



PHYS 3800 Physical Geology

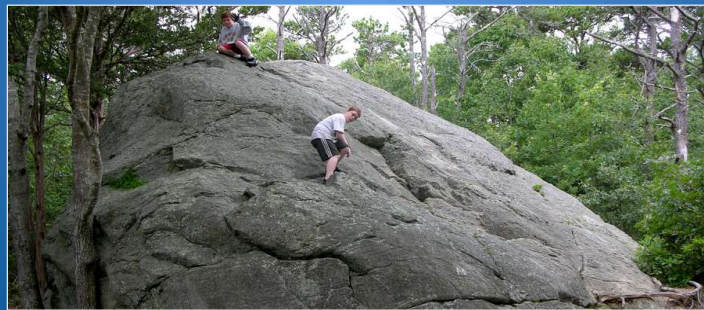
Chapter 18: Amazing Ice: Glaciers and Ice Ages



1

The Theory of Glaciation

- European farmers broke plows on large rocks.
 - Buried in fine-grained soils, often of enormous size.
 - Unlike local bedrock, they had come from hundreds of kilometers away.
- These rocks became known as erratics.
- The origin of erratics became a scientific mystery.



Essentials of Geology, 4th edition by Stephen Marshak

© 2013 W.W. Norton

Chapter 18: Amazing Ice: Glaciers and Ice Ages



The Theory of Glaciation

- Louis Agassiz, a Swiss geologist, observed glaciers.
- He saw glaciers as agents of landscape change.
 - They carried sand, mud, and huge boulders long distances.
 - They dropped these materials, unsorted, upon melting.
- He realized that glaciers could explain erratic boulders.



Fig. 18.1

3

The Theory of Glaciation

- Agassiz proposed that an ice age had frozen Europe.
 - Ice sheets covered land.
 - Ice carried and dropped:
 - Fine-grained unsorted sediment.
 - Erratic boulders.





The Theory of Glaciation

- When first proposed, Agassiz's idea was criticized.
- By the 1850s, many geologists agreed that he was right.
- Agassiz saw evidence for a North American ice age.



5

Glaciers and Ice Ages

- **Glaciers**
 - Thick masses of recrystallized ice
 - Last all year long
 - Flow via gravity
 - Mountain and continental
 - Presently cover ~10% of Earth
 - During ice ages, coverage expands to ~30%.
 - The most recent ice age ended ~11 ka.
 - Covered New York, Montreal, London, and Paris.
 - Ice sheets were hundreds to thousands of meters thick.



Fig. 18.23



Ice: The Water Mineral

- Ice is solid water (H_2O).
- Forms when water cools below the freezing point.
- Natural ice is a mineral; it grows in hexagonal crystals.

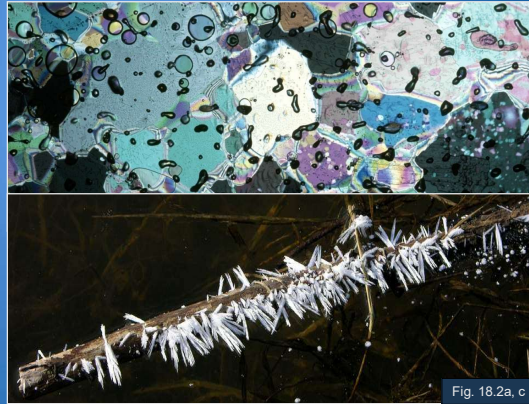


Fig. 18.2a, c

7

How a Glacier Forms

- Snowfall accumulates and survives the following summer.
- Snow is transformed into ice.
 - Snow is buried by later falls.
 - Compression reduces volume.
 - Burial pressure causes melting and recrystallization.
 - Snow turns into granular firn.
 - Over time, firn becomes interlocking crystals of ice.
- Glacial ice may form:
 - Quickly (tens of years)
 - Slowly (thousands of years)

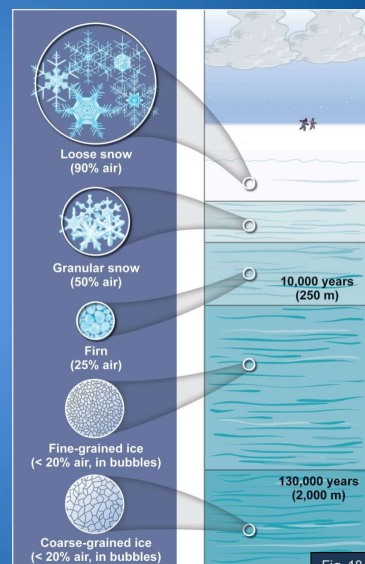


Fig. 18.2d



Forming a Glacier

- Three conditions are necessary to form a glacier:
 - Cold local climate (polar latitudes or high elevation).
 - Snow must be abundant; more snow must fall than melts.
 - Snow must not be removed by avalanches or wind.

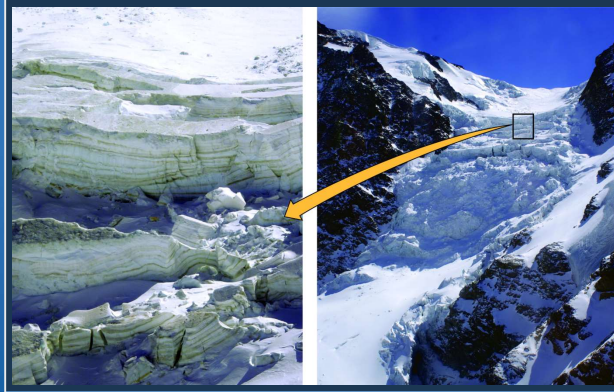
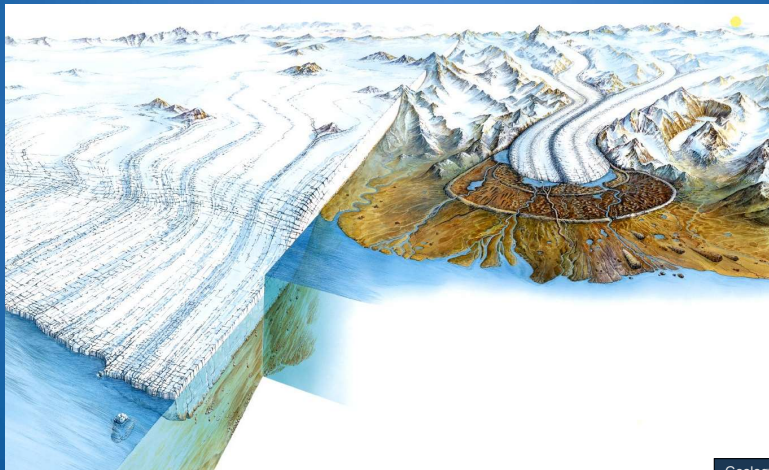


Fig. 18.2b

9

Glaciers

- Thick masses of recrystallized ice
- Two categories of glaciers: mountain and continental

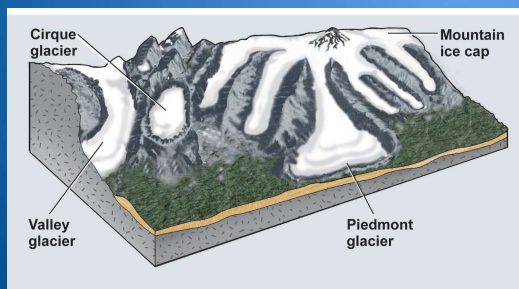


Geology at a Glance



Mountain Glaciers

- Flow from high to low elevation in mountain settings.
- Include a variety of types:
 - Cirque glaciers fill mountain-top bowls.
 - Valley glaciers flow like rivers down valleys.
 - Mountain ice caps cover peaks and ridges.
 - Piedmont glaciers spread out at the end of a valley.



11

Mountain Glaciers

- Flow from high to low elevation in mountain settings.
- Include a variety of types:
 - Ice caps cover peaks and ridges.
 - Piedmont glaciers spread out at the end of a valley.





Continental Glaciers

- Vast ice sheets covering large land areas.
- Ice flows outward from thickest part of sheet.
- Two major ice sheets remain on Earth:
 - Greenland
 - Antarctica

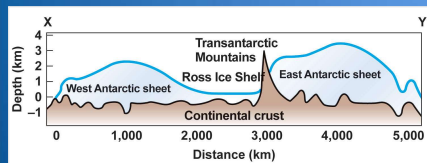
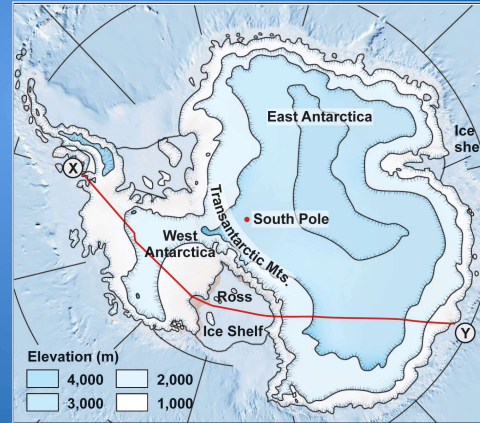


Fig. 18.4



13

Movement of Glacial Ice

- How do glaciers move?
 - Basal sliding.
 - Significant quantities of meltwater forms at base of glacier.
 - Water decreases friction, ice slides along substrate.
 - Plastic deformation.

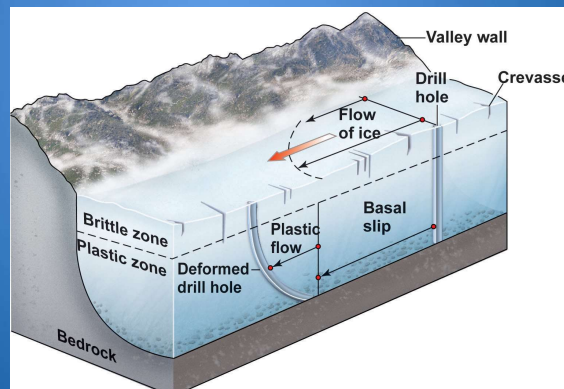


Fig. 18.7a



Movement of Glacial Ice

How do glaciers move?

- Plastic deformation occurs below about 60 m depth.
 - Grains of ice change shape slowly.
 - New grains form while old grains disappear.
 - Crevasses form at surface—upper zone too brittle to flow.

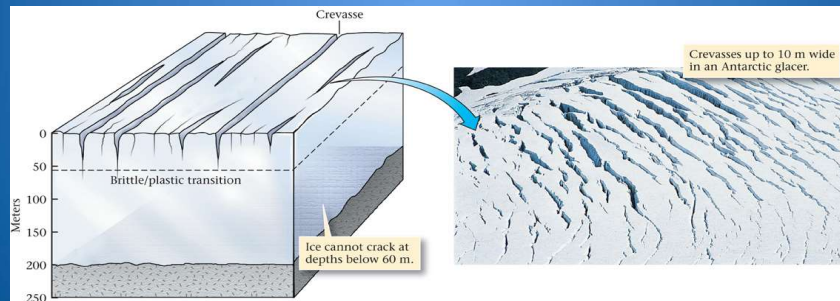


Fig. 18.5

15

Movement of Glacial Ice

Why do glaciers move?

- The pull of gravity is strong enough to make ice flow.
 - A glacier moves in the direction of its surface slope.
 - The ice base can flow up a local incline.

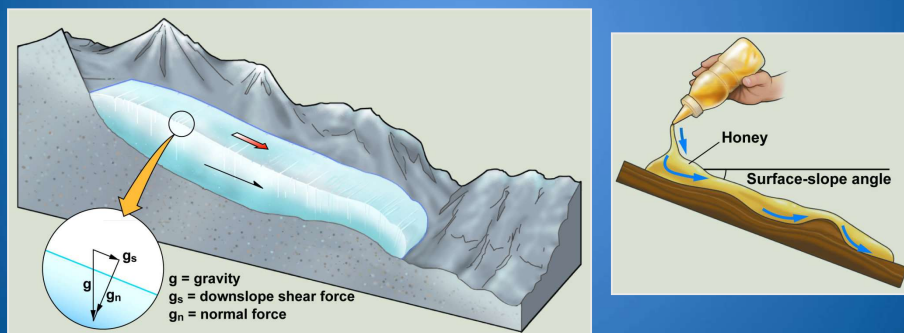


Fig. 18.6a



Movement of Glacial Ice

■ Why do glaciers move?

- In continental glaciers, ice spreads away from center of accumulation.
 - The ice sheet is always thicker in the middle, so it spreads toward the edges.

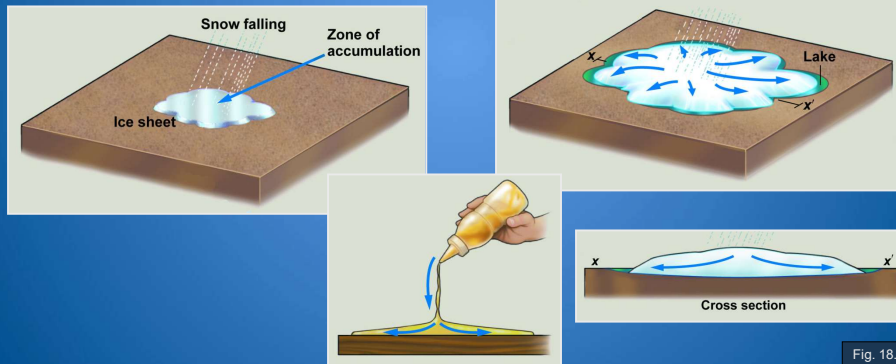


Fig. 18.6b

17

Movement of Glacial Ice

- Rates of flow vary widely (10 to 300 m per year).
- Rarely, glaciers may surge (20 to 110 m per day).
- The rate of flow is controlled by:
 - The severity of slope angle: steeper = faster
 - Basal water: wet-bottom = faster
 - Location within glacier
 - Greater velocity in ice center
 - Friction slows ice at margins.

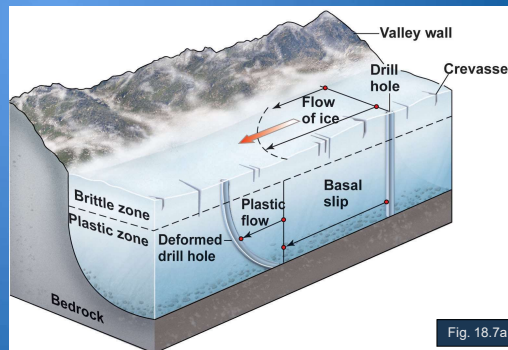
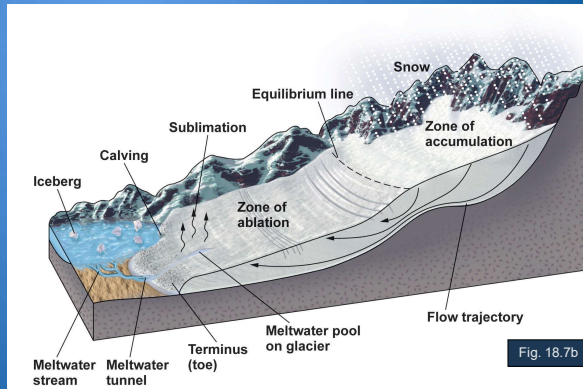


Fig. 18.7a



Glacial Advance and Retreat

- Glaciers behave like bank accounts.
- Zone of accumulation—area of net snow addition.
 - Colder temperatures prevent melting.
 - Snow remains across the summer months.
- Zone of ablation—area of net ice loss.
- Zones meet at the equilibrium line.



19

Glacial Advance and Retreat

- Toe—the leading edge of a glacier
- Ice always flows downhill, even during toe retreat.





Glacial Advance and Retreat

■ Toe position

- If accumulation = ablation, the glacial toe stays in the same place.

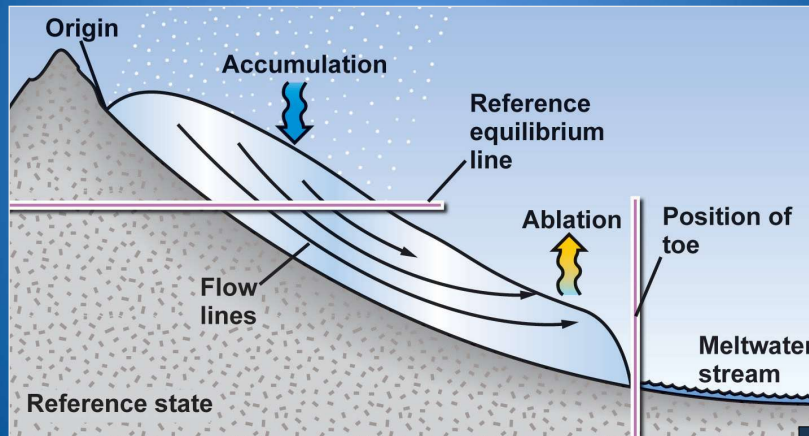


Fig. 18.8a

21

Glacial Advance and Retreat

■ Toe position

- If accumulation > ablation, the glacial toe advances.

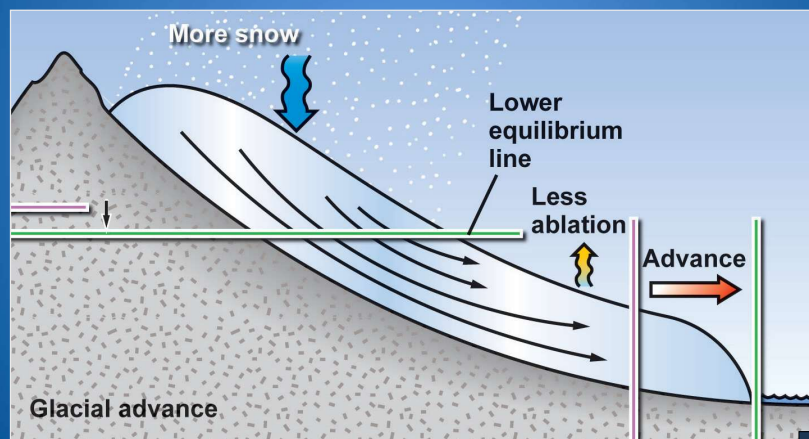


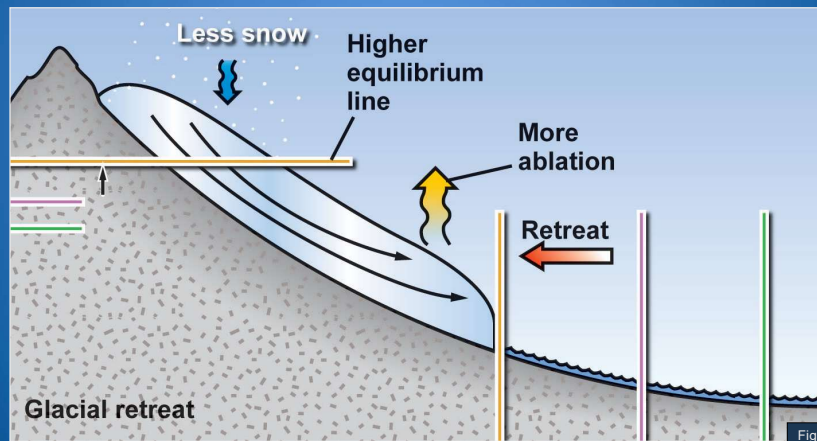
Fig. 18.8b



Glacial Advance and Retreat

■ Toe position

- If accumulation < ablation, the glacial toe will retreat upslope.



23

Ice in the Sea

- In polar regions, glaciers flow out over ocean water.
 - Tidewater glaciers—valley glaciers entering the sea
 - Ice shelves—continental glaciers entering the sea
 - Sea ice—nonglacial ice formed of frozen seawater

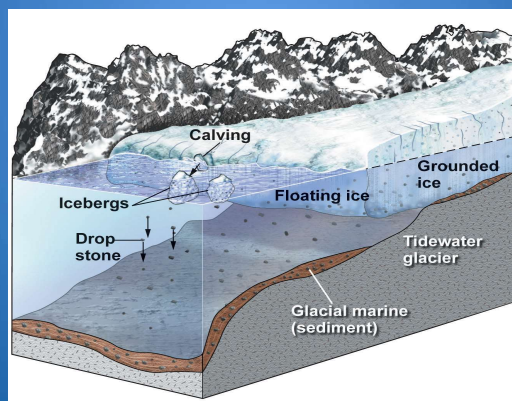


Fig. 18.9a



Ice in the Sea

- Floating ice is normally four fifths beneath the waterline.
- Floating ice exhibits a variety of shapes and sizes.
 - Iceberg—greater than 6 m above water
 - Ice shelves yield tabular bergs.

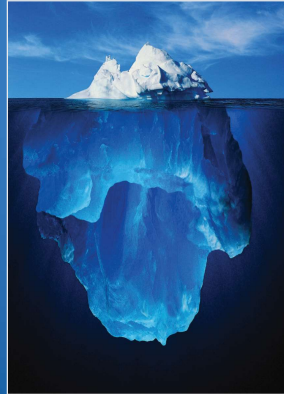


Fig. 18.9b, c



25

Ice in the Sea

- Large areas of the polar seas are covered with ice.
- Global warming is causing a reduction in ice cover.

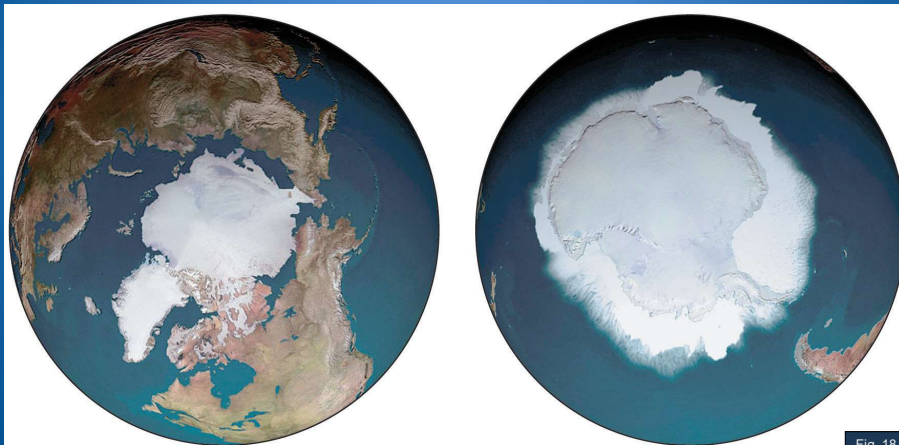


Fig. 18.9d



Carving and Carrying by Ice

- Glaciers are important forces of landscape change.
 - Erosion
 - Transport
 - Deposition



Fig. 18.10b

27

Glacial Erosion and Its Products

- Glaciers carve deep valleys, such as Yosemite Valley.
 - Polished granite domes and vertical cliffs are the result of glacial erosion.



Fig. 18.10a



Glacial Erosion and Its Products

- Glacial abrasion—a “sandpaper” effect on substrate
 - Substrate is pulverized to fine “rock flour.”
 - Sand in moving ice abrades and polishes bedrock.

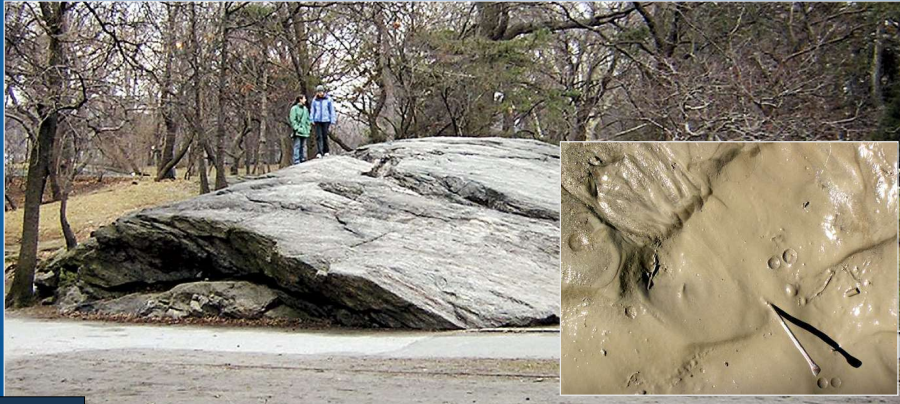


Fig. 18.10c

29

Glacial Erosion and Its Products

- Glacial abrasion—a “sandpaper” effect on substrate
 - Large rocks are dragged across bedrock gouge striations.
 - Striations run parallel to direction of ice movement.



Fig. 18.10d



Glacial Erosion and Its Products

■ Erosional features of glaciated valleys:

- Cirques
- Tarns
- Aretes
- Horns
- U-shaped valleys
- Hanging valleys
- Fjords

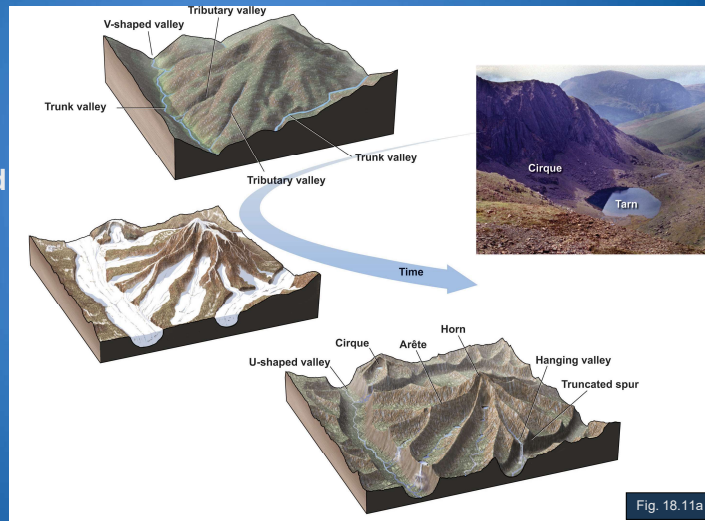


Fig. 18.11a

31

Glacial Erosion and Its Products

- Cirques—bowl-shaped basins high on a mountain
 - Form at the uppermost portion of a glacial valley.
 - Freeze-thaw mass wasting chews into the cirque headwall.
 - After ice melts, the cirque often becomes a tarn (lake).



PowerPoint slides prepared by Rick Oches, Professor of Geology & Environmental Sciences, Bentley University, Waltham, Massachusetts

32



Glacial Erosion and Its Products

- **Arete—a “knife-edge” ridge**
 - Formed by two cirques that have eroded toward one another



33

Glacial Erosion and Its Products

- **Horn—a pointed mountain peak**
 - Formed by three or more cirques that surround the peak



Fig. 18.11b



Glacial Erosion and Its Products

■ U-shaped valleys

- Glacial erosion creates a distinctive trough.
- Compare to V-shaped fluvial valleys.

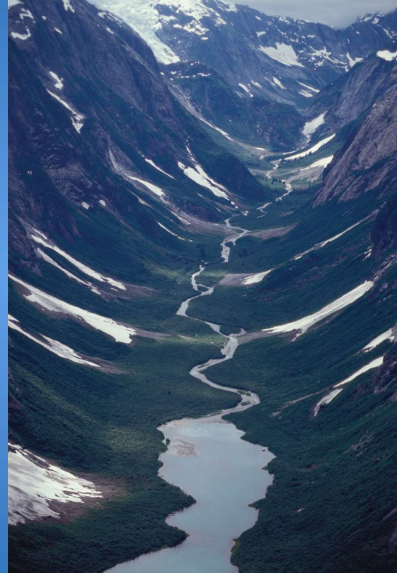


Fig. 18.11c

35

Glacial Erosion and Its Products

■ Hanging valleys

- The intersection of a tributary glacier with a trunk glacier
- Trunk glacier incises deeper into bedrock.
- Troughs have different elevations.
- A waterfall results.

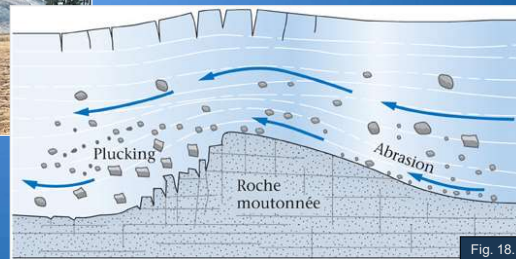


Fig. 18.11d



Glacial Erosion and Its Products

- Glaciers can also erode by plucking.
 - Ice freezes around bedrock fragments and plucks chunks as glacier advances.
 - It forms a distinctive asymmetric hill called a roche moutonnée.



37

Glacial Erosion and Its Products

- Fjords
 - U-shaped glacial troughs flooded by the sea
 - Accentuated by isostatic rebound



Fig. 18.13



Deposition Associated with Glaciation

- Glaciers act as large-scale conveyor belts.
 - They pick up, transport, and deposit a lot of sediment.
 - Sediment transport is always in one direction (downhill).
 - Debris at the toe of a glacier is called an end moraine.

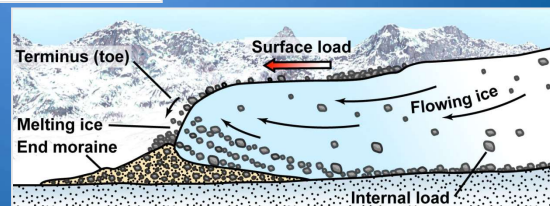
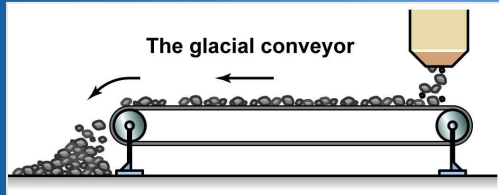


Fig. 18.14a

39

Deposition Associated with Glaciation

- Moraines—unsorted debris deposited by a glacier
 - Lateral—forms along the flank of a valley glacier
 - Medial—mid-ice moraine from merging of lateral moraines

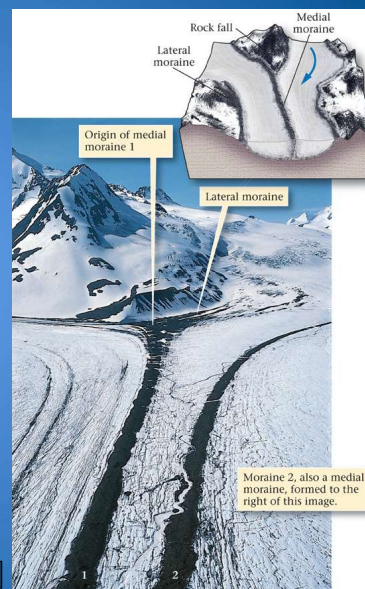
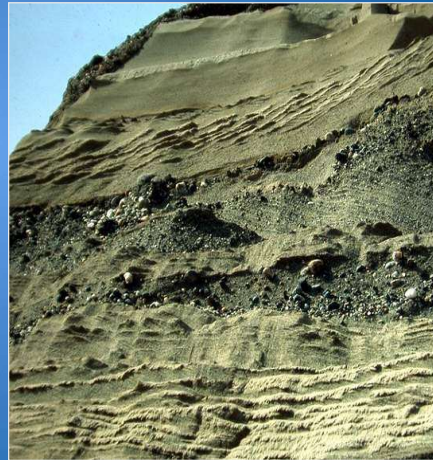


Fig. 18.14b



Types of Glacial Sedimentary Deposits

- Many types of sediment derive from glaciation.
- Called glacial drift, these include:
 - Glacial till
 - Erratics
 - Glacial marine sediments
 - Glacial outwash
 - Loess
 - Glacial lake-bed sediment
- Stratified drift is water sorted; unstratified drift is not sorted.



41

Glacial Deposits

- Glacial till—sediment dropped by glacial ice
 - Consists of all grain sizes—boulders to clay.
 - Unmodified by water, hence:
 - Unsorted
 - Unstratified
 - Accumulates:
 - Beneath glacial ice
 - At the toe of a glacier
 - Along glacial flanks



Fig. 18.15a



Glacial Deposits

- Erratics—boulders dropped by glacial ice.
 - These rocks are different from the underlying bedrock.
 - Often, they have been carried long distances in ice.

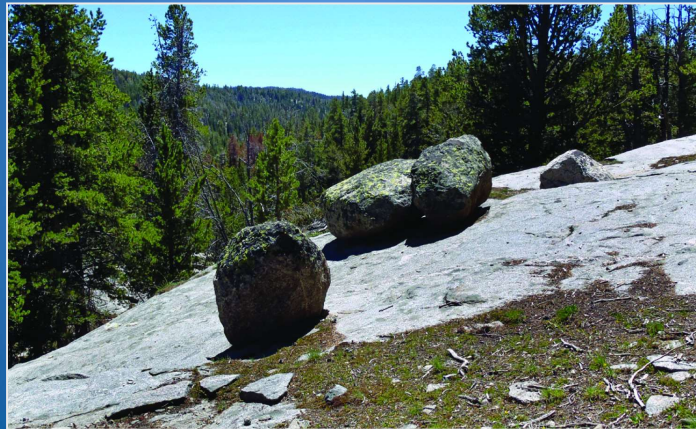


Fig. 18.15b

43

Glacial Deposits

- Glacial marine—sediments from an oceanic glacier
 - Calving icebergs raft sediments away from the ice.
 - Melting icebergs drop stones into bottom mud.

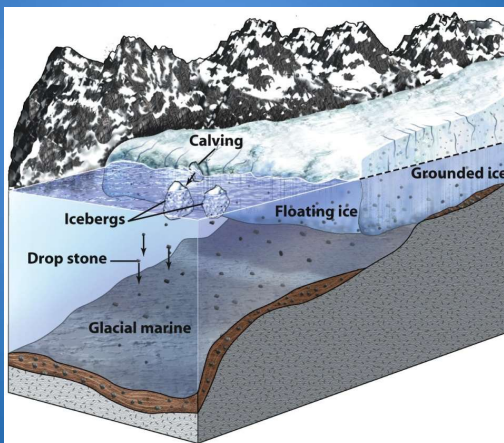


Fig. 18.9a



Glacial Deposits

- Glacial outwash—sediment transported by meltwater
 - Muds are removed.
 - Sizes are graded and stratified.
 - Grains are abraded and rounded.
- Outwash is dominated by sand and gravel.



Fig. 18.15c

45

Glacial Deposits

- Glacial lake-bed sediment
 - Lakes are abundant in glaciated landscapes.
 - Fine rock flour settles out of suspension in deep lakes.
 - Muds display seasonal varve couplets.
 - ▶ Finest silt and clay are from frozen winter months.
 - ▶ Coarser silt and sand are from summer months.

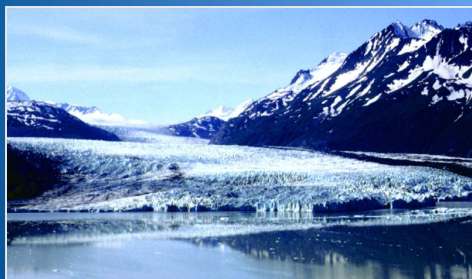


Fig. 18.15e





Glacial Deposits

■ Loess—wind-transported silt. Pronounced “luss.”

- Glaciers produce abundant amounts of fine sediment.
- Strong winds over ice blow the rock flour away.
- This sediment settles out near glaciated areas as loess deposits.
- Deposits are unstratified and distinct in color.



Fig. 18.15d

47

Glacial Depositional Landforms

■ Glacial sediments create distinctive landforms:

- End moraines and terminal moraines
- Recessional moraines
- Ground moraine
- Drumlins
- Kettle lakes
- Eskers

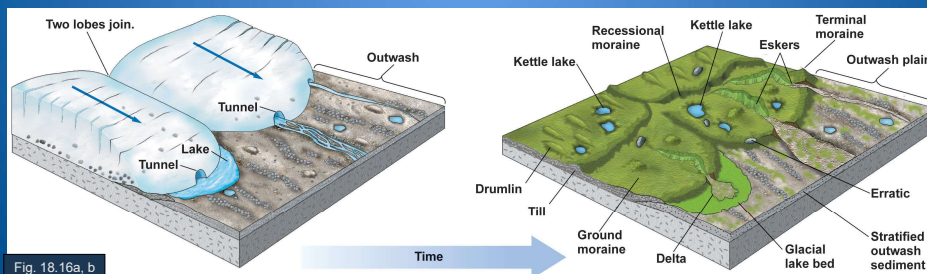


Fig. 18.16a, b



Depositional Landforms

- End moraines form at the stable toe of a glacier.
- Terminal moraines form at the farthest edge of flow.
- Recessional moraines form as retreating ice stalls.

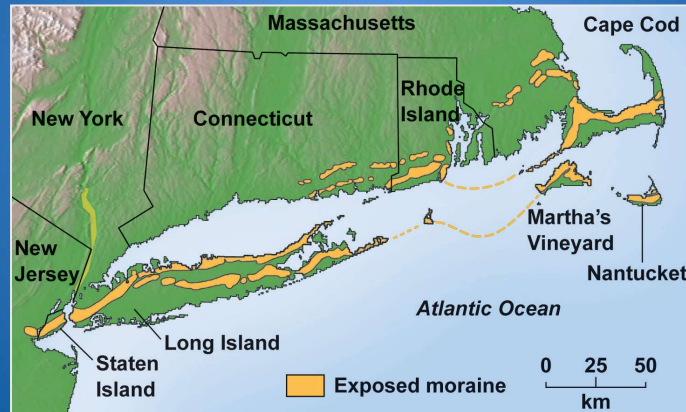


Fig. 18.16c

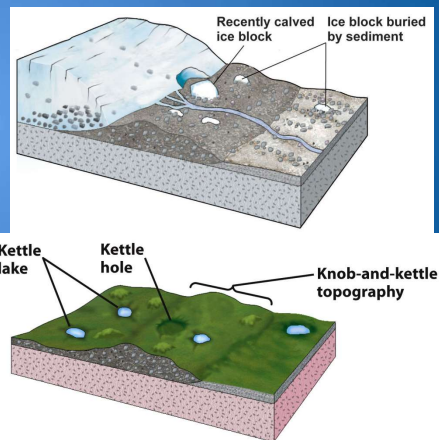
49

Depositional Landforms

- Ground moraine is till left behind by rapid ice retreat.
 - Creates a hummocky, mostly flat land surface.
 - Kettle lakes form from stranded ice blocks.



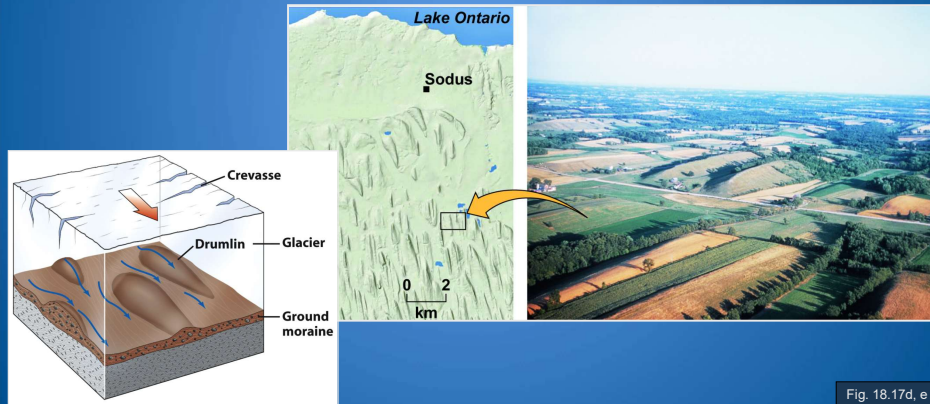
Fig. 18.17a-c





Depositional Landforms

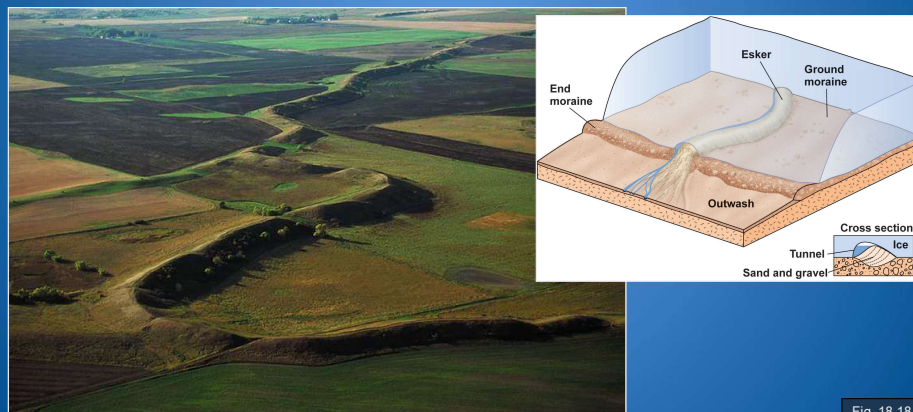
- **Drumlins**—long, aligned hills of molded lodgment till
 - Asymmetric form—steep up-ice; tapered down-ice.
 - Commonly occur as swarms aligned parallel to ice-flow direction.



51

Depositional Landforms

- **Eskers** are long, sinuous ridges of sand and gravel.
- They form as meltwater channels within or below ice.
- Channel sediment is released when the ice melts.





Consequences of Continental Glaciation

■ Ice loading and glacial rebound

- Ice sheets depress the lithosphere into the mantle.
- Slow crustal subsidence follows flow of asthenosphere.
- After ice melts, the depressed lithosphere rebounds.
- The last ice-age glacial rebound continues slowly today.

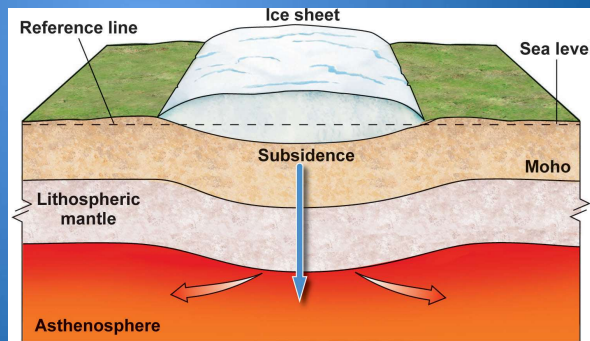


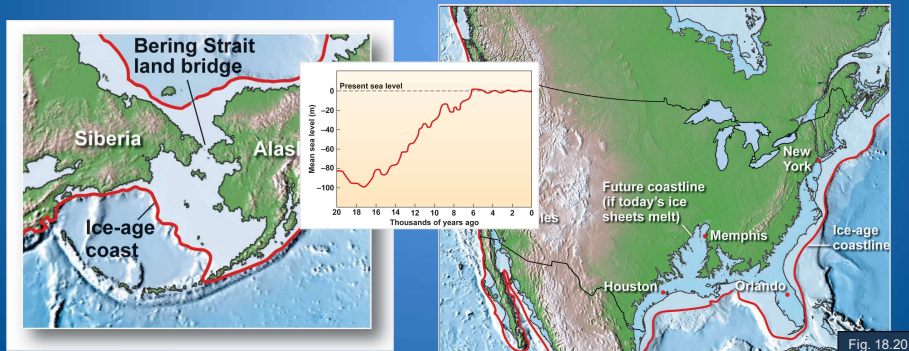
Fig. 18.19

53

Glacial Consequences

■ Sea level—ice ages cause sea level to rise and fall.

- Water is stored on land during an ice age; sea level falls.
- Deglaciation returns water to the oceans; sea level rises.
- Sea level was ~100 m lower during the last ice age.
- If ice sheets melted, coastal regions would be flooded.





Glacial Consequences

■ Gigantic proglacial lakes formed near the ice margin.

● Glacial Lake Agassiz

- ▶ Covered a huge area.
- ▶ Existed for 2,700 years.
- ▶ Drained abruptly.
- ▶ Exposed mud-rich, extremely flat land.



Fig. 18.21a

55

Glacial Consequences

■ Pluvial features—large lakes formed during ice age.

● The American Southwest was much wetter.

- ▶ Large lakes occupied today's deserts.
- ▶ Lake Bonneville (remnant is Great Salt Lake).



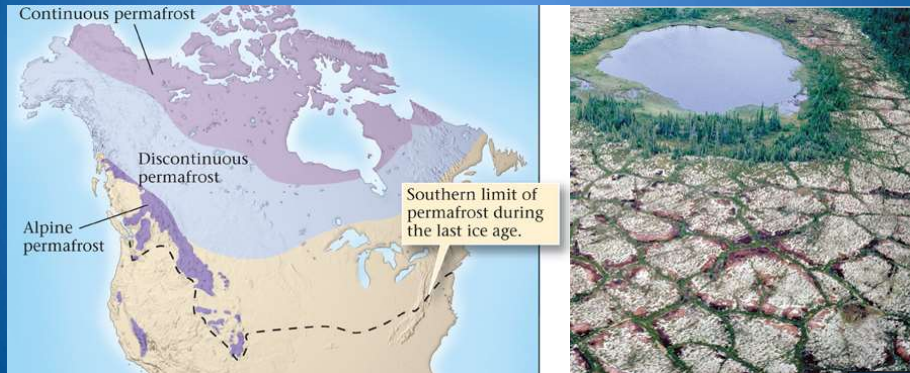
Fig. 18.21





Glacial Consequences

- Periglacial (near-ice) environments are unique.
 - Characterized by year-round frozen ground (permafrost).
 - Freeze-thaw cycles generate unusual patterned ground.



57

Pleistocene Ice Ages

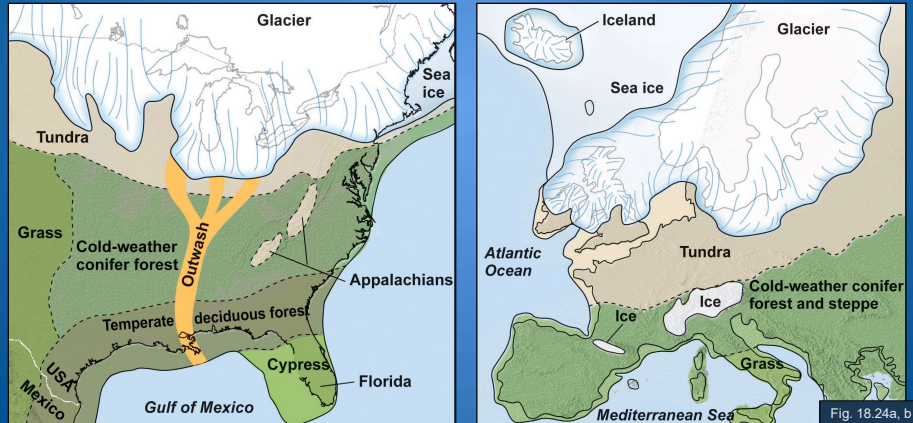
- Young (<2.6 Ma) glacial remnants are abundant.
 - Northern North America
 - Scandinavia and Europe
 - Siberia
- Landscapes in these regions are clearly glacial.





Pleistocene Life and Climate

- All climate and vegetation belts were shifted southward.
 - The tundra limit was $\sim 48^\circ$ N. Today, it is above 68° N.
 - Vegetation evidence is preserved as pollen found in bogs.



59

Pleistocene Life and Climate

- Pleistocene fauna were well adapted.
- Mammals included now-extinct giants:
 - Giant beaver
 - Giant ground sloth
 - Mammoths and mastodons
- Modern humans proliferated.

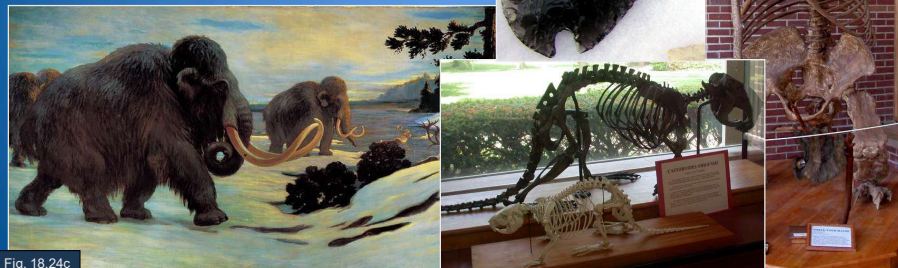


Fig. 18.24c



Timing of the Pleistocene Ice Age

- In North America, multiple Pleistocene glacial advances are recognized. Youngest to oldest:
 - Wisconsinan
 - Illinoian
 - Pre-Illinoian
- Ice ages separated by interglacials intervals

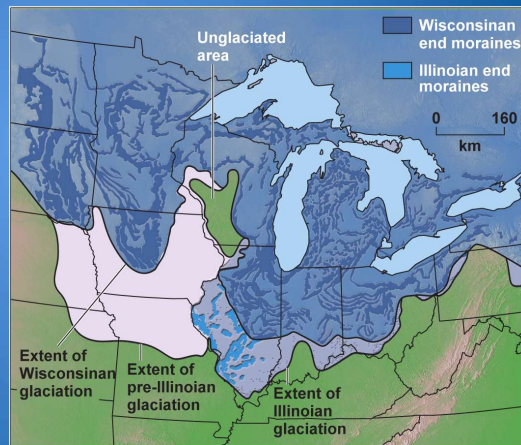


Fig. 18.25

61

Timing of the Pleistocene Ice Age

- Oxygen isotopes suggest twenty or more glaciations throughout Earth history.
 - Higher $^{18}\text{O}/^{16}\text{O}$ = colder.
 - Lower $^{18}\text{O}/^{16}\text{O}$ = warmer.
- The “original four” ice ages may simply have been the largest.

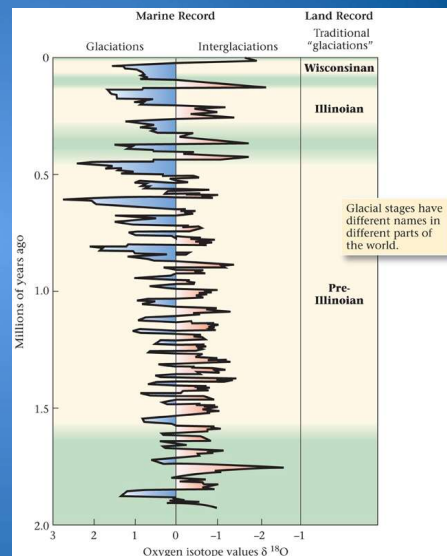


Fig. 18.26a



Earlier Glaciations

- Glaciations have occurred before in Earth history.
- They are indicated by fossil tills and striated bedrock:
 - Pleistocene
 - Permian
 - Ordovician
 - Late Proterozoic—tillites at equatorial latitudes suggest an ice-covered world (“Snowball Earth”).

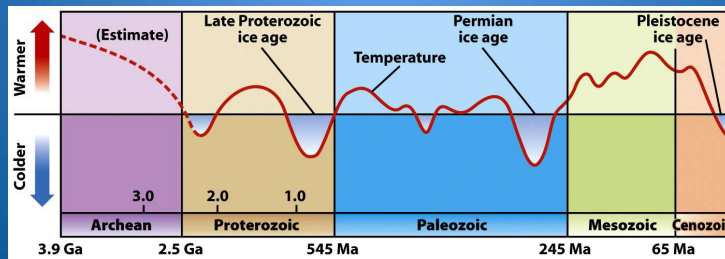


Fig. 18.26b

63

Causes of Glaciation

- Long-term causes—set the stage for ice ages.
 - Plate tectonics – control factors that influence glaciation.
 - Distribution of continents toward high latitudes
 - Sea-level flux by mid-ocean-ridge volume changes
 - Oceanic currents
 - Atmospheric chemistry
 - Changes in greenhouse gas concentrations
 - ✓ Carbon dioxide (CO₂)
 - ✓ Methane (CH₄)

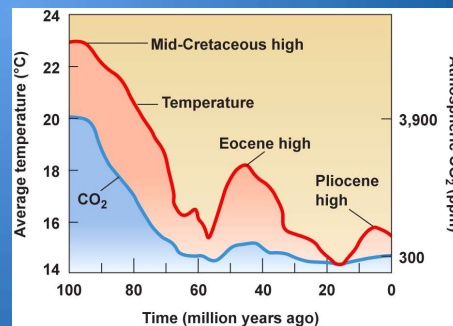
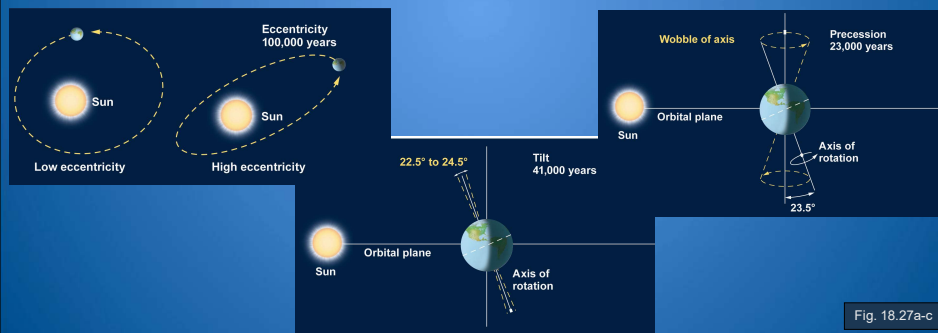


Fig. 18.28



Causes of Glaciation

- Short-term causes—govern advances and retreats
 - Milankovitch hypothesis—climate variation over 100 to 300 ka predicted by cyclic changes in orbital geometry.
 - ▶ The shape of Earth's orbit varies (~100,000 year cyclicality).
 - ▶ Tilt of Earth's axis varies from 22.5° to 24.5° (~41,000 years).
 - ▶ Precession—Earth's axis wobbles like a top (23,000 years).



65

Causes of Glaciation

- Short-term causes – govern advances and retreats
 - Milankovitch cycles drive global climate and glacial cycles.
 - ▶ Stage 1: average temperature drops, glaciers are born.
 - ▶ Stage 2: glaciers grow, albedo causes further cooling.
 - ▶ Stage 3: temperatures warm, glaciers shrink, interglacial begins.

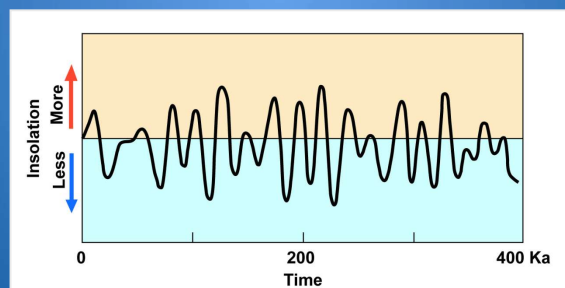


Fig. 18.27d



Will There Be Another Glaciation?

- Are we living in an interglacial (will ice return)?
 - Very likely. Interglacials last ~10,000 years.
 - It has been ~11,000 years since the last deglaciation.
 - A cool period (1300–1850) resulted in the Little Ice Age.

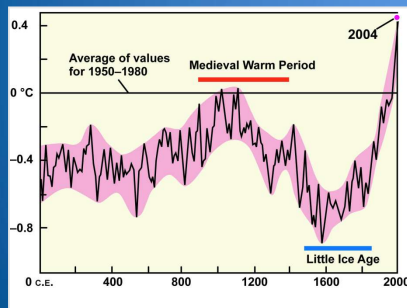


Fig. 18.29a, b

67

Will There Be Another Glaciation?

- During the last 150 years, temperatures have risen and most mountain glaciers have dramatically retreated.
- Earth's climate could now be in "super-interglacial" period.



Fig. 18.29c



Useful Web Resources

- NOAA Weather and Atmosphere
 - http://www.education.noaa.gov/Weather_and_Atmosphere/
- The American Quaternary Association, Friends of the Pleistocene
 - <http://www.amqua.org/friends/>
- Antarctic Research
 - <http://www.antarcticconnection.com/antarctic/stations/index.shtml>
- Byrd Polar Research Center
 - <http://bprc.osu.edu/>
- Rocky Mountain National Park: Glaciers and Glacier Change: Glacier Research
 - <http://www.nps.gov/features/romo/feat0001/GlcResearch.html>

69

Useful Web Resources

- USGS Northern Rocky Mountain Science Center, Repeat Photography Project
<http://www.nrmsc.usgs.gov/repeatphoto>
- USGS Glacier and Landscape Change in Response to Changing Climate
http://www.usgs.gov/global_change/glaciers/default.asp
- SwissEduc, Glaciers Online
<http://www.swisseduc.ch/glaciers/>
- National Snow and Ice Data Center
<http://nsidc.org/index.html>
- PBS, Cracking the Ice Age
<http://www.pbs.org/wgbh/nova/ice/>
- Extreme Ice Survey
<http://www.extremeicesurvey.org/>