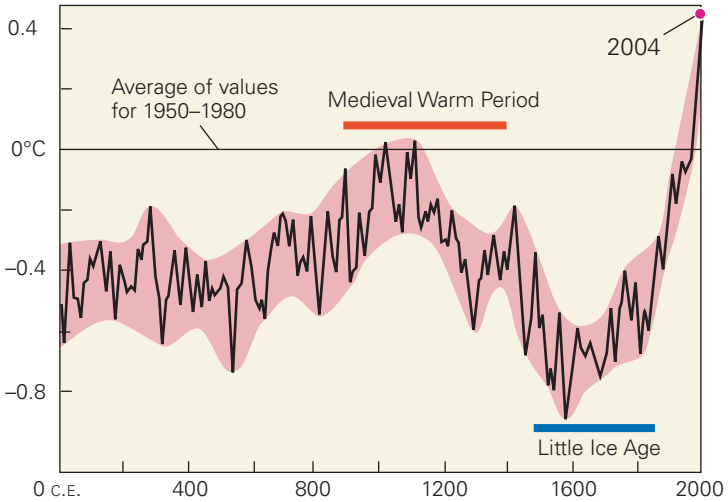


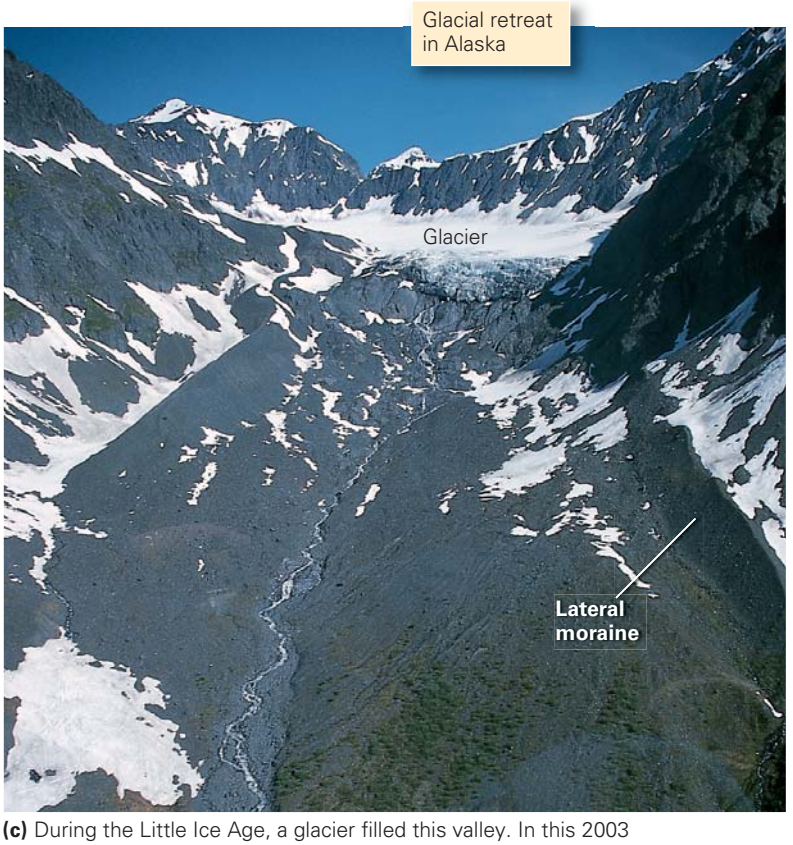
FIGURE 18.29 The Little Ice Age and its demise. Glaciers that advanced between 1550 and 1850 have since retreated.



(a) A model of global temperature for the past 2,000 years. Overall trends display the Medieval Warm Period followed by the Little Ice Age. Since 1850, temperatures have warmed.



(b) Skaters (ca. 1600) on the frozen canals of the Netherlands during the Little Ice Age.



(c) During the Little Ice Age, a glacier filled this valley. In this 2003 photo, most of the glacier has vanished. Most of the retreat has happened in the last century.

to cool because of the albedo effect. But now, the weight of the ice loads the continent and makes it sink, so the elevation of the glacier decreases, and its surface approaches the equilibrium line. Also, the temperature becomes cold enough that in high latitudes the Atlantic Ocean begins to freeze. As the sea ice covers the ocean, the amount of seawater evaporation decreases, so the source of moisture for snow is cut off and the amount of snowfall diminishes. The glacial advance pretty much chokes on its own success.

- *Stage 3*: As the glacier retreats, albedo decreases, temperatures gradually increase, and the sea ice begins to melt. The supply of water to the atmosphere from evaporation increases once again, but with the warmer temperatures and lower elevations, this water precipitates as rain during the summer. The rain drastically accelerates the rate of ice melting, so the retreat can progress quite rapidly.

Will There Be Another Glacial Advance?

What does the future hold? Considering the periodicity of glacial advances and retreats during the Pleistocene Epoch, we may be living in an interglacial period. Pleistocene interglacials lasted about 10,000 years, and since the present interglacial began about 11,000 years ago, the time may be ripe for a new glaciation. If a glacier on the scale of the Laurentide ice sheet were to develop, major cities and agricultural belts would be overrun by ice, and their populations would have to migrate southward. Long before the ice front arrived, though, the climate would become so hostile that the cities would already be abandoned.

The Earth actually had a brush with ice-age-like conditions between the 1300s and the mid-1800s, when average annual temperatures in the northern hemisphere fell sufficiently for mountain glaciers to advance significantly. During this period, now known as the Little Ice Age, sea ice surrounded Iceland and canals froze in the Netherlands, leading to that country's tradition of skating (Fig. 18.29a, b).

During the past 150 years, temperatures have warmed, and most mountain glaciers have retreated significantly (Fig. 18.29c). Such global warming could conceivably cause a "super-interglacial" period. The next chapter addresses the causes and consequences of such change.

Take-Home Message

Ice ages occur when the distribution of continents, ocean currents, and the concentration of atmospheric CO_2 are appropriate. Advances and retreats during an ice age are controlled by Milanković cycles defining variations in Earth's orbit and rotation axis. We may be living in a super-interglacial period.

Chapter Summary

- Glaciers are streams or sheets of recrystallized ice that survive for the entire year and flow in response to gravity. Mountain glaciers exist in high regions and fill cirques and valleys. Continental glaciers (ice sheets) spread over substantial areas of the continents.
- Glaciers form when snow accumulates over a long period of time. With progressive burial, the snow first turns to firn and then to ice.
- Temperate glaciers melt during part of the year. Polar glaciers do not. Glaciers move by basal sliding over water or wet sediment, and/or by plastic deformation of ice grains. In general, glaciers move tens of meters per year.
- Glaciers move because of gravitational pull; they flow in the direction of their overall surface slope.
- Whether the toe of a glacier stays fixed in position, advances, or retreats depends on the balance between the rate at which snow builds up in the zone of accumulation and the rate at which glaciers melt, calve, or sublimate in the zone of ablation.
- Icebergs break off glaciers that flow into the sea. Continental glaciers that flow into the sea along a coast make ice shelves. Sea ice forms where the ocean's surface freezes.
- As glacial ice flows over sediment, it incorporates clasts. The clasts embedded in glacial ice abrade the substrate.
- Mountain glaciers carve numerous landforms, including cirques, arêtes, horns, U-shaped valleys, hanging valleys, and truncated spurs. Fjords are glacially carved valleys that filled with water when sea level rose after an ice age.
- Glaciers can transport sediment of all sizes. Glacial drift includes till, glacial marine, glacial outwash, lake-bed mud, and loess. Lateral moraines accumulate along the sides of valley glaciers, medial moraines form down the middle, and end moraines accumulate at a glacier's toe.
- Glacial depositional landforms include moraines, knob-and-kettle topography, drumlins, kames, eskers, meltwater lakes, and outwash plains.
- Continental crust subsides as a result of ice loading. When the glacier melts away, the crust rebounds.
- When water is stored in continental glaciers, sea level drops. When glaciers melt, sea level rises.
- During past ice ages, the climate in regions south of the continental glaciers was wetter, and pluvial lakes formed. Permafrost exists in periglacial environments.
- During the Pleistocene Ice Age, large continental glaciers covered much of North America, Europe, and Asia.
- The stratigraphy of Pleistocene glacial deposits indicates that glaciers advanced and retreated many times during the ice age. The record of glaciations is more complete in oceanic sediment.
- Long-term causes of ice ages include plate tectonics and changes in the concentration of CO_2 in the atmosphere. Short-term causes include the Milanković cycles.

Key Terms

ablation (p. 520)
arête (p. 524)
cirque (p. 524)
continental glacier (ice sheet) (p. 518)
crevasse (p. 520)
drumlin (p. 529)
equilibrium line (p. 522)
erratic (p. 515)
esker (p. 532)
fjord (p. 526)
glacial drift (p. 527)
glacially polished surface (p. 524)
glacial outwash (p. 527)
glacial rebound (p. 532)
glacial striation (p. 523)
glacial subsidence (p. 532)
glacial till (p. 527)
glacier (p. 515)
hanging valley (p. 524)
horn (p. 524)
ice age (p. 516)
iceberg (p. 522)
ice shelf (p. 522)
interglacial (p. 536)
kettle hole (p. 529)
loess (p. 527)
Milanković cycle (p. 539)
moraine (p. 527)
mountain (alpine) glacier (p. 518)
patterned ground (p. 534)
permafrost (p. 534)
pluvial lake (p. 534)
polar glacier (p. 519)
roche moutonnée (p. 526)
sea ice (p. 523)
snowball Earth (p. 538)
tarn (p. 524)
temperate glacier (p. 518)
tidewater glacier (p. 522)
U-shaped valley (p. 524)
zone of ablation (p. 522)
zone of accumulation (p. 522)

Review Questions

1. What evidence did Louis Agassiz offer to support the idea of an ice age?
2. How do mountain glaciers and continental glaciers differ?
3. Describe the transformation from snow to glacial ice.
4. Explain how arêtes, cirques, and horns form.

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Interactive exercises on the process of glacial flow.
- A What a Geologist Sees question on glacial features.
- Problems that help students calculate rates of glacial advance and retreat.

5. Describe the mechanisms that enable glaciers to move, and explain why glaciers move.
6. How fast do glaciers normally move? How fast can they move during a surge?
7. Explain how the balance between ablation and accumulation controls advances and retreats.
8. How can a glacier continue to flow toward its toe even though its toe is retreating?
9. How does a glacier transform a V-shaped valley into a U-shaped valley? Discuss how hanging valleys form.
10. Describe the various kinds of glacial deposits. Be sure to note the materials from which the deposits are made and the landforms that result from deposition.
11. How does the lithosphere respond to the weight of glacial ice?
12. How was the world different during the glacial advances of the Pleistocene Ice Age? Be sure to mention the relation between glaciations and sea level.
13. How was the on-land chronology of glaciations developed? Why was it so incomplete? How was it modified with the study of marine sediment?
14. Were there ice ages before the Pleistocene? If so, when?
15. What are some of the long-term causes that lead to ice ages? What are the short-term causes that trigger glaciations and interglacials?

On Further Thought

16. If you fly over the barren cornfields of central Illinois during the early spring, you will see slight differences in soil color due to variations in moisture content—wetter soil is darker. These variations outline the shapes of polygons that are tens of meters across. What do these patterns represent, and how might they have formed?
17. An unusual late Precambrian rock unit crops out in the Flinders Range, a small mountain belt in South Australia, near Adelaide. Structures in the belt formed at the beginning of the Paleozoic. This unit consists of clasts of granite and gneiss, in a wide range of sizes, suspended through a matrix of slate. The rock unit lies unconformably above a basement of granite and gneiss, and if you dig out the unconformity surface, you will find that it is polished and striated. What is the unusual rock?

SEE FOR YOURSELF R. . . Glacial Landscapes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet R of our **Geotours Workbook**.



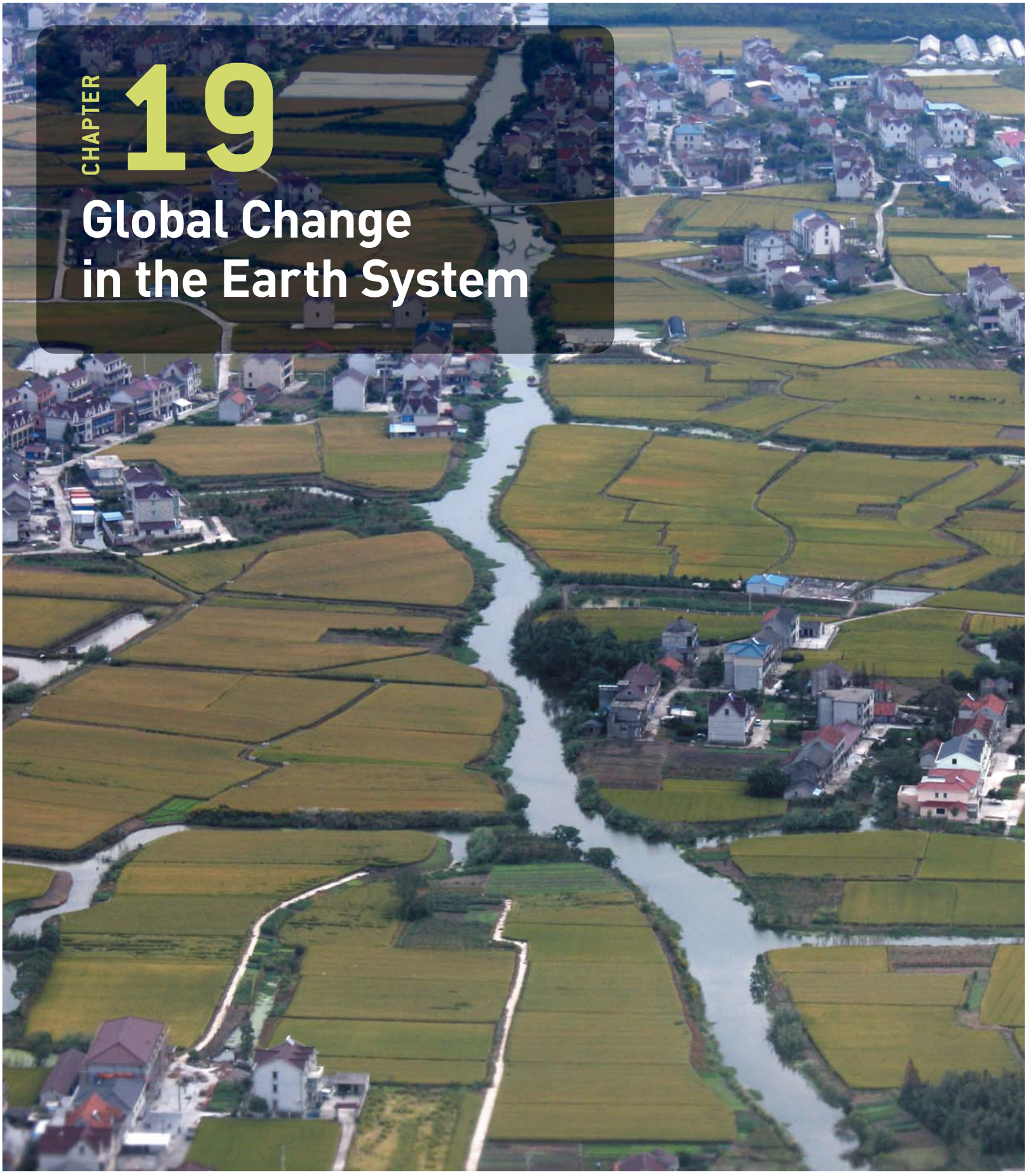
Baffin Island, Canada
Latitude 67°8′27.56″N,
Longitude 64°49′49.31″W

From 40 km, you can see two valley glaciers draining the Baffin Island ice cap. They merge into a trunk glacier that flows NE and then into a fjord, partly filling a U-shaped valley. Note the lateral and medial moraines. In some nearby fjords, meltwater has deposited a delta of outwash at the end of the glacier.



Glaciated Peaks, Montana
Latitude 48°56′33.66″N,
Longitude 113°49′54.59″W

Viewed from 8 km, you can see three cirques bounding a horn in the Rocky Mountains, north of Glacier National Park. Note the knife-edge arêtes between the cirques. The glaciers that carved the cirques have melted away. The thin stripes on the mountain face are traces of bedrock sedimentary beds.



CHAPTER 19

Global Change in the Earth System



In the last 0.00002% of Earth's history, humanity has modified much of this planet's surface. The land cover, drainage, and vegetation of this landscape in China have all been changed dramatically due to human activity.

Chapter Objectives

By the end of this chapter you should know . . .

- why the Earth is a dynamic planet and ways that it can change.
- that some changes in the Earth System are unidirectional whereas others are cyclic and that some changes are gradual and some are catastrophic.
- during biogeochemical cycles, elements or compounds flow among various reservoirs.
- how the climate has changed significantly over geologic time, and how greenhouse gases play an important role in regulating the climate.
- how humans have significantly changed aspects of the Earth System.
- that addition of greenhouse gases during the past two centuries can cause warming.

All we in one long caravan
are journeying since the world began,
we know not whither, we know . . . all must go.

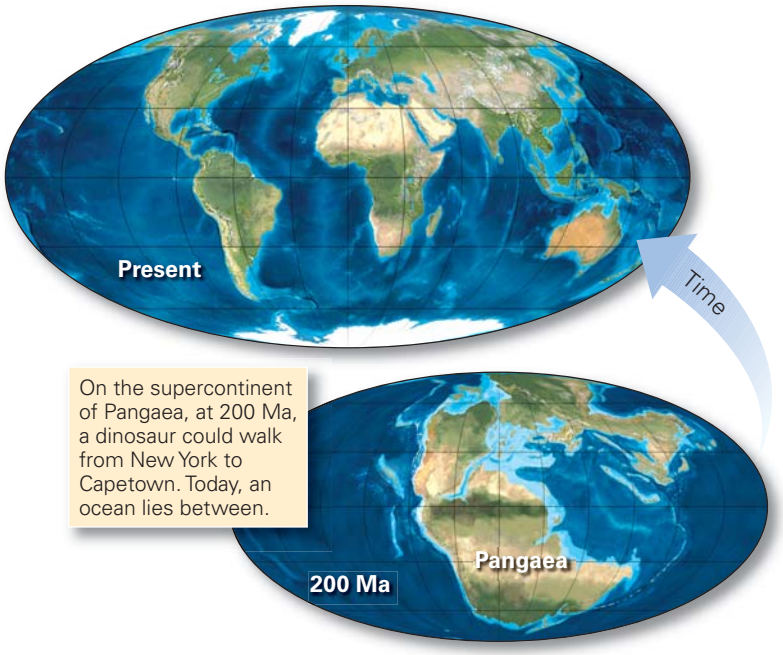
—Bhartrihari (Indian poet, CA. 500 C.E.)

19.1 Introduction

Did the Earth's surface look the same in the Jurassic Period as it does today? Definitely not! During the Jurassic, the North Atlantic Ocean was a narrow sea and the South Atlantic Ocean didn't exist at all, so most dry land connected to form a single vast continent (**Fig. 19.1**). Today, both parts of the Atlantic are wide oceans, and the Earth has seven separate continents. Moreover, during the Jurassic, the call of the wild rumbled from the throats of dinosaurs, whereas today, the largest land animals are mammals. In essence, what we see of the Earth today is just a snapshot, an instant in the life story of a constantly changing planet. This idea arguably stands as geology's greatest philosophical contribution to humanity's understanding of our Universe.

Why has the Earth changed so much over geologic time, and why can it continue to change? Ultimately, change happens both because the Earth's internal heat makes the asthenosphere weak enough to flow, and because the Sun's heat keeps most of the Earth's surface at temperatures above the freezing point of water. Flow in the asthenosphere permits plate

FIGURE 19.1 The map of Earth's surface changes over time because of plate motions.



tectonics, which in turn leads to continental drift, volcanism, and mountain building. Solar heat, along with gravity, keeps streams, glaciers, waves, and wind in motion, thereby causing erosion and deposition. Solar warmth plays an additional role by keeping the Earth's surface and near-surface regions at conditions appropriate for sustaining life. If the Earth did not have just the right mix of tectonic activity and solar heat, it would be a frozen dust bowl like Mars, a crater-pocked wasteland like the Moon, or a cloud-choked oven like Venus.

Many of the changes that take place on Earth reflect complex interactions among geologic and biological phenomena. For example, photosynthetic organisms affect the composition of the atmosphere by providing oxygen, and atmospheric composition in turn determines the nature of chemical weathering reactions that take place in rocks. We've referred to the global interconnecting web of physical and biological phenomena on Earth as the *Earth System* (see **Geology at a Glance,** pp. 548–549). We can now define **global change** as transformations or modifications of physical and biological components in the Earth System through time.

Geologists distinguish among different types of global change, on the basis of the rate or way in which change progresses with time. *Gradual* change takes place over long periods of geologic time (millions to billions of years). *Catastrophic* change takes place relatively rapidly in the context of geologic time (seconds to millennia). *Unidirectional* change involves transformations that never repeat. *Cyclic* change repeats the same steps over and over, though not necessarily with the same results. Some types of cyclic change are periodic, in that the cycles happen with a definable frequency; others are not.

In this chapter, we begin by reviewing examples of global change involving phenomena discussed earlier in this book. Then we introduce the concept of a biogeochemical cycle, the exchange of chemicals among various living and nonliving reservoirs, for some kinds of global change reflect changes in the proportions of chemicals held in different reservoirs through time. Finally, we focus on global climate change, transformations or modifications in Earth's climate over time. We conclude this chapter, and this book, by considering hypotheses that describe the ultimate global change—the end of the Earth in the distant future.

19.2 Unidirectional Changes

The Evolution of the Solid Earth

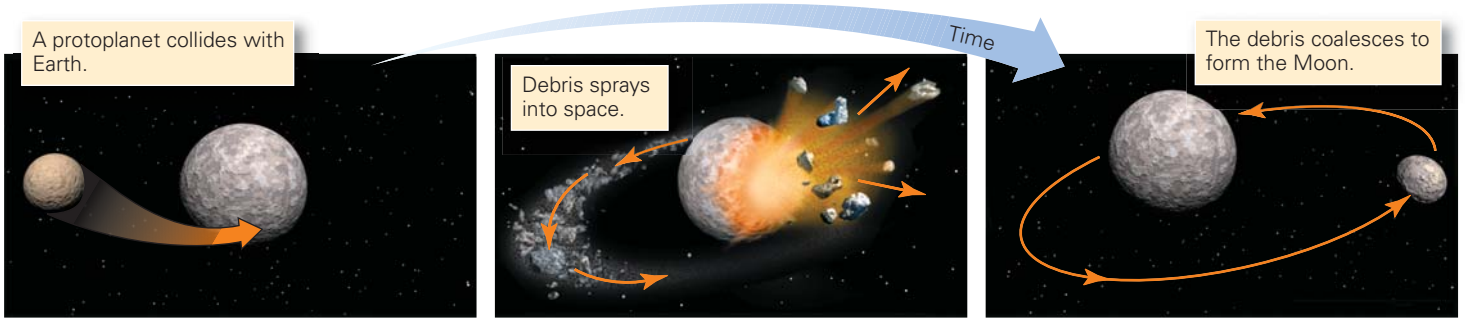
Recall from Chapter 1 that Earth began as a fairly homogenous mass, formed by the coalescence of planetesimals. But the homogeneous proto-Earth did not last long—within about 100 million years of its birth, or even as it formed, the planet began to melt, yielding liquid iron alloy that sank rapidly to the center to form the core. This process of **differentiation** represents major unidirectional change: it produced a layered planet with an iron alloy core surrounded by a rocky mantle.

According to one supported model, a protoplanet appears to have collided with the rapidly spinning newborn Earth soon after differentiation. This collision caused a catastrophic change—a significant portion of the Earth and the colliding object fragmented and vaporized, creating a ring of debris that quickly coalesced to form the Moon (**Fig. 19.2**). After the collision, the Earth's mantle was probably partially molten, and the planet's surface became a sea of magma. The Earth endured intense bombardment by asteroids and comets between about 4.0 and 3.9 Ga, so any crust that had formed prior to 3.9 Ga was largely pulverized, melted, and recycled. Eventually, however, bombardment ceased and our planet gradually cooled, permitting a crust to stabilize at its surface and plate tectonics to begin operating. Over time, igneous activity produced lasting continental crust. Differentiation, Moon formation, and crust formation all represent major unidirectional changes that took place in the first 600 million or so years of Earth's history.

The Evolution of the Atmosphere and Oceans

Like its surface, the Earth's atmosphere has also changed unidirectionally over time. It initially formed from gases released by volcanic activity. More gases may have arrived when comets

FIGURE 19.2 The formation of the Moon is an example of a catastrophic unidirectional change.



collided with our new planet. Eventually, Earth accumulated an early atmosphere composed dominantly of carbon dioxide (CO_2) and water (H_2O). Other gases, such as nitrogen (N_2), composed only a minor proportion of the early atmosphere. When the Earth's surface cooled, however, water condensed and fell as rain, collecting in low areas to form oceans. This may have happened before 4.0 Ga, but it had certainly happened by 3.8 Ga. Gradually, CO_2 dissolved in the oceans and was absorbed by chemical-weathering reactions on land, so its concentration in the atmosphere decreased. Nitrogen, which doesn't react with other chemicals, was left behind. Thus, the atmosphere's composition changed to become dominated by nitrogen. Photosynthetic organisms appeared early in the Archean. But it probably wasn't until between 2.5 and 2.0 Ga, the early Proterozoic, that oxygen (O_2) became a significant proportion of the atmosphere and it didn't reach breathable concentrations for another billion years.

Did you ever wonder . . .
has the Earth's atmosphere always been breathable?

The Evolution of Life

During most of the Hadean Eon, Earth's surface was probably lifeless, for carbon-based organisms could not survive the high temperatures of the time. The fossil record indicates that life had appeared at least by 3.8 billion years ago and has undergone unidirectional change (evolution) in fits and starts ever since (see Interlude E). Though simple organisms such as archaea and bacteria still exist, life evolution during the late Proterozoic and early Phanerozoic yielded multicellular plants and animals. Life now inhabits regions from a few kilometers below the surface to a few kilometers above, yielding a diverse and complex biosphere.

Take-Home Message

Since it first formed, the Earth has undergone major changes that are unidirectional, in that they will never repeat. Examples include internal differentiation (core formation), Moon formation, atmospheric evolution, ocean formation, and life evolution.

19.3 Physical Cycles

The Supercontinent Cycle

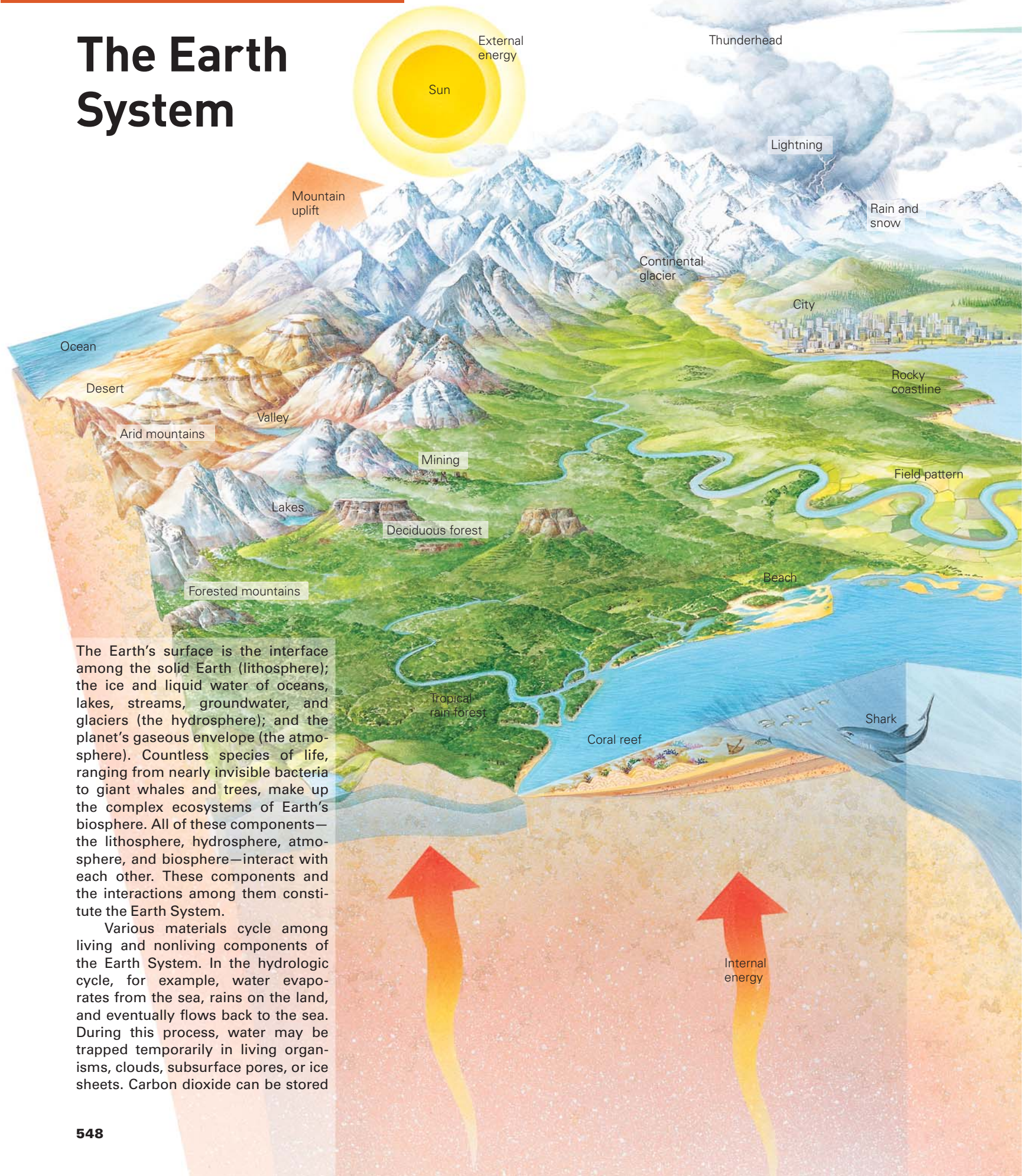
During Earth history, the map of the planet's surface has constantly changed. At times, almost all continental crust merged to form a single supercontinent, but usually the crust is distributed among several smaller continents. The process of change during which a supercontinent forms and later breaks apart is the **supercontinent cycle**. Geologists have found evidence that supercontinents existed at least three or four times during the past 3 billion years of Earth history—no two were alike. The most recent supercontinent, Pangaea, formed at the end of the Paleozoic Era.

The Sea-Level Cycle

Global sea level rose and fell by as much as 300 m during the Phanerozoic, and likely did the same in the Precambrian. When sea level rises, the shoreline migrates inland, and low-lying plains in the continents become submerged. In fact, during periods of particularly high sea level, more than half of Earth's continental area can become covered by shallow seas; at such times, sediment buries continental regions. When sea level falls, the continents become dry again, and regional unconformities develop.

After studying sedimentary sequences around the world, geologists have pieced together a chart defining the succession of global transgressions and regressions during the Phanerozoic Eon. The global sedimentary cycle chart may largely reflect the cycles of *eustatic* (worldwide) sea-level change (Fig. 19.3). However, the chart probably does not give us an exact image of sea-level change, because the sedimentary record reflects other factors as well, such as changes in sediment supply, and remains controversial. Eustatic sea-level changes may be due to a variety of factors, including advances and retreats of continental glaciers, changes in the volume of mid-ocean ridge systems, and changes in continental elevation and area.

The Earth System



The Earth's surface is the interface among the solid Earth (lithosphere); the ice and liquid water of oceans, lakes, streams, groundwater, and glaciers (the hydrosphere); and the planet's gaseous envelope (the atmosphere). Countless species of life, ranging from nearly invisible bacteria to giant whales and trees, make up the complex ecosystems of Earth's biosphere. All of these components—the lithosphere, hydrosphere, atmosphere, and biosphere—interact with each other. These components and the interactions among them constitute the Earth System.

Various materials cycle among living and nonliving components of the Earth System. In the hydrologic cycle, for example, water evaporates from the sea, rains on the land, and eventually flows back to the sea. During this process, water may be trapped temporarily in living organisms, clouds, subsurface pores, or ice sheets. Carbon dioxide can be stored

in the air, dissolved in water, or trapped in plants, coal, or limestone. Some limestone forms when coral extracts ions from water. Meanwhile, the atoms that make up minerals, over the vastness of geologic time, pass through the rock cycle. New elements from the mantle may enter the cycles of the Earth System at volcanoes or black smokers. Elements at the surface may be carried back into the mantle at subduction zones. Some atoms escape from the atmosphere into space.

Two key sources of energy fuel the dynamic Earth System. External energy comes from solar radiation, which drives the hydrologic cycle and the circulation of the atmosphere and oceans. These, in turn, cause erosion of the land surface. Internal energy, a relict of Earth formation and a product of radioactive decay, drives volcanism and the uplift of mountains.

Because of cycles, features of the Earth System undergo cyclic change. For example, in the time frame of centuries to millions of years, climate changes and sea-level changes have markedly affected the character of the planet's surface. Plate interactions constantly, though slowly, change the map of the planet. And over geologic history, life and the atmosphere have evolved. Despite its immensity, the Earth System is fragile; human activity, which helps create global change, has had major effects on the Earth System.

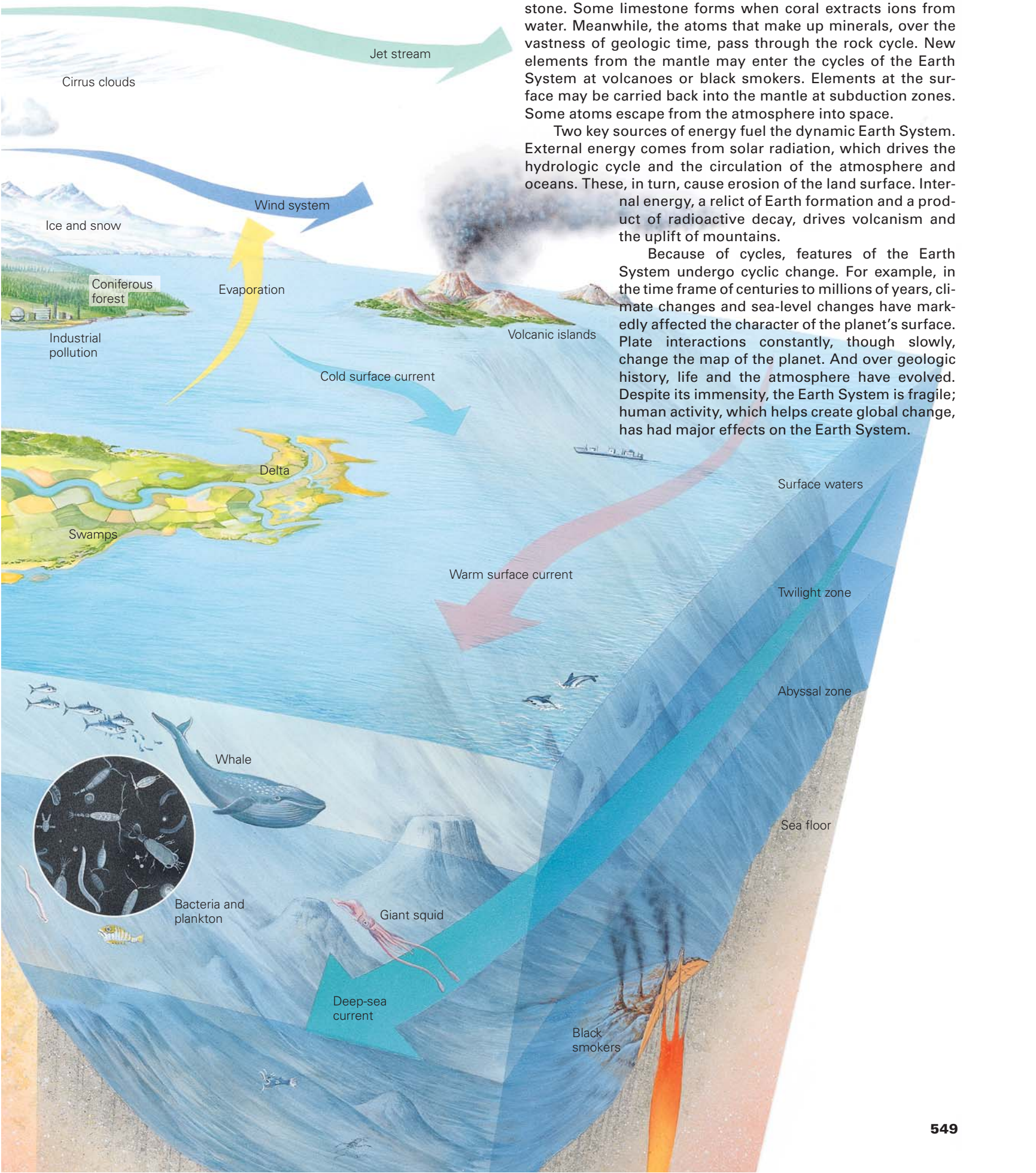
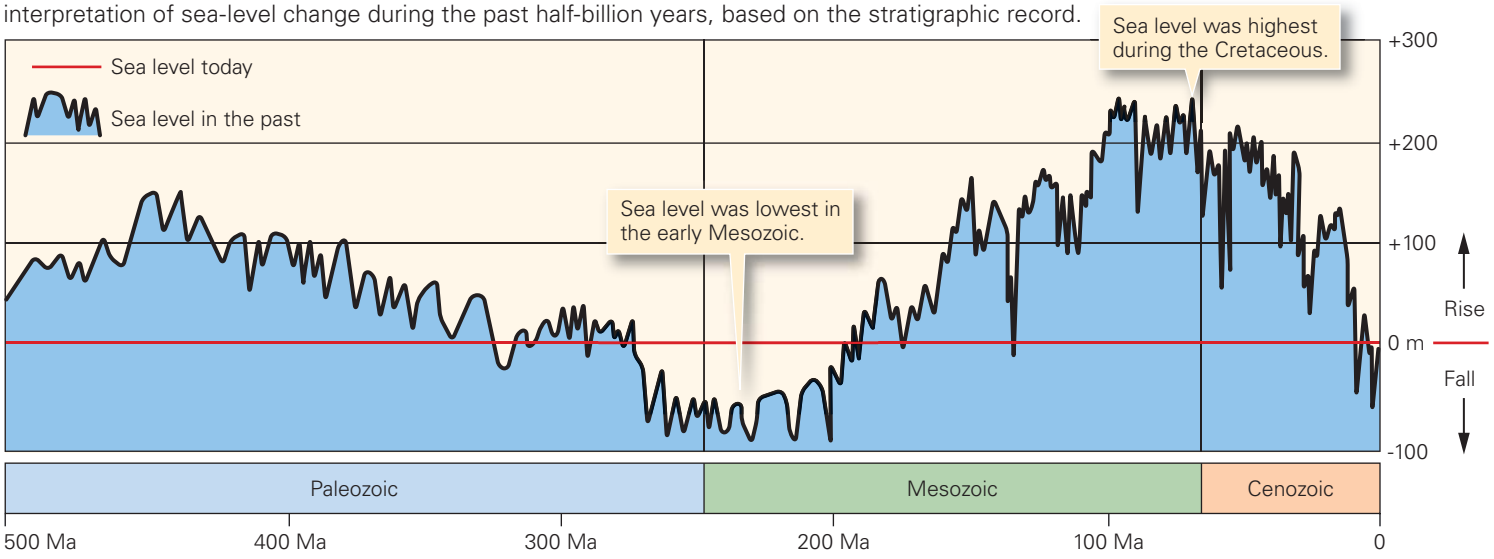


FIGURE 19.3 Sea-level change, and its manifestations, over geologic time. This chart provides one interpretation of sea-level change during the past half-billion years, based on the stratigraphic record.



The Rock Cycle

We learned early in this book that the crust of the Earth consists of three rock types: igneous, sedimentary, and metamorphic. Atoms making up the minerals of one rock type may later become part of another rock type. In effect, rocks are simply reservoirs of atoms, and the atoms can move from reservoir to reservoir over time. Each stage in the rock cycle changes the Earth by redistributing and modifying material.

Take-Home Message

Some changes in the Earth System are cyclic in that they have stages that may be repeated. Examples include the supercontinent cycle (accumulation of continents by collision, and then dispersal by rifting), the sea-level cycle (rise and fall of the sea), and the rock cycle.

19.4 Biogeochemical Cycles

A **biogeochemical cycle** involves the passage of a chemical among nonliving and living reservoirs in the Earth System, mostly on or near the planet's surface. Nonliving reservoirs include the atmosphere, the crust, and the ocean; living reservoirs include plants, animals, and microbes. Although a great variety of chemicals (water, carbon, oxygen, sulfur, ammonia, phosphorus, and nitrogen) participate in biogeochemical cycles, here we look at only two: water (H_2O) and carbon (C).

Some stages in a biogeochemical cycle may take only hours, some may take thousands of years, and others may take millions of years. The transfer of a chemical from reservoir to reservoir during these cycles doesn't really seem like a change in the Earth in the way that the movement of continents or the metamorphism of rock seems like a change. In fact, for intervals of time, biogeochemical cycles attain a **steady-state condition**, meaning that the proportions of a chemical in different reservoirs remain fairly constant even though there is a constant flux (flow) of the chemical among reservoirs. When we speak of global change in a biogeochemical cycle, we mean a change in the relative proportions of a chemical held in different reservoirs at a given time—in other words, a change in the steady-state condition.

The Hydrologic Cycle

As we learned in Interlude F, the hydrologic cycle involves the movement of water from reservoir to reservoir on or near the surface of the Earth. The hydrologic cycle is an example of a biogeochemical cycle in that a chemical (H_2O) passes through both nonliving and living entities—the oceans, the atmosphere, surface water, groundwater, glaciers, soil, and living organisms. Global change in the hydrologic cycle occurs primarily when a change in global climate alters the ratio between the amount of water held in the ocean and the amount held in continental ice sheets. For example, during an ice age, water that had been stored in oceans moves into glacial reservoirs. Thus, the continents become covered with ice, and sea level drops. When the climate warms, water returns to the oceans, and sea level rises.

The Carbon Cycle

Most carbon in the near-surface realm of Earth originally bubbled out of the mantle in the form of CO_2 gas released by volcanoes (Fig. 19.4). Once it enters the atmosphere, it can be removed in various ways. Some dissolves in seawater to form bicarbonate (HCO_3^-) ions, whereas some is absorbed by photosynthetic organisms that convert it to sugar and other organic chemicals. This carbon enters the food chain and ultimately

makes up the flesh, fat, and sinew of animals. Some of the reactions that take place when rock undergoes chemical weathering incorporate atmospheric CO_2 and thus also remove carbon from the atmosphere.

Some carbon returns directly to the atmosphere through the respiration of animals (again as CO_2), by the flatulence of animals as methane (CH_4), or by the decay (oxidation) of dead organisms. But some can be stored for long periods of time in fossil fuels (oil and coal), in organic shale, in methane hydrates, or in limestone. These reservoirs contain most of the carbon in the near-surface realm of Earth and can hold on to it for long periods of time. But the carbon in these reservoirs can return to the atmosphere in the form of CO_2 due to the burning of fossil fuels and due to the metamorphism of rocks containing carbonate, or it can return to the sea after undergoing dissolution in river water or groundwater.

Take-Home Message

In the Earth System, chemicals—such as carbon and water—cycle through living and nonliving reservoirs. CO_2 gas in the atmosphere can dissolve in seawater to form bicarbonate ions, or be trapped in rock as calcite or as fossil fuel (oil, gas, and coal).

19.5 Global Climate Change

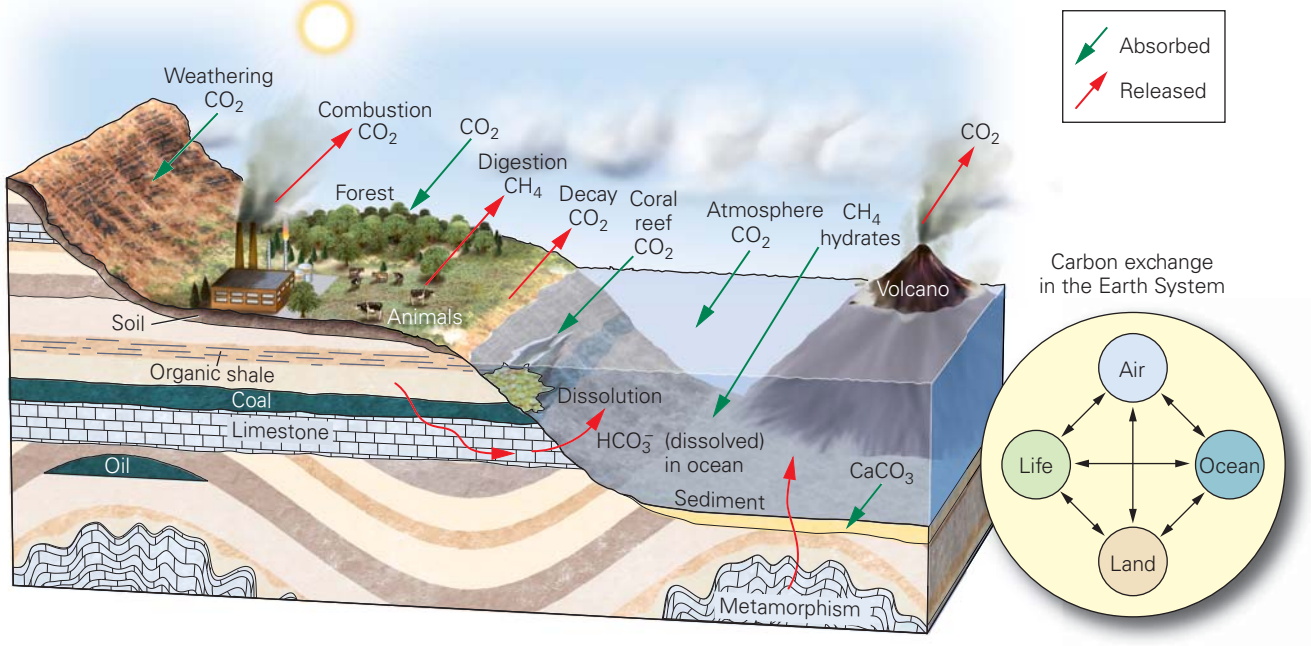
The **climate** is the average range of weather conditions (such as temperature, humidity, wind speed, and seasonality) for a given region. **Global climate change**, the transformation of Earth's climate over time, has happened repeatedly throughout Earth's history for natural reasons. Measurements indicate that global climate change is now occurring, and that human activities may be a cause.

For purposes of discussion, we distinguish between *long-term climate change*, which takes place over millions to tens of millions of years, and *short-term climate change*, which takes place over tens to thousands of years. If the average atmospheric and sea-surface temperature rises, we have **global warming**, and if it falls, we have **global cooling**. Below, we discuss how researchers study climate change and how their observations characterize long-term and short-term changes.

Methods of Study

Geologists and climatologists are working hard to define the nature of climate change, the rates at which change can take place, and the effects that change may have on our planet. There are three basic approaches to studying global climate change: (1) researchers measure past climate change, as indicated by the stratigraphic record, to document the magnitude of changes that have happened, the rate at which such changes occurred, and the consequence of such changes; (2) researchers conduct experiments and calculations to see how changes in atmospheric components, such as CO_2 (**Box 19.1**) or dust, might affect climate; (3) researchers develop computer programs to calculate how factors such as atmospheric composition, topography, ocean currents, and Earth's orbit affect the circulation of the atmosphere and, therefore, the distribution of climate belts. They then use such **general circulation models (GCMs)** to develop computer-generated **climate-change models** in order to provide insight into when and

FIGURE 19.4 In the carbon cycle, carbon transfers among various reservoirs at or near the Earth's surface. Red arrows indicate release to the air, and green arrows indicate absorption from air.



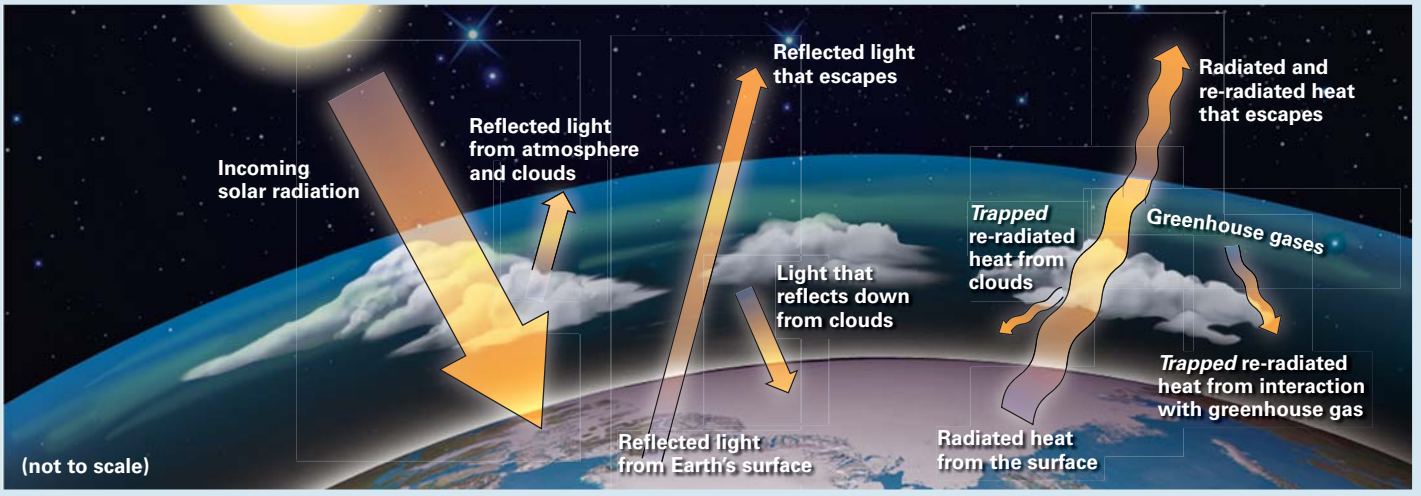
BOX 19.1 CONSIDER THIS . . .

The Role of Greenhouse Gases

The Sun constantly bathes the Earth in visible light. Some of this energy reflects off the atmosphere and the Earth's surface, so that our planet shines when viewed from space. The Earth's surface absorbs the remainder of the incoming visible light, and then releases it in the form of thermal energy (infrared radiation) that heads back upward. If the Earth had no atmosphere, all of this thermal energy would escape back into space. But our planet does have an atmosphere, and certain gases in air absorb thermal radiation and re-radiate it. Some of the re-radiated energy continues up into space, but some heads downward and warms the lower atmosphere (**Fig. Bx 19.1**). In effect, these gases trap infrared radiation and keep the lower atmosphere warm, somewhat like the way glass traps heat in a greenhouse. Thus, the overall trapping process is called the **greenhouse effect**, and the gases (such as H_2O, CO_2, and CH_4) that cause it are called **greenhouse gases**.

Warming or cooling due to changes in the concentration of greenhouse gases can be amplified by positive or negative **feedback mechanisms**. Negative feedback slows a process down or even reverses it, whereas positive feedback enhances a process and amplifies its consequences. Let's consider an example of a feedback mechanism involving the greenhouse effect. Imagine that global average atmospheric temperature has increased due to an increase in CO_2. This increase will, in turn, cause the oceans to warm and evaporate more, so more water transfers into the atmospheric reservoir globally, causing still more warming—this is a positive feedback.

FIGURE Bx19.1 The greenhouse effect shows how thermal energy can be trapped in the atmosphere.



why changes took place in the past, and to predict how rainfall, sea level, ice cover, and other physical phenomena may be influenced by the warming or cooling of the atmosphere.

Did you ever wonder . . .
how do researchers study past climates on Earth?

Let's look first at how geologists study the **paleoclimate** (past climate), so as to document climate changes throughout Earth history. Any feature whose character depends on the climate and whose age can be determined can be a clue to defining paleoclimate.

- *The stratigraphic record*: The nature of sedimentary strata deposited at a certain location reflects the climate at that location. For example, a bed of coal represents deposits of a warm climate, whereas a bed of till represents deposits of a glacial climate.
- *Paleontological evidence*: Different assemblages of species survive in different climatic belts. Thus, the succession of fossils in a sedimentary sequence provides clues to the changes in climate at that site. For example, a record of short-term climate change can be obtained by studying the succession of plankton fossils in sea-floor sediments, for cold-water species of plankton are different from warm-water species. Fossil plant pollen preserved in the mud of bogs also provides information about paleoclimate, because different plant species live in different climates (**Fig. 19.5a**). Pollen studies show, for example, that spruce forests, indicative of cool climates, have slowly migrated north since the last ice age (**Fig. 19.5b**).
- *Oxygen–isotope ratios*: Geologists have found that the ratio of ^{18}O to ^{16}O in glacial ice indicates the atmospheric temperature in which the snow that made up the ice formed: simplistically, the ratio is larger in snow that forms in warmer air,

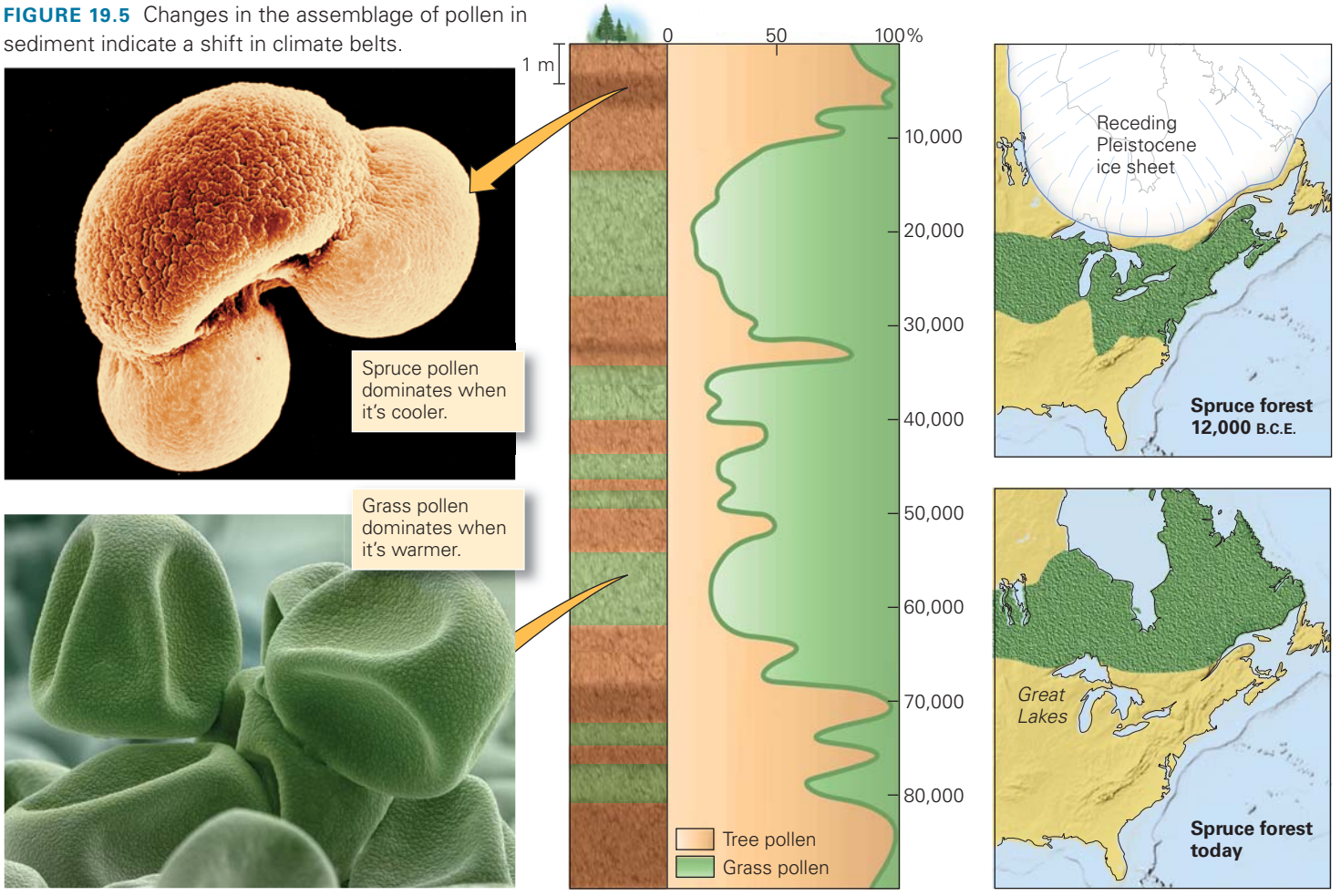
but smaller in snow that forms in colder air. Because of this relationship, the isotope ratio of the oxygen in H_2O measured in a succession of ice layers in a glacier indicates temperature change over time. Researchers have now obtained ice cores down to a depth of almost 3 km in Antarctica and in Greenland; this record spans up to 720,000 years (**Fig. 19.6a**). For similar reasons, the $^{18}O/^{16}O$ ratio in the $CaCO_3$ making up plankton shells also gives geologists an indication of past temperatures. Thus, measurement of oxygen–isotope ratios in drill cores of marine sediment extends the record of temperature change back over millions of years (**Fig. 19.6b, c**).

- *Growth rings*: If you've ever looked at a tree stump, you'll have noticed the concentric rings visible in the wood. Each ring represents one year of growth, and the thickness of the ring indicates the rate of growth in a given year. Trees grow faster during warmer, wetter years and more slowly during cold, dry years. Thus, the succession of ring widths provides a record of climate during the lifetime of the tree. Growth rings in corals and shells can provide similar information.
- *Human history*: Researchers have been able to make careful, direct measurements of climate changes only for the past few decades. This record is not long enough to document long-term climate change. But history, both written and archaeological, contains important clues to climates at times in the past. Periods of unusual cold or drought leave an impression on people, who record them in paintings, stories, and records of crop success or failure.

Long-Term Climate Change

Using the variety of techniques described above, geologists have reconstructed an approximate record of global climate, represented by mean global temperature, for geologic time. The record shows that Earth's surface temperature has stayed between the freezing point of water and the boiling point of water since the beginning of the Archean. But at times in the past, the Earth's atmosphere was significantly warmer than it is today, whereas at other times, it was significantly cooler. The warmer periods have come to be known as **greenhouse periods** (or hothouse periods) and the colder ones as **icehouse periods**. (The more familiar term, *ice age*, refers to the times during an icehouse period when the Earth was cold enough for ice sheets to advance and cover substantial areas of the continents.) As the chart in **Figure 19.7** shows, at least five major icehouse periods have occurred during geologic time.

FIGURE 19.5 Changes in the assemblage of pollen in sediment indicate a shift in climate belts.



(a) The proportion of tree pollen relative to grass pollen can change in a sedimentary sequence through time. Researchers plot changes in the proportion of pollen types over time by examining samples from a column of sediment. A higher proportion of grass pollen indicates warmer climate.

(b) Spruce forests (green) grew farther south 12,000 years ago than they do today.

What caused long-term global climate changes? The answer may lie in the complex relationships among the various solar, geologic, and biogeochemical components of the Earth System, as described earlier. For example:

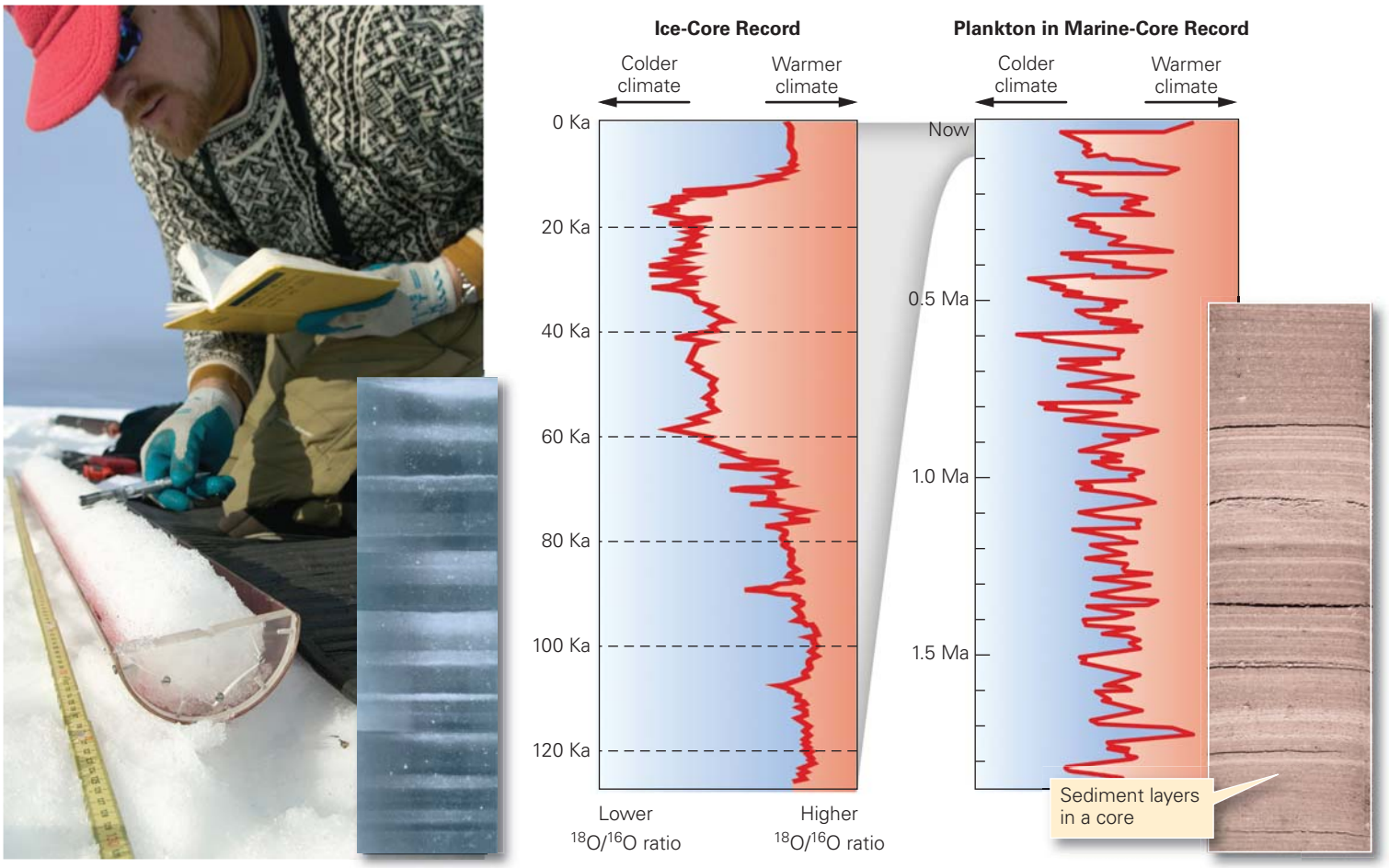
- *Positions of continents*: Continental drift influences the climate by controlling the pattern of oceanic currents, which redistribute heat around the planet's surface. Drift also determines whether the land is at high or low latitudes (and thus how much solar radiation strikes it), whether or not there are large continental interior regions where extremely cold winter temperatures can develop, and/or whether there is a lot of rainfall that could cause weathering.
- *The uplift of land surfaces*: Tectonic events that lead to the long-term uplift of the land affect atmospheric CO_2 concentration, because such events expose land to weathering, and chemical-weathering reactions absorb CO_2. Such uplift will also affect atmospheric circulation and rainfall rates.
- *The formation of coal and oil*: At various times during Earth history, environments suitable for coal and oil formation have been particularly widespread. Such formation removes CO_2 from the atmosphere and may result in global cooling. The cooling that occurred in the late Paleozoic, a time when coal swamps were abundant, may be a manifestation of the process.
- *Life evolution*: The appearance or extinction of certain life forms may have affected climate significantly by removing or adding CO_2 from the atmosphere.

It is important to note the feedback among some of the above phenomena. For example, if global temperature rises due to an increase in CO_2, then rates of evaporation and therefore amounts of rainfall increase. As a consequence, weathering rates (which absorb CO_2) increase, so the concentration of CO_2 may then go down (a negative feedback).

Natural Short-Term Climate Change

So far, we've emphasized how climate has changed over periods of tens to hundreds of millions of years. The geologic record of the past few million years provides enough detail to allow us to detect cycles of climate change that have durations of centuries to hundreds of thousands of years. Such short-term climate change events must be a consequence of factors that can operate quickly in the context of geologic time.

FIGURE 19.6 The proportion of isotopes transferred between reservoirs during evaporation or precipitation depends on temperature. The $^{18}O/^{16}O$ ratio can be studied in glacial ice (H_2O) and fossil shells ($CaCO_3$).



(a) A researcher examines an ice core in the field. Lab photos reveal annual layers.

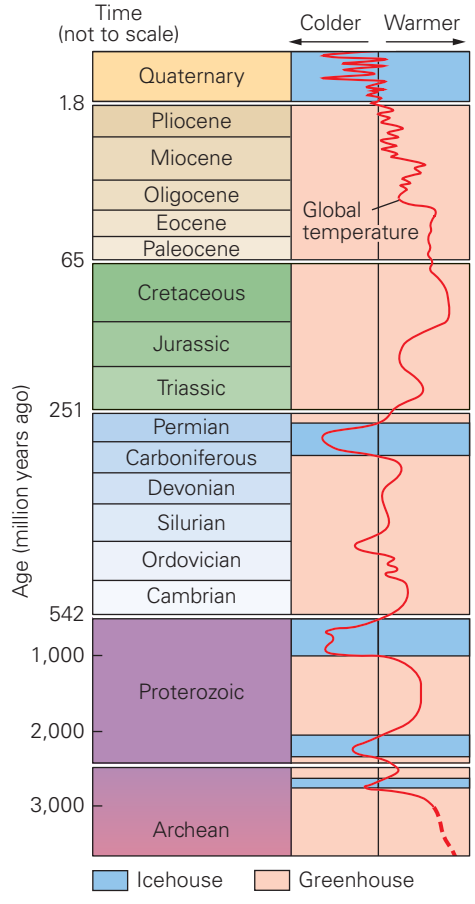
(b) The $^{18}O/^{16}O$ ratios in an ice core represent temperature changes.

(c) Studies of $^{18}O/^{16}O$ ratios in deep-sea cores also provide a climate record.

We can get a sense of short-term climate change events by considering the Pleistocene stratigraphic record. Changes in fossil assemblages, sediment composition, and isotopic ratios of minerals indicate that continental glaciers advanced and retreated about 20 to 30 times in the northern hemisphere. Each advance (glaciation) represents an interval of global cooling, and each retreat (interglacial) represents an interval of global warming. If we focus on the last 15,000 years, a period that includes all of the Holocene, we see trends of cooling or warming that last thousands of years, within which there are events whose duration lasts centuries or less (**Fig. 19.8a**).

Specifically, the time between about 15,000 and 10,500 B.C.E. was a warming period, during which the last ice-age glaciers retreated. This warming trend was followed by the Younger Dryas, an interval of cooler temperatures named for an Arctic flower that became widespread during the interval. Then, climate warmed again, reaching a peak at 5,000 to 6,000 years ago, a period called the Holocene maximum, when average temperatures were about 2°C above temperatures of today. This warming peak led to increased evaporation and therefore precipitation, making the Middle East unusually wet and fertile—conditions that may partially account for the rise of civilization in this part of the world.

FIGURE 19.7 This chart shows the timing of icehouse and greenhouse phases at various times during Earth history.

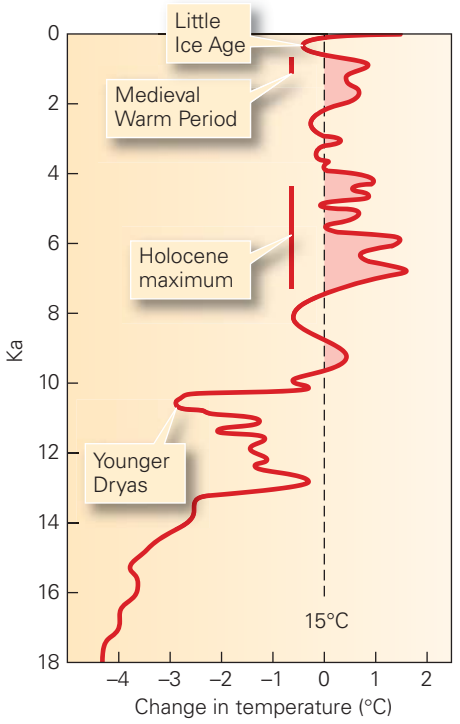


The temperature dipped to a low about 3,000 years ago, before returning to a high during the Middle Ages, a time called the Medieval Warm Period. During this time, Vikings established self-supporting agricultural settlements along the coast of Greenland (**Fig. 19.8b**). The temperature dropped again from 1500 C.E. to about 1800 C.E., a period known as the Little Ice Age, when Alpine glaciers advanced and the canals of the Netherlands froze over in winter (**Fig. 19.8c**; see Fig. 18.29). Overall, the climate has warmed since the end of the Little Ice Age, and today it is as warm or warmer than it was during the Medieval Warm Period.

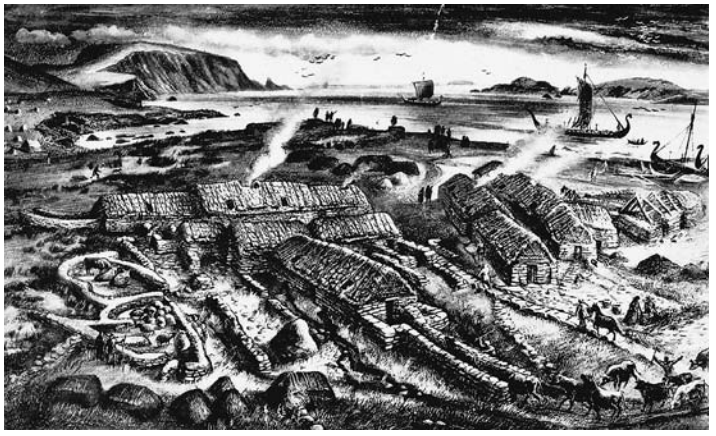
Geologists have focused on several factors to explain short-term climate change.

- *Fluctuations in solar radiation and cosmic rays*: The amount of energy produced by the Sun varies with the sunspot cycle. This cycle involves the appearance of large numbers of sunspots (black spots thought to be magnetic storms on the Sun's surface) about every 9 to 11.5 years. There may be longer-term cycles that have not yet been identified. Changes in the rate of influx of cosmic rays may affect climate, perhaps by generating clouds. Recent research suggests that cosmic rays striking the atmosphere produce clusters of ions that become condensation nuclei around which water molecules congregate, thus forming the mist droplets making up clouds.
- *Changes in Earth's orbit and tilt*: As Milanković first recognized in 1920, the change in the tilt of Earth's axis, the Earth's precession cycle, and changes in the eccentricity of its orbit together cause the amount of summer heat in high latitudes to vary. They also cause the overall amount of heat reaching Earth to vary (see Chapter 18). These changes correlate with observed ups and downs in atmospheric and oceanic temperature.
- *Changes in volcanic emissions*: Not all of the sunlight that reaches the Earth penetrates its atmosphere and warms the ground. Some is reflected by the atmosphere. The degree of reflectivity, or **albedo**, of the atmosphere increases if the concentration of volcanic aerosols in the atmosphere increases.
- *Changes in ocean currents*: Recent studies suggest that the configuration of currents can change quite quickly, and that this configuration affects the climate.
- *Changes in surface albedo*: Regional-scale changes in the nature of continental vegetation cover, and/or the proportion of snow and ice on the Earth's surface, and/or the sudden deposition of reflective volcanic ash affect our planet's albedo. Increasing surface albedo causes cooling, whereas decreasing albedo causes warming.
- *Abrupt changes in concentrations of greenhouse gases*: A sudden change in greenhouse gas concentration in the atmosphere could affect climate. One such change might happen if sea temperature warmed or sea level dropped, causing some of the methane hydrate that crystallized in sediment on the sea

FIGURE 19.8 Climate during the Holocene. Measurements suggest that temperature has varied significantly.



(a) There have been several temperature highs and lows during the Holocene.



(b) During the Medieval Warm Period, Vikings settled in Greenland, where the climate was warm enough for agriculture.



(c) Glaciers advanced in Europe during the Little Ice Age.

floor to melt and release CH_4 to the atmosphere. Melting of permafrost can have a similar effect, for the resulting rot of organic material preserved in the permafrost produces CH_4. Algal blooms and reforestation (or deforestation) absorb CO_2 and cause cooling.

Catastrophic Climate Change and Mass-Extinction Events

Changes that happen on Earth almost instantaneously are called catastrophic changes. For example, a volcanic explosion, an earthquake, a tsunami, or a landslide can change a local landscape in seconds or minutes. But such events affect only relatively small areas. Can such catastrophes happen on a global scale? In the past decades, geoscientists have come to the conclusion that the answer is yes. The stratigraphic record shows that Earth history includes several **mass-extinction events**, during which large numbers of species abruptly vanished. Some of these events define boundaries between geologic periods. A mass-extinction event decreases the biodiversity (the number of different species that exist at a given time) of life on Earth. It takes millions of years after a mass-extinction event for biodiversity to increase again, and the new species that appear differ from those that vanished, for evolution is unidirectional.

Geologists speculate that some mass-extinction events reflect a catastrophic change in the planet's climate, brought about by unusually voluminous volcanic eruptions or by the impact of a comet or an asteroid with the Earth. Either of these events could eject enough debris into the atmosphere to block sunlight. Without the warmth of the Sun, winter-like or night-like conditions would last for weeks to years, long enough to disrupt the food chain. In addition, either event could eject aerosols that would turn into global acid rain, scatter hot debris that would ignite forest fires, or give off chemicals that, when dissolved in the ocean, would make the ocean either toxic, killing marine life, or so nutritious that oxygen-consuming algae could thrive. At present, many geologists favor the hypothesis that the Permian-Triassic extinction was due to the eruption

of 3 million cubic km of basalt in Siberia, and that the Cretaceous-Tertiary extinction was due to a giant meteorite impact near the Yucatán peninsula in Mexico.

Take-Home Message

Geologic study shows that past climate alternates between greenhouse and icehouse conditions. Factors including life evolution, continental drift, and orbital change cause long- and short-term change. Volcanoes and meteorites can cause catastrophic change.

19.6 Human Impact on the Earth System

According to some researchers, perhaps only 20,000 people lived on Earth after the catastrophic eruption of the Toba volcano about 70,000 years ago. By the dawn of civilization, 4000 B.C.E., the population was still, at most, a few tens of millions. But by the beginning of the 19th century, revolutions in industrial methods, agriculture, medicine, and hygiene had substantially lowered death rates and raised living standards, so that the human population began to grow at accelerating rates and reached 1 billion in 1850. It took only 80 years for the population to double, reaching 2 billion in 1930. Now the doubling time is only 44 years, and the population passed the 6 billion mark just before the year 2000 (Fig. 19.9). Global population surpassed 7 billion during 2012.

As the population grows and the standard of living improves, per capita usage of resources increases. We use land for agriculture and grazing, forests for wood, rock and dirt for construction, oil and coal for energy or plastics, and ores for metals (see Chapter 12). Without a doubt, our usage of resources has affected the Earth System profoundly, and thus humanity has become a major agent of global change. Here, we examine some of these anthropogenic (human-induced) impacts.

The Modification of Landscapes

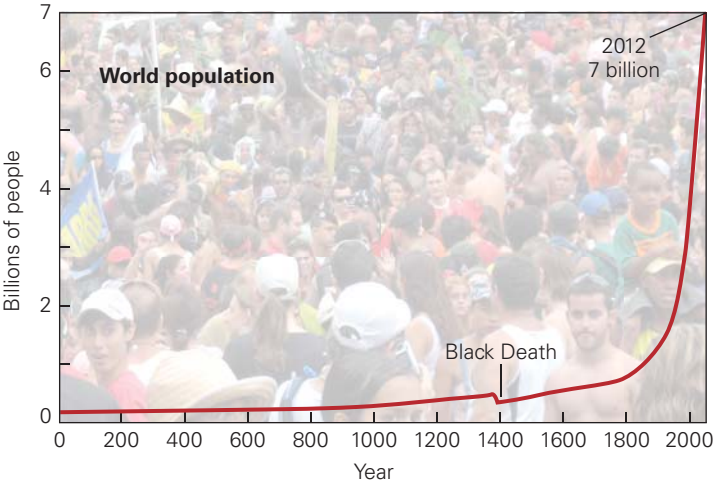
Every time we pick up a shovel and move a pile of rock or soil, we redistribute a portion of the Earth's crust. In the last century, the pace of Earth movement has accelerated, for now we have shovels in coal mines that can move 300 cubic meters of rock in a single scoop, trucks that can carry 200 tons of ore in a single load, and tankers that can transport 500 million liters (~3 million barrels) of oil during a single journey. In North America, human activity now moves more sediment each year than the continent's rivers do. The extraction of rock during mining, the building of levees and dams along rivers or of sea walls along the coast, and the construction of highways and cities all involve the redistribution of Earth materials (Fig. 19.10). In addition, people clear and plow fields, drain and fill wetlands, and pave over the land surface. All these activities change the landscape, the water table, and the supply of sediment.

The Modification of Ecosystems

In an undisturbed area, the **ecosystem** (an interconnected network of organisms and the physical environment in which they live) of a region is the product of evolution for an extended period of time. The ecosystem's flora and fauna include species that have adapted to living together in a particular climate and on the substrate available. Human-caused deforestation, overgrazing, agriculture, and urbanization disrupt ecosystems and lead to a decrease in biodiversity.

Archaeological studies have found that the earliest example of human modification of an ecosystem occurred in the Stone Age, when hunters played a major role in causing the mass extinction of many species of large mammals (mammoths, giant sloths, giant bears). Today, less than 5% of Europe retains its original habitats. The same number can be applied to the eastern United States, which lost its original forest and prairie. Tropical rain forests cover less than about half the area worldwide that they covered before the dawn of civilization, and they are disappearing at a rate of about 1.8% per year (Fig. 19.11a, b). Much of this loss comes from slash-and-burn agriculture, in which farmers and ranchers destroy forest to make open land for farming and grazing (Fig. 19.11c). Unfortunately, the heavy rainfall of tropical regions removes nutrients from the soil, making the soil useless in just a few years. Overgrazing by domesticated animals can remove vegetation so completely that some grasslands have undergone desertification. And urbanization replaces the natural land surface with concrete or asphalt, a process that completely destroys an ecosystem and radically changes the amount of rain that infiltrates the land surface to become groundwater.

FIGURE 19.9 Population now doubles about every 44 years. The Black Death pandemic caused an abrupt drop that lasted for several decades.



Pollution

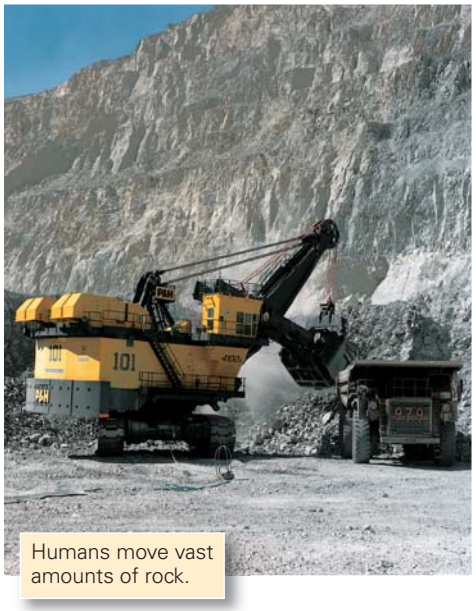
The environment has always contained contaminants such as soot, dust, and the by-products of organisms. But when human populations grew, urbanization, industrial and agricultural activity, the production of electricity, and modern modes of transportation greatly increased both the quantity and diversity of contaminants that entered the air, surface water, and groundwater. These contaminants, or **pollution**, include both natural and synthetic materials in liquid, solid, and gaseous form. They have become a problem because they are produced too fast for the Earth System to naturally absorb or modify. For example, small quantities of sewage can be absorbed by clay minerals in the soil or destroyed by bacterial metabolism, but large quantities overwhelm natural controls and can accumulate in destructive concentrations. Pollution of the Earth System is a type of global change because it is a redistribution and reformulation of materials. Some key problems associated with this change include the following:

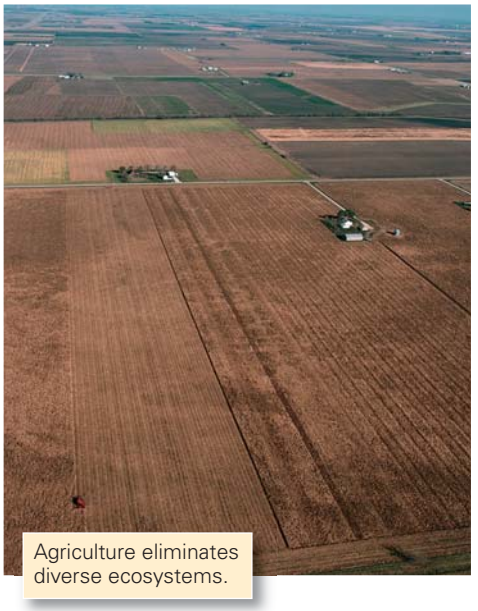
- *Smog*: The term was originally coined to refer to the dank, dark air that resulted when smoke from the burning of coal mixed with fog in London and other industrial cities. Another kind of smog, called photochemical smog, is the ozone-rich brown haze that blankets cities when exhaust from cars and trucks reacts with air in the presence of sunlight.
- *Water contamination*: We dump a great variety of chemicals into surface water and groundwater. Examples include gasoline, other organic chemicals, radioactive waste, acids, fertilizers—the list could go on for pages. These chemicals affect biodiversity.
- *Acid runoff*: Dissolution of sulfide-containing minerals in ores or coal by groundwater or stream water makes the water acidic.
- *Acid rain*: When rain passes through air that contains sulfur-containing aerosols (emitted from power plants), the water dissolves the sulfur and creates sulfuric acid, or **acid rain**. Wind can carry aerosols far from a power plant, so acid rain can damage a broad region.
- *Radioactive materials*: Nuclear weapons, nuclear energy, and medical waste transfer radioactive materials from rock to Earth's surface environment.
- *Ozone depletion*: When emitted into the atmosphere, human-produced chemicals, most notably chlorofluorocarbons (CFCs), react with ozone in the stratosphere. This reaction, which happens most rapidly on the surfaces of tiny ice crystals in polar stratospheric clouds, destroys ozone molecules, thus creating an **ozone hole** over high-latitude regions, particularly during the spring (Fig. 19.12). Note that the "hole" is not an area where no ozone is present, but rather is a region where atmospheric ozone has been reduced substantially. Ozone holes have dangerous consequences, for they affect the ability of the atmosphere to shield the Earth's surface from harmful ultraviolet radiation.

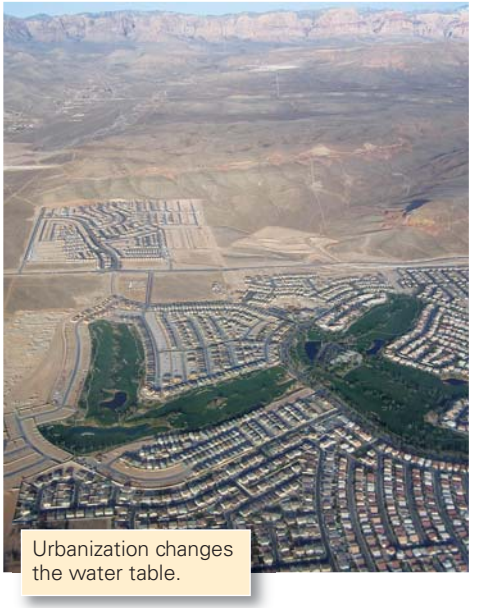
Recent Global Warming

We've seen that greenhouse gases, most notably CO_2 and CH_4, play a major role in the regulation of the Earth's surface temperatures—without these gases, the Earth could not be a home for life. Both CO_2 and CH_4 cycle through various biogeochemical reservoirs of the Earth System, and the fluxes between reservoirs determine the amount in any given reservoir at any given time. For most of geologic time, the concentration of these gases in the atmosphere was governed by natural processes—volcanic eruptions, life evolution events (appearance of new genera or extinction of existing ones), forest fires, orogenic uplift and related weathering, warming and cooling due to the Milanković cycle, changes in solar activity or cosmic-ray flux, and even meteor impact. But beginning around 8,000 years ago, human society began to modify the environment significantly, first with the invention of agriculture and then, during the past two centuries, with the advent of major industrialization.

FIGURE 19.10 Excavation, agriculture, and construction modify topography, drainage, infiltration, and ecology.


Humans move vast amounts of rock.


Agriculture eliminates diverse ecosystems.


Urbanization changes the water table.

Both industry and agriculture produce greenhouse gases that transfer carbon from underground reservoirs or biomass reservoirs into the atmospheric reservoir. For example: the burning of fossil fuels oxidizes vast quantities of carbon that had previously been held in oil, gas, or coal underground to produce CO_2 that mixes into the atmosphere; the heating of calcite ($CaCO_3$) to produce the lime (CaO) of cement takes carbon that had been locked in limestone and produces CO_2 that also mixes into the air; the clear-cutting of forests to make way for grazing land or fields replaces high-biomass vegetation (trees) with low-biomass vegetation (grasses or crops) thereby leaving CO_2 in the atmosphere; and the decay of organic material in soggy rice paddies, as well as the flatulence of cattle herds, produces significant quantities of CH_4 that would otherwise remain locked in biomass.

About 85% of the CO_2 that we send into the atmosphere comes from burning fossil fuels and producing cement, while about 15% is a consequence of deforestation. How does the rate of production of CO_2 by humanity compare to the rate of production by volcanic eruptions? Researchers estimate that in a year all volcanic eruptions together (including both submarine and subaerial eruptions) emit about 0.15 to 0.26 gigatons of CO_2. By comparison, activities of humanity emit about 35 gigatons of CO_2 every year, or at least 135 times as much. Significantly, not all of the greenhouse gases that society sends into the atmosphere stay there. In the case of CO_2, some dissolves in the ocean, some reacts with minerals in rocks during chemical weathering, and some is utilized by plants during photosynthesis. But calculations and isotopic studies suggest that only 43% of the CO_2 that society produces (what researchers refer to as anthropogenic CO_2) returns into the Earth in biogeochemical cycles—the remaining 57% stays in the atmosphere.

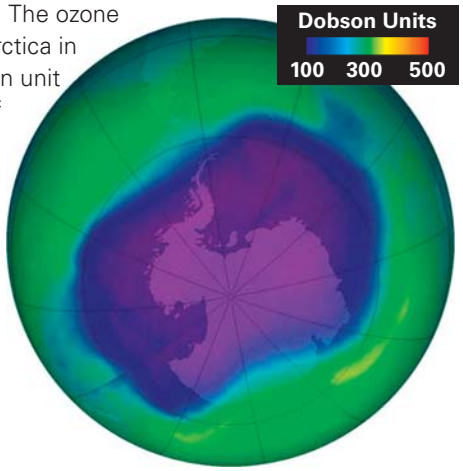
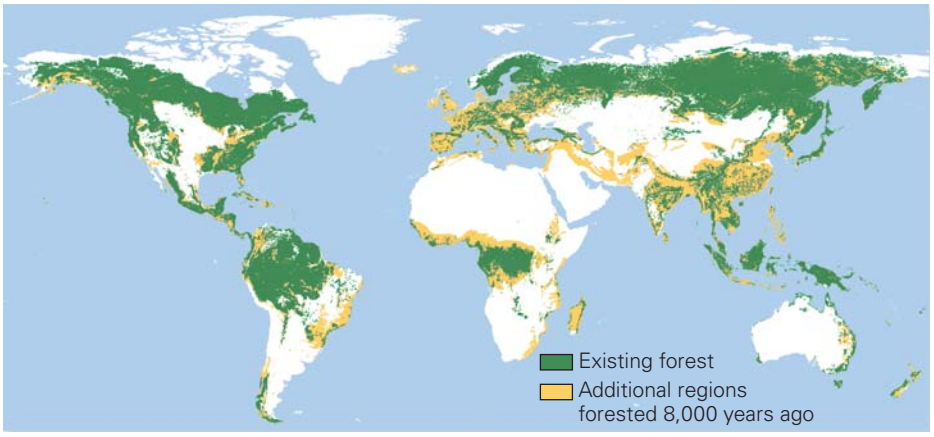


FIGURE 19.12 The ozone hole over Antarctica in 2006. A Dobson unit is a measure of the amount of ozone in the atmosphere; red is more, purple is less.

FIGURE 19.11 The area of the Earth covered by forests has been shrinking.



(a) Comparison of exisiting forest area (green) to precivilization forest area (gold and green together) emphasizes changes in Earth's forest cover. Tropical rainforest areas are shrinking rapidly.

(b) Satellite images of a region in the Amazon show the increase in cleared areas (light).



(c) Slash-and-burn agriculture.



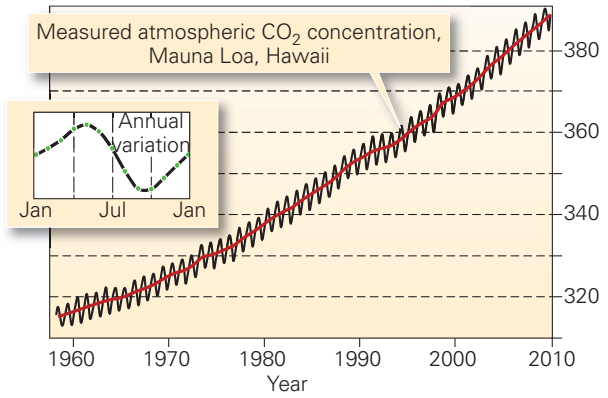
In the early 1960s, a chemist named Charles Keeling wondered whether changes in atmospheric CO_2 concentration could be detected, and he set out to measure the concentration of CO_2 in the atmosphere using the most accurate methods available. To avoid areas with urban pollution, he decided to analyze air samples collected every month at the summit of Mauna Kea volcano in Hawaii. After completing many years of measurements, Keeling showed not only that distinct seasonal variations occurred (CO_2 concentration goes down in the warm summer when rates of photosynthesis increase, and it goes up in the winter when organic matter dies and decays), but also that the *average annual concentration* of CO_2 was steadily rising (**Fig. 19.13a**)! The average yearly CO_2 concentration was 320 ppm in 1965, and it reached 360 ppm in 1995. Charles Keeling died in 2005, but measurements at Mauna Kea have continued, and in 2012, the average yearly CO_2 concentration there reached 394 ppm.

Using records in ice cores, researchers extended the record of CO_2 concentration further back in time and have found that in 1750, CO_2 concentration was only 280 ppm (**Fig. 19.13b**). Thus, atmospheric CO_2 concentration has increased by about 40% since the beginning of the industrial revolution. Ice cores from the Antarctic ice sheet now provide a CO_2 record back through the last 800,000 years, and they demonstrate that during the alternating glacial and interglacial periods of the Late Pleistocene, CO_2 concentration varied between about 180 and 300 ppm (**Fig. 19.13c**). Thus, the increases that have happened since the beginning of the industrial revolution appear to be beyond the range of natural fluctuations that occurred during the last 800,000 years. Have CO_2 concentrations ever been higher than they are today? Probably. For example, a recent study suggests that CO_2 concentration during the Eocene climate optimum (49 to 56 Ma) was over 1,000 ppm, about three times what it is today. CH_4 concentrations have also demonstrably increased over the past two centuries (**Fig. 19.13d**).

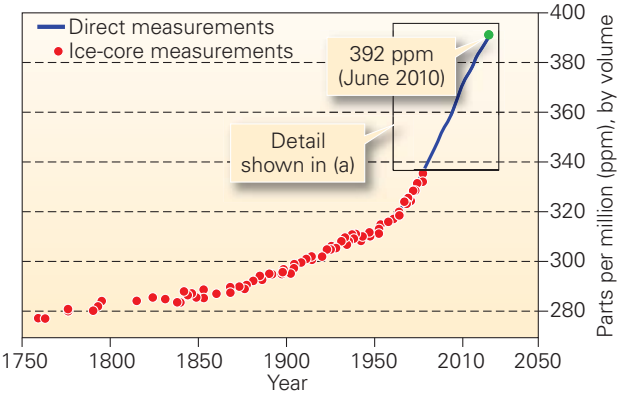
The fundamental principles of the greenhouse effect require that an increase in CO_2 concentration cause warming. But has warming taken place during the past 200 years? During the past 30 years, researchers have published thousands of observations suggesting that it has. For example:

- Large ice shelves, such as the Larsen B Ice Shelf, along the Antarctic Peninsula, and the Ayles Ice Shelf, along Ellesmere Island in northernmost Canada, are breaking up (**Fig. 19.14a**).
- The area covered by sea ice in the Arctic Ocean has decreased substantially in recent decades. Some estimates place the rate of ice-cover loss at about 3% per decade. This observation leads to the prediction that it may be possible to sail across the Arctic Ocean within decades (**Fig.19.14b**).
- The Greenland ice sheet is melting at an accelerating pace. Studies suggest that the rate of ice loss has increased from 90 to 220 cubic km per year in the last 10 years and that, in places, the sheet is thinning by about 1 m per year. In addition, the annual melt zone along the margins of the ice sheet has widened dramatically because the elevation of the equilibrium line (see Chapter 18) has risen (**Fig. 19.14c**). Valley glaciers draining the ice sheet flowed 50% faster in 2003 than they did in 1992.
- Valley glaciers worldwide, with few exceptions, have been retreating rapidly, so that areas that were once ice covered are now bare. The change is truly dramatic in many locations (**Fig. 19.14d**).
- Worldwide, glacial volumes have been diminishing. About 400 km^3 of ice disappears every year.
- Biological phenomena that are sensitive to climate are being disrupted. For example, the time at which sap in the maple trees of the northeastern United States starts to flow has changed, and the mosquito line (the elevation at which mosquitoes can survive) has risen substantially. Plant hardiness zones in North America have migrated northward

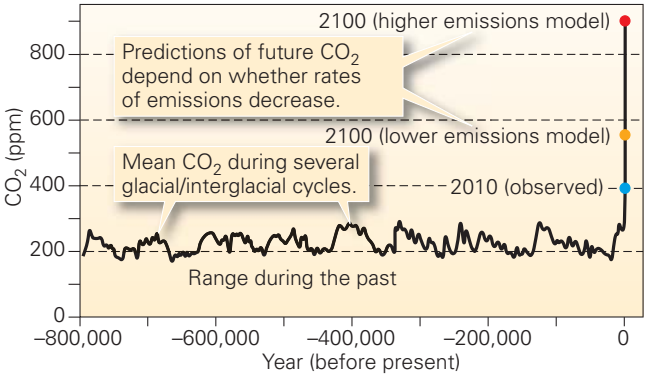
FIGURE 19.13 Changes in carbon dioxide (CO_2) and methane (CH_4) concentrations over time.



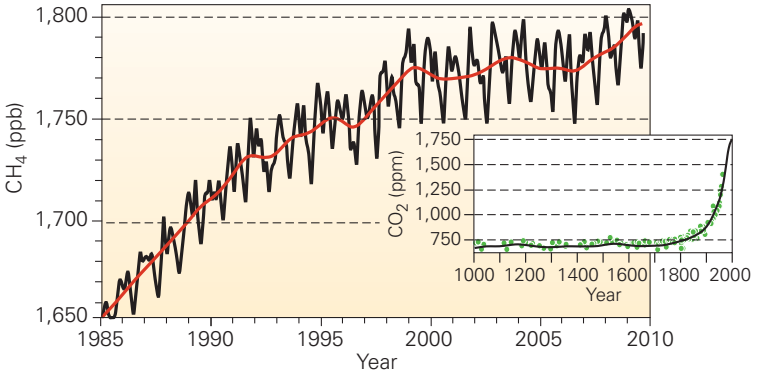
(a) Daily measurements began in 1960. There is an annual cycle, related to seasons, but the overall increase is clear; CO_2 reached 394 in 2012.



(b) Since the industrial revolution, CO_2 concentration has steadily increased.

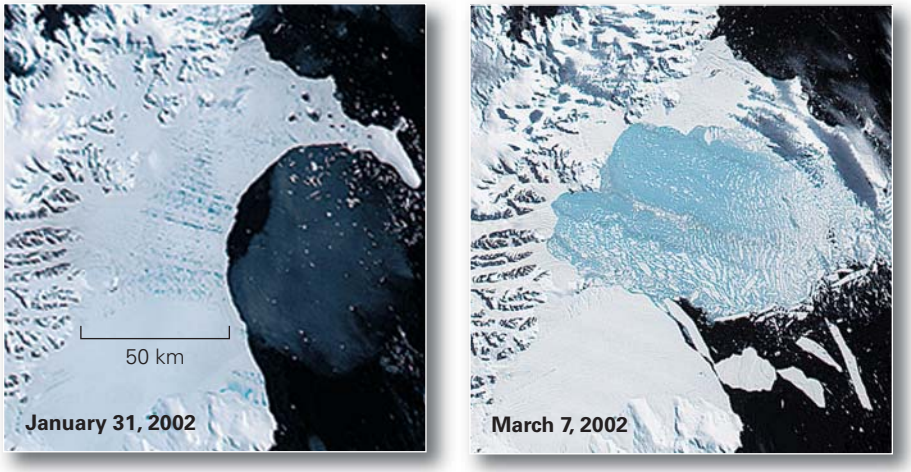


(c) Based on ice-core studies in glaciers, researchers find that CO_2 concentration varied between 180 and 280 ppm throughout glacial advances and retreats. The 2012 value, 394 ppm, is above this range.

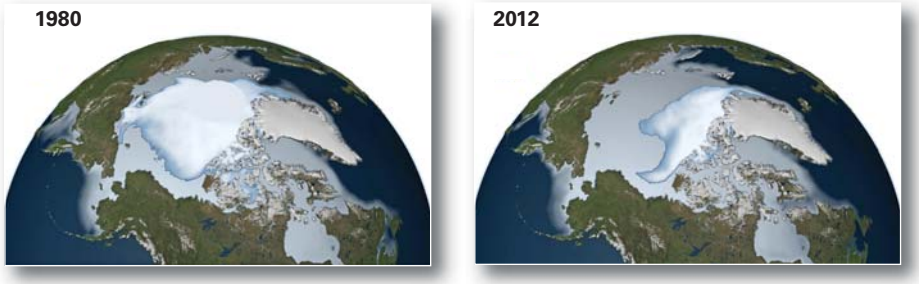


(d) Methane, another greenhouse gas, has been increasing, too. The inset shows CH_4 concentration for the past 1,000 years.

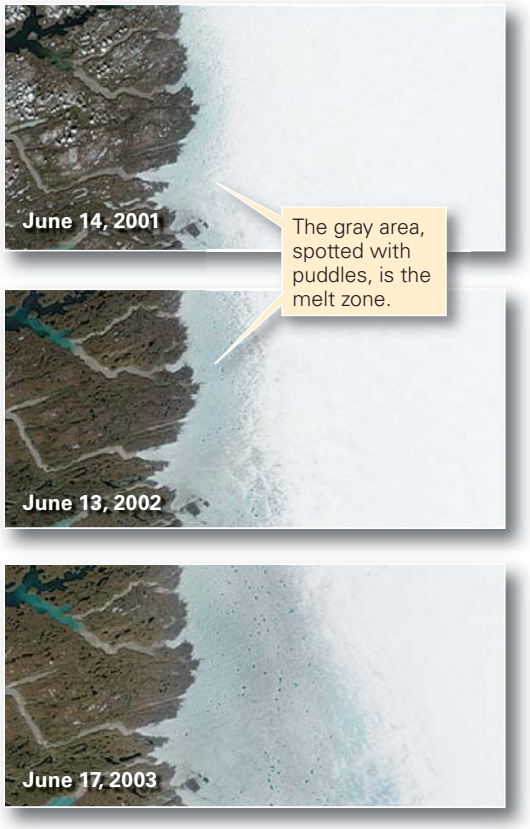
FIGURE 19.14 Visible examples of large-scale changes in Earth's ice cover.



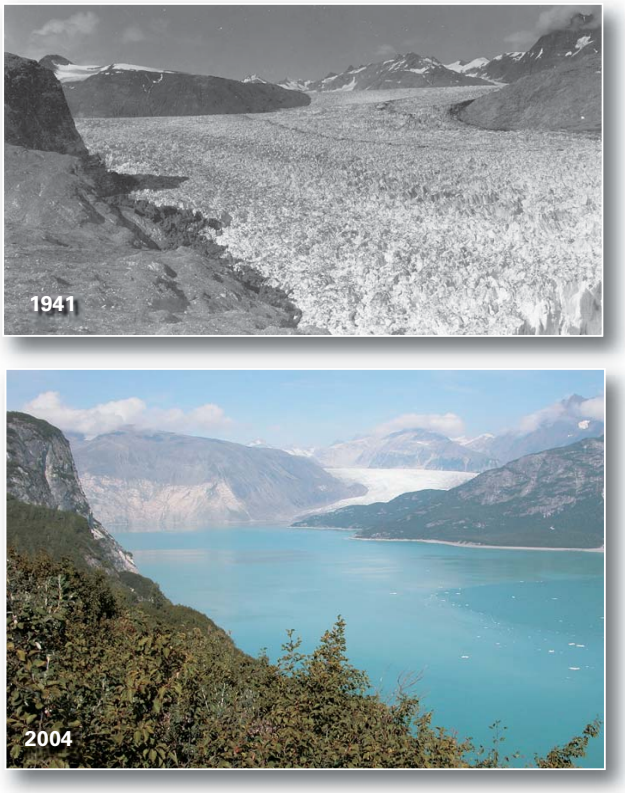
(a) The Larsen B Ice Shelf consisted of glacial ice flowing off the Antarctic Peninsula. In 2002, the shelf disintegrated.



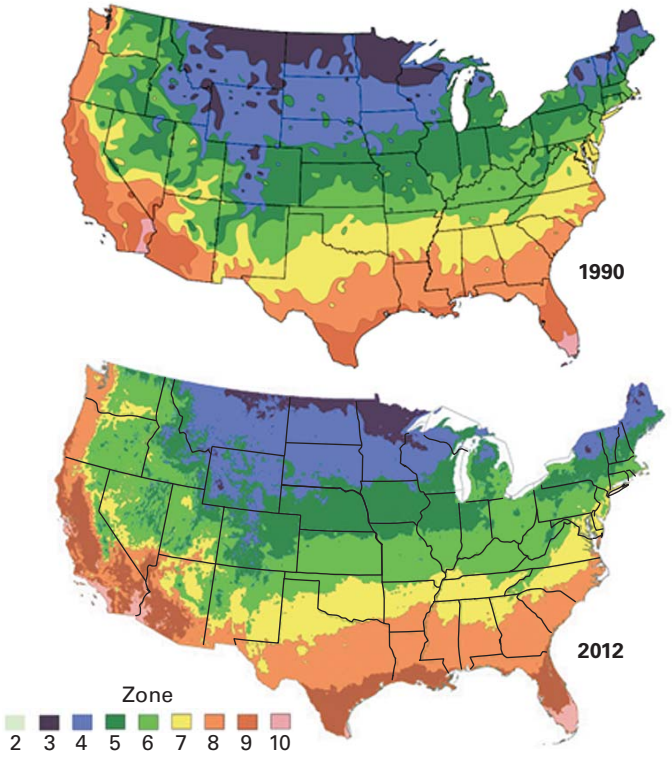
(b) The northern polar ice cap shrank significantly between 1980 and 2012.



(c) The summer melt line has risen along the edge of Greenland's ice sheet. Each photo shows the same area.

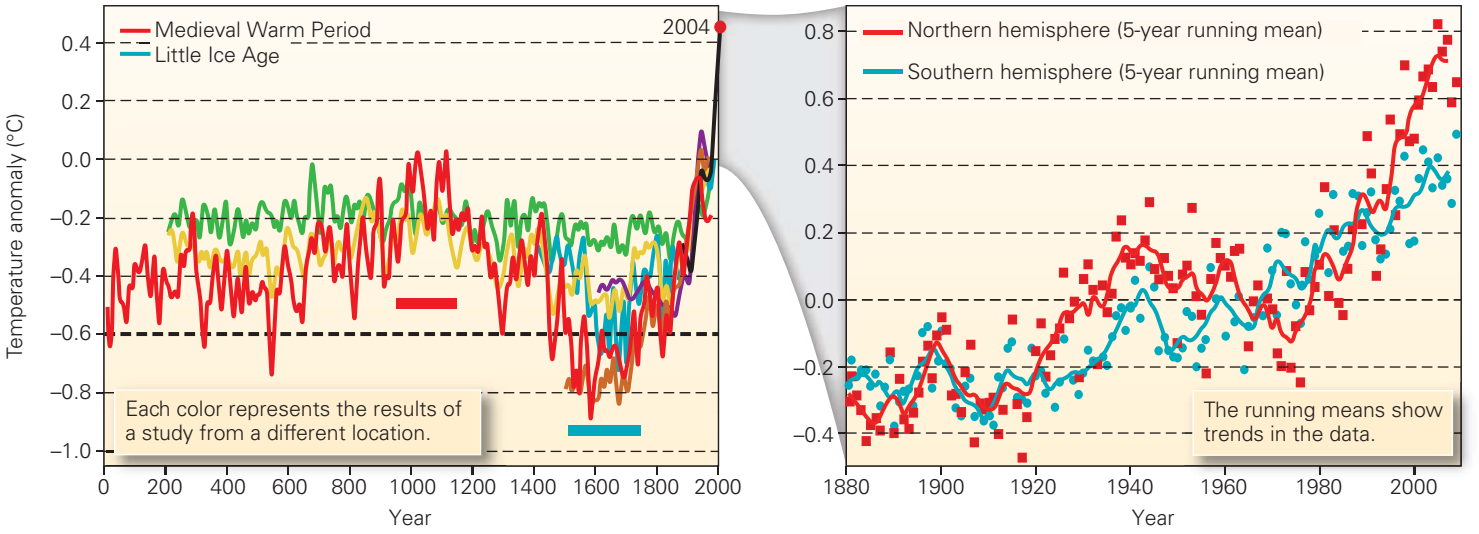


(d) The Muir Glacier, Alaska, retreated 12 km between 1941 and 2004.



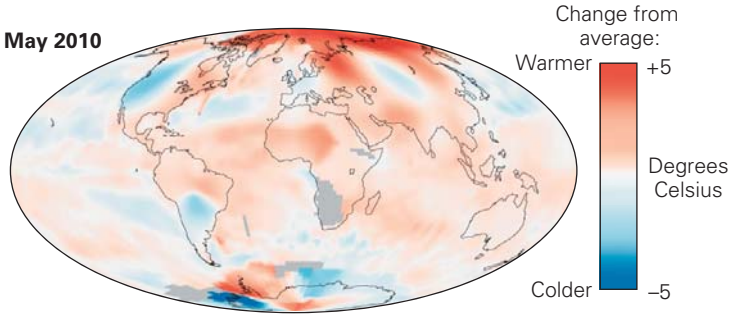
(e) Plant hardiness is an indication of the earliest date in a year when crops can be planted. The zones are moving north.

FIGURE 19.15 Measurements of global warming and global temperature anomalies.



(a) Reconstructions of temperature during the past 2000 years. The black line is the average of direct measurements.

(b) The change in global average temperature from 1880 to 2008, relative to a reference value. Both hemispheres show a temperature increase.



(c) Colors represent differences relative to the average temperature of the period from 1951 to 1980. Redder areas are warmer than the 1951–1980 average.

(**Fig. 19.14e**). Also, the average weight of polar bears has been decreasing, because the bears can no longer walk over pack ice to reach their hunting grounds in the sea.

- The area of permafrost in high latitutdes has substantially decreased, and melt ponds have replaced frozen land.
- Water vapor in the atmosphere has been increasing due to evaporation of warmer seas, possibly leading to more severe hurricanes.
- Measured values of *average* global surface atmospheric temperature are rising, a phenomenon widely referred to as global warming (**Fig. 19.15a–c**). Specifically, global mean atmospheric temperature has risen by about 1°C during the last century. Although such a change may seem small, the magnitude of temperature change between the last ice age and now, by comparison, was only 3° to 5°C. A small change in average temperature may have major consequences.
- Measured values of near-surface ocean-water temperatures are rising. Studies of global averages of temperatures in the sea indicate that overall, the oceans have been warming over the past century and a half (**Fig. 19.16**).

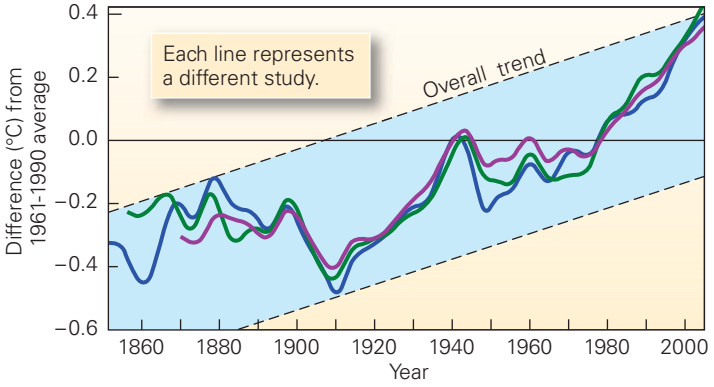
Climate data are not easy to obtain and are not easy to interpret. Because climate studies can have major implications for global policy decisions, a group of leading scientists founded the Intergovernmental Panel on Climate Change (IPCC) in 1988. This panel, sponsored by the World Meteorological Organization and the United Nations, reviews published research on climate change and, every five years, summarizes the conclusions in an assessment report. The language describing the likelihood that global warming is happening, and that humans have contributed significantly to causing it, has become progressively less equivocal in successive versions of the report. *The Fourth Assessment Report*, published in 2007, states:

> Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. . . . The understanding of anthropogenic [human-caused] warming and cooling influences on climate has improved since the Third Assessment Report, leading to very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming.

In other words, most climate researchers have concluded that global warming is real, and that the actions of people—burning fossil fuels, cutting down forests, paving over wetlands—have played a significant role in causing it. Other possible causes, such as changes in solar radiation or cosmic-ray flux, do not appear to be of sufficient magnitude to cause observed warming.

If the *Fourth Assessment* of the IPCC is correct, then society faces the challenge of either slowing climate change or dealing with the consequences. The effects of global warming over the coming decades to centuries remains the subject of intense

FIGURE 19.16 Measurements of average global temperature in shallow waters of the ocean.



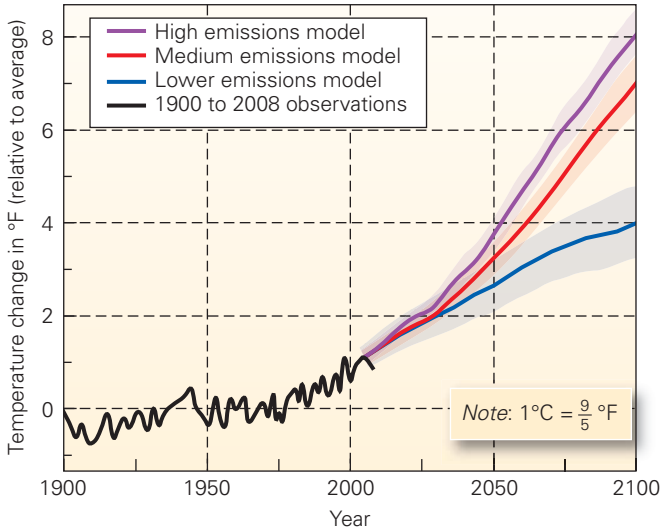
debate, because predictions depend on computer models and not all researchers agree on how to construct or interpret these models. The role of clouds in climate change, for example, remains poorly understood and inadequately addressed by such models. In the worst-case scenario, global warming will continue into the future at the present rate, so that by 2050—within the lifetime of many readers of this book—the average annual temperature will have increased in some parts of the world by 1.5° to 2.0°C. At these rates, by the end of the century, temperatures could be almost 4°C warmer depending on the model used (**Fig. 19.17a**), and by 2150, global temperatures may be 5° to 11°C warmer than at present—the warmest since the Eocene Epoch, 40 million years ago. Models predict that warming will not be the same everywhere—the greatest impact will be in the Arctic (**Fig. 19.17b**).

The effects of such a change are controversial, but according to some climate models, the following events might happen:

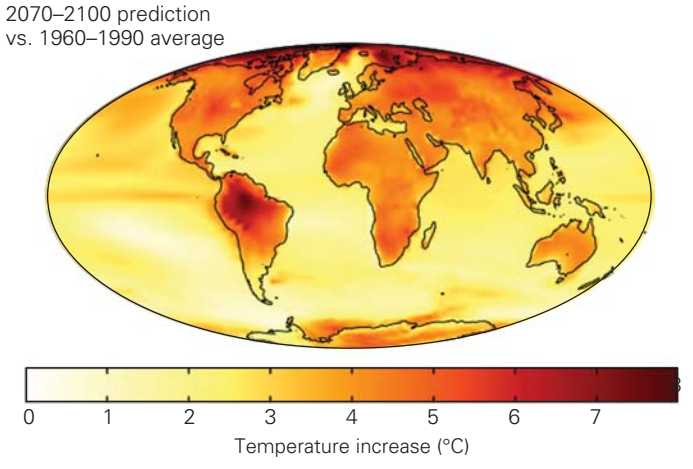
- *A shift in climate belts*: As the climate overall warms, temperate and desert regions would occur at higher latitudes. Thus, regions that are now agricultural areas may dry out and become unfarmable. The change in climate would also affect the amount and distribution of precipitation (rain and snow) that falls.
- *Ice retreat and snow-line rise*: Global warming will decrease the volume of water held in glacial reservoirs and will cause areas covered by sea ice to decrease. It will also cause snow-line elevations in mountainous areas to rise—this change will affect the amount of water held in the winter snowpack, and therefore, will decrease summer runoff, and may even impact tourism by shortening the ski season at resorts.
- *Melting permafrost*: Warming climates will cause areas of unglaciated land that previously had remained frozen most of the year to thaw during the summer. Such melting of permafrost will permit organic matter that had been stored in frozen form to decompose and release methane.
- *A rise in sea level*: Water expands when heated, so warming of the global ocean causes sea level to rise. Glacial melting due to global warming adds to the rise. Sea level has already changed noticeably in the last century (**Fig. 19.18a, b**), and as a result, some coastal wetlands have flooded and some oceanic islands have become submerged. Dikes that protect coastal areas of the Netherlands from flooding will need to be raised in coming decades to counter sea-level rise.

The amount of sea-level rise in the future depends on the rate of global warming. Models suggest that by 2100, it may rise by an additional 20 to 60 cm. A map showing the elevations of coastal areas emphasizes that a meter or two of sea-level rise could inundate regions of the world where 20% of the human population currently lives (**Fig. 19.18c**).

FIGURE 19.17 Model predictions of future global warming.

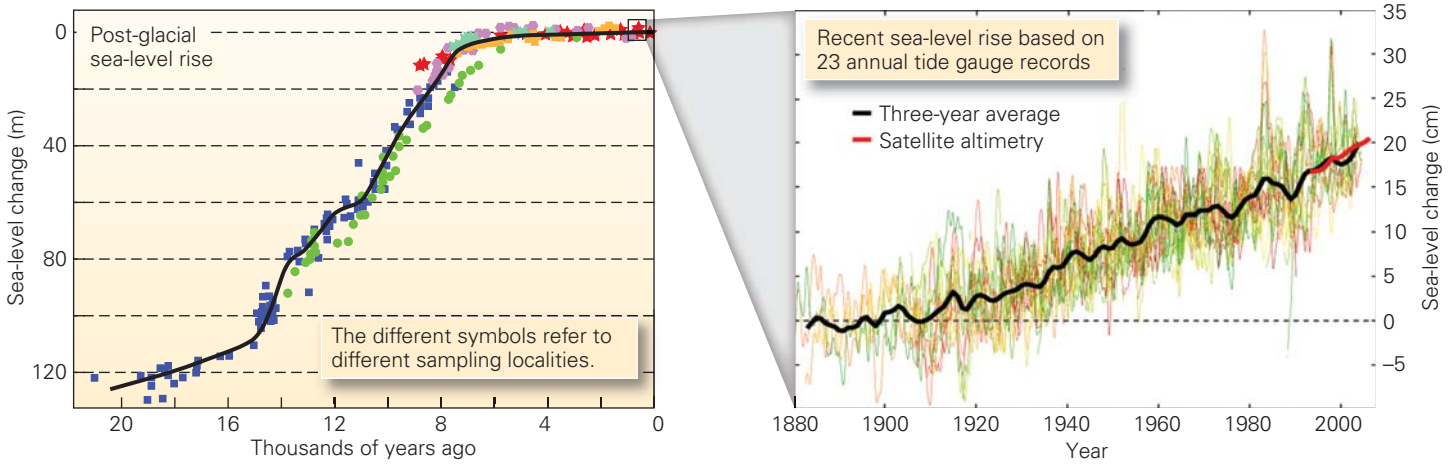


(a) Model calculations of global warming. Different models assume different rates of CO_2 emissions. All suggest significant global temperature increase by 2100.



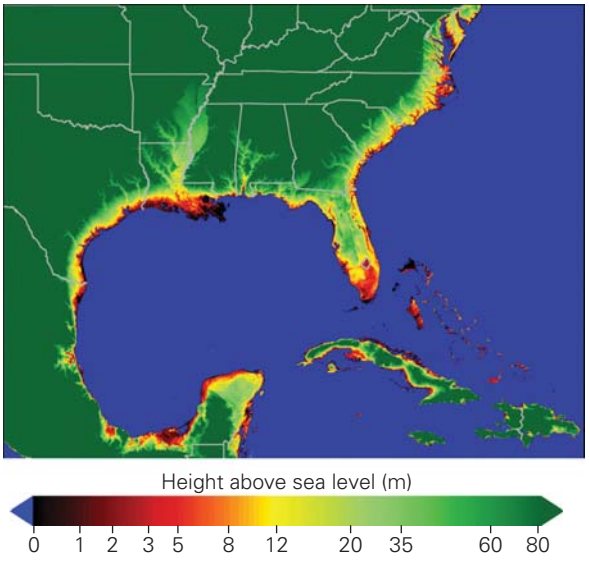
(b) Global warming does not mean that all locations warm by the same amount. This map shows a model prediction of how temperature may vary with location for the time period 2070 to 2100.

FIGURE 19.18 Sea-level rise of the recent past, and possible sea-level rise of the future.



(a) Sea level rose rapidly after the last ice age, due to melting of continental glaciers.

(b) Tide gauges document sea-level rise of the past 130 years.



(c) The red and black areas of this map are so low that they could be flooded if sea level rose a few meters.

- *Stronger storms*: An increase in average ocean temperatures means that more of the ocean evaporates when a tropical depression passes over. This evaporation might nourish stronger hurricanes. In nondesert areas, there might be more precipitation and, therefore, flooding.
- *An increase in wildfires*: Warmer temperatures may lead to an increase in the frequency of wildfires because the moisture content of plants is lower.
- *An interruption of the oceanic heat conveyor*: Oceanic currents play a major role in transferring heat across latitudes. If global warming melts polar ice, the resulting freshwater would dilute surface ocean water at high latitudes. This water could not sink, and thus thermohaline circulation would be shut off (see Chapter 15), preventing the water from conveying heat.

The potential changes described above, along with other studies that estimate the large economic cost of global warming, imply that the issue needs to be addressed seriously and soon. But what can be done? The 160 nations that signed the 1997 Kyoto Accord, at a summit meeting held in Japan, propose that the first step would be to slow the input of greenhouse gases into the atmosphere by decreasing the burning of fossil fuels and/or by forcing the CO_2 produced at power plants down wells into pore space underground by a process called **carbon capture and sequestration** (CCS). Such proposals, needless to say, remain very controversial.

Take-Home Message

Human activities impact the landscape and ecosystems. Evidence indicates that, globally, glacial and sea ice volume is decreasing, sea level is rising, and climate belts are shifting. Researchers conclude that release of greenhouse gases causes global warming.

19.7 The Future of the Earth

Most of the discussion in this book has focused on the past, for the geologic record preserved in rocks tells us of earlier times. Let's now bring this book to a close by facing in the opposite direction and speculating what the world might look like in geologic time to come.

In the geologic near term, the future of the world depends largely on human activities. Whether the Earth System undergoes a major disruption and shifts to a new equilibrium, whether a catastrophic mass-extinction event takes place, or whether society achieves **sustainable growth** (an ability to prosper within the constraints of the Earth System) will depend on our own foresight and ingenuity.

Projecting thousands of years into the future, we might well wonder if the Earth will return to ice-age conditions, with glaciers growing over major cities and the continental shelf

becoming dry land, or if the ice age is over for good because of global warming. No one really knows for sure.

If we project millions of years into the future, it is clear that the map of the planet will change significantly because of the continuing activity of plate tectonics. For example, during the next 50 million years or so, the Atlantic Ocean will probably become bigger, the Pacific Ocean will shrink, and the western part of California will migrate northward. Eventually, Australia will crush against the southern margin of Asia, and the islands of Indonesia may be flattened in between.

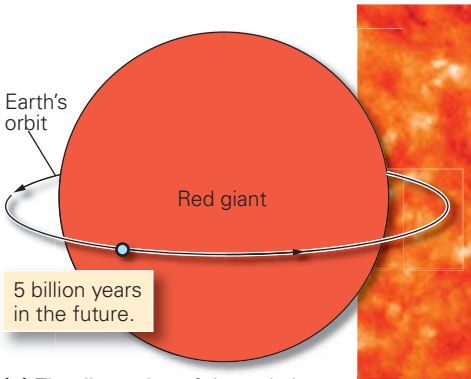
Predicting the map of the Earth hundreds of millions of years into the future is hard, because we don't know for sure where new subduction zones will develop. Perhaps subduction of the Pacific Ocean will lead to the collision of the Americas with Asia, to produce a supercontinent ("Amasia"). A subduction zone eventually will form on one side of the Atlantic Ocean, and the ocean will be consumed. As a consequence, the eastern margin of the Americas will likely collide with the western margin of Europe and Africa. The sites of major cities—New York, Miami, Rio de Janeiro, Buenos Aires, and London—will be incorporated into a collisional mountain belt, and likely will be subjected to metamorphism and igneous intrusion before being uplifted and eroded. Shallow seas may once again cover the interiors of continents and then later retreat, and glaciers may once again cover the continents—it happened in the past, so it could happen again. And if the past is the key to the future, we *Homo sapiens* might not be around to watch our cities enter the rock cycle, for biological evolution may have introduced new species to the biosphere, and there is no way to predict what these species will be like.

And what of the end of the Earth? Geologic catastrophes resulting from asteroid and comet collisions will undoubtedly occur in the future as they have in the past. We can't predict when the next strike will come, but unless the object can be diverted, Earth is in for another radical readjustment of surface conditions. But it's not likely that such collisions will destroy our planet. Rather, astronomers predict that the end of the Earth will occur some 5 billion years from now, when the Sun begins to run out of nuclear fuel. When this happens, thermal pressure caused by fusion reactions will no longer be able to prevent the Sun from collapsing inward, because of the immense gravitational pull of its mass. Were the Sun a few times larger than it is, the collapse would trigger a supernova explosion that would blast matter of the Universe out into space to form a new nebula, perhaps surrounding a black hole. But since the Sun is not that large, the thermal energy generated when its interior collapses inward will heat the gases of its outer layers sufficiently to cause them to expand. As a result, the Sun will become a red giant, a huge star (**Fig. 19.19a, b**). Our planet will then vaporize, and its atoms will join an expanding ring of gas—the ultimate global change. If this happens, the atoms that once formed Earth and all its inhabitants through geologic time may eventually be incorporated in a future solar system, where the cycle of planetary formation and evolution will begin anew.

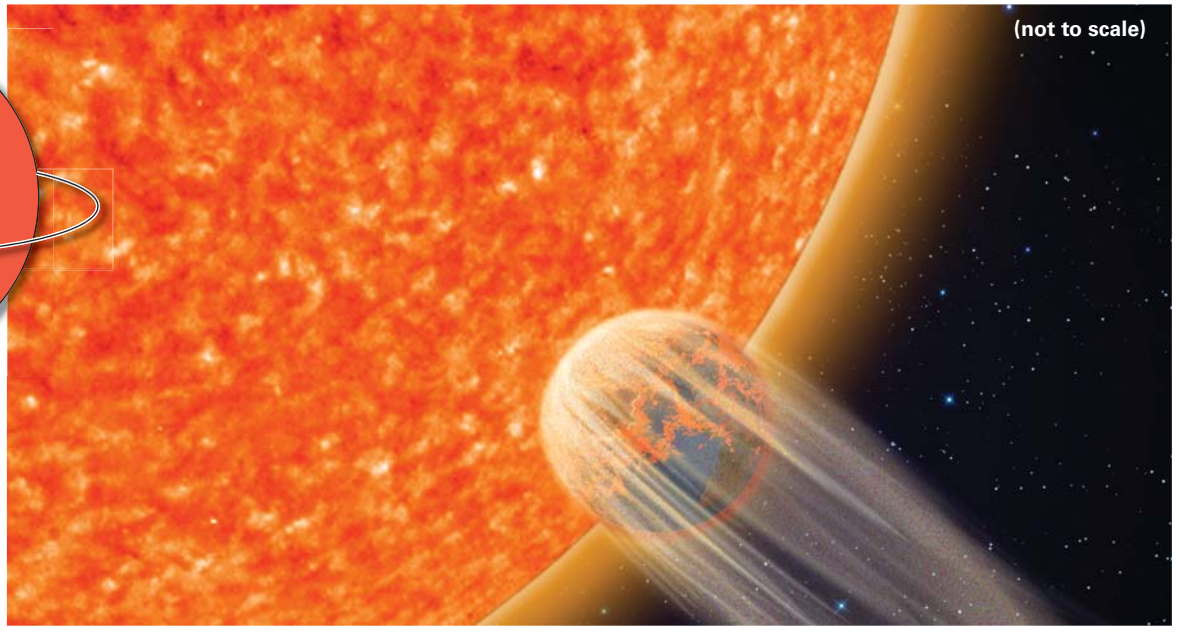
Take-Home Message

In the near term, Earth's surface will be affected by decisions of human society. Over longer time scales, the map of the Earth will change due to plate interactions and sea-level change. The end of the Earth will likely happen when the Sun becomes a red giant.

FIGURE 19.19 In about 5 billion years, the Sun will become a red giant. When that happens, the Earth will first dry out, then vaporize; initially, it may look like a giant comet.



(a) The dimension of the red giant relative to Earth's orbit.



(b) Earth heating up and evaporating.

CHAPTER 19 REVIEW

Chapter Summary

- We refer to the global interconnecting web of physical and biological phenomena on Earth as the Earth System. Global change involves the transformations or modifications of physical and biological components of the Earth System through time. Unidirectional change results in transformations that never repeat, whereas cyclic change involves repetition of the same steps over and over.
- Examples of unidirectional change include the gradual evolution of the solid Earth from a homogeneous collection of planetesimals to a layered planet, the formation of the oceans and the gradual change in the composition of the atmosphere, and the evolution of life.
- Examples of physical cycles that take place on Earth include the supercontinent cycle, the sea-level cycle, and the rock cycle.
- A biogeochemical cycle involves the passage of a chemical among nonliving and living reservoirs. Examples include the hydrologic cycle and the carbon cycle. Global change occurs when factors change the relative proportions of the chemical in different reservoirs.
- Tools for documenting global climate change include the stratigraphic record, paleontology, oxygen–isotope ratios, bubbles in ice, growth rings in trees, and human history.
- Studies of long-term climate change show that, at times in the past, the Earth experienced greenhouse (warmer) periods; at other times, there were icehouse (cooler) periods. Factors leading to long-term climate change include the positions of continents, volcanic activity, the uplift of land, and the addition or removal of CO_2, an important greenhouse gas.
- Short-term climate change can be seen in the record of the last million years. In fact, during only the past 15,000 years, we see that the climate has warmed and cooled a few times. Causes of short-term climate change include fluctuations in solar radiation and cosmic rays, changes in Earth's orbit and tilt, changes in reflectivity, and changes in ocean currents.
- Mass extinction, a catastrophic change in biodiversity, may be caused by the impact of a comet or asteroid or by intense volcanic activity associated with a superplume.
- During the last two centuries, humans have changed landscapes; modified ecosystems; and added pollutants to the land, air, and water at rates faster than the Earth System can process.
- The addition of CO_2 and CH_4 to the atmosphere appears to be causing global warming, which could shift climate belts and lead to a rise in sea level. Sources for the added CO_2 include fossil fuel burning, cement production, and deforestation.
- In the future, in addition to climate change, the Earth will witness a continued rearrangement of continents resulting from plate tectonics and will likely suffer the impact of asteroids and comets. The end of the Earth may come in about 5 billion years, when the Sun runs out of fuel and becomes a red giant.

Key Terms

acid rain (p. 558)
albedo (p. 555)
biogeochemical cycle (p. 550)
carbon capture and sequestration (p. 564)
climate (p. 551)
climate-change model (p. 551)
differentiation (p. 546)
ecosystem (p. 557)
feedback mechanism (p. 552)
general circulation model (p. 551)
global change (p. 546)
global climate change (p. 551)
global cooling (p. 551)
global warming (p. 551)
greenhouse effect (p. 552)
greenhouse gas (p. 552)
greenhouse (hothouse) period (p. 553)
icehouse period (p. 553)
mass-extinction event (p. 556)
ozone hole (p. 558)
paleoclimate (p. 552)
pollution (p. 558)
steady-state condition (p. 550)
supercontinent cycle (p. 547)
sustainable growth (p. 564)

Review Questions

1. Why do we use the term *Earth System* to describe the components of processes operating on this planet?
2. How have the Earth's crust and atmosphere changed since they first formed?
3. What processes control the rise and fall of sea level on Earth?
4. How does carbon cycle through the various Earth systems?
5. How do paleoclimatologists study ancient climate change?
6. Contrast icehouse and greenhouse conditions.
7. What are the possible causes of long-term climatic change?
8. What factors explain short-term climatic change?
9. Give some examples of events that cause catastrophic change.
10. Give some examples of how humans have changed the Earth.
11. What is the ozone hole, and how does it affect us?

smartwork smartwork.wwnorton.com

Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- A video-based exercise on how we measure the hole in the ozone layer.
- Drag-and-drop exercises on the carbon cycle.
- A problem that helps students calculate rates of deforestation.

12. Describe how CO_2-induced global warming takes place, and how humans may be responsible. What effects might global warming have on the Earth System?
13. What are some likely scenarios for the long-term future of the Earth?

On Further Thought

14. If global warming continues, how will the distribution of grain crops change? Might this affect national economies? Why?
15. Currently, tropical rain forests are being cut down at a rate of about 1.8% per year. At this rate, how many more years will the forests survive? In the eastern United States, the proportion of land with forest cover today has increased over the past century. In fact, most of the farmland that existed in New York State in 1850 is forestland today. Why? How might this change affect erosion rates in the region?
16. Using the library or the Web, examine the change in the nature of world fisheries that has taken place in the last 50 years. Is the world's fish biomass sustainable if these patterns continue? What has happened to whale populations during the past 50 years?

SEE FOR YOURSELF S. . . Global Change

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet R of our **Geotours Workbook**.



Deforestation, Amazon

Latitude 4°4′22.81″S,
Longitude 54°54′43.06″W

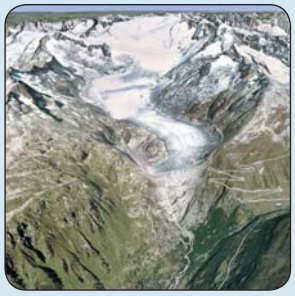
From 100 km, you can see the patchwork of fields that have been cut into the Amazon rainforest, south of the Amazon River in Brazil. Note the pattern of cutting—the fields border a grid of logging roads bulldozed across the landscape. Uncut forest remains in the upper left.



Urbanizing a Desert, Arizona

Latitude 33°33′18.59″N,
Longitude 111°49′25.19″W

Viewed from 9 km, you can see the intense change that the growing population of Phoenix causes in a desert. The central portion of the image shows a network of dry washes in the original desert. To the north, we see new housing developments and a water canal, and to the south, farmlands and a golf course. Water usage in the area has increased dramatically.



Receding Glacier, Switzerland

Latitude 46°34′48.75″N,
Longitude 8°22′58.53″E

Look NNE, obliquely across the landscape from 4 km. You can see a valley glacier near the town of Gletsch. The bare land down from the toe of the glacier was ice-covered a century ago. Note that the lateral moraine now lies like a bathtub ring high above the present-day ice surface, because the glacier has thinned.



Fields and Villages, China

Latitude 35°6′46.35″N,
Longitude 114°30′7.81″E

Look down from 4 km, and you see a landscape that has been completely altered by human society. What was once forest or grassland has been divided into cultivated rectangles. In villages, houses and roads cover the surface. These changes affect both the carbon cycle and the hydrologic cycle.

Metric Conversion Chart

Length

1 kilometer (km) = 0.6214 mile (mi)
1 meter (m) = 1.094 yards = 3.281 feet
1 centimeter (cm) = 0.3937 inch
1 millimeter (mm) = 0.0394 inch
1 mile (mi) = 1.609 kilometers (km)
1 yard = 0.9144 meter (m)
1 foot = 0.3048 meter (m)
1 inch = 2.54 centimeters (cm)

Area

1 square kilometer (km^2) = 0.386 square mile (mi^2)
1 square meter (m^2) = 1.196 square yards (yd^2)
= 10.764 square feet (ft^2)
1 square centimeter (cm^2) = 0.155 square inch (in^2)
1 square mile (mi^2) = 2.59 square kilometers (km^2)
1 square yard (yd^2) = 0.836 square meter (m^2)
1 square foot (ft^2) = 0.0929 square meter (m^2)
1 square inch (in^2) = 6.4516 square centimeters (cm^2)

Volume

1 cubic kilometer (km^3) = 0.24 cubic mile (mi^3)
1 cubic meter (m^3) = 264.2 gallons
= 35.314 cubic feet (ft^3)
1 liter (1) = 1.057 quarts
= 33.815 fluid ounces
1 cubic centimeter (cm^3) = 0.0610 cubic inch (in^3)
1 cubic mile (mi^3) = 4.168 cubic kilometers (km^3)
1 cubic yard (yd^3) = 0.7646 cubic meter (m^3)
1 cubic foot (ft^3) = 0.0283 cubic meter (m^3)
1 cubic inch (in^3) = 16.39 cubic centimeters (cm^3)

Mass

1 metric ton = 2,205 pounds
1 kilogram (kg) = 2.205 pounds
1 gram (g) = 0.03527 ounce
1 pound (lb) = 0.4536 kilogram (kg)
1 ounce (oz) = 28.35 grams (g)

Pressure

1 kilogram per square centimeter (kg/cm^2)* = 0.96784 atmosphere (atm)
= 0.98066 bar
= 9.8067×10^4 pascals (Pa)
1 bar = 10 megapascals (Mpa)
= 1.0×10^5 pascals (Pa)
= 29.53 inches of mercury (in a barometer)
= 0.98692 atmosphere (atm)
= 1.02 kilograms per square centimeter (kg/cm^2)
1 pascal (Pa) = 1 $kg/m/s^2$
1 pound per square inch = 0.06895 bars
= 6.895×10^3 pascals (Pa)
= 0.0703 kilogram per square centimeter

Temperature

To change from Fahrenheit (F) to Celsius (C):

$$°C = \frac{(°F - 32°)}{1.8}$$

To change from Celsius (C) to Fahrenheit (F):

$$°F = (°C \times 1.8) + 32°$$

To change from Celsius (C) to Kelvin (K):

$$K = °C + 273.15$$

To change from Fahrenheit (F) to Kelvin (K):

$$K = \frac{(°F - 32°)}{1.8} + 273.15$$

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*Note: Because kilograms are a measure of mass whereas pounds are a unit of weight, pressure units incorporating kilograms assume a given gravitational constant (g) for Earth. In reality, the gravitational for Earth varies slightly with location.

Alkali metals

Symbol — He 2 Helium 4.002 — Atomic number, Name, Atomic weight

Inert gases

Nonmetals

Transition elements (metals)

H 1 Hydrogen 1.007																	He 2 Helium 4.002
Li 3 Lithium 6.941	Be 4 Beryllium 9.0121											B 5 Boron 10.811	C 6 Carbon 12.011	N 7 Nitrogen 14.006	O 8 Oxygen 15.999	F 9 Fluorine 18.998	Ne 10 Neon 20.179
Na 11 Sodium 22.989	Mg 12 Magnesium 24.305											Al 13 Aluminum 26.981	Si 14 Silicon 28.085	P 15 Phosphorus 30.973	S 16 Sulfur 32.066	Cl 17 Chlorine 35.452	Ar 18 Argon 39.948
K 19 Potassium 39.098	Ca 20 Calcium 40.078	Sc 21 Scandium 44.955	Ti 22 Titanium 47.88	V 23 Vanadium 50.941	Cr 24 Chromium 51.996	Mn 25 Manganese 54.938	Fe 26 Iron 55.847	Co 27 Cobalt 58.933	Ni 28 Nickel 58.693	Cu 29 Copper 63.546	Zn 30 Zinc 65.39	Ga 31 Gallium 69.723	Ge 32 Germanium 72.61	As 33 Arsenic 74.921	Se 34 Selenium 78.96	Br 35 Bromine 79.904	Kr 36 Krypton 83.80
Rb 37 Rubidium 85.467	Sr 38 Strontium 87.62	Y 39 Yttrium 88.905	Zr 40 Zirconium 91.224	Nb 41 Niobium 92.906	Mo 42 Molybdenum 95.94	Tc 43 Technetium 98.907	Ru 44 Ruthenium 101.07	Rh 45 Rhodium 102.905	Pd 46 Palladium 106.42	Ag 47 Silver 107.868	Cd 48 Cadmium 112.411	In 49 Indium 114.82	Sn 50 Tin 118.710	Sb 51 Antimony 121.757	Te 52 Tellurium 127.60	I 53 Iodine 126.904	Xe 54 Xenon 131.29
Cs 55 Cesium 132.905	Ba 56 Barium 137.327	La 57 Lanthanum 138.905	Hf 72 Hafnium 178.49	Ta 73 Tantalum 180.947	W 74 Tungsten 183.85	Re 75 Rhenium 186.207	Os 76 Osmium 190.2	Ir 77 Iridium 192.22	Pt 78 Platinum 195.08	Au 79 Gold 196.966	Hg 80 Mercury 200.59	Tl 81 Thallium 204.383	Pb 82 Lead 207.2	Bi 83 Bismuth 208.980	Po 84 Polonium 208.982	At 85 Astatine 209.987	Rn 86 Radon 222.017
Fr 87 Francium 223.019	Ra 88 Radium 226.025	Ac 89 Actinium 227.027															

Ce 58 Cerium 140.115	Pr 59 Praseodymium 140.907	Nd 60 Neodymium 144.24	Pm 61 Promethium 144.912	Sm 62 Samarium 150.36	Eu 63 Europium 151.965	Gd 64 Gadolinium 157.25	Tb 65 Terbium 158.925	Dy 66 Dysprosium 162.50	Ho 67 Holmium 164.930	Er 68 Erbium 167.26	Tm 69 Thulium 168.934	Yb 70 Ytterbium 173.04	Lu 71 Lutetium 174.967
Th 90 Thorium 232.038	Pa 91 Protactinium 231.035	U 92 Uranium 238.028	Np 93 Neptunium 237.048	Pu 94 Plutonium 244.064	Am 95 Americium 243.061	Cm 96 Curium 247.070	Bk 97 Berkelium 247.070	Cf 98 Californium 251.079	Es 99 Einsteinium 252.083	Fm 100 Fermium 257.095	Md 101 Mendelevium 258.10	No 102 Nobelium 259.100	Lr 103 Lawrencium 262.11

The modern periodic table of the elements. Each column groups elelments with related properties. For example, inert gases are listed in the column on the right. metals are found in the central and left parts of the chart.

Glossary

a'a A lava flow with a rubbly surface.
abandoned meander A meander that dries out after it was cut off.
ablation The removal of ice at the toe of a glacier by melting, sublimation (the evaporation of ice into water vapor), and/or calving.
abrasion The process in which one material (such as sand-laden water) grinds away at another (such as a stream channel's floor and walls).
absolute age Numerical age (the age specified in years).
absolute plate velocity The movement of a plate relative to a fixed point in the mantle.
absolute zero The lowest temperature possible (–273.15°C); at absolute zero, vibrations and movements of atoms in a material cease.
abyssal plain A broad, relatively flat region of the ocean that lies at least 4.5 km below sea level.
Acadian orogeny A convergent mountain-building event that occurred around 400 million years ago, during which continental slivers accreted to the eastern edge of the North American continent.
accreted terrane A block of crust that collided with a continent at a convergent margin and stayed attached to the continent.
accretionary coast A coastline that receives more sediment than erodes away.
accretionary lapilli Hailstone-like clumps of wet ash that fall from a volcanic eruptive cloud.
accretionary orogen An orogen formed by the attachment of numerous buoyant slivers of crust to an older, larger continental block.
accretionary prism A wedge-shaped mass of sediment and rock scraped off the top of a downgoing plate and accreted onto the overriding plate at a convergent plate margin.
acid mine runoff A dilute solution of sulfuric acid, produced when sulfur-bearing minerals in mines react with rainwater, that flows out of a mine.
acid rain Precipitation in which air pollutants react with water to make a weak acid that then falls from the sky.
active continental margin A continental margin that coincides with a plate boundary.
active fault A fault that has moved recently or is likely to move in the future.
active sand The top layer of beach sand, which moves daily because of wave action.
active volcano A volcano that has erupted within the past few centuries and will likely erupt again.
adiabatic cooling The cooling of a body of air or matter without the addition or subtraction of thermal energy (heat).
adiabatic heating The warming of a body of air or matter without the addition or subtraction of heat.
advection A process of heat transfer in which heat is carried into a solid by a liquid or gas moving through fractures or pores in the solid.
aerosols Tiny solid particles or liquid droplets that remain suspended in the atmosphere for a long time.
aftershocks The series of smaller earthquakes that follow a major earthquake.
air The mixture of gases that make up the Earth's atmosphere.
air-fall tuff Tuff formed when ash settles gently from the air.
air mass A body of air, about 1,500 km across, that has recognizable physical characteristics.
air pressure The push that air exerts on its surroundings.
albedo The reflectivity of a surface.
Alleghenian orogeny The orogenic event that occurred about 270 million years ago when Africa collided with North America.
alloy A metal containing more than one type of metal atom.
alluvial fan A gently sloping apron of sediment dropped by an ephemeral stream at the base of a mountain in arid or semiarid regions.
alluvium Sorted sediment deposited by a stream.
alluvium-filled valley A valley whose floor fills with sediment.
Alpine-Himalayan chain The largest orogenic belt on Earth today, formed by collisions of the former Gondwana continents with the southern margins of Europe and Asia.
amber Hardened (fossilized) ancient sap or resin.
amphibolite facies A set of metamorphic mineral assemblages formed under intermediate pressures and temperatures.
amplitude The height of a wave from crest to trough.
Ancestral Rockies The late Paleozoic uplifts of the Rocky Mountain region; they eroded away long before the present Rocky Mountains formed.
angiosperm A flowering plant.
angle of repose The angle of the steepest slope that a pile of uncemented material can attain without collapsing from the pull of gravity.
angularity The degree to which grains have sharp or rounded edges or corners.
angular unconformity An unconformity in which the strata below were tilted or folded before the unconformity developed; strata below the unconformity therefore have a different tilt than strata above.
anhedral grains Crystalline mineral grains without well-formed crystal faces.
anion A negatively charged ion.
annual probability The likelihood that a flood of a given size or larger will happen at a specified locality during any given year.
Antarctic bottom water mass The mass of cold, dense water that sinks along the coast of Antarctica.
antecedent stream A stream that cuts across an uplifted mountain range; the stream must have existed before the range uplifted and must then have been able to downcut as fast as the land was rising.
anthracite coal Shiny black coal formed at temperatures between 200°C and 300°C. A high-rank coal.
anticline A fold with an arch-like shape in which the limbs dip away from the hinge.
anticyclone The clockwise flow of air around a high-pressure mass.
anticyclonic flow A circulation of air around a high-pressure region in the atmosphere; it rotates clockwise in the northern hemisphere.
Antler orogeny The Late Devonian mountain-building event in which slices of deep-marine strata were pushed eastward, up and over the shallow-water strata on the western coast of North America.

anvil cloud A large cumulonimbus cloud that spreads laterally at the tropopause to form a broad, flat top.
aphanitic A textural term for fine-grained igneous rock.
apparent polar-wander path A path on the globe along which a magnetic pole appears to have wandered over time; in fact, the continents drift, while the magnetic pole stays fairly fixed.
aquiclude Sediment or rock that transmits no water.
aquifer Sediment or rock that transmits water easily.
aquitard Sediment or rock that does not transmit water easily and therefore retards the motion of the water.
archaea A kingdom of "old bacteria," now commonly found in extreme environments like hot springs. (Also called archaeobacteria.)
Archean Eon The middle Precambrian eon.
Archimedes' principle The mass of the water displaced by a block of material equals the mass of the whole block of material.
arête A residual knife-edge ridge of rock that separates two adjacent cirques.
argillaceous sedimentary rock Sedimentary rock that contains abundant clay.
arkose A clastic sedimentary rock containing both quartz and feldspar grains.
arroyo The channel of an ephemeral stream; dry wash; wadi.
artesian spring A location where the ground surface intersects a natural fracture (joint) that taps a confined aquifer in which the pressure can drive the water to the surface.
artesian well A well in which water rises on its own.
artificial levee A man-made retaining wall to hold back a river from flooding.
ash *See* Volcanic ash.
ash fall Ash that falls to the ground out of an ash cloud.
ash flow An avalanche of ash that tumbles down the side of an explosively erupting volcano.
assimilation The process of magma contamination in which blocks of wall rock fall into a magma chamber and dissolve.
asteroid One of the fragments of solid material, left over from planet formation or produced by collision of planetesimals, that resides between the orbits of Mars and Jupiter.
asthenosphere The layer of the mantle that lies between 100–150 km and 350 km deep; the asthenosphere is relatively soft and can flow when acted on by force.
atm A unit of air pressure that approximates the pressure exerted by the atmosphere at sea level.
atmosphere A layer of gases that surrounds a planet.
atoll A coral reef that develops around a circular reef surrounding a lagoon.
atom The smallest piece of an element that has the properties of the element; it consists of a nucleus surrounded by an electron cloud.
atomic mass The amount of matter in an atom; roughly, it is the sum of the number of protons plus the number of neutrons in the nucleus.
atomic number The number of protons in the nucleus of a given element.
atomic weight The number of protons plus the number of neutrons in the nucleus of a given element. (Also known as atomic mass.)
aurora australis The same phenomenon as the aurora borealis, but in the southern hemisphere.
aurora borealis A ghostly curtain of varicolored light that appears across the night sky in the northern hemisphere when charged particles from the Sun interact with the ions in the ionosphere.
avalanche A turbulent cloud of debris mixed with air that rushes down a steep hill slope at high velocity; the debris can be rock and/or snow.
avalanche chute A downslope hillside pathway along which avalanches repeatedly fall, consequently clearing the pathway of mature trees.
avulsion The process in which a river overflows a natural levee and begins to flow in a new direction.
axial plane The imaginary surface that encompasses the hinges of successive layers of a fold.
axial trough A narrow depression that runs along a mid-ocean ridge axis.
axis An imaginary line around which an object spins.

backscattered light Atmospheric scattered sunlight that returns to space.
backshore zone The zone of beach that extends from a small step cut by high-tide swash to the front of the dunes or cliffs that lie farther inshore.
backswamp The low marshy region between the bluffs and the natural levees of a floodplain.
backwash The gravity-driven flow of water back down the slope of a beach.
bacteria A type of tiny prokaryotic single-celled organism.
bajada An elongate wedge of sediment formed by the overlap of several alluvial fans emerging from adjacent valleys.
Baltica A Paleozoic continent that included crust that is now part of today's Europe.
banded-iron formation (BIF) Iron-rich sedimentary layers consisting of alternating gray beds of iron oxide and red beds of iron-rich chert.
bar (1) A sheet or elongate lens or mound of alluvium; (2) a unit of air-pressure measurement approximately equal to 1 atm.
barchan dune A crescent-shaped dune whose tips point downwind.
barrier island An offshore sand bar that rises above the mean high-water level, forming an island.
barrier reef A coral reef that develops offshore, separated from the coast by a lagoon.
basal sliding The phenomenon in which meltwater accumulates at the base of a glacier, so that the mass of the glacier slides on a layer of water or on a slurry of water and sediment.
basalt A fine-grained, mafic, igneous rock.
base level The lowest elevation a stream channel's floor can reach at a given locality.
basement Older igneous and metamorphic rocks making up the Earth's crust beneath sedimentary cover.
basement uplift Uplift of basement rock by faults that penetrate deep into the continental crust.
base metals Metals that are mined but not considered precious. Examples include copper, lead, zinc, and tin.
basin A fold or depression shaped like a right-side-up bowl.
Basin and Range Province A broad, Cenozoic continental rift that has affected a portion of the western United States in Nevada, Utah, and Arizona; in this province, tilted fault blocks form ranges, and alluvium-filled valleys are basins.
batholith A vast composite, intrusive, igneous rock body up to several hundred km long and 100 km wide, formed by the intrusion of numerous plutons in the same region.
bathymetric map A map illustrating the shape of the ocean floor.
bathymetric profile A cross section showing ocean depth plotted against location.

bathymetry Variation in depth.
bauxite A residual mineral deposit rich in aluminum.
baymouth bar A sandspit that grows across the opening of a bay.
beach A gently sloping fringe of sediment along the shore.
beach drift The gradual migration of sand along a beach.
beach erosion The removal of beach sand caused by wave action and longshore currents.
beach face A steeply concave part of the foreshore zone formed where the swash of the waves actively scours the sand.
bedding Layering or stratification in sedimentary rocks.
bed load Large particles, such as sand, pebbles, or cobbles, that bounce or roll along a streambed.
bedrock Rock still attached to the Earth's crust.
Bergeron process Precipitation involving the growth of ice crystals in a cloud at the expense of water droplets.
berm A horizontal or landward-sloping terrace in the backshore zone of a beach that receives sediment during a storm.
Big Bang A cataclysmic explosion that scientists suggest represents the formation of the Universe; before this event, all matter and all energy were packed into one volumeless point.
biochemical sedimentary rock Sedimentary rock formed from material (such as shells) produced by living organisms.
biodiversity The number of different species that exist at a given time.
biofuel Gas or liquid fuel made from plant material (biomass). Examples of biofuel include alcohol (from fermented sugar), biodiesel from vegetable oil, and wood.
biogenic minerals Substances that meet the definition of a mineral and are produced naturally by organisms (e.g., calcite in shells).
biogeochemical cycle The exchange of chemicals between living and nonliving reservoirs in the Earth System.
biomass The amount of organic material in a specified volume.
bioremediation The injection of oxygen and nutrients into a contaminated aquifer to foster the growth of bacteria that will ingest or break down contaminants.
biosphere The region of the Earth and atmosphere inhabited by life; this region stretches from a few km below the Earth's surface to a few km above.
bioturbation The mixing of sediment by burrowing animals such as clams and worms.
bituminous coal Dull, black intermediate-rank coal formed at temperatures between 100°c and 200°C.
black-lung disease Lung disease contracted by miners from the inhalation of too much coal dust.
black smoker The cloud of suspended minerals formed where hot water spews out of a vent along a mid-ocean ridge; the dissolved sulfide components of the hot water instantly precipitate when the water mixes with seawater and cools.
blind fault A fault that does not intersect the ground surface.
block Large, angular pyroclastic fragments consisting of volcanic rock, broken up during the eruption.
blocking temperature The temperature below which isotopes in a mineral are no longer free to move, so the radiometric clock starts.
blocky lava Lava that is so viscous that it breaks into boulder-like blocks as it moves; typically, such lavas are andesitic or rhyolitic.
blowout A deep, bowl-like depression scoured out of desert terrain by a turbulent vortex of wind.
blue shift The phenomenon in which a source of light moving toward you appears to have a higher frequency.
body fossil A relict of an organism's body, preserved in rock.
body waves Seismic waves that pass through the interior of the Earth.
bog A wetland dominated by moss and shrubs.
bolide A solid extraterrestrial object such as a meteorite, comet, or asteroid that explodes in the atmosphere.
bornhardt An inselberg with a loaf geometry, like that of Uluru (Ayers Rock) in central Australia.
Bowen's reaction series The sequence in which different silicate minerals crystallize during the progressive cooling of a melt.
braided stream A sediment-choked stream consisting of entwined subchannels.
breaker A water wave in which water at the top of the wave curves over the base of the wave.
breakwater An offshore wall, built parallel or at an angle to the beach, that prevents the full force of waves from reaching a harbor.
breccia Coarse sedimentary rock consisting of angular fragments; or rock broken into angular fragments by faulting.
breeder reactor A nuclear reactor that produces its own fuel.
brine Water that is not fresh but is less salty than seawater; brine may be found in estuaries.
brittle deformation The cracking and fracturing of a material subjected to stress.
brittle-ductile transition (brittle-plastic transition) The depth above which materials behave brittlely and below which materials behave ductilely (plastically); this transition typically lies between a depth of 10 and 15 km in continental crustal rock, and 60 m deep in glacial ice.
buoyancy The upward force acting on an object immersed or floating in fluid; the tendency of an object to float when placed in a fluid.
burial metamorphism Metamorphism due only to the consequences of very deep burial.
butte A medium-sized, flat-topped hill in an arid region.

caldera A large circular depression with steep walls and a fairly flat floor, formed after an eruption as the center of the volcano collapses into the drained magma chamber below.
caliche A solid mass created where calcite cements the soil together. (Also called calcrete.)
calorie A unit of energy approximately equal to 4.2 joules; 1 calorie can raise the temperature of 1 gm of water by 1°C.
calving The breaking off of chunks of ice at the edge of a glacier.
Cambrian explosion of life The remarkable diversification of life, indicated by the fossil record, that occurred at the beginning of the Cambrian Period.
Canadian Shield A broad, low-lying region of exposed Precambrian rock in the Canadian interior.
canyon A trough or valley with steeply sloping walls, cut into the land by a stream.
capacity (of a stream) The total quantity of sediment a stream can carry.
capillary fringe The thin subsurface layer in which water molecules seep up from the water table by capillary action to fill pores.
carbonate rocks Rocks containing calcite and/or dolomite.
carbon-14 A radioactive isotope of the element carbon; the ratio of C^{14} to C^{12} can provide an isotopic date of organic carbon.
carbon-14 dating A radiometric dating process that can tell us the age of organic material containing carbon originally extracted from the atmosphere.
carbon sequestration The process of extracting carbon dioxide from sources (e.g., power plants) and sending it back underground to keep it out of the atmosphere and diminish the greenhouse effect.

cast Sediment that preserves the shape of a shell it once filled before the shell dissolved or mechanically weathered away.

catabatic winds Strong winds that form at the margin of a glacier where the warmer air above ice-free land rises and the cold, denser air from above the glaciers rushes in to take its place.

catastrophic change Change that takes place either instantaneously or rapidly in geologic time.

catchment *See* Drainage network.

cation A positively charged ion.

Celsius scale A metric-system measure of temperature in which the difference between the freezing point (0°C) and boiling point (100°C) of water is divided into 100 units; equivalent to centigrade scale.

cement Mineral material that precipitates from water and fills the spaces between grains, holding the grains together.

cementation The phase of lithification in which cement, consisting of minerals that precipitate from groundwater, partially or completely fills the spaces between clasts and attaches each grain to its neighbor.

Cenozoic Era The most recent era of the Phanerozoic Eon, lasting from 65 Ma up until the present.

chain reaction A self-perpetuating process in a nuclear reaction, whereby neutrons released during the fission trigger more fission.

chalk Very fine-grained limestone consisting of weakly cemented plankton shells.

change of state The process in which a material changes from one phase (liquid, gas, or solid) to another.

channel A trough dug into the ground surface by flowing water.

channeled scablands A barren, soil-free landscape in eastern Washington, scoured clean by a flood unleashed when a large glacial lake drained.

chatter marks Wedge-shaped indentations left on rock surfaces by glacial plucking.

chemical A material consisting of a distinct element or compound.

chemical bond The invisible link that holds together atoms in a molecule and/or in a crystal.

chemical formula The "recipe" that specifies the elements and their proportions in a compound.

chemical fossil Distinctive molecules or molecular fragments, formed from the remains of living organisms, that can be preserved in rock.

chemical reaction Interactions among atoms and/or molecules involving breaking or forming chemical bonds.

chemical sedimentary rocks Sedimentary rocks made up of minerals that precipitate directly from water solution.

chemical weathering The process in which chemical reactions alter or destroy minerals when rock comes in contact with water solutions and/or air.

chert A sedimentary rock composed of very fine-grained silica (cryptocrystalline quartz).

Chicxulub crater A circular excavation buried beneath younger sediment on the Yucatán Peninsula; geologists suggest that a meteorite landed there 65 Ma.

chimney (1) A conduit in a magma chamber in the shape of a long vertical pipe through which magma rises and erupts at the surface; (2) an isolated column of strata in an arid region.

chron The time interval between successive magnetic reversals.

cinder cone A subaerial volcano consisting of a cone-shaped pile of tephra whose slope approaches the angle of repose for tephra.

cinders Fragments of glassy rock ejected from a volcano.

cirque A bowl-shaped depression carved by a glacier on the side of a mountain.

cirrus cloud A wispy cloud that tapers into delicate, feather-like curls.

clast A fragment or grain produced by the physical or chemical weathering of a pre-existing rock.

clastic (detrital) sedimentary rock Sedimentary rock consisting of cemented-together detritus derived from the weathering of preexisting rock.

cleavage (1) The tendency of a mineral to break along preferred planes; (2) a type of foliation in low-grade metamorphic rock.

cleavage planes A series of surfaces on a crystal that form parallel to the weakest bonds holding the atoms of the crystal together.

cliff (scarp) retreat The change in the position of a cliff face caused by erosion.

climate The average weather conditions, along with the range of conditions, of a region over a year.

climate-change model A computer-generated model designed to provide insight into how climate changed in the past and may change in the future, and what the consequences of climate change may be.

cloud A mist of tiny water droplets in the sky.

coal A black, organic rock consisting of greater than 50% carbon; it forms from the buried and altered remains of plant material.

coalbed methane Natural gas created during the formation of coal, that gets trapped within the coal.

coal gasification The process of producing relatively clean-burning gases from solid coal.

coal rank A measurement of the carbon content of coal; higher-rank coal forms at higher temperatures.

coal reserve The quantities of discovered, but not yet mined, coal in sedimentary rock of the continents.

coal swamp A swamp whose oxygen-poor water allows thick piles of woody debris to accumulate; this debris transforms into coal upon deep burial.

coast The belt of land bordering the sea.

coastal plain Low-relief regions of land adjacent to the coast.

coastal wetland A flat-lying coastal area that floods during high tide and drains during low tide, and hosts salt-resistant plants.

cold front The boundary at which a cold air mass pushes underneath a warm air mass.

collision The process of two buoyant pieces of lithosphere converging and squashing together.

color The characteristic of a material due to the spectrum of light emitted or reflected by the material, as perceived by eyes or instruments.

columnar jointing A type of fracturing that yields roughly hexagonal columns of basalt; columnar joints form when a dike, sill, or lava flow cools.

comet A ball of ice and dust, probably remaining from the formation of the Solar System, that orbits the Sun.

compaction The phase of lithification in which the pressure of the overburden on the buried rock squeezes out water and air that was trapped between clasts, and the clasts press tightly together.

competence (of a stream) The maximum particle size a stream can carry.

composite volcano *See* Stratovolcano.

compositional banding A type of metamorphic foliation, found in gneiss, defined by alternating bands of light and dark minerals.

compound A material composed of two or more elements that cannot be separated mechanically; the smallest piece is a molecule.

compressibility The degree to which a material's volume changes in response to squashing.
compression A push or squeezing felt by a body.
compressional waves Waves in which particles of material move back and forth parallel to the direction in which the wave itself moves.
concentration The proportion of one substance (the solute) dissolved within another (the solvent).
conchoidal fractures Smoothly curving, clamshell-shaped surfaces along which materials with no cleavage planes tend to break.
condensation The process of gas molecules linking together to form a liquid.
condensation nuclei Preexisting solid or liquid particles, such as aerosols, onto which water condenses during cloud formation.
conduction A process of heat transfer involving progressive migration of thermal energy from cooler to warmer regions in a material, without the physical flow of the material itself.
cone of depression The downward-pointing, cone-shaped surface of the water table in a location where the water table is experiencing drawdown because of pumping at a well.
confined aquifer An aquifer that is separated from the Earth's surface by an overlying aquitard.
conglomerate Very coarse-grained sedimentary rock consisting of rounded clasts.
consuming boundary *See* Convergent plate boundary.
contact The boundary surface between two rock bodies (as between two stratigraphic formations, between an igneous intrusion and adjacent rock, between two igneous rock bodies, or between rocks juxtaposed by a fault).
contact metamorphism *See* Thermal metamorphism.
contaminant plume A cloud of contaminated groundwater that moves away from the source of the contamination.
continental crust The crust beneath the continents.
continental divide A highland separating drainage that flows into one ocean from drainage that flows into another.
continental-drift hypothesis The idea that continents have moved and are still moving slowly across the Earth's surface.
continental glacier A vast sheet of ice that spreads over thousands of square km of continental crust.
continental-interior desert An inland desert that develops because by the time air masses reach the continental interior, they have lost all of their moisture.
continental lithosphere Lithosphere topped by continental crust; this lithosphere reaches a thickness of 150 km.
continental margin A continent's coastline.
continental rift A linear belt along which continental lithosphere stretches and pulls apart.
continental rifting The process by which a continent stretches and splits along a belt; if it is successful, rifting separates a larger continent into two smaller continents separated by a divergent boundary.
continental rise The sloping sea floor that extends from the lower part of the continental slope to the abyssal plain.
continental shelf A broad, shallowly submerged fringe of a continent; ocean-water depth over the continental shelf is generally less than 200 meters; the widest continental shelves occur over passive margins.
continental slope The slope at the edge of a continental shelf, leading down to the deep sea floor.
continental volcanic arc A long, curving chain of subaerial volcanoes on the margin of a continent adjacent to a convergent plate boundary.
contour lines Lines on a map along which a parameter has a constant value; for example, all points along a contour line on a topographic map are at the same elevation.
control rod Rods that absorb neutrons in a nuclear reactor and thus decrease the number of collisions between neutrons and radioactive atoms.
convection Heat transfer that results when warmer, less dense material rises while cooler, denser material sinks.
convective cell A distinct flow configuration for a volume of material that is moving during convective heat transport; simplistically, the material rises when warm and sinks when cool, and thus follows a loop-like path.
convergence zone A place where two surface air flows meet so that air has to rise.
convergent margin *See* Convergent plate boundary.
convergent plate boundary A boundary at which two plates move toward each other so that one plate sinks (subducts) beneath the other; only oceanic lithosphere can subduct.
coral reef A mound of coral and coral debris forming a region of shallow water.
core The dense, iron-rich center of the Earth.
core-mantle boundary An interface 2,900 km below the Earth's surface separating the mantle and core.
Coriolis effect The deflection of objects, winds, and currents on the surface of the Earth owing to the planet's rotation.
cornice A huge, overhanging drift of snow built up by strong winds at the crest of a mountain ridge.
correlation The process of defining the age relations between the strata at one locality and the strata at another.
cosmic rays Nuclei of hydrogen and other elements that bombard the Earth from deep space.
cosmology The study of the overall structure of the Universe.
country rock (wall rock) The preexisting rock into which magma intrudes.
covalent bonding The attachment of one atom to another that develops when the atoms share electrons; one type of chemical bond.
crater (1) A circular depression at the top of a volcanic mound; (2) a depression formed by the impact of a meteorite.
craton A long-lived block of durable continental crust commonly found in the stable interior of a continent.
cratonic platform A province in the interior of a continent in which Phanerozoic strata bury most of the underlying Precambrian rock.
creep The gradual downslope movement of regolith.
crevasse A large crack that develops by brittle deformation in the top 60 m of a glacier.
critical mass A sufficiently dense and large mass of radioactive atoms in which a chain reaction happens so quickly that the mass explodes.
cross bed Internal laminations in a bed, inclined at an angle to the main bedding; cross beds are a relict of the slip face of dunes or ripples.
cross section A diagram depicting the geometry of materials underground as they would appear on an imaginary vertical slice through the Earth.
crude oil Oil extracted directly from the ground.
crust The rock that makes up the outermost layer of the Earth.
crustal root Low-density crustal rock that protrudes downward beneath a mountain range.

crustal thickening The process by which the continental crust increases in thickness, becoming up to 70 km thick (vs. normal thickness of about 35–40 km); it can occur during continental collision.
crystal A single, continuous piece of a mineral bounded by flat surfaces that formed naturally as the mineral grew.
crystal face The flat surfaces of a crystal, formed during the crystal's growth.
crystal form The geometric shape of a crystal, defined by the arrangement of crystal faces.
crystal habit The general shape of a crystal or cluster of crystals that grew unimpeded.
crystal lattice The orderly framework within which the atoms or ions of a mineral are fixed.
crystal structure The arrangement of atoms in a crystal.
crystalline Containing a crystal lattice.
crystalline igneous rock A rock that consists of minerals that grew when a melt solidified, and eventually interlock like pieces of a jigsaw puzzle.
cuesta An asymmetric ridge formed by tilted layers of rock, with a steep cliff on one side cutting across the layers and a gentle slope on the other side; the gentle slope is parallel to the layering.
cumulonimbus cloud A rain-producing, puffy cloud.
cumulus cloud A puffy, cotton-ball-shaped cloud.
current (1) A well-defined stream of ocean water; (2) the moving flow of water in a stream.
cut bank The outside bank of the channel wall of a meander, which is continually undergoing erosion.
cutoff A straight reach in a stream that develops when erosion eats through a meander neck.
cyanobacteria Blue-green algae; a type of archaea.
cycle A series of interrelated events or steps that occur in succession and can be repeated, perhaps indefinitely.
cyclone (1) The counterclockwise flow of air around a low-pressure mass; (2) the equivalent of a hurricane in the Indian Ocean.
cyclonic flow A circulation of air around a low-pressure region in the atmosphere; it rotates counterclockwise in the northern hemisphere.
cyclothem A repeated interval within a sedimentary sequence that contains a specific succession of sedimentary beds.

Darcy's law A mathematical equation stating that a volume of water, passing through a specified area of material at a given time, depends on the material's permeability and hydraulic gradient.
daughter isotope The decay product of radioactive decay.
day The time it takes for the Earth to spin once on its axis.
debris avalanche An avalanche in which the falling debris consists of rock fragments and dust.
debris flow A downslope movement of mud mixed with larger rock fragments.
debris slide A sudden downslope movement of material consisting only of regolith.
decompression melting The kind of melting that occurs when hot mantle rock rises to shallower depths in the Earth so that pressure decreases while the temperature remains unchanged.
deep current An ocean current at a depth greater than 100 m.
deep-focus earthquake An earthquake that occurs at a depth between 300 and 670 km; below 670 km, earthquakes do not happen.
deflation The process of lowering the land surface by wind abrasion.
deformation A change in the shape, position, or orientation of a material, by bending, breaking, or flowing.
dehydration Loss of water.
delamination (plate tectonics) The process by which dense lithospheric mantle separates from the base of a plate and sinks into the mantle.
delta A wedge of sediment formed at a river mouth when the running water of the stream enters standing water, the current slows, the stream loses competence, and sediment settles out.
delta plain The low, swampy land on the surface of a delta.
delta-plain flood A flood in which water submerges a delta plain.
dendritic network A drainage network whose interconnecting streams resemble the pattern of branches connecting to a deciduous tree.
dendrochronologist A scientist who analyzes tree rings to determine the geologic age of features.
density Mass per unit volume.
denudation The removal of rock and regolith from the Earth's surface.
deposition The process by which sediment settles out of a transporting medium.
depositional environment A setting in which sediments accumulate; its character (fluvial, deltaic, reef, glacial, etc.) reflects local conditions.
depositional landform A landform resulting from the deposition of sediment where the medium carrying the sediment evaporates, slows down, or melts.
desert A region so arid that it contains no permanent streams, except for those that bring water in from elsewhere, and has very sparse vegetation cover.
desertification The process of transforming nondesert areas into desert.
desert pavement A mosaic-like stone surface forming the ground in a desert.
desert varnish A dark, rusty-brown coating of iron oxide and magnesium oxide that accumulates on the surface of the rock.
detachment fault A nearly horizontal fault at the base of a fault system.
detritus The chunks and smaller grains of rock broken off outcrops by physical weathering.
dewpoint temperature The temperature at which air becomes saturated so that dew can form.
diagenesis All of the physical, chemical, and biological processes that transform sediment into sedimentary rock and that alter the rock after the rock has formed.
differential stress A condition causing a material to experience a push or pull in one direction of a greater magnitude than the push or pull in another direction; in some cases, differential stress can result in shearing.
differential weathering What happens when different rocks in an outcrop undergo weathering at different rates.
differentiation (of a planet) A process early in a planet's history during which dense iron alloy melted and sank downward to form the core, leaving less-dense mantle behind.
diffraction The splitting of light into many tiny beams that interfere with one another.
digital elevation map (DEM) A computer-produced portrayal of elevation differences commonly using shading to simulate shadows; the data used to produce the map assigns elevations to each point on the map.
dike A tabular (wall-shaped) intrusion of rock that cuts across the layering of country rock.

dimension stone An intact block of granite or marble to be used for architectural purposes.
dip The angle of a plane's slope as measured in a vertical plane perpendicular to the strike.
dipole A magnetic field with a north and south pole, like that of a bar magnet.
dipole field (for Earth) The part of the Earth's magnetic field, caused by the flow of liquid iron alloy in the outer core, that can be represented by an imaginary bar magnet with a north and south pole.
dip-slip fault A fault in which sliding occurs up or down the slope (dip) of the fault.
dip slope A hill slope underlain by bedding parallel to the slope.
directional drilling The process of controlling the trajectory of a drill bit to make sure that the drill hole goes exactly where desired.
disappearing stream A stream that intersects a crack or sinkhole leading to an underground cavern, so that the water disappears into the subsurface and becomes an underground stream.
discharge The volume of water in a conduit or channel passing a point in 1 second.
discharge area A location where groundwater flows back up to the surface and may emerge at springs.
disconformity An unconformity parallel to the two sedimentary sequences it separates.
displacement (offset) The amount of movement or slip across a fault plane.
disseminated deposit A hydrothermal ore deposit in which ore minerals are dispersed throughout a body of rock.
dissolution A process during which materials dissolve in water.
dissolved load Ions dissolved in a stream's water.
distillation column A vertical pipe in which crude oil is separated into several components.
distributaries The fan of small streams formed where a river spreads out over its delta.
divergence zone A place where sinking air separates into two flows that move in opposite directions.
divergent plate boundary A boundary at which two lithosphere plates move apart from each other; they are marked by mid-ocean ridges.
diversification The development of many different species.
DNA (deoxyribonucleic acid) The complex molecule, shaped like a double helix, containing the code that guides the growth and development of an organism.
doldrums A belt with very slow winds along the equator.
dome Folded or arched layers with the shape of an overturned bowl.
Doppler effect The phenomenon in which the frequency of wave energy appears to change when a moving source of wave energy passes an observer.
dormant volcano A volcano that has not erupted for hundreds to thousands of years but does have the potential to erupt again in the future.
downcutting The process in which water flowing through a channel cuts into the substrate and deepens the channel relative to its surroundings.
downdraft Downward-moving air.
downgoing plate (slab) A lithosphere plate that has been subducted at a convergent margin.
downslope force The component of the force of gravity acting in the downslope direction.
downslope movement The tumbling or sliding of rock and sediment from higher elevations to lower ones.
downwelling zone A place where near-surface water sinks.
drag fold A fold that develops in layers of rock adjacent to a fault during or just before slip.
drainage divide A highland or ridge that separates one watershed from another.
drainage network (basin) An array of interconnecting streams that together drain an area.
drainage reversal When the overall direction of flow in a drainage network becomes the opposite of what it once had been.
drawdown The phenomenon in which the water table around a well drops because the users are pumping water out of the well faster than it flows in from the surrounding aquifer.
drilling mud A slurry of water mixed with clay that oil drillers use to cool a drill bit and flush rock cuttings up and out of the hole.
dripstone Limestone (travertine in a cave) formed by the precipitation of calcium carbonate out of groundwater.
dropstone A rock that drops to the sea floor once the iceberg that was carrying the rock melts.
drumlin A streamlined, elongate hill formed when a glacier overrides glacial till.
dry-bottom (polar) glacier A glacier so cold that its base remains frozen to the substrate.
dry wash The channel of an ephemeral stream when empty of water.
dry well (1) A well that does not supply water because the well has been drilled into an aquitard or into rock that lies above the water table; (2) a well that does not yield oil, even though it has been drilled into an anticipated reservoir.
ductile (plastic) deformation The bending and flowing of a material (without cracking and breaking) subjected to stress.
dune A pile of sand generally formed by deposition from the wind.
dust storm An event in which strong winds hit unvegetated land, strip off the topsoil, and send it skyward to form rolling dark clouds that block out the Sun.
dynamic metamorphism Metamorphism that occurs as a consequence of shearing alone, with no change in temperature or pressure.
dynamo A power plant generator in which water or wind power spins an electrical conductor around a permanent magnet.
dynamothermal metamorphism Metamorphism that involves heat, pressure, and shearing.

earthquake A vibration caused by the sudden breaking or frictional sliding of rock in the Earth.
earthquake belt A relatively narrow, distinct belt of earthquakes that defines the position of a plate boundary.
earthquake engineering The design of buildings that can withstand shaking.
earthquake warning system A communications network that provides an alert within microseconds after the first earthquake waves arrive at a seismograph near the epicenter, but before damaging vibrations reach population centers.
earthquake zoning The determination of where land is relatively stable and where it might collapse because of seismicity.
Earth System The global interconnecting web of physical and biological phenomena involving the solid Earth, the hydrosphere, and the atmosphere.
ebb tide The falling tide.
eccentricity cycle The cycle of the gradual change of the Earth's orbit from a more circular to a more elliptical shape; the cycle takes around 100,000 years.
ecliptic The plane defined by a planet's orbit.
ecosystem An environment and its inhabitants.

eddy An isolated, ring-shaped current of water.
Ediacaran fauna Multicellular invertebrate organisms that lived perhaps as early as 620 Ma and certainly by 565 Ma. They were named for a region in southern Australia.
effusive eruption An eruption that yields mostly lava, not ash.
Ekman spiral The change in flow direction of water with depth, caused by the Coriolis effect.
Ekman transport The overall movement of a mass of water, resulting from the Eckman spiral, in a direction 90° to the wind direction.
elastic-rebound theory The concept that earthquakes happen because stress builds up, causing rock adjacent to a fault to bend elastically until breaking and slip on a fault occurs; the slip relaxes the elastic bending and decreases stress.
elastic strain A change in shape of a material; the change disappears instantly when stress is removed.
electromagnet An electrical device that produces a magnetic field.
electron A negatively charged subatomic particle that orbits the nucleus of an atom; electrons are about 0.0005 × the size of a proton.
electron microprobe A laboratory instrument that can focus a beam of electrons on a small part of a mineral grain in order to create a signal that defines its chemical composition.
element A material consisting entirely of one kind of atom; elements cannot be subdivided or changed by chemical reactions.
El Niño The flow of warm water eastward from the Pacific Ocean that reverses the upwelling of cold water along the western coast of South America and causes significant global changes in weather patterns.
embayment A low area of coastal land.
emergent coast A coast where the land is rising relative to sea level or sea level is falling relative to the land.
end moraine (terminal moraine) A low, sinuous ridge of till that develops when the terminus (toe) of a glacier stalls in one position for a while.
energy The capacity to do work.
energy resource Something that can be used to produce work; in a geologic context, a material (such as oil, coal, wind, flowing water) that can be used to produce energy.
eon The largest subdivision of geologic time.
epeirogenic movement The gradual uplift or subsidence of a broad region of the Earth's surface.
epeirogeny An event of epeirogenic movement; the term is usually used in reference to the formation of broad mid-continent domes and basins.
ephemeral (intermittent) stream A stream whose bed lies above the water table, so that the stream flows only when the rate at which water enters the stream from rainfall or meltwater exceeds the rate at which water infiltrates the ground below.
epicenter The point on the surface of the Earth directly above the focus of an earthquake.
epicontinental sea A shallow sea overlying a continent.
epoch An interval of geologic time representing the largest subdivision of a period.
equant A term for a grain that has the same dimensions in all directions.
equatorial low The area of low pressure that develops over the equator because of the intertropical convergence zone.
equilibrium line (of a glacier) The boundary between the zone of accumulation and the zone of ablation.
equinox One of two days out of the year (September 22 and March 21) in which the Sun is directly overhead at noon at the equator.
era An interval of geologic time representing the largest subdivision of the Phanerozoic Eon.
erg Sand seas formed by the accumulation of dunes in a desert.
erosion The grinding away and removal of Earth's surface materials by moving water, air, or ice.
erosional coast A coastline where sediment is not accumulating and wave action grinds away at the shore.
erosional landform A landform that results from the breakdown and removal of rock or sediment.
erratic A boulder or cobble that was picked up by a glacier and deposited hundreds of kilometers away from the outcrop from which it detached.
eruptive style The character of a particular volcanic eruption; geologists name styles based on typical examples (e.g., Hawaiian, Strombolian).
esker A ridge of sorted sand and gravel that snakes across a ground moraine; the sediment of an esker was deposited in subglacial meltwater tunnels.
estuary An inlet in which seawater and river water mix; created when a coastal valley is flooded because of either rising sea level or land subsidence.
Eubacteria The kingdom of "true bacteria."
euhedral crystal A crystal whose faces are well formed and whose shape reflects crystal form.
eukaryote An organism whose cells contain a nucleus; all plants and animals consist of eukaryotic cells.
eukaryotic cell A cell with a complex internal structure, capable of building multicellular organisms.
eustatic sea-level change A global rising or falling of the ocean surface.
evaporate To change from liquid to vapor.
evaporite Thick salt deposits that form as a consequence of precipitation from saline water.
evapotranspiration The sum of evaporation from bodies of water and the ground surface and transpiration from plants and animals.
exfoliation The process by which an outcrop of rock splits apart into onion-like sheets along joints that lie parallel to the ground surface.
exhumation The process (involving uplift and erosion) that returns deeply buried rocks to the surface.
exotic terrane A block of land that collided with a continent along a convergent margin and attached to the continent; the term exotic implies that the land was not originally part of the continent to which it is now attached.
expanding Universe theory The theory that the whole Universe must be expanding because galaxies in every direction seem to be moving away from us.
explosive eruptions Violent volcanic eruptions that produce clouds and avalanches of pyroclastic debris.
external process A geomorphologic process—such as downslope movement, erosion, or deposition—that is the consequence of gravity or of the interaction between the solid Earth and its fluid envelope (air and water). Energy for these processes comes from gravity and sunlight.
extinction The death of the last members of a species so that there are no parents to pass on their genetic traits to offspring.
extinct volcano A volcano that was active in the past but has now shut off entirely and will not erupt in the future.
extraordinary fossil A rare fossilized relict, or trace, of the soft part of an organism.

extratropical cyclone (wave cyclone, mid-latitude cyclone) A large, rotating storm system, in mid-latitudes, associated with a regional-scale low-pressure zone.
extrusive igneous rock Rock that forms by the freezing of lava above ground, after it flows or explodes out (extrudes) onto the surface and comes into contact with the atmosphere or ocean.
eye The relative calm in the center of a hurricane.
eye wall A rotating vertical cylinder of clouds surrounding the eye of a hurricane.

facet (of a gem) The ground and polished surface of a gem, produced by a gem cutter using a grinding lap.
facies (1) Sedimentary: a group of rocks and primary structures indicative of a given depositional environment; (2) metamorphic: a set of metamorphic mineral assemblages formed under a given range of pressures and temperatures.
Fahrenheit scale An English-system measure of temperature in which the difference between the freezing point (32°F) and the boiling point (212°F) is divided into 180 units.
failure surface A weak surface that forms the base of a landslide.
faint young Sun paradox The apparent contradiction implied by the fact that much of the Earth's surface temperature has remained above the melting point of water during the past 4 Ga, even though calculations indicate that the Sun produced much less energy when young.
fault A fracture on which one body of rock slides past another.
fault-block mountains An outdated term for a narrow, elongate range of mountains that develops in a continental-rift setting as normal faulting drops down blocks of crust or tilts blocks.
fault breccia Fragmented rock in which angular fragments were formed by brittle fault movement; fault breccia occurs along a fault.
fault creep Gradual movement along a fault that occurs in the absence of an earthquake.
fault gouge Pulverized rock consisting of fine powder that lies along fault surfaces; gouge forms by crushing and grinding.
faulting Slip events along a fault.
fault scarp A small step on the ground surface where one side of a fault has moved vertically with respect to the other.
fault system A grouping of numerous related faults.
fault trace (fault line) The intersection between a fault and the ground surface.
feedback mechanism A condition that arises when the consequence of a phenomenon influences the phenomenon itself.
felsic An adjective used in reference to igneous rocks that are rich in elements forming feldspar and quartz.
Ferrel cells The name given to the middle-latitude convection cells in the atmosphere.
fetch The distance across a body of water along which a wind blows to build waves.
field force A push or pull that applies across a distance (i.e., without contact between objects); examples are gravity and magnetism.
fine-grained A textural term for rock consisting of many fine grains or clasts.
firn Compacted granular ice (derived from snow) that forms where snow is deeply buried; if buried more deeply, firn turns into glacial ice.
fission A nuclear reaction during which the nucleus of a large atom splits to form two nuclei of smaller atoms; the process also releases neutrons and energy.
fission track A line of damage formed in the crystal lattice of a mineral by the impact of an atomic particle ejected during the decay of a radioactive isotope.
fissure A conduit in a magma chamber in the shape of a long crack through which magma rises and erupts at the surface.
fjord A deep, glacially carved, U-shaped valley flooded by rising sea level.
flank eruption An eruption that occurs when a secondary chimney, or fissure, breaks through the flank of a volcano.
flash flood A flood that occurs during unusually intense rainfall or as the result of a dam collapse, during which the floodwaters rise very fast.
flexing The process of folding in which a succession of rock layers bends and slip occurs between the layers.
flocculation The clumping together of clay suspended in river water into bunches that are large enough to settle out.
flood An event during which the volume of water in a stream becomes so great that it covers areas outside the stream's normal channel.
flood basalt Vast sheets of basalt that spread from a volcanic vent over an extensive surface of land; they may form where a rift develops above a continental hot spot, and where lava is particularly hot and has low viscosity.
flood-hazard map A representation of a portion of the Earth's surface that is designed to show how the danger of flooding varies with location.
floodplain The flat land on either side of a stream that becomes covered with water during a flood.
floodplain flood A flood during which a floodplain is submerged.
flood stage The stage when water reaches the top of a stream channel.
flood tide The rising tide.
floodway A mapped region likely to be flooded, in which people avoid constructing buildings.
flow fold A fold that forms when the rock is so soft that it behaves like weak plastic.
flowstone A sheet of limestone that forms along the wall of a cave when groundwater flows along the surface of the wall.
fluvial deposit Sediment deposited in a stream channel, along a stream bank, or on a floodplain.
flux Flow.
flux melting The transformation of hot solid to liquid that occurs when a volatile material injects into the solid.
focus The location where a fault slips during an earthquake (hypocenter).
fog A cloud that forms at ground level.
fold A bend or wrinkle of rock layers or foliation; folds form as a consequence of ductile deformation.
fold axis An imaginary line that, when moved parallel to itself, can trace out the shape of a folded surface.
fold-thrust belt An assemblage of folds and related thrust faults that develop above a detachment fault.
foliation Layering formed as a consequence of the alignment of mineral grains, or of compositional banding in a metamorphic rock.
foraminifera Microscopic plankton with calcitic shells, components of some limestones.
foreland sedimentary basin A basin located under the plains adjacent to a mountain front, which develops as the weight of the mountains pushes the crust down, creating a depression that traps sediment.
foreshocks The series of smaller earthquakes that precede a major earthquake.
foreshore zone The zone of beach regularly covered and uncovered by rising and falling tides.

formation *See* Stratigraphic formation.
fossil The remnant, or trace, of an ancient living organism that has been preserved in rock or sediment.
fossil assemblage A group of fossil species found in a specific sequence of sedimentary rock.
fossil correlation A determination of the stratigraphic relation between two sedimentary rock units, reached by studying fossils.
fossil fuel An energy resource such as oil or coal that comes from organisms that lived long ago and thus stores solar energy that reached the Earth then.
fossiliferous limestone Limestone consisting of abundant fossil shells and shell fragments.
fossilization The process of forming a fossil.
fractional crystallization The process by which a magma becomes progressively more silicic as it cools, because early-formed crystals settle out.
fracture zone A narrow band of vertical fractures in the ocean floor; fracture zones lie roughly at right angles to a mid-ocean ridge, and the actively slipping part of a fracture zone is a transform fault.
fragmental igneous rock A rock consisting of igneous chunks and/or shards that are packed together, welded together, or cemented together after having solidified.
frequency The number of waves that pass a point in a given time interval.
fresh rock Rock whose mineral grains have their original composition and shape.
friction Resistance to sliding on a surface.
fringing reef A coral reef that forms directly along the coast.
front The boundary between two air masses.
frost wedging The process in which water trapped in a joint freezes, forces the joint open, and may cause the joint to grow.
fuel rod A metal tube that holds the nuclear fuel in a nuclear reactor.
Fujita scale A scale that distinguishes among tornadoes on the basis of wind speed, path dimensions, and possible damage.
fusion A type of nuclear reaction during which nuclei collide and bond; fusion occurs in stars and hydrogen bombs.

Ga Billions of years ago (abbreviation).
gabbro A coarse-grained, intrusive, mafic igneous rock.
Gaia The term used for the Earth System, with the implication that it resembles a complex living entity.
galaxy An immense system of hundreds of billions of stars.
gem A finished (cut and polished) gemstone ready to be set in jewelry.
gemstone A mineral that has special value because it is rare and people consider it beautiful.
gene An individual component of the DNA code that guides the growth and development of an organism.
general circulation model A numerical calculation that simulates the flow of the atmosphere and resulting phenomena, due to changes in atmospheric temperature and other parameters.
genetics The study of genes and how they transmit information.
geocentric Universe concept An ancient Greek idea suggesting that the Earth sat motionless in the center of the Universe while stars and other planets and the Sun orbited around it.
geochronology The science of dating geologic events in years.
geode A cavity in which euhedral crystals precipitate out of water solutions passing through a rock.
geographical pole The locations (north and south) where the Earth's rotational axis intersects the planet's surface.
geologic column A composite stratigraphic chart that represents the entirety of the Earth's history.
geologic history The sequence of geologic events that has taken place in a region.
geologic map A map showing the distribution of rock units and structures across a region.
geologic time The span of time since the formation of the Earth.
geologic time scale A scale that describes the intervals of geologic time.
geology The study of the Earth, including our planet's composition, behavior, and history.
geotherm The change in temperature with depth in the Earth.
geothermal energy Heat and electricity produced by using the internal heat of the Earth.
geothermal gradient The rate of change in temperature with depth.
geothermal region A region of current or recent volcanism in which magma or very hot rock heats up groundwater, which may discharge at the surface in the form of hot springs and/or geysers.
geyser A fountain of steam and hot water that erupts periodically from a vent in the ground in a geothermal region.
giant planets The four outer, or Jovian, planets of our Solar System, which are significantly larger than the rest of the planets and consist largely of gas and/or ice.
glacial abrasion The process by which clasts embedded in the base of a glacier grind away at the substrate as the glacier flows.
glacial advance The forward movement of a glacier's toe when the supply of snow exceeds the rate of ablation.
glacial drift Sediment deposited in glacial environments.
glacial incorporation The process by which flowing ice surrounds and incorporates debris.
glacial marine Sediment consisting of ice-rafted clasts mixed with marine sediment.
glacial outwash Coarse sediment deposited on a glacial outwash plain by meltwater streams.
glacially polished surface A polished rock surface created by the glacial abrasion of the underlying substrate.
glacial plucking (glacial quarrying) The process by which a glacier breaks off and carries away fragments of bedrock.
glacial rebound The process by which the surface of a continent rises back up after an overlying continental ice sheet melts away and the weight of the ice is removed.
glacial retreat The movement of a glacier's toe back toward the glacier's origin; glacial retreat occurs if the rate of ablation exceeds the rate of supply.
glacial striation Grooves or scratches cut into bedrock when clasts embedded in the moving glacier act like the teeth of a giant rasp.
glacial subsidence The sinking of the surface of a continent caused by the weight of an overlying glacial ice sheet.
glacial till Sediment transported by flowing ice and deposited beneath a glacier or at its toe.
glaciation (glacial period) A portion of an ice age during which huge glaciers grew and covered substantial areas of the continents.
glacier A river or sheet of ice that slowly flows across the land surface and lasts all year long.
glass A solid in which atoms are not arranged in an orderly pattern.
glassy igneous rock Igneous rock consisting entirely of glass, or of tiny crystals surrounded by a glass matrix.
glide horizon The surface along which a slump slips.
global change The transformations or modifications of both physical and biological components of the Earth System through time.

global circulation The movement of volumes of air in paths that ultimately take it around the planet.
global climate change Transformations or modifications in Earth's climate over time.
global cooling A fall in the average atmospheric temperature.
global positioning system (GPS) A satellite system people can use to measure rates of movement of the Earth's crust relative to one another, or simply to locate their position on the Earth's surface.
global warming A rise in the average atmospheric temperature.
gneiss A compositionally banded metamorphic rock typically composed of alternating dark- and light-colored layers.
Gondwana A supercontinent that consisted of today's South America, Africa, Antarctica, India, and Australia. (Also called Gondwanaland.)
graben A down-dropped crustal block bounded on either side by a normal fault dipping toward the basin.
grade (of an ore) The concentration of a useful metal in an ore—the higher the concentration, the higher the grade.
graded bed A layer of sediment, deposited by a turbidity current, in which grain size varies from coarse at the bottom to fine at the top.
graded stream A stream that has attained an equilibrium longitudinal profile in which the sediment input into an area equals sediment removal.
gradualism The theory that evolution happens at a constant, slow rate.
grain A fragment of a mineral crystal or of a rock.
grain rotation The process by which rigid, inequant mineral grains distributed through a soft matrix may rotate into parallelism as the rock changes shape owing to differential stress.
granite A coarse-grained, intrusive, silicic igneous rock.
granulite facies A set of metamorphic mineral assemblages formed at very high pressures and temperatures.
gravitational spreading A process of lateral spreading that occurs in a material because of the weakness of the material; gravitational spreading causes continental glaciers to grow and mountain belts to undergo orogenic collapse.
gravity The attractive force that one mass exerts on another; the magnitude depends on the size of the objects and the distance between them.
graywacke An informal term used for sedimentary rock consisting of sand-sized up to small-pebble-sized grains of quartz and rock fragments all mixed together in a muddy matrix; typically, graywacke occurs at the base of a graded bed.
great oxygenation event The time in Earth's history, about 2.4 Ga, when the concentration of oxygen in the atmosphere increased dramatically.
greenhouse conditions (greenhouse period) Relatively warm global climate leading to the rising of sea level for an interval of geologic time.
greenhouse effect The trapping of heat in the Earth's atmosphere by carbon dioxide and other greenhouse gases, which absorb infrared radiation; somewhat analogous to the effect of glass in a greenhouse.
greenhouse gases Atmospheric gases, such as carbon dioxide and methane, that regulate the Earth's atmospheric temperature by absorbing infrared radiation.
greenschist facies A set of metamorphic mineral assemblages formed under relatively low pressures and temperatures.
greenstone A low-grade metamorphic rock formed from basalt; if foliated, the rock is called greenschist.
Greenwich mean time (GMT) The time at the astronomical observatory in Greenwich, England; time in all other time zones is set in relation to GMT.
Grenville orogeny The orogeny that occurred about 1 billion years ago and yielded the belt of deformed and metamorphosed rocks that underlie the eastern fifth of the North American continent.
groin A concrete or stone wall built perpendicular to a shoreline in order to prevent beach drift from removing sand.
ground moraine A thin, hummocky layer of till left behind on the land surface during a rapid glacial recession.
groundwater Water that resides under the surface of the Earth, mostly in pores or cracks of rock or sediment.
groundwater contamination Addition of chemicals or microbes (e.g., from agricultural and industrial activities, and landfills or septic tanks) to the groundwater supply.
group A succession of stratigraphic formations that have been lumped together, making a single, thicker stratigraphic entity.
growth ring A rhythmic layering that develops in trees, travertine deposits, and shelly organisms as a consequence of seasonal changes.
gusher A fountain of oil formed when underground pressure causes the oil to rise on its own out of a drilled hole.
guyot A seamount that had a coral reef growing on top of it, so that it is now flat-crested.
gymnosperm A plant whose seeds are "naked," not surrounded by a fruit.
gyre A large, circular flow pattern of ocean surface currents.

habitable zone (astronomy) The region in the Solar System where the intensity of radiation is sufficient to allow water to exist in liquid form on the surface of a planet.
Hadean Eon The oldest of the Precambrian eons; the time between Earth's origin and the formation of the first rocks that have been preserved.
Hadley cells The name given to the low-latitude convection cells in the atmosphere.
hail Falling ice balls from the sky, formed when ice crystallizes in turbulent storm clouds.
hail streak An approximately 2-by-10-km stretch of ground, elongate in the direction of a storm, onto which hail has fallen.
half-graben A wedge-shaped basin in cross section that develops as the hanging-wall block above a normal fault slides down and rotates; the basin develops between the fault surface and the top surface of the rotated block.
half-life The time it takes for half of a group of a radioactive element's isotopes to decay.
halocline The boundary in the ocean between surface-water and deep-water salinities.
hamada Barren, rocky highlands in a desert.
hanging valley A glacially carved tributary valley whose floor lies at a higher elevation than the floor of the trunk valley.
hanging wall The rock or sediment above an inclined fault plane.
hardness (of a mineral) A measure of the relative ability of a mineral to resist scratching; it represents the resistance of bonds in the crystal structure from being broken.
hard water Groundwater that contains dissolved calcium and magnesium, usually after passing through limestone or dolomite.
head (1) The elevation of the water table above a reference horizon; (2) the edge of ice at the origin of a glacier.
headland A place where a hill or cliff protrudes into the sea.

head scarp The distinct step along the upslope edge of a slump where the regolith detached.
headward erosion The process by which a stream channel lengthens up its slope as the flow of water increases.
headwaters The beginning point of a stream.
heat Thermal energy resulting from the movement of molecules.
heat capacity A measure of the amount of heat that must be added to a material to change its temperature.
heat flow The rate at which heat rises from the Earth's interior up to the surface.
heat-transfer melting Melting that results from the transfer of heat from a hotter magma to a cooler rock.
heliocentric Universe concept An idea proposed by Greek philosophers around 250 B.C.E. suggesting that all heavenly objects including the Earth orbited the Sun.
heliosphere A bubble-like region in space in which solar wind has blown away most interstellar atoms.
Hercynian orogen The late Paleozoic orogen that affected parts of Europe; a continuation of the Alleghenian orogen.
heterosphere A term for the upper portion of the atmosphere, in which gases separate into distinct layers on the basis of composition.
hiatus The interval of time between deposition of the youngest rock below an unconformity and deposition of the oldest rock above the unconformity.
high-altitude westerlies Westerly winds at the top of the troposphere.
high-grade metamorphic rocks Rocks that metamorphose under relatively high temperatures.
high-level waste Nuclear waste containing greater than 1 million times the safe level of radioactivity.
hinge The portion of a fold where curvature is greatest.
hogback A steep-sided ridge of steeply dipping strata.
Holocene The period of geologic time since the last glaciation.
Holocene climatic maximum The period from 5,000 to 6,000 years ago, when Holocene temperatures reached a peak.
homosphere The lower part of the atmosphere, in which the gases have stirred into a homogenous mixture.
hoodoo The local name for the brightly colored shale and sandstone chimneys found in Bryce Canyon National Park in Utah.
horn A pointed mountain peak surrounded by at least three cirques.
hornfels Rock that undergoes metamorphism simply because of a change in temperature, without being subjected to differential stress.
horse latitudes The region of the subtropical high in which winds are weak.
horst The high block between two grabens.
hot spot A location at the base of the lithosphere, at the top of a mantle plume, where temperatures can cause melting.
hot-spot track A chain of now-dead volcanoes transported off the hot spot by the movement of a lithosphere plate.
hot-spot volcano An isolated volcano not caused by movement at a plate boundary, but rather by the melting of a mantle plume.
hot spring A spring that emits water ranging in temperature from about 30°C to 104°C.
hummocky surface An irregular and lumpy ground surface.
hurricane A huge rotating storm, resembling a giant spiral in map view, in which sustained winds blow over 119 km per hour.
hurricane track The path a hurricane follows.
hyaloclastite A rubbly extrusive rock consisting of glassy debris formed in a submarine or sub-ice eruption.
hydration The absorption of water into the crystal structure of minerals; a type of chemical weathering.
hydraulic conductivity The coefficient K in Darcy's law; hydraulic conductivity takes into account the permeability of the sediment or rock as well as the fluid's viscosity.
hydraulic gradient The slope of the water table.
hydraulic head The potential energy available to drive the flow of a given volume of groundwater at a location; it can be measured as an elevation above a reference.
hydrocarbon A chain-like or ring-like molecule made of hydrogen and carbon atoms; petroleum and natural gas are hydrocarbons.
hydrocarbon generation A process in which oil shale warms to temperatures of greater than about 90°C so kerogen molecules transform into oil and natural gas molecules.
hydrocarbon reserve A known supply of oil and gas held underground.
hydrocarbon system The association of source rock, migration pathway, reservoir rock, seal, and trap geometry that leads to the occurrence of a hydrocarbon reserve.
hydrofracturing ("fracking") A process by which drillers generate new fractures or open preexisting ones underground, by pumping a high-pressure fluid into a portion of the drill hole, in order to increase the permeability of surrounding hydrocarbon-bearing rocks.
hydrogen bond The attraction of a hydrogen atom to a negatively charged atom or molecule (e.g., hydrogen bonds attach water molecules to each other).
hydrologic cycle The continual passage of water from reservoir to reservoir in the Earth System.
hydrolysis The process in which water chemically reacts with minerals and breaks them down.
hydrosphere The Earth's water, including surface water (lakes, rivers, and oceans), groundwater, and liquid water in the atmosphere.
hydrothermal deposit An accumulation of ore minerals precipitated from hot-water solutions circulating through a magma or through the rocks surrounding an igneous intrusion.
hydrothermal metamorphism When very hot water passes through the crust and causes metamorphism of rock.
hypocenter (focus) The place within the Earth where earthquake energy originates; commonly, the hypocenter is the place on a fault where slip took place.
hypsometric curve A graph that plots surface elevation on the vertical axis and the percentage of the Earth's surface on the horizontal axis.

ice age An interval of time in which the climate was colder than it is today, glaciers occasionally advanced to cover large areas of the continents, and mountain glaciers grew; an ice age can include many glacials and interglacials.
iceberg A large block of ice that calves off the front of a glacier and drops into the sea.
icehouse period A period of time when the Earth's temperature was cooler than it is today and ice ages could occur.
ice-margin lake A meltwater lake formed along the edge of a glacier.
ice-rafted sediment Sediment carried out to sea by icebergs.
ice sheet A vast glacier that covers the landscape.
ice shelf A broad, flat region of ice along the edge of a continent formed where a continental glacier flowed into the sea.
ice stream A portion of a glacier that travels much more quickly than adjacent portions of the glacier.

ice tongue The portion of a valley glacier that has flowed out into the sea.
igneous rock Rock that forms when hot molten rock (magma or lava) cools and freezes solid.
ignimbrite Rock formed when deposits of pyroclastic flows solidify.
inactive fault A fault that last moved in the distant past and probably won't move again in the near future, yet is still recognizable because of displacement across the fault plane.
inactive sand The sand along a coast that is buried beneath a layer of active sand and moves only during severe storms or not at all.
incised meander A meander that lies at the bottom of a steep-walled canyon.
index minerals Minerals that serve as good indicators of metamorphic grade.
induced seismicity Seismic events caused by the actions of people (e.g., filling a reservoir that lies over a fault with water).
industrial minerals Minerals that serve as the raw materials for manufacturing chemicals, concrete, and wallboard, among other products.
inequant A term for a mineral grain whose length and width are not the same.
inertia The tendency of an object at rest to remain at rest.
infiltrate Seep down into.
injection well A well in which a liquid is pumped down into the ground under pressure so that it passes from the well back into the pore space of the rock or regolith.
inner core The inner section of the core, extending from 5,155 km deep to the Earth's center at 6,371 km and consisting of solid iron alloy.
inselberg An isolated mountain or hill in a desert landscape created by progressive cliff retreat, so that the hill is surrounded by a pediment or an alluvial fan.
insolation Exposure to the Sun's rays.
intensity (seismology) A measure of the relative size of an earthquake (the severity of ground shaking) at a location, as determined by examining the amount of damage caused.
interglacial A period of time between two glaciations.
interior basin A basin with no outlet to the sea.
interlocking texture The texture of crystalline rocks in which mineral grains fit together like pieces of a jigsaw puzzle.
internal process A process in the Earth System, such as plate motion, mountain building, or volcanism, ultimately caused by Earth's internal heat.
intertidal zone The area of coastal land across which the tide rises and falls.
intertropical convergence zone The equatorial convergence zone in the atmosphere.
intraplate earthquakes Earthquakes that occur away from plate boundaries.
intrusive contact The boundary between country rock and an intrusive igneous rock.
intrusive igneous rock Rock formed by the freezing of magma underground.
ion A version of an atom that has lost or gained electrons, relative to an electrically neutral version, so that it has a net electrical charge.
ionic bond The attachment of one atom to another that happens when one atom transfers electrons to another; one type of chemical bond.
ionosphere The interval of Earth's atmosphere, at an elevation between 50 and 400 km, containing abundant positive ions.
iron catastrophe The proposed event very early in Earth history when the Earth partly melted and molten iron sank to the center to form the core.
isobar A line on a map along which the air has a specified pressure.
isograd (1) A line on a pressure-temperature graph along which all points are taken to be at the same metamorphic grade; (2) a line on a map making the first appearance of a metamorphic index mineral.
isostasy (isostatic equilibrium) The condition that exists when the buoyancy force pushing lithosphere up equals the gravitational force pulling lithosphere down.
isostatic compensation The process in which the surface of the crust slowly rises or falls to reestablish isostatic equilibrium after a geologic event changes the density or thickness of the lithosphere.
isotherm Lines on a map or cross section along which the temperature is constant.
isotopes Different versions of a given element that have the same atomic number but different atomic weights.

jet stream A fast-moving current of air that flows at high elevations.
jetty A man-made wall that protects the entrance to a harbor.
joints Naturally formed cracks in rocks.
joint set A group of systematic joints.
Jovian A term used to describe the outer gassy, Jupiter-like planets (gas-giant planets).

kame A stratified sequence of lateral-moraine sediment that's sorted by water flowing along the edge of a glacier.
karst landscape A region underlain by caves in limestone bedrock; the collapse of the caves creates a landscape of sinkholes separated by higher topography, or of limestone spires separated by low areas.
Kelvin (K) scale A measure of temperature in which 0 K is absolute zero and the freezing point of water is 273.15 K; divisions in the Kelvin scale have the same value as those in the Celsius scale.
kerogen The waxy molecules into which the organic material in shale transforms on reaching about 100°C. At higher temperatures, kerogen transforms into oil.
kettle hole A circular depression in the ground made when a block of ice calves off the toe of a glacier, becomes buried by till, and later melts.
knob-and-kettle topography A land surface with many kettle holes separated by round hills of glacial till.
K-T boundary event The mass extinction that happened at the end of the Cretaceous Period, 65 million years ago, possibly due to the collision of an asteroid with the Earth.
Kuiper Belt A diffuse ring of icy objects, remnants of Solar System formation, that orbit our Sun outside the orbit of Neptune.

laccolith A blister-shaped igneous intrusion that forms when magma injects between layers underground in a manner that pushes overlying layers upward to form a dome.
lag deposit The coarse sediment left behind in a desert after wind erosion removes the finer sediment.
lagoon A body of shallow seawater separated from the open ocean by a barrier island.
lahar A thick slurry formed when volcanic ash and debris mix with water, either in rivers or from rain or melting snow and ice on the flank of a volcano.
landslide A sudden movement of rock and debris down a nonvertical slope.

landslide-potential map A map on which regions are ranked according to the likelihood that a mass movement will occur.
land subsidence Sinking elevation of the ground surface; the process may occur over an aquifer that is slowly draining and decreasing in volume because of pore collapse.
La Niña Years in which the El Niño event is not strong.
lapilli Any pyroclastic particle that is 2 to 64 mm in diameter (i.e., marble-sized); the particles can consist of frozen lava clots, pumice fragments, or ash clumps.
Laramide orogeny The mountain-building event that lasted from about 80 Ma to 40 Ma, in western North America; in the United States, it formed the Rocky Mountains as a result of basement uplift and the warping of the younger overlying strata into large monoclines.
large igneous province (LIP) A region in which huge volumes of lava and/or ash erupted over a relatively short interval of geologic time.
latent heat of condensation The heat released during condensation, which comes only from a change in state.
lateral moraine A strip of debris along the side margins of a glacier.
laterite soil A hard, brick-red, soil formed from iron-rich rock in a tropical environment; it consists primarily of insoluble iron and aluminum oxide and hydroxide and forms due to extreme leaching.
Laurentia A continent in the early Paleozoic Era composed of today's North America and Greenland.
Laurentide ice sheet An ice sheet that spread over northeastern Canada during the Pleistocene ice age(s).
lava Molten rock that has flowed out onto the Earth's surface.
lava dome A dome-like mass of rhyolitic lava that accumulates above the eruption vent.
lava flows Sheets or mounds of lava that flow onto the ground surface or sea floor in molten form and then solidify.
lava lake A large pool of lava produced around a vent when lava fountains spew forth large amounts of lava in a short period of time.
lava tube The empty space left when a lava tunnel drains; this happens when the surface of a lava flow solidifies while the inner part of the flow continues to stream downslope.
leach To dissolve and carry away.
leader A conductive path stretching from a cloud toward the ground, along which electrons leak from the base of the cloud, and which provides the start for a lightning flash to the ground.
lightning bolt (lightning flash, lightning stroke) A giant spark or pulse of current that jumps across a gap of charge separation.
light year The distance that light travels in one Earth year (about 6 trillion miles or 9.5 trillion km).
lignite Low-rank coal that consists of 50% carbon.
limb The side of a fold, showing less curvature than at the hinge.
limestone Sedimentary rock composed of calcite.
liquefaction The process by which saturated, unconsolidated sediments are transformed into a substance that acts like a liquid as a result of ground shaking.
liquidus The lowest temperature at which all the components of a material have melted and transformed into liquid.
liquification The process by which wet sediment becomes a slurry; liquification may be triggered by earthquake vibrations.
lithification The transformation of loose sediment into solid rock through compaction and cementation.
lithologic correlation A correlation based on similarities in rock type.
lithosphere The relatively rigid, nonflowable, outer 100- to 150-km-thick layer of the Earth, constituting the crust and the top part of the mantle.
lithosphere plate One of many distinct pieces of the lithosphere (Earth's relatively rigid shell) that are separated from one another by breaks (plate boundaries).
little ice age A period of cooler temperatures, between 1500 and 1800 C.E., during which many glaciers advanced.
loam A type of soil consisting of roughly equal parts of sand, silt, and clay; it tends to be good for growth of crops.
local base level A base level upstream from a drainage network's mouth.
lodgment till A flat layer of till smeared out over the ground when a glacier overrides an end moraine as it advances.
loess Layers of fine-grained sediments deposited from the wind; large deposits of loess formed from fine-grained glacial sediment blown off outwash plains.
longitudinal (seif) dune A dune formed when there is abundant sand and a strong, steady wind, and whose axis lies parallel to the wind direction.
longitudinal profile A cross-sectional image showing the variation in elevation along the length of a river.
longshore current The flow of water parallel to the shore just off a coast, because of the diagonal movement of waves toward the shore.
longshore drift The movement of sediment laterally along a beach; it occurs when waves wash up a beach diagonally.
lower mantle The deepest section of the mantle, stretching from 670 km down to the core-mantle boundary.
low-grade metamorphic rocks Rocks that underwent metamorphism at relatively low temperatures.
low-velocity zone The asthenosphere underlying oceanic lithosphere in which seismic waves travel more slowly, probably because rock has partially melted.
luster The way a mineral surface scatters light.
L-waves (Love waves) Surface seismic waves that cause the ground to ripple back and forth, creating a snake-like movement.

Ma Millions of years ago (abbreviation).
macrofossil A fossil large enough to be seen with the naked eye.
mafic A term used in reference to magmas or igneous rocks that are relatively poor in silica and rich in iron and magnesium.
magma Molten rock beneath the Earth's surface.
magma chamber A space below ground filled with magma.
magma contamination The process in which flowing magma incorporates components of the country rock through which it passes.
magmatic deposit An ore deposit formed when sulfide ore minerals accumulate at the bottom of a magma chamber.
magnetic anomaly The difference between the expected strength of the Earth's magnetic field at a certain location and the actual measured strength of the field at that location.
magnetic declination The angle between the direction a compass needle points at a given location and the direction of true north.
magnetic dipole An imaginary vector that points from the north magnetic pole to the south magnetic pole of a magnetic field.
magnetic field The region affected by the force emanating from a magnet.
magnetic field lines The trajectories along which magnetic particles would align, or charged particles would flow, if placed in a magnetic field.
magnetic force The push or pull exerted by a magnet.

magnetic inclination The angle between a magnetic needle free to pivot on a horizontal axis and a horizontal plane parallel to the Earth's surface.

magnetic poles The ends of a magnetic dipole; all magnetic dipoles have a north pole and a south pole.

magnetic reversal The change of the Earth's magnetic polarity; when a reversal occurs, the field flips from normal to reversed polarity, or vice versa.

magnetic-reversal chronology The history of magnetic reversals through geologic time.

magnetism An attractive or repulsive field force generated by permanent magnets or by an electrical current.

magnetization The degree to which a material can exert a magnetic force.

magnetometer An instrument that measures the strength of the Earth's magnetic field.

magnetosphere The region protected from the electrically charged particles of the solar winds by Earth's magnetic field.

magnetostratigraphy The comparison of the pattern of magnetic reversals in a sequence of strata, with a reference column showing the succession of reversals through time.

magnitude (of an earthquake) The number that represents the maximum amplitude of ground motion that would be measured by a seismometer placed at a specified distance from the epicenter.

manganese nodules Lumpy accumulations of manganese-oxide minerals precipitated onto the sea floor.

mantle The thick layer of rock below the Earth's crust and above the core.

mantle plume A column of very hot rock rising up through the mantle.

marble A metamorphic rock composed of calcite and transformed from a protolith of limestone.

mare The broad, darker areas on the Moon's surface; they consist of flood basalts that erupted over 3 billion years ago and spread out across the Moon's lowlands.

marginal sea A small ocean basin created when sea-floor spreading occurs behind an island arc.

marine magnetic anomaly The difference between the *expected* strength of the Earth's main dipole field at a certain location on the sea floor and the *actual* measured strength of the magnetic field at that location.

maritime tropical air mass A mass of air that originates over tropical or subtropical oceanic regions.

marker bed A particularly unique layer that provides a definitive basis for correlation.

marsh A wetland dominated by grasses.

mass The amount of matter in an object; mass differs from weight in that its value does not depend on the strength of gravity.

mass-extinction event A time when vast numbers of species abruptly vanish.

mass movement (mass wasting) The gravitationally caused downslope transport of rock, regolith, snow, or ice.

matter The material substance of the universe; it consists of atoms and has mass.

matrix Finer-grained material surrounding larger grains in a rock.

meander A snake-like curve along a stream's course.

meandering stream A reach of stream containing many meanders (snake-like curves).

meander neck A narrow isthmus of land separating two adjacent meanders.

mean sea level The average level between the high and low tide over a year at a given point.

mechanical force A push, pull, or shear applied by one object on another; it can be applied only if the objects are in contact.

mechanical weathering *See* Physical weathering.

medial moraine A strip of sediment in the interior of a glacier, parallel to the flow direction of the glacier, formed by the lateral moraines of two merging glaciers.

Medieval Warm Period A period of high temperatures in the Middle Ages.

melt Molten (liquid) rock.

meltdown The melting of the fuel rods in a nuclear reactor that occurs if the rate of fission becomes too fast and the fuel rods become too hot.

melting curve The line defining the range of temperatures and pressures at which a rock melts.

melting temperature The temperature at which the thermal vibration of the atoms or ions in the lattice of a mineral is sufficient to break the chemical bonds holding them to the lattice, so a material transforms into a liquid.

meltwater lake A lake fed by glacial meltwater.

mesa A large, flat-topped hill (with a surface area of several square km) in an arid region.

mesopause The boundary that marks the top of the mesosphere of Earth's atmosphere.

mesosphere The cooler layer of atmosphere overlying the stratosphere.

Mesozoic Era The middle of the three Phanerozoic eras; it lasted from 245 Ma to 65 Ma.

metaconglomerate A metamorphic rock produced by metamorphism of a conglomerate; typically, it contains flattened pebbles and cobbles.

metal A solid composed almost entirely of atoms of metallic elements; it is generally opaque, shiny, smooth, malleable, and can conduct electricity.

metallic bond A chemical bond in which the outer atoms are attached to each other in such a way that electrons flow easily from atom to atom.

metamorphic aureole The region around a pluton, stretching tens to hundreds of meters out, in which heat transferred into the country rock and metamorphosed the country rock.

metamorphic facies A set of metamorphic mineral assemblages indicative of metamorphism under a specific range of pressures and temperatures.

metamorphic foliation A fabric defined by parallel surfaces or layers that develop in a rock as a result of metamorphism; schistocity and gneissic layering are examples.

metamorphic grade A representation of the intensity of metamorphism, meaning the amount or degree of metamorphic change.

metamorphic mineral New minerals that grow in place within a solid rock under metamorphic temperatures and pressures.

metamorphic mineral assemblage A group of minerals that form in a rock as a result of metamorphism.

metamorphic rock Rock that forms when preexisting rock changes into new rock as a result of an increase in pressure and temperature and/or shearing under elevated temperatures; metamorphism occurs without the rock first becoming a melt or a sediment.

metamorphic texture A distinctive arrangement of mineral grains produced by metamorphism.

metamorphic zone The region between two metamorphic isograds, typically named after an index mineral found within the region.

metamorphism The process by which one kind of rock transforms into a different kind of rock.
metasomatism The process by which a rock's overall chemical composition changes during metamorphism because of reactions with hot water that bring in or remove elements.
meteor A streak of bright, glowing gas created as a meteoroid vaporizes in the atmosphere due to friction.
meteoric water Water that falls to Earth from the atmosphere as either rain or snow.
meteorite A piece of rock or metal alloy that fell from space and landed on Earth.
micrite Limestone consisting of lime mud (i.e., very fine-grained limestone).
microfossil A fossil that can be seen only with a microscope or an electron microscope.
mid-ocean ridge A 2-km-high submarine mountain belt that forms along a divergent oceanic plate boundary.
migmatite A rock formed when gneiss is heated high enough so that it begins to partially melt, creating layers, or lenses, of new igneous rock that mix with layers of the relict gneiss.
Milanković cycles Climate cycles that occur over tens to hundreds of thousands of years because of changes in Earth's orbit and tilt.
mine A site at which ore is extracted from the ground.
mineral A homogenous, naturally occurring, solid inorganic substance with a definable chemical composition and an internal structure characterized by an orderly arrangement of atoms, ions, or molecules in a lattice. Most minerals are inorganic.
mineral classes Groups of minerals distinguished from each other on the basis of chemical composition.
mineralogist A geoscientist specializing in the study of minerals.
mineral resources The minerals extracted from the Earth's upper crust for practical purposes.
Mississippi Valley–type (MVT) ore An ore deposit, typically in dolostone, containing lead- and zinc-bearing minerals that precipitated from groundwater that had moved up from several km depth in the upper crust; such deposits occur in the upper Mississippi Valley.
mixture A material consisting of two or more substances that can be separated mechanically (i.e., without chemical reactions).
Modified Mercalli scale An earthquake characterization scale based on the amount of damage that the earthquake causes.
Moho The seismic-velocity discontinuity that defines the boundary between the Earth's crust and mantle. Named for Andrija Mohorovičić.
Mohs hardness scale A list of ten minerals in a sequence of relative hardness, with which other minerals can be compared.
mold A cavity in sedimentary rock left behind when a shell that once filled the space weathers out.
molecule The smallest piece of a compound that has the properties of the compound; it consists of two or more atoms attached by chemical bonds.
monocline A fold in the land surface whose shape resembles that of a carpet draped over a stair step.
monsoon A seasonal reversal in wind direction that causes a shift from a very dry season to a very rainy season in some regions of the world.
moon A sizable solid body locked in orbit around a planet.
moraine A sediment pile composed of till deposited by a glacier.
mountain front The boundary between a mountain range and adjacent plains.
mountain (alpine) glacier A glacier that exists in or adjacent to a mountainous region.
mountain ice cap A mound of ice that submerges peaks and ridges at the crest of a mountain range.
mouth The outlet of a stream where it discharges into another stream, a lake, or a sea.
mudflow A downslope movement of mud at slow to moderate speed.
mud pot A viscuous slurry that forms in a geothermal region when hot water or steam rises into soils rich in volcanic ash and clay.
mudstone Very fine-grained sedimentary rock that will not easily split into sheets.
mylonite Rock formed during dynamic metamorphism and characterized by foliation that lies roughly parallel to the fault (shear zone) involved in the shearing process; mylonites have very fine grains formed by the nonbrittle subdivision of larger grains.

native metal A naturally occurring pure mass of a single metal in an ore deposit.
natural arch An arch that forms when erosion along joints leaves narrow walls of rock; when the lower part of the wall erodes while the upper part remains, an arch results.
natural hazard A natural feature of the environment that can cause injury to living organisms and/or damage to buildings and the landscape.
natural levees A pair of low ridges that appear on either side of a stream and develop as a result of the accumulation of sediment deposited naturally during flooding.
natural selection The process by which the fittest organisms survive to pass on their characteristics to the next generation.
neap tide An especially low tide that occurs when the angle between the direction of the Moon and the direction of the Sun is 90°.
nebula A cloud of gas or dust in space.
nebular theory of planet formation The concept that planets grow out of rings of gas, dust, and ice surrounding a newborn star.
negative anomaly An area where the magnetic field strength is less than expected.
negative feedback Feedback that slows a process down or reverses it.
neocrystallization The growth of new crystals, not in the protolith, during metamorphism.
neutron A subatomic particle, in the nucleus of an atom, that has a neutral charge.
Nevadan orogeny A convergent-margin mountain-building event that took place in western North America during the Late Jurassic Period.
nonconformity A type of unconformity at which sedimentary rocks overlie basement (older intrusive igneous rocks and/or metamorphic rocks).
nonflowing artesian well An artesian well in which water rises on its own up to a level that lies below the ground surface.
nonfoliated metamorphic rock Rock containing minerals that recrystallized during metamorphism but has no foliation.
nonmetallic mineral resources Mineral resources that do not contain metals; examples include building stone, gravel, sand, gypsum, phosphate, and salt.
nonplunging fold A fold with a horizontal hinge.
nonrenewable resource A resource that nature will take a long time (hundreds to millions of years) to replenish or may never replenish.
nonsystematic joints Short cracks in rocks that occur in a range of orientations and are randomly placed and oriented.

nor'easter A large, midlatitude North American cyclone; when it reaches the east coast, it produces strong winds that come out of the northeast.
normal fault A fault in which the hanging-wall block moves down the slope of the fault.
normal force The component of the gravitational force acting perpendicular to a slope.
normal polarity Polarity in which the paleomagnetic dipole has the same orientation as it does today.
normal stress The push or pull that is perpendicular to a surface.
North Atlantic deep-water mass The mass of cold, dense water that sinks in the north polar regions.
northeast tradewinds Surface winds that come out of the northeast and occur in the region between the equator and 30°N.
nuclear bond The force that attaches subatomic particles to each other within the nucleus of an atom.
nuclear fuel Pellets of concentrated uranium oxide or a comparable radioactive material that can provide energy in a nuclear reactor.
nuclear fusion The process by which the nuclei of atoms fuse together, thereby creating new, larger atoms.
nuclear reaction A process that results in changing the nucleus of an atom by breaking or forming nuclear bonds.
nuclear reactor The part of a nuclear power plant where the fission reactions occur.
nuclear waste The radioactive material produced as a byproduct in a nuclear plant that must be disposed of carefully due to its dangerous radioactivity.
nucleus The central ball of an atom that consists of protons and neutrons (except for hydrogen, whose nuclei contains only a proton).
nuée ardente *See* Pyroclastic flow.
numerical age (in older literature, "absolute age") The age of a geologic feature given in years.

oasis A verdant region surrounded by desert, occurring at a place where natural springs provide water at the surface.
oblique-slip fault A fault in which sliding occurs diagonally along the fault plane.
obsidian An igneous rock consisting of a solid mass of volcanic glass.
occluded front A front that no longer intersects the ground surface.
oceanic crust The crust beneath the oceans; composed of gabbro and basalt, overlain by sediment.
oceanic plateau A region of oceanic floor that is higher than surrounding areas; such regions have particularly thick oceanic crust and are relicts of submarine large igneous provinces.
oceanic lithosphere Lithosphere topped by oceanic crust; it reaches a thickness of 100 km.
offshore bar A narrow ridge of sand that forms off the shore of a beach; some offshore bars rise above sea level, and separate a lagoon on one side from the open ocean on the other.
oil (geology) A liquid hydrocarbon that can be burned as a fuel.
Oil Age The period of human history, including our own, so named because the economy depends on oil.
oil field A region containing a significant amount of accessible oil underground.
oil reserve The known supply of oil held underground.
oil shale Shale containing kerogen.
oil trap A geologic configuration that keeps oil underground in the reservoir rock and prevents it from rising to the surface.
oil window The narrow range of temperatures under which oil can form in a source rock.
olistotrome A large, submarine slump block, buried and preserved.
Oort Cloud A cloud of icy objects, left over from Solar System formation, that orbit the Sun in a region outside of the heliosphere.
ophiolite A slice of oceanic crust that has been thrust onto continental crust.
ordinary well A well whose base penetrates below the water table and can thus provide water.
ore Rock containing native metals or a concentrated accumulation of ore minerals.
ore deposit An economically significant accumulation of ore.
ore minerals Minerals that have metal in high concentrations and in a form that can be easily extracted.
organic carbon Carbon that has been incorporated in an organism.
organic chemical A carbon-containing compound that occurs in living organisms, or that resembles such compounds; it consists of carbon atoms bonded to hydrogen atoms along with varying amounts of oxygen, nitrogen, and other chemicals.
organic coast A coast along which living organisms control landforms along the shore.
organic sedimentary rock Sedimentary rock (such as coal) formed from carbon-rich relicts of organisms.
organic shale Lithified, muddy, organic-rich ooze that contains the raw materials from which hydrocarbons eventually form.
orogen (orogenic belt) A linear range of mountains.
orogenic collapse The process in which mountains begin to collapse under their own weight and spread out laterally.
orogeny A mountain-building event.
orographic barrier A landform that diverts air flow upward or laterally.
outcrop An exposure of bedrock.
outer core The section of the core, between 2,900 and 5,150 km deep, that consists of liquid iron alloy.
outwash plain A broad area of gravel and sandbars deposited by a braided stream network, fed by the melt water of a glacier.
overburden The weight of overlying rock on rock buried deeper in the Earth's crust.
overriding plate (slab) The plate at a subduction zone that overrides the downgoing plate.
oversaturated solution A solution that contains so much solute (dissolved ions) that precipitation begins.
oversized stream valley A large valley with a small stream running through it; the valley formed earlier when the flow was greater.
oxbow lake A meander that has been cut off yet remains filled with water.
oxidation reaction A reaction in which an element loses electrons; an example is the reaction of iron with air to form rust.
ozone O_3, an atmospheric gas that absorbs harmful ultraviolet radiation from the Sun.
ozone hole An area of the atmosphere, over polar regions, from which ozone has been depleted.

pahoehoe A lava flow with a surface texture of smooth, glassy, rope-like ridges.
paleoclimate The past climate of the Earth.
paleomagnetism The record of ancient magnetism preserved in rock.
paleopole The supposed position of the Earth's magnetic pole in the past, with respect to a particular continent.
paleosol Ancient soil preserved in the stratigraphic record.
Paleozoic Era The oldest era of the Phanerozoic Eon.

Pangaea A supercontinent that assembled at the end of the Paleozoic Era.

Pannotia A supercontinent that may have existed sometime between 800 Ma and 600 Ma.

parabolic dunes Dunes formed when strong winds break through transverse dunes to make new dunes whose ends point upwind.

parallax The apparent movement of an object seen from two different points not on a straight line from the object (e.g., from your two different eyes).

parallax method A trigonometric method used to determine the distance from the Earth to a nearby star.

parent isotope A radioactive isotope that undergoes decay.

partial melting The melting in a rock of the minerals with the lowest melting temperatures, while other minerals remain solid.

passive margin A continental margin that is not a plate boundary.

passive-margin basin A thick accumulation of sediment along a tectonically inactive coast, formed over crust that stretched and thinned when the margin first began.

patterned ground A polar landscape in which the ground splits into pentagonal or hexagonal shapes.

pause An elevation in the atmosphere where temperature stops decreasing and starts increasing, or vice versa.

peat Compacted and partially decayed vegetation accumulating beneath a swamp.

pedalfer soil A temperate-climate soil characterized by well-defined soil horizons and an organic A-horizon.

pediment The broad, nearly horizontal bedrock surface at the base of a retreating desert cliff.

pedocal soil Thin soil, formed in arid climates. It contains very little organic matter, but significant precipitated calcite.

pegmatite A coarse-grained igneous rock containing crystals of up to tens of centimeters across and occurring in dike-shaped intrusions.

pelagic sediment Microscopic plankton shells and fine flakes of clay that settle out and accumulate on the deep-ocean floor.

Pelé's hair Droplets of basaltic lava that mold into long, glassy strands as they fall.

Pelé's tears Droplets of basaltic lava that mold into tear-shaped, glassy beads as they fall.

peneplain A nearly flat surface that lies at an elevation close to sea level; thought to be the product of long-term erosion.

perched water table A quantity of groundwater that lies above the regional water table because an underlying lens of impermeable rock or sediment prevents the water from sinking down to the regional water table.

percolation The process by which groundwater meanders through tiny, crooked channels in the surrounding material.

peridotite A coarse-grained ultramafic rock.

periglacial environment A region with widespread permafrost but without a blanket of snow or ice.

period An interval of geologic time representing a subdivision of a geologic era.

permafrost Permanently frozen ground.

permanent magnet A special material that behaves magnetically for a long time all by itself.

permanent stream A stream that flows year-round because its bed lies below the water table, or because more water is supplied from upstream than can infiltrate the ground.

permeability The degree to which a material allows fluids to pass through it via an interconnected network of pores and cracks.

permineralization The fossilization process in which plant material becomes transformed into rock by the precipitation of silica from groundwater.

petrified A term used by geologists to describe plant material that has transformed into rock by permineralization.

petroglyph Drawings formed by chipping into the desert varnish of rocks to reveal the lighter rock beneath.

petroleum *See* Oil.

phaneritic A textural term used to describe coarse-grained igneous rock.

Phanerozoic Eon The most recent eon, an interval of time from 542 Ma to the present.

phenocryst A large crystal surrounded by a finer-grained matrix in an igneous rock.

photochemical smog Brown haze that blankets a city when exhaust from cars and trucks reacts in the presence of sunlight.

photosynthesis The process during which chlorophyll-containing plants remove carbon dioxide from the atmosphere, form tissues, and expel oxygen back to the atmosphere.

phreatomagmatic eruption An explosive eruption that occurs when water enters the magma chamber and turns into steam.

phyllite A fine-grained metamorphic rock with a foliation caused by the preferred orientation of very fine-grained mica.

phyllitic luster A silk-like sheen characteristic of phyllite, a result of the rock's fine-grained mica.

phylogenetic tree A chart representing the ideas of paleontologists showing which groups of organisms radiated from which ancestors.

physical weathering The process in which intact rock breaks into smaller grains or chunks.

piedmont glacier A fan or lobe of ice that forms where a valley glacier emerges from a valley and spreads out into the adjacent plain.

pillow basalt Glass-encrusted basalt blobs that form when magma extrudes on the sea floor and cools very quickly.

placer deposit Concentrations of metal grains in stream sediment that develop when rocks containing native metals erode and create a mixture of sand grains and metal fragments; the moving water of the stream carries away lighter mineral grains.

planet An object that orbits a star, is roughly spherical, and has cleared its neighborhood of other objects.

planetesimal Tiny, solid pieces of rock and metal that collect in a planetary nebula and eventually accumulate to form a planet.

plankton Tiny plants and animals that float in sea or lake water.

plastic deformation The deformational process in which mineral grains behave like plastic and, when compressed or sheared, become flattened or elongate without cracking or breaking.

plate One of about 20 distinct pieces of the relatively rigid lithosphere.

plate boundary The border between two adjacent lithosphere plates.

plate-boundary earthquakes The earthquakes that occur along and define plate boundaries.

plate-boundary volcano A volcanic arc or mid-ocean ridge volcano, formed as a consequence of movement along a plate boundary.

plate interior A region away from the plate boundaries that consequently experiences few earthquakes.

plate tectonics *See* Theory of plate tectonics.

playa The flat, typically salty lake bed that remains when all the water evaporates in drier times; forms in desert regions.

Pleistocene Epoch The period of time from about 2 Ma to 14,000 years ago, during which the Earth experienced an ice age.

plunge pool A depression at the base of a waterfall scoured by the energy of the falling water.
plunging fold A fold with a tilted hinge.
pluton An irregular or blob-shaped intrusion; can range in size from tens of m across to tens of km across.
pluvial lake A lake formed to the south of a continental glacier as a result of enhanced rainfall during an ice age.
point bar A wedge-shaped deposit of sediment on the inside bank of a meander.
polar cell A high-latitude convection cell in the atmosphere.
polar easterlies Prevailing winds that come from the east and flow from the polar high to the subpolar low.
polar front The convergence zone in the atmosphere at latitude 60°.
polar glacier *See* Dry-bottom glacier.
polar high The zone of high pressure in polar regions created by the sinking of air in the polar cells.
polarity The orientation of a magnetic dipole.
polarity chron The time interval between polarity reversals of Earth's magnetic field.
polarity subchron The time interval between magnetic reversals if the interval is of short duration (less than 200,000 years long).
polarized light A beam of filtered light waves that all vibrate in the same plane.
polar wander The phenomenon of the progressive changing through time of the position of the Earth's magnetic poles relative to a location on a continent; significant polar wander probably doesn't occur—in fact, poles seem to remain fairly fixed, while continents move.
polar-wander path The curving line representing the apparent progressive change in the position of the Earth's magnetic pole, relative to a locality X, assuming that the position of X on Earth has been fixed through time (in fact, poles stay fixed while continents move).
pollen Tiny grains involved in plant reproduction.
pollution Natural and synthetic contaminant materials introduced to the Earth's environment by the activities of humans.
polymorphs Two minerals that have the same chemical composition but a different crystal lattice structure.
pore A small, open space within sediment or rock.
pore collapse The closer packing of grains that occurs when groundwater is extracted from pores, thus eliminating the support holding the grains apart.
porosity The total volume of empty space (pore space) in a material, usually expressed as a percentage.
porphyritic A textural term for igneous rock that has phenocrysts distributed throughout a finer matrix.
Portland cement Cement made by mechanically mixing limestone, sandstone, and shale in just the right proportions, before heating in a kiln, to provide the correct chemical makeup of cement.
positive anomaly An area where the magnetic field strength is stronger than expected.
positive-feedback mechanism A mechanism that enhances the process that causes the mechanism in the first place.
potentiometric surface The elevation to which water in an artesian system would rise if unimpeded; where there are flowing artesian wells, the potentiometric surface lies above ground.
pothole A bowl-shaped depression carved into the floor of a stream by a long-lived whirlpool carrying sand or gravel.
Precambrian Period The interval of geologic time between Earth's formation about 4.57 Ga and the beginning of the Phanerozoic Eon 542 Ma.
precession The gradual conical path traced out by Earth's spinning axis; simply put, it is the "wobble" of the axis.
precious metals Metals (like gold, silver, and platinum) that have high value.
precipitate (chemistry, n.) A solid substance formed when atoms attach and settle out of a solution, or attach to the walls of the container holding the solution; (chemistry, v.) the action of forming a solid substance from a solution; (meteorology, v.) the dropping of snow or rain from the sky.
precipitation (1) The process by which atoms dissolved in a solution come together and form a solid; (2) rainfall or snow.
preferred mineral orientation The metamorphic texture that exists where platy grains lie parallel to one another and/or elongate grains align in the same direction.
pressure Force per unit area, or the "push" acting on a material in cases where the push (compressional stretch) is the same in all directions.
pressure gradient The rate of pressure change over a given horizontal distance.
pressure solution The process of dissolution at points of contact, between grains, where compression is greatest, producing ions that then precipitate elsewhere, where compression is less.
prevailing winds Surface winds that generally flow in the same direction for long time periods.
primary porosity The space that remains between solid grains or crystals immediately after sediment accumulates or rock forms.
principal aquifer The geologic unit that serves as the primary source of groundwater in a region.
principle of baked contacts When an igneous intrusion "bakes" (metamorphoses) surrounding rock, the rock that has been baked must be older than the intrusion.
principle of cross-cutting relations If one geologic feature cuts across another, the feature that has been cut is older.
principle of fossil succession In a stratigraphic sequence, different species of fossil organisms appear in a definite order; once a fossil species disappears in a sequence of strata, it never reappears higher in the sequence.
principle of inclusions If a rock contains fragments of another rock, the fragments must be older than the rock containing them.
principle of original continuity Sedimentary layers, before erosion, formed fairly continuous sheets over a region.
principle of original horizontality Layers of sediment, when originally deposited, are fairly horizontal.
principle of superposition In a sequence of sedimentary rock layers, each layer must be younger than the one below, for a layer of sediment cannot accumulate unless there is already a substrate on which it can collect.
principle of uniformitariansim The physical processes we observe today also operated in the past in the same way, and at comparable rates.
product (chemistry, n.) materials produced or formed by a chemical reaction.
prograde metamorphism Metamorphism that occurs as temperatures and pressures are increasing.
prokaryote An organism whose cells do not contain a nucleus; archaea and bacteria consist of prokaryotic cells.
Proterozoic Eon The most recent of the Precambrian eons.
protocontinent A block of crust composed of volcanic arcs and hotspot volcanoes sutured together.

protolith The original rock from which a metamorphic rock formed.
proton A positively charged subatomic particle in the nucleus of an atom.
protoplanet A body that grows by the accumulation of planetesimals but has not yet become big enough to be called a planet.
protoplanetary nebula A ring of gas and dust that surrounded the newborn Sun, from which the planets were formed.
protostar A dense body of gas that is collapsing inward because of gravitational forces and that may eventually become a star.
pumice A glassy igneous rock that forms from felsic frothy lava and contains abundant (over 50%) pore space.
pumice lapilli Marble-sized chunks consisting of frothy, siliceous igneous rock that fall from a volcanic eruptive cloud.
punctuated equilibrium The hypothesis that evolution takes place in fits and starts; evolution occurs very slowly for quite a while and then, during a relatively short period, takes place very rapidly.
P-waves Compressional seismic waves that move through the body of the Earth.
P-wave shadow zone A band between 103° and 143° from an earthquake epicenter, as measured along the circumference of the Earth, inside which P-waves do not arrive at seismograph stations.
pycnocline The boundary between layers of water of different densities.
pyroclastic debris Fragmented material that sprayed out of a volcano and landed on the ground or sea floor in solid form.
pyroclastic flow A fast-moving avalanche that occurs when hot volcanic ash and debris mix with air and flow down the side of a volcano.
pyroclastic rock Rock made from fragments that were blown out of a volcano during an explosion and were then packed or welded together.

quarry A site at which stone is extracted from the ground.
quartzite A metamorphic rock composed of quartz and transformed from a protolith of quartz sandstone.
quenching A sudden cooling of molten material to form a solid.
quick clay Clay that behaves like a solid when still (because of surface tension holding the water-coated clay flakes together) but that flows like a liquid when shaken.

radial network A drainage network in which the streams flow outward from a cone-shaped mountain and define a pattern resembling spokes on a wheel.
radiation (physics) Electromagnetic energy traveling away from a source through a medium or space.
radioactive decay The process by which a radioactive atom undergoes fission or releases particles, thereby being transformed into a new element.
radioactive isotope An unstable isotope of a given element.
radiometric dating The science of dating geologic events in years by measuring the ratio of parent radioactive atoms to daughter product atoms.
rain band A spiraling arm of a hurricane radiating outward from the eye.
rain shadow The inland side of a mountain range, which is arid because the mountains block rain clouds from reaching the area.
range (for fossils) The interval of a sequence of strata in which a specific fossil species appears.
rapids A reach of a stream in which water becomes particularly turbulent; as a consequence, waves develop on the surface of the stream.
rare earth element One of a group of 17 elements including the lanthanides, scandium, and yttrium; they are essential in the production of high-tech devices.
reach A specified segment of a stream's path.
reactant (chemistry) The starting materials of a chemical reaction.
recessional moraine The end moraine that forms when a glacier stalls for a while as it recedes.
recharge area A location where water enters the ground and infiltrates down to the water table.
recrystallization The process in which ions or atoms in minerals rearrange to form new minerals.
rectangular network A drainage network in which the streams join each other at right angles because of a rectangular grid of fractures that breaks up the ground and localizes channels.
recurrence interval The average time between successive geologic events.
red giant A huge red star that forms when Sun-sized stars start to die and expand.
red shift The phenomenon in which a source of light moving away from you very rapidly shifts to a lower frequency; that is, toward the red end of the spectrum.
reef bleaching The death and loss of color of a coral reef.
reflected ray A ray that bounces off a boundary between two different materials.
refracted ray A ray that bends as it passes through a boundary between two different materials.
refraction The bending of a ray as it passes through a boundary between two different materials.
refractory materials Substances that have a relatively high melting point and tend to exist in solid form.
reg A vast stony plain in a desert.
regional metamorphism *See also* Dynamothermal metamorphism; metamorphism of a broad region, usually the result of deep burial during an orogeny.
regolith Any kind of unconsolidated debris that covers bedrock.
regression The seaward migration of a shoreline caused by a lowering of sea level.
relative age The age of one geologic feature with respect to another.
relative humidity The ratio between the measured water content of air and the maximum possible amount of water the air can hold at a given condition.
relative plate velocity The movement of one lithosphere plate with respect to another.
relief The difference in elevation between adjacent high and low regions on the land surface.
renewable resource A resource that can be replaced by nature within a short time span relative to a human life span.
reservoir rock Rock with high porosity and permeability, so it can contain an abundant amount of easily accessible oil.
residence time The average length of time that a substance stays in a particular reservoir.
residual mineral deposit Soils in which the residuum left behind after leaching by rainwater is so concentrated in metals that the soil itself becomes an ore deposit.
resonance (seismology) A situation that arises when earthquake waves of a particular frequency cause particularly large-amplitude movements because energy input happens at just the right time.
resurgent dome The new mound, or cone, of igneous rock that grows within a caldera as an eruption begins anew.

retrograde metamorphism Metamorphism that occurs as pressures and temperatures are decreasing; for retrograde metamorphism to occur, water must be added.

return stroke An upward-flowing electric current from the ground that carries positive charges up to a cloud during a lightning flash.

reversed polarity Polarity in which the paleomagnetic dipole points north.

reverse fault A steeply dipping fault on which the hanging-wall block slides up.

rhythmic layering Banding in sediments, shells, trees, corals, or ice that repeats periodically; it may be correlated to annual cycles.

Richter magnitude scale A scale that defines earthquakes on the basis of the amplitude of the largest ground motion recorded on a seismogram.

ridge axis The crest of a mid-ocean ridge; the ridge axis defines the position of a divergent plate boundary.

ridge-push force A process in which gravity causes the elevated lithosphere at a mid-ocean ridge axis to push on the lithosphere that lies farther from the axis, making it move away.

right-lateral strike-slip fault A strike-slip fault in which the block on the opposite fault plane from a fixed spot moves to the right of that spot.

rip current A strong, localized seaward flow of water perpendicular to a beach.

ripple mark Relatively small elongated ridges that form on a sedimentary bed surface at right angles to the direction of current flow.

riprap Loose boulders or concrete piled together along a beach to absorb wave energy before it strikes a cliff face.

roche moutonnée A glacially eroded hill that becomes elongate in the direction of flow and asymmetric; glacial rasping smoothes the upstream part of the hill into a gentle slope, while glacial plucking erodes the downstream edge into a steep slope.

rock A coherent, naturally occurring solid, consisting of an aggregate of minerals or a mass of glass.

rock burst A sudden explosion of rock off the ceiling or wall of an underground mine.

rock cycle The succession of events that results in the transformation of Earth materials from one rock type to another, then another, and so on.

rockfall A mass of rock that separates from a cliff, typically along a joint, and then free-falls downslope.

rock flour Fine-grained sediment produced by glacial abrasion of the substrate over which a glacier flows.

rock glacier A slow-moving mixture of rock fragments and ice.

rockslide A sudden downslope movement of rock.

rocky coast An area of coast where bedrock rises directly from the sea, so beaches are absent.

Rodinia A proposed Precambrian supercontinent that existed around 1 billion years ago.

rogue wave Waves that are two to five times the size of most of the large waves passing a locality in a given time interval.

rotational axis The imaginary line through the center of the Earth around which the Earth spins.

running water Water that flows down the surface of sloping land in response to the pull of gravity.

R-waves (Rayleigh waves) Surface seismic waves that cause the ground to ripple up and down, like water waves in a pond.

sabkah A region of formerly flooded coastal desert in which stranded seawater has left a salt crust over a mire of mud that is rich in organic material.

salinity The degree of concentration of salt in water.

saltation The movement of a sediment in which grains bounce along their substrate, knocking other grains into the water column (or air) in the process.

salt dome A rising bulbous dome of salt that bends up the adjacent layers of sedimentary rock.

salt wedging The process in arid climates by which dissolved salt in groundwater crystallizes and grows in open pore spaces in rocks and pushes apart the surrounding grains.

sand dune A relatively large ridge of sand built up by a current of wind (or water); cross bedding typically occurs within the dune.

sandspit An area where the beach stretches out into open water across the mouth of a bay or estuary.

sandstone Coarse-grained sedimentary rock consisting almost entirely of quartz.

sand volcano (sand blow) A small mound of sand produced when sand layers below the ground surface liquify as a result of seismic shaking, causing the sand to erupt onto the Earth's surface through cracks or holes in overlying clay layers.

saprolite A layer of rotten rock created by chemical weathering in warm, wet climates.

Sargasso Sea The center of North Atlantic Gyre, named for the tropical seaweed sargassum, which accumulates in its relatively noncirculating waters.

saturated solution Water that carries as many dissolved ions as possible under given environmental conditions.

saturated zone The region below the water table where pore space is filled with water.

scattering The dispersal of energy that occurs when light interacts with particles in the atmosphere.

schist A medium-to-coarse-grained metamorphic rock that possesses schistosity.

schistosity Foliation caused by the preferred orientation of large mica flakes.

scientific method A sequence of steps for systematically analyzing scientific problems in a way that leads to verifiable results.

scoria A glassy, mafic, igneous rock containing abundant air-filled holes.

scoria cone An accumulation of lapilli-sized or larger fragments formed from a volcanic eruption that spatters clots of basaltic lava. (Also called cinder cone.)

scouring A process by which running water removes loose fragments of sediment from a streambed.

sea arch An arch of land protruding into the sea and connected to the mainland by a narrow bridge.

sea-floor spreading The gradual widening of an ocean basin as new oceanic crust forms at a mid-ocean ridge axis and then moves away from the axis.

sea ice Ice formed by the freezing of the surface of the sea.

seal A relatively impermeable rock, such as shale, salt, or unfractured limestone, that lies above a reservoir rock and stops the oil from rising further.

seam A sedimentary bed of coal interlayered with other sedimentary rocks.

seamount An isolated submarine mountain.

seasonal floods Floods that appear almost every year during seasons when rainfall is heavy or when winter snows start to melt.

seasonal well A well that provides water only during the rainy season when the water table rises below the base of the well.
sea stack An isolated tower of land just offshore, disconnected from the mainland by the collapse of a sea arch.
seawall A wall of riprap built on the landward side of a backshore zone in order to protect shore cliffs from erosion.
second The basic unit of time measurement, now defined as the time it takes for the magnetic field of a cesium atom to flip polarity 9,192,631,770 times, as measured by an atomic clock.
secondary enrichment The process by which a new ore deposit forms from metals that were dissolved and carried away from preexisting ore minerals.
secondary porosity New pore space in rocks, created some time after a rock first forms.
secondary recovery technique A process used to extract the quantities of oil that will not come out of a reservoir rock with just simple pumping.
sediment An accumulation of loose mineral grains, such as boulders, pebbles, sand, silt, or mud, that are not cemented together.
sediment liquefaction When pressure in the water in the pores push sediment grains apart so that they become surrounded by water and no longer rest against each other, and the sediment becomes able to flow like a liquid.
sedimentary basin A depression, created as a consequence of subsidence, that fills with sediment.
sedimentary rock Rock that forms either by the cementing together of fragments broken off preexisting rock or by the precipitation of mineral crystals out of water solutions at or near the Earth's surface.
sedimentary sequence A grouping of sedimentary units bounded on top and bottom by regional unconformities.
sediment budget The proportion of sand supplied to sand removed from a depositional setting.
sediment load The total volume of sediment carried by a stream.
sediment maturity The degree to which a sediment has evolved from a crushed-up version of the original rock into a sediment that has lost its easily weathered minerals and become well sorted and rounded.
sediment sorting The segregation of sediment by size.
seep A place where oil-filled reservoir rock intersects the ground surface, or where fractures connect a reservoir to the ground surface, so that oil flows out onto the ground on its own.
seiche Rhythmic movement in a body of water caused by ground motion.
seismic belts (seismic zones) The relatively narrow strips of crust on Earth under which most earthquakes occur.
seismicity Earthquake activity.
seismic-moment magnitude scale A scale that defines earthquake size on the basis of calculations involving the amount of slip, length of rupture, depth of rupture, and rock strength.
seismic ray The changing position of an imaginary point on a wave front as the front moves through rock.
seismic-reflection profile A cross-sectional view of the crust made by measuring the reflection of artificial seismic waves off boundaries between different layers of rock in the crust.
seismic retrofitting The strengthening of an already existing structure (building, bridge, etc.) so that it can withstand earthquake vibrations.
seismic tomography Analysis by sophisticated computers of global seismic data in order to create a three-dimensional image of variations in seismic-wave velocities within the Earth.
seismic velocity The speed at which seismic waves travel.
seismic-velocity discontinuity A boundary in the Earth at which seismic velocity changes abruptly.
seismic (earthquake) waves Waves of energy emitted at the focus of an earthquake.
seismogram The record of an earthquake produced by a seismograph.
seismometer (seismograph) An instrument that can record the ground motion from an earthquake.
semipermanent pressure cell A somewhat elliptical zone of high or low atmospheric pressure that lasts much of the year; it forms because high-pressure zones tend to be narrower over land than over sea.
Sevier orogeny A mountain-building event that affected western North America between about 150 Ma and 80 Ma, a result of convergent margin tectonism; a fold-thrust belt formed during this event.
shale Very fine-grained sedimentary rock that breaks into thin sheets.
shale gas Gas that comes directly from a source rock (organic shale).
shatter cones Small, cone-shaped fractures formed by the shock of a meteorite impact.
shear When one part of a material moves sideways, relative to another.
shear strain A change in shape of an object that involves the movement of one part of a rock body sideways past another part so that angular relationships within the body change.
shear stress A stress that moves one part of a material sideways past another part.
shear waves Seismic waves in which particles of material move back and forth perpendicular to the direction in which the wave itself moves.
shear zone A fault in which movement has occurred ductilely.
sheetwash A film of water less than a few mm thick that covers the ground surface during heavy rains.
shell (biology) A relatively hard, protective structure formed of minerals and surrounding the soft part of an invertebrate organism.
shield An older, interior region of a continent.
shield volcano A subaerial volcano with a broad, gentle dome, formed either from low-viscosity basaltic lava or from large pyroclastic sheets.
shocked quartz Grains of quartz that have been subjected to intense pressure such as occurs during a meteorite impact.
shock metamorphism The changes that can occur in a rock due to the passage of a shock wave, generally resulting from a meteorite impact.
shoreline The boundary between the water and land.
shortening The process during which a body of rock or a region of crust becomes shorter.
short-term climate change Climate change that takes place over hundreds to thousands of years.
Sierran arc A large continental volcanic arc along western North America that was initiated at the end of the Jurassic Period and lasted until about 80 million years ago.
silica SiO_2.
silicate rock Rock composed of silicate minerals.
silicates (silicate minerals) Minerals built from silicon-oxygen tetrahedra arranged in chains, sheets, or 3-D networks; they make up most of the Earth's crust and mantle.
siliceous sedimentary rock Sedimentary rock that contains abundant quartz.
silicon-oxygen tetrahedron The SiO_4^{4-} anionic group, in which four oxygen atoms surround a single silicon atom, thereby defining the corners of a tetrahedron.

silicic Rich in silica with relatively little iron and magnesium.
sill A nearly horizontal tabletop-shaped tabular intrusion that occurs between the layers of country rock.
siltstone Fine-grained sedimentary rock generally composed of very small quartz grains.
sinkhole A circular depression in the land that forms when an underground cavern collapses.
slab-pull force The force that downgoing plates (or slabs) apply to oceanic lithosphere at a convergent margin.
slate Fine-grained, low-grade metamorphic rock, formed by the metamorphism of shale.
slaty cleavage The foliation typical of slate, and reflective of the preferred orientation of slate's clay minerals, that allows slate to be split into thin sheets.
slickensides The polished surface of a fault caused by slip on the fault; lineated slickensides also have grooves that indicate the direction of fault movement.
slip face The leeward slope of a dune; sand that builds up at the crest of the dune slides down this face; slip faces are preserved as cross beds within sandstone layers.
slip lineations Linear marks on a fault surface created during movement on the fault; some slip lineations are defined by grooves, some by aligned mineral fibers.
slope failure The downslope movement of material on an unstable slope.
slumping Downslope movement in which a mass of regolith detaches from its substrate along a spoon-shaped, sliding surface and slips downward semicoherently.
smelting The heating of a metal-containing rock to high temperatures in a fire so that the rock will decompose to yield metal plus a nonmetallic residue (slag).
snotite A long gob of bacteria that slowly drips from the ceiling of a cave.
snowball Earth A model proposing that, at times during Earth history, glaciers covered all land, and the entire ocean surface froze.
snow line The boundary above which snow remains all year.
soda straw A hollow stalactite in which calcite precipitates around the outside of a drip.
soil Sediment that has undergone changes at the surface of the Earth, including reaction with rainwater and the addition of organic material.
soil erosion The removal of soil by wind and runoff.
soil horizon Distinct zones within a soil, distinguished from each other by factors such as chemical composition and organic content.
soil moisture Underground water that wets the surface of the mineral grains and organic material making up soil, but lies above the water table.
soil profile A vertical sequence of distinct zones of soil.
Solar System Our Sun and all the materials that orbit it (including planets, moons, asteroids, Kuiper Belt objects, and Oort Cloud objects).
solar wind A stream of particles with enough energy to escape from the Sun's gravity and flow outward into space.
solid-state diffusion The slow movement of atoms or ions through a solid.
solidus The highest temperature at which all the components of a material are solid; at the solidus temperature, the material begins to melt.
solifluction The type of creep characteristic of tundra regions; during the summer, the uppermost layer of permafrost melts, and the soggy, weak layer of ground then flows slowly downslope in overlapping sheets.
solstice A day on which the polar ends of the terminator (the boundary between the day hemisphere and the night hemisphere) lie 23.5° away from the associated geographic poles.
solution A material containing dissolved ions.
Sonoma orogeny A convergent-margin mountain-building event that took place on the western coast of North America in the Late Permian and Early Triassic periods.
sorting (1) The range of clast sizes in a collection of sediment; (2) the degree to which sediment has been separated by flowing currents into different-sized fractions.
source rock A rock (organic-rich shale) containing the raw materials from which hydrocarbons eventually form.
southeast tradewinds Tradewinds in the southern hemisphere, which start flowing northward, deflect to the west, and end up flowing from southeast to northwest.
southern oscillation The movement of atmospheric pressure cells back and forth across the Pacific Ocean, in association with El Niño.
specific gravity A number representing the density of a mineral, as specified by the ratio between the weight of a volume of the mineral and the weight of an equal volume of water.
speleothem A formation that grows in a limestone cave by the accumulation of travertine precipitated from water solutions dripping in a cave or flowing down the wall of a cave.
sphericity The measure of the degree to which a clast approaches the shape of a sphere.
spreading boundary *See* Divergent plate boundary.
spreading rate The rate at which sea floor moves away from a mid-ocean ridge axis, as measured with respect to the sea floor on the opposite side of the axis.
spring A natural outlet from which groundwater flows up onto the ground surface.
spring tide An especially high tide that occurs when the Sun is on the same side of the Earth as the Moon.
stable air Air that does not have a tendency to rise rapidly.
stable slope A slope on which downward sliding is unlikely.
stalactite An icicle-like cone that grows from the ceiling of a cave as dripping water precipitates limestone.
stalagmite An upward-pointing cone of limestone that grows when drips of water hit the floor of a cave.
standing wave A wave whose crest and trough remain in place as water moves through the wave.
star An object in the Universe in which fusion reactions occur pervasively, producing vast amounts of energy; our Sun is a star.
star dune A constantly changing dune formed by frequent shifts in wind direction; it consists of overlapping crescent dunes pointing in many different directions.
steady state condition The condition when proportions of a chemical in different reservoirs remain fairly constant even though there is a constant flux (flow) of the chemical among the reservoirs.
stellar nucleosynthesis The production of new, larger atoms by fusion reactions in stars; the process generates more massive elements that were not produced by the Big Bang.
stellar wind The stream of atoms emitted from a star into space.
stick-slip behavior Stop-start movement along a fault plane caused by friction, which prevents movement until stress builds up sufficiently.

stone rings Ridges of cobbles between adjacent bulges of permafrost ground.
stoping A process by which magma intrudes; blocks of wall rock break off and then sink into the magma.
storm An episode of severe weather in which winds, precipitation, and in some cases lightning become strong enough to be bothersome and even dangerous.
storm-center velocity A storm's (hurricane's) velocity along its track.
storm surge Excess seawater driven landward by wind during a storm; the low atmospheric pressure beneath the storm allows sea level to rise locally, increasing the surge.
strain The change in shape of an object in response to deformation (i.e., as a result of the application of a stress).
strata A succession of several layers or beds together.
stratified drift Glacial sediment that has been redistributed and stratified by flowing water.
stratigraphic column A cross-section diagram of a sequence of strata summarizing information about the sequence.
stratigraphic formation A recognizable layer of a specific sedimentary rock type or set of rock types, deposited during a certain time interval, that can be traced over a broad region.
stratigraphic group Several adjacent stratigraphic formations in a succession.
stratigraphic sequence An interval of strata deposited during periods of relatively high sea level, and bounded above and below by regional unconformities.
stratopause The temperature pause that marks the top of the stratosphere.
stratosphere The stable, stratified layer of atmosphere directly above the troposphere.
stratovolcano A large, cone-shaped subaerial volcano consisting of alternating layers of lava and tephra.
stratus cloud A thin, sheet-like, stable cloud.
streak The color of the powder produced by pulverizing a mineral on an unglazed ceramic plate.
stream A ribbon of water that flows in a channel.
streambed The floor of a stream.
stream capacity The total quantity of sediment a stream carries.
stream capture (stream piracy) The situation in which headward erosion causes one stream to intersect the course of another, previously independent stream, so that the intersected stream starts to flow down the channel of the first stream.
stream competence The maximum particle size that a stream can carry.
stream gradient The slope of a stream's channel in the downstream direction.
stream piracy A process that happens when headward erosion by one stream causes the stream to intersect the course of another stream and capture its flow.
stream rejuvenation The renewed downcutting of a stream into a floodplain or peneplain, caused by a relative drop of the base level.
stream terrace When a stream downcuts through the alluvium of a floodplain so that a new, lower floodplain develops and the original floodplain becomes a step-like platform.
stress The push, pull, or shear that a material feels when subjected to a force; formally, the force applied per unit area over which the force acts.
stretching The process during which a layer of rock or a region of crust becomes longer.
striations Linear scratches in rock.
strike-slip fault A fault in which one block slides horizontally past another (and therefore parallel to the strike line), so there is no relative vertical motion.
strip mining The scraping off of all soil and sedimentary rock above a coal seam in order to gain access to the seam.
stromatolite Layered mounds of sediment formed by cyanobacteria; cyanobacteria secrete a mucous-like substance to which sediment sticks, and as each layer of cyanobacteria gets buried by sediment, it colonizes the surface of the new sediment, building a mound upward.
structural control The condition in which geologic structures, such as faults, affect the distribution and drainage of water or the shape of the land surface.
subaerial Pertaining to land regions above sea level (i.e., under air).
subduction The process by which one oceanic plate bends and sinks down into the asthenosphere beneath another plate.
subduction zone The region along a convergent boundary where one plate sinks beneath another.
sublimation The evaporation of ice directly into vapor without first forming a liquid.
submarine canyon A narrow, steep canyon that dissects a continental shelf and slope.
submarine fan A wedge-shaped accumulation of sediment at the base of a submarine slope; fans usually accumulate at the mouth of a submarine canyon.
submarine slump The underwater downslope movement of a semicoherent block of sediment along a weak mud detachment.
submergent coast A coast at which the land is sinking relative to sea level.
subpolar low The rise of air where the surface flow of a polar cell converges with the surface flow of a Ferrel cell, creating a low-pressure zone in the atmosphere.
subsidence The vertical sinking of the Earth's surface in a region, relative to a reference plane.
substrate A general term for material just below the ground surface.
subtropical high (subtropical divergence zone) A belt of high pressure in the atmosphere at 30° latitude formed where the Hadley cell converges with th Ferrel cell, causing cool, dense air to sink.
subtropics Desert climate regions that lie on either side of the equatorial tropics between the lines of 20° and 30° north or south of the equator.
summit eruption An eruption that occurs in the summit crater of a volcano.
sunspot cycle The cyclic appearance of large numbers of sunspots (black spots thought to be magnetic storms on the Sun's surface) every 9 to 11.5 years.
supercontinent cycle The process of change during which supercontinents develop and later break apart, forming pieces that may merge once again in geologic time to make yet another supercontinent.
supernova A short-lived, very bright object in space that results from the cataclysmic explosion marking the death of a very large star; the explosion ejects large quantities of matter into space to form new nebulae.
superplume A huge mantle plume.
superposed stream A stream whose geometry has been laid down on a rock structure and is not controlled by the structure.
superrotation The faster rotation of the core, relative to the rest of the Earth.

supervolcano A volcano that erupts a vast amount (more than 1,000 cubic km) of volcanic material during a single event; none have erupted during recorded human history.
surface current An ocean current in the top 100 m of water.
surface load (bed load) Sediment that rolls and bounce along the ground (under the air) or along a stream bed (under water).
surface water Liquid or seasonally frozen water that resides at the surface of the Earth in oceans, lakes, streams, and marshes.
surface waves Seismic waves that travel along the Earth's surface.
surface westerlies The prevailing surface winds in North America and Europe, which come out of the west or southwest.
surf zone A region of the shore in which breakers crash onto the shore.
surge (glacial) A pulse of rapid flow in a glacier.
suspended load Tiny solid grains carried along by a stream without settling to the floor of the channel.
sustainable growth The ability of society to prosper without depleting the supply of natural resources, and without destroying the environment.
swamp A wetland dominated by trees.
swash The upward surge of water that flows up a beach slope when breakers crash onto the shore.
S-waves Seismic shear waves that pass through the body of the Earth.
S-wave shadow zone A band between 103° and 180° from the epicenter of an earthquake inside of which S-waves do not arrive at seismograph stations.
swelling clay Clay possessing a mineral structure that allows it to absorb water between its layers and thus swell to several times its original size.
symmetry The condition in which the shape of one part of an object is a mirror image of the other part.
syncline A trough-shaped fold whose limbs dip toward the hinge.
systematic joints Long planar cracks that occur fairly regularly throughout a rock body.

tabular intrusions Sheet intrusions that are planar and of roughly uniform thickness.
Taconic orogeny A convergent mountain-building event that took place around 400 million years ago, in which a volcanic island arc collided with eastern North America.
tailings pile A pile of waste rock from a mine.
talus A sloping apron of fallen rock along the base of a cliff.
tar Hydrocarbons that exist in solid form at room temperature.
tarn A lake that forms at the base of a cirque on a glacially eroded mountain.
tar sand Sandstone reservoir rock in which less viscous oil and gas molecules have either escaped or been eaten by microbes, so that only tar remains.
taxonomy The study and classification of the relationships among different forms of life.
tectonic foliation A planar fabric, such as cleavage, schistocity, or gneissic banding, that develops in rocks; caused by compression or shearing during deformation (e.g., during mountain building).
temperature A measure of the hotness or coldness of a material.
tension A stress that pulls on a material and could lead to stretching.
tephra Unconsolidated accumulations of pyroclastic grains.
terminal moraine The end moraine at the farthest limit of glaciation.
terminator The boundary between the half of the Earth that has daylight and the half experiencing night.
terrace The elevated surface of an older floodplain into which a younger floodplain had cut down.
terrestrial planets Planets that are of comparable size and character to the Earth and consist of a metallic core surrounded by a rock mantle.
thalweg The deepest part of a stream's channel.
theory A scientific idea supported by an abundance of evidence that has passed many tests and failed none.
theory of plate tectonics The theory that the outer layer of the Earth (the lithosphere) consists of separate plates that move with respect to one another.
thermal energy The total kinetic energy in a material due to the vibration and movement of atoms in the material.
thermal metamorphism Metamorphism caused by heat conducted into country rock from an igneous intrusion.
thermocline A boundary between layers of water with differing temperatures.
thermohaline circulation The rising and sinking of water driven by contrasts in water density, which is due in turn to differences in temperature and salinity; this circulation involves both surface and deep-water currents in the ocean.
thermosphere The outermost layer of the atmosphere, containing very little gas.
thin section A 3/100-mm-thick slice of rock that can be examined with a petrographic microscope.
thin-skinned deformation A distinctive style of deformation characterized by displacement on faults that terminate at depth along a subhorizontal detachment fault.
thrust fault A gently dipping reverse fault; the hanging-wall block moves up the slope of the fault.
tidal bore A visible wall of water that moves toward shore with the rising tide in quiet waters.
tidal flat A broad, nearly horizontal plain of mud and silt, exposed or nearly exposed at low tide but totally submerged at high tide.
tidal power Energy produced by the daily rise and fall of the tides; people can utilize this energy, for example, by damming a bay or estuary, so that water passes through turbines when the tide changes.
tidal reach The difference in sea level between high tide and low tide at a given point.
tide The daily rising or falling of sea level at a given point on the Earth.
tide-generating force The force, caused in part by the gravitational attraction of the Sun and Moon and in part by the centrifugal force created by the Earth's spin, that generates tides.
tidewater glacier A glacier that has entered the sea along a coast.
till A mixture of unsorted mud, sand, pebbles, and larger rocks deposited by glaciers.
tillite A rock formed from hardened ancient glacial deposits and consisting of larger clasts distributed through a matrix of sandstone and mudstone.
toe (terminus) The leading edge or margin of a glacier.
tombolo A narrow ridge of sand that links a sea stack to the mainland.
topographical map A map that uses contour lines to represent variations in elevation.
topography Variations in elevation.
topsoil The top soil horizons, which are typically dark and nutrient-rich.
tornado A near-vertical, funnel-shaped cloud in which air rotates extremely rapidly around the axis of the funnel.
tornado swarm Dozens of tornadoes produced by the same storm.
tower karst A karst landscape in which steep-sided residual bedrock towers remain between sinkholes.

trace fossil Fossilized imprints or debris that an organism leaves behind while moving on or through sediment; examples include footprints, burrows, and fecal matter.
transform fault A fault marking a transform plate boundary; along mid-ocean ridges, transform faults are the actively slipping segment of a fracture zone between two ridge segments.
transform plate boundary A boundary at which one lithosphere plate slips laterally past another.
transgression The inland migration of shoreline resulting from a rise in sea level.
transition zone The middle portion of the mantle, from 400 to 670 km deep, in which there are several jumps in seismic velocity.
transpiration The release of moisture as a metabolic by-product.
transverse dune A simple, wave-like dune that appears when enough sand accumulates for the ground surface to be completely buried, but only moderate winds blow.
trap A subsurface configuration of seal rocks and structures that keep oil and/or gas underground, so it doesn't seep out at the surface.
travel-time curve A graph that plots the time since an earthquake began on the vertical axis and the distance to the epicenter on the horizontal axis.
travertine A rock composed of crystalline calcium carbonate ($CaCO_3$) formed by chemical precipitation from groundwater that has seeped out at the ground surface.
trellis network A drainage system that develops across a landscape of parallel valleys and ridges so that major tributaries flow down the valleys and join a trunk stream that cuts through the ridge; the resulting map pattern resembles a garden trellis.
trench A deep, elongate trough bordering a volcanic arc; a trench defines the trace of a convergent plate boundary.
triangulation The method for determining the map location of a point from knowing the distance between that point and three other points; this method is used to locate earthquake epicenters.
tributary A smaller stream that flows into a larger stream.
triple junction A point where three lithosphere plate boundaries intersect.
tropical depression A tropical storm with winds reaching up to 61 km per hour; such storms develop from tropical disturbances, and may grow to become hurricanes.
tropical disturbance Cyclonic winds that develop in the tropics.
tropopause The temperature pause marking the top of the troposphere.
troposphere The lowest layer of the atmosphere, where air undergoes convection and where most wind and clouds develop.
truncated spur A spur (elongate ridge between two valleys) whose end was eroded off by a glacier.
trunk stream The single larger stream into which an array of tributaries flow.
tsunami A large wave along the sea surface triggered by an earthquake or large submarine slump.
tuff A pyroclastic igneous rock composed of volcanic ash and fragmented pumice, formed when accumulations of the debris cement together.
tundra A cold, treeless region of land at high latitudes, supporting only species of shrubs, moss, and lichen capable of living on permafrost.
turbidite A graded bed of sediment built up at the base of a submarine slope and deposited by turbidity currents.
turbidity current A submarine avalanche of sediment and water that speeds down a submarine slope.
turbulence The chaotic twisting, swirling motion in flowing fluid.
typhoon The equivalent of a hurricane in the western Pacific Ocean.
ultimate base level Sea level; the level below which a trunk stream cannot cut.
ultramafic A term used to describe igneous rocks or magmas that are rich in iron and magnesium and very poor in silica.
unconfined aquifer An aquifer that intersects the surface of the Earth.
unconformity A boundary between two different rock sequences representing an interval of time during which new strata were not deposited and/or were eroded.
unconsolidated Consisting of unattached grains.
undercutting Excavation at the base of a slope that results in the formation of an overhang.
undersaturated A term used to describe a solution capable of holding more dissolved ions.
Universe All of space and all the matter and energy within it.
unsaturated zone The region of the subsurface above the water table.
unstable air Air that is significantly warmer than air above and has a tendency to rise quickly.
unstable ground Land capable of slumping or slipping downslope in the near future.
unstable slope A slope on which sliding will likely happen.
updraft Upward-moving air.
upper mantle The uppermost section of the mantle, reaching down to a depth of 400 km.
upwelling zone A place where deep water rises in the ocean, or where hot magma rises in the asthenosphere.
U-shaped valley A steep-walled valley shaped by glacial erosion into the form of a U.

vacuum Space that contains very little matter in a given volume (e.g., a region in which air has been removed).
valley A trough with sloping walls, cut into the land by a stream.
valley glacier A river of ice that flows down a mountain valley.
Van Allen radiation belts Belts of solar wind particles and cosmic rays that surround the Earth, trapped by Earth's magnetic field.
van der Waals bonding The relatively weak attachment of two elements or molecules due to their polarity and not due to covalent or ionic bonding.
varve A pair of thin layers of glacial lake-bed sediment, one consisting of silt brought in during the spring floods and the other of clay deposited during the winter when the lake's surface freezes over and the water is still.
vascular plant A plant with woody tissue and seeds and veins for transporting water and food.
vein A seam of minerals that forms when dissolved ions carried by water solutions precipitate in cracks.
vein deposit A hydrothermal deposit in which the ore minerals occur in veins that fill cracks in preexisting rocks.
velocity-versus-depth curve A graph that shows the variation in the velocity of seismic waves with increasing depth in the Earth.
ventifact (faceted rock) A desert rock whose surface has been faceted by the wind.
vesicles Open holes in igneous rock formed by the preservation of bubbles in magma as the magma cools into solid rock.
viscosity The resistance of material to flow.
volatiles (volatile materials) Elements or compounds such as H_2O and CO_2 that evaporate at relatively low temperatures and can exist in gaseous forms at the Earth's surface.
volatility A specification of the ease with which a material evaporates.

volcanic agglomerate An accumulation consisting dominantly of volcanic bombs and other relatively large chunks of igneous material.
volcanic arc A curving chain of active volcanoes formed adjacent to a convergent plate boundary.
volcanic ash Tiny glass shards formed when a fine spray of exploded lava freezes instantly upon contact with the atmosphere.
volcanic bomb A large piece of pyroclastic debris thrown into the atmosphere during a volcanic eruption.
volcanic breccia A pyroclastic igneous rock that consists of fragments of volcanic debris, which either fall through the air and accumulate, or form when solidfying lava breaks up during flow.
volcanic danger-assessment map A map delineating areas that lie in the path of potential lava flows, lahars, debris flows, or pyroclastic flows of an active volcano.
volcanic debris flow A mixture of water and pyroclastic debris that moves downslope like wet concrete.
volcanic gas Elements or compounds that bubble out of magma or lava in gaseous form.
volcanic island arc The volcanic island chain that forms on the edge of the overriding plate where one oceanic plate subducts beneath another oceanic plate.
volcaniclastic deposit An accumulation of large quantities of fragmental igneous material (including both pyroclastic debris, and water-transported debris).
volcaniclastic rock A material composed of cemented-together grains of volcanic material; it includes both pyroclastic rocks and rocks formed from accumulations of water-transported volcanic debris.
volcano (1) A vent from which melt from inside the Earth spews out onto the planet's surface; (2) a mountain formed by the accumulation of extrusive volcanic rock.
V-shaped valley A valley whose cross-sectional shape resembles the shape of a V; the valley probably has a river running down the point of the V.

Wadati-Benioff zone A sloping band of seismicity defined by intermediate- and deep-focus earthquakes that occur in the downgoing slab of a convergent plate boundary.
wadi The name used in the Middle East and North Africa for a dry wash.
warm front A front in which warm air rises slowly over cooler air in the atmosphere.
waste rock Rock dislodged by mining activity yet containing no ore minerals.
waterfall A place where water drops over an escarpment.
water gap An opening in a resistant ridge where a trunk river has cut through the ridge.
watershed The region that collects water that feeds into a given drainage network.
water table The boundary, approximately parallel to the Earth's surface, that separates substrate in which groundwater fills the pores from substrate in which air fills the pores.
wave A disturbance that transmits energy from one point to another in the form of periodic motions.
wave base The depth, approximately equal in distance to half a wavelength in a body of water, beneath which there is no wave movement.
wave-cut bench A platform of rock, cut by wave erosion, at the low-tide line that was left behind a retreating cliff.
wave-cut notch A notch in a coastal cliff cut out by wave erosion.
wave erosion The combined effects of the shattering, wedging, and abrading of a cliff face by waves and the sediment they carry.
wave front The boundary between the region through which a wave has passed and the region through which it has not yet passed.
wavelength The horizontal difference between two adjacent wave troughs or two adjacent crests.
wave refraction (ocean) The bending of waves as they approach a shore so that their crests make no more than a 5° angle with the shoreline.
weather Local-scale conditions as defined by temperature, air pressure, relative humidity, and wind speed.
weathered rock Rock that has reacted with air and/or water at or near the Earth's surface.
weathering The processes that break up and corrode solid rock, eventually transforming it into sediment.
weather system A specific set of weather conditions, reflecting the configuration of air movement in the atmosphere, that affects a region for a period of time.
welded tuff Tuff formed by the welding together of hot volcanic glass shards at the base of pyroclastic flows.
well A hole in the ground dug or drilled in order to obtain water.
Western Interior Seaway A north-south-trending seaway that ran down the middle of North America during the Late Cretaceous Period.
wet-bottom (temperate) glacier A glacier with a thin layer of water at its base, over which the glacier slides.
wetted perimeter The area in which water touches a stream channel's walls.
wind abrasion The grinding away at surfaces in a desert by windblown sand and dust.
wind gap An opening through a high ridge that developed earlier in geologic history by stream erosion, but that is now dry.

xenolith A relict of wall rock surrounded by intrusive rock when the intrusive rock freezes.

yardang A mushroom-like column with a resistant rock perched on an eroding column of softer rock; created by wind abrasion in deserts where a resistant rock overlies softer layers of rock.
yazoo stream A small tributary that runs parallel to the main river in a floodplain because the tributary is blocked from entering the main river by levees.
Younger Dryas An interval of cooler temperatures that took place 4,500 years ago during a general warming/glacier-retreat period.

zeolite facies The metamorphic facies just above diagenetic conditions, under which zeolite minerals form.
zone of ablation The area of a glacier in which ablation (melting, sublimation, calving) subtracts from the glacier.
zone of accumulation (1) The layer of regolith in which new minerals precipitate out of water passing through, thus leaving behind a load of fine clay; (2) the area of a glacier in which snowfall adds to the glacier.
zone of aeration *See* Unsaturated zone.
zone of leaching The layer of regolith in which water dissolves ions and picks up very fine clay; these materials are then carried downward by infiltrating water.

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Chapter 19

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