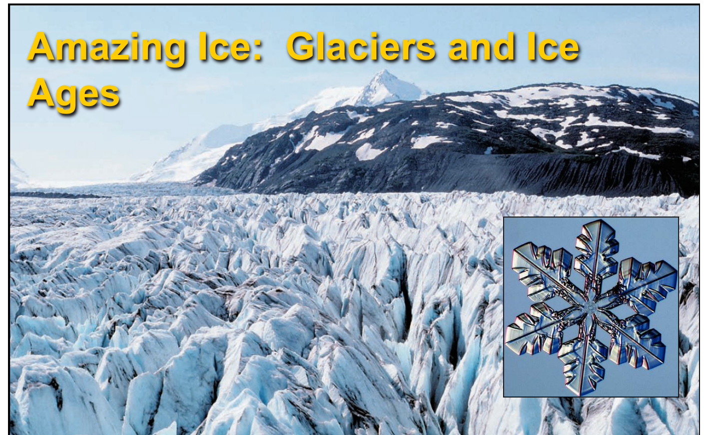
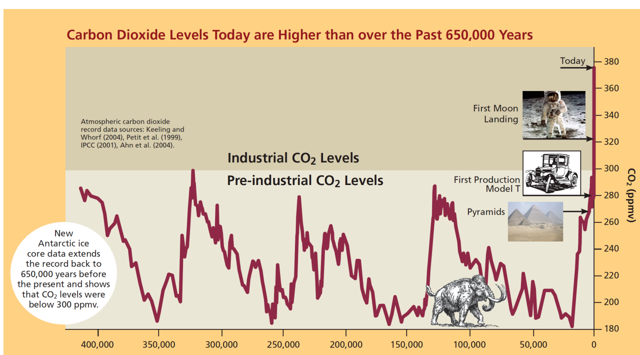
Geology 800

- Today
  - Glaciers and Ice Ages Chapter 18
- Next Class Mon Dec 1
  - Final Exam on Chapters 14 (Running Water), 15 (Oceans), 17 (Deserts) and 18 (Glaciers)

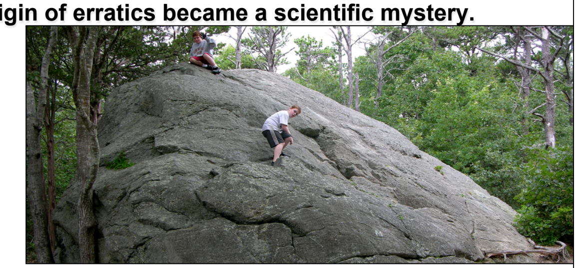
Amazing Ice: Glaciers and Ice Ages





The Theory of Glaciation

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



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 glaciers could explain erratic boulders.

The Theory of Glaciation

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

The Theory of Glaciation

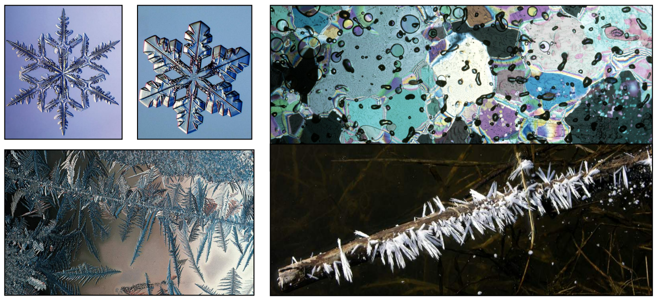
- When 1st proposed, Agassiz's idea was criticized.
- By the 1850s, many geologists agreed that he was right.
- Agassiz saw evidence for a North American ice age.

Ice Ages

- Glaciers 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, Paris.
  - Ice sheets were hundreds to thousands of meters thick.

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 forms.

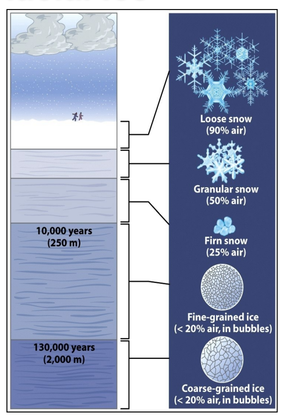


Ice: The Water Rock

- Natural ice is a type of rock.
  - Igneous – A frozen pond.
  - Sedimentary – Weakly-cemented fallen snow.
  - Metamorphic – Deformed, plastic, glacial ice.

Formation of Glacial Ice

- Snow is transformed into ice.
  - Delicate flakes accumulate.
  - Snow is buried by later falls.
  - Compression expels air.
  - Burial pressure causes melting and recrystallization.
  - Snow turns into granular firn.
  - Over time, firn melds into interlocking crystals of ice.



Formation of Glacial Ice

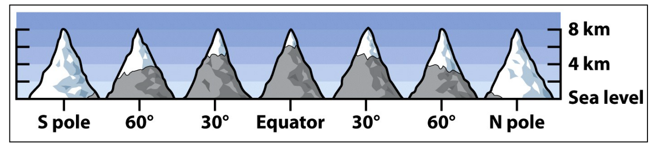
- Glacial ice may form…
  - Quickly (tens of years)
  - Slowly (thousands of years).

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.

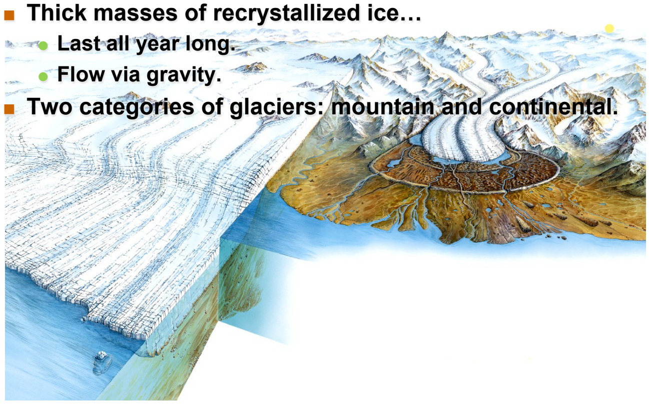
Forming a Glacier

- Glacier-sustaining elevation is controlled by latitude.
  - In polar regions, glaciers form at sea level.
  - In equatorial regions, glaciers form above 5 km elevation.
- This elevation is marked by the "snow line."



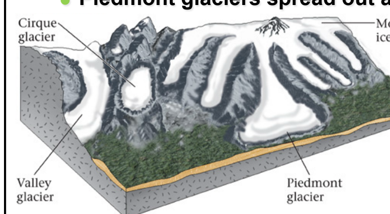
Glaciers

- Thick masses of recrystallized ice…
  - Last all year long.
  - Flow via gravity.
- Two categories of glaciers: mountain and continental.



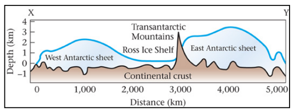
Mountain Glaciers

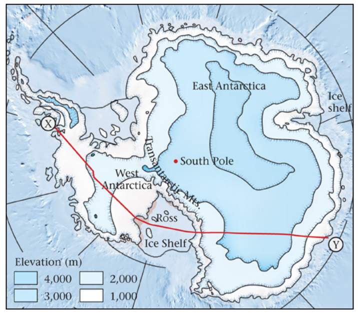
- Flow from high to low elevation in mountain settings.
- Include a variety of types.
  - Cirque glaciers fill mountain-top bowls.
  - Valley glaciers flow like rivers down valleys.
  - Mountain ice caps cover peaks and ridges.
  - Piedmont glaciers spread out at the end of a valley.



Continental Glaciers

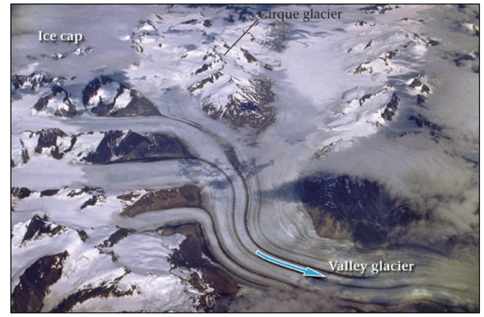
- Vast ice sheets covering large land areas.
- Ice flows outward from thickest part of sheet.
- Two major ice sheets remain on Earth:
  - Greenland.
  - Antarctica.





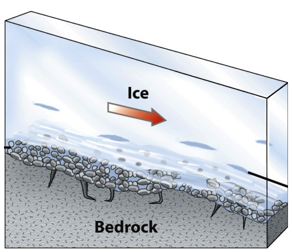
Thermal Categories

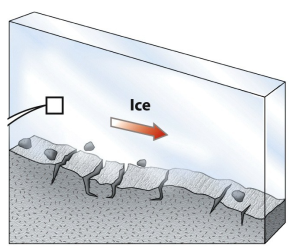
- Used to classify glaciers; determined by climate.
  - Temperate glaciers – Ice is at or near melting temperature.
  - Polar glaciers – Ice is well below melting temperature.



Movement of Glacial Ice

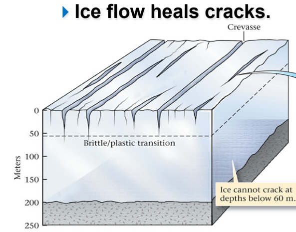
- How do glaciers move?
  - Wet-bottom glaciers – Water flows along base of glacier.
    - Basal sliding – Ice slips over a meltwater / sediment slurry.
  - Dry-bottom glaciers – Cold base is frozen to substrate.
    - Movement is by internal plastic deformation of ice.

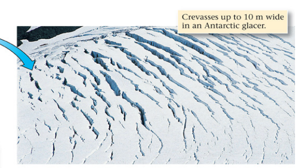




Movement of Glacial Ice

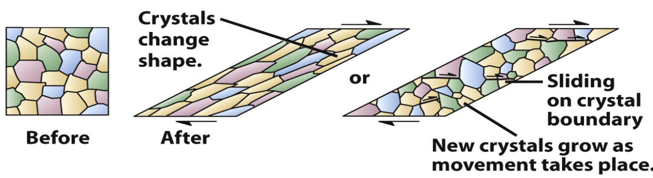
- Two types of mechanical behavior:
  - Brittle – Uppermost 60 m.
    - Tension initiates cracking of the ice.
    - Crevasses may open and close with movement.
  - Plastic – Lower than 60 m.
    - Ductile flow occurs in deeper ice.
    - Ice flow heals cracks.





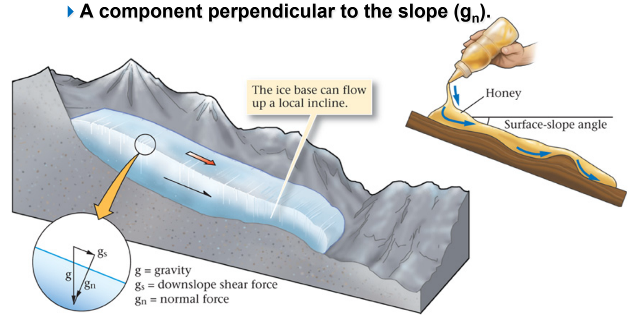
Movement of Glacial Ice

- Internal plastic (ductile) deformation.
  - Ice crystals may stretch or rotate.
  - Ice crystals may shear past one another.



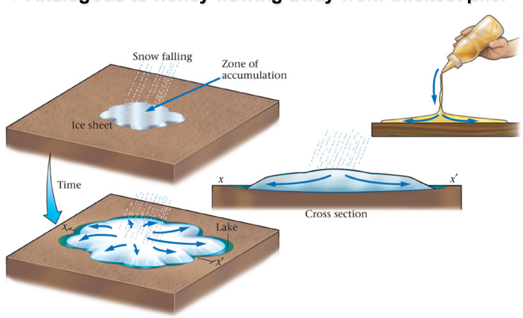
Movement of Glacial Ice

- Ice flows downhill via gravity.
  - Gravity (g) can be resolved into two vectors.
    - A component parallel to the slope (g_s), which drives flow.
    - A component perpendicular to the slope (g_n).



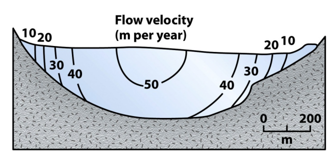
Movement of Glacial Ice

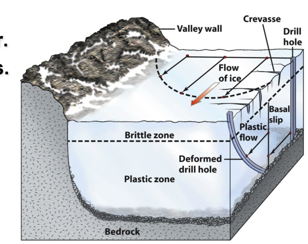
- Ice flows downhill via gravity.
  - Flow is away from the thickest part of continental glaciers.
    - Analogous to honey flowing away from thickest pile.



Movement of Glacial Ice

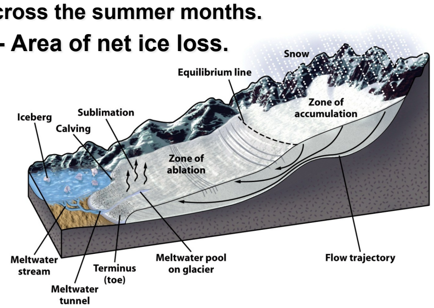
- Rates of flow vary widely (10 to 300 m/yr).
- Rarely, glaciers may surge (20 to 110 m/day).
- The rate of flow is controlled by…
  - The severity of slope angle: Steeper = faster.
  - Basal water: Wet-bottom = faster.
  - Location within glacier.
    - Greater velocity in ice center.
    - Friction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





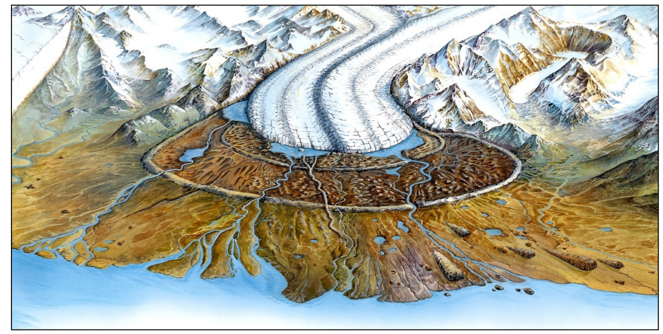
Glacial Advance and Retreat

- 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 abut at the equilibrium line.



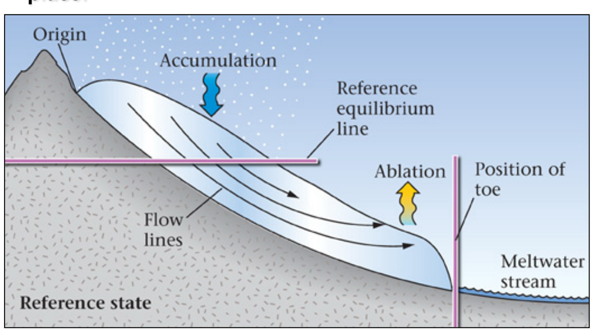
Glacial Advance and Retreat

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



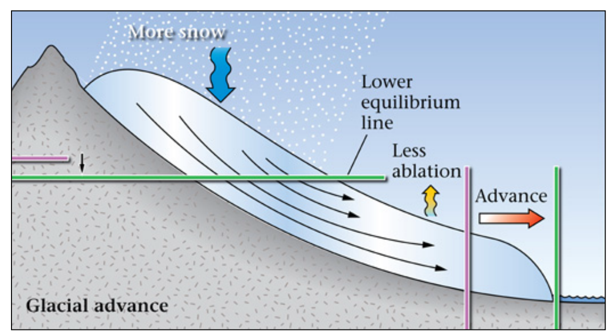
Glacial Advance and Retreat

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



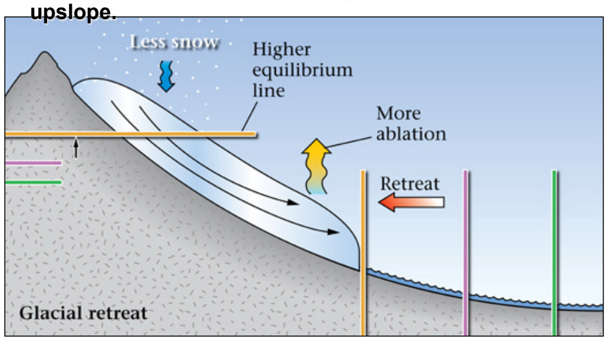
Glacial Advance and Retreat

- Toe position.
  - If accumulation > ablation, the glacial toe advances.



Glacial Advance and Retreat

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

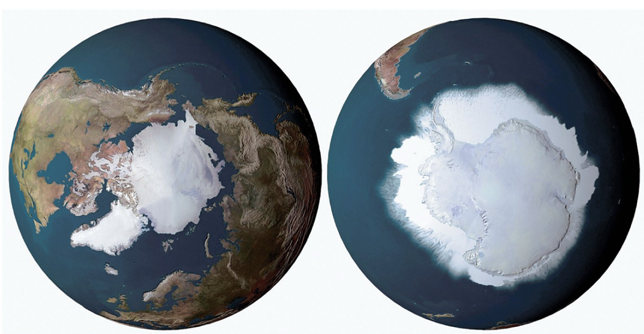


Ice in the Sea

- 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 – Non-glacial ice formed of frozen seawater.

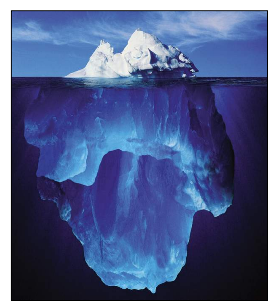
Ice in the Sea

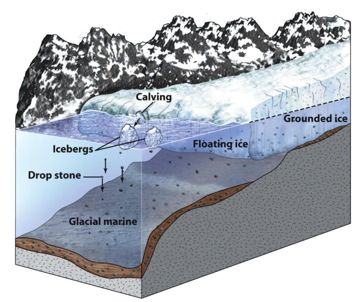
- Large areas of the polar seas are covered with ice.
- Global warming appears to be reducing ice cover.



Ice in the Sea

- Marine glaciers have both grounded and floating ice.
- Ice debris calves off the edge, forming icebergs.
- Melting icebergs release dropstones to deep water.



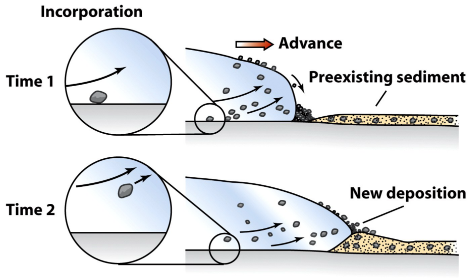


Glacial Effects

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

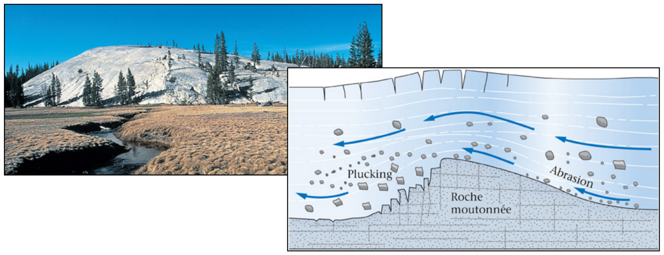
Glacial Erosion

- Glaciers erode substrates in several ways.
  - Glacial incorporation – Rock is surrounded and carried off.



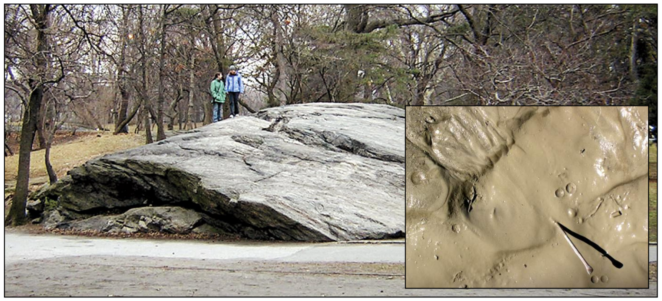
Glacial Erosion

- Glaciers erode substrates in several ways.
  - Plucking – Ice breaks off and removes bedrock fragments.
    - Pressure melts ice against the surface of an obstruction.
    - Entering bedrock cracks, this water refreezes to the glacier.
    - Glacial movement plucks away bedrock chunks.



Glacial Erosion

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

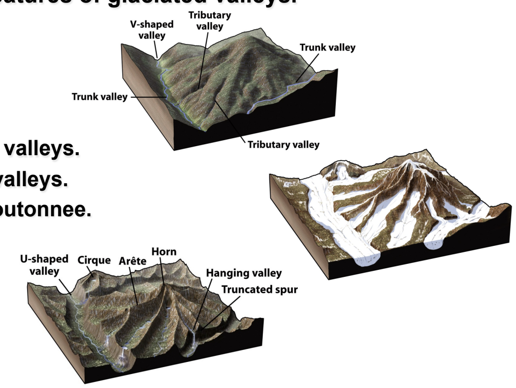


Glacial Erosion

- Glacial abrasion – A “sandpaper” effect on substrate.
  - Large rocks dragged across bedrock gouge striations.
  - Boulders crack crescentic chatter marks into bedrock.

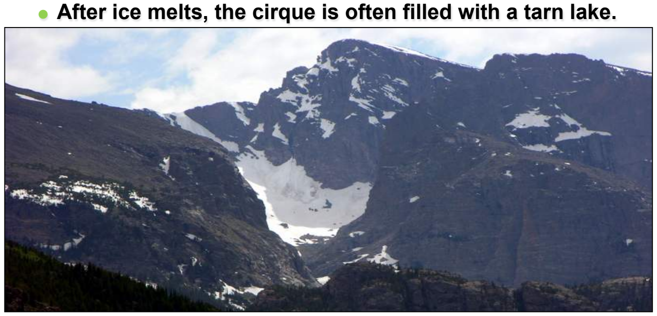
Glacial Erosion

- Erosional features of glaciated valleys.
  - Cirques.
  - Tarns.
  - Aretes.
  - Horns.
  - U-shaped valleys.
  - Hanging valleys.
  - Roche moutonnee.
  - Fjords.



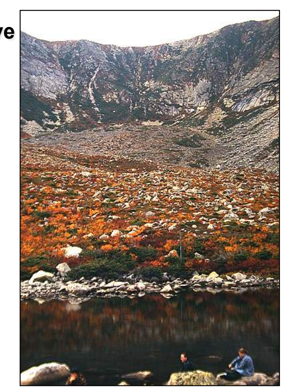
Glacial Erosion

- Cirques – Bowl-shaped basin 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 is often filled with a tarn lake.



Glacial Erosion

- Arete – A “knife-edge” ridge.
  - Formed by two cirques that have eroded toward one another.

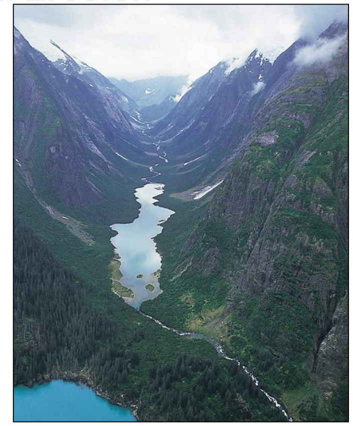


Glacial Erosion

- Horn – A pointed mountain peak.
  - Formed by three or more cirques that coalesce.

Glacial Erosion

- U-shaped valleys.
  - Glacial erosion creates a distinctive trough.
  - Unlike V-shaped fluvial valleys.



Glacial Erosion

- 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.

Glacial Erosion

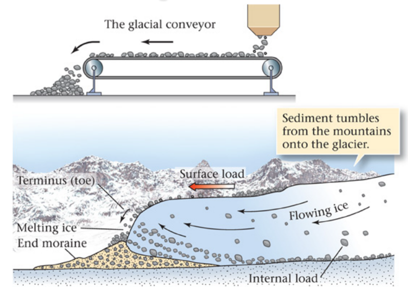
- Fjords.
  - U-shaped glacial troughs flooded by the sea.
  - Accentuated by isostatic rebound.

Glacial Sediment Transport

- Glaciers carry sediment of all sizes – lots of it!
  - Some sediment falls onto the ice from adjacent cliffs.
  - Some sediment is entrained from erosion of the substrate.
- When glacial ice melts, this material is dropped.

Glacial Sediment Transport

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



Glacial Deposition

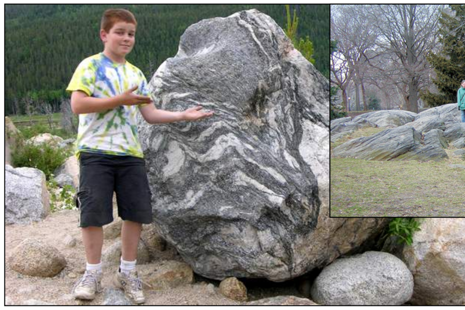
- Many types of sediment derive from glaciation.
- Called glacial drift, these include…
  - Glacial till.
  - Erratics.
  - Glacial marine sediments.
  - Glacial outwash.
  - Glacial lake-bed sediment.
  - Loess.
- Stratified drift is water sorted; unstratified drift isn't.

Glacial Deposition

- Glacial till – Sediment dropped by glacial ice.
  - Consists of all grain sizes.
  - Aka "boulder clay."
  - Unmodified by water, hence…
    - Unsorted.
    - Unstratified.
  - Accumulates…
    - Beneath glacial ice.
    - At the toe of a glacier.
    - Along glacial flanks.

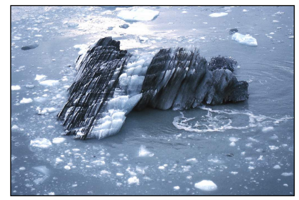
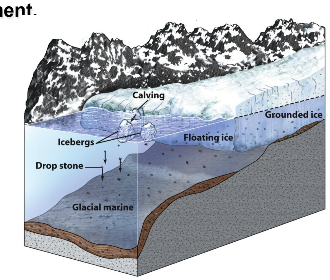
Glacial Deposition

- Erratics – Boulders dropped by glacial ice.
  - These rocks are different than the underlying bedrock.
  - Often, they have been carried long distances in ice.




Glacial Deposition

- Glacial marine – Sediments from an oceanic glacier.
  - Calving icebergs raft sediments away from the ice.
  - Melting, bergs drop stones into bottom muds.
  - Dropstones…
    - Differ from ambient sediment.
    - Indicate glaciation.

Glacial Deposition

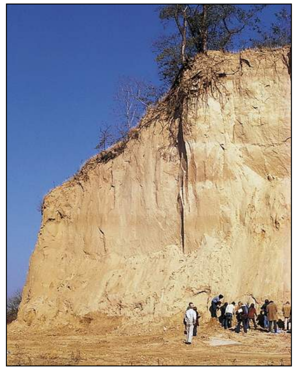
- Glacial outwash – Sediment transported in meltwater.
  - Muds are removed.
  - Sizes are graded and stratified.
  - Grains are abraded and rounded.
- Outwash is dominated by sand and gravel.


Glacial Deposition

- 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 from frozen winter months.
    - Coarser silt and sand from summer months.

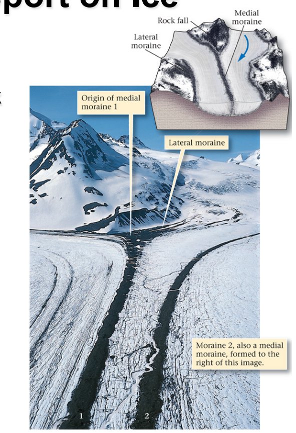
Glacial Deposition

- Loess – Wind-transported silt. Pronounced “luss.”
  - Glaciers produce abundant amounts of fine sediment.
  - Strong winds off ice blows the rock flour away.
  - This sediment settles out near glaciated areas as loess deposits.



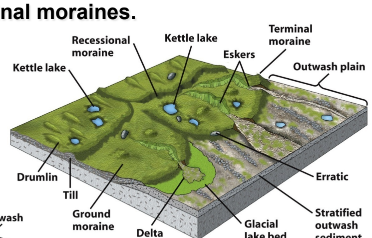
Sediment Transport on Ice

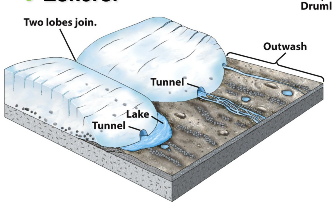
- Moraines – Unsorted debris dumped by a glacier.
  - Lateral – Forms along the flank of a valley glacier.
  - Medial – Mid-ice moraine from merging lateral moraines.



Depositional Landforms

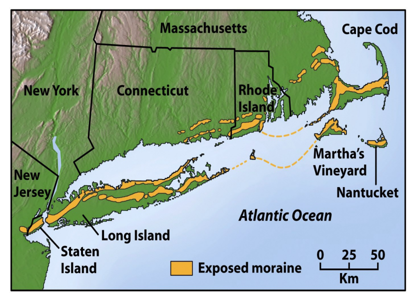
- Glacial sediments create distinctive landforms.
  - End moraines and terminal moraines.
  - Recessional moraines.
  - Drumlins.
  - Ground moraine.
  - Kettle lakes.
  - Eskers.

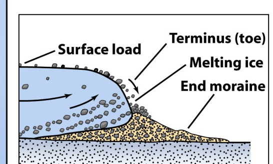




Depositional Landforms

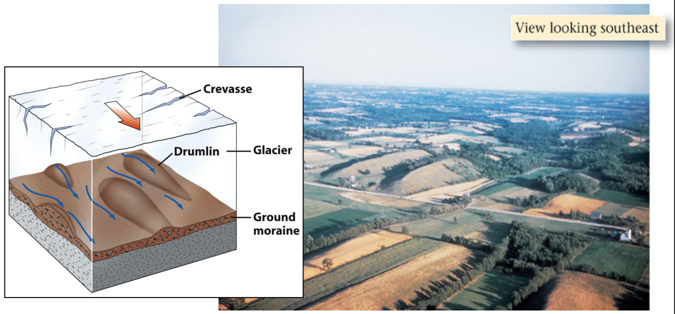
- End moraines form at the stable toe of a glacier.
- Terminal moraines form at the farthest edge of flow.
- Recessional moraines form as retreating ice stalls.





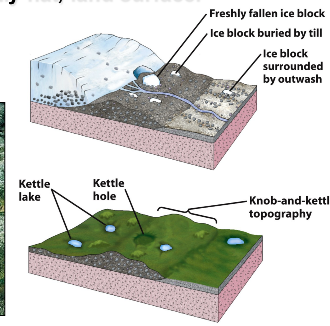
Depositional Landforms

- Drumlins – Long, aligned hills of molded lodgment till.
  - Asymmetric form – Steep up-ice; tapered down-ice.
  - Common as swarms aligned parallel to ice-flow direction.



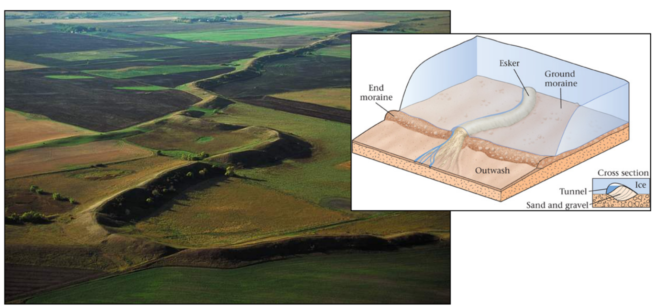
Depositional Landforms

- Ground moraine is till left behind by rapid ice retreat.
  - It fills preexisting topography like a layer of asphalt.
  - Creates a hummocky, mostly flat, land surface.
  - Studded with kettle lakes from stranded ice blocks.



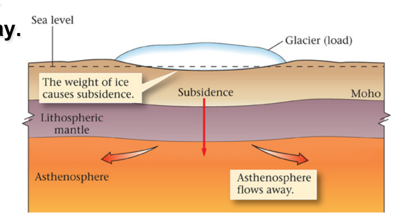
Depositional Landforms

- 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.



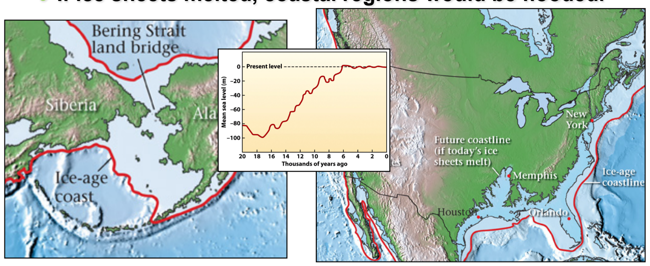
Glacial Consequences

- Subsidence and rebound.
  - Ice sheets depress the lithosphere into the mantle.
  - Slow crustal subsidence follows flow of asthenosphere.
  - After ice melts, the depressed lithosphere rebounds.
  - Continues slowly today.



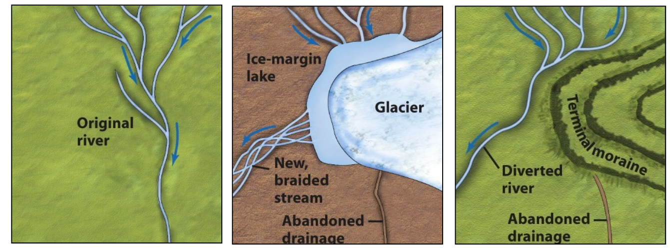
Glacial Consequences

- 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 Wisconsinan.
  - If ice sheets melted, coastal regions would be flooded.



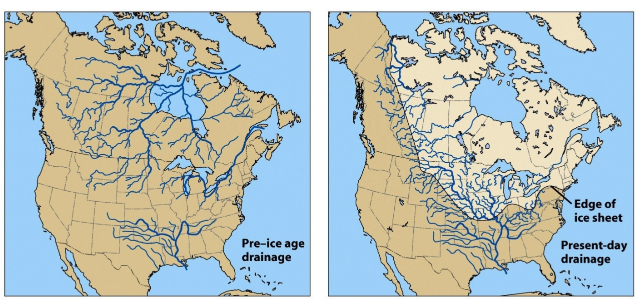
Glacial Consequences

- Drainages – Glaciation replumbs river systems.
  - Ice and glacial drift block preexisting drainages.
  - After melting, altered river courses remain.



Glacial Consequences

- North America: Glaciation completely changed drainage.

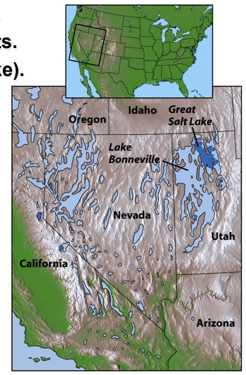


Glacial Consequences

- Gigantic proglacial lakes formed near the ice margin.
  - Glacial Lake Agassiz.
    - Covered a huge area.
    - Existed for 2,700 years.
    - Drained abruptly.
    - Exposed very mud-rich, extremely flat land.

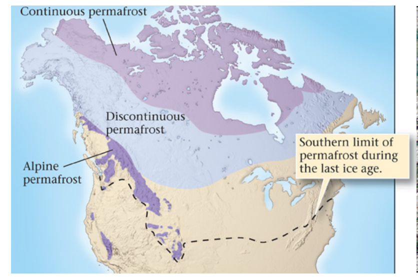
Glacial Consequences

- Climatic changes – Weather patterns were different.
  - The American SW was much wetter.
    - Large lakes occupied today's deserts.
    - Lake Bonneville (now Great Salt Lake).



Periglacial Environments

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

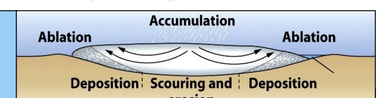


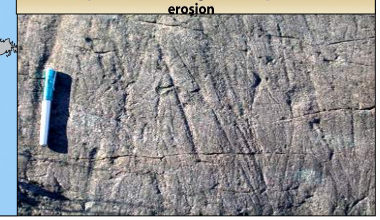
Pleistocene Ice Ages

- Young (< 1.8 Ma) glacial remnants are abundant.
  - Northern North America.
  - Scandinavia and Europe.
  - Siberia.
- Landscapes in these regions are clearly glacial.

Pleistocene Ice Ages

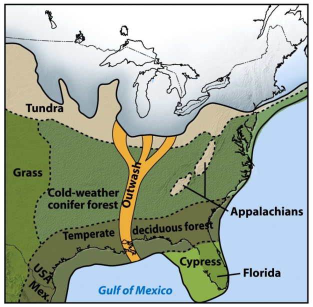
- Ice sheets were 2 to 3 km thick in accumulation centers.
- Near centers, ice scoured bedrock, leaving striations.
- Ice sheets thinned outward, depositing debris.

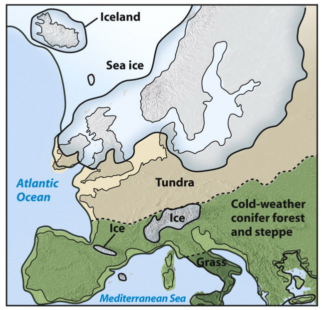




Pleistocene Life

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



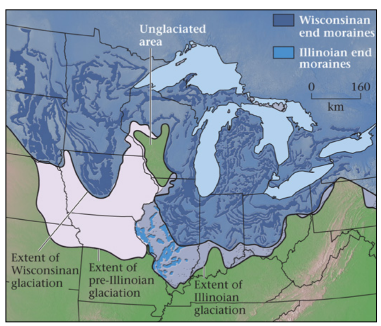


Pleistocene Life

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

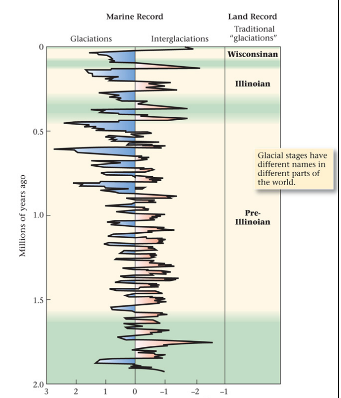
Pleistocene Chronology

- There have been several Pleistocene glacial advances.
  - In North America, four are recognized – youngest to oldest:
    - Wisconsinan.
    - Illinoian.
    - Kansan.
    - Nebraskan.
  - The last two are poorly preserved.
- Ice ages are separated by interglacials.



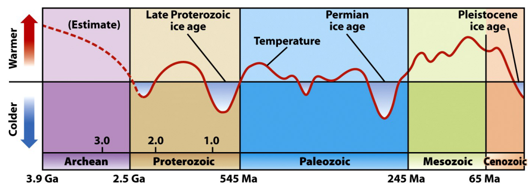
Pleistocene Chronology

- Oxygen isotopes suggest twenty or more glaciations.
  - Higher $^{18}O/^{16}O$ = colder.
  - Lower $^{18}O/^{16}O$ = warmer.
- The "original four" ice ages may simply be the largest.



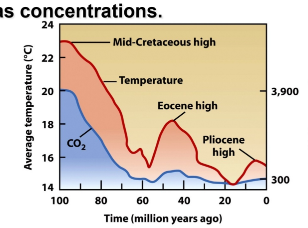
Earlier Glaciations

- Glaciations have occurred before in Earth history.
- They are indicated by fossil tills and striated bedrock.
  - Pleistocene.
  - Permian.
  - Ordovician.
  - Late Precambrian – Tillites at equatorial latitudes suggest an ice-covered world (snowball Earth).



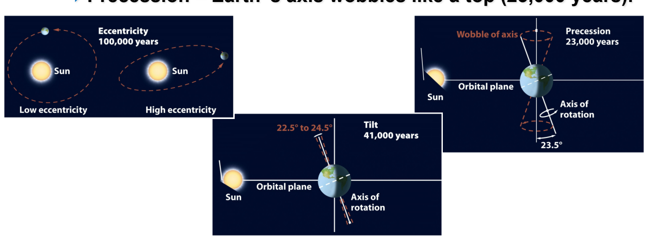
Causes of Glaciation

- Long-term causes – Set the stage for ice ages.
  - Plate tectonics – Controls 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 (CO_2).
      - Methane (CH_4).



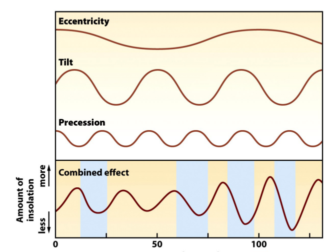
Causes of Glaciation

- Short-term causes – Govern advances and retreats.
  - Milankovitch hypothesis – Climate variation over 100-300 Ka predicted by cyclic changes in orbital geometry.
    - The shape of Earth's orbit varies (~ 100,000 year cyclicity).
    - Tilt of Earth's axis varies from 22.5º to 24.5º (~41,000 years).
    - Precession – Earth's axis wobbles like a top (23,000 years).



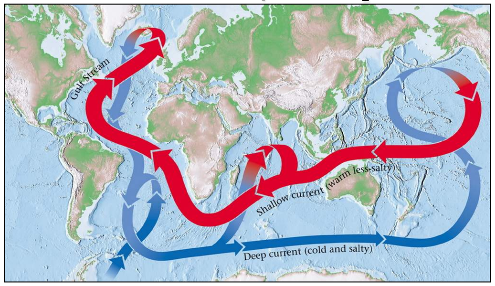
Causes of Glaciation

- Short-term causes – Govern advances and retreats.
  - Milankovitch hypothesis – Climate variation over 100 to 300 Ka predicted by cyclic changes in orbital geometry.
    - These variations lead to excess warming or cooling.
    - Ice ages may result when cooling effects coincide.



Causes of Glaciation

- Short-term causes – Govern advances and retreats.
  - Changes in albedo (reflectivity).
  - Oceanic thermohaline circulation changes.
  - Biotic modification of atmospheric CO_2 concentrations.



Pleistocene Model

- A long-term cooling trend defines the Cenozoic Era.
  - Cessation of warm current flow to the Mediterranean.
  - Development of the circum-Antarctic current.
  - Uplift of the Himalayas altered atmospheric circulation.
  - Closing the Isthmus of Panama.

Glacial Reprise?

- 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 to 1850) resulted in the Little Ice Age.
  - Today, a warming trend has caused glaciers to recede.
  - Earth's climate changes without consulting humanity.