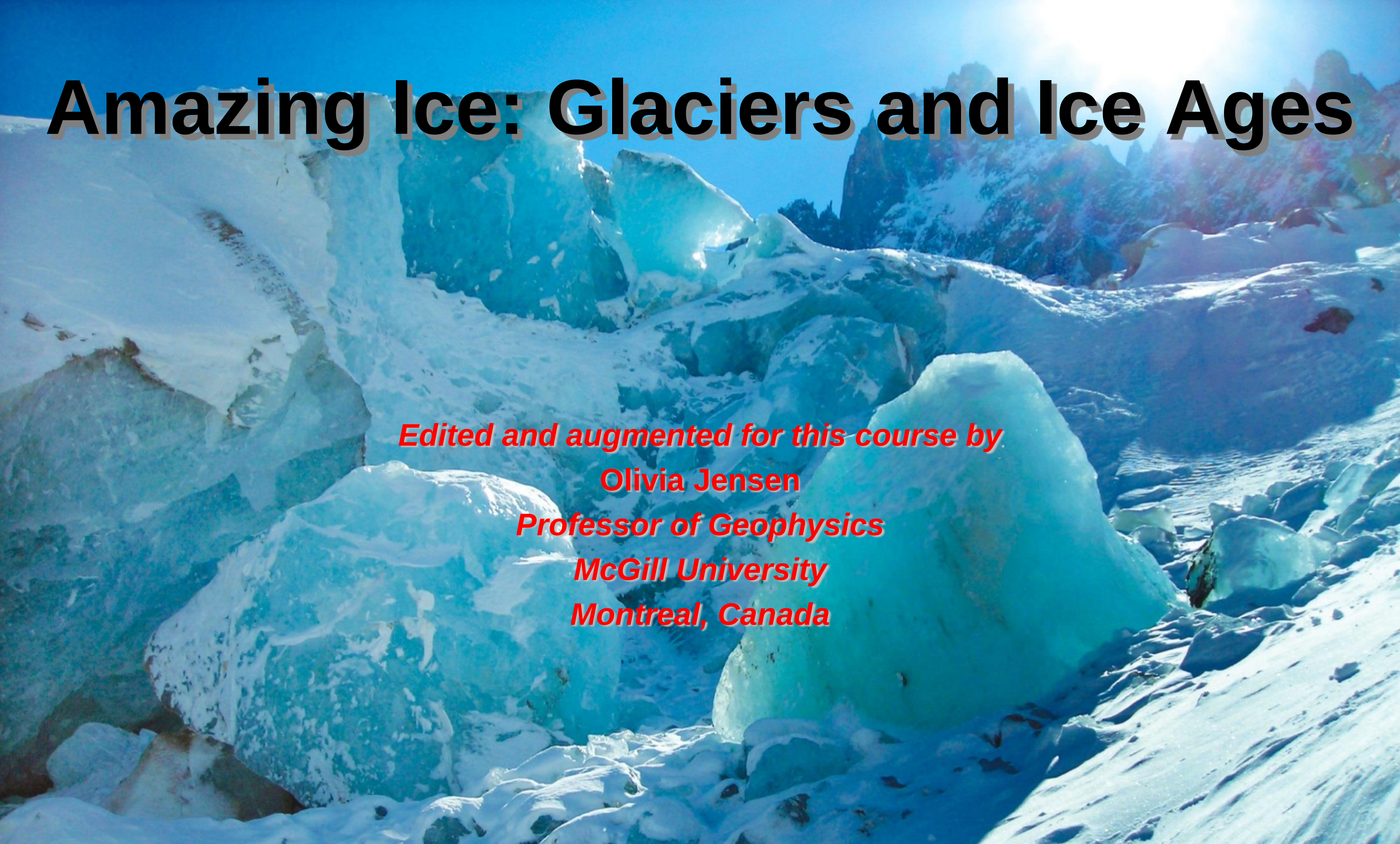

Amazing Ice: Glaciers and Ice Ages

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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.

The Theory of Glaciation

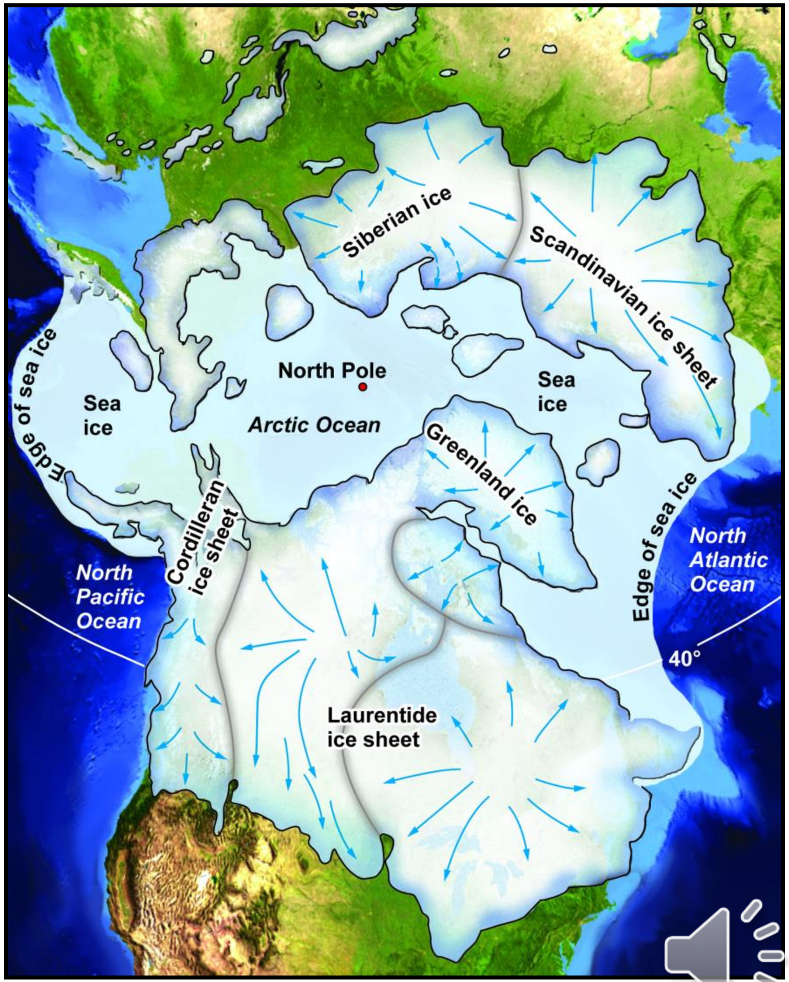
- Agassiz proposed that an ice age had frozen Europe.
  - Ice sheets covered land.
  - Ice carried and dropped:
    - Fine-grained unsorted sediment.
    - Erratic boulders.

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.

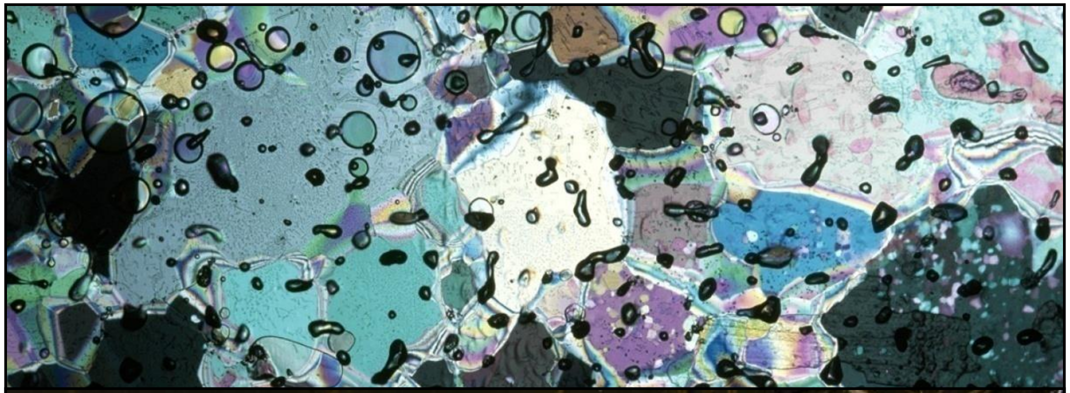
Glaciers and Ice Ages

- 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.



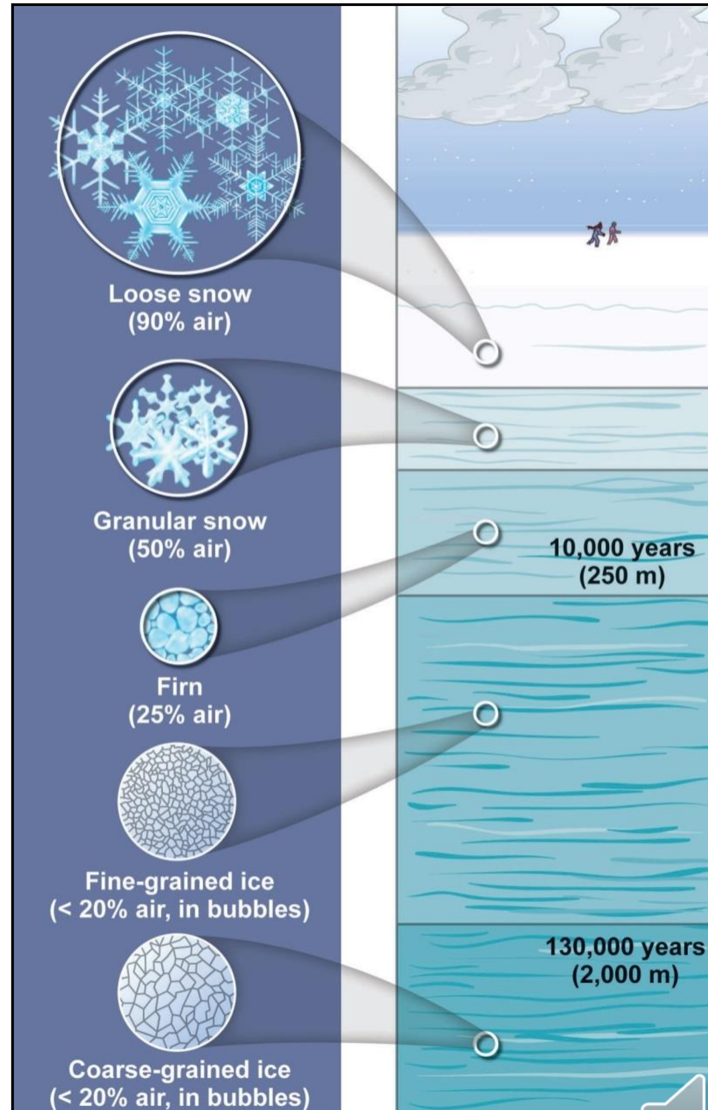
Ice: The Water Mineral

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



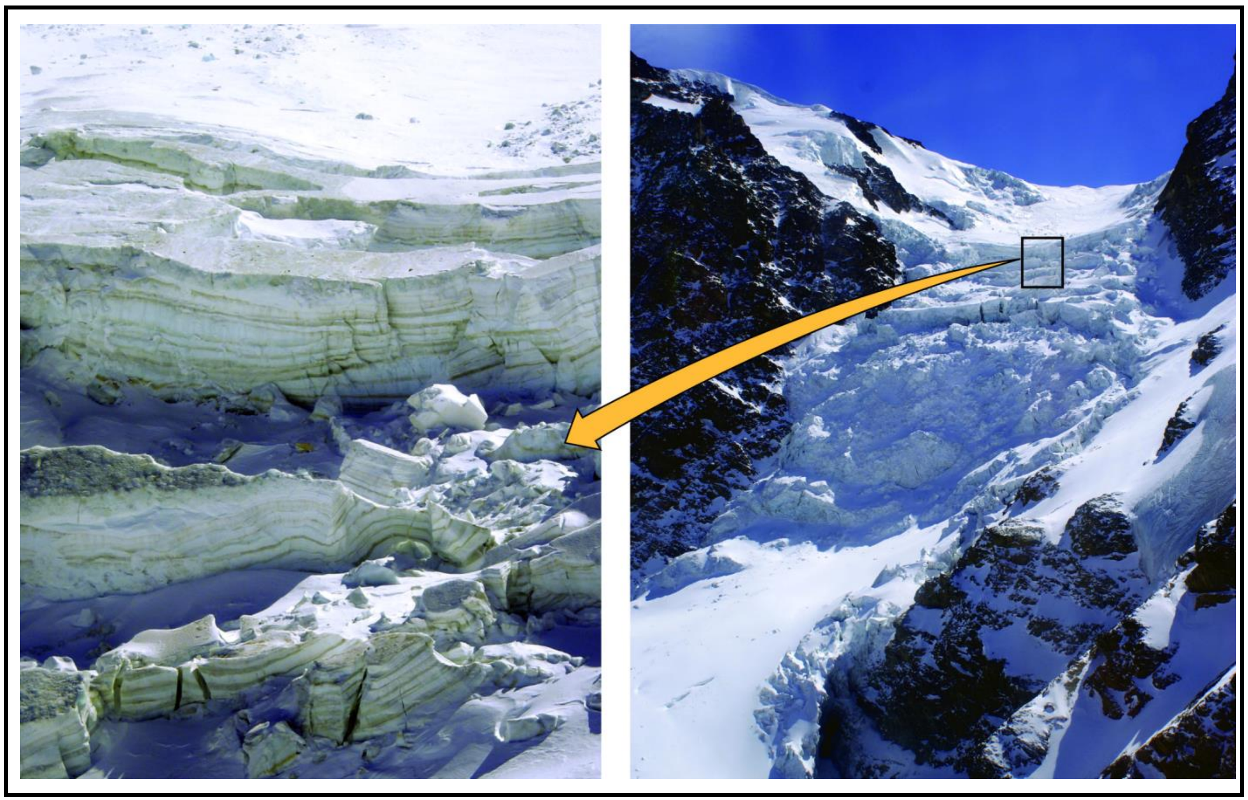
How a Glacier Forms

- 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)



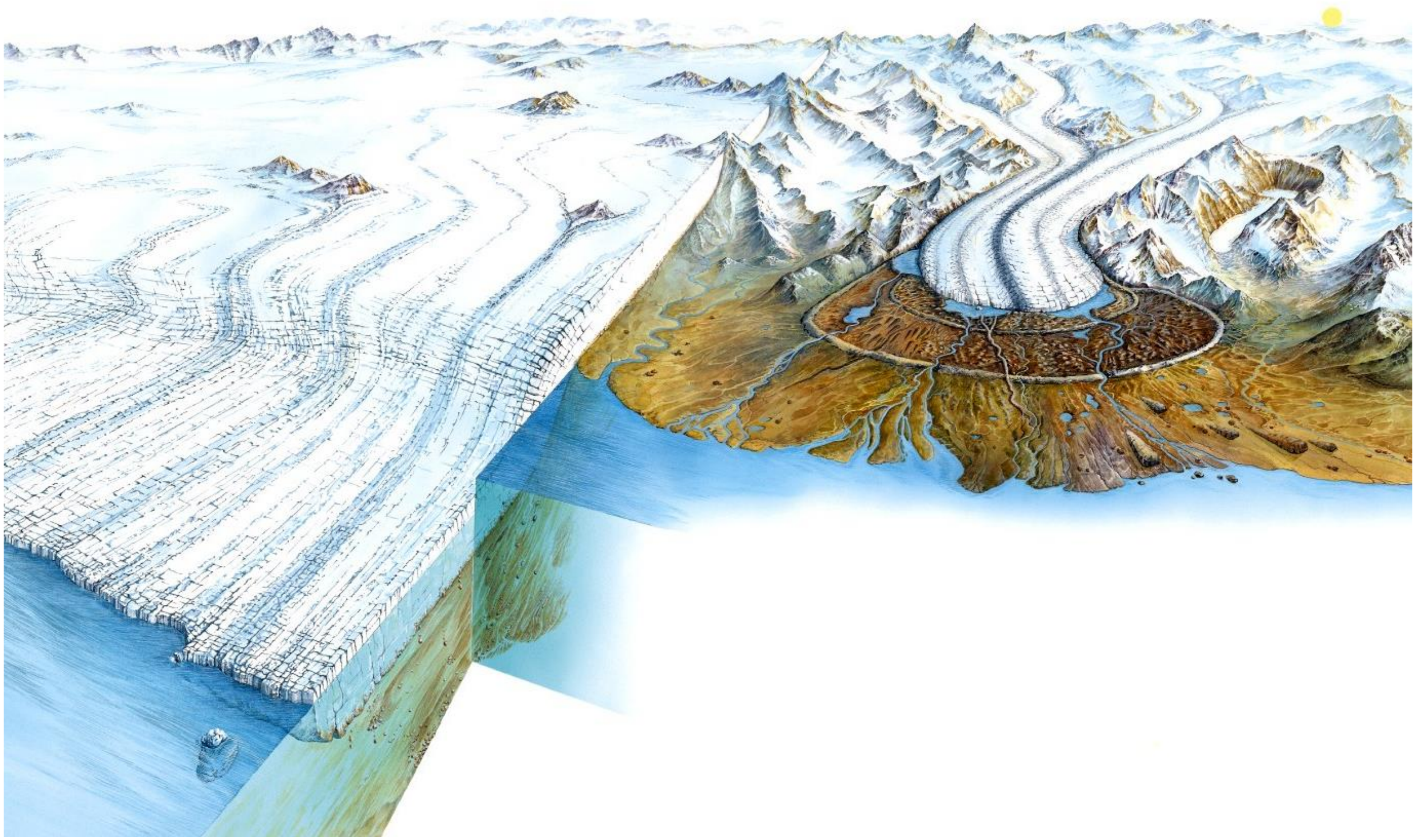
Forming a Glacier

- **Conditions that are necessary to form a glacier:**
  - **Cold local climate (polar latitudes or high elevation).**
  - **Snow must be abundant and accumulate in winter; *more snow must fall than melts* in the subsequent summer.**



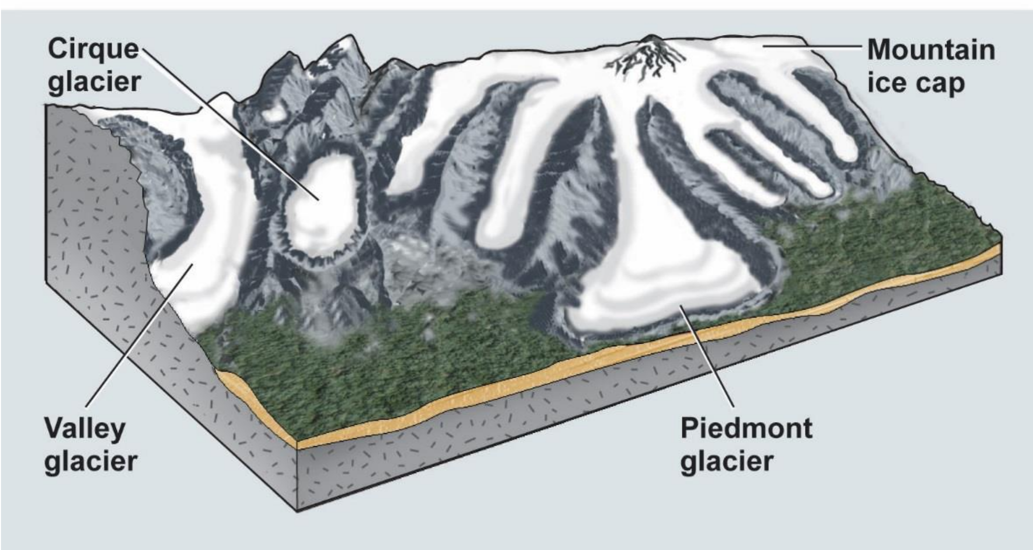
Glaciers

- Thick masses of recrystallized ice
- 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.



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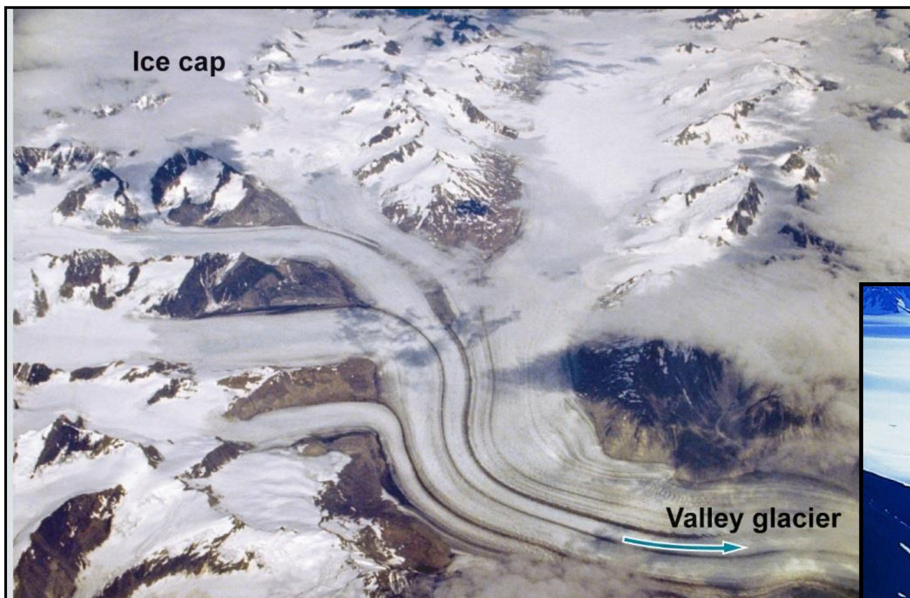
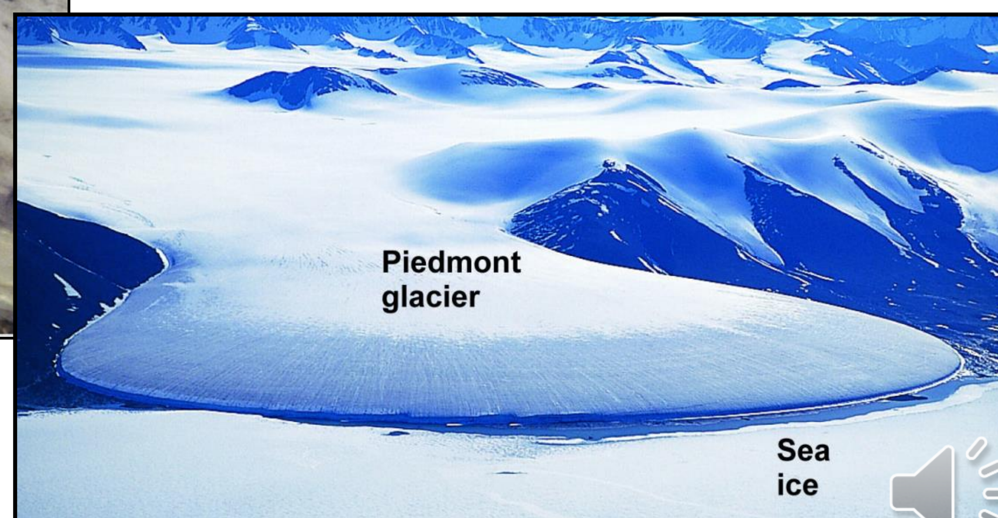
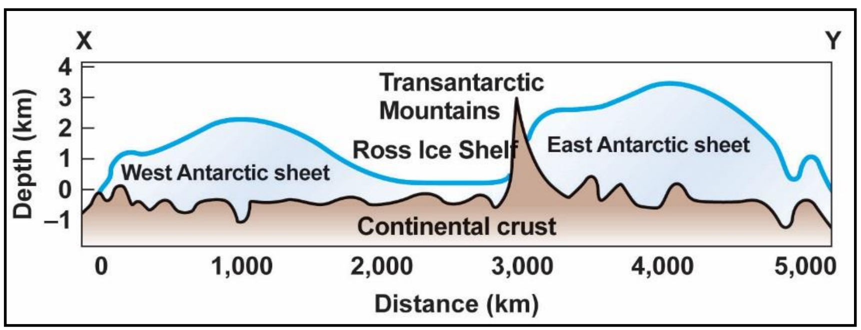
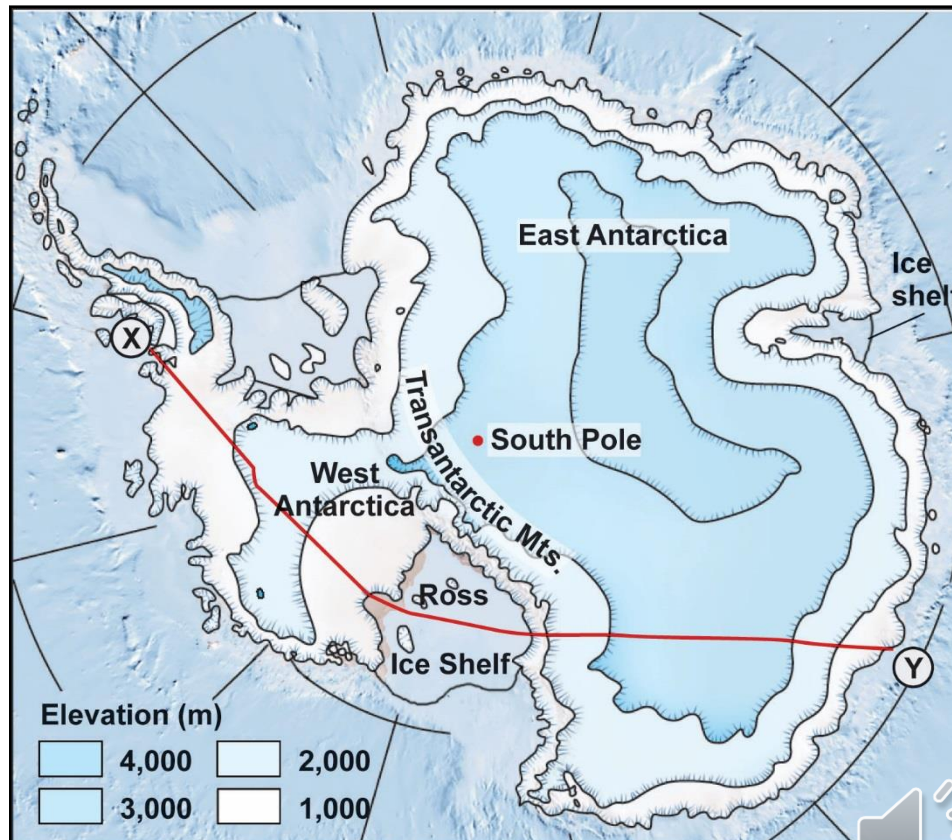




Continental Glaciers – Ice Sheets

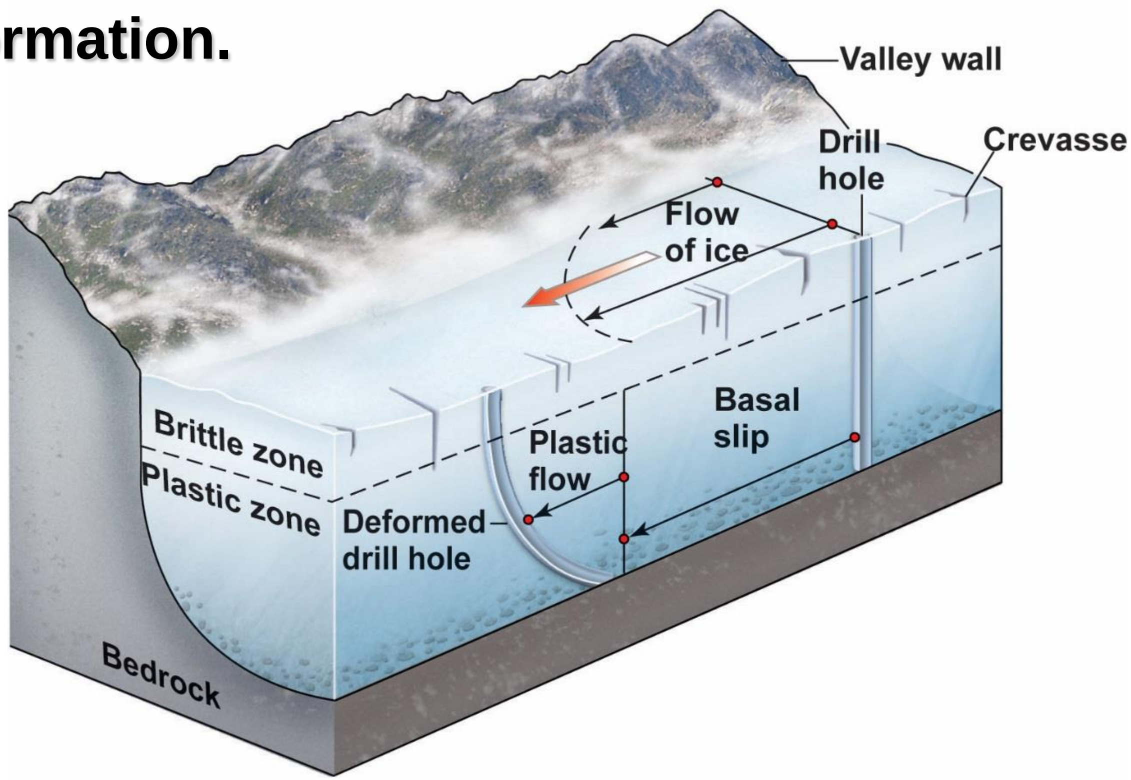
- Vast ice sheets covering large land areas.
- Ice flows outward from thickest part of sheet.
- Two major ice sheets remain on Earth:
  - Greenland
  - Antarctica





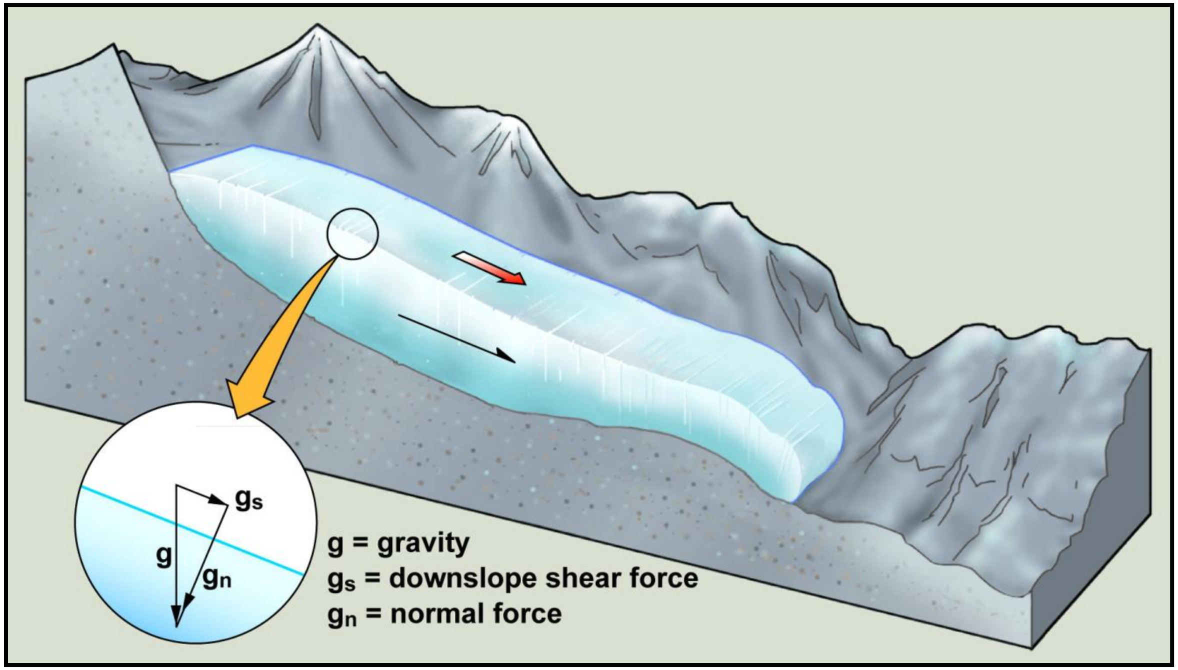
Movement of Glacial Ice

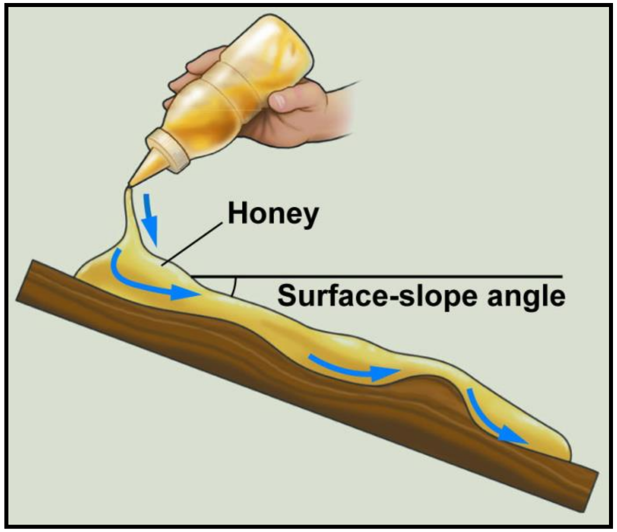
- **How do glaciers move?**
  - **Basal sliding.**
    - **Significant quantities of meltwater forms at base of glacier.**
    - **Water decreases friction, ice slides along substrate.**
  - **Plastic deformation.**



Movement of Glacial Ice

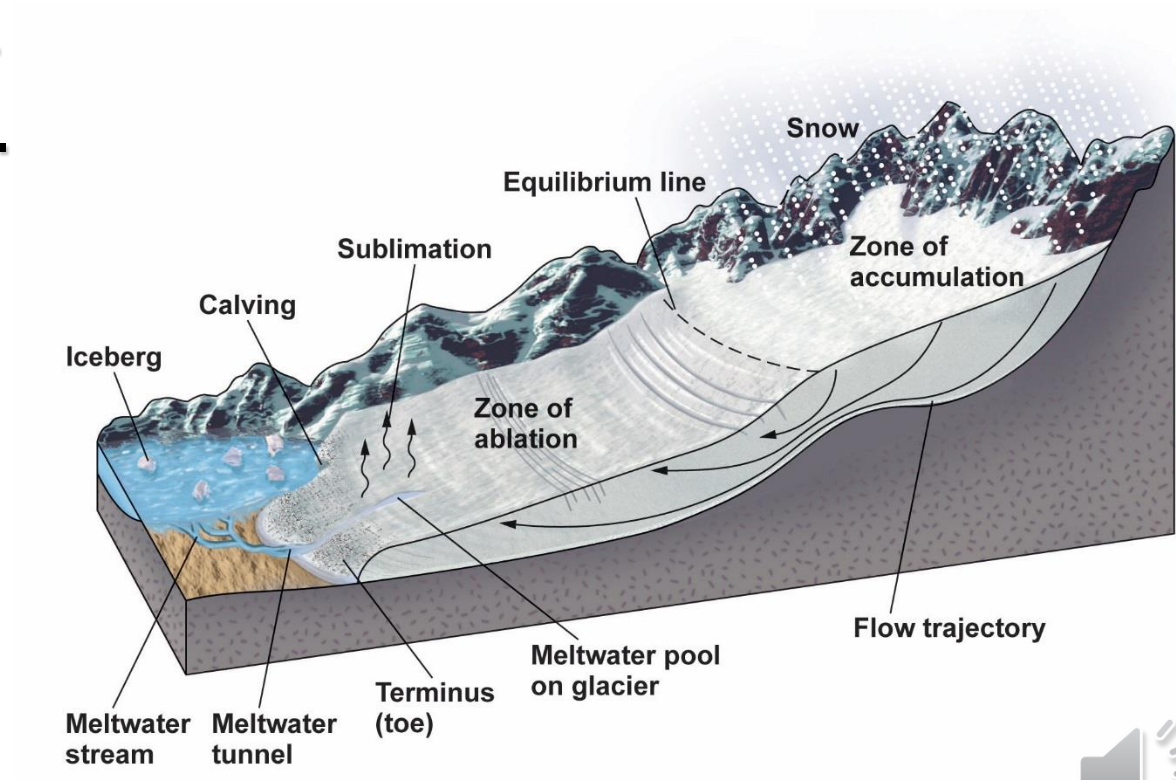
- Why do glaciers move?
  - The pull of *gravity* is strong enough to make ice flow.
    - A glacier moves in the direction of its surface slope.
    - The ice base can flow up a local incline.





Glacial Advance and Retreat

- Glaciers behave like bank accounts for water.
- 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.

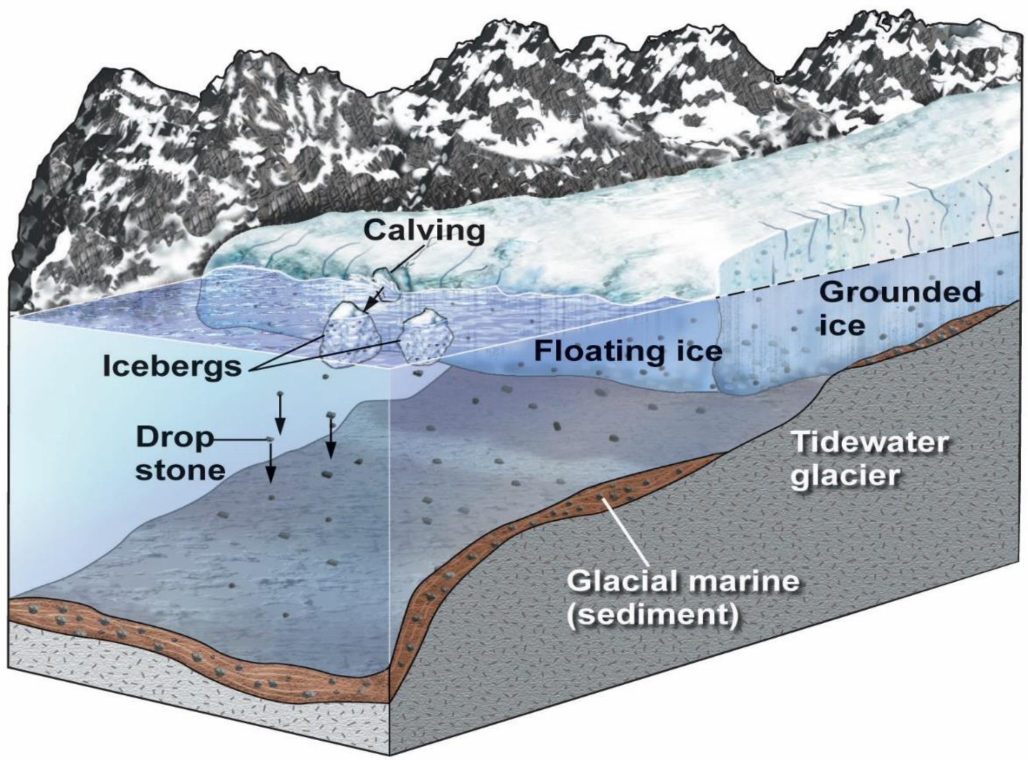


Glacial Advance and Retreat

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

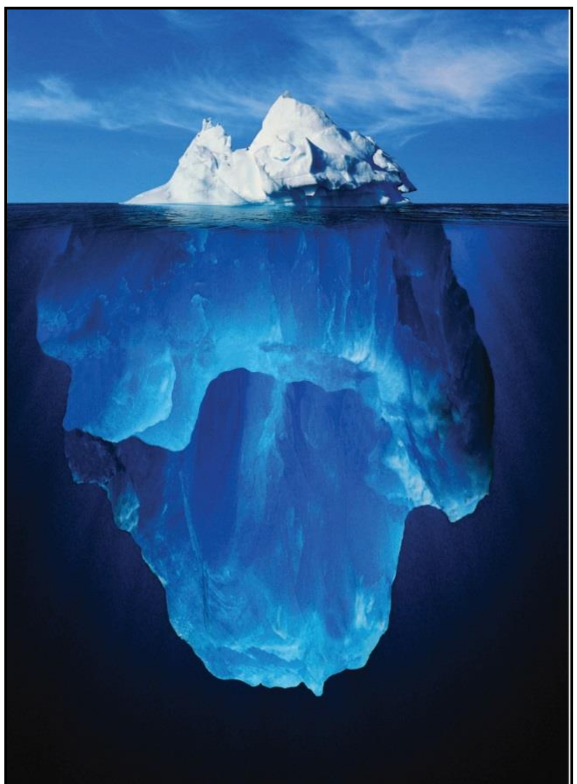
Ice in the Sea

- 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 (Arctic Ocean) — nonglacial ice formed of frozen seawater



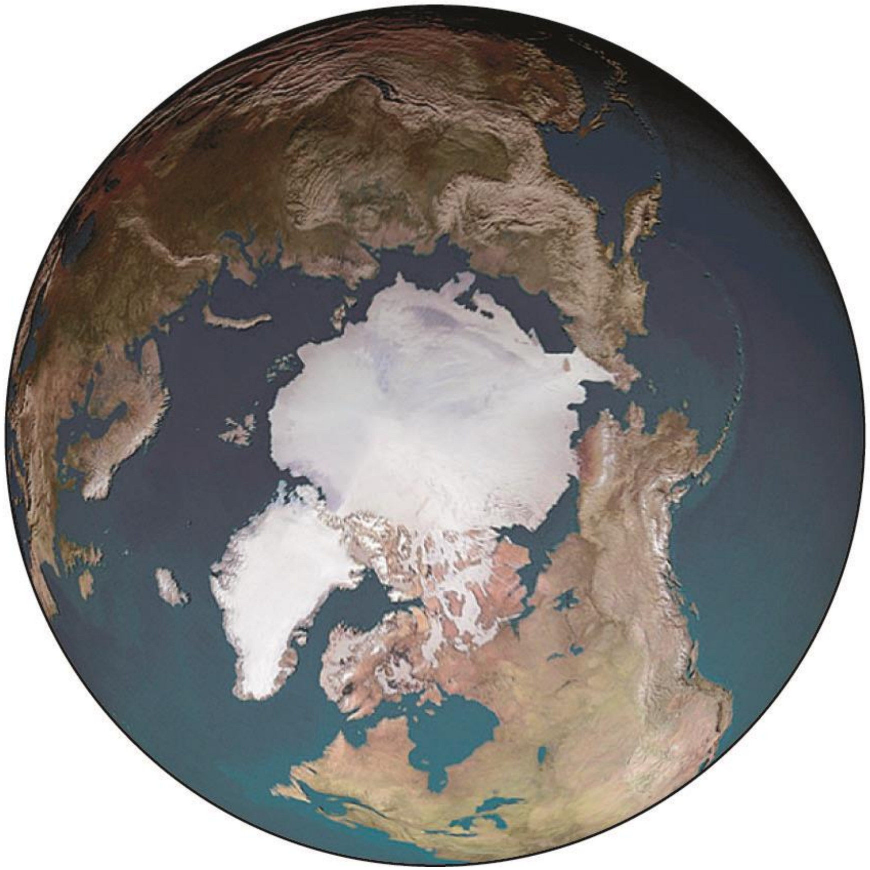
Ice in the Sea

- 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.



Ice in the Sea

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



Carving and Carrying by Ice

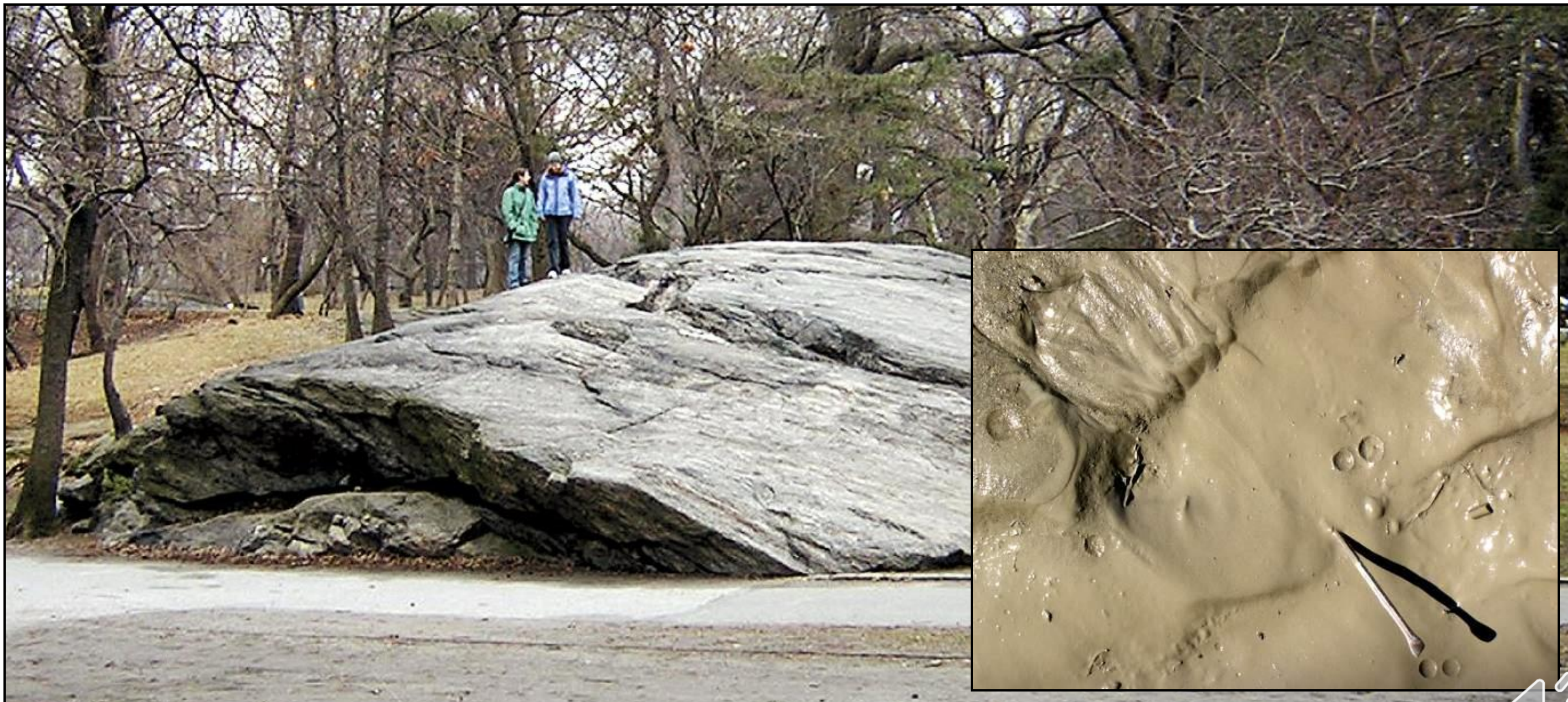
- **Glaciers are important forces of landscape change.**
  - **Erosion**
  - **Transport**
  - **Deposition**

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.**

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.

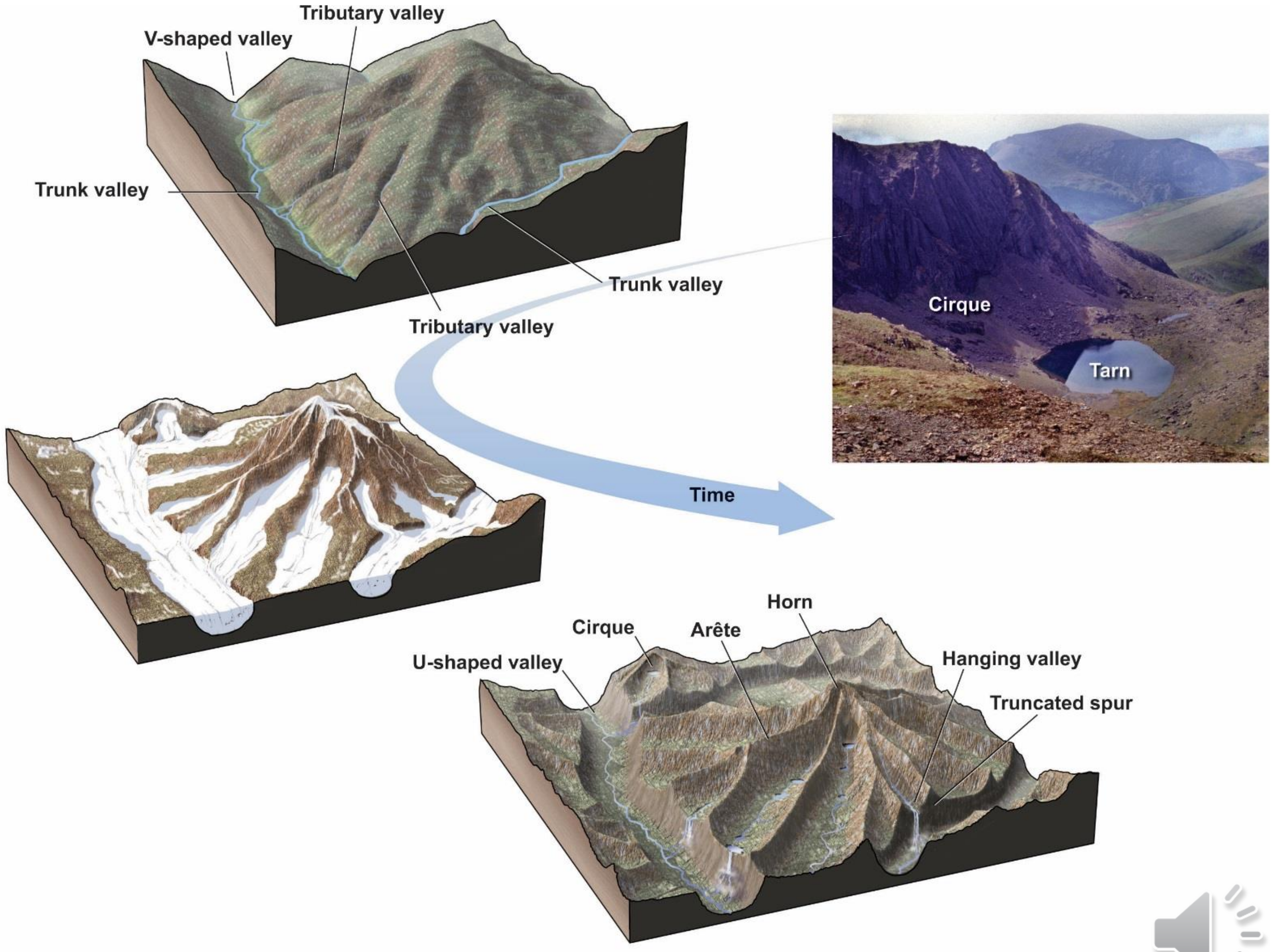


Glacial Erosion and Its Products

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

Glacial Erosion and Its Products

- Erosional features of glaciated valleys:
  - Cirques
  - Tarns
  - Aretes
  - Horns
  - U-shaped valleys
  - Hanging valleys
  - Fjords

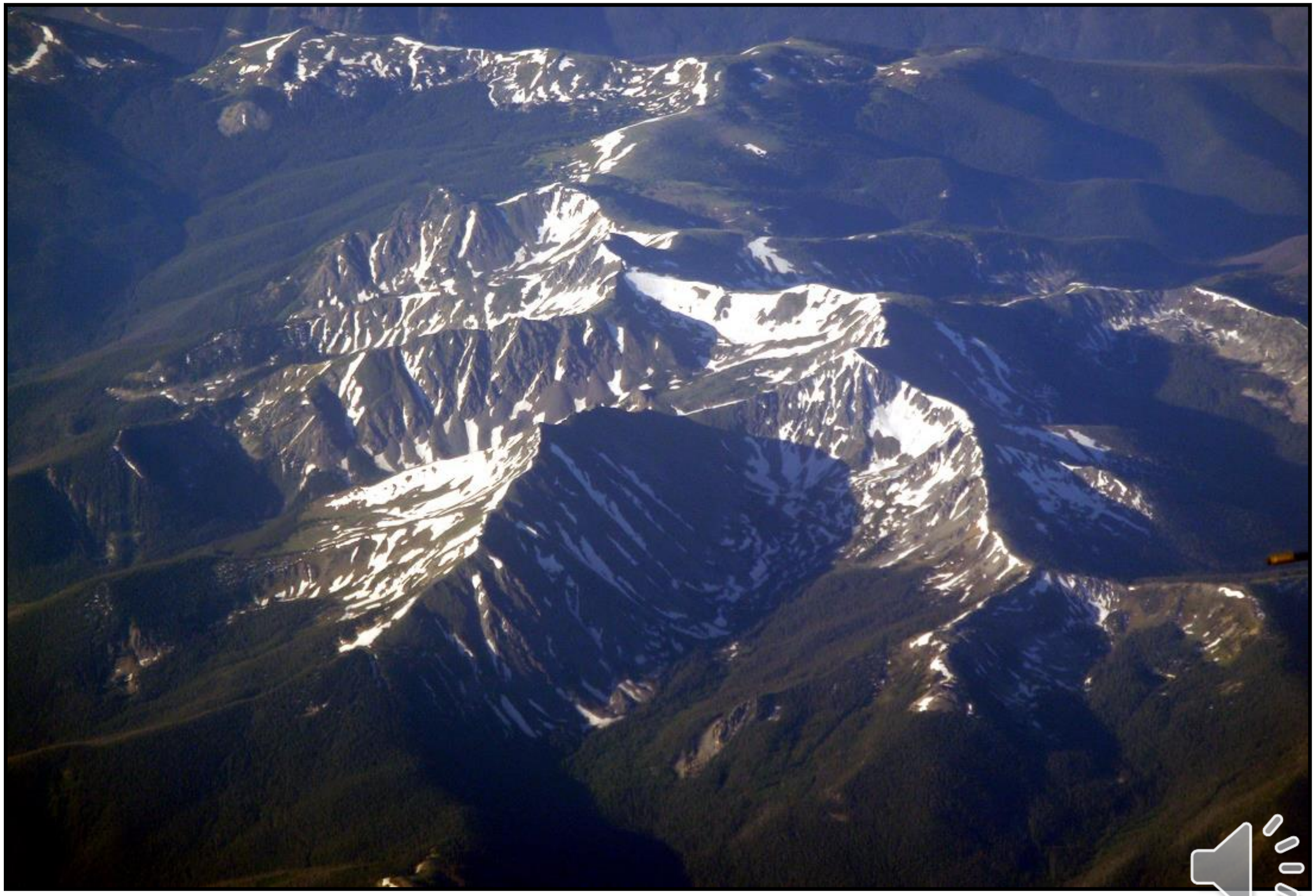


Glacial Erosion and Its Products

- **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).**

Glacial Erosion and Its Products

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

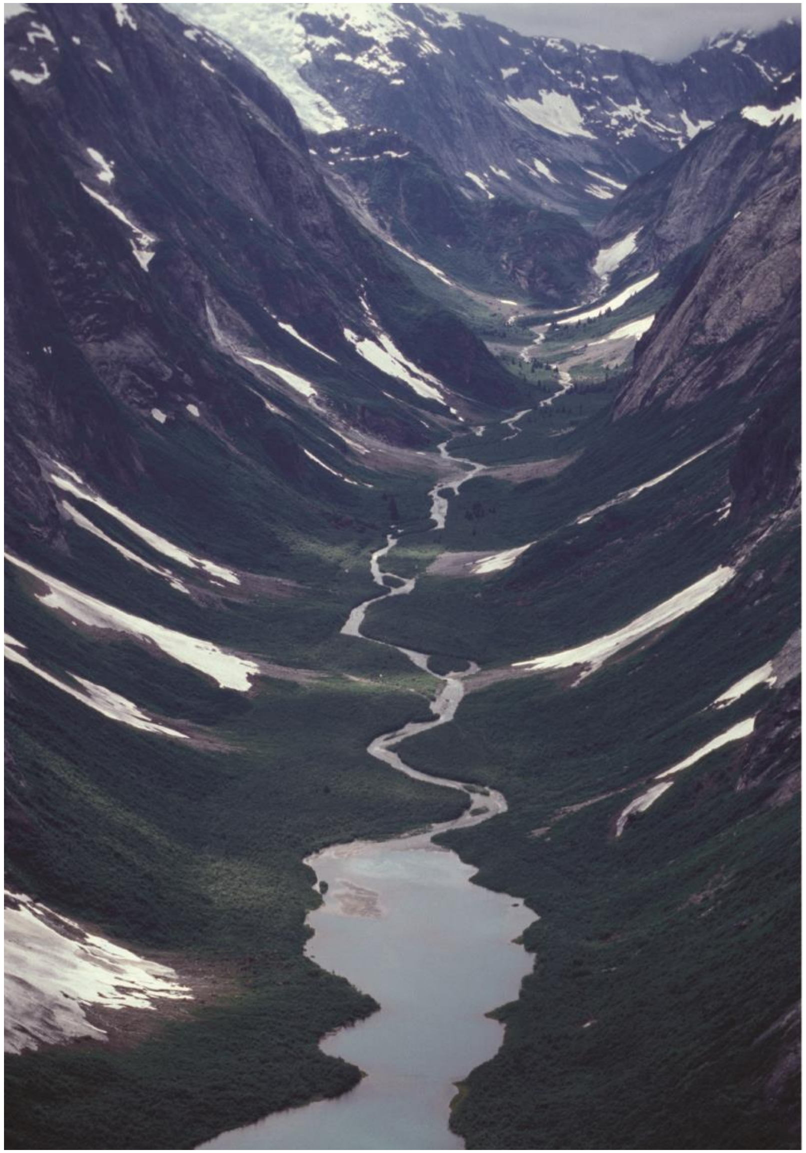


Glacial Erosion and Its Products

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

Glacial Erosion and Its Products

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

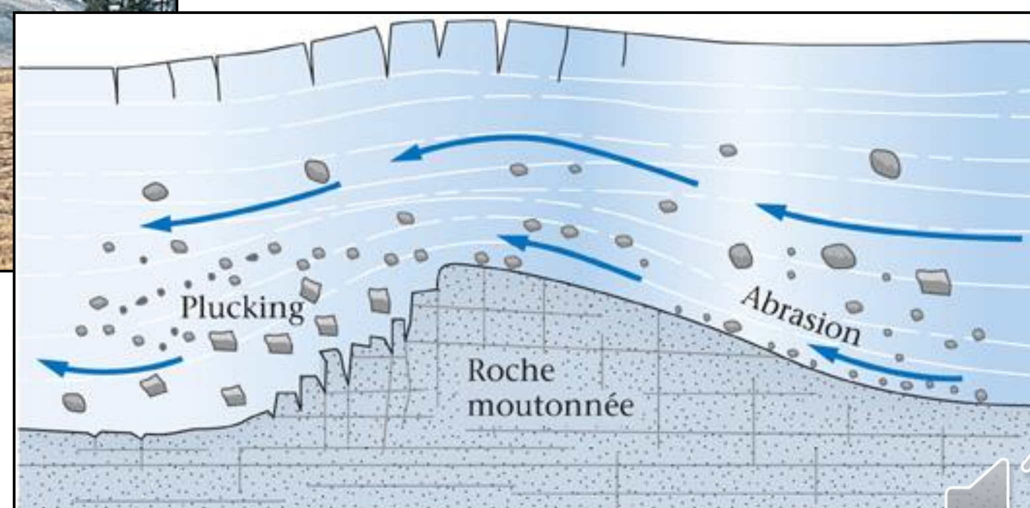


Glacial Erosion and Its Products

- 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.

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 moutonée.



Glacial Erosion and Its Products

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

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Glacial Erosion and Its Products

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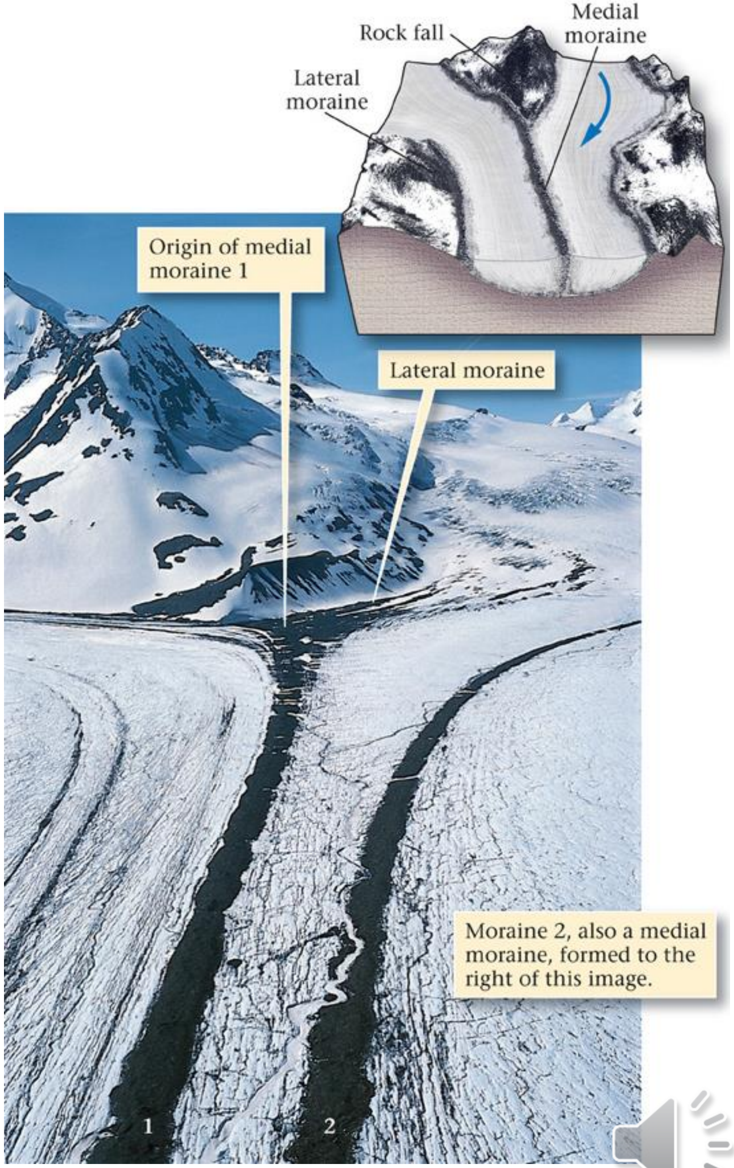
Deposition Associated with Glaciation

- **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**



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 (aeolian)
  - Glacial lake-bed sediment
- Stratified drift is water sorted; unstratified drift is not sorted.

Glacial Deposits

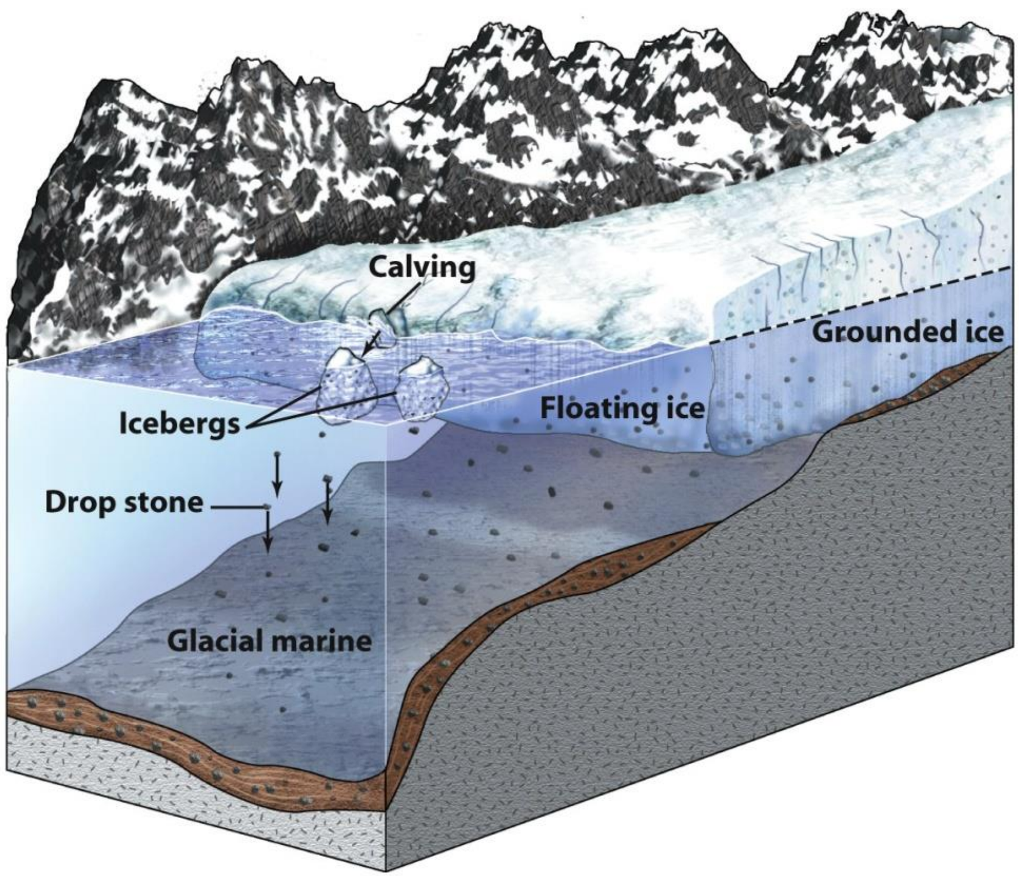
- Glacial till—sediment dropped by glacial ice
  - Consists of all grain sizes—boulders to clay.
  - Unmodified by water, hence:
    - Unsorted
    - Unstratified
  - Accumulates:
    - Beneath glacial ice
    - At the toe of a glacier
    - Along glacial flanks

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.

Glacial Deposits

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



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.

Glacial Deposits

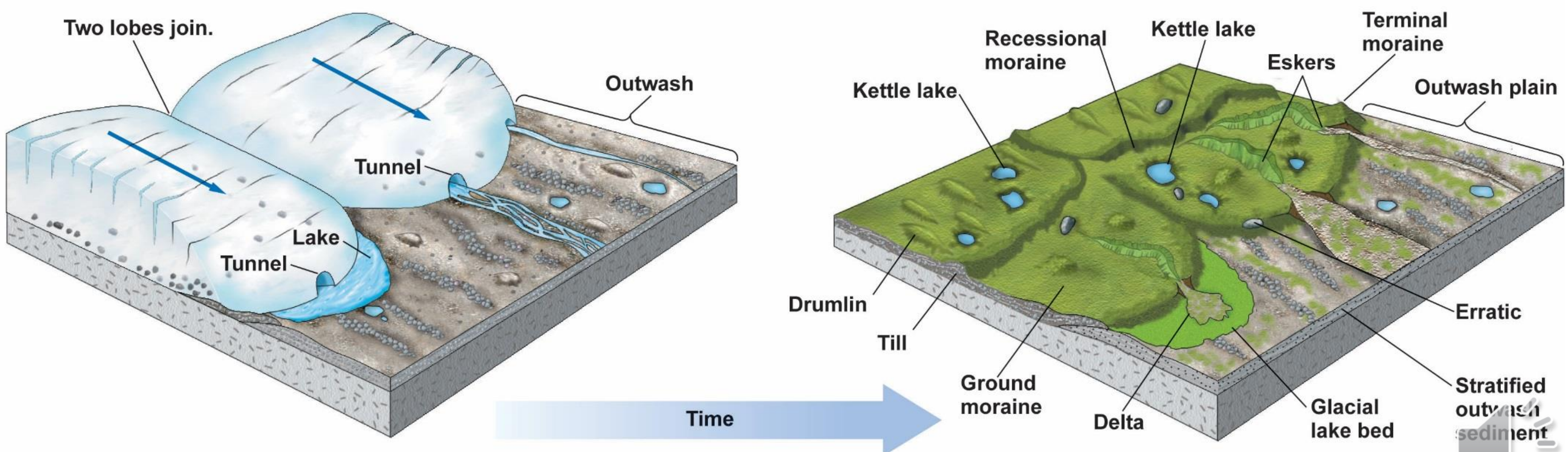
- Glacial lake-bed sediment
  - Lakes are abundant in glaciated landscapes.
  - Fine rock flour settles out of suspension in deep lakes.
  - Muds display seasonal varve couplets.
    - Finest silt and clay are from frozen winter months.
    - Coarser silt and sand are from summer months.

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.**

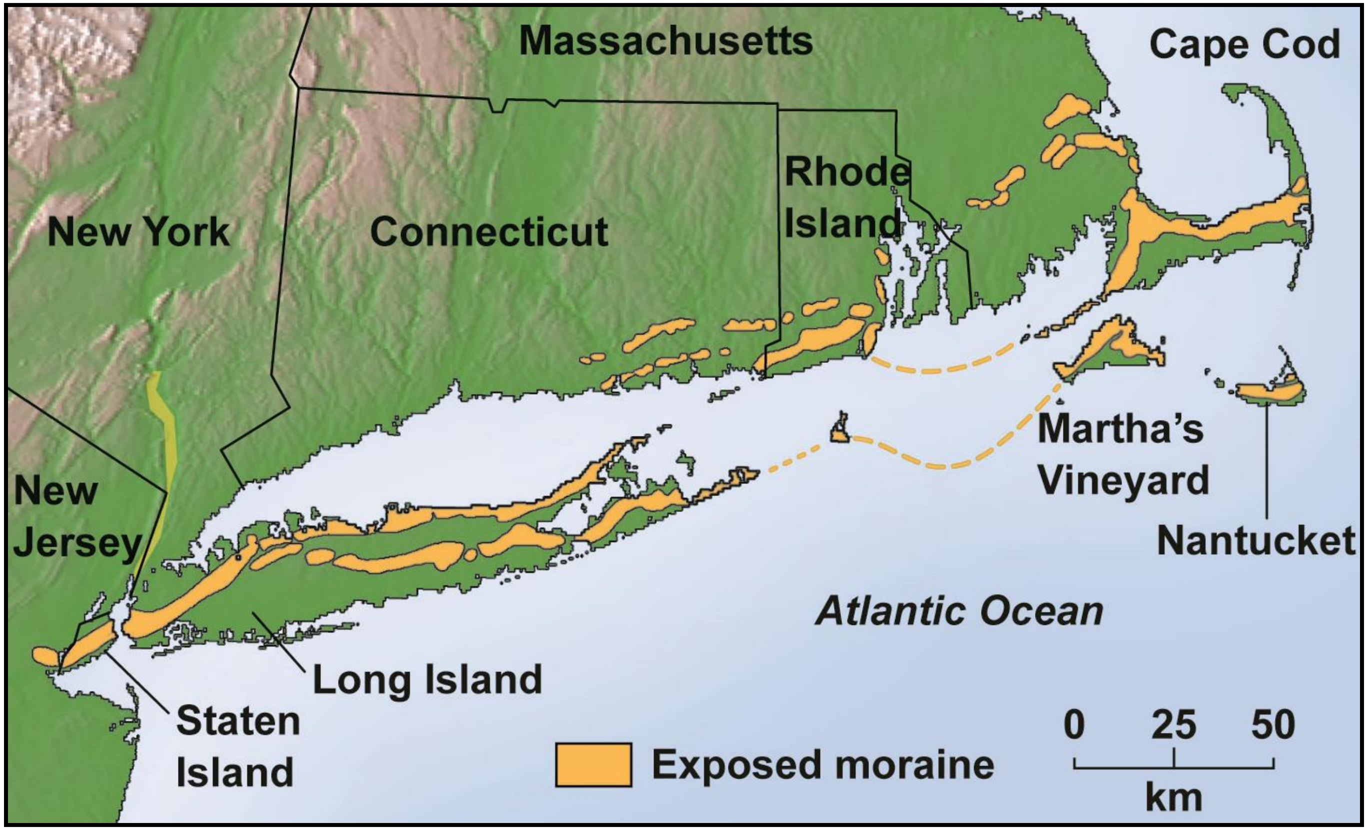
Glacial Depositional Landforms

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



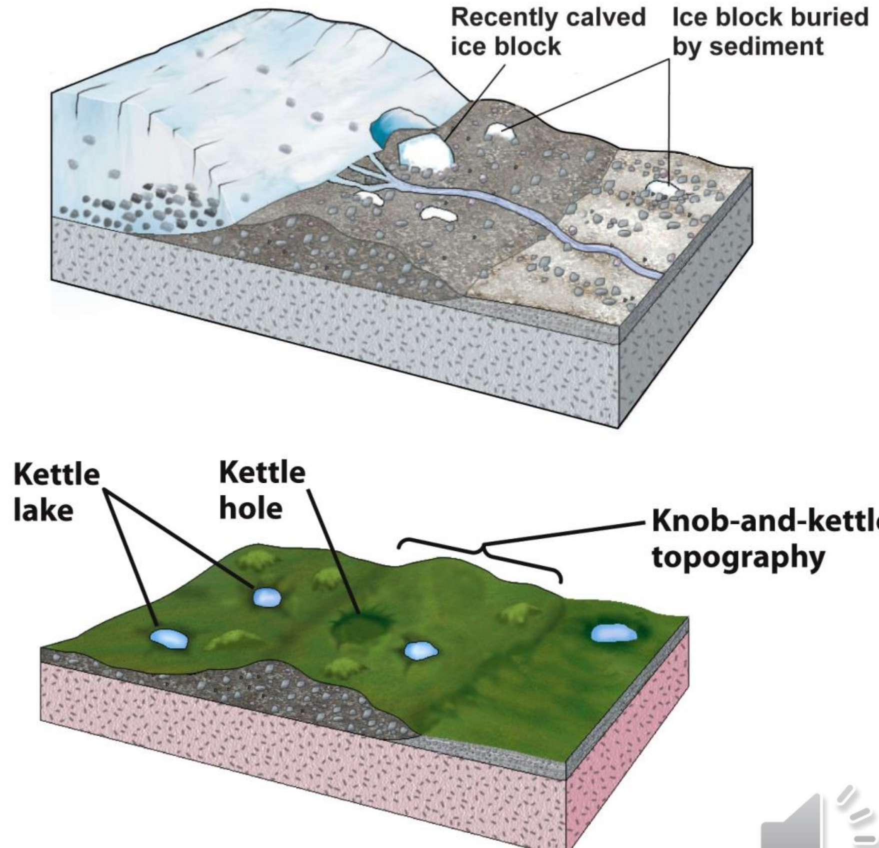
Depositional Landforms

- 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.



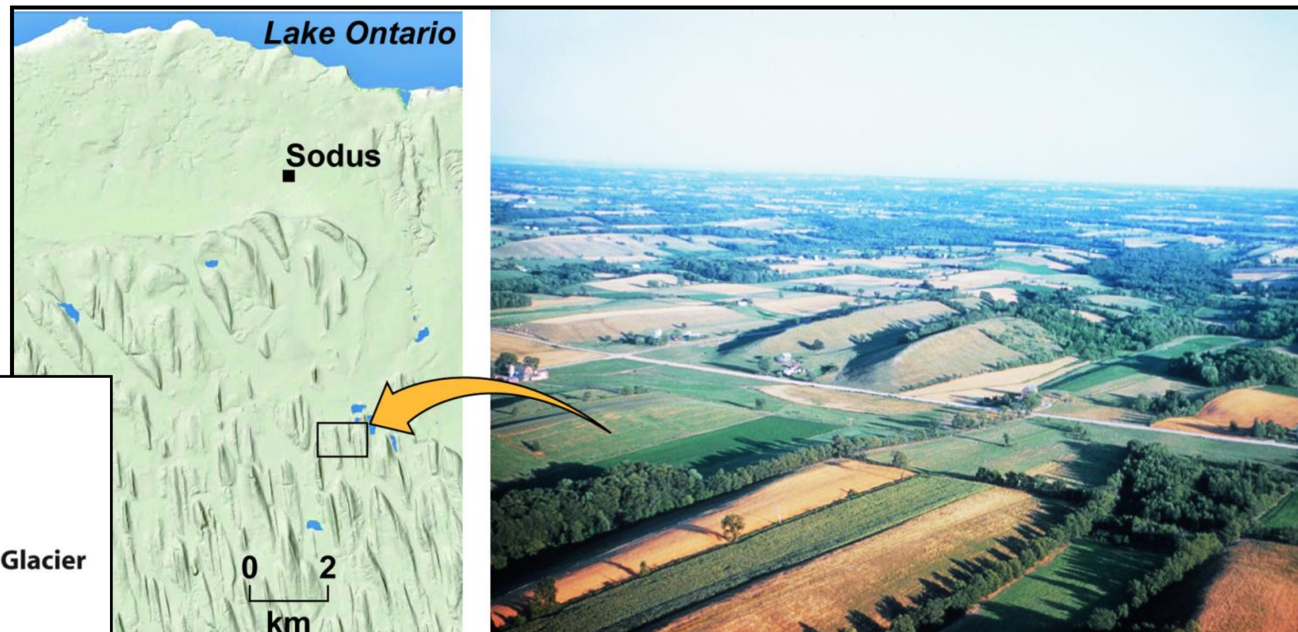
Depositional Landforms

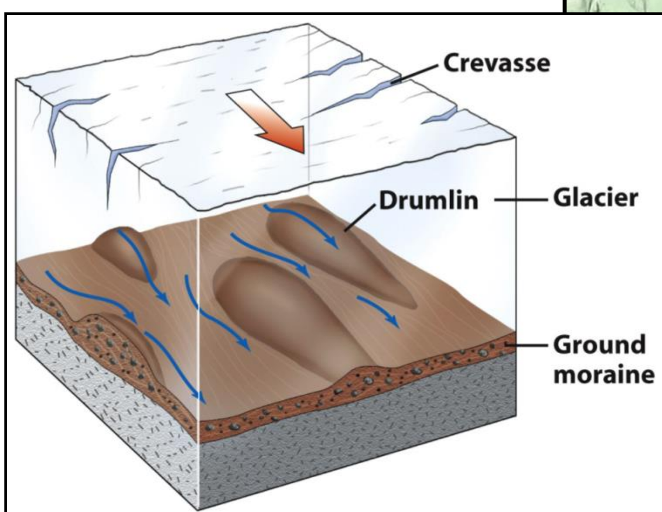
- Ground moraine is till left behind by rapid ice retreat.
  - Creates a hummocky, mostly flat land surface.
  - Kettle lakes form from stranded ice blocks.



Depositional Landforms

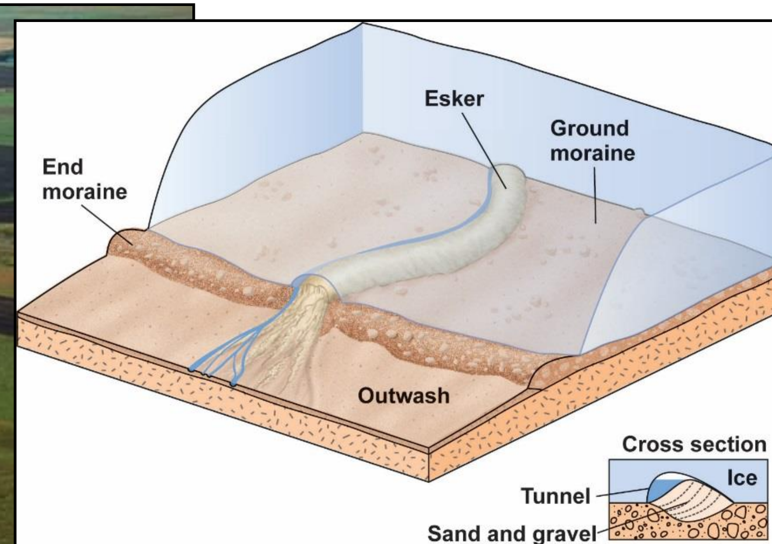
- Drumlins—long, aligned hills of molded lodgment till
  - Asymmetric form—steep up-ice; tapered down-ice.
  - Commonly occur as swarms aligned parallel to ice-flow direction.





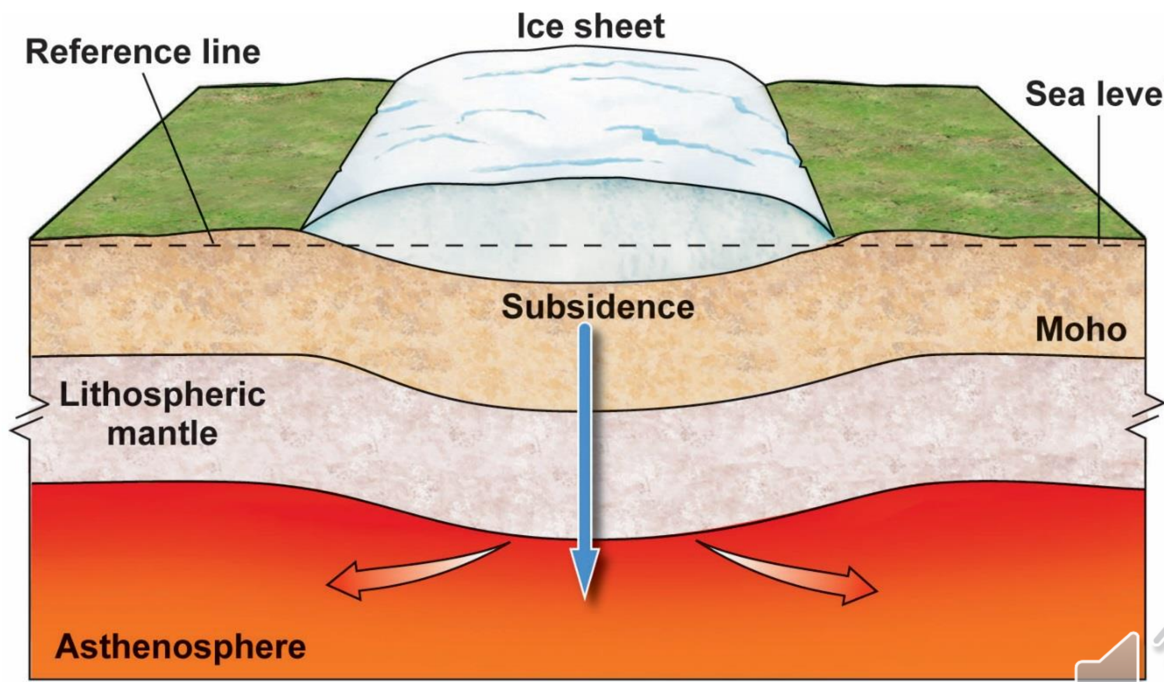
Depositional Landforms

- 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.



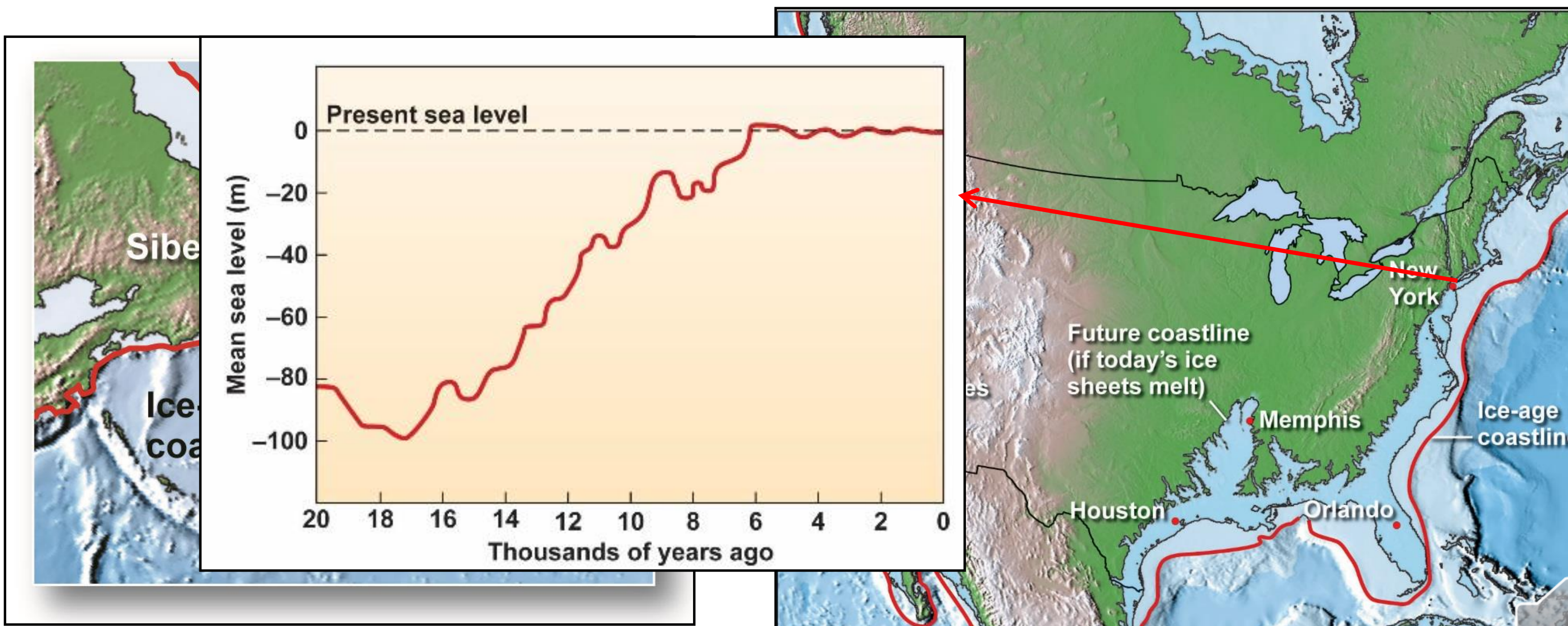
Consequences of Continental Glaciation

- 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.



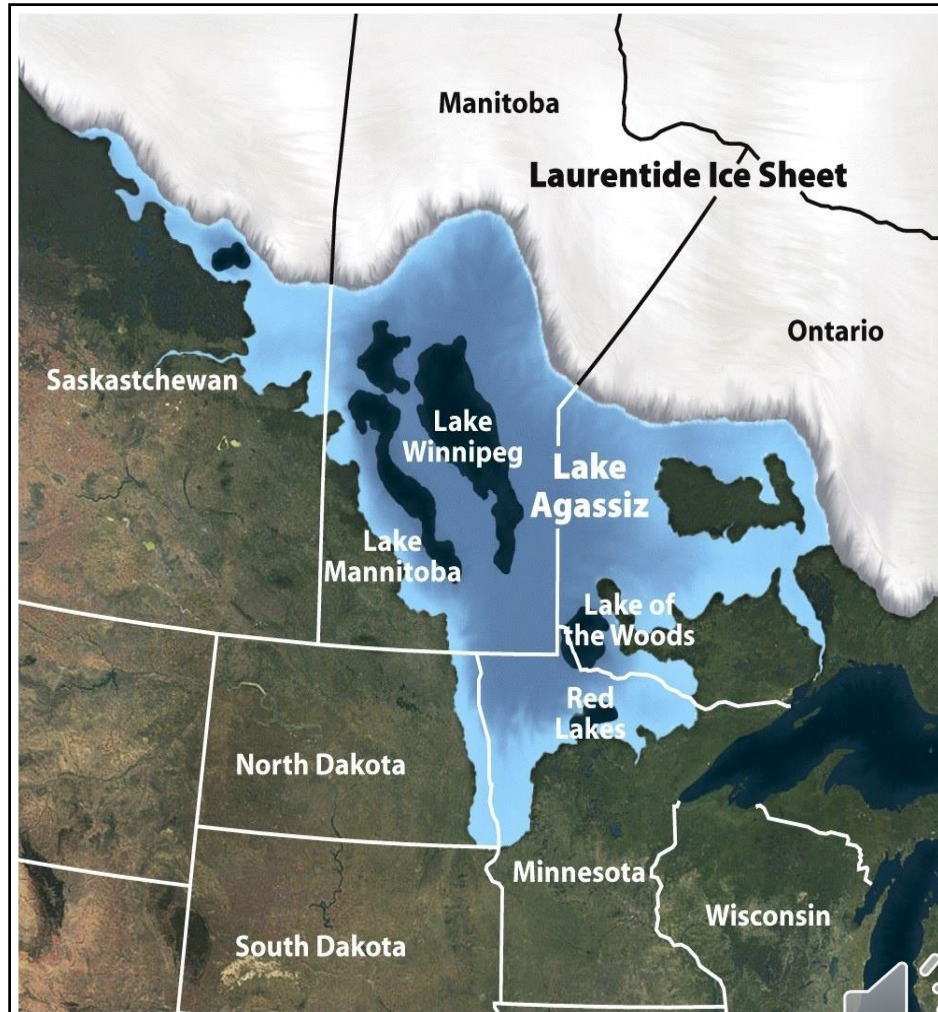
Glacial Consequences

- 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.

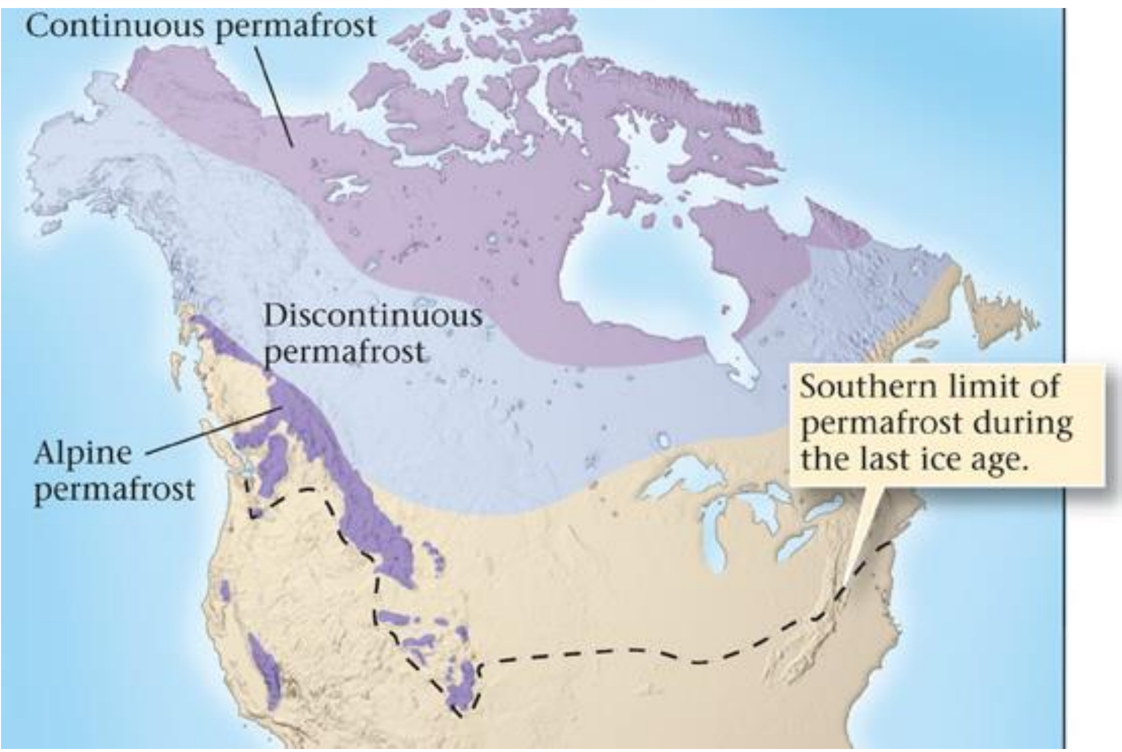


Glacial Consequences

- 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).

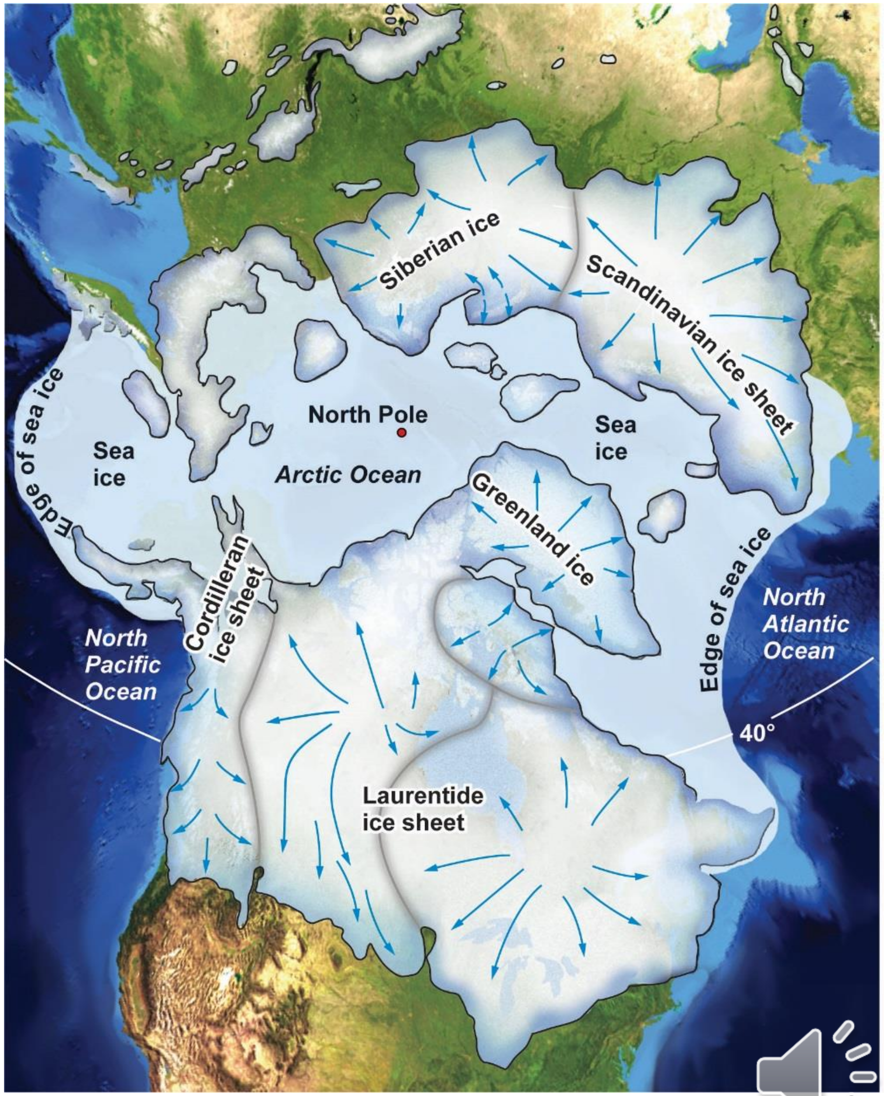
Glacial Consequences

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



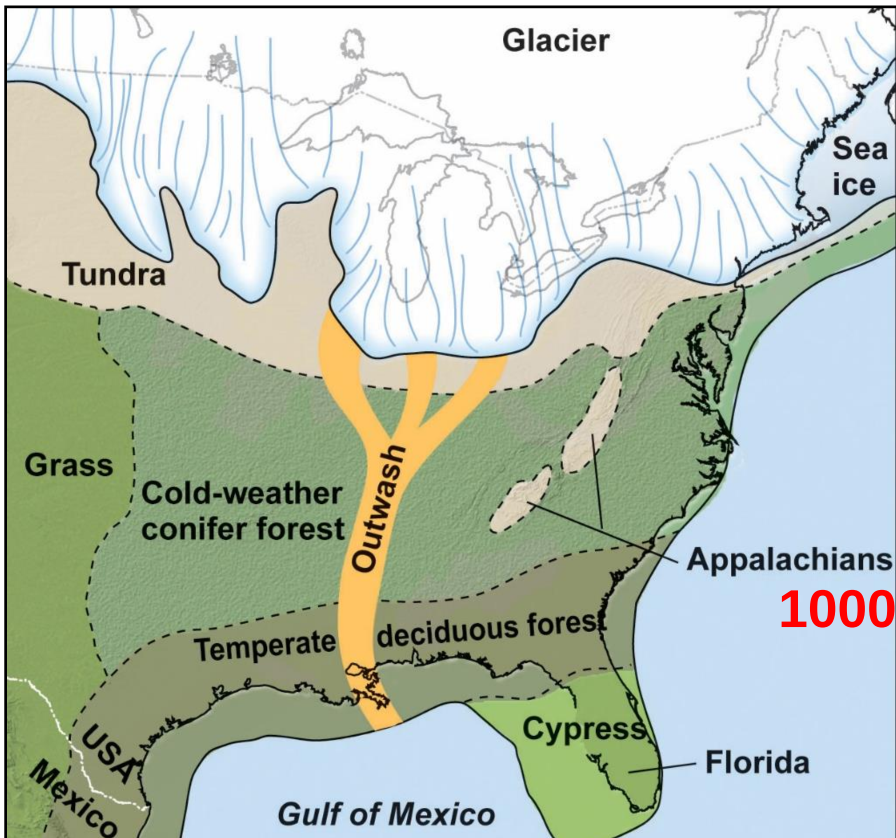
Pleistocene Ice Ages

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

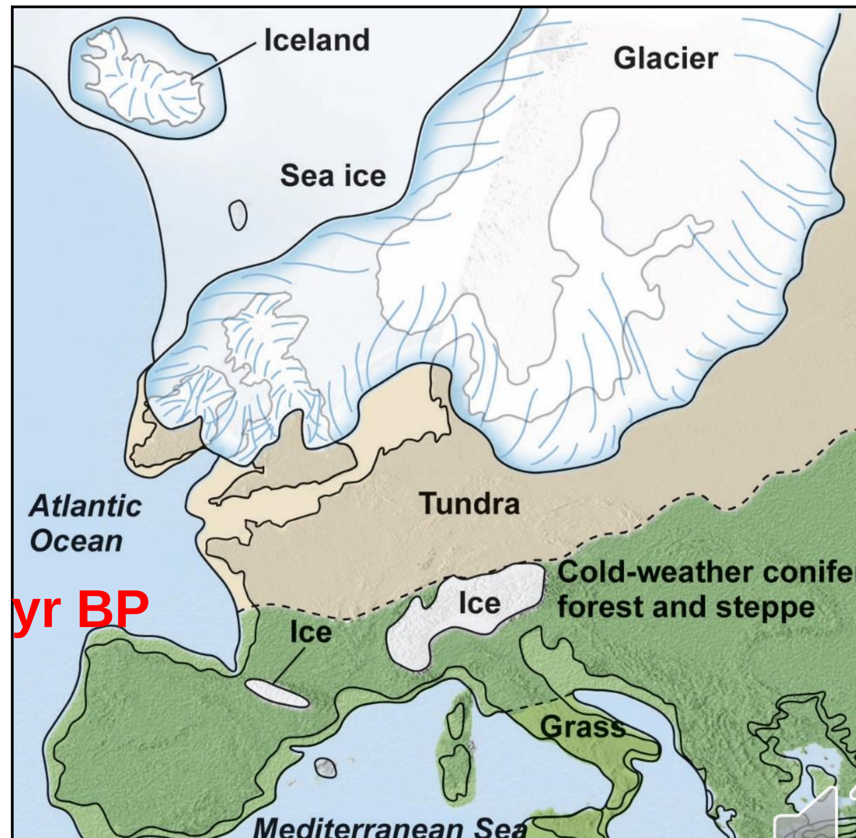


Pleistocene Life and Climate

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



10000 yr BP

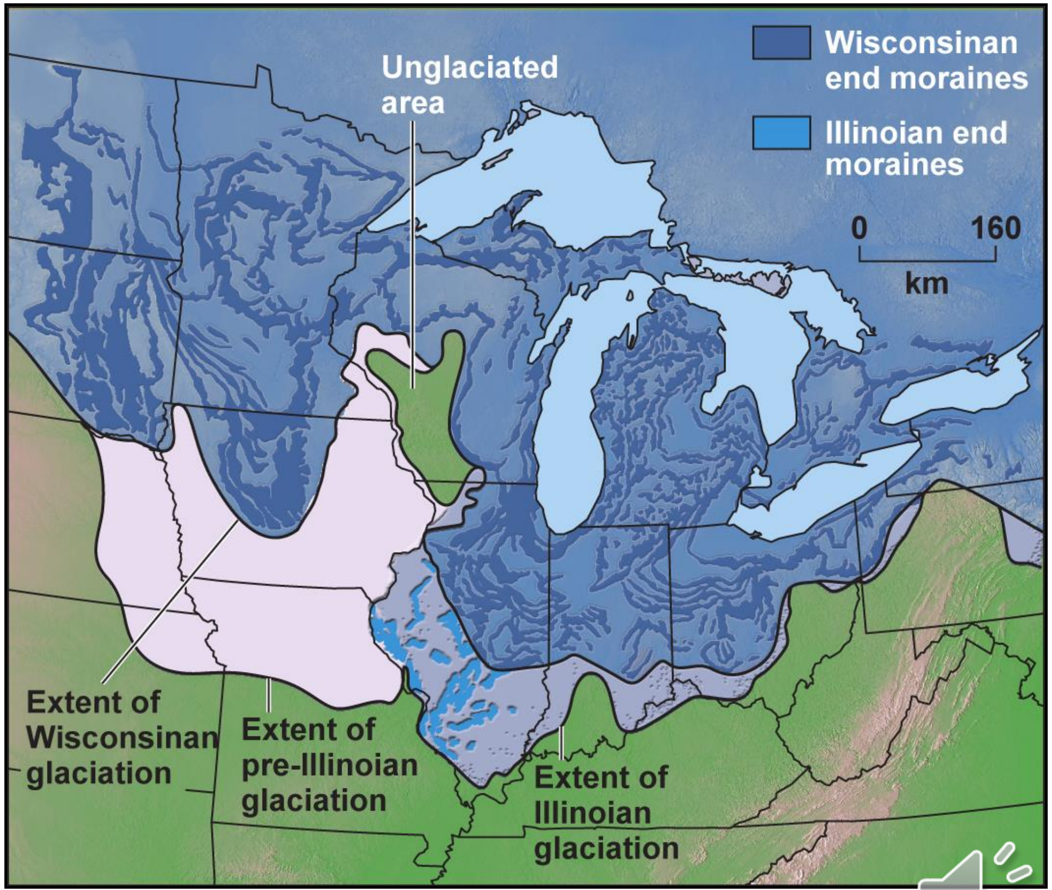


Pleistocene Life and Climate

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

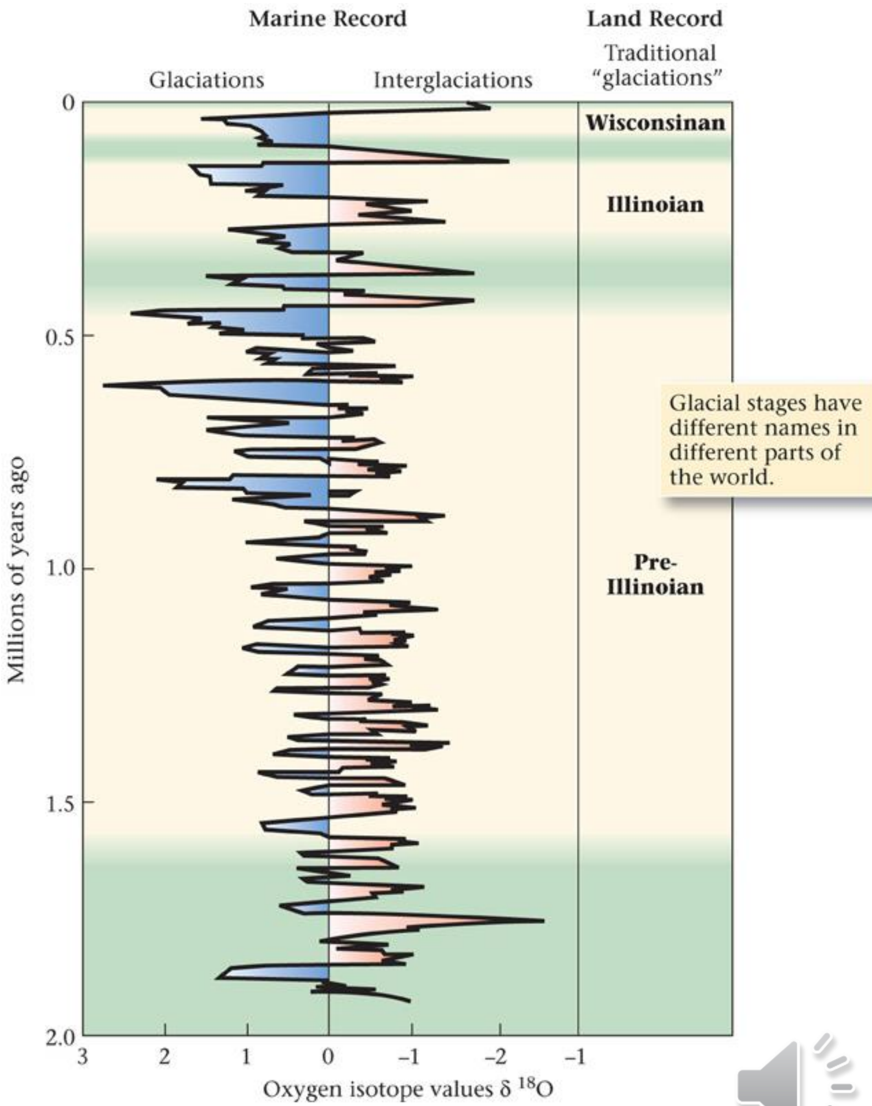
Timing of the Pleistocene Ice Age

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



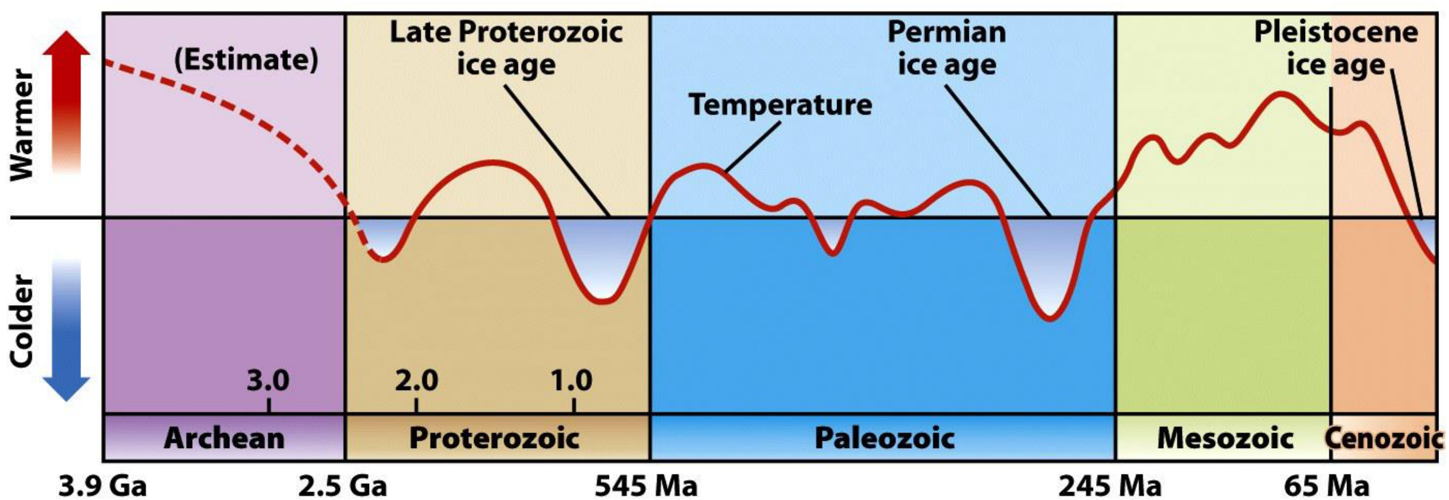
Timing of the Pleistocene Ice Age

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



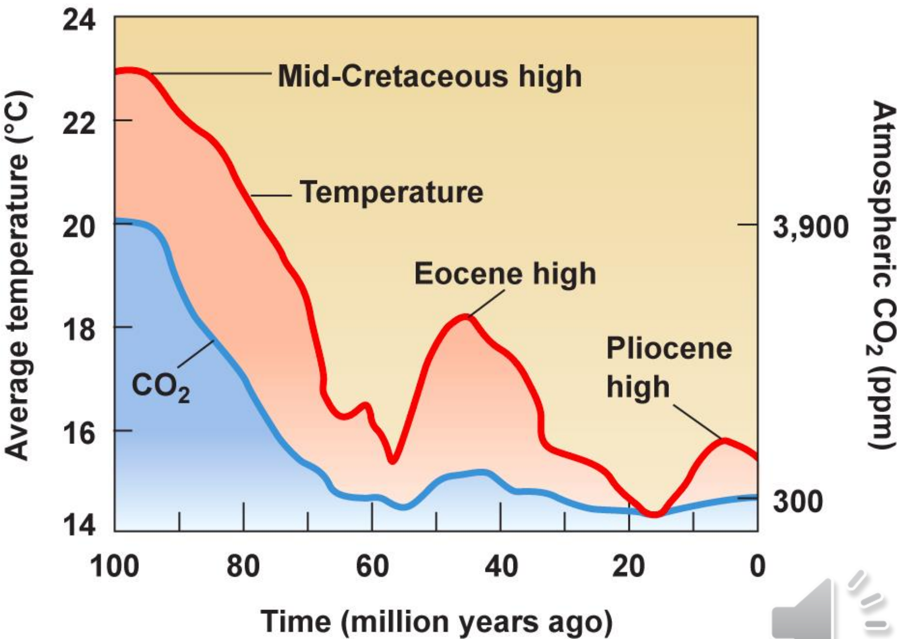
Earlier Glaciations

- Glaciations have occurred before in Earth history.
- They are indicated by fossil tills and striated bedrock:
  - Pleistocene (since 2.5Ma ago)
  - Permian
  - Ordovician
  - Late Proterozoic—tillites at equatorial latitudes suggest an ice-covered world (“Snowball Earth”).



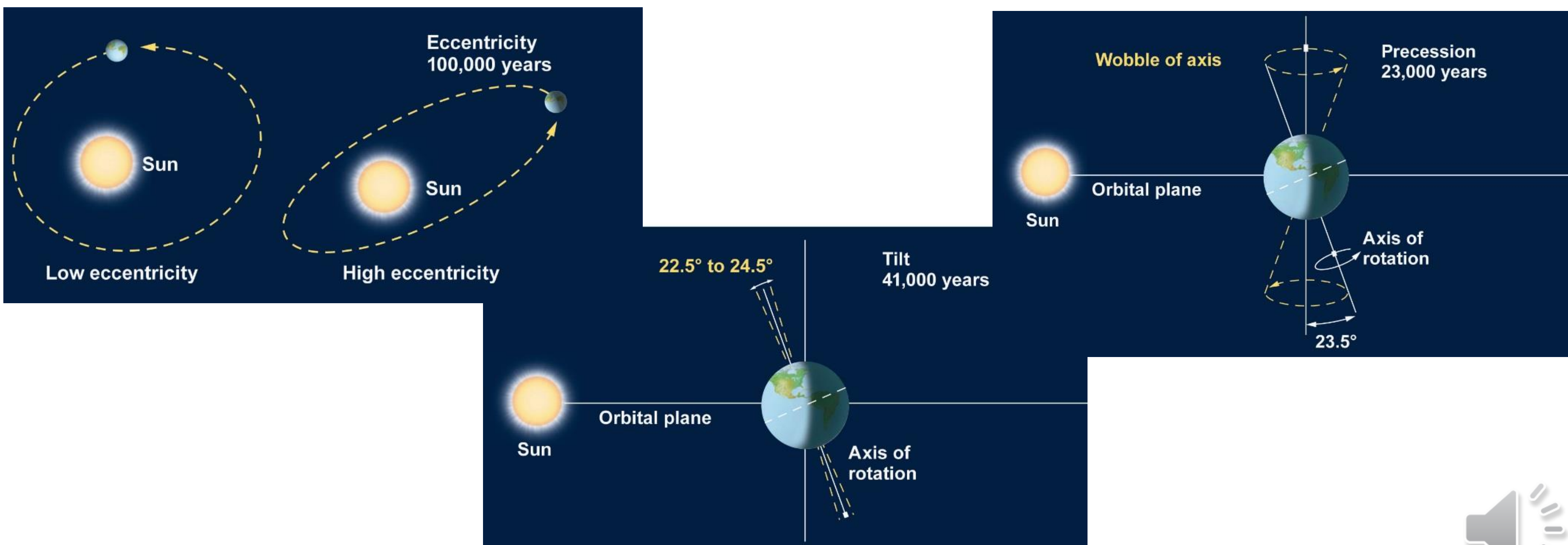
Causes of Glaciation

- Long-term causes—set the stage for ice ages.
  - Plate tectonics – 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 (CO_2)
      - Methane (CH_4)
  - Global average temperature today: ~14C



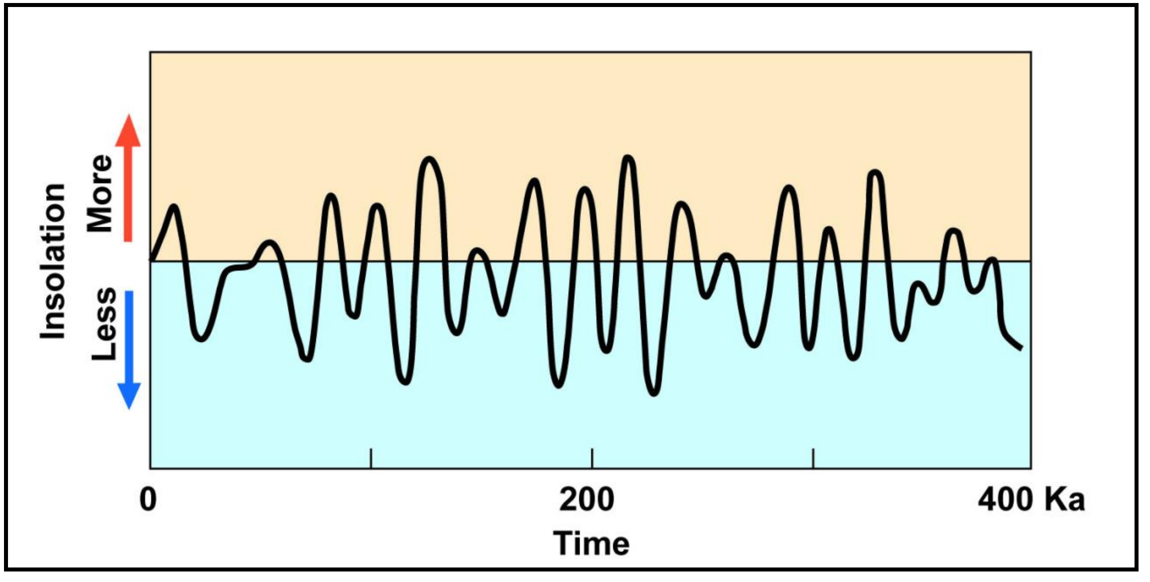
Causes of Glaciation

- 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 cyclicity).
    - Tilt of Earth’s axis varies from 22.5^{o} to 24.5^{o} (~41,000 years).
    - Precession—Earth’s axis wobbles like a top (23,000 years).



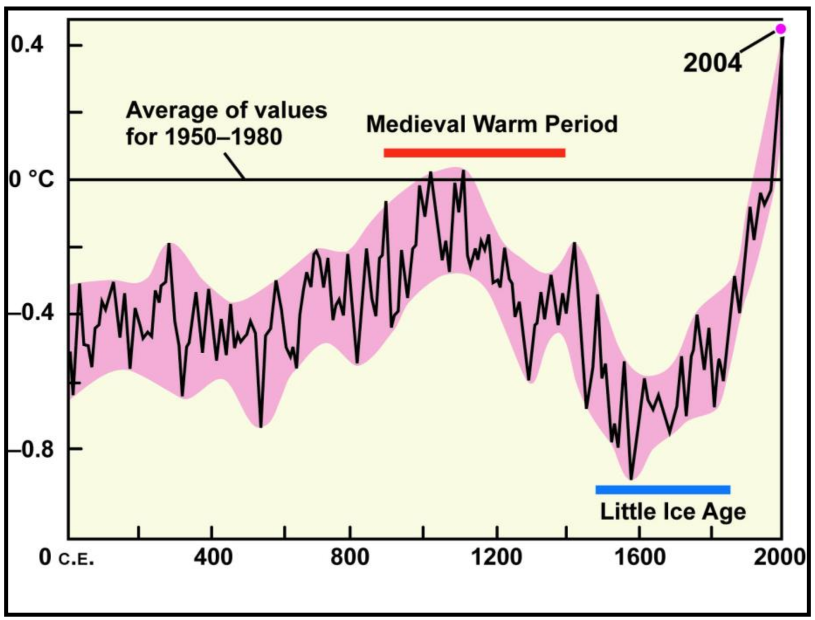
Causes of Glaciation

- Short-term causes – govern advances and retreats
  - Milankovitch 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.



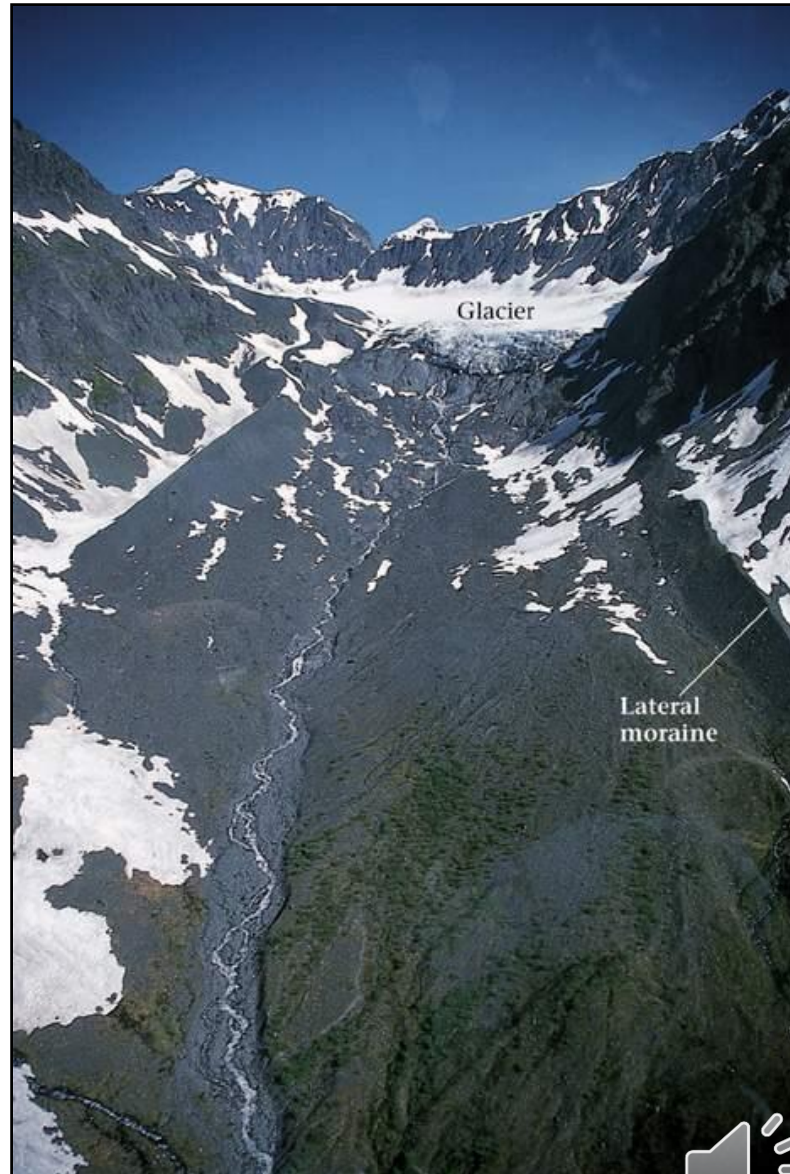
Will There Be Another Glaciation?

- **We are living in an interglacial. Ice will return! but when?**
  - **Recent interglacials have lasted ~10,000 years.**
  - **But, it has been ~11,000 years since the last deglaciation.**
  - **A cool period (1300–1850) resulted in the Little Ice Age.**
  - **We may have forestalled the next glaciation…. How?**



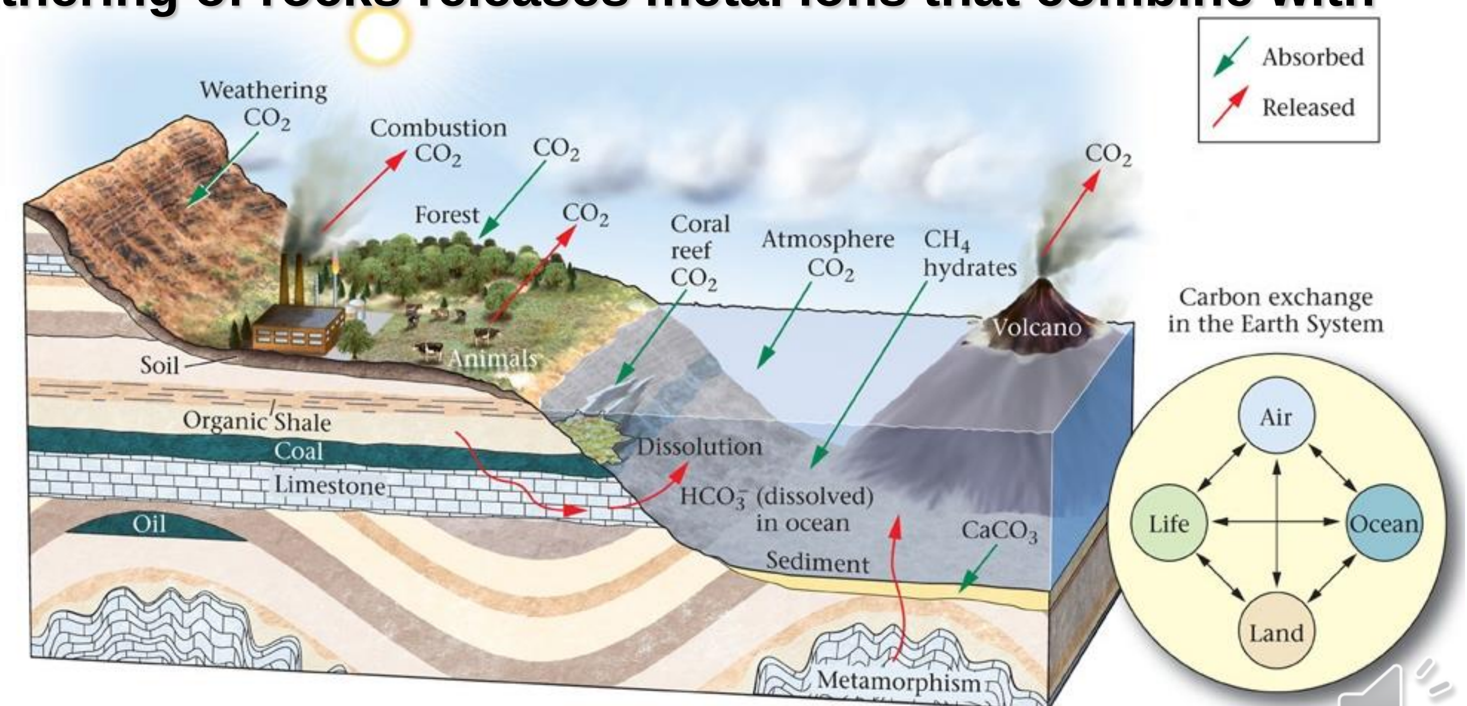
Will There Be Another Glaciation?

- 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.
- This current interglacial might be in extension because of human-induced warming!
- Recurrence may depend on the Carbon cycle



The Carbon Cycle

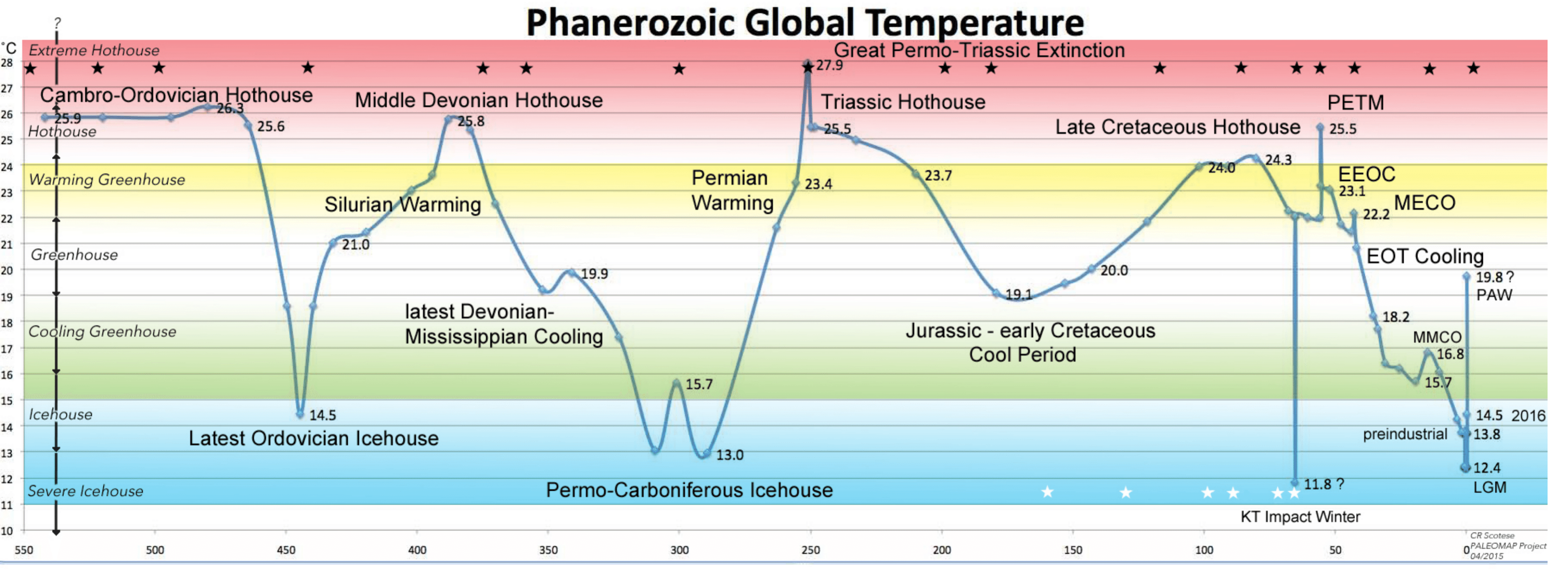
- A biogeochemical cycle that regulates climate
  - Volcanoes continually add carbon to the atmosphere.
  - Atmospheric CO_2 is removed in several ways:
    - It dissolves in water as carbonic acid and bicarbonate.
    - Photosynthesis removes CO_2.
    - Weathering of rocks releases metal ions that combine with CO_2.



The Gaïa hypothesis

- James Lovelock in 1970, elaborated the Gaïa principle: *living organisms interact with their inorganic surroundings on Earth to form a synergistic and self-regulating, complex system that helps to maintain and perpetuate the conditions for life on the planet*.
- An important piece of this synergistic system is the regulation of surface temperature via the C-cycle.
- Carbon sequestration by plants and animals has largely contributed to hold global temperature within a range in which they can survive throughout the Phanerozoic.

Phanerzoic Temperature



- **We are now in an "[Icehouse Earth]" condition, colder than 95% of the duration of the Phanerozoic.**
- **Global average temperatures have been constrained within a range 20C (+/- 10C) for the past 541 million years.**
- **Perhaps our CO_2 infusions into the atmosphere will hold off a complete freezeup into a "[Snowball Earth]" condition????**