CE/SC 10110-20110: Planet Earth

Glaciers & Ice Ages

Earth

Portrait of a Planet

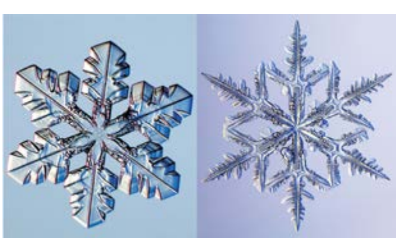
Fifth Edition

Chapter 22

Ice ages recognized by the observation of large boulders of non-local country rock being present in certain areas - erratics.

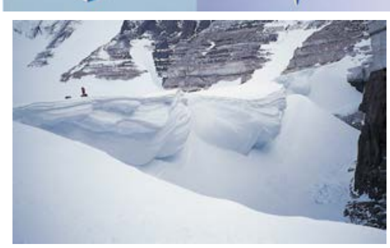
Glacier: masses of **ice** formed on land and moving because of their weight.

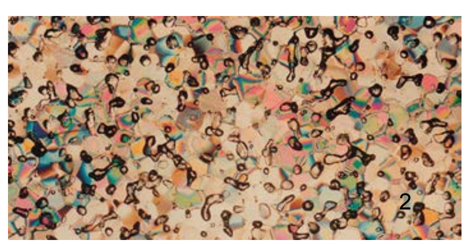
Glaciers have covered up to one third of the Earth's surface in the recent geologic past, with most of the recent ice ending ~10,000 years ago. Proterozoic = snowball earth - complete ice cover.



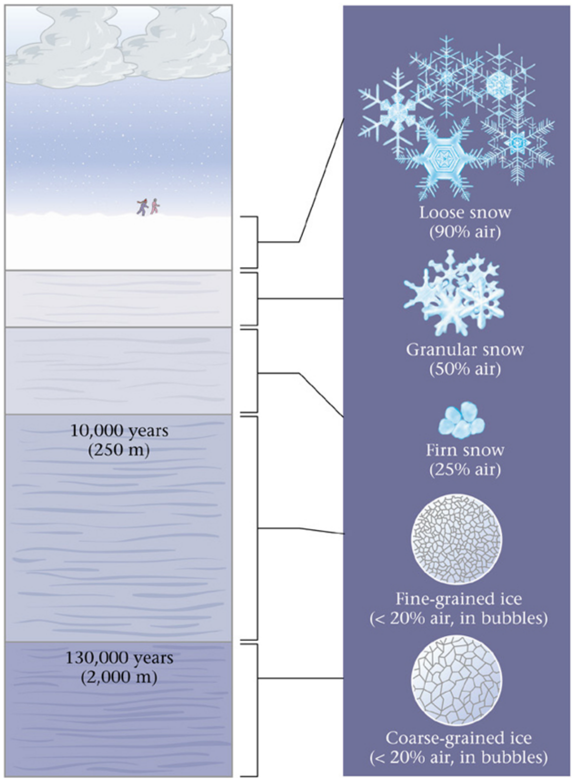
Ice forms from snow that forms in layers (sedimentary rock).

The snow recrystallizes into ice - metamorphic rock.





Ice Formation



Snowflakes fall and accumulate.

As ice compacts, flakes undergo pressure solution.

Continual compaction produces packed granular snow - firn.

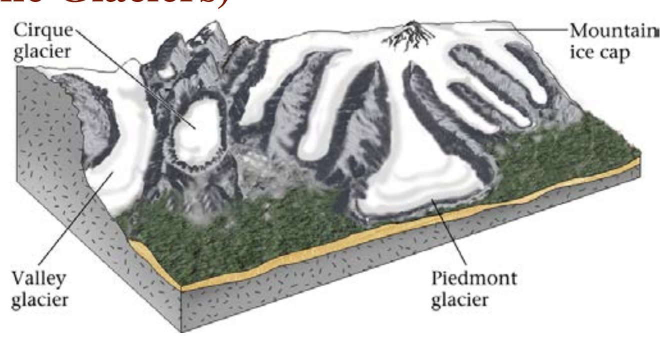
Pressure solution of firn produces glacial ice with trapped air that produces the blue color.

Older ice is coarser grained.

Types of Glaciers

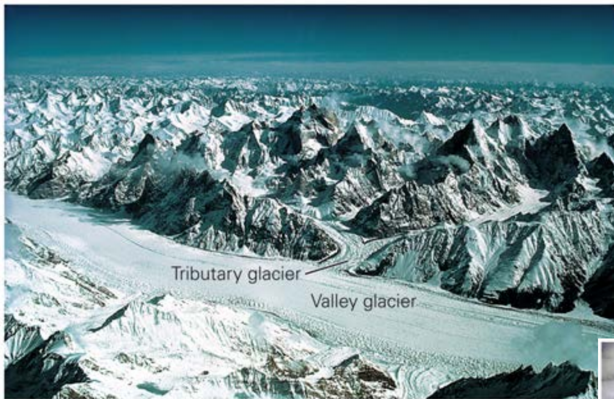
Mountain Glaciers (Alpine Glaciers)

Exist in or adjacent to mountain ranges.
Include valley glaciers, mountain ice caps (cover the mountains), piedmont glaciers.



Types of Glaciers

Mountain Glaciers (Alpine Glaciers)



Types of Glaciers

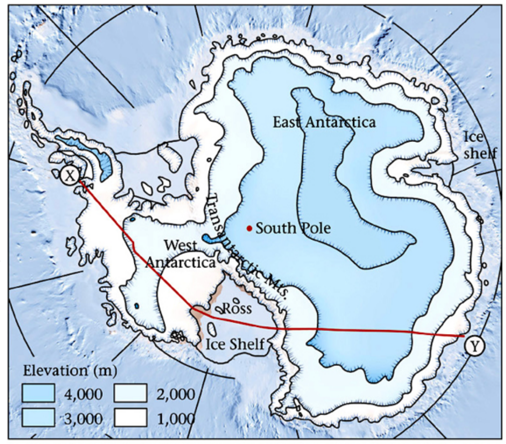
Piedmont Glaciers

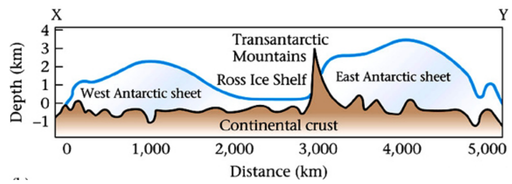
Piedmont glaciers spread out at the base of a mountain valley.

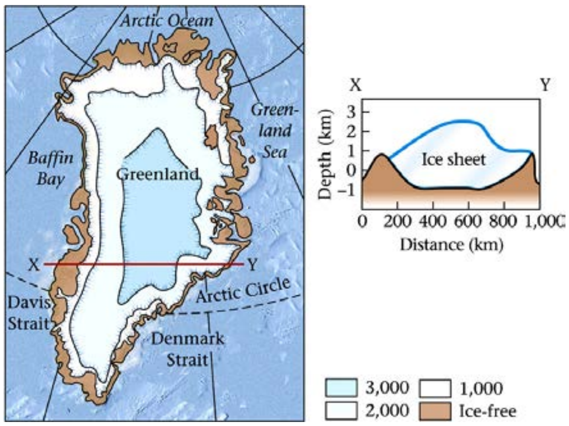
Types of Glaciers

Continental Glaciers

Vast ice sheets covering continents - Greenland, Antarctica.
Flow out from the thickest point.
Front edge may form several tongue-shaped lobes due to differential speed.



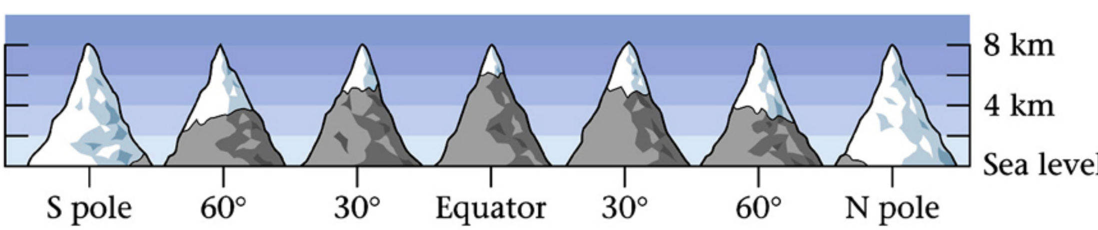




Types of Glaciers

Temperate Glaciers: temperature is at or near to the melting point of ice for a substantial portion of the year.
Polar Glaciers: temperature is below freezing year round.

Glaciers can form at any latitude as long as altitude permits.



Conditions for glacier formation:
1) Local climate - cold enough for snow to remain year round;
2) Snowfall is sufficient for accumulation;
3) Surface is gentle so snow does not slide away (glaciers do not exist on slopes >30˚ - avalanches).

Glacial Movement

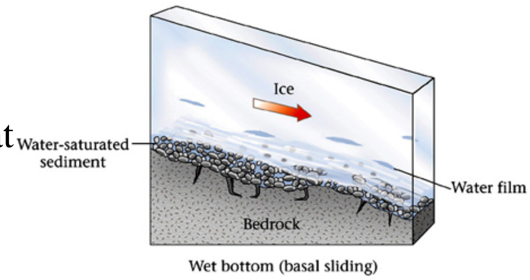
Gravity driven.

Wet-Bottomed Glaciers: meltwater at the base reduces friction.

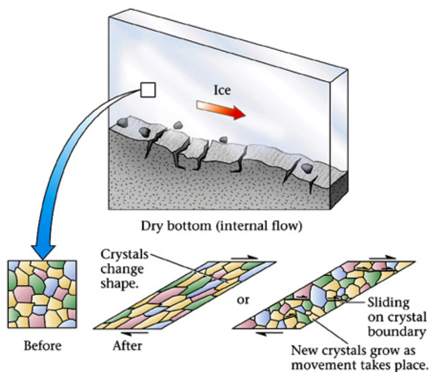
Melting occurs because of climate, heat flow, and/or pressure solution.

End up with a slurry of material at the base of the glacier.

Typifies temperate glacier movement.



Wet bottom (basal sliding)



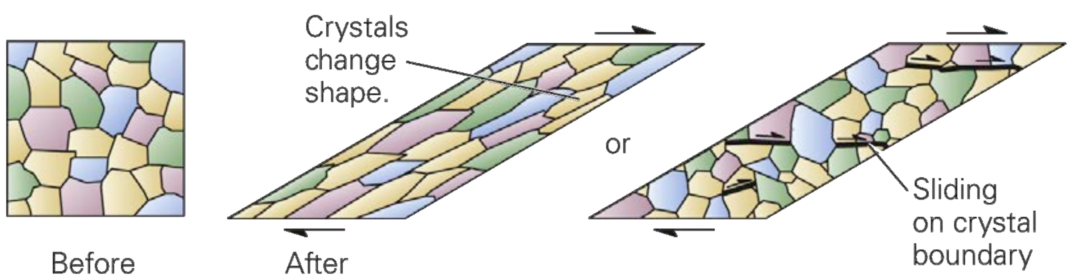
Dry bottom (internal flow)

Dry-Bottom Glaciers:
Movement occurs through plastic ice crystal deformation and pressure solution.
Typifies polar glacier movement.
Slower than above.

Glacial Movement

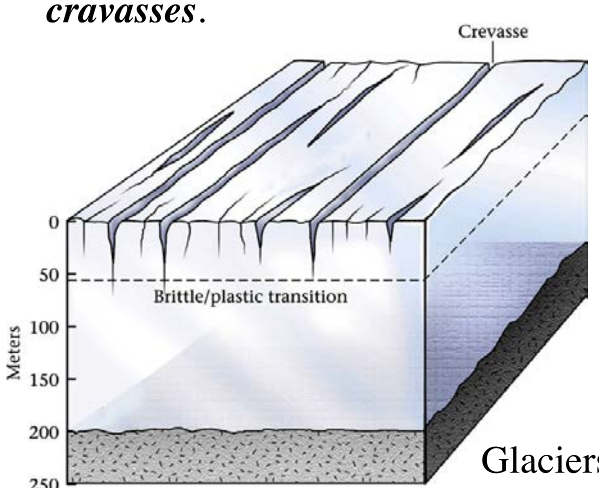
Plastic Deformation.

Internal plastic deformation involves recrystallization, stretching, and rotating of grains. It occurs in both wet- and dry-based glaciers.



Glacial Movement

Plastic deformation of a glacier occurs below ~60 m (compare with rocks - 10-15 km).
Above this, glaciers undergo brittle deformation and create ***cravasses***.

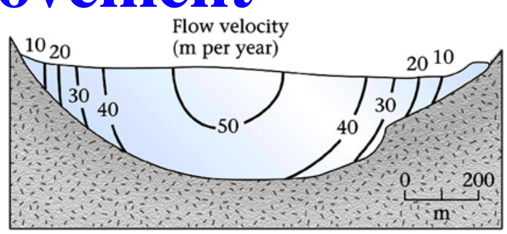


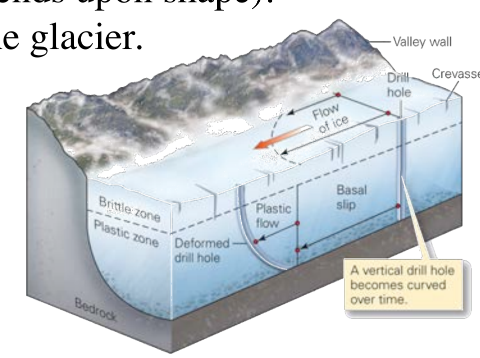
Glaciers can speed up and slow down. If water builds up beneath a glacier it can undergo a ***surge*** until the water is released.

Glacial Movement

Velocity depends upon:

(i) slope
(ii) thickness
(iii) temperature
(iv) friction along base & edges (depends upon shape).
Movement not constant throughout the glacier.





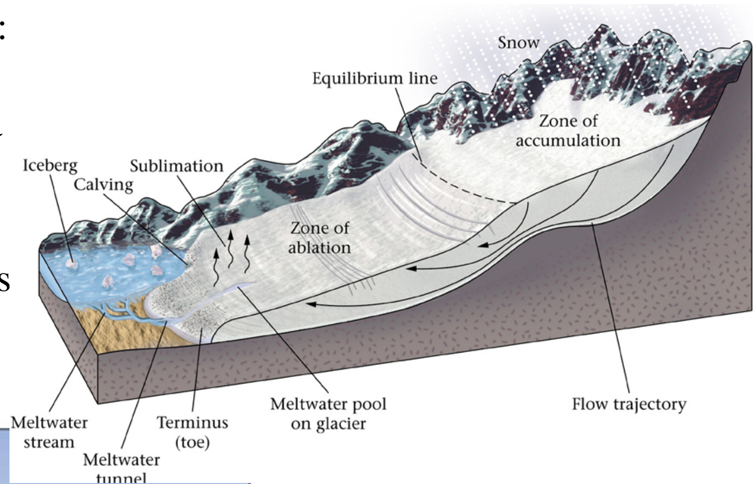
- Flow velocities vary with location in a glacier.
- Overall, ice flows from the zone of accumulation to the toe.
- Flow velocity is greatest in the center of the glacier.
- Velocity decreases at the ice margins due to friction with the substrate.

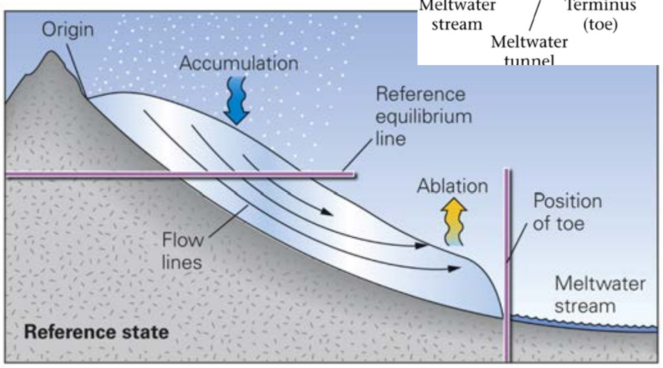
Growth/Retreat

Zone of Accumulation:
& melting.

Zone of Ablation: Area evaporation, “calving” of icebergs.

Glacier continually moves





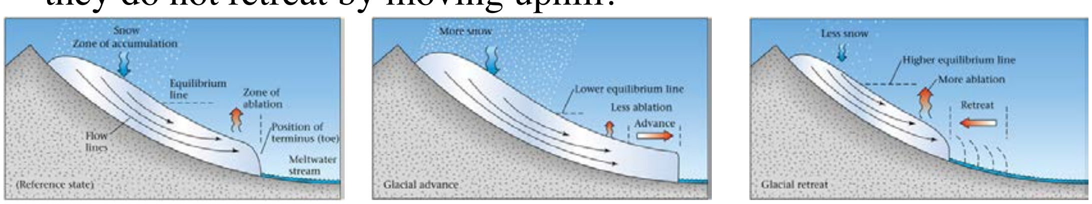
The position of the toe represents a balance between addition by accumulation and loss by ablation.

Growth/Retreat

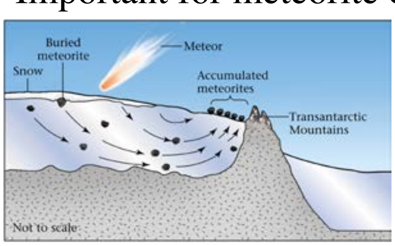
Accumulation > wastage: terminus advances (i.e., glacier advances).

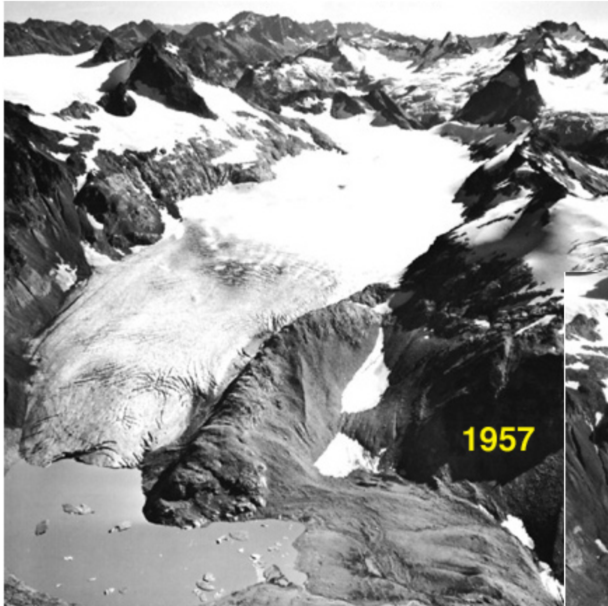
Accumulation < Wastage: glacier retreats.

NOTE: Glaciers always move outwards from zone of accumulation – they do not retreat by moving uphill!

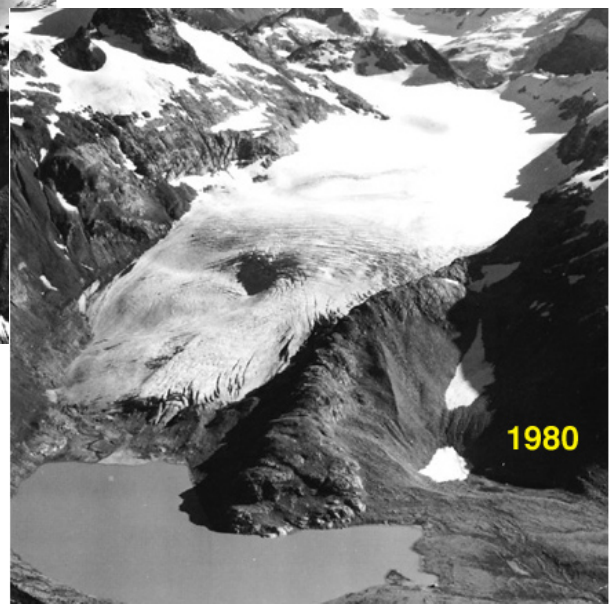


Ice crystals move in a concave upward profile.
Important for meteorite collections.



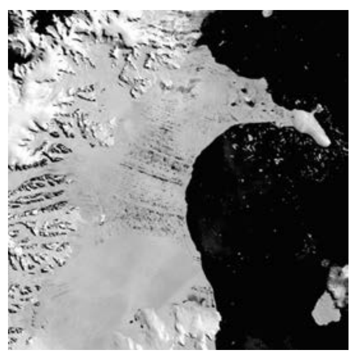


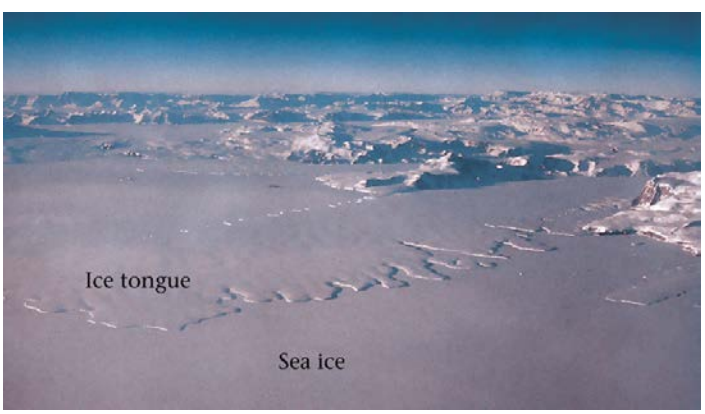
South Cascade Glacier, Washington.



Ice in the Sea

Ice shelves: ice entering the sea becomes a broad flat shelf.





Sea Ice: temperature low enough for sea to freeze (North pole). Sea ice is currently shrinking

Ice in the Sea

Icebergs

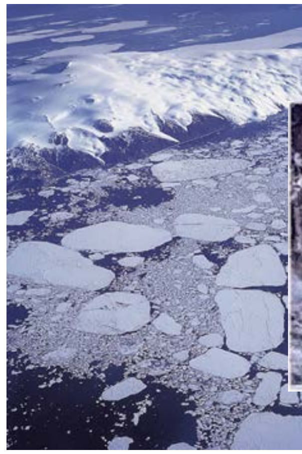
Pieces of ice sheet/glacier calve off the main mass and float in the sea. 4/5ths below sea level

Bergy bits: rise 1-5 m above the water, area = 100-200 m^2.

Growlers: rise less that a meter above the water.

Polynyas: large openings in sea ice.

Blocks that calve off valley glaciers are pointed - “castle-bergs” or “pinnacle-bergs”. Blocks that calve off continental ice sheets are tabular and can be >100 km across.



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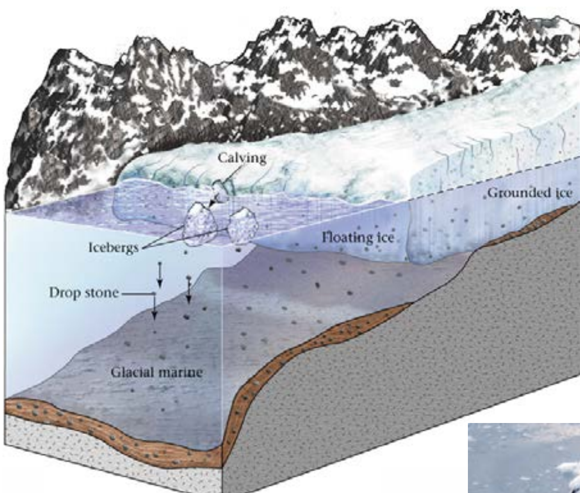
Ice in the Sea



Drop Stones: erratics in sediments from melting icebergs.

Can show past glaciations by finding drop stones in marine sediments.

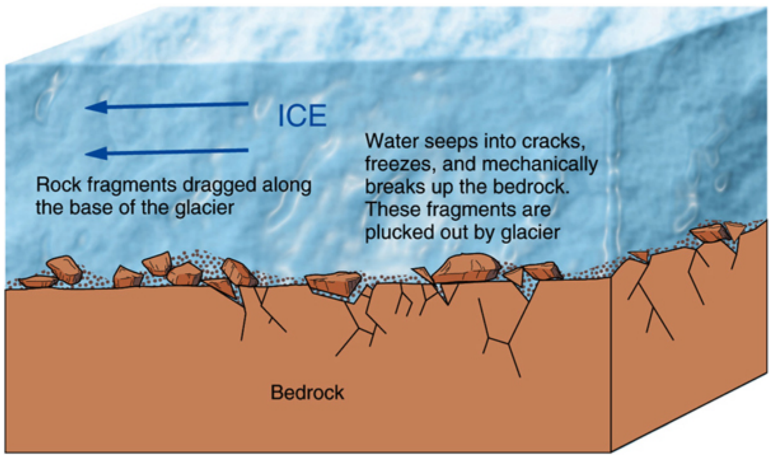
Erosion due to Glaciers

Base of Glacier: Basal sliding causes scouring, grinding, crushing, etc. *Erosion is proportional to thickness*.

Glacier has rocks frozen into base – increases the amount of erosion.

Results in fine rock powder called "**rock flour**".

Results in polished rock surface scraped clean of soil and vegetation.

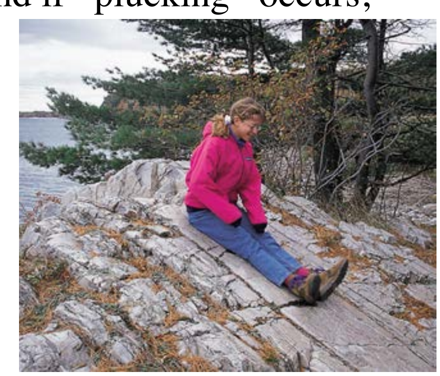


Erosion due to Glaciers

Half Dome, Yosemite National Park. The complete dome was truncated due to glacial erosion.

Rocks dragged over bed rock can produce **glacial striations** and **polished surfaces**.

These give sense of glacier movement and if "plucking" occurs, direction of movement can be deduced.

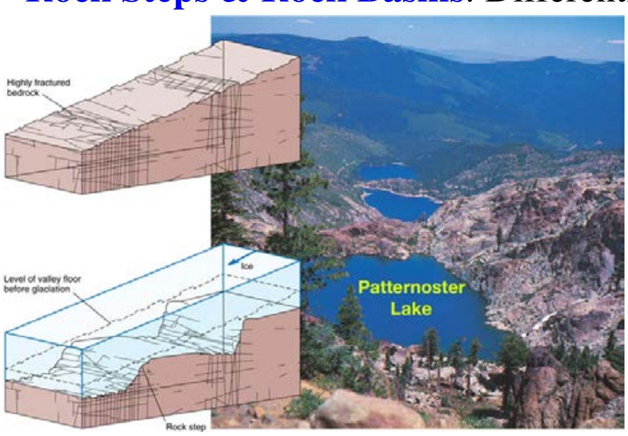


Glacial Striations

Kelly Island, OH

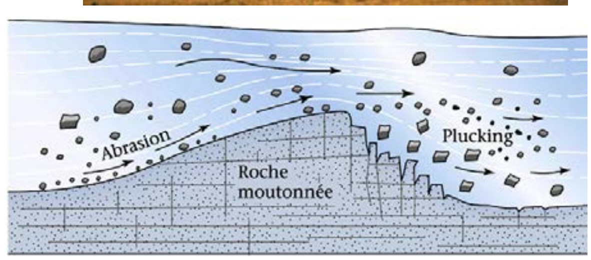
Erosion due to Glaciers

Rock Steps & Rock Basins: Differential erosion down a valley.

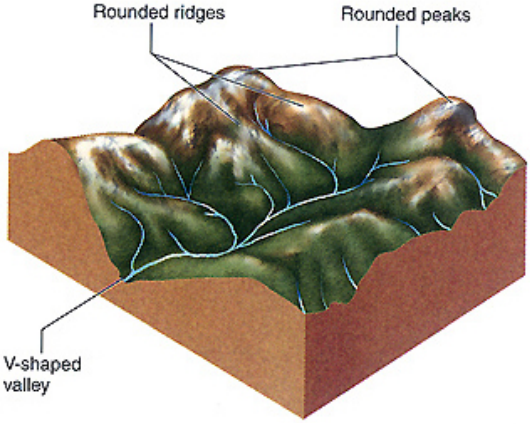


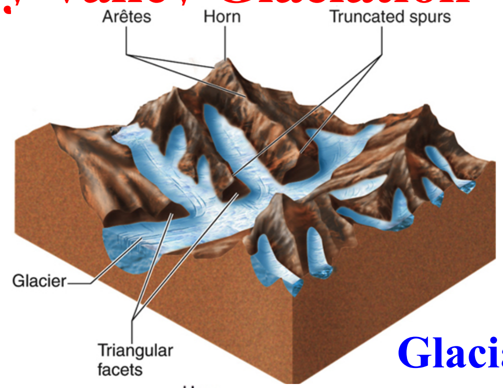
Series of lakes formed in this way are called "**patternoster lakes**".

If rock steps are rounded they are called "**roche mountonées**". These can also form as isolated hills because of difference in rock strength (e.g., Edinburgh Castle).



Landscapes Caused by Valley Glaciation

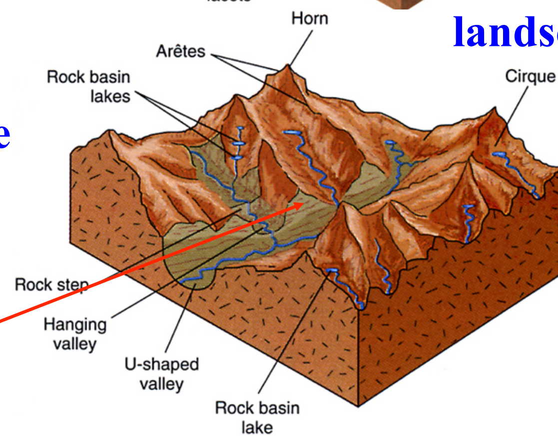




Glacial landscape

Pre-glacial landscape

Post-glacial landscape

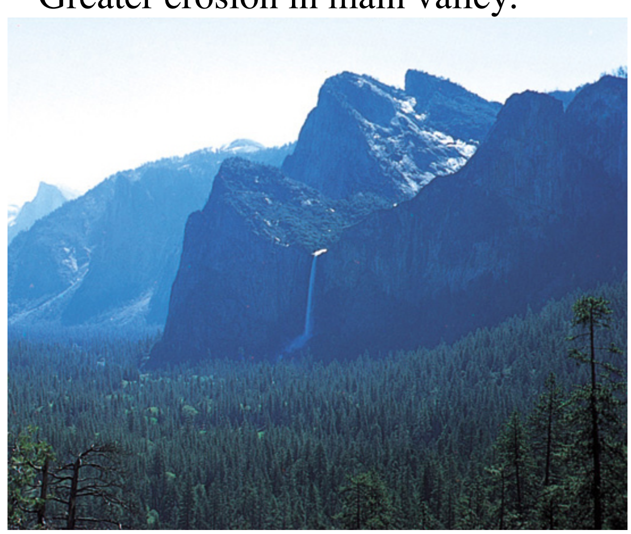


Truncated Spurs: When arêtes are truncated by U-shaped valleys.

Landscapes Caused by Valley Glaciation

U-Shaped Valley: As opposed to "V-shaped" valleys caused by rivers or water flow. These can be recognized on topographic maps.

Hanging Valley: Due to tributary glaciers joining the main glacier. Greater erosion in main valley.

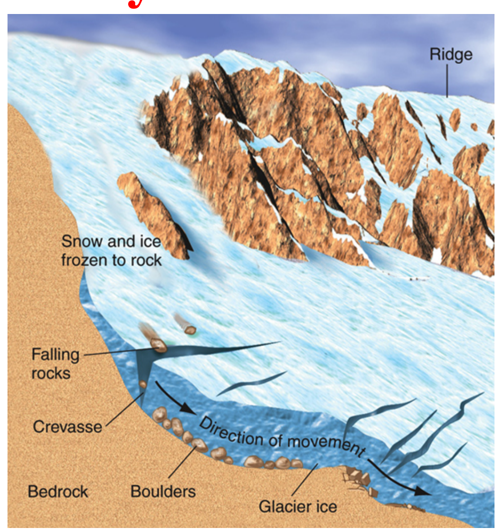


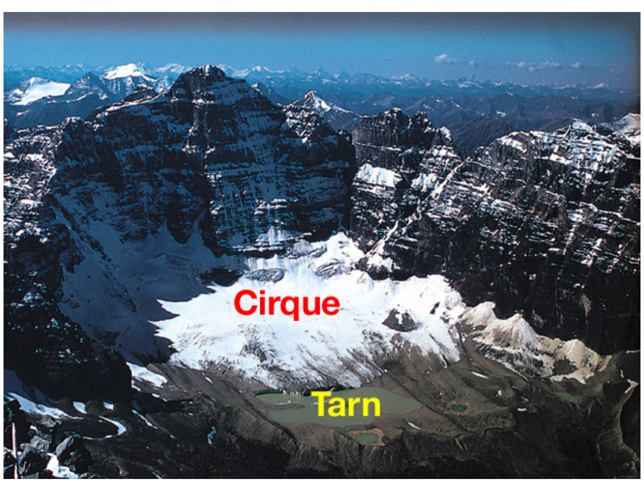
Landscapes Caused by Valley Glaciation

Fiord (or Fjord): Drowned U-shaped valleys. Called "lochs" in Scotland.

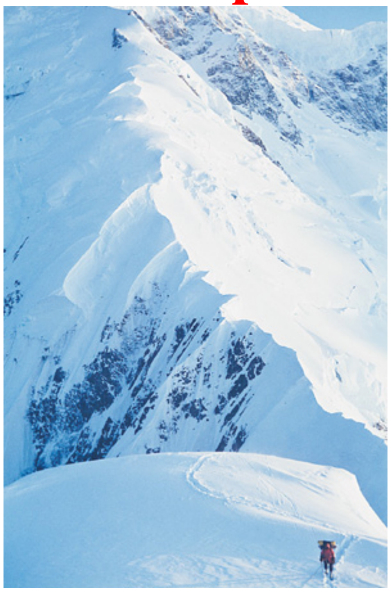
Landscapes Caused by Valley Glaciation

Cirque: Upper part of U-shaped valley where the glacier originated; basically a feature formed at the head of the glacier. Has steep sides, often (now) with a lake or "**tarn**" in it.





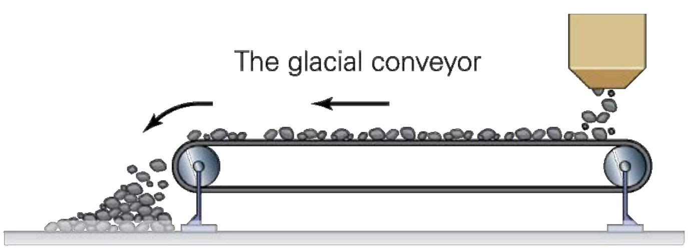
Landscapes Caused by Valley Glaciation

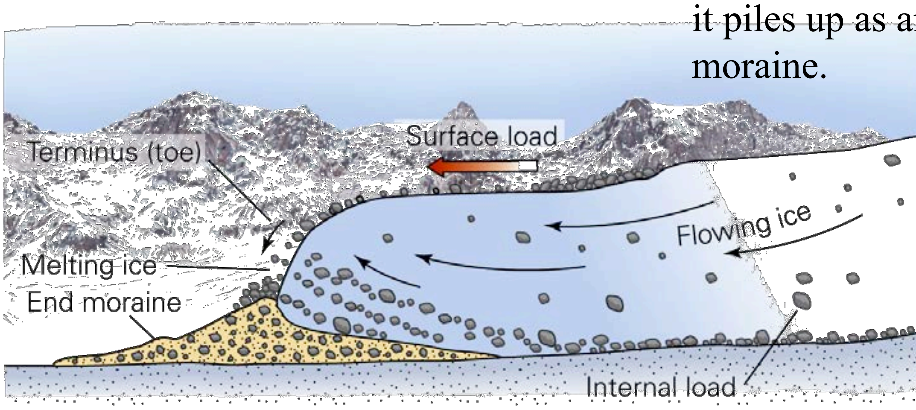


Arête: Sharp ridge that separates valleys sculptured by glaciation.

Horn: A sharp peak formed where several cirques meet at the same point.

Glacial Deposition: Transport of Sediment by Ice





Glaciers act as large-scale sediment conveyor belts. Sediment falls onto a glacier and gets plucked up from below. This material is transported to the toe where it piles up as an end moraine.

Deposits due to Glaciers

Sediment derived from glaciation is called glacial drift.

Stratified drift is water sorted; unstratified drift isn't.

Glacial drift includes:

- glacial till,
- erratics,
- glacial outwash,
- glacial marine sediments,
- loess,
- glacial lake-bed sediment.

Deposits due to Glaciers

Glaciers are dirt machines; they carry an enormous amount of sediment.

Till: sediment carried or deposited by glaciers – unsorted and unstratified (immature). Deposited beneath or at the toe of a glacier.

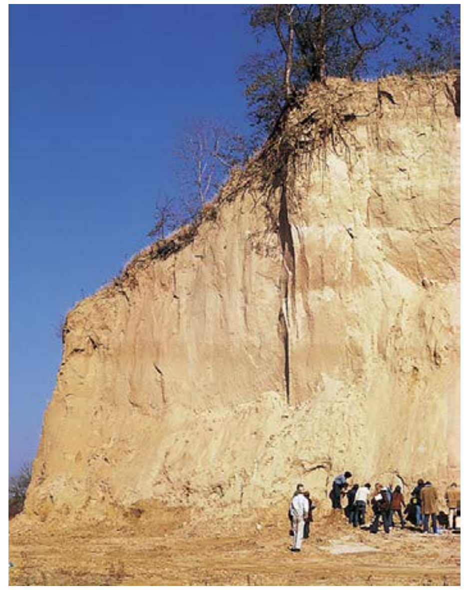
Tillite: lithified till.

Erratic: boulder transported from a distant area and deposited (usually) in a geologically different region.

Deposits due to Glaciers

Glacial Marine: Drop stones; sediment carried into the sea by a glacier.

Glacial Outwash: sediment deposited at the toe is picked up are redeposited by meltwater streams that sort the material. Sand and gravel bars deposited by braided streams.



Loess ("Lurss"): Air above ice-free land is warmer and rises. Cold air off the glacier rushes in - ***catabatic wind***. Picks up fine material from the glacier's toe and deposits it as **loess**.

Deposits due to Glaciers

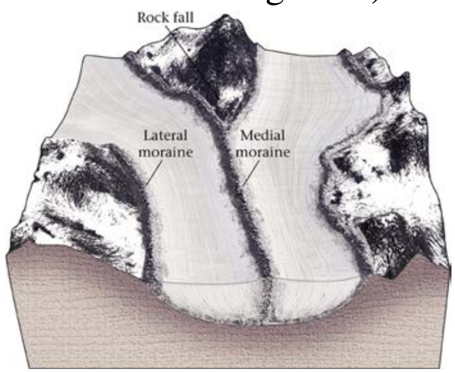
Glacial Lake Sediments: meltwater streams carry fine particles away that settle out in meltwater lakes. ***Varves*** represent a pair of layers - light colored = spring floods (silt); usually darker colored = winter (clay + organics because of death!).

Deposits due to Glaciers

Moraine: unit of till carried or deposited by the glacier.

(a) Lateral Moraine: ridge-like pile along the edge of a glacier.

(b) Medial Moraine: single long ridge of till on a glacier – formed when tributary glaciers merge (i.e., merging of lateral moraines to form one in the interior of the glacier).



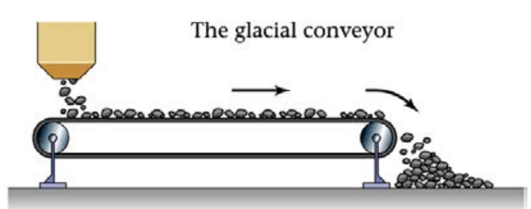
Deposits due to Glaciers

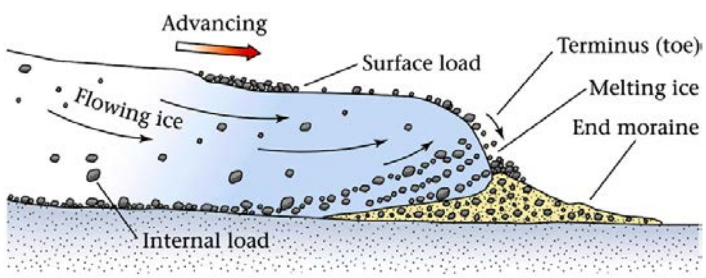
(c) End Moraine:

(i) Terminal: marks the farthest advance of the glacier;

(ii) Recessional: built up during the retreat (defines periods of no retreat or small advances).

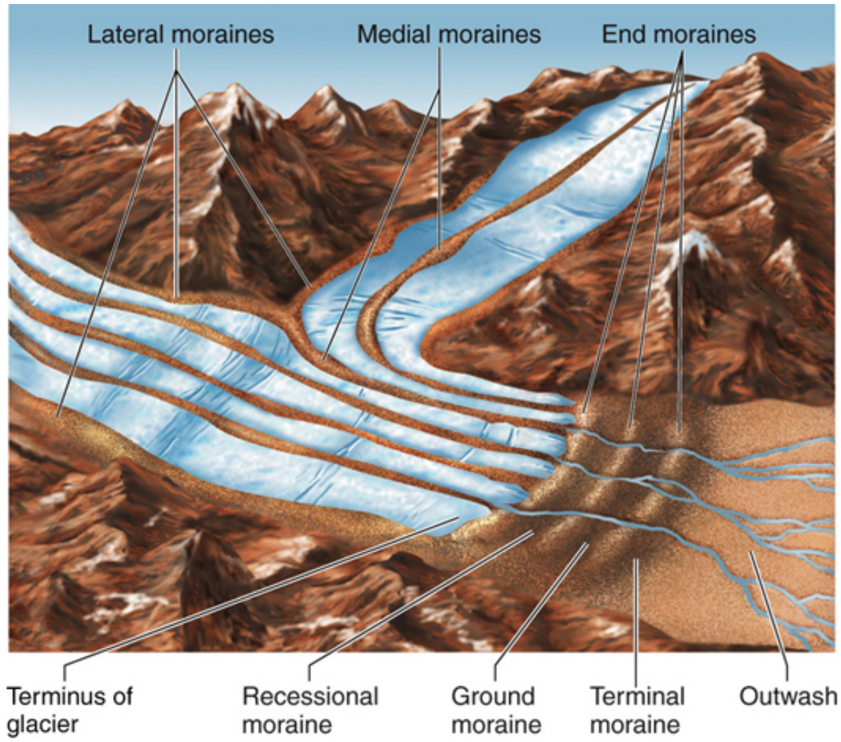
Both represent periods of glacial stagnation.



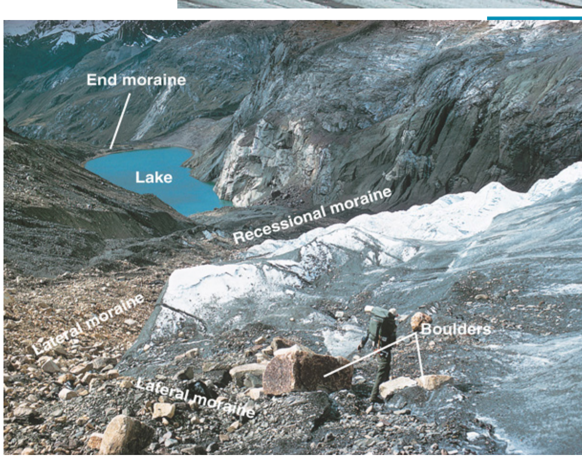


(d) Ground Moraine: blanket of till.

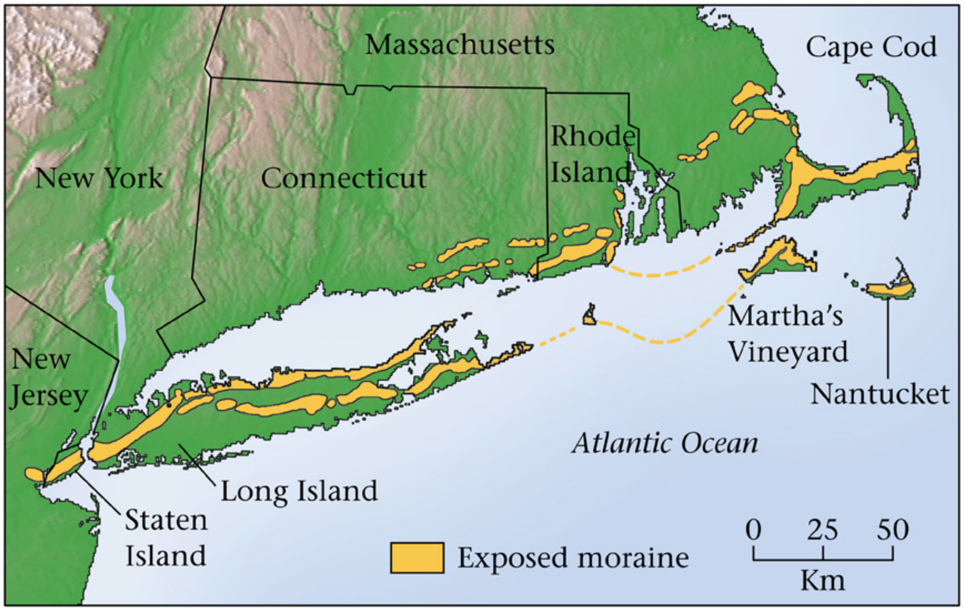
Deposits due to Glaciers



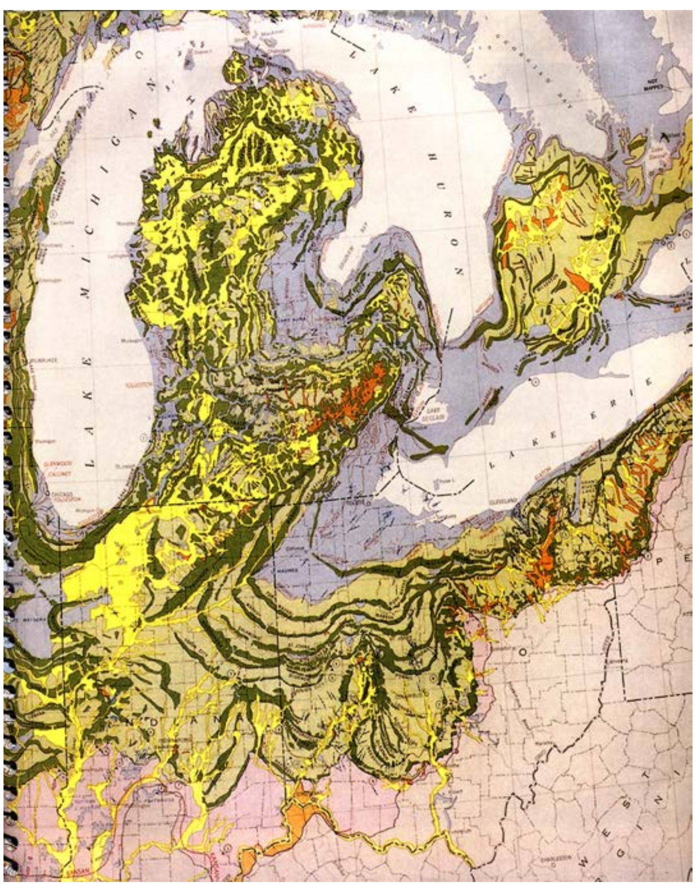
Deposits due to Glaciers



Deposits due to Glaciers



Long Island and Cape Cod = Moraines



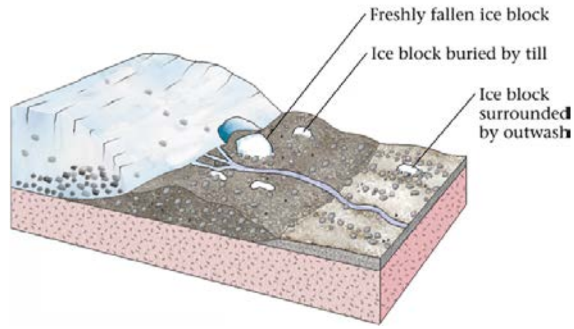
The Great Lakes

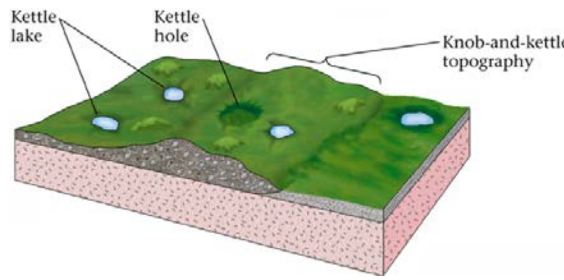
Deposits due to Glaciers

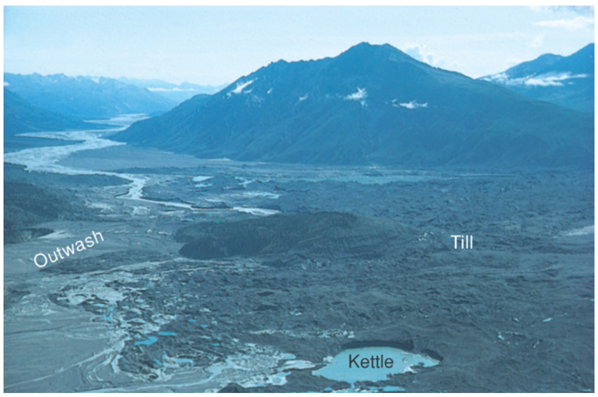
Outwash

Kettle: Depression in glacial outwash formed by the melting of a detached block of ice.

Kettle Lake: the "kettle" is filled with water!

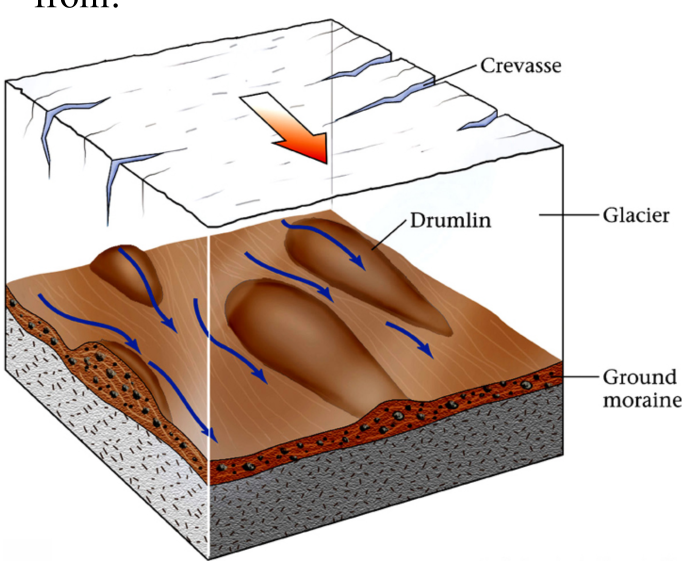


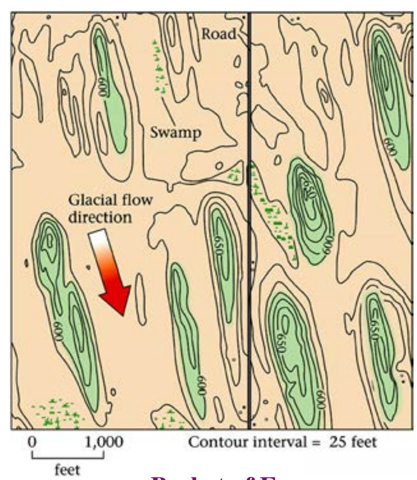




Deposits due to Glaciers

Drumlins: long, steep-sided hills of till; glacier overrode a moraine. The "bulb" points in the direction the glacier came from.

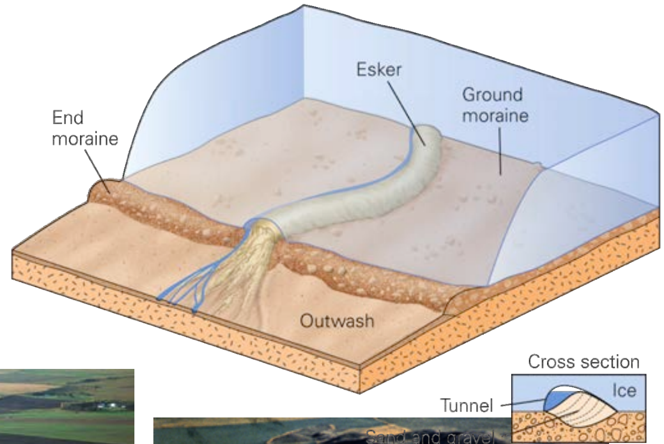


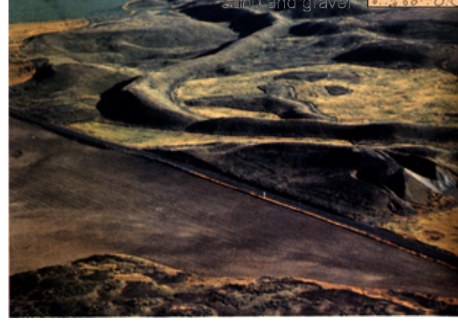


Basket of Eggs

Deposits due to Glaciers

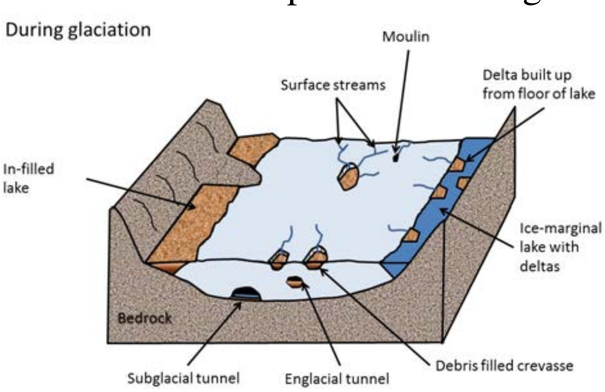
Esker: Sinuous ridge of sediment deposited by glacial meltwater flowing within the glacier.

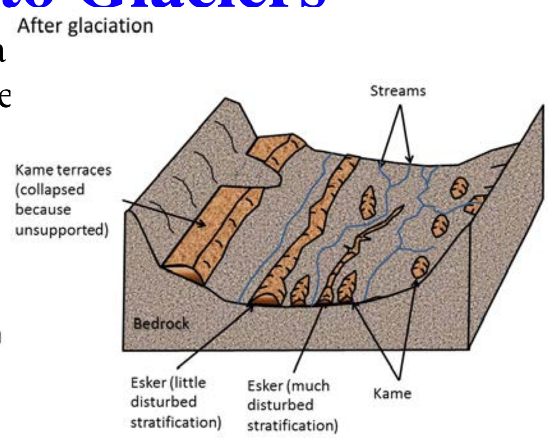




Deposits due to Glaciers

Kame: low, steep-sided hill that was a sediment filled depression in the glacie

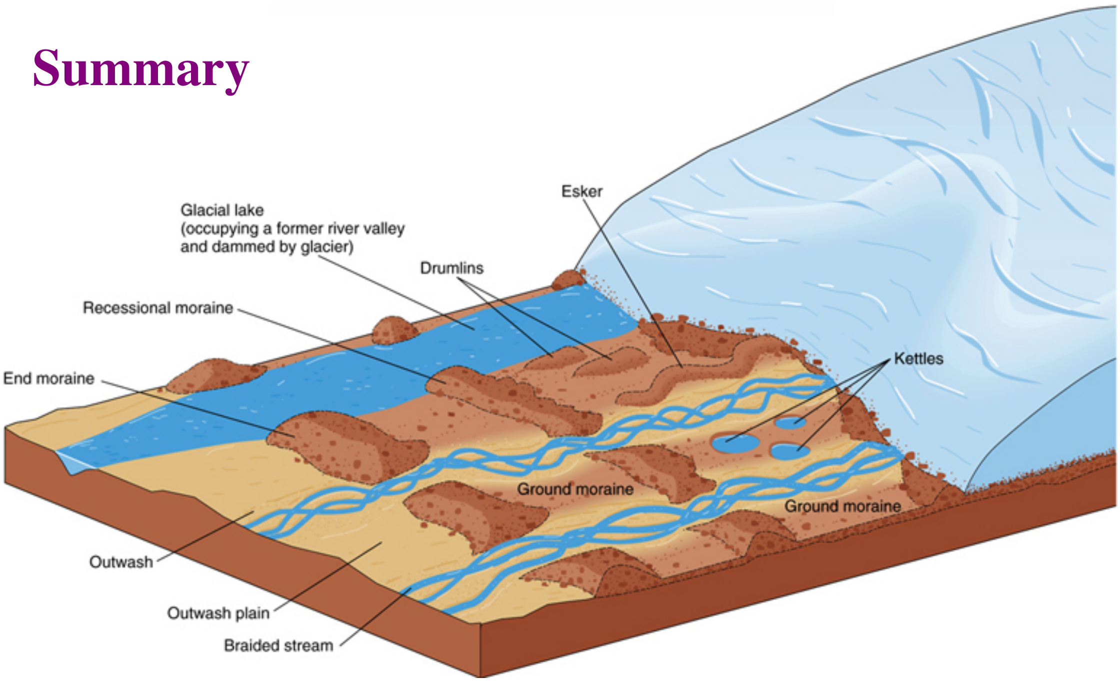




Kame Terrace: form in a similar manner to Kames but between the lateral margin of a glacier and the valley wall.
Moulin: Point at which a stream on the surface of a glacier disappears into it.

Deposits due to Glaciers

Summary



Lakes

Glacial Lakes: Ice-margin lakes due to melting, deltas, beaches, lake clays remain.

Pluvial Lakes: Large lakes formed as a result of greater precipitation and overall cooler temperatures – far away from glaciers.

Largest: Lake Bonneville. 50,000 km^2, 335 m deep. Salt deposits of Salt Lake City formed as part of it dried up.

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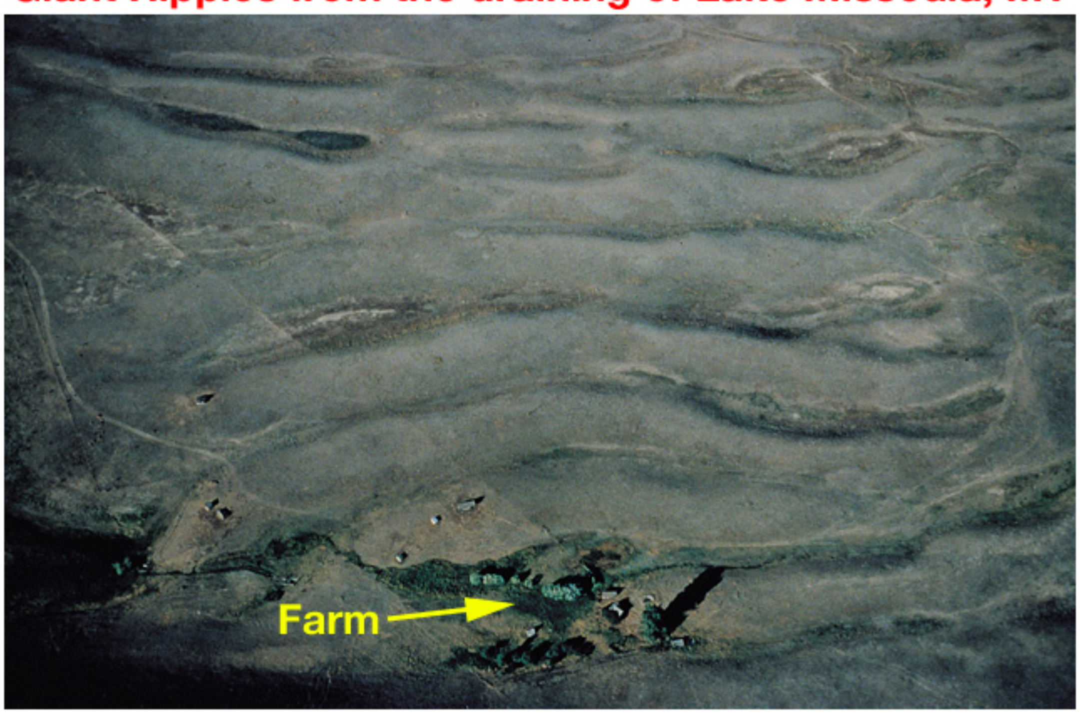
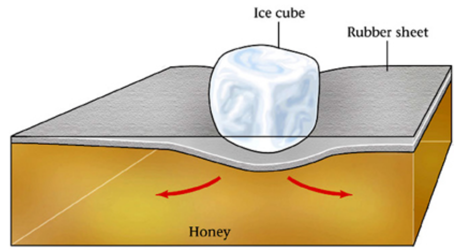
Giant Ripples from the draining of Lake Missoula, MT

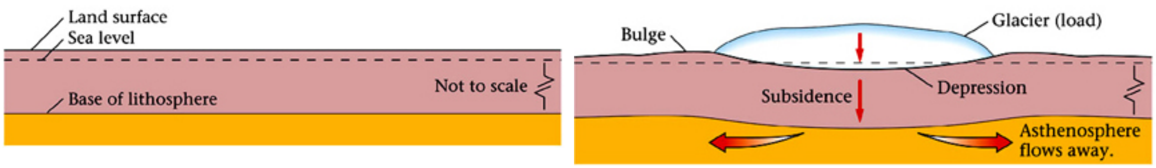


Sea-Level Changes

Huge amounts of water become tied up on continents.

Last ice age dropped sea level ~130 m = Glacial Subsidence.





<u>Consequences</u>:

(a) Continental shelves partly exposed.

(b) Britain connected to Europe.

(c) Base level of streams lowered (more erosion).

(d) Bering Sea land bridge formed.

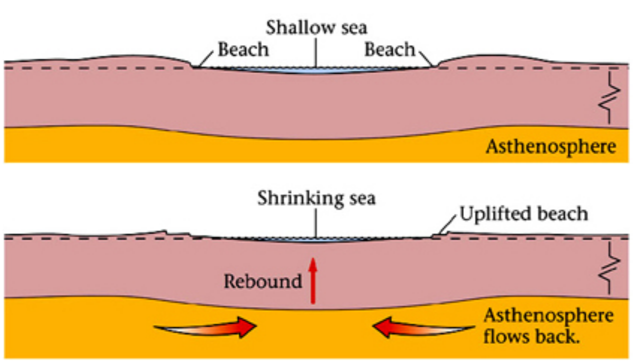
Sea-Level Changes

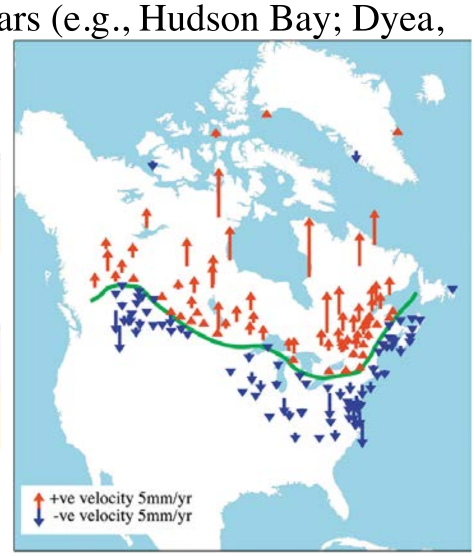
Isostatic Readjustment

Weight of ice causes uppermost mantle to move aside, crust sinks.

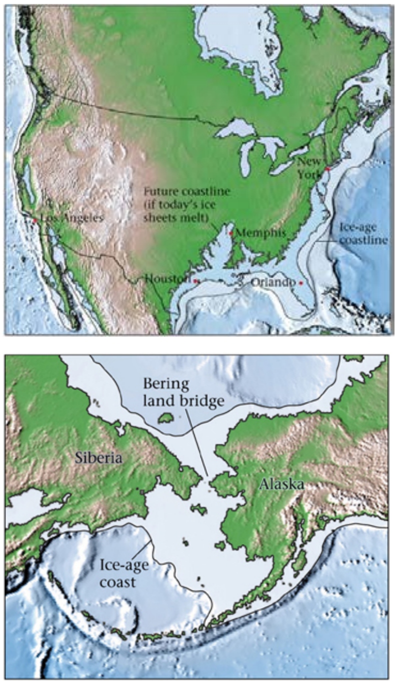
When ice melts it takes a while for the mantle to flow back.

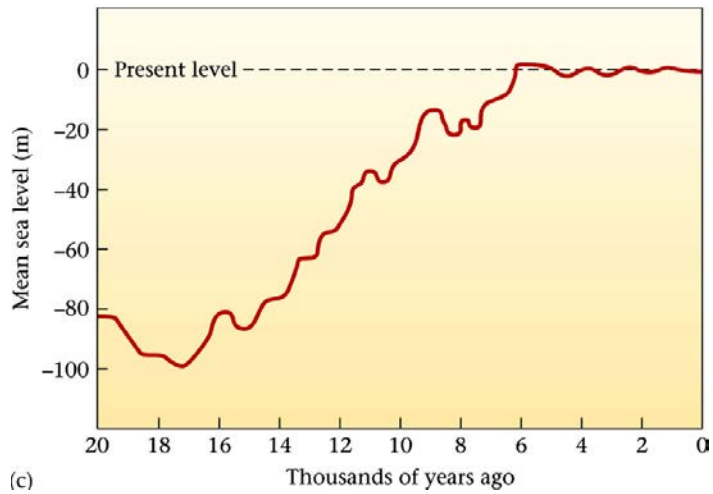
Rebound occurs over thousands of years (e.g., Hudson Bay; Dyea, Alaska; Scandinavia).





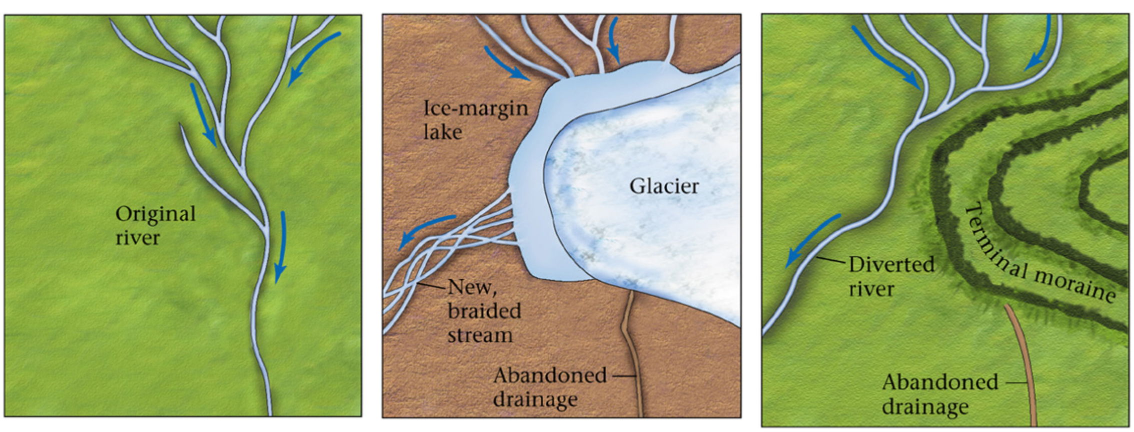
Sea-Level Changes





Drainage Patterns

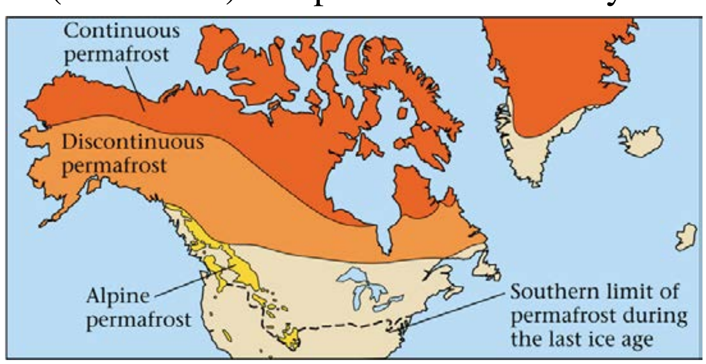
Glaciation can dramatically alter the pre-glacial drainage pattern.



Drainage Patterns

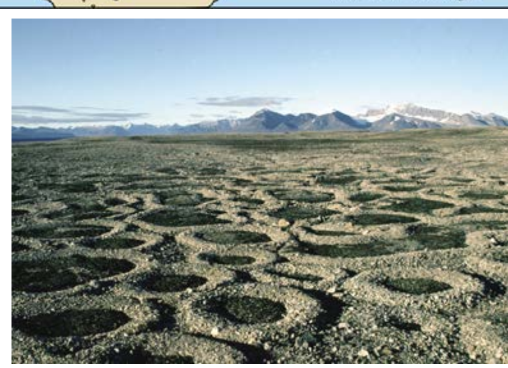
Periglacial Environments

Regions with snow cover (but not ice) and permafrost - usually peripheral to ice caps.



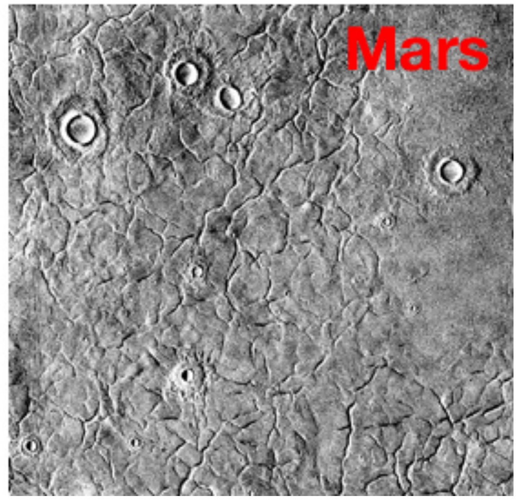
Permafrost - permanently frozen ground up to 1,500 m depth.

Patterned Ground: produced by freeze-thaw action. Pushes cobbles into “walls” as expansion is not even.



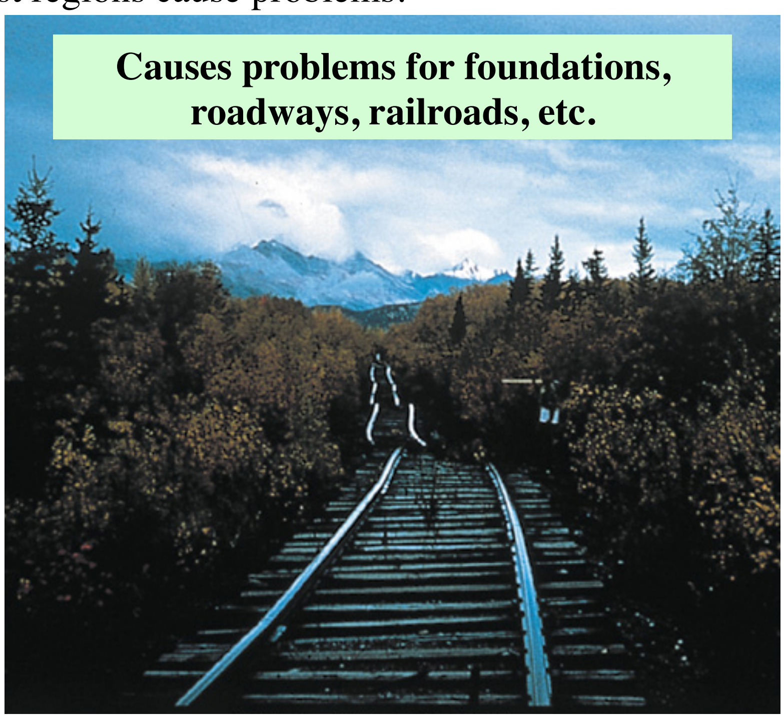
Periglacial Environments

Patterned Ground - Planetary Connection



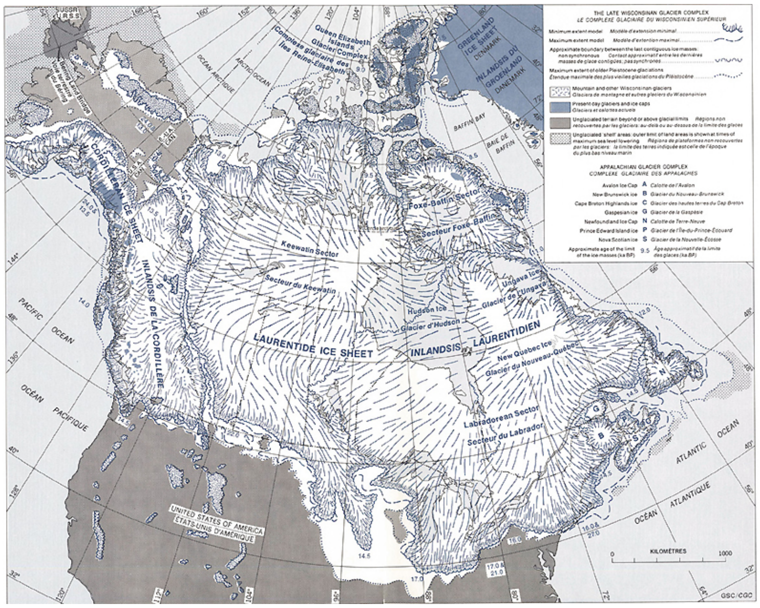
Periglacial Environments

Permafrost regions cause problems.



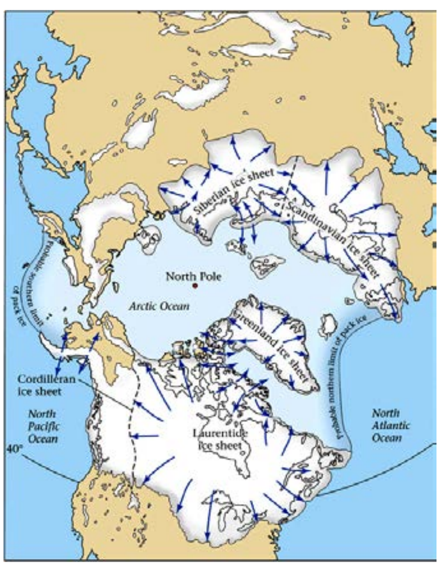
Pleistocene Ice Age(s)

Pleistocene: 1.8 m.y to 11,000 years (**last** ice advance).
Holocene: 11,000 years to Present.

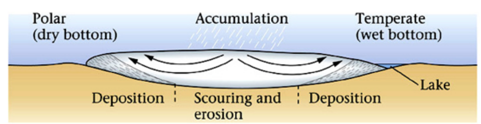


North America: ice sheet started as two - Laurentide in NE Canada and the Keewatin in NW Canada. These merged, based on mapping of glacial striations.

Pleistocene Ice Age(s)



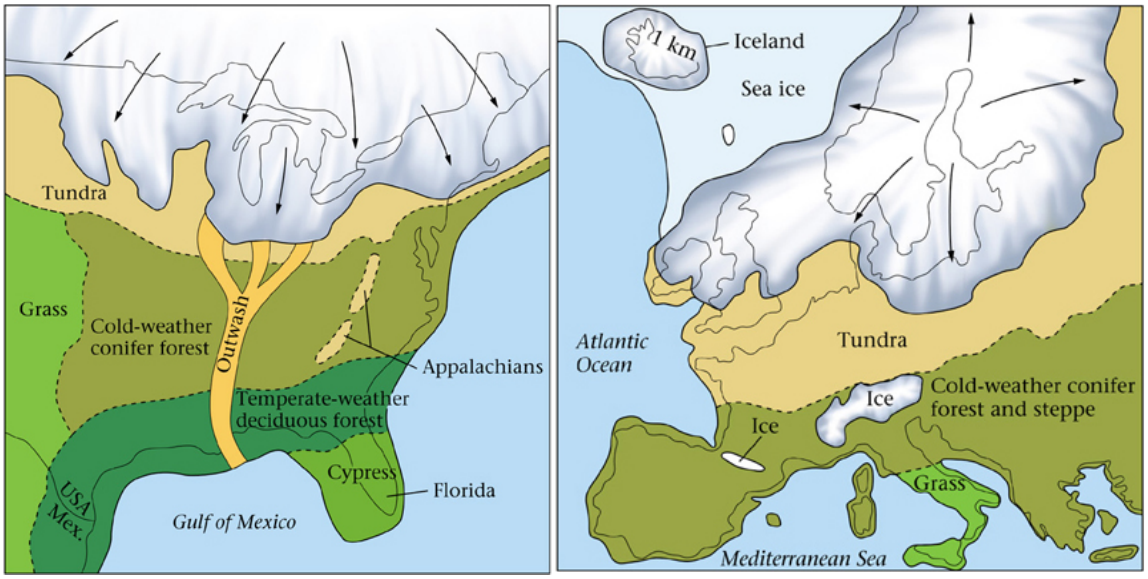
Similar ice sheets throughout the N. hemisphere.



Laurentide/Keewatin ice sheet eventually merged with Greenland ice sheet.
N. American ice sheet: 2-3 km at thickest.
Extended into northern USA.

Pleistocene Ice Age(s)

Climatic Belts

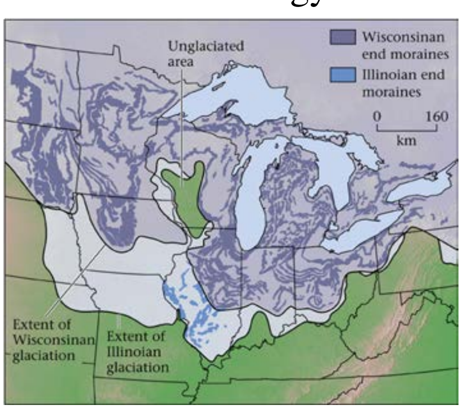


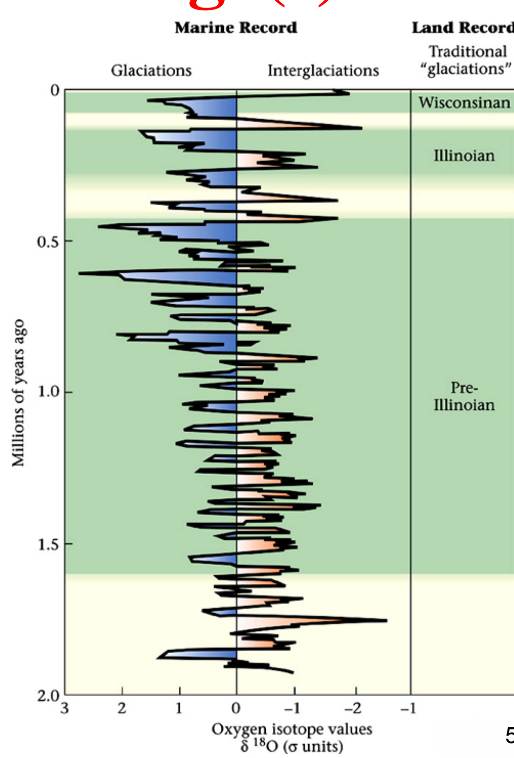
Southern shift of climatic belts

Pleistocene Ice Age(s)

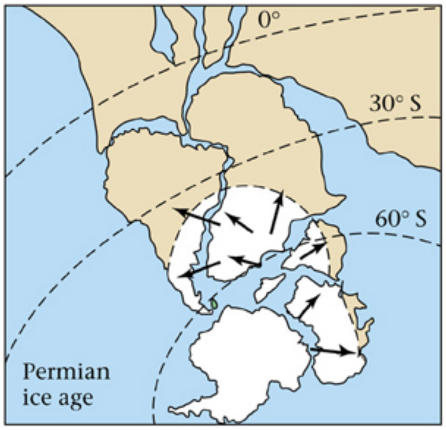
Sediment record demonstrates advance and retreat of glaciers. Marine sediments confirm interglacials (warming periods) occurred during the Pleistocene.

Names used from North American Pleistocene chronology.



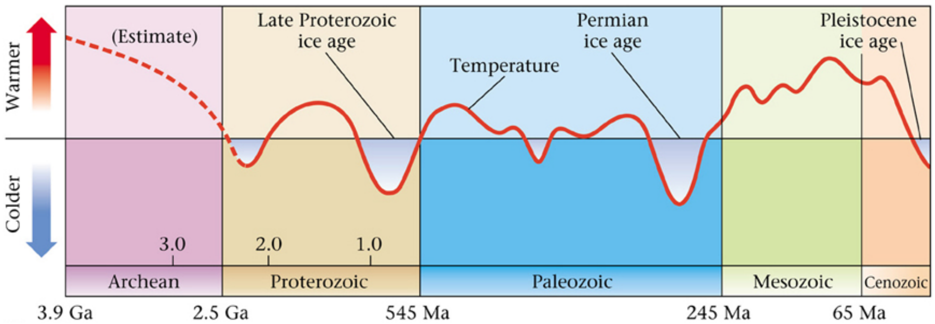


Previous Ice Age(s)



Last major ice age peaked ~18,000 yrs.
Zone of accumulation: Hudson Bay region.
End moraines show the extent of glacial advances.

Preserved as deposits of ***tillite***.
Late Proterozoic tillites appear to be world-wide = ***Snowball Earth***.
Permian ice age = extinction?



Causes of Ice Ages

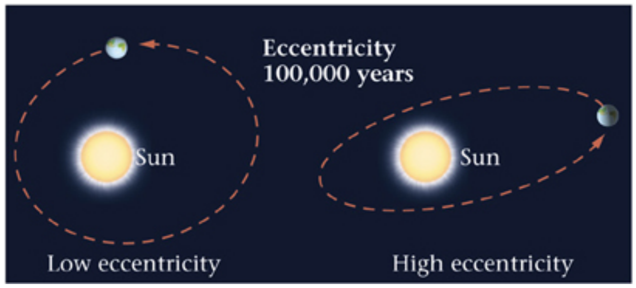
Long Term

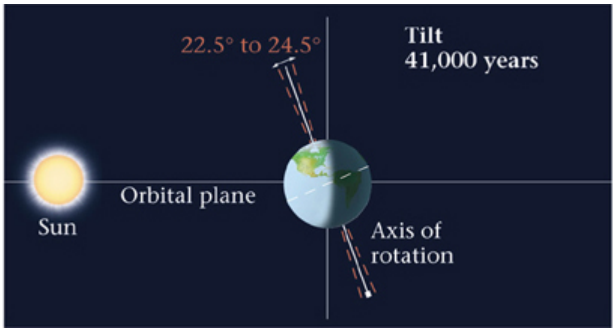
Plate Tectonics: drift to high latitudes;
Continents must be well above sea level;
Ocean currents must be restricted - warm water doesn't move far from the equator.
Greenhouse gas (e.g., CO_2): input to atmosphere (from volcanoes, fossil fuel burning); output from atmosphere (plants; coal/oil formation, shells, limestone deposition, etc.).

Causes of Ice Ages

Milutin Milankovitch studied a number of aspects of Earth's rotation.

Orbital Eccentricity: Earth slowly changes from circular to elliptical orbit in ~100,000 years.

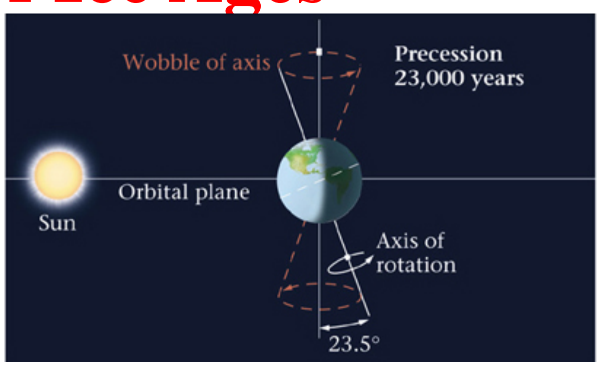


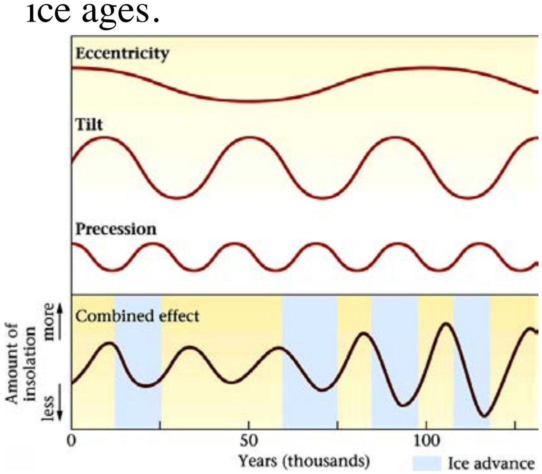


Axis Tilt: Earth's rotational axis is inclined to its orbit around the sun, but this varies between 22.5° to 24.5° over ~41,000 years.

Causes of Ice Ages

Wobble of Earth's Orbit: variations in the Earth's orbit and inclination to the Sun. The Earth's rotational axis is precessing – this may trigger ice ages.





Milankovich Theory - Cycles recorded in tills and from oceanic cores suggest wobbles every 21,000, 41,000, and 100,000 years.

This may account for recent glaciations, but there have been long periods without glaciations.

Ice Age Theories

Other Factors

Positive feedback mechanisms that enhance the processes that cause them.

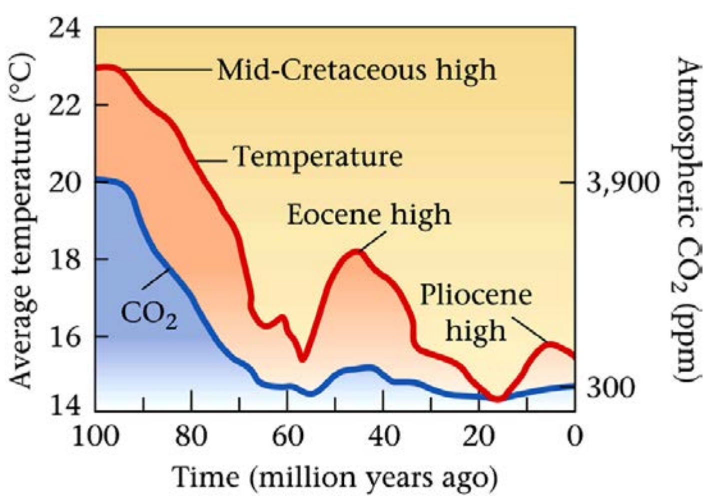
Changing Albedo - loss of the Antarctic ice shelf means more of the suns rays are absorbed.

Interrupting the Global Heat Conveyor: as climate cools, evaporation from the sea decreases so the sea is less salty. This can alter ocean currents and may cut off warm ocean currents to high latitudes. This may also occur with global warming as more freshwater may enter the system due to higher rainfall, also reducing salinity in some parts of the oceans.

Ice Age Theories

Other Factors

Biological Controls on CO_2 Production/Consumption.



Summary

Ice is a Metamorphic Rock.

Ice Formation: Snowflakes, Granular Snow, Firn, Glacial Ice.

Types of Glaciers: Mountain (Alpine); Continental; Temperate; Polar.

Glacial Movement: Wet-Bottomed/Dry-Bottomed Glaciers; Plastic vs. Brittle Deformation; Crevasses; Slope, Thickness, Temperature, Friction.

Growth/Retreat: Zone of Ablation/Accumulation; Equilibrium Line; Flow Trajectory; Meteorite Hunting.

Ice in the Sea: Ice Shelves; Sea Ice; Icebergs (Bergy Bits, Growlers, Castle-bergs); Polynyas, Drop Stones.

Erosion: Proportional to Thickness; Rock Flour, Glacial Striations; Polished Surfaces; Roche Moutonees; Patternoster Lakes.

Landscapes: Horns; Aretes; U-shaped Valleys; Hanging Valleys; Truncated Spurs; Cirques; Tarns; Fjords.

Deposits: Till (Tillite); Erratics; Glacial Marine; Glacial Outwash; Loess; Varved Sediments; Moraines (Lateral, Medial, End, Terminal, Recessional, Ground; Outwash; Kettles/Kettle Lakes; Drumlins; Kames; Kame Terraces; Moulins; Eskers.

Summary (cont.)

Lakes: Glacial; Pluvial.

Sea-Level Changes: Glacial Subsidence; Glacial Rebound; Isostatic Readjustment.

Drainage Patterns.

Periglacial Environments: Permafrost; Patterned Ground;

Pleistocene Ice Age(s): Pleistocene; Holocene; North America; Climatic Belts; Interglacials;

Causes of Ice Ages: Long Term (plate tectonics, Ocean Currents; Greenhouse Gases); Milankovitch Cycles (Orbital Eccentricity, Axis Tilt; Orbit Wobble); Positive Feedback Mechanisms (Changing Albedo, Ocean currents, Biological Controls on CO_2 Production/ Consumption).