

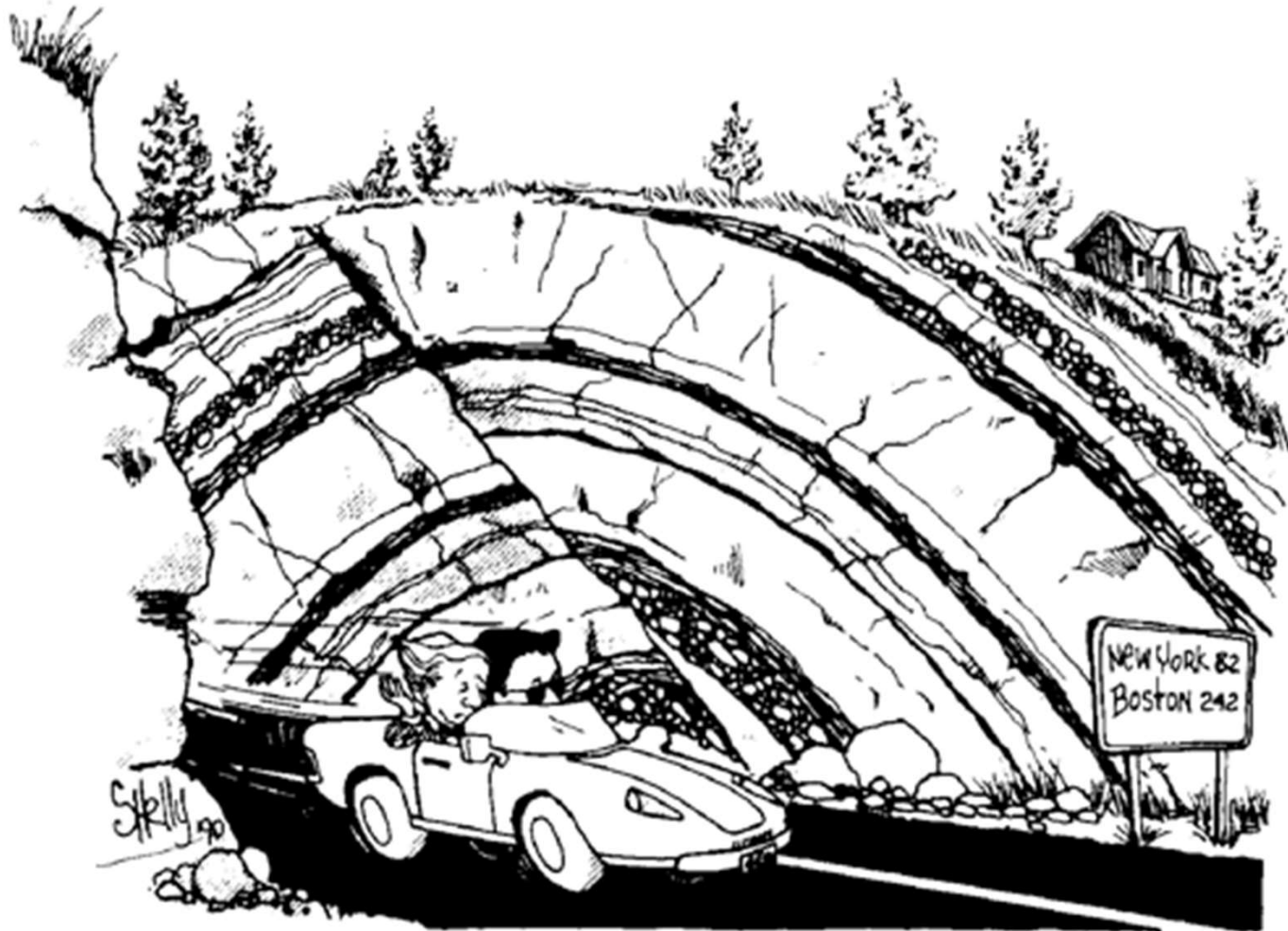
PHYS 3800: Physical Geology

Chapter 4: Up from the Inferno: Magma and Igneous Rocks



Thought for the Day

EARTHQUAKES. HERE ON THE EAST COAST? IMPOSSIBLE. THEY CAN'T HAPPEN HERE - THEY'VE NEVER HAPPENED HERE!



Introduction

- **Volcano**—a vent where molten rock comes out of Earth
 - **Example: Kilauea Volcano, Hawaii**
 - ▶ Hot ($\sim 1,200^{\circ}\text{C}$) lava pools around the volcanic vent.
 - ▶ Hot, syrupy lava runs downhill as a lava flow.
 - ▶ The lava flow slows, loses heat, and crusts over.
 - ▶ Finally, the flow stops and cools, forming an igneous rock.



Introduction

- Igneous rock is formed by cooling from a melt.
 - Magma—melted rock below ground
 - Lava—melted rock once it has reached the surface
- Igneous rock freezes at high temperatures (T).
 - 1,100 ° C–650 ° C, depending on composition.
- There are many types of igneous rock.



Introduction

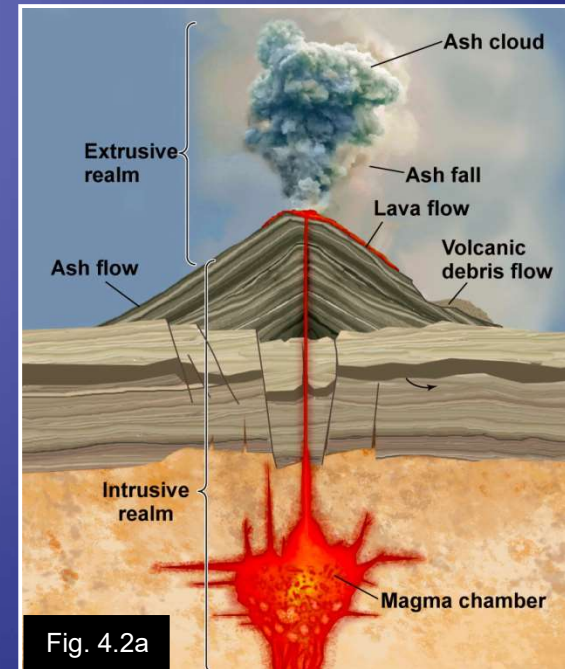
■ In this chapter:

- How igneous rocks are formed
- How magma and lava move
- Why there are different igneous rocks
- How to classify the many types of igneous rocks
- Tectonic settings that create igneous rocks

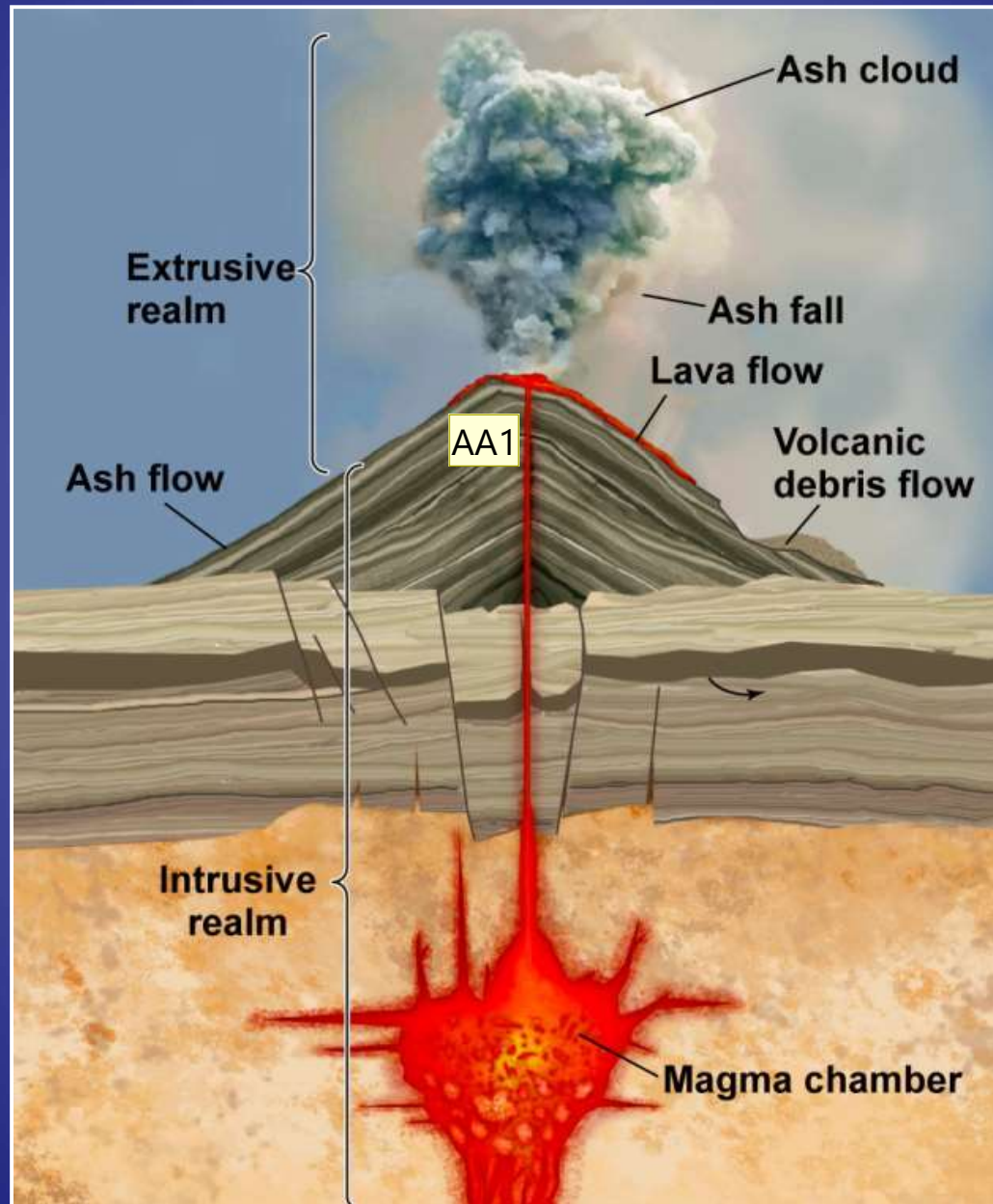


Igneous Rocks

- Melted rock can cool above or below ground.
 - Extrusive igneous rocks—cool quickly at the surface
 - ▶ Lava flows—streams or mounds of cooled melt
 - ▶ Pyroclastic debris—cooled fragments
 - ✓ Volcanic ash—fine particles of volcanic glass
 - ✓ Volcanic rock—fragmented by eruption



Igneous Rocks



Slide 7

AA1

Important for final exam and maybe exam 1

Alrediny, Ahmed, 1/28/2020

Igneous Rocks

- Melted rock can cool above or below ground.
 - Intrusive igneous rocks—cool out of sight, underground
 - Much greater volume than extrusive igneous rocks
 - Cooling rate is slower than for extrusives.
 - ▶ Large volume magma chambers
 - ▶ Smaller volume tabular bodies or columns



Fig. 4.9b

Why Does Magma Form?

- Magma is not everywhere below Earth's crust.
- Magma only forms in special tectonic settings.
 - Partial melting occurs in the crust and upper mantle.
 - Melting is caused by
 - ▶ pressure release.
 - ▶ volatile addition.
 - ▶ heat transfer.



Fig. 4.1a

Causes of Melting

- **Decrease in pressure (P)—decompression**
 - The base of the crust is hot enough to melt mantle rock.
 - But, due to high P, the rock doesn't melt.
 - Melting will occur if P is decreased.
 - ▶ P drops when hot rock is carried to shallower depths.
 - ✓ Mantle plumes
 - ✓ Beneath rifts
 - ✓ Beneath mid-ocean ridges

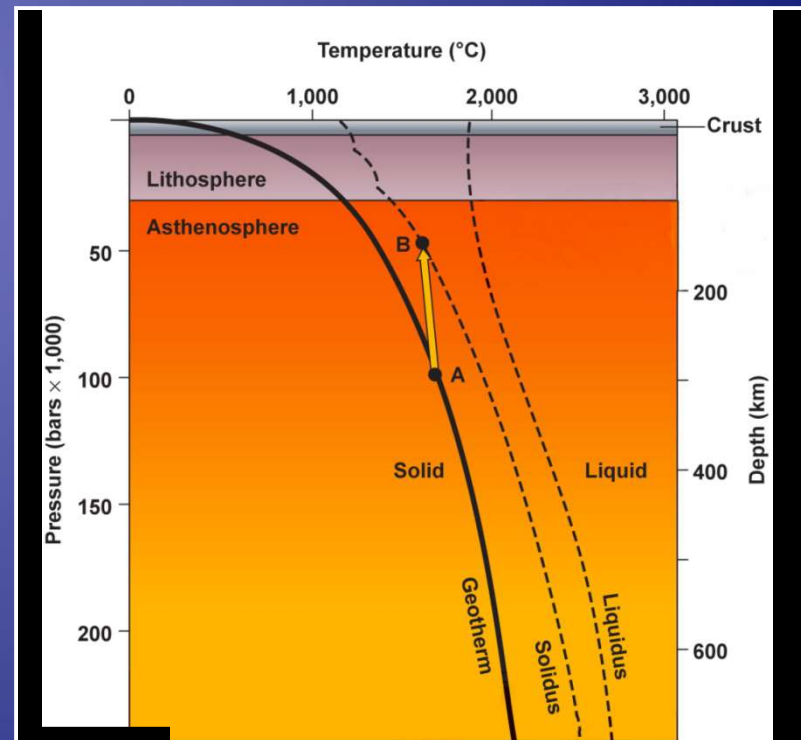


Fig. 4.3a

Causes of Melting

- P drops when hot rock is carried to shallower depths.
 - Mantle plumes
 - Beneath rifts
 - Under mid-ocean ridges

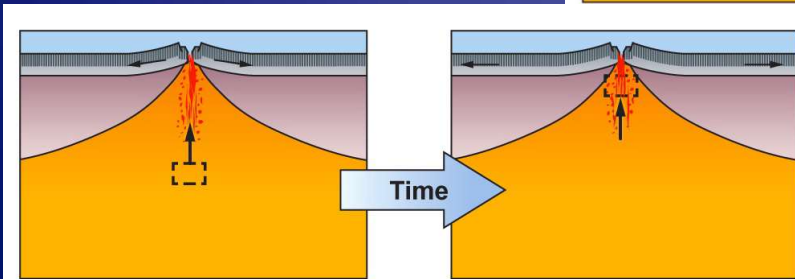
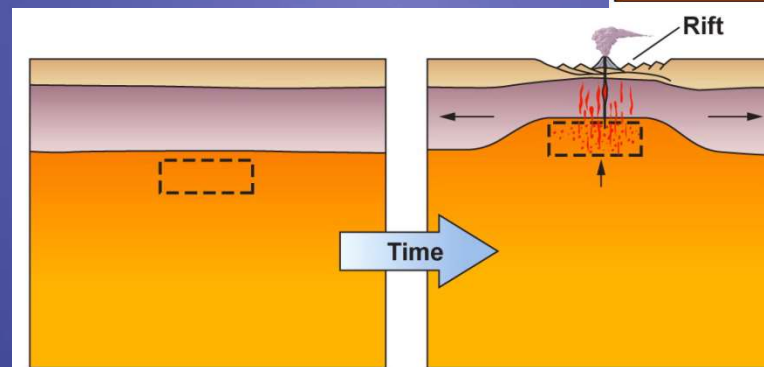
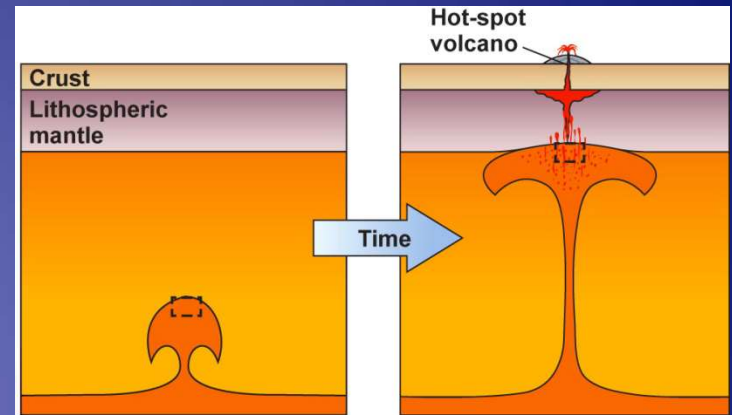


Fig. 4.3b

Causes of Melting

- Addition of volatiles (flux melting)
 - Volatiles lower the melting T of a hot rock.
 - Common volatiles include H_2O and CO_2 .
 - Subduction carries water into the mantle, melting rock.

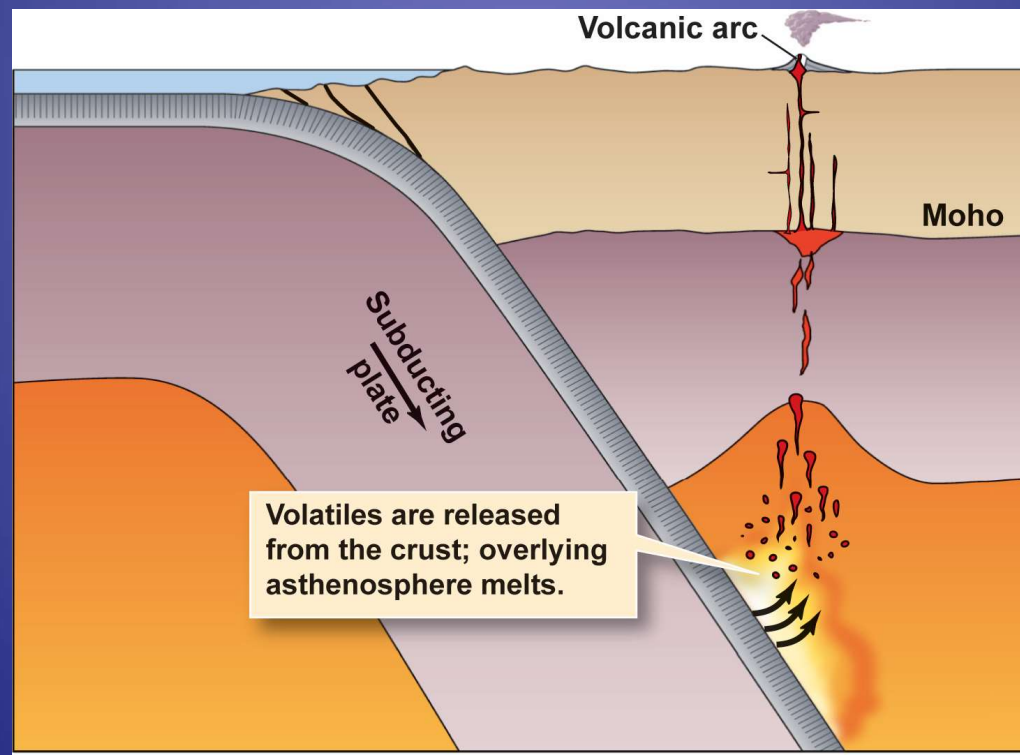
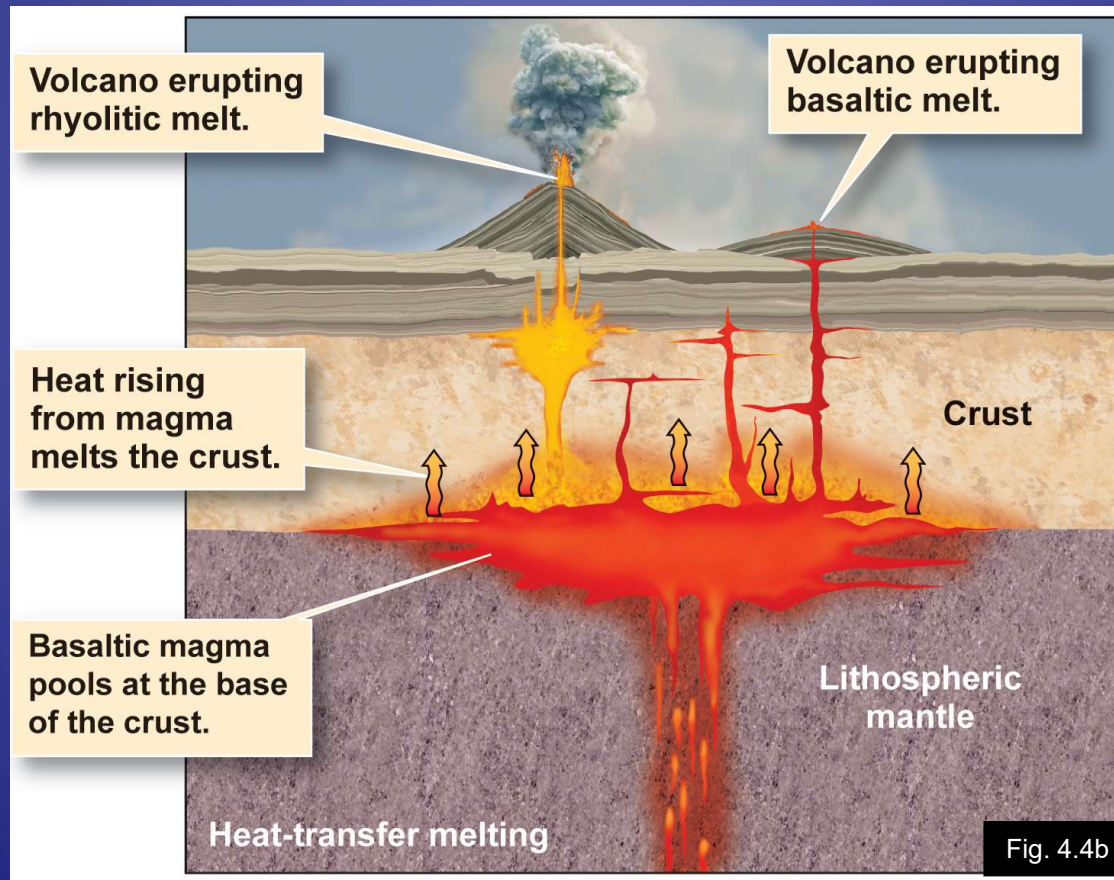


Fig. 4.4a

Causes of Melting

■ Heat transfer melting

- Rising magma carries mantle heat with it.
- This raises the T in nearby crustal rock, which then melts.



What Is Magma Made Of?

- **Magma** have three components (solid, liquid, and gas).
 - **Solid**—solidified mineral crystals are carried in the melt.
 - **Liquid**—the melt itself is composed of mobile ions.
 - ▶ Dominantly Si and O; lesser Al, Ca, Fe, Mg, Na, and K
 - ▶ Other ions to a lesser extent.
 - **Different mixes of elements yield different magmas.**



What Is Magma Made Of?

- Gas—variable amounts of dissolved gas occur in magma.
 - ▶ Dry magma—scarce volatiles
 - ▶ Wet magma—up to 15% volatiles
 - ✓ Water vapor (H_2O)
 - ✓ Carbon dioxide (CO_2)
 - ✓ Sulfur dioxide (SO_2)
 - ✓ Nitrogen (N_2)
 - ✓ Hydrogen (H_2)



Major Types of Magma

- There are four major magma types based on % silica (SiO_2).

● Felsic (feldspar and silica)	66–76% SiO_2
● Intermediate	52–66% SiO_2
● Mafic (Mg- and Fe-rich)	45–52% SiO_2
● Ultramafic	38–45% SiO_2



Major Types of Magma

- Why are there different magma compositions?
- Magmas vary chemically due to
 - initial source rock compositions.
 - partial melting.
 - assimilation.
 - magma mixing.



Magma Variation

- Source rock dictates initial magma composition.
 - Mantle source—ultra-mafic and mafic magmas.
 - Crustal source—mafic, intermediate, and felsic magmas.



Partial Melting

- Upon melting, rocks rarely dissolve completely.
- Instead, only a portion of the rock melts.
 - Si-rich minerals melt first; Si-poor minerals melt last.
- Partial melting, therefore, yields a silica-rich magma.
- Removing a partial melt from its source creates
 - felsic magma.
 - mafic residue.

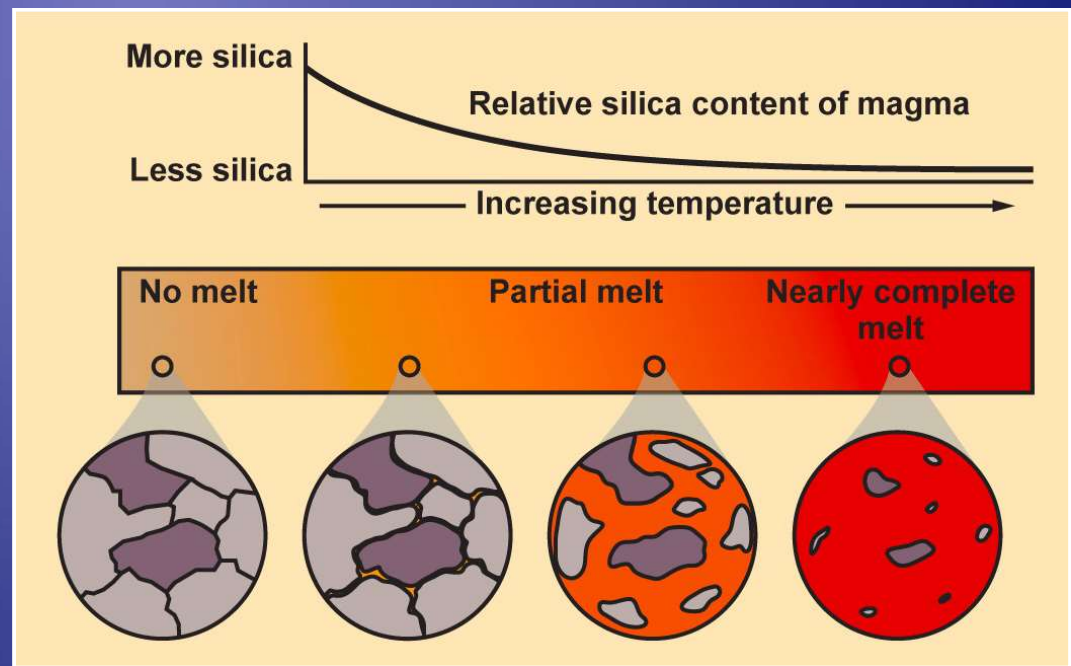
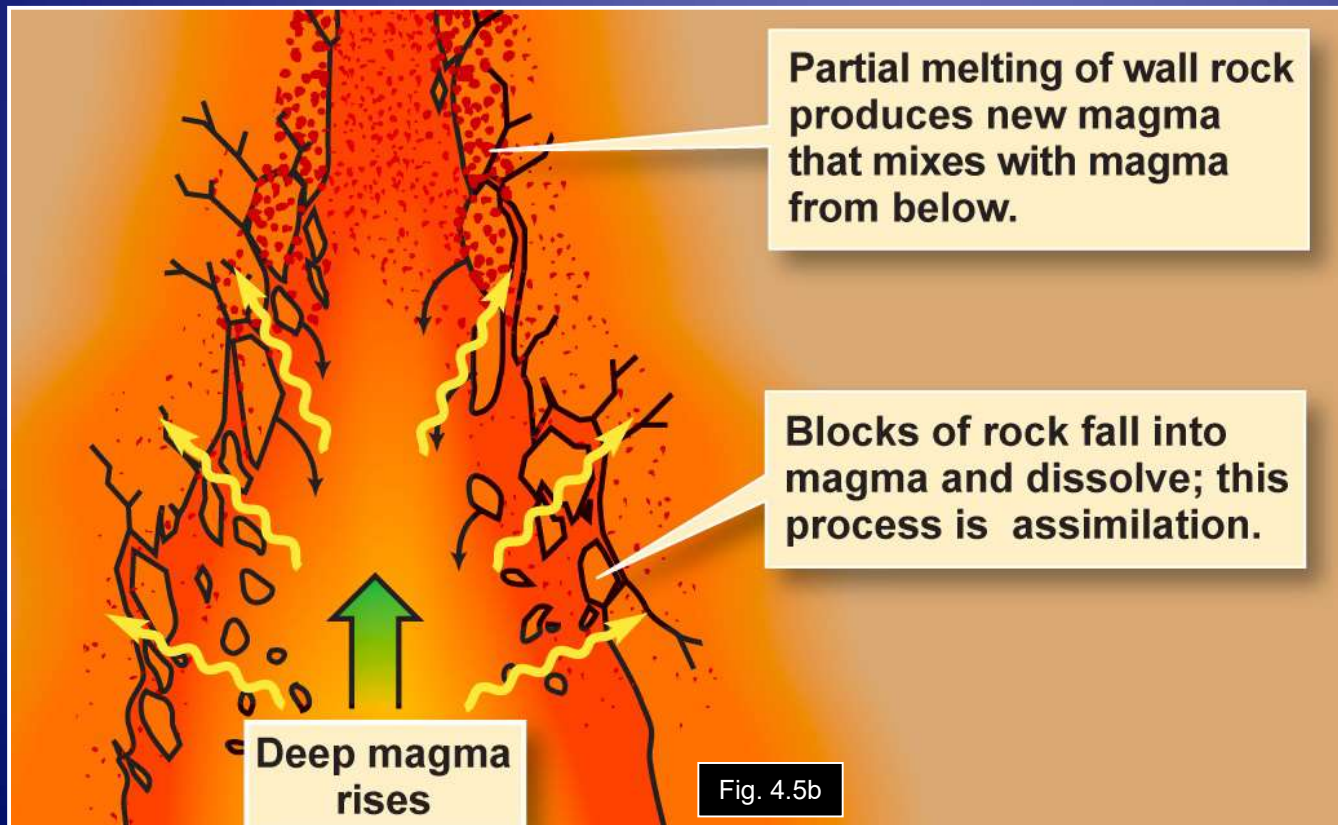


Fig. 4.5a

Assimilation

- Magma melts the wall rock it passes through.
- Blocks of wall rock (xenoliths) fall into magma.
- Assimilation of these rocks alters magma composition.



Mafic xenoliths in granite. The one below has partially dissolved.



Magma Mixing

- Different magmas may blend in a magma chamber.
- The result combines the characteristics of the two.
- Often magma mixing is incomplete, resulting in blobs of one rock type suspended within the other.



Magma Movement

- Magma doesn't stay put; it tends to rise upward.
 - Magma may move upward in the crust.
 - Magma may breach the surface—a volcano.
- This transfers mass from deep to shallow parts of Earth.
 - A crucial process in the Earth System
 - Provides the raw material for soil, atmosphere, and ocean



Magma Movement

■ Why does magma rise?

- It is less dense than surrounding rocks.
 - ▶ Magma is more buoyant.
 - ▶ Buoyancy lifts magma upward.
- Weight of overlying rock creates pressure.
 - ▶ Pressure squeezes magma upward.
 - ▶ It is like mud squeezed between your toes.



Magma Movement

- Speed of magma flow governed by viscosity.
 - Lower viscosity eases movement.
 - Lower viscosity is generated by
 - ▶ higher T.
 - ▶ lower SiO_2 content.
 - ▶ higher volatile content.



Magma Movement

- Viscosity depends on temperature, volatiles, and silica.
 - Temperature:
 - ▶ hot = lower viscosity; cooler = higher viscosity
 - Volatile content:
 - ▶ More volatiles—lower viscosity
 - ▶ Less volatiles—higher viscosity
 - Silica (SiO_2) content:
 - ▶ Less SiO_2 (mafic)—lower viscosity.
 - ▶ More SiO_2 (felsic)—higher viscosity.

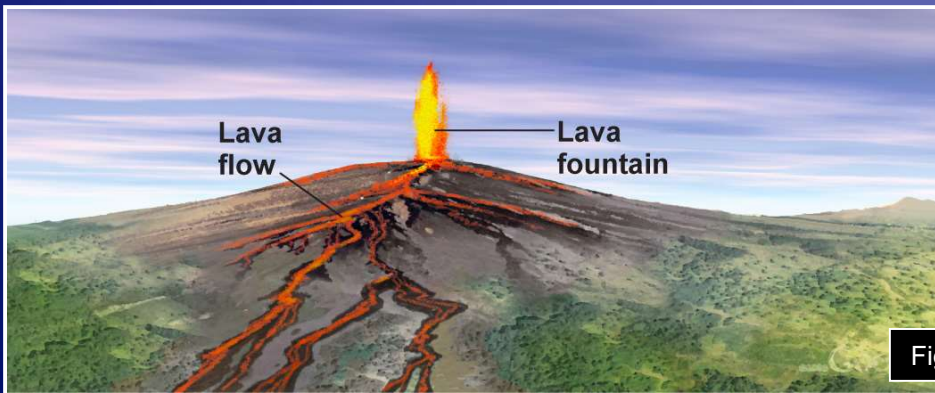


Fig. 4.6a, b

Making Igneous Rock

- **Cooling rate**—how fast does magma cool?
 - **Depth**—deeper is hotter; shallower is cooler.
 - ▶ Deep plutons lose heat very slowly; take a long time to cool.
 - ▶ Shallow flows lose heat more rapidly; cool quickly.
 - **Shape**—spherical bodies cool slowly; tabular faster.
 - **Groundwater**—circulating water removes heat.

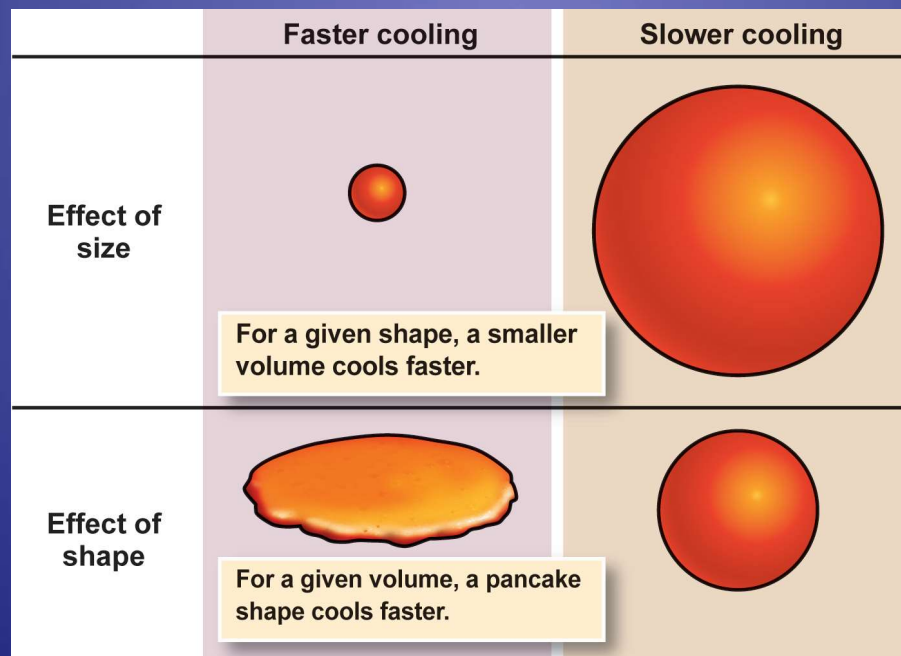


Fig. 4.7a

Making Igneous Rock

■ Changes with cooling

- Fractional crystallization—early crystals settle by gravity.
- Melt composition changes as a result.
 - ▶ Fe, Mg, Ca are removed as early mafic minerals settle out.
 - ▶ Remaining melt becomes enriched in Si, Al, Na, and K.

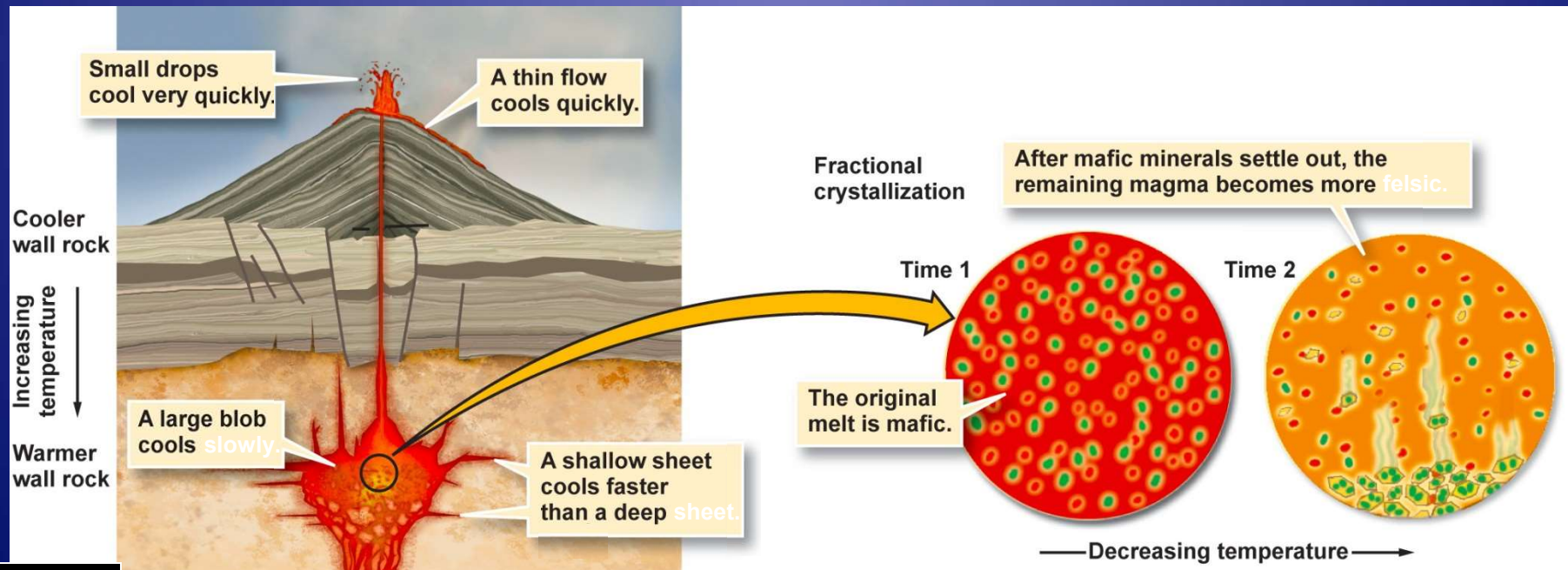
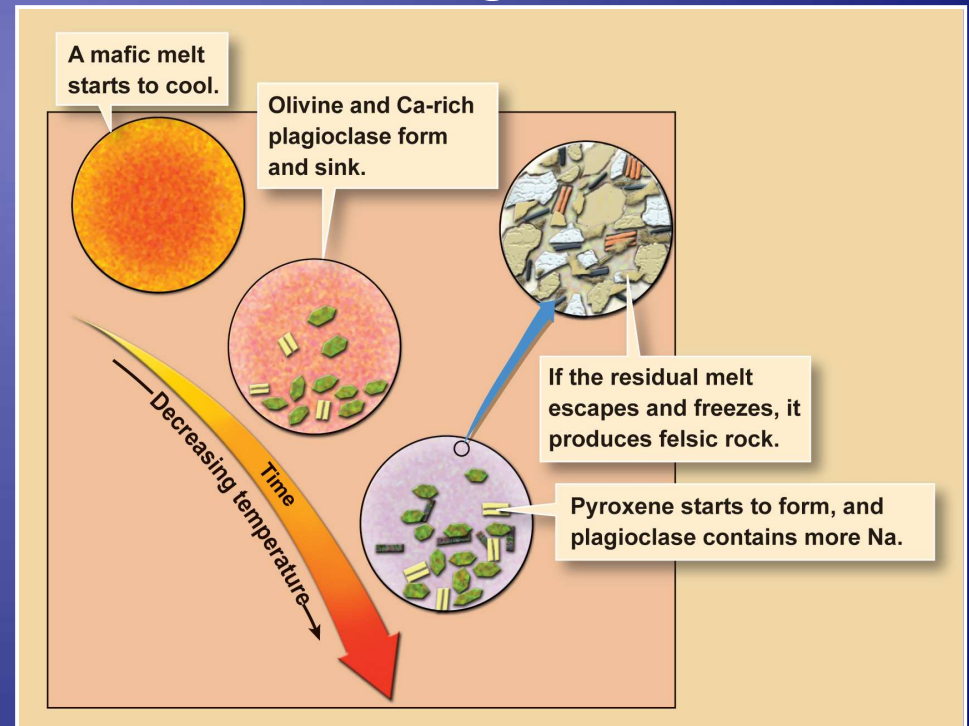


Fig. 4.7b, c

Making Igneous Rock

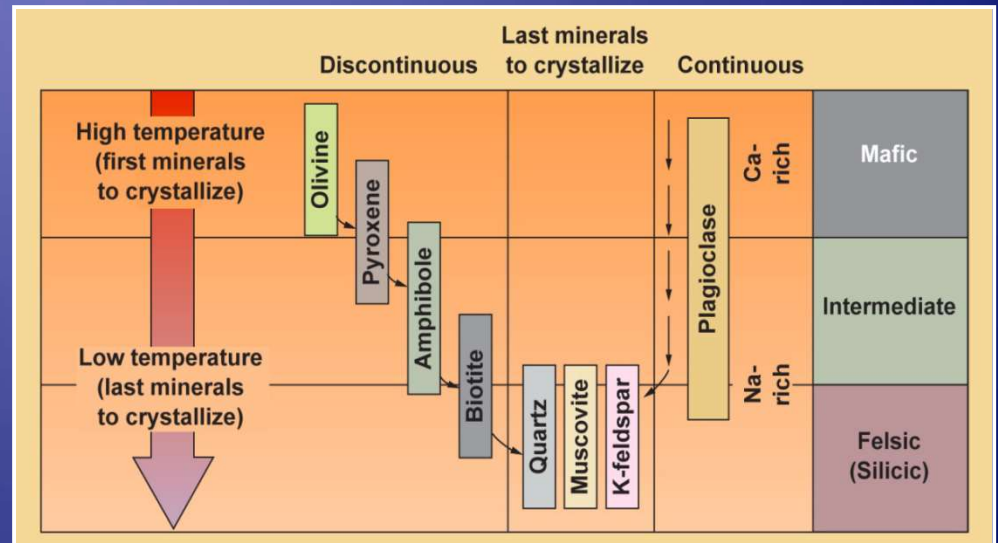
- Fractional crystallization—settling early formed crystals.
 - Felsic magma can evolve from mafic magma.
 - Modeled by Bowen's reaction series
 - ▶ Experimental results of mineral growth in magmas
 - ▶ A mineral succession proceeds from cooling.



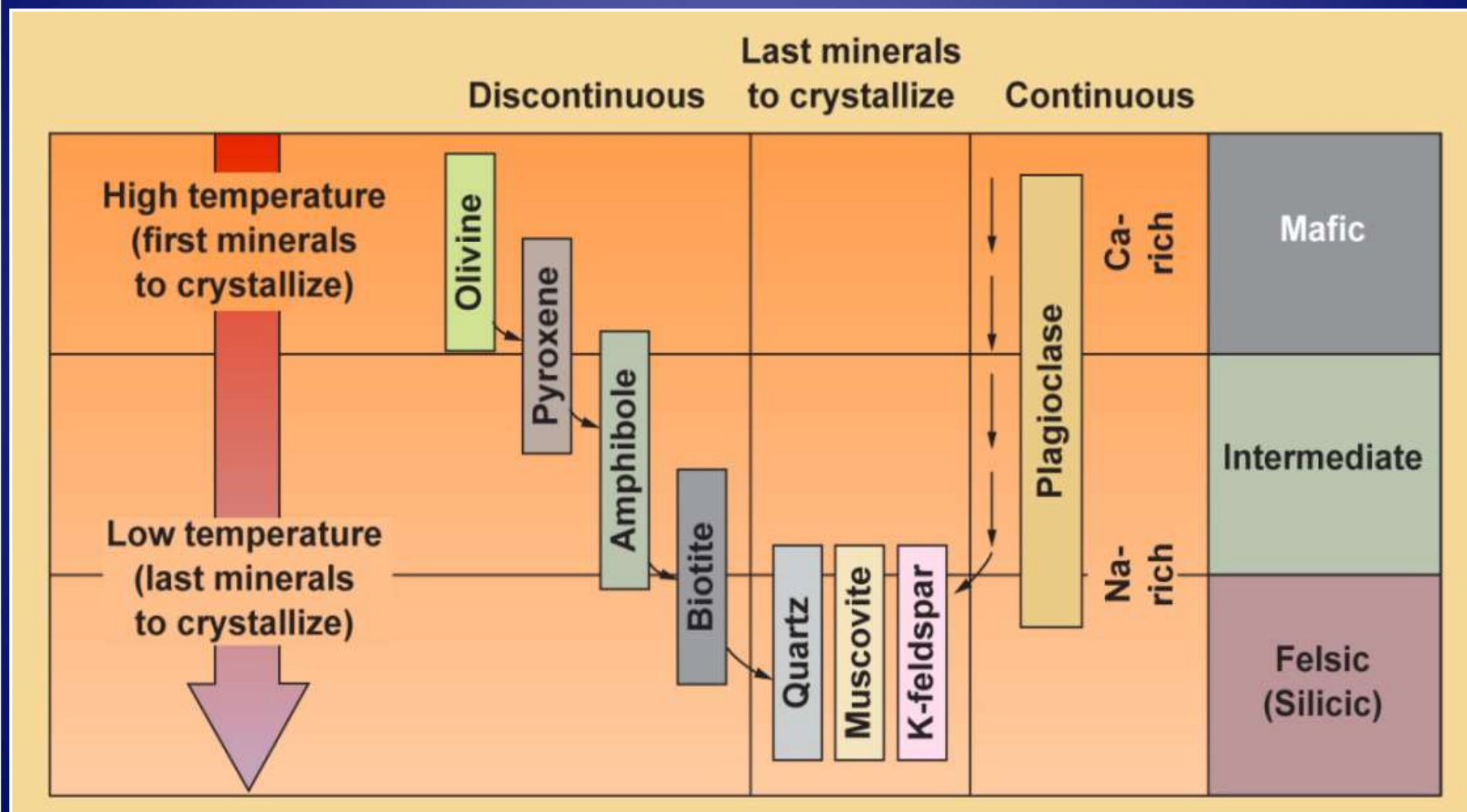
Bowen's Reaction Series

- N. L. Bowen—devised experiments cooling melts (1920s).
 - Early crystals settled out, removing Fe, Mg, and Ca.
 - Remaining melt progressively enriched in Si, Al, and Na.
- He discovered that minerals solidify in a specific series.
 - Continuous—plagioclase changed from Ca-rich to Na-rich.
 - Discontinuous—minerals start and stop crystallizing.

- ▶ Olivine
- ▶ Pyroxene
- ▶ Amphibole
- ▶ Biotite



Bowen's Reaction Series



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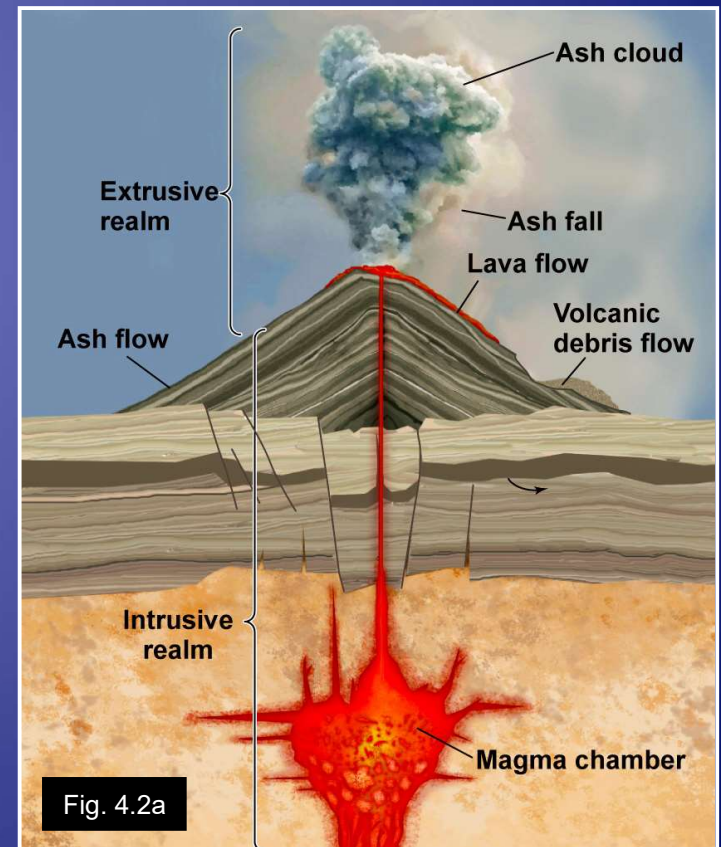
AA2

Very Important slide (for either exam 1 or final exam)

Alrediny, Ahmed, 1/28/2020

Igneous Environments

- Two major categories—based on cooling locale.
 - Extrusive settings—cool at or near the surface.
 - ▶ Cool rapidly.
 - ▶ Chill too fast to grow big crystals.
 - Intrusive settings—cool at depth.
 - ▶ Lose heat slowly.
 - ▶ Crystals often grow large.



Extrusive Settings

- Lava flows cool as blankets that often stack vertically.
- Lava flows exit volcanic vents and spread outward.
- Low-viscosity lava (basalt) can flow long distances.
- Lava cools as it flows, eventually solidifying.



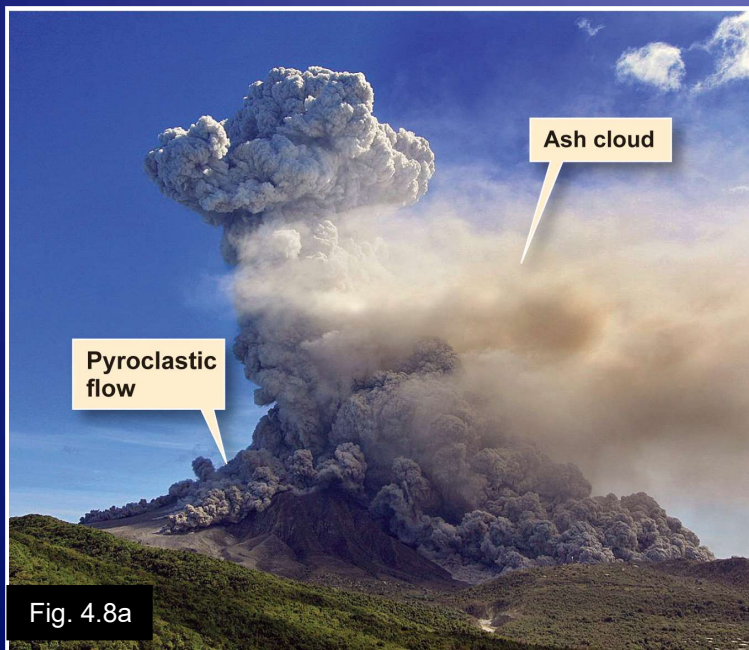
Fig. 4.8c



Extrusive Settings

■ Explosive ash eruptions

- High-viscosity felsic magma erupts explosively.
- Yield huge volumes of ash that can cover large regions
- Pyroclastic flow—volcanic ash and debris avalanche
 - ▶ Races down the volcanic slope as a density current
 - ▶ Often deadly



Intrusive Settings

- Magma invades preexisting wall rock by
 - percolating upward between grains.
 - forcing open cracks.
- The wall rock—magma-intrusive contact reveals high heat.
 - Baked zone—rim of heat-altered wall rock
 - Chill margin—rim of quenched magma at contact



Fig. 4.11d

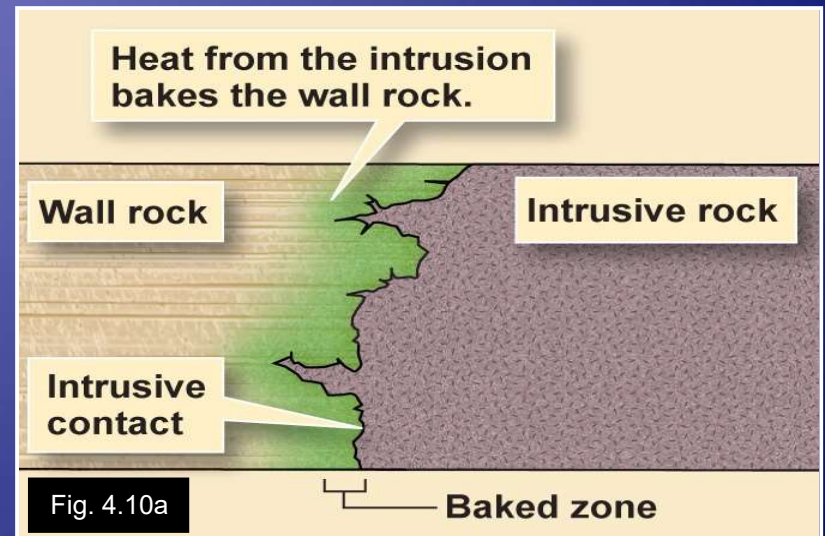


Fig. 4.10a

Intrusive Settings

- Magma invades colder wall rock, initiating
 - thermal (heat) metamorphism and melting.
 - inflation of fractures, wedging wall rock apart.
 - detachment of large wall rock blocks (stoping), and
 - incorporation of wall rock fragments (xenoliths).
- Magma that doesn't reach the surface freezes slowly.

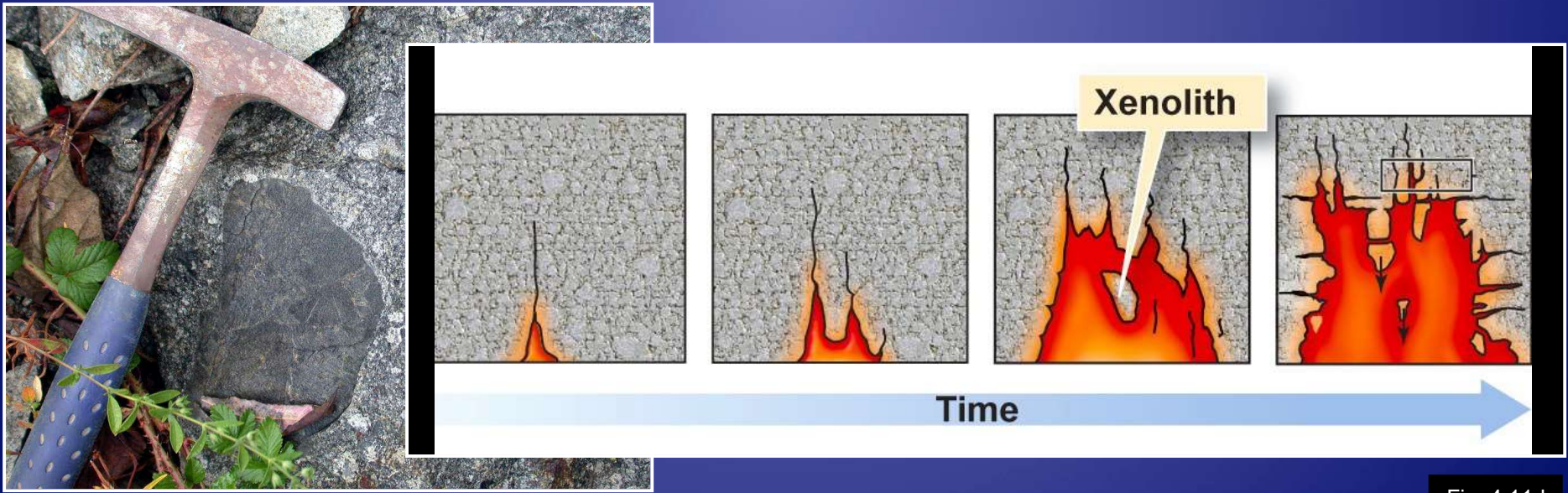
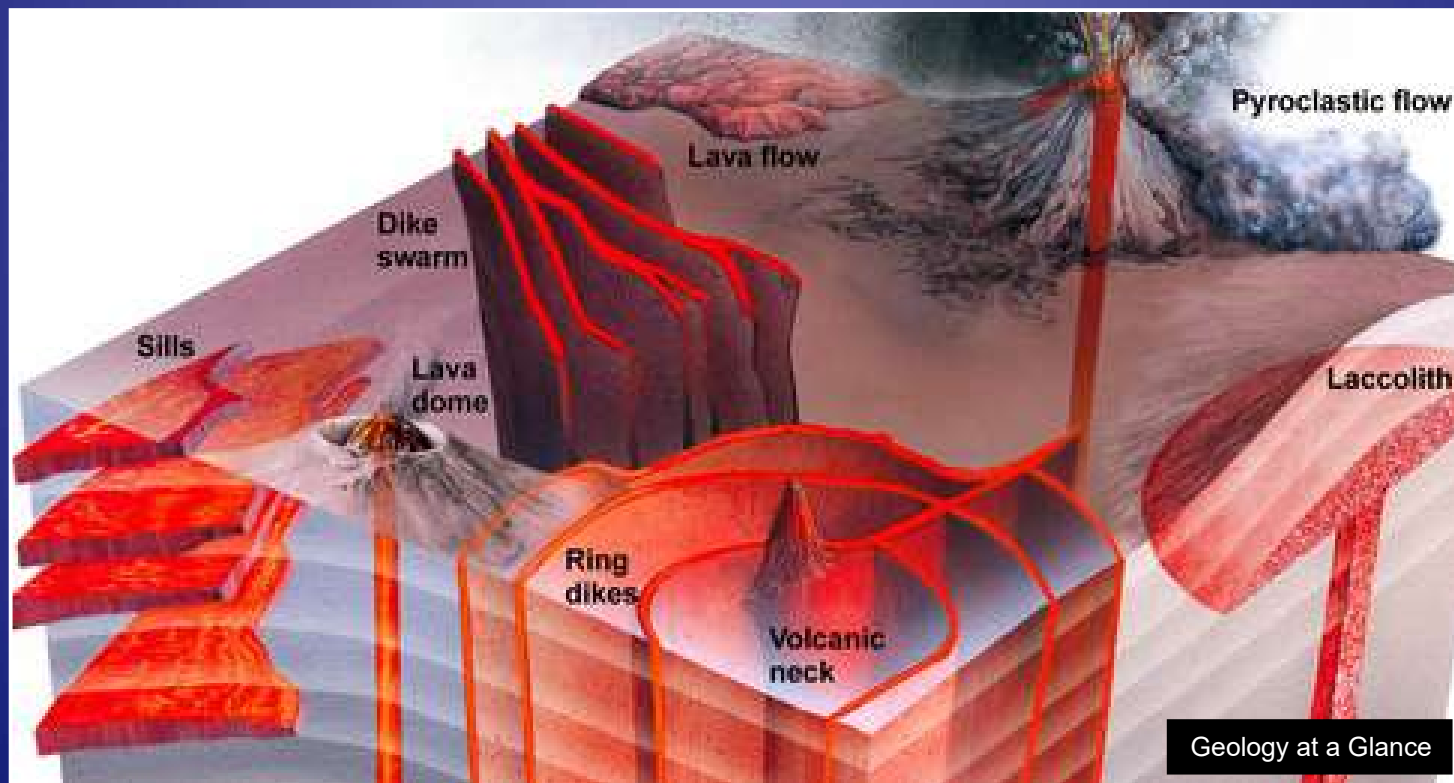


Fig. 4.11d

Intrusive Settings

- Geologists categorize intrusions by shape.
 - Tabular (sheet)—planar with uniform thickness
 - Blister-shaped—a sill that domes upward
 - Balloon-shaped—blobs of melted rock



Intrusive Settings

■ Tabular intrusions

- tend to have uniform thicknesses.
- often can be traced laterally.
- have two major subdivisions.
 - ▶ Sill—injects parallels to rock layering
 - ▶ Dike—cuts across rock layering

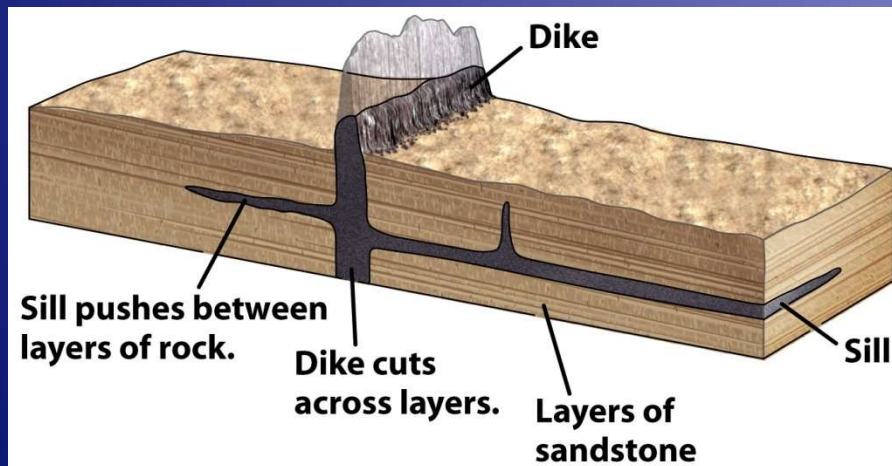
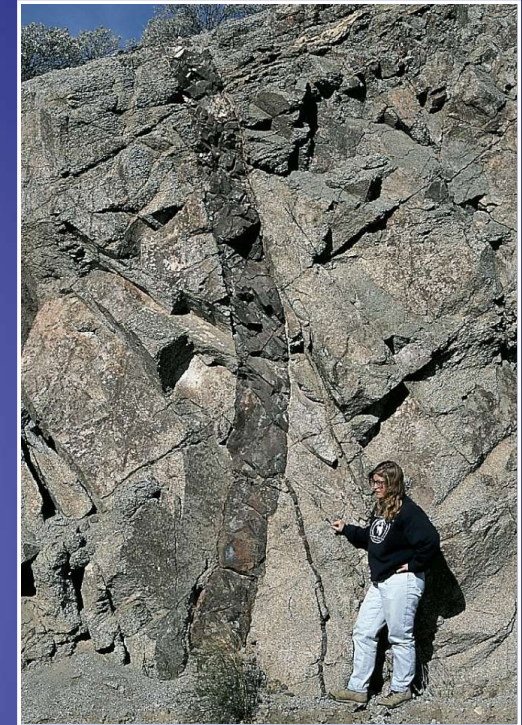
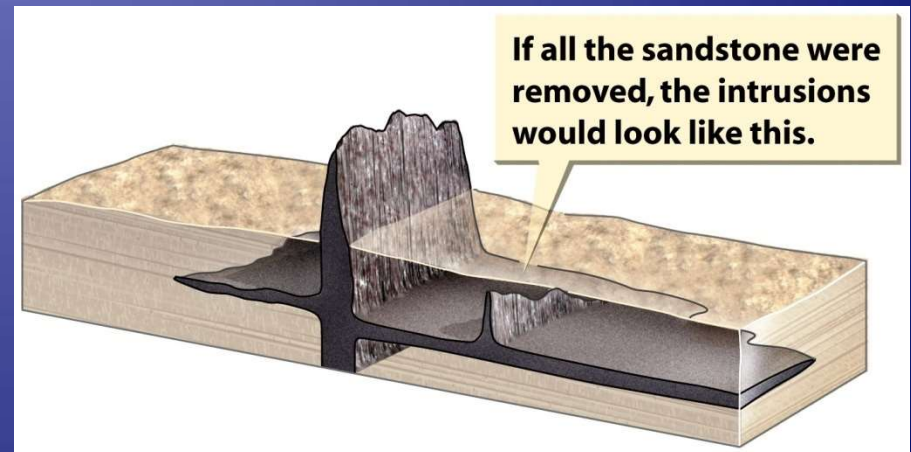


Fig. 4.9a



Intrusive Settings

■ Tabular intrusions

- Dikes and sills modify invaded country rock.
 - ▶ They cause the rock to expand and inflate.
 - ▶ They thermally alter the country rock.
- Dikes
 - ▶ cut across preexisting layering (bedding or foliation).
 - ▶ spread rocks sideways.
 - ▶ dominate in extensional settings.

Dike

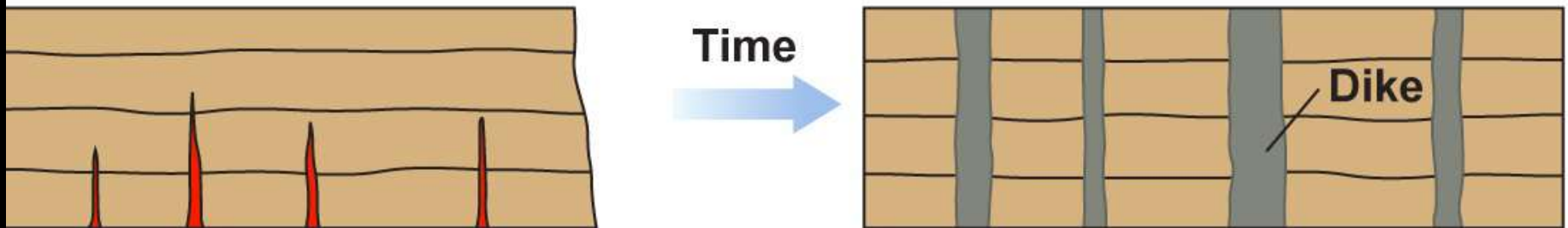


Fig. 4.11a

Tabular Intrusions

■ Sills

- are injected parallel to preexisting layering.
- are usually intruded close to the surface.

■ Both dikes and sills exhibit wide variability in

- size.
- thickness (or width).
- lateral continuity.

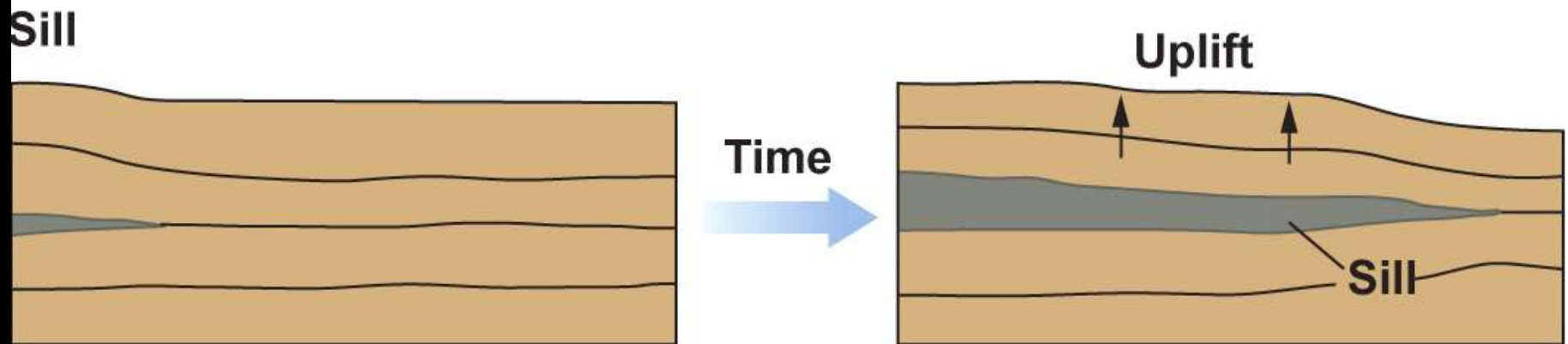


Fig. 4.11b

Intrusive Settings

■ Tabular intrusions

- Dikes—cut across rock layering.
 - ▶ Dikes sometimes occur in swarms.
 - ▶ Three dikes radiate away from Shiprock, New Mexico, an eroded volcanic neck.

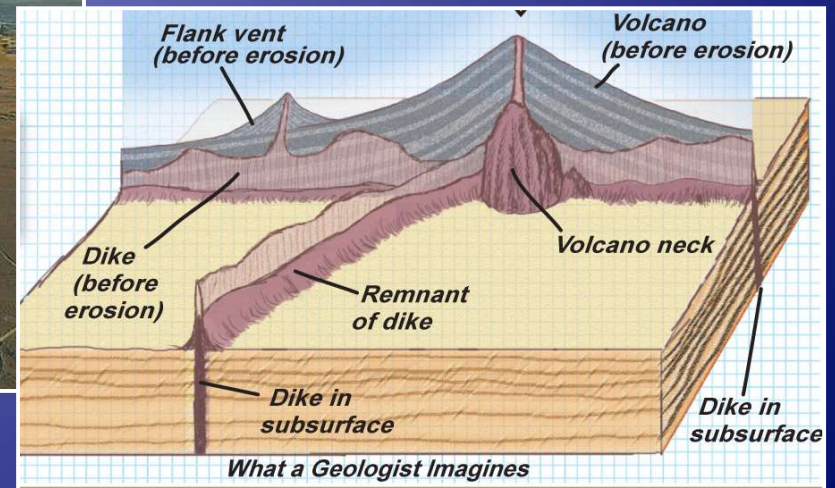


Fig. 4.9c

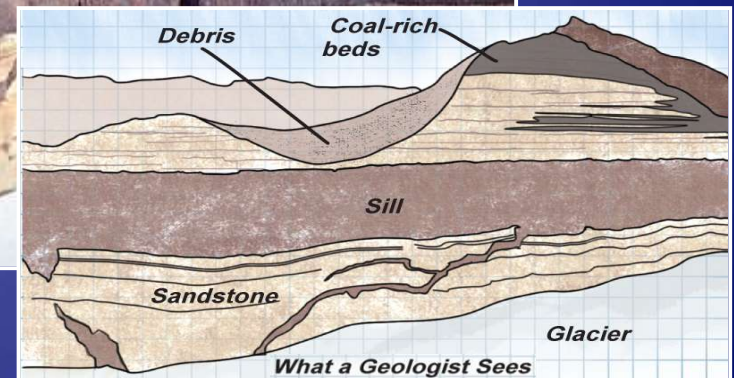
Intrusive Settings

■ Tabular intrusions

- Sills—**injected parallel to layering.**
 - ▶ Basalt (dark) intruded light sandstones in Antarctica.
 - ▶ Intrusion lifted the entire landscape above.



Fig. 4.9b



Plutonic Activity

- Plutons may amass into a batholith.
 - Immense volumes of intrusives
 - Form above subduction zones
 - May add magma for tens of Ma
 - Batholiths mark former subduction.

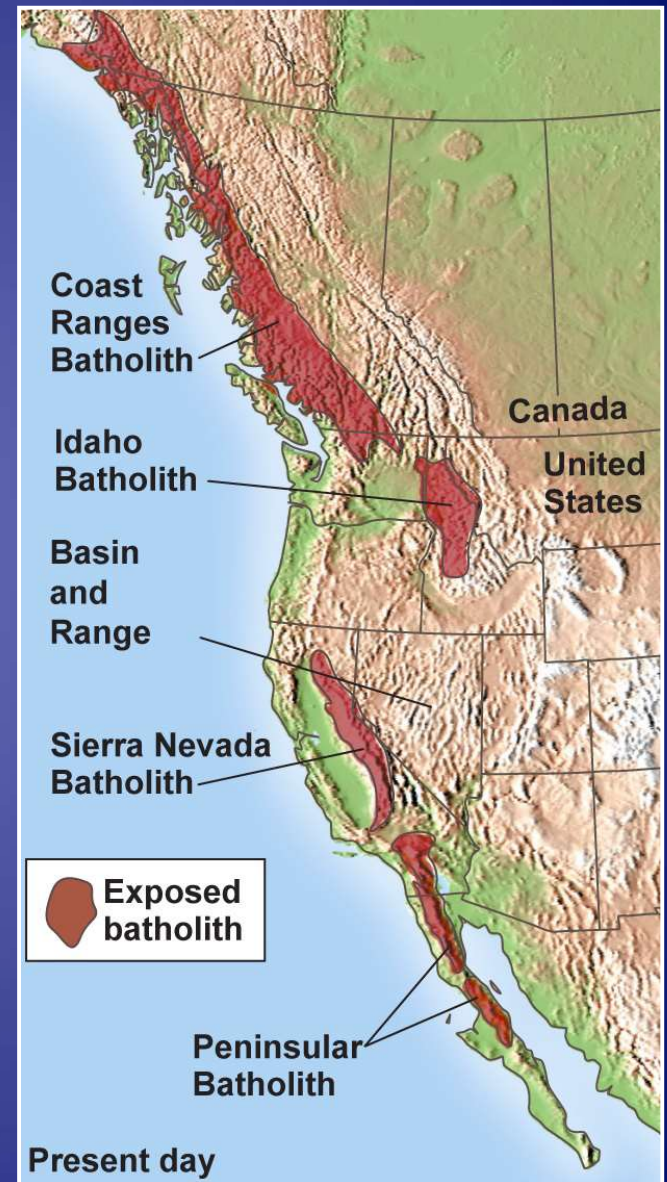


Fig. 4.10d

Intrusive and Extrusive

- Intrusive and extrusive rocks commonly co-occur.
- Magma chambers feed overlying volcanoes.
- Magma chambers may cool to become plutons.
- Many igneous geometries are possible.

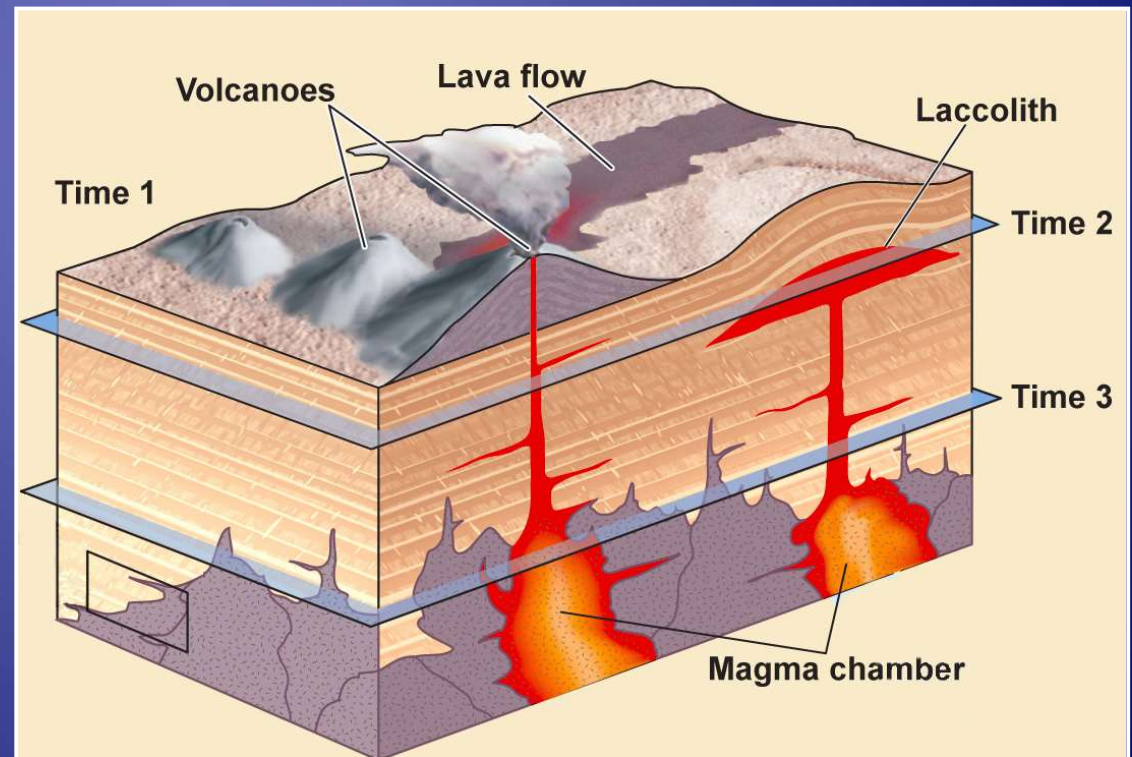


Fig. 4.10a

Intrusive and Extrusive

- With erosion, progressively deeper features are exposed.
 - Vertical dikes
 - Horizontal sills
 - Mushroom-shaped laccoliths

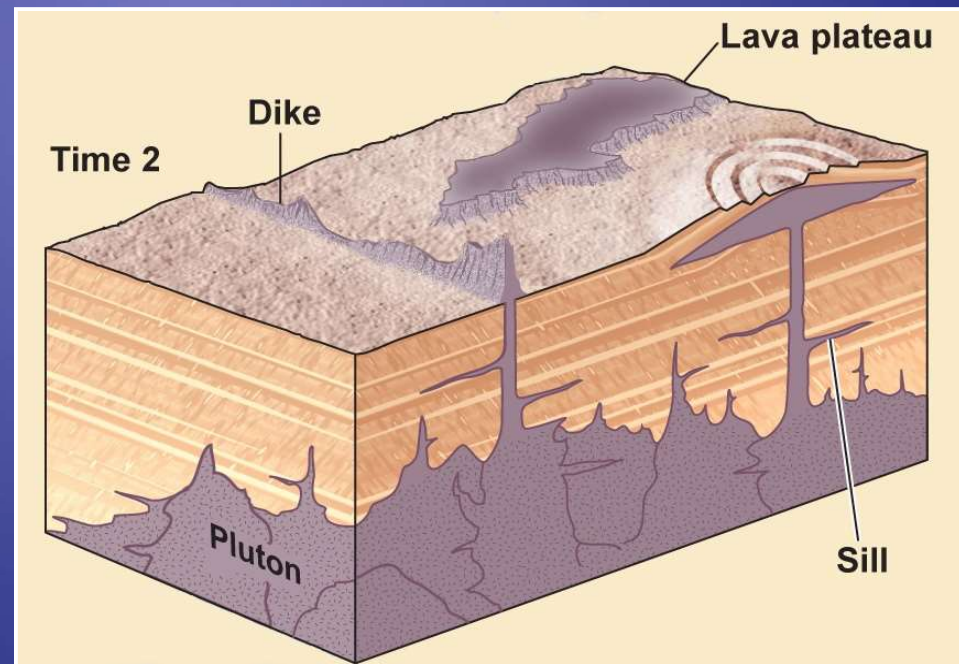


Fig. 4.10b

Influence on Landscape

- Continued uplift and erosion exposes the pluton.
 - Intrusive rocks are usually more resistant to erosion.
 - Thus, intrusive rocks often stand high on the landscape.
- “Unroofing” takes long periods of geologic time.

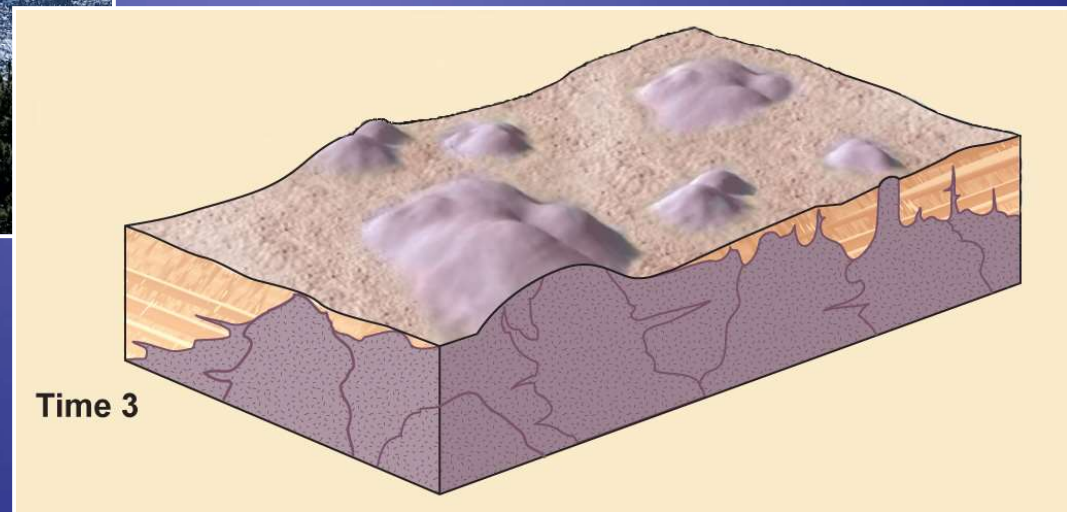


Fig. 4.10c

Describing Igneous Rock

- Igneous rock is used extensively as building stone.

- Office buildings
- Kitchens

- Why?

- Durable (hard)
- Beautiful



- Often called “granite”; it is not always true granite.

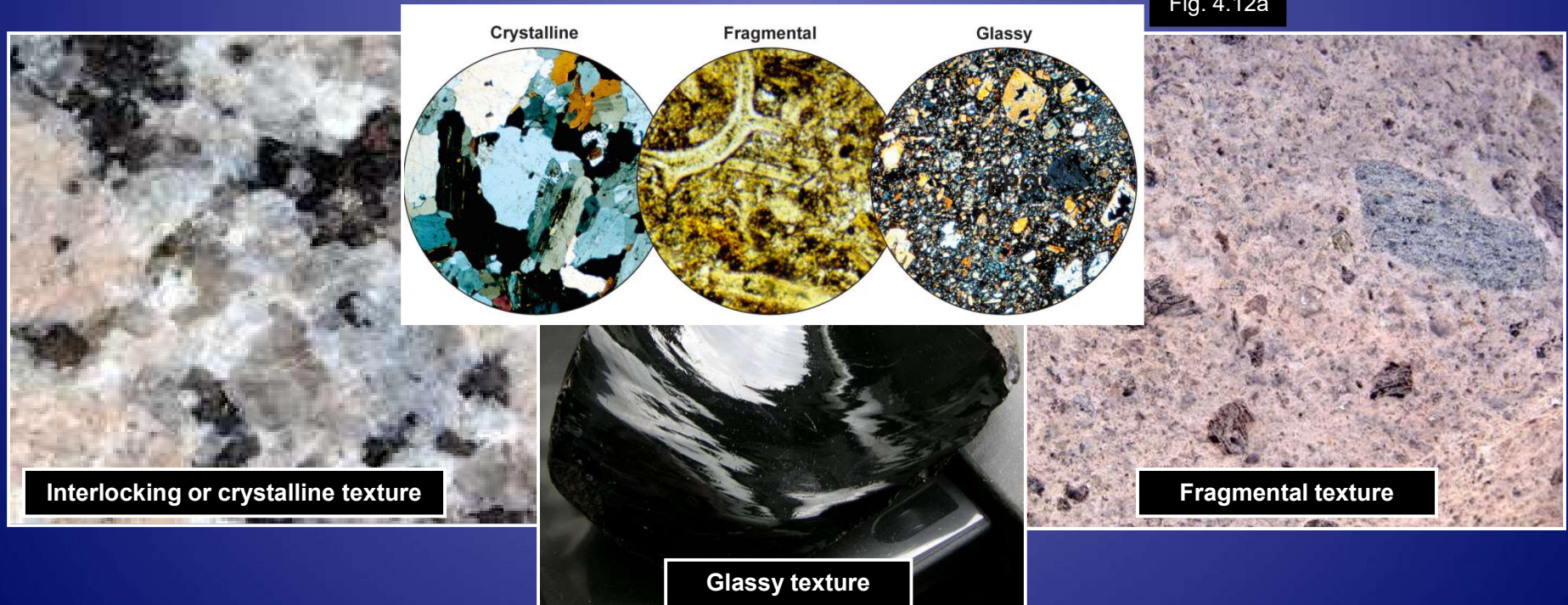
- Useful descriptions of igneous rock

- Color (light or dark)
- Texture



Describing Igneous Rocks

- The size, shape, and arrangement of the minerals
 - Crystalline—interlocking crystals fit like jigsaw puzzle
 - Fragmental—pieces of preexisting rocks, often shattered
 - Glassy—made of solid glass or glass shards
- Texture directly reflects magma history.



Crystalline Igneous Textures

- Interlocking mineral grains from solidifying melt
- Texture reveals cooling history.
 - Fine-grained
 - ▶ Rapid cooling
 - ▶ Crystals do not have time to grow.
 - ▶ Extrusive
 - Coarse-grained
 - ▶ Slow cooling
 - ▶ Crystals have a long time to grow.
 - ▶ Intrusive

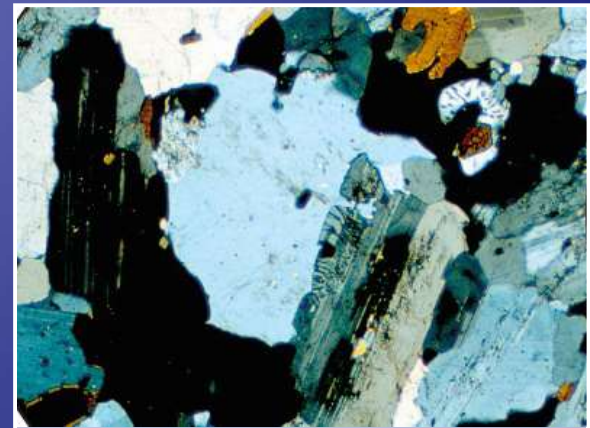
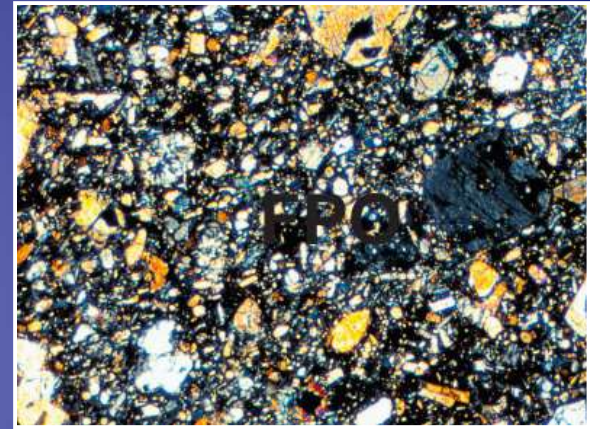


Fig. 4.12a

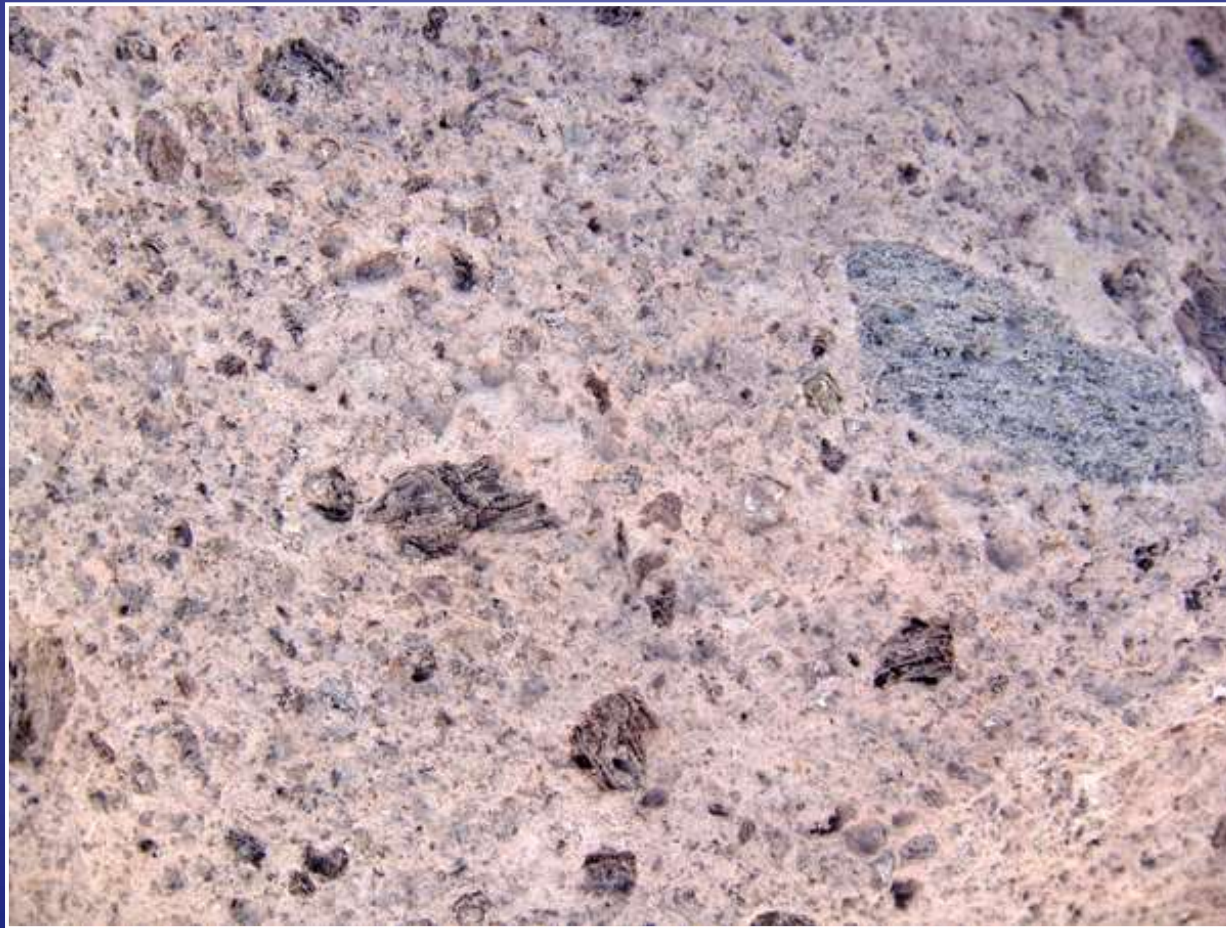
Crystalline Textures

- Texture reveals cooling history.
 - Porphyritic texture—a mixture of coarse and fine crystals
 - ▶ Indicates a two-stage cooling history.
 - ✓ Initial slow cooling creates large phenocrysts.
 - ✓ Subsequent eruption cools remaining magma more rapidly.



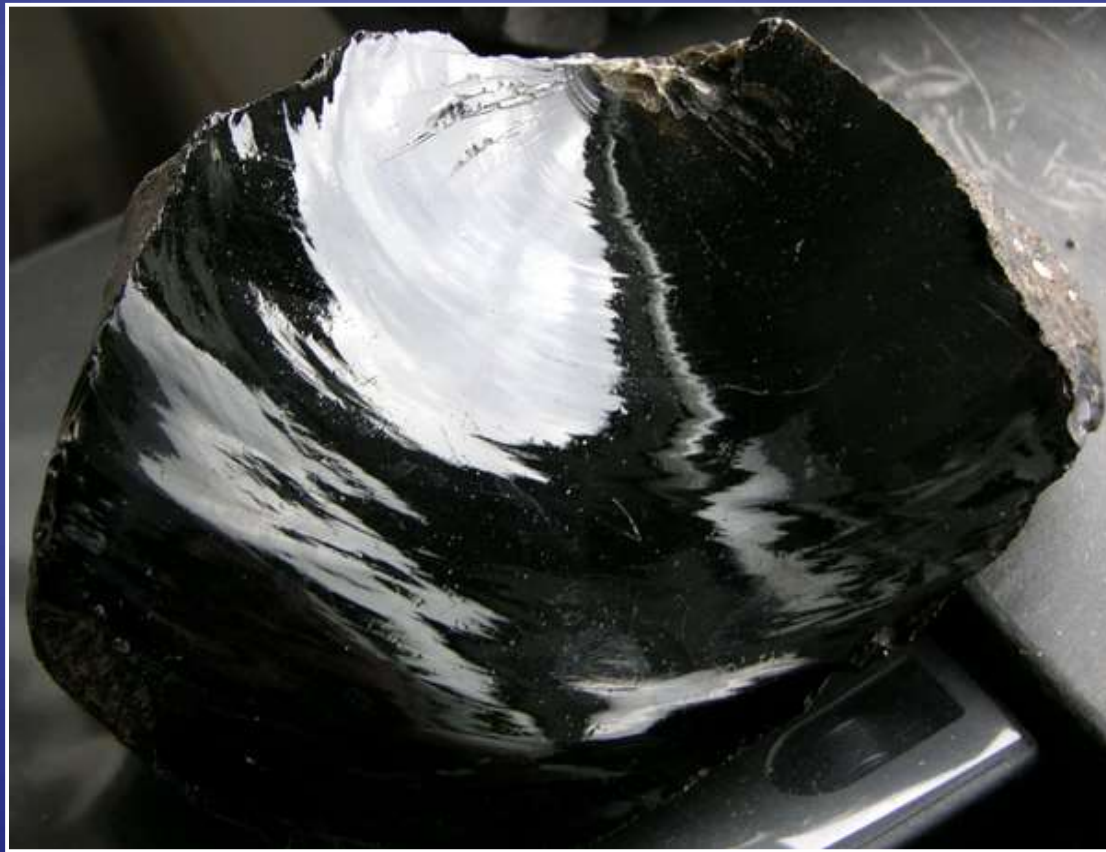
Fragmental Textures

- Preexisting rocks that were shattered by eruption
- After fragmentation, the pieces fall and are cemented.



Glassy Textures

- Solid mass of glass or crystals surrounded by glass
- Fracture conchoidally
- Result from rapid cooling of lava



Crystalline Classification

- Classification is based on composition and texture.



Fig. 4.12c

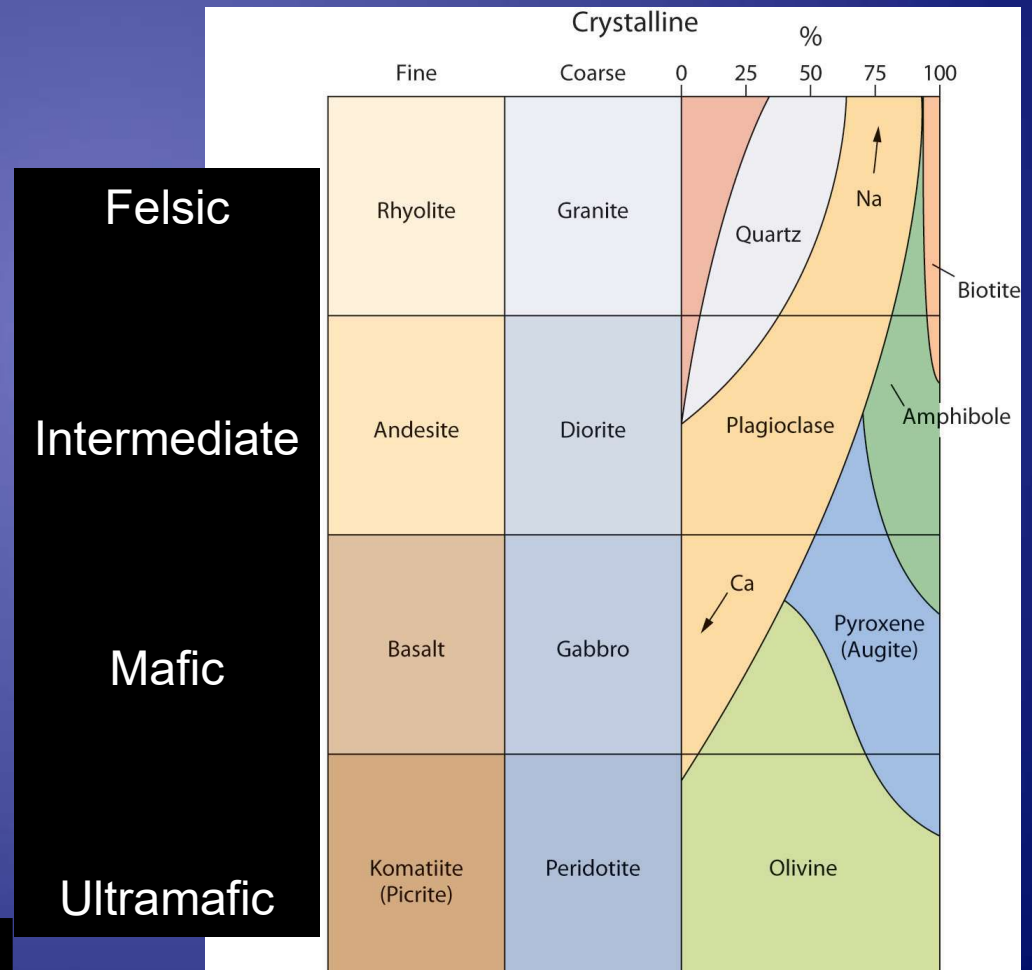
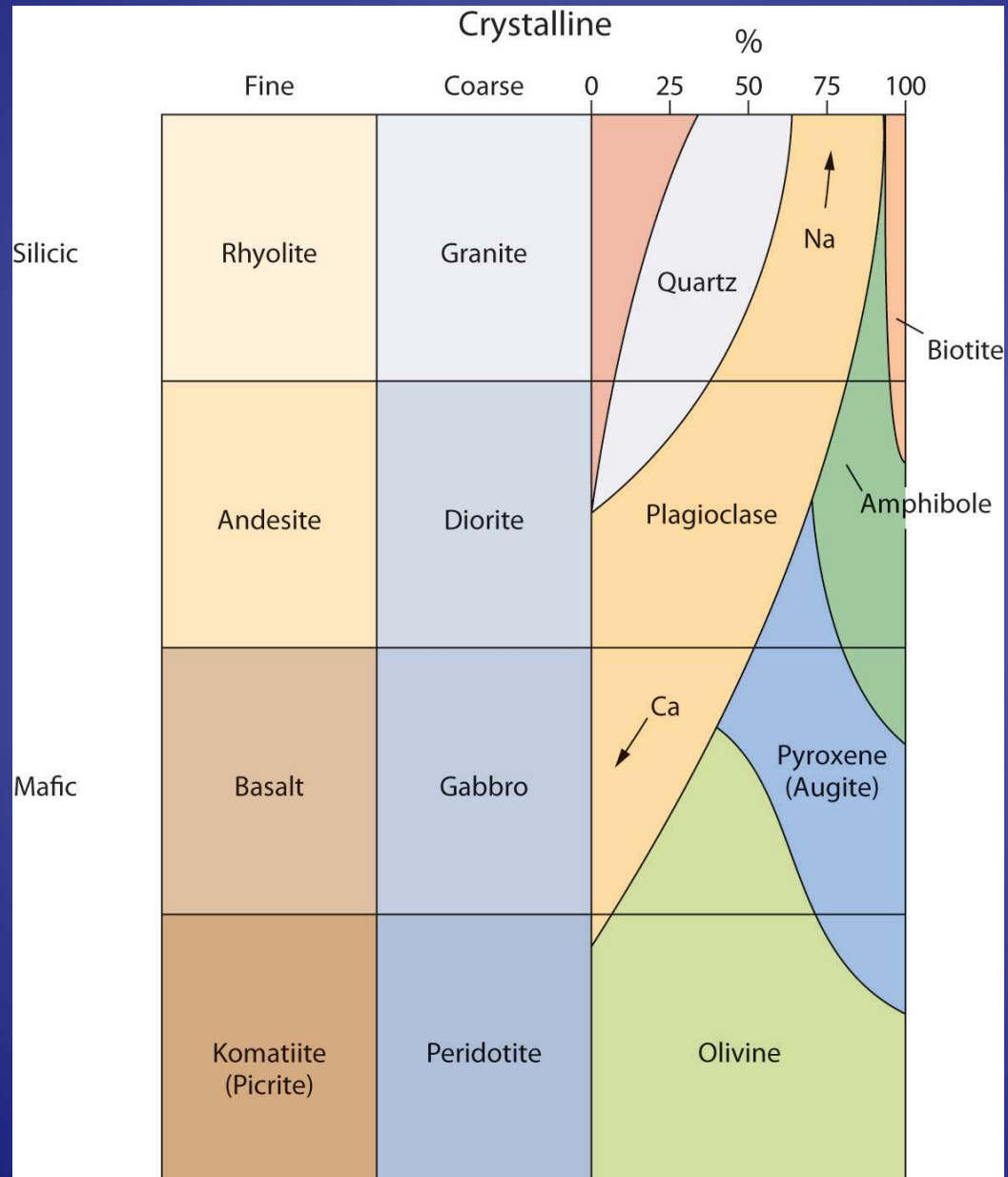


Fig. 4.13

Crystalline Classification



Glassy Classification

- More common in felsic igneous rocks
 - Obsidian—felsic volcanic glass
 - Pumice—frothy felsic rock full of vesicles; it floats.
 - Scoria—glassy, vesicular mafic rock



Fig. 4.12b



Fig. 4.14



Pyroclastic Classification

- **Pyroclastic**—fragments of violent eruptions
 - **Tuff**—volcanic ash that has fallen on land
 - **Volcanic breccia**—made of larger volcanic fragments



Where Does Igneous Activity Occur?

- Igneous activity occurs in four plate-tectonic settings.
 - Volcanic arcs bordering deep ocean trenches
 - Isolated hot spots
 - Continental rifts
 - Mid-ocean ridges
- Established or newly formed tectonic plate boundaries
- Except: hot spots, which are independent of plates

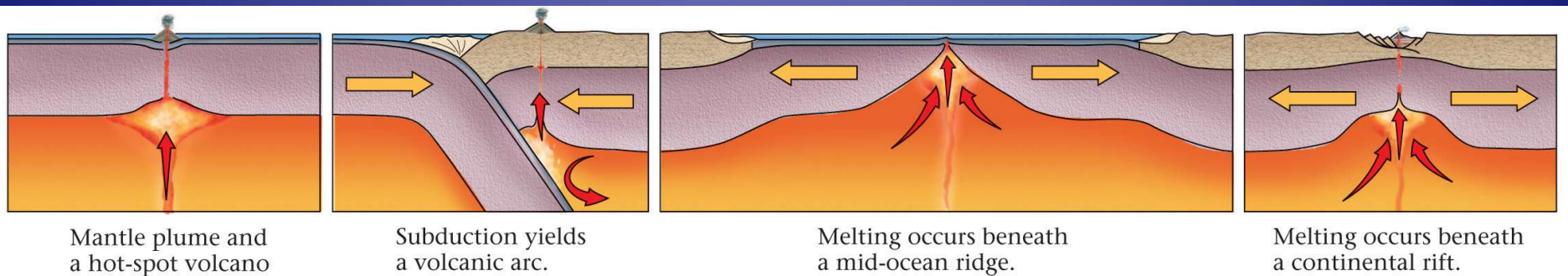


Fig. 4.15

Volcanic Arcs

- Most subaerial volcanoes on Earth reside in arcs.
- Mark convergent tectonic plate boundaries
 - Deep oceanic trenches and accretionary prisms
 - Subducting oceanic lithosphere adds volatiles (water).
 - Rocks of the asthenosphere partially melt.
 - Magma rises and creates volcanoes on overriding plate.
 - Magma may differentiate.
- Examples:
 - Aleutian Islands
 - Japan
 - Java and Sumatra

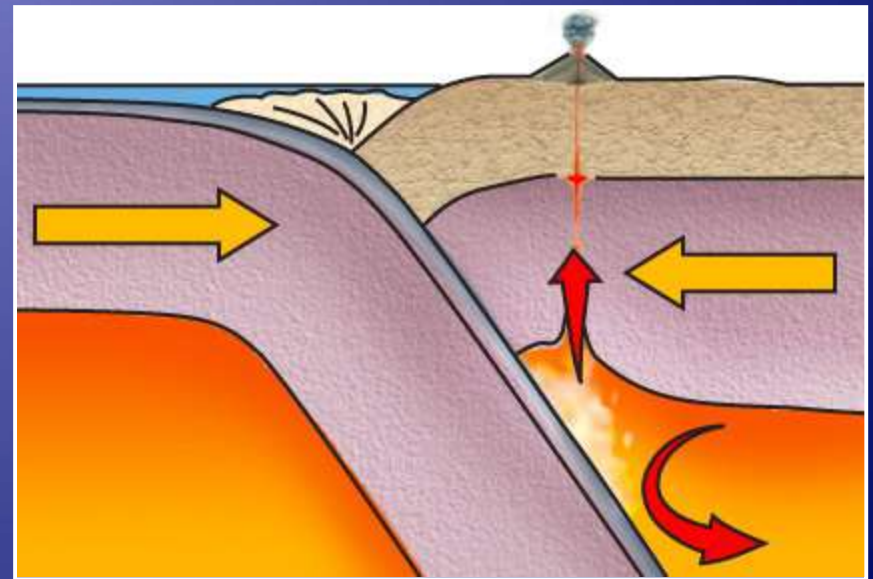


Fig. 4.15

Hot Spots

- About 50–100 mantle-plume hot-spot volcanoes exist.
- Independent tectonic plate boundaries
- May erupt through oceanic or continental crust.
 - Oceanic—mostly mafic magma (basalt)
 - Continental—mafic and felsic (basalt and rhyolite)
- Burn a volcano chain through overriding tectonic plate
 - Creates a hot-spot track

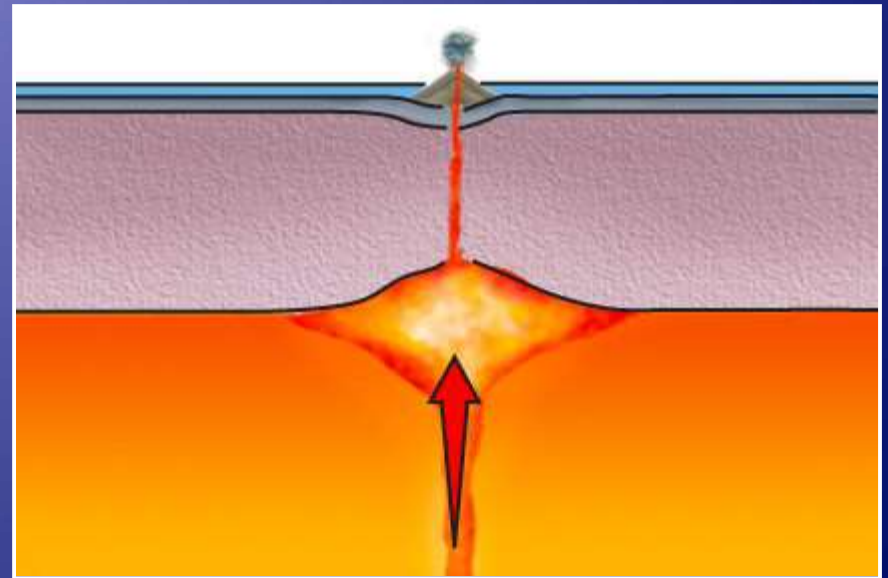


Fig. 4.15

Large Igneous Provinces

- LIPs—unusually large outpourings of magma
 - Mostly mafic, include some felsic examples
 - Mantle plume first reaches the base of the lithosphere.
 - Erupts huge volumes of mafic magma as flood basalts.
 - ▶ Low viscosity
 - ▶ Can flow tens to hundreds of kms
 - ▶ Accumulate in thick piles



Fig. 4.17c

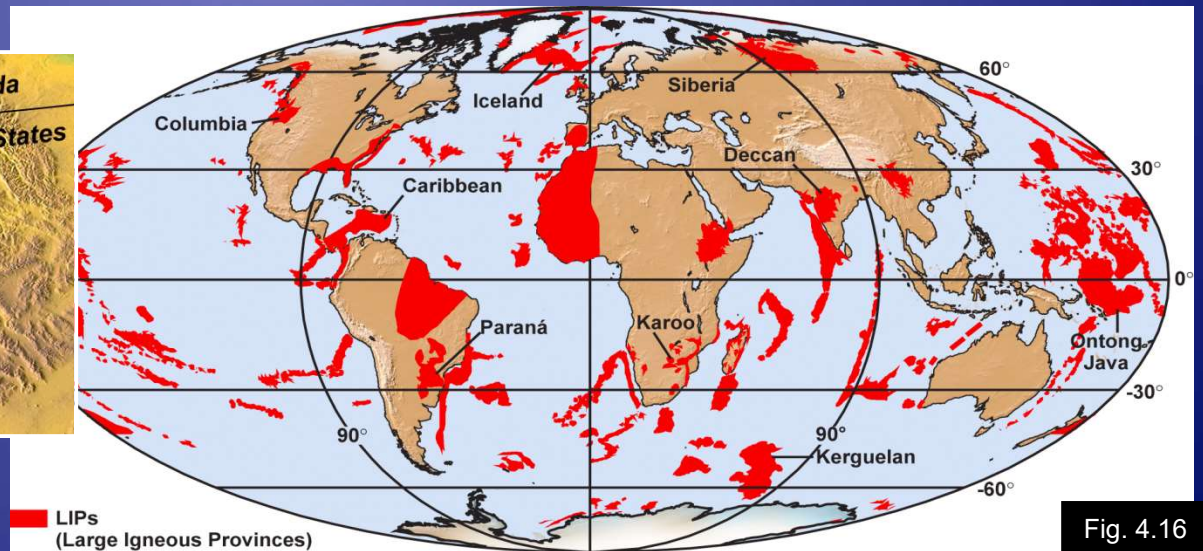


Fig. 4.16

Continental Rifts

- Places where continental lithosphere is being stretched
- Rifting thins the lithosphere.
 - Causes decompressional melting of mafic rock.
 - Heat transfer melts crust, creating felsic magmas.
- Example: East African Rift Valley

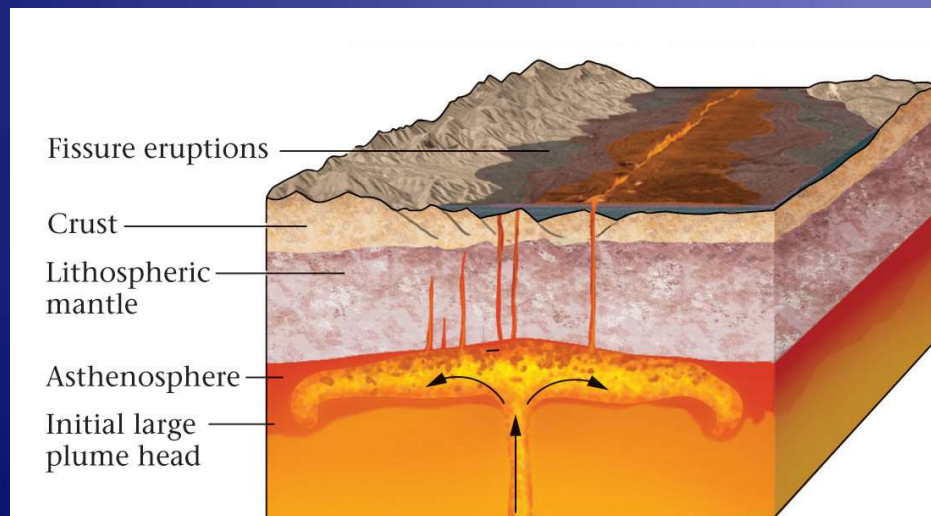


Fig. 4.17a, b

Mid-Ocean Ridges

- Most igneous activity takes place at mid-ocean ridges.
 - Rifting spreads plates leading to decompression melting.
 - Basaltic magma wells up and fills magma chambers.
 - Solidifies as gabbro at depth.
 - Moves upward to form dikes or extrude as pillow basalt.

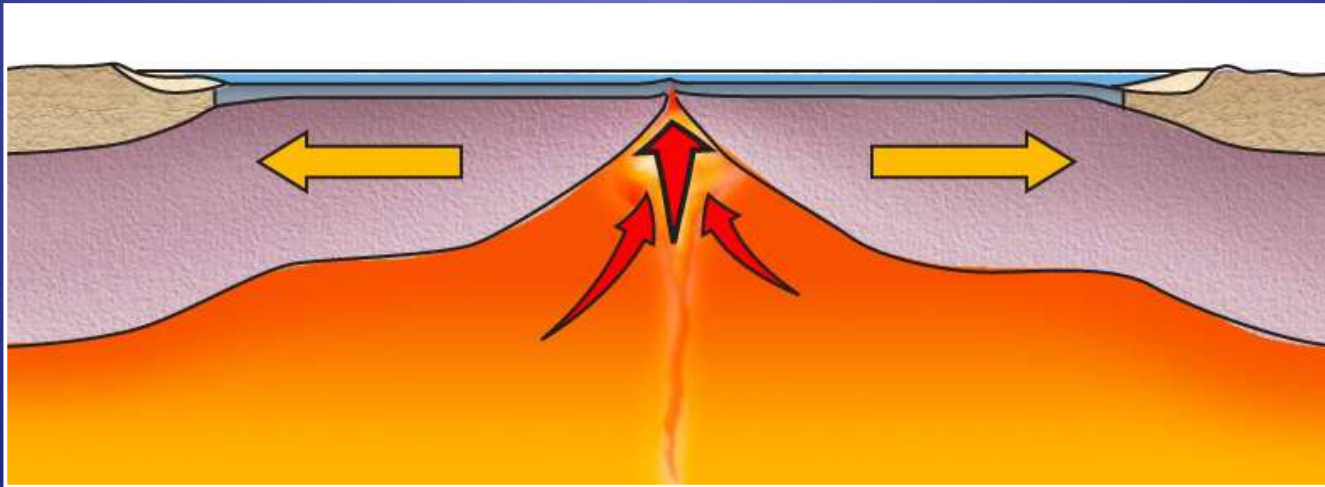


Fig. 4.15

Useful Web Resources

- **USGS Volcano Hazards Program**
 - <http://volcanoes.usgs.gov/>
- **USGS Hawaiian Volcano Observatory**
 - <http://hvo.wr.usgs.gov/>
- **Oregon State University Volcano World**
 - <http://volcano.oregonstate.edu/>
- **Geology.com, Pictures of Extrusive and Intrusive Igneous Rocks**
 - <http://geology.com/rocks/igneous-rocks.shtml>
- **EARTHCHEM Rock Geochemistry Database**
 - www.earthchem.org/
- **Large Igneous Provinces Commission**
 - www.largeigneousprovinces.org/
- **MantlePlumes.org**
 - www.mantleplumes.org/
- **UNC Atlas of Igneous and Metamorphic Rocks, Minerals, and Textures**
 - www.geolab.unc.edu/Petunia/IgMetAtlas/mainmenu.html