GLACIERS AND GLACIATION

Glaciers and Earth's Systems

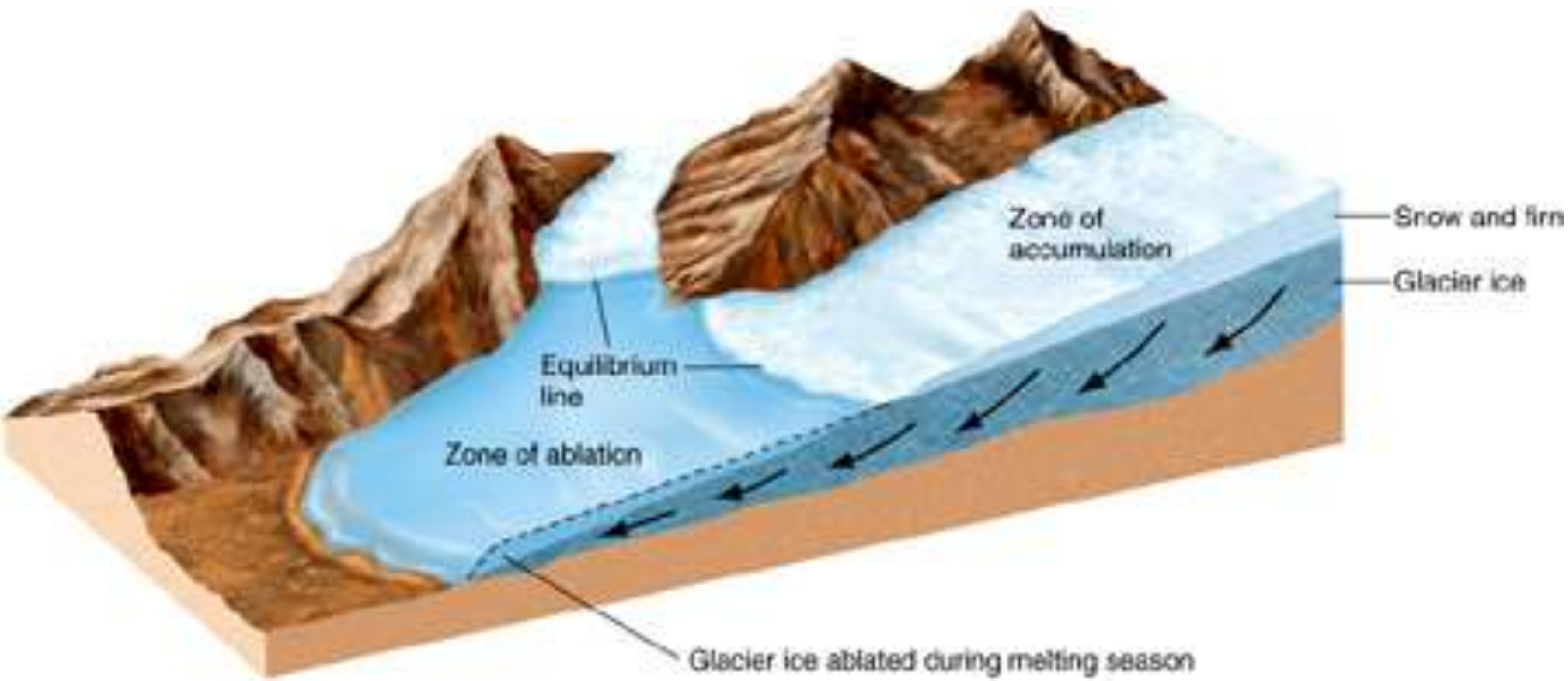
- A *glacier* is a large, long-lasting mass of ice, formed on land, that moves under its own weight
- Glaciers, along with oceans, lakes, and rivers, are part of the Earth's *hydrosphere*
- Along with sea ice, *glaciers* are a portion of the hydrosphere known as the *cryosphere*
- About 75% of the world's supply of fresh water is locked up as glacial ice

GLACIER

- A body of ice
- Formed on land
- Recrystallization of snow
- Evidence of movement
- Alpine glaciation
- Continental glaciation

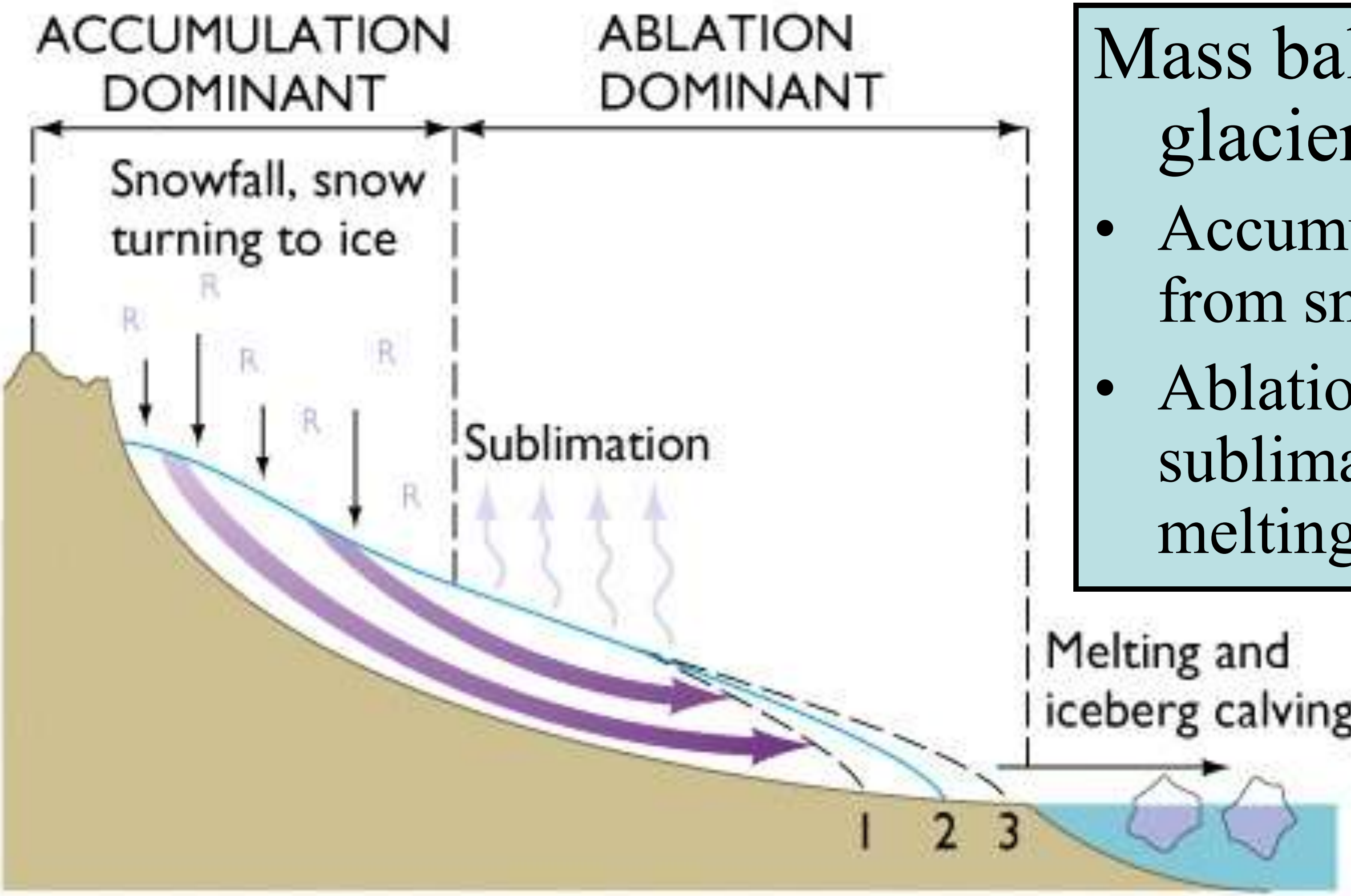
Anatomy of a Glacier

- Snow is added in the *zone of accumulation* of glaciers and melting occurs in the *zone of ablation*
- The *equilibrium line* separates accumulation and ablation zones, and will advance or retreat depending on whether accumulation or ablation dominates



Mass balance in glaciers

- Accumulation from snow to ice
- Ablation by sublimation, melting, calving



GLACIAL BUDGET

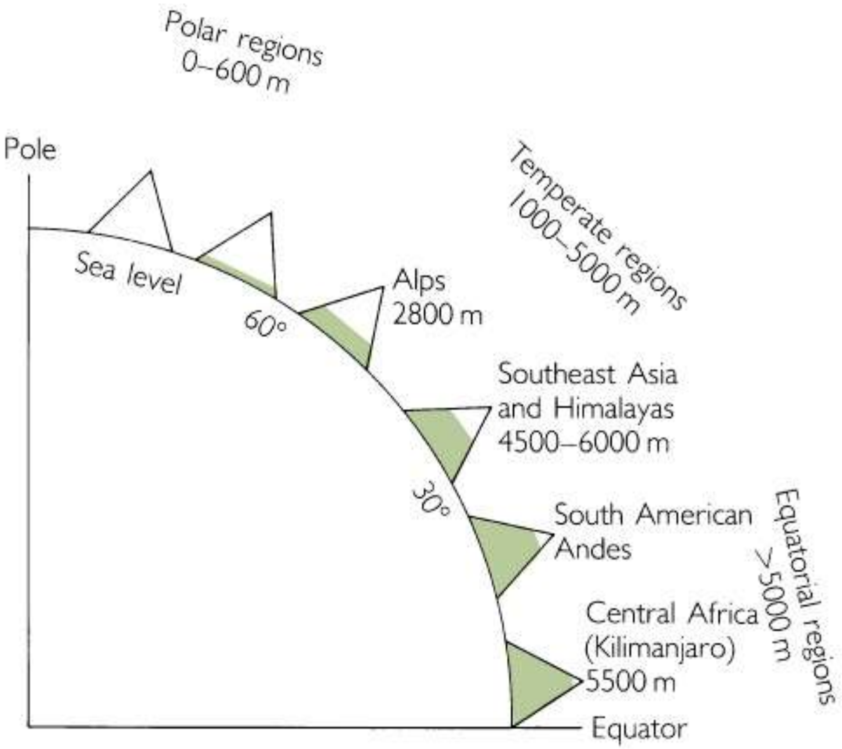
1	Accumulation < ablation	**= retreating**
2	Accumulation = ablation	**= steady state**
3	Accumulation > ablation	**= advancing**

Types of Glaciers

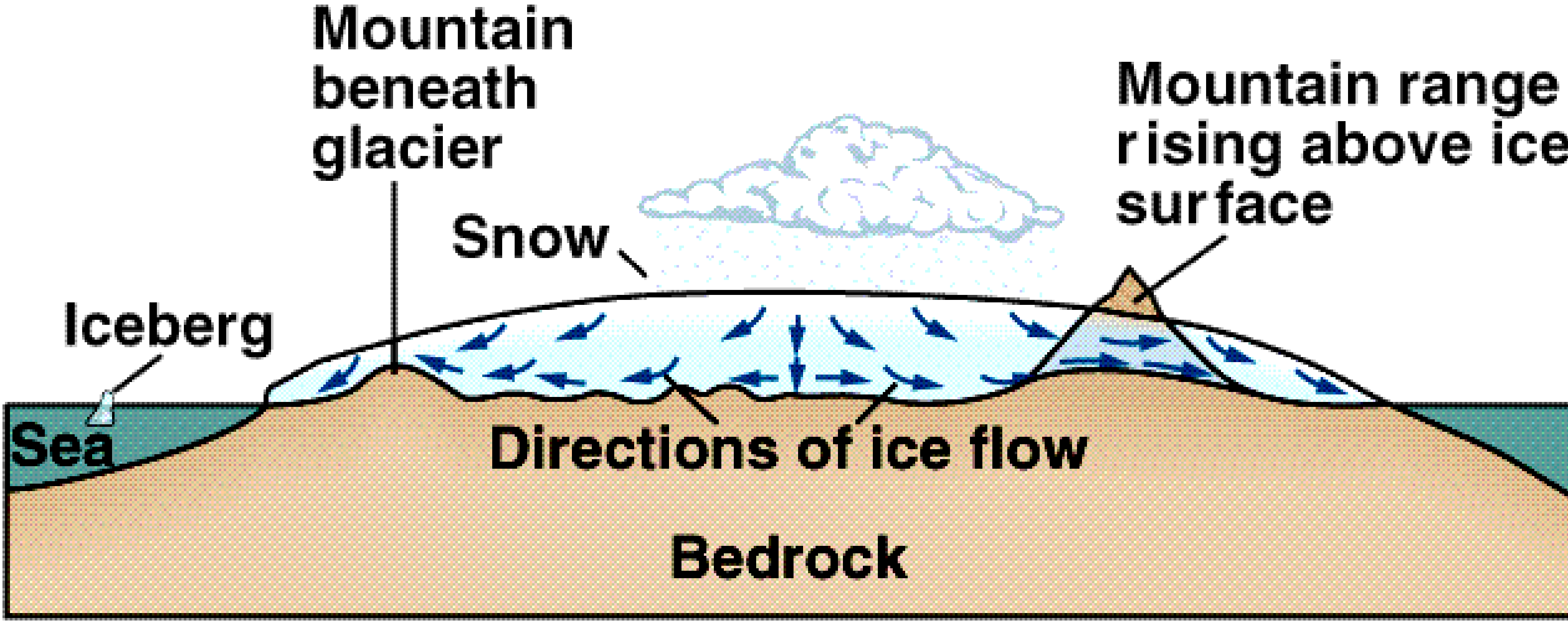
- Valley or Alpine glaciers
- Ice sheet or Continental glaciers
  - Ice cap

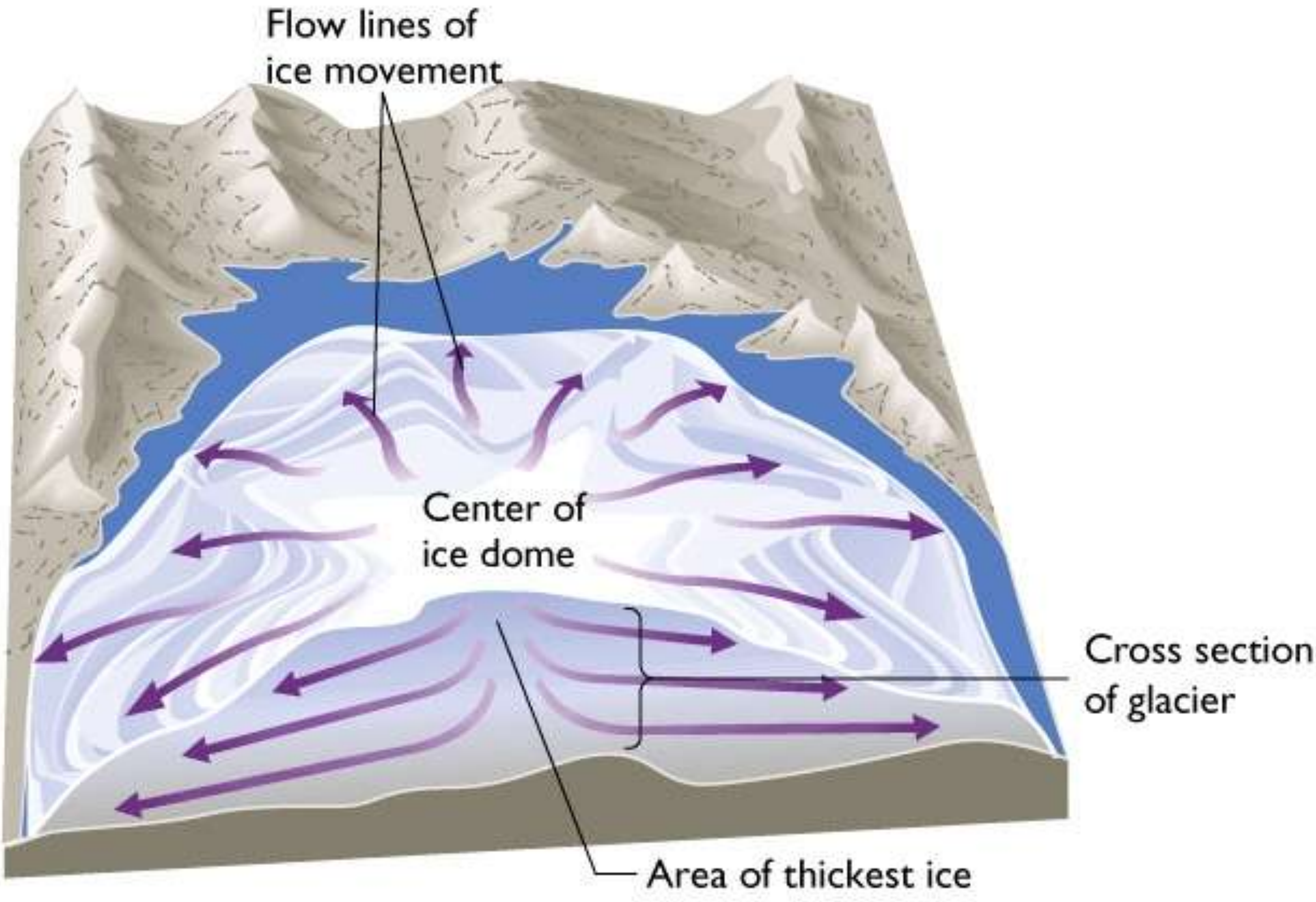
Valley (alpine) and continental glaciers (ice sheet)

- Climate controls distribution



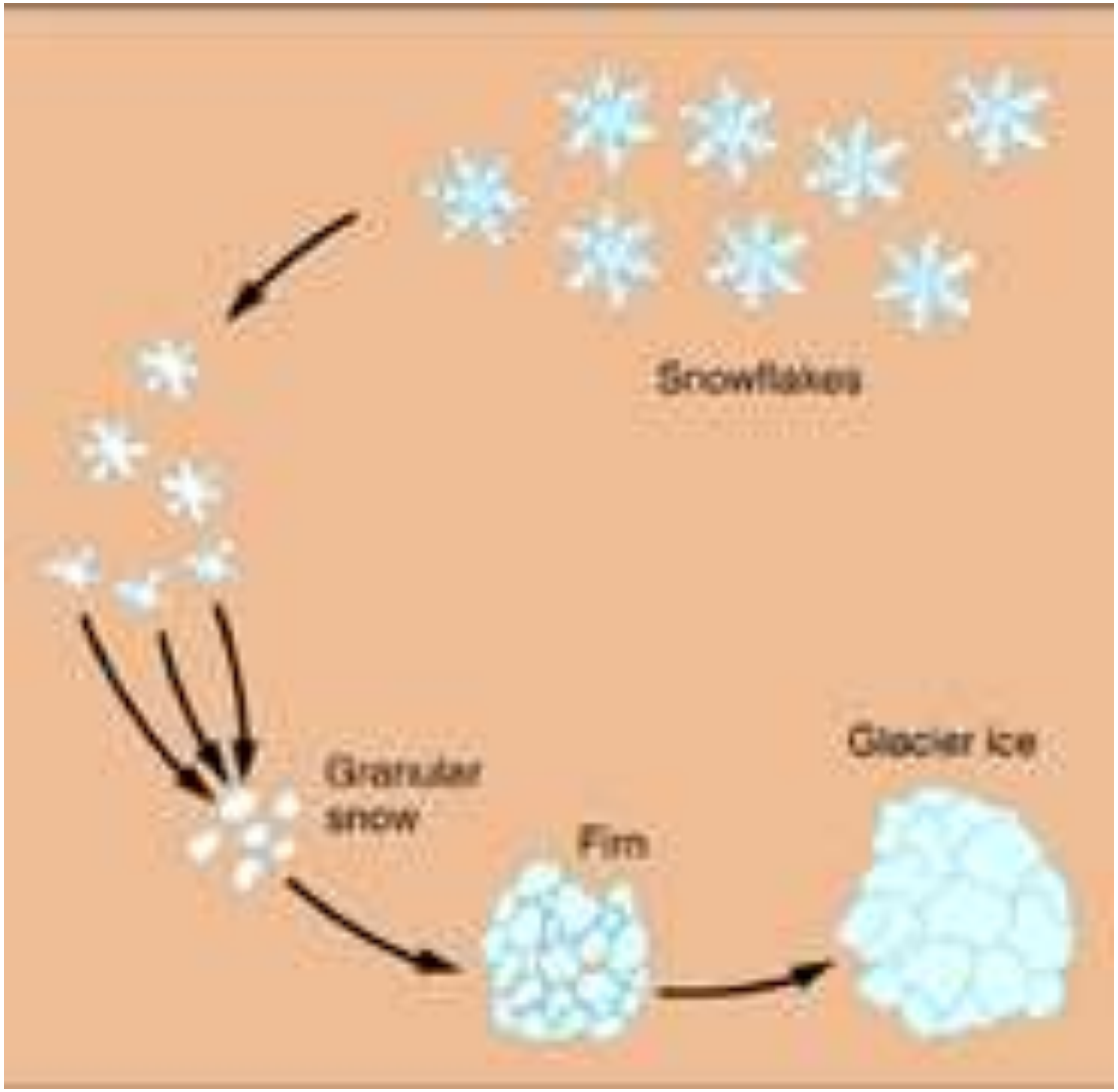
Ice Sheet


Mountain beneath glacier
Mountain range rising above ice surface
Snow
Iceberg
Sea
Directions of ice flow
Bedrock


Flow lines of ice movement
Center of ice dome
Cross section of glacier
Area of thickest ice

Formation of Glaciers

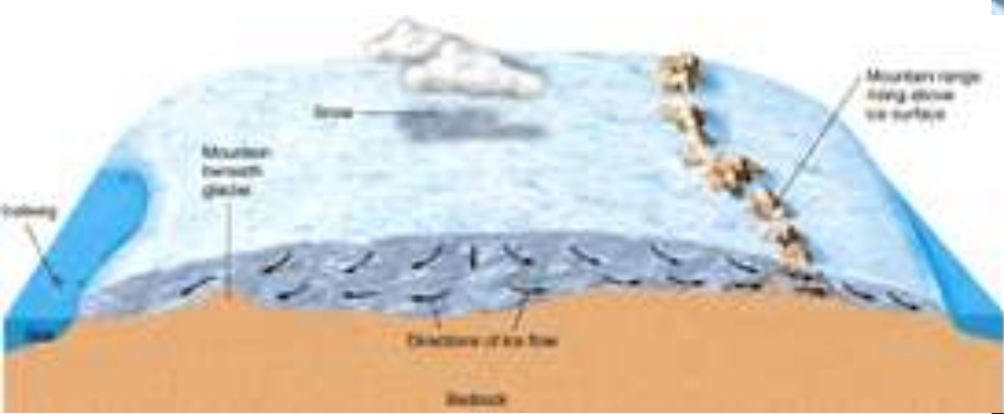
- Glaciers develop as *snow* is compacted and recrystallized, first into *firn* and then *glacial ice*
- A glacier can only form where *more snow accumulates during the winter than melts away* during the spring and summer



Formation of Glaciers

Two types of glaciated terrains on Earth:

- *Alpine glaciation* occurs in mountainous regions in the form of *valley glaciers*
- *Continental glaciation* covers large continental masses in Earth's polar regions in the form of *ice sheets*
- Both types occur in areas cold enough to allow accumulated snow to *persist from year to year*

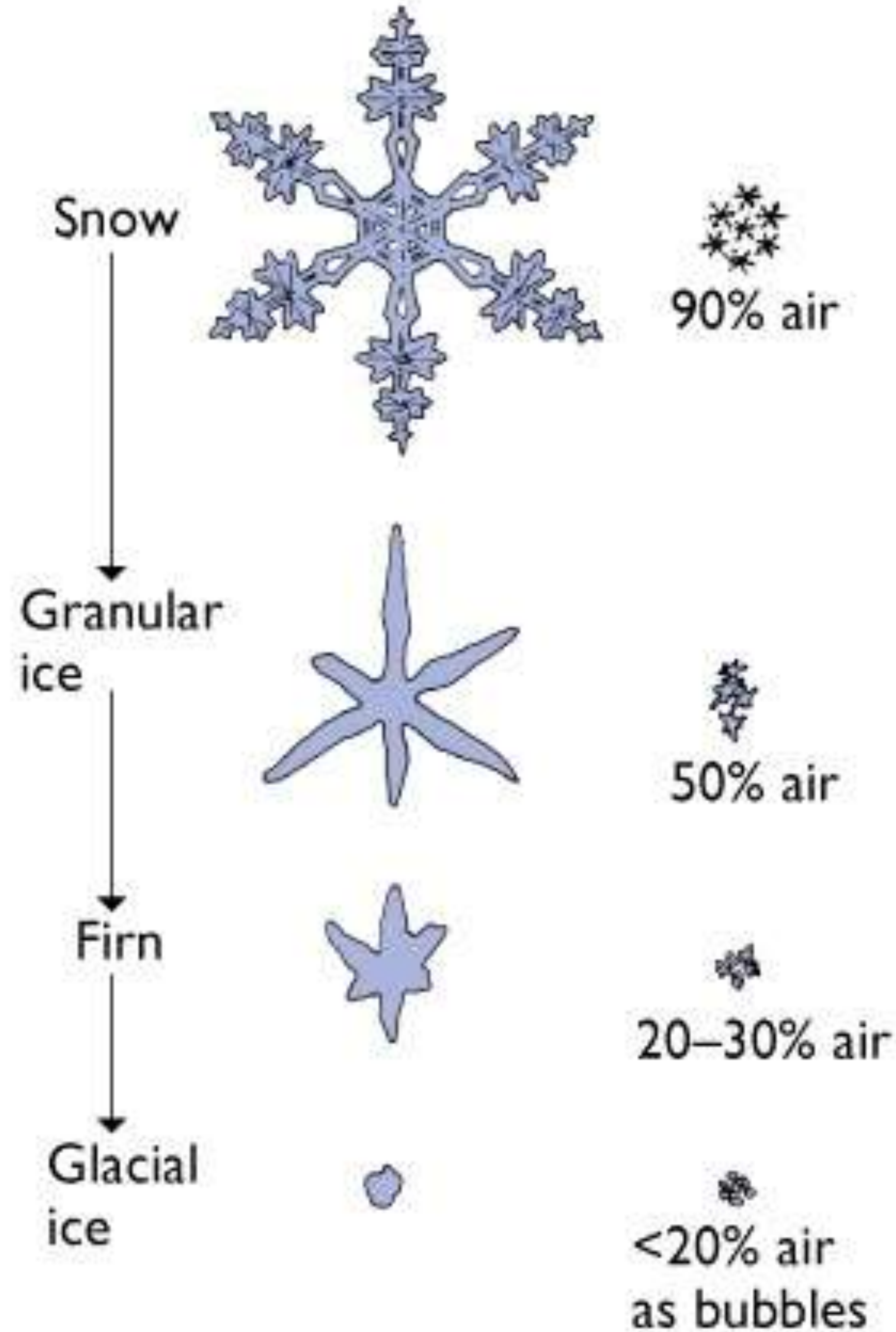


Formation and Growth of Glaciers

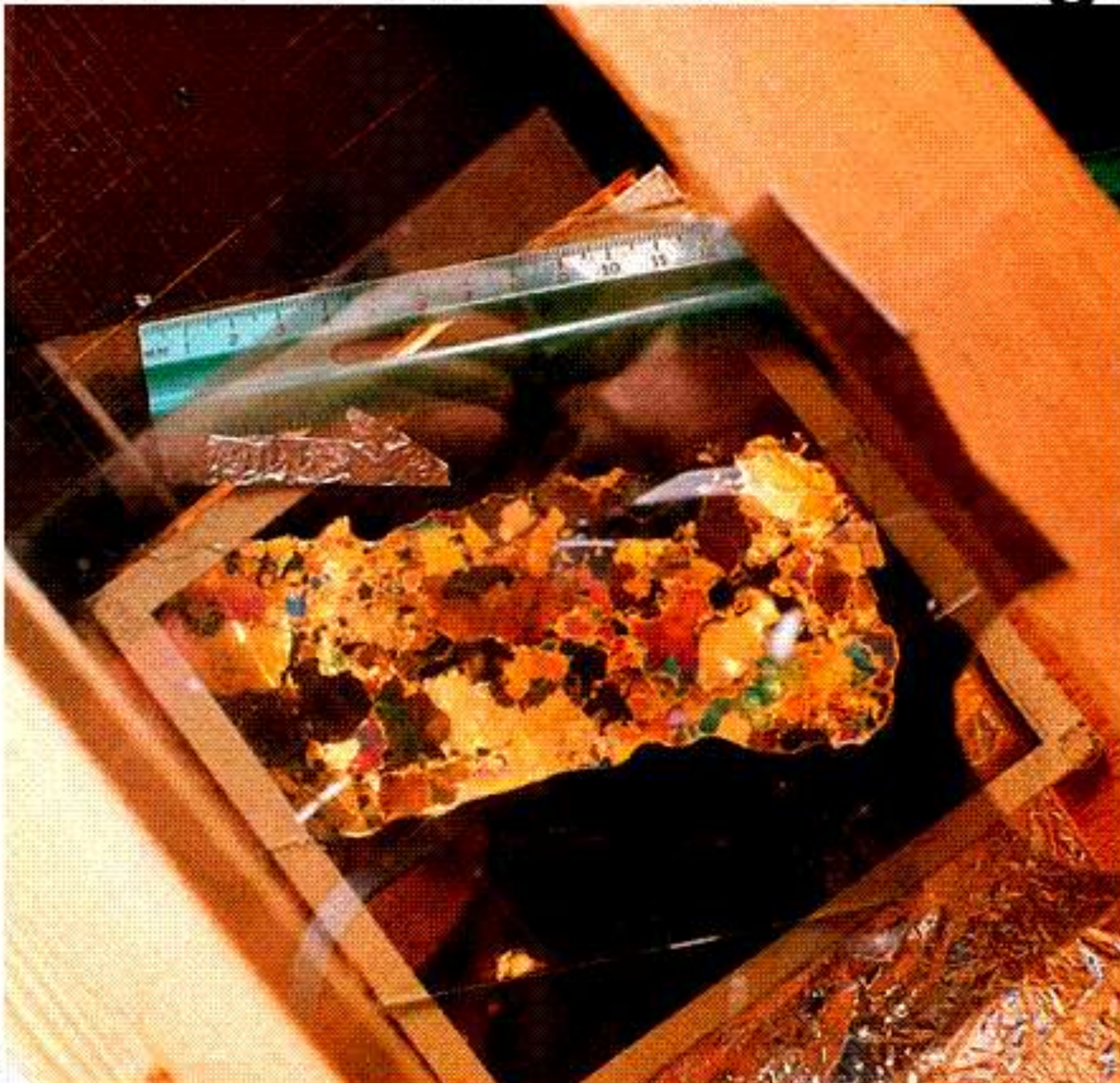
- Snow to *firn* to *glacier ice*
- Wastage (or ablation)
  - Melting, evaporation,
  - Calving into icebergs
- Glacial Budgets
  - Negative budget- *Receding glacier*
  - Positive budget- *Advancing glacier*
  - Zone of *accumulation;* Zone of *wastage*
    - *Snow line*- divides the zones
  - *Terminus*- movement reflects budget

Formation of glacial ice

- Requires:
  net accumulation of ice from snow (climate)
- Compaction "lithifies" snow (makes glacial ice) by squeezing out air due to reorientation and recrystallization
- *Compare with diagenesis of sediments*



Glacier Ice in Polarized Light

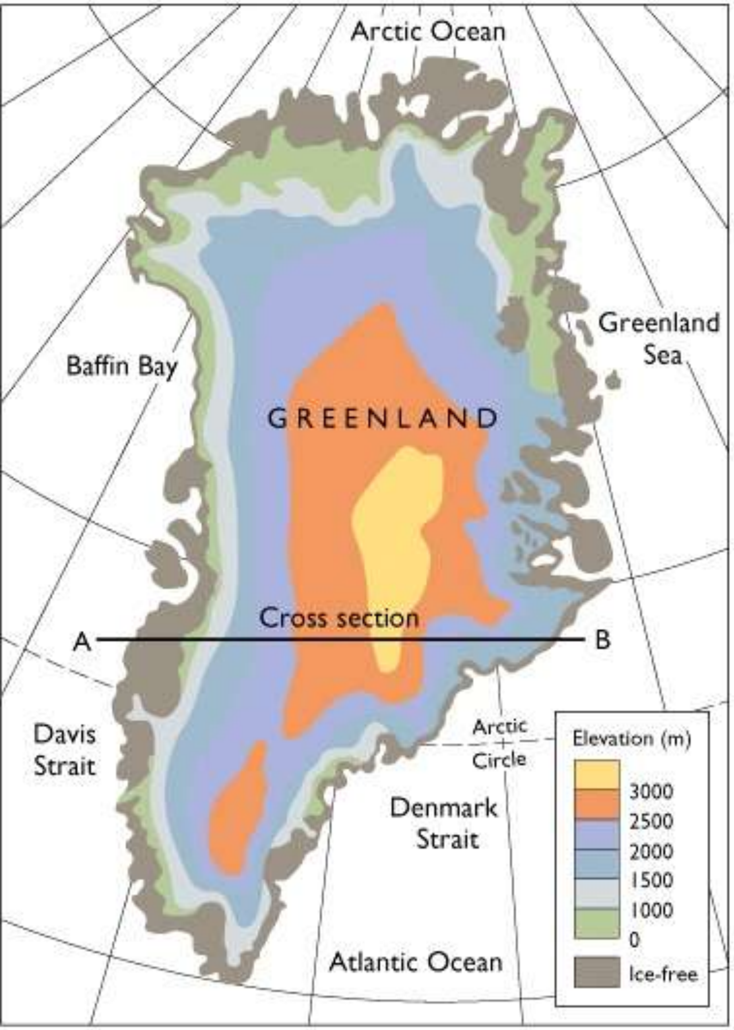


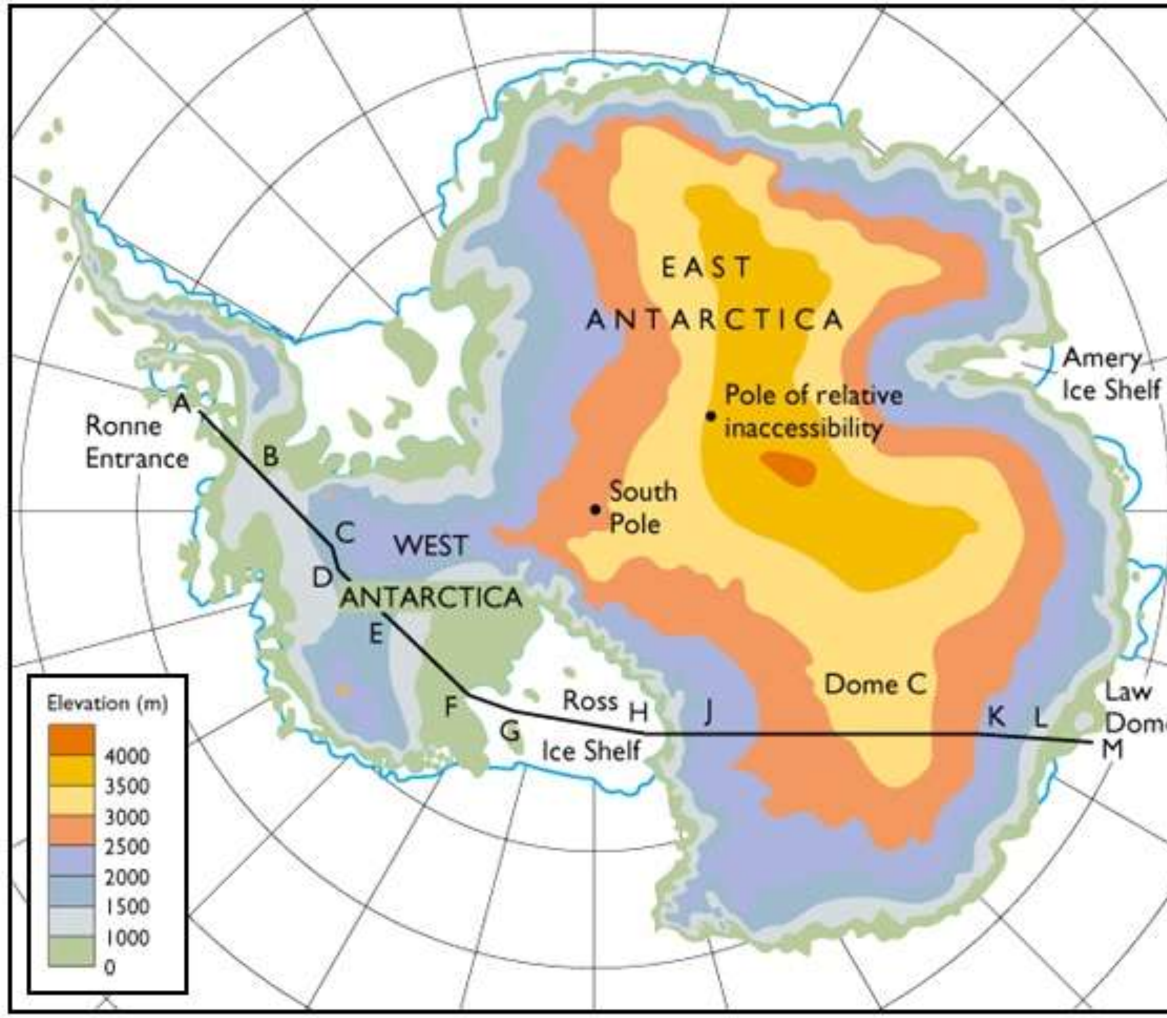
B

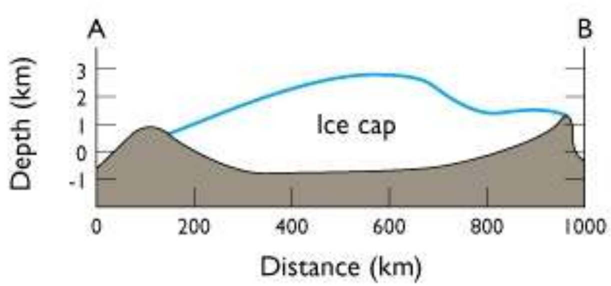
GLACIERS

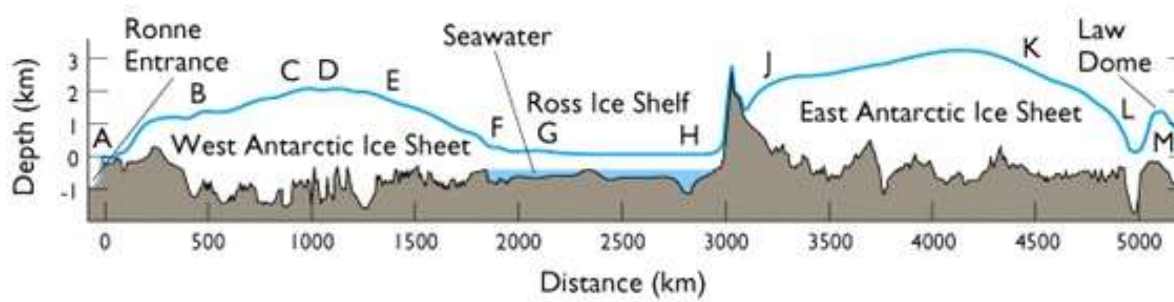
- Advancing vs. Receding Glaciers
- Zone of accumulation
  - Where some snow remains after the melt season
- Zone of Wastage
  - Where all snow & some glacier melt
- Advancing glacier-
  - positive budget - terminus (end) moves forward
- Receding glacier
  - negative budget - terminus (end)retreats
- Glacier always moving downslope

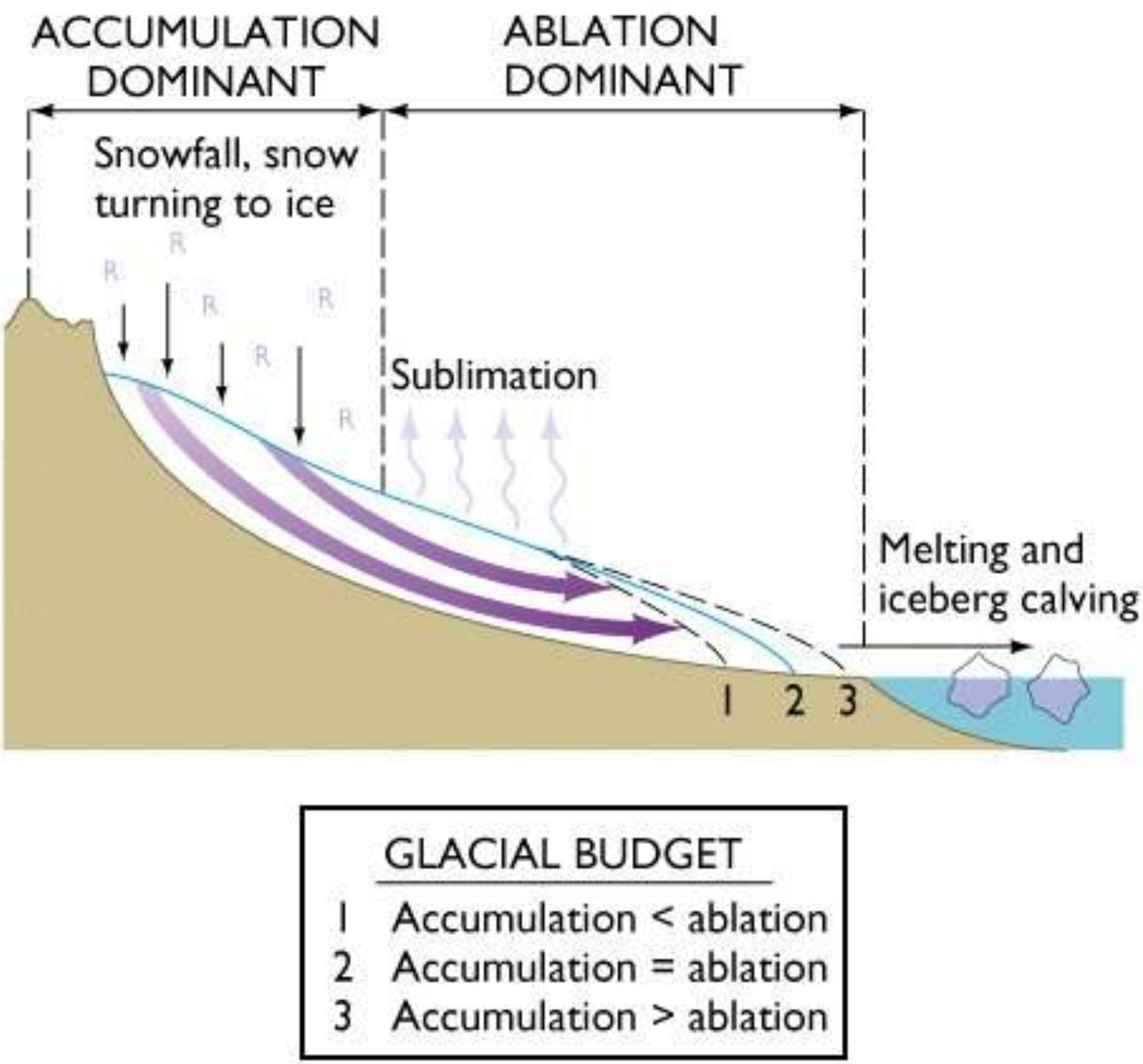
Modern Ice Caps







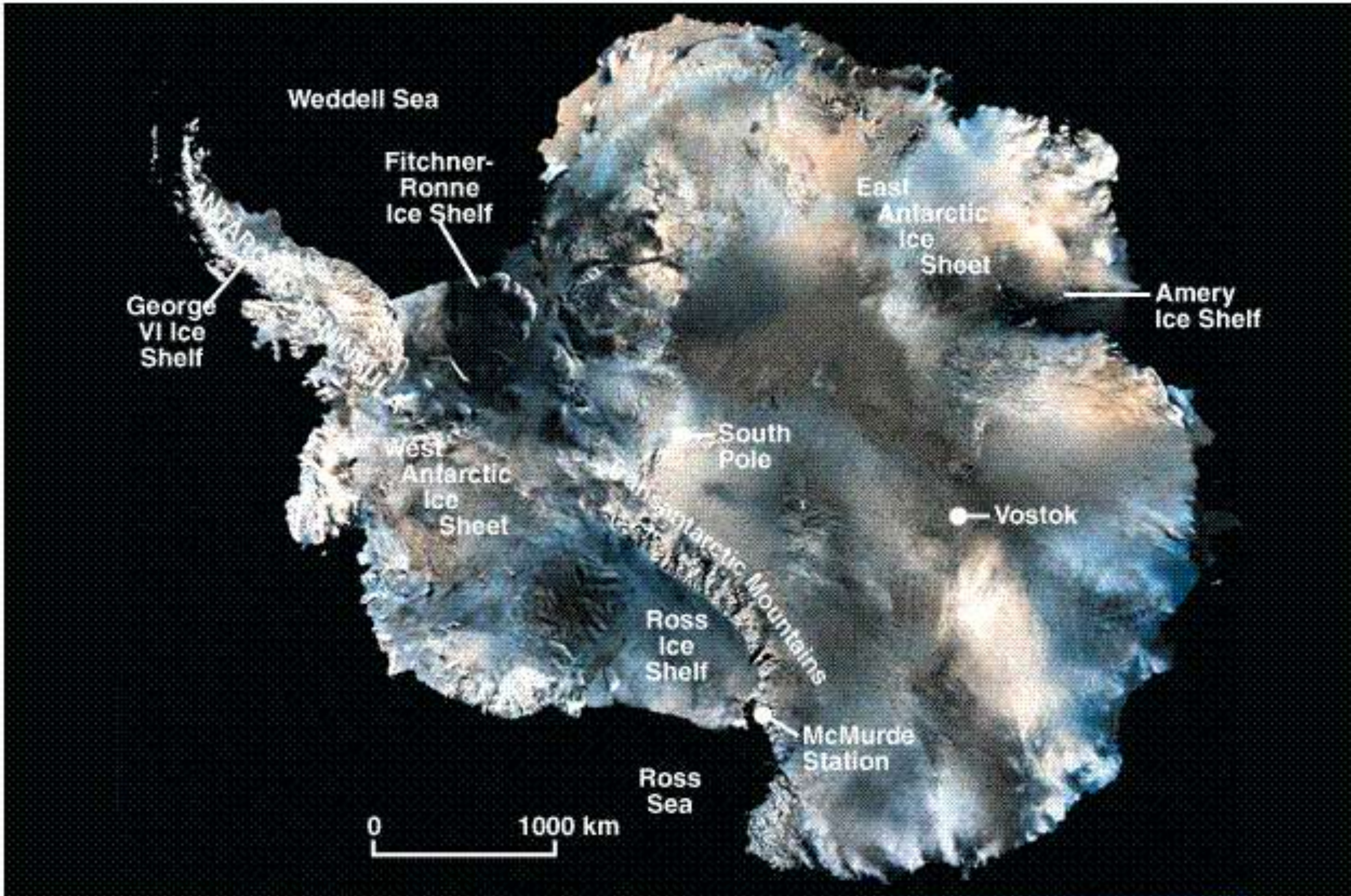




Antarctica

- Blue ice (sky color)—so clean because it came from depth
- Abundant meteorites, including Martian Alan Hills

Antarctic Ice Sheets



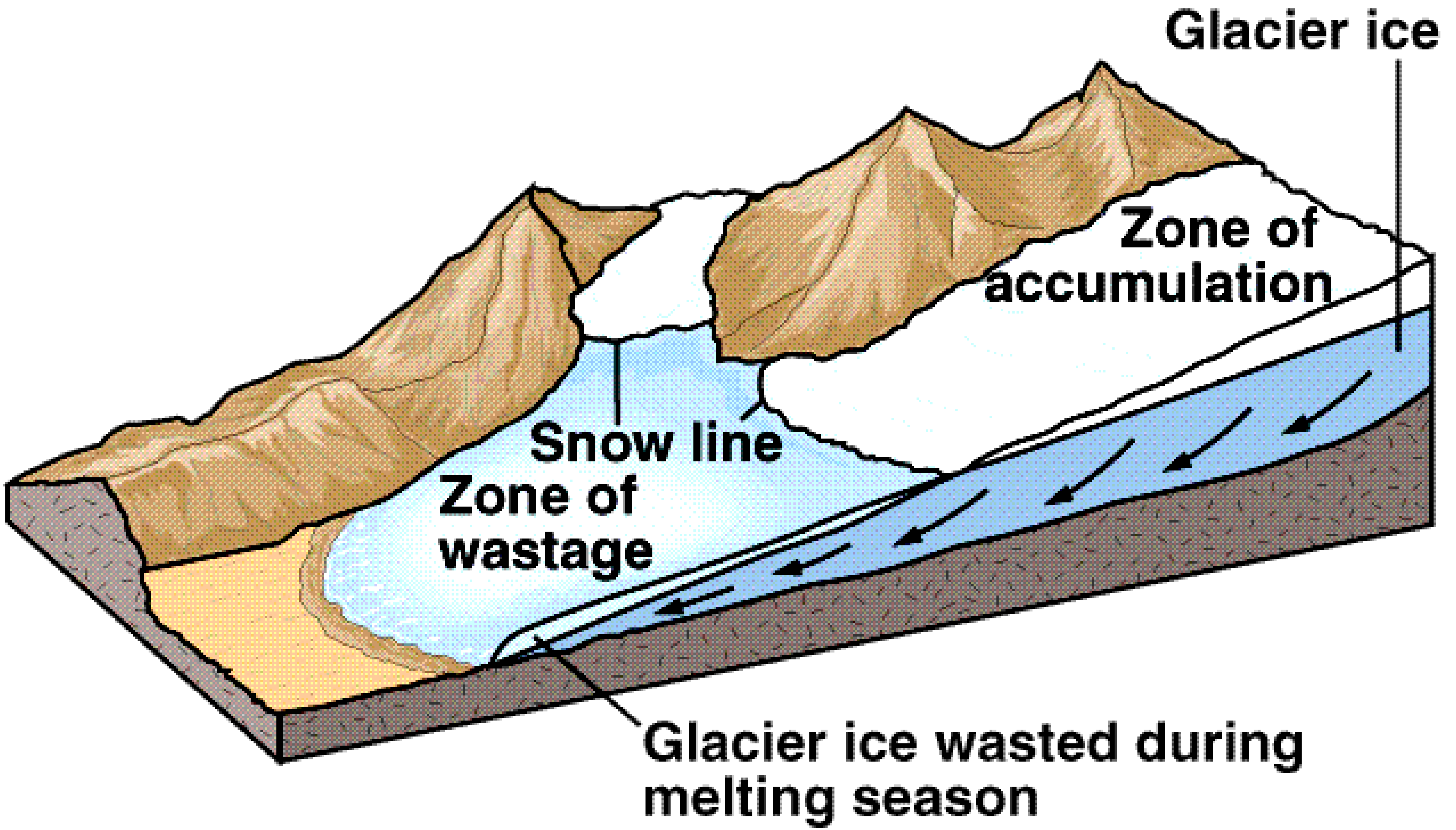
The South Pole

Antarctic Iceberg

Calving — loss of ice into the sea and formation of icebergs

- Ice moving out into water spalls off creating icebergs
- From being unsupported
- An ice shelf can become unstable and fall apart very quickly
- West Antarctica and Ross Ice Shelf

Glacier Wastage

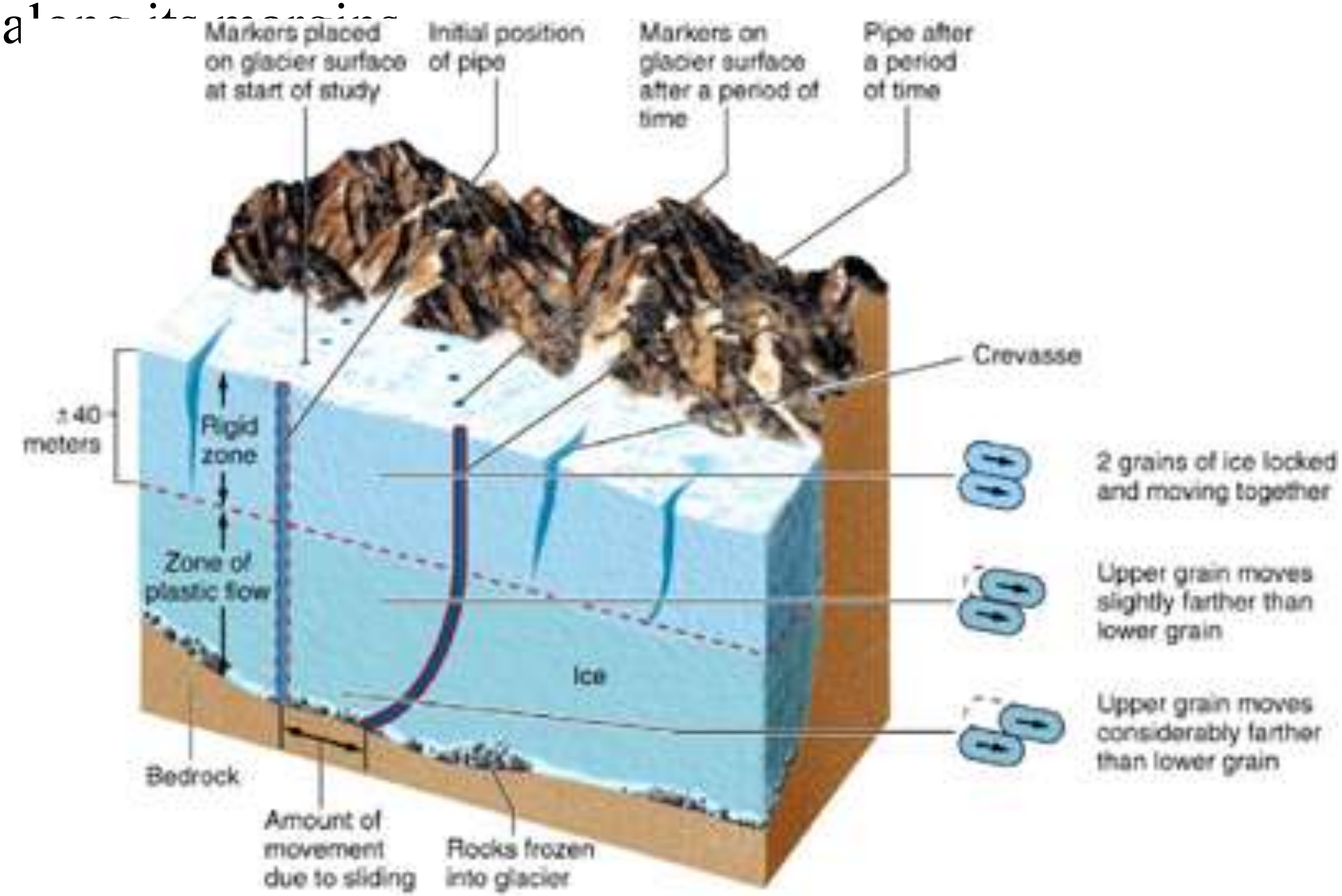


GLACIERS

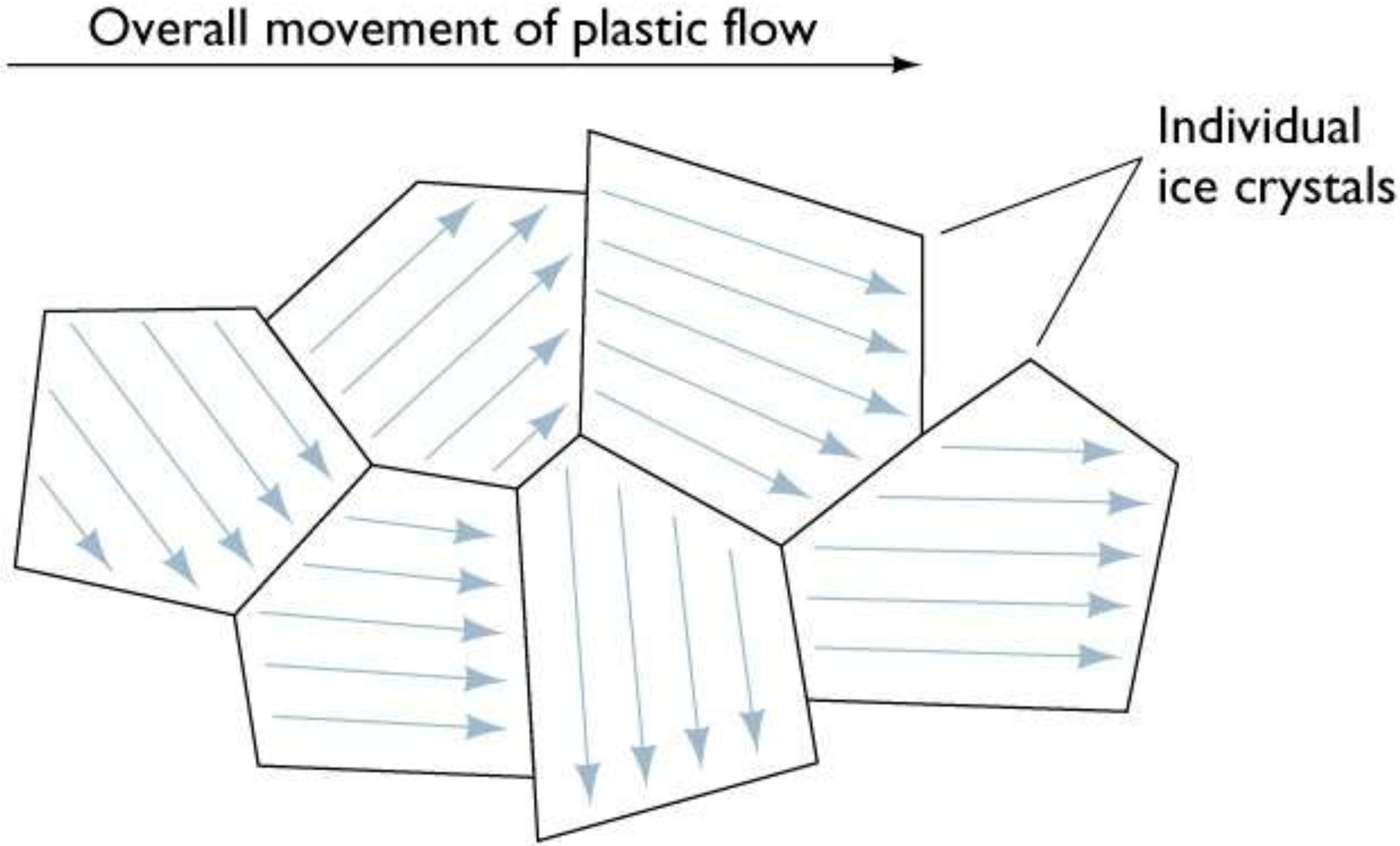
- Wastage of glaciers (“shrinkage”)
  - Melting
    - more melting at lower elevations
  - Evaporation
  - Calving into Icebergs
    - where a glacier flows onto a sea

Movement of Glaciers

Due to friction between the glacial ice and the valley sides and floor, valley glacier flow is fastest at the top center of a glacier and slowest along its margins.



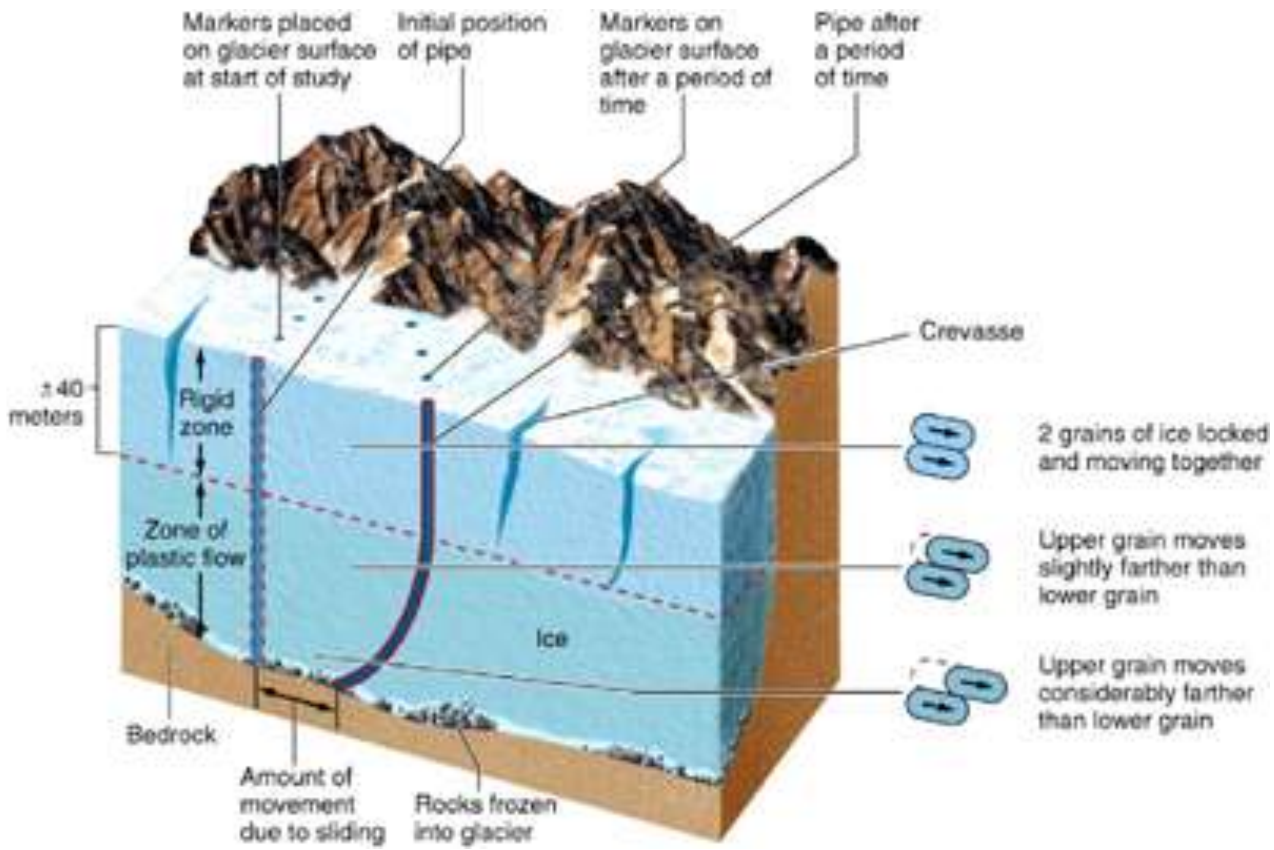
Plastic flow mechanism



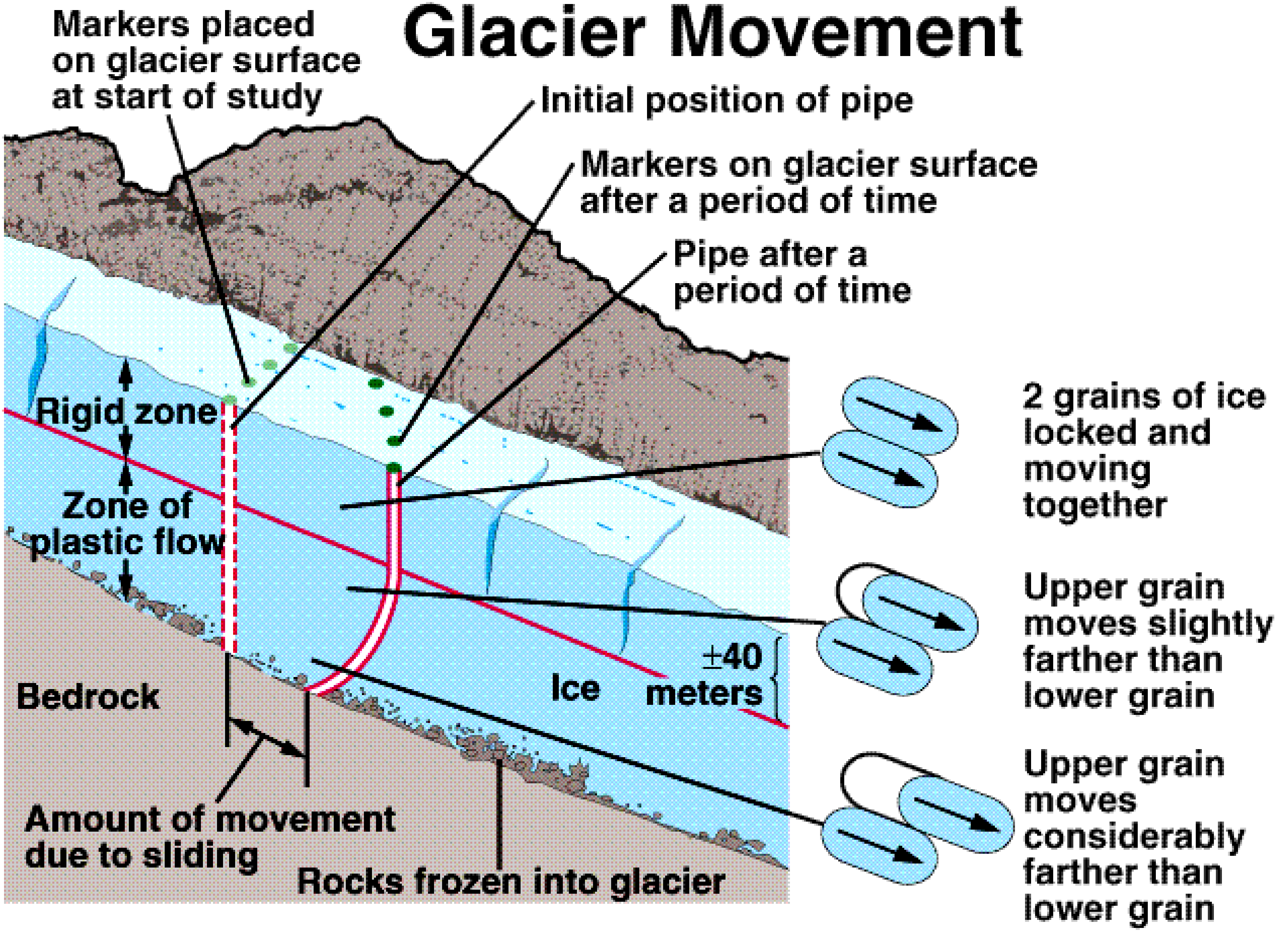
- As recrystallization proceeds with depth, individual crystals become more aligned
- Predominates in cold, dry regions--ice mostly frozen to ground

Movement of Glaciers

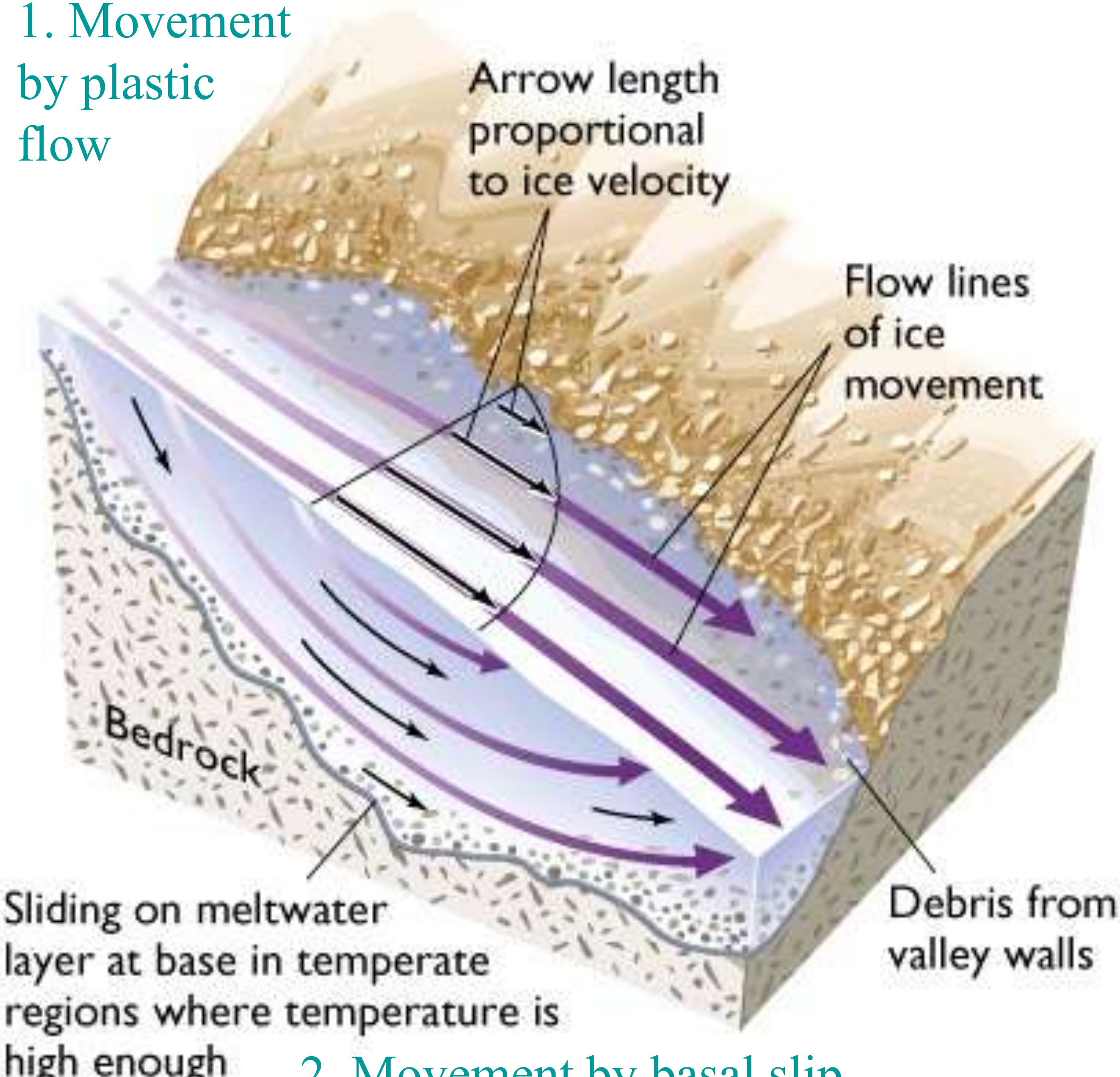
- Valley glaciers and ice sheets move downslope under the force of *gravity*
- Movement occurs by *basal sliding* and *plastic flow* of the lower part of the glacier, and passive "riding along" of an overlying *rigid zone*
  - *Crevasses* are fractures formed in the upper rigid zone during glacier flow



Glacier Movement



1. Movement by plastic flow

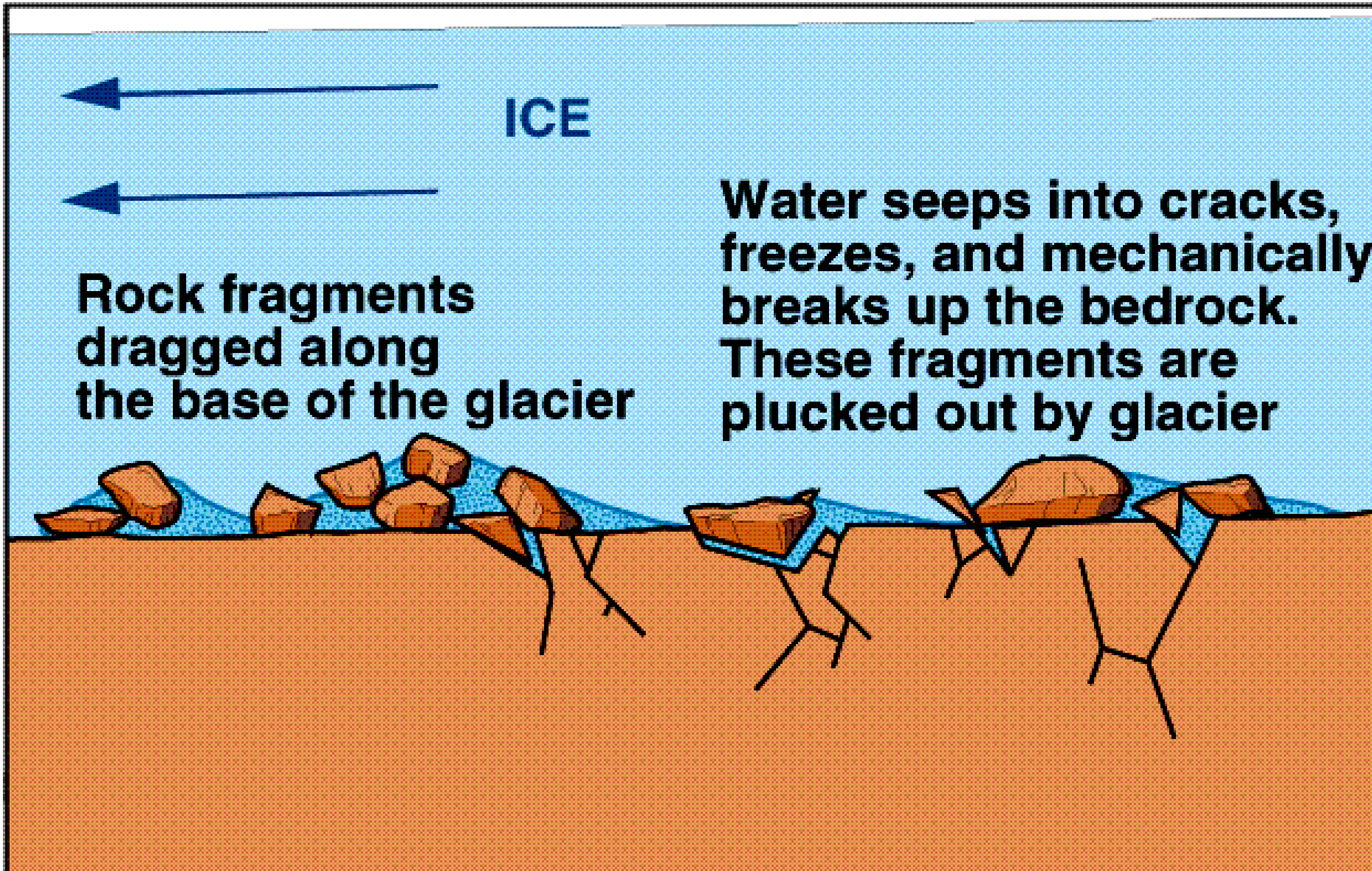


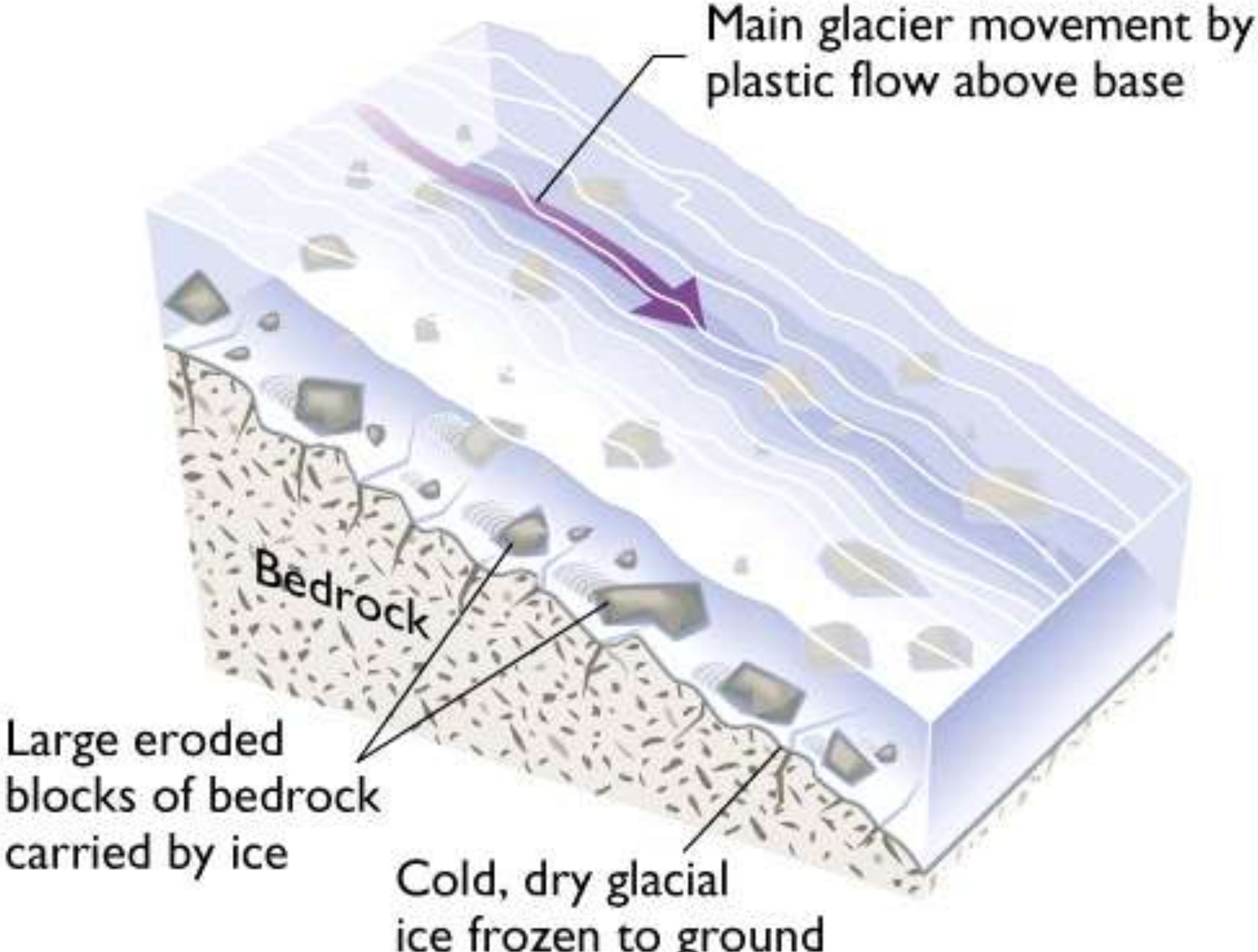
2. Movement by basal slip

Movement of Glaciers

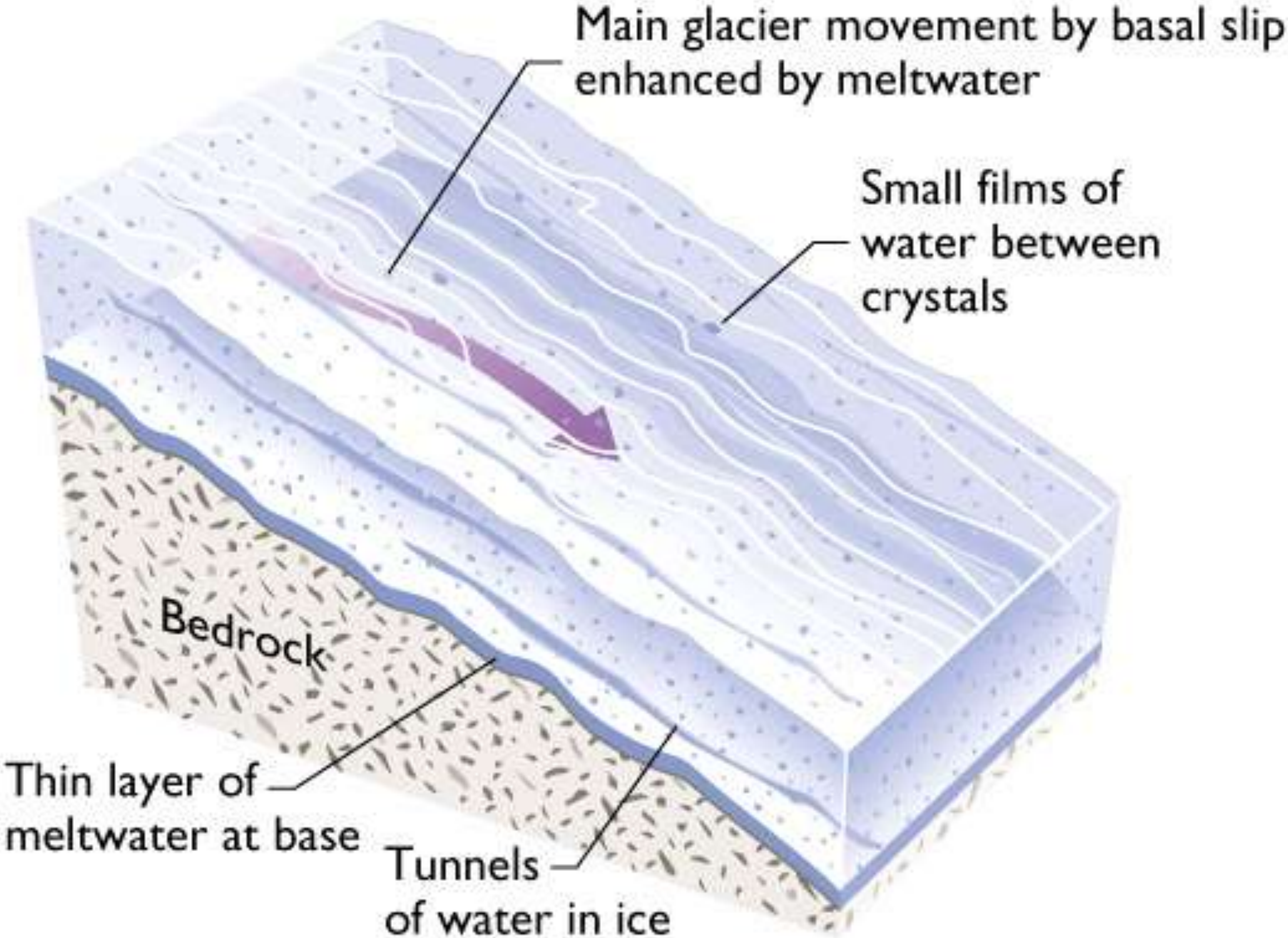
- Valley Glaciers
  - Gravity driving force
  - Sliding along its base -*basal sliding*
  - Internal flowage- *plastic flow*
  - *Rigid zone*
    - Crevasses may form here
- Ice sheets
  - Move downward & outward from central high

Plucking and Abrasion beneath Glacier



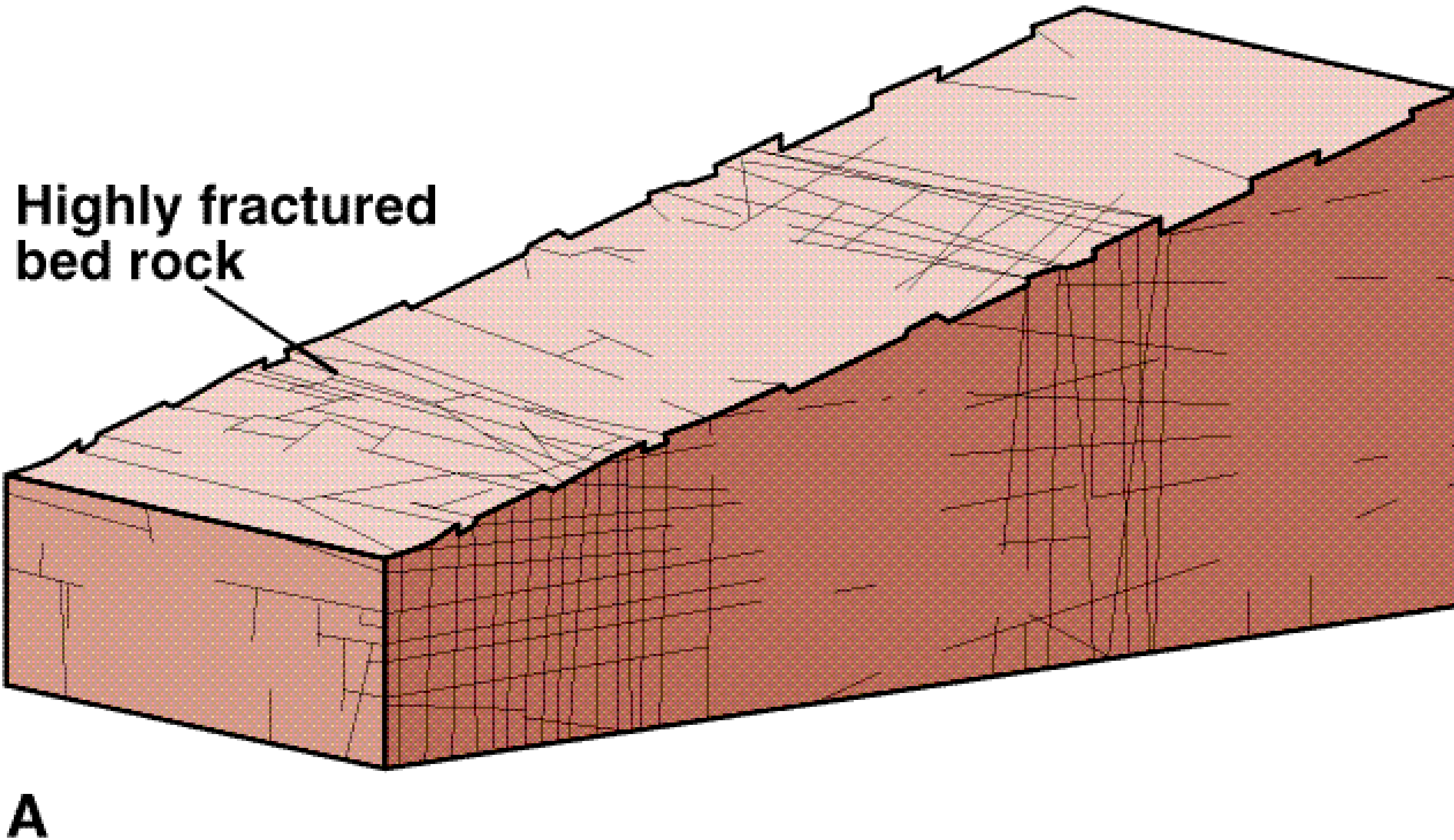


Cold, dry glacier

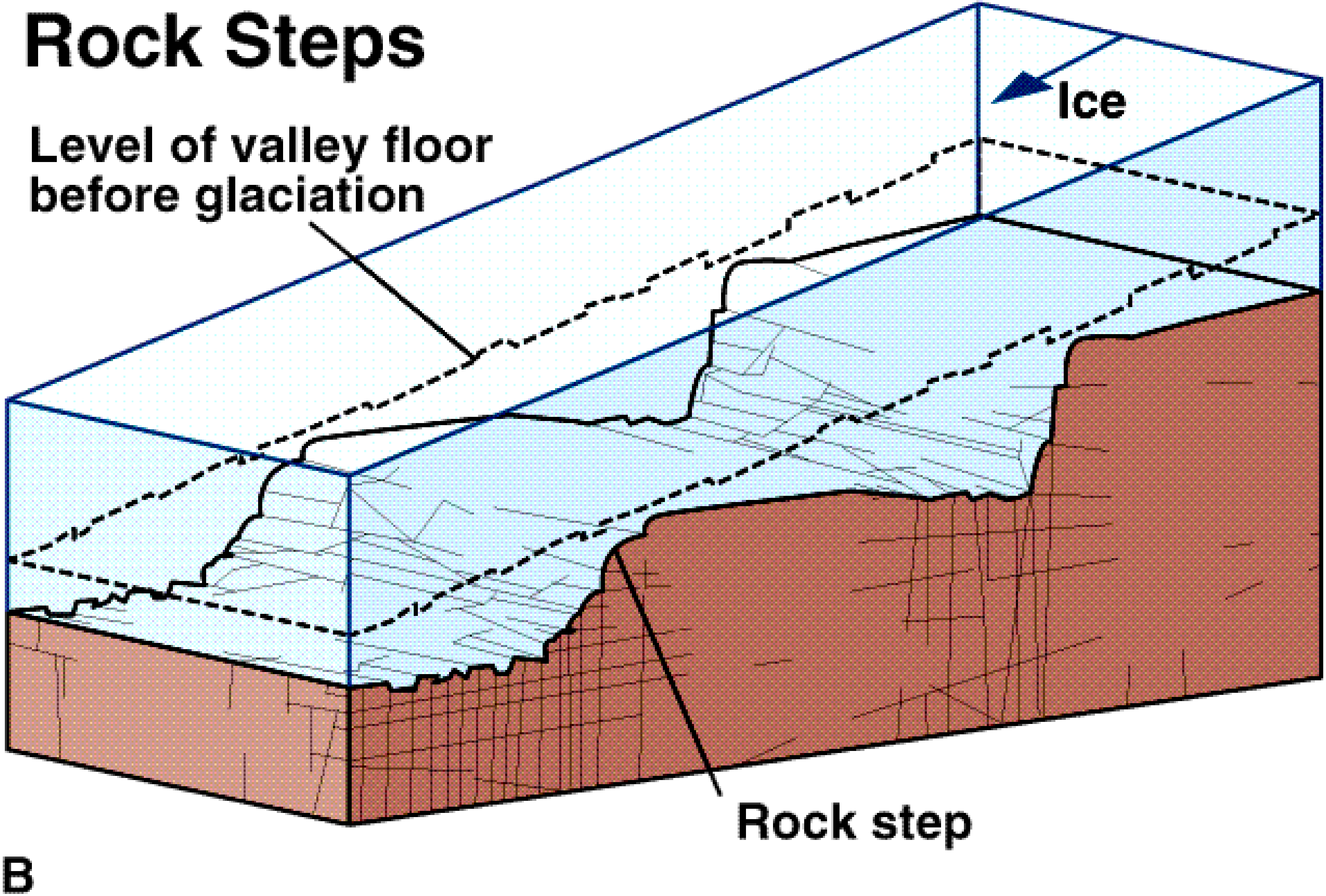

Main glacier movement by basal slip enhanced by meltwater
Small films of water between crystals
Bedrock
Thin layer of meltwater at base
Tunnels of water in ice

Wet glacier

Valley Floor before Glaciation



Glaciation and Creation of Rock Steps

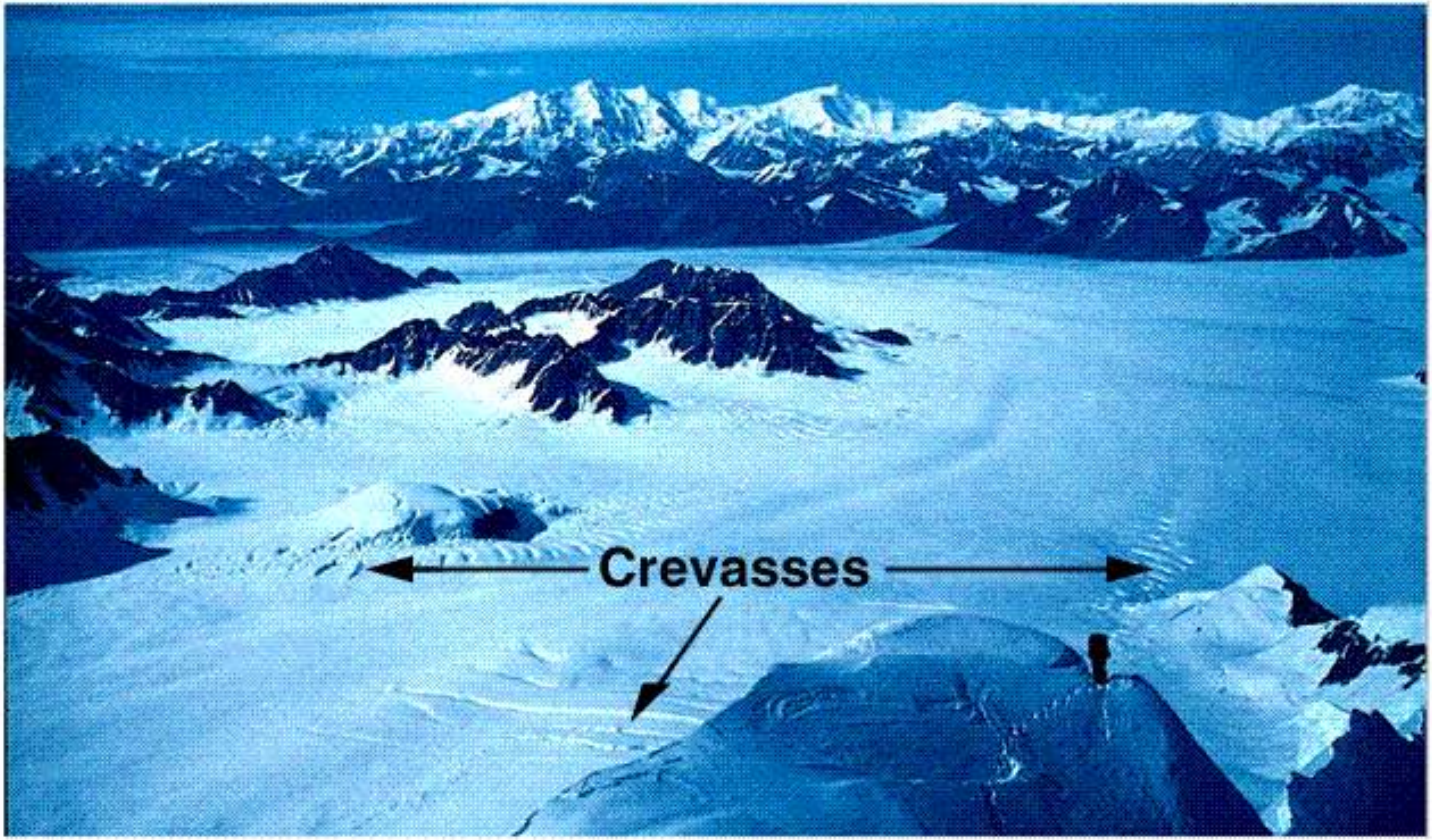


Glaciers-Where they are

- Develop where all of annual snow doesn't melt away in warm seasons
  - Polar regions
  - Heavy winter snowfall
  - High elevations
  - 85% in Antarctica
  - 10% in Greenland

Glacial Striation

Crevasses on Glacier

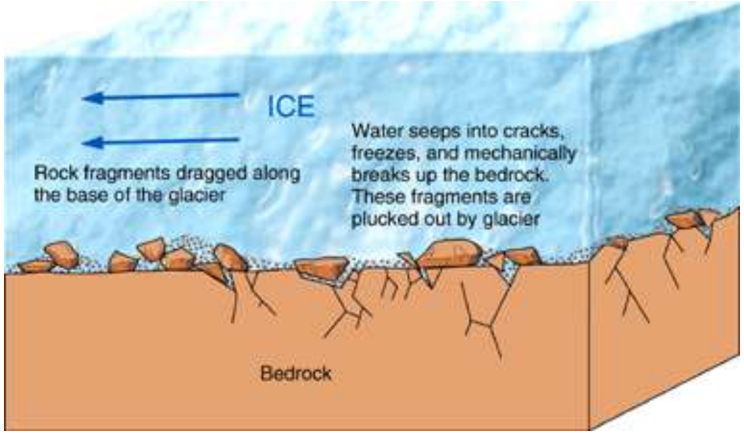


Crevasses — the brittle surface of glaciers

- Form where the ice flow bends around or over something

Glacial Erosion

- Glaciers erode underlying rock by *plucking* of rock fragments and *abrasion* as they are dragged along
  - Basal abrasion *polishes* and *striates* the underlying rock surface and produces abundant fine rock powder known as *rock flour*



Erosional Landscapes Associated with Alpine Glaciation

- Glacial valleys
  - U-shaped valleys
  - Hanging valleys
  - Truncated spurs
    - Triangular facets
  - Rock -basin lakes (tarns)
  - Rounded knobs- *rouche moutonnees*

Glacially Carved Valley, Yosemite National Park

Erosional Landscapes

- Erosional landforms produced by valley glaciers include:
  - *U-shaped valleys*
  - *Hanging valleys*
    - Smaller tributary glacial valleys left stranded high above more quickly eroded central trunk valleys

Erosional Landscapes

- Erosional landforms produced by valley glaciers include:
  - *Cirques*
    - Steep-sided, half-bowl-shaped recesses carved into mountains at the heads of a glacial valleys

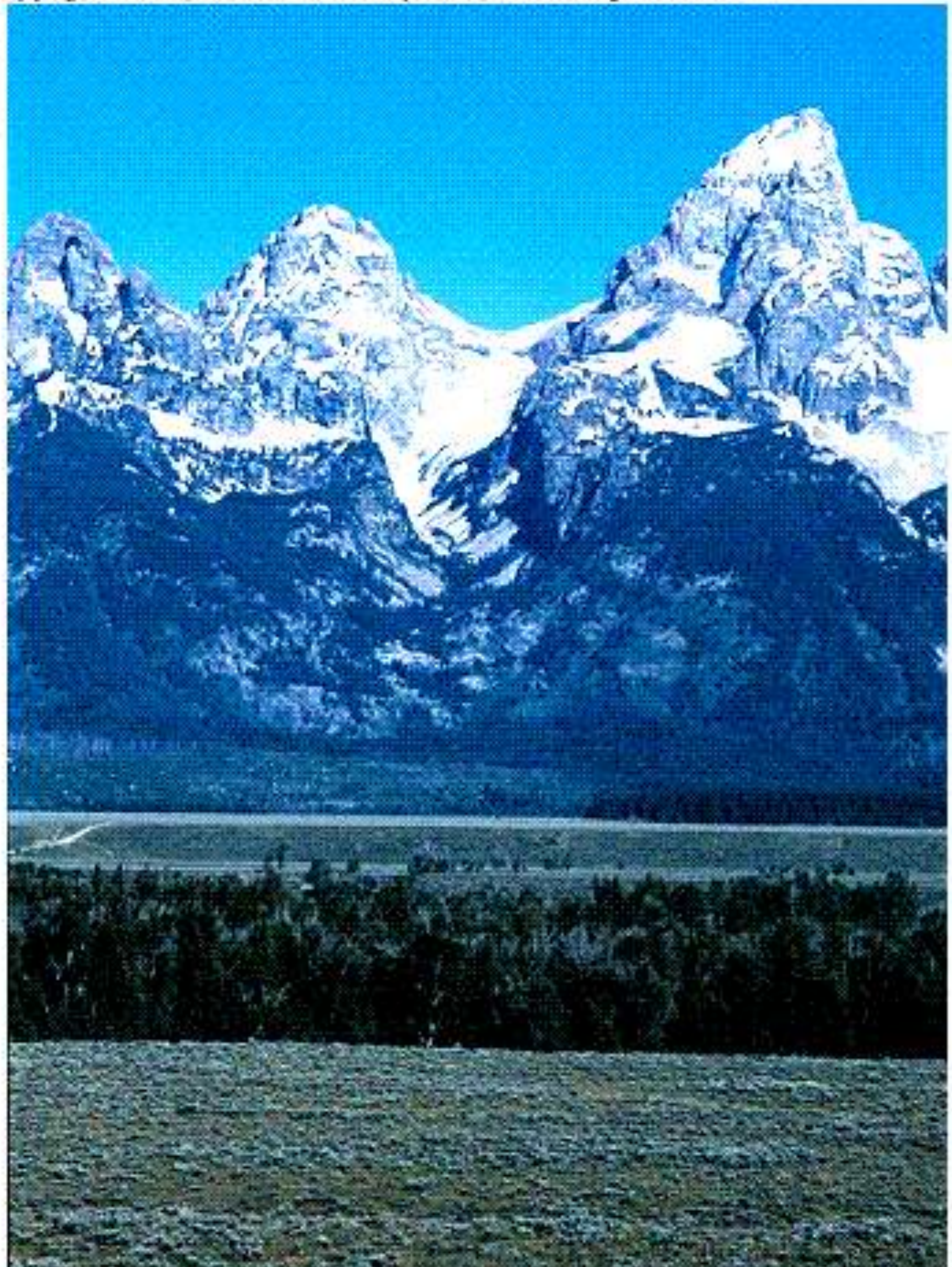
Erosional Landscapes

- Erosional landforms produced by valley glaciers include:
  - *Arêtes*
    - Sharp ridges separating glacial valleys
  - *Horns*
    - Sharp peaks remaining after cirques have cut back into a mountain on several sides

Glacial Erosion

- Under glacier
  - Abrasion & plucking
  - Bedrock polished & striated
  - Rock flour washes out of glacier
  - Polishing and rounding
    - “Sheep Rocks”
  - Striations- scratches & grooves on rock
- Above glacier
  - Frost wedging takes place
  - Erosion by glaciers steepens slopes

Glacially Carved Valley, Wyoming



Glacial valleys

- U - shaped cross sections with lateral moraines and drift
- Hanging valleys where tributary glaciers entered

Erosional Landscapes

- Erosional landforms produced by valley glaciers include:
  - *U-shaped valleys*
  - *Hanging valleys*
    - Smaller tributary glacial valleys left stranded high above more quickly eroded central trunk valleys
  - *Cirques*
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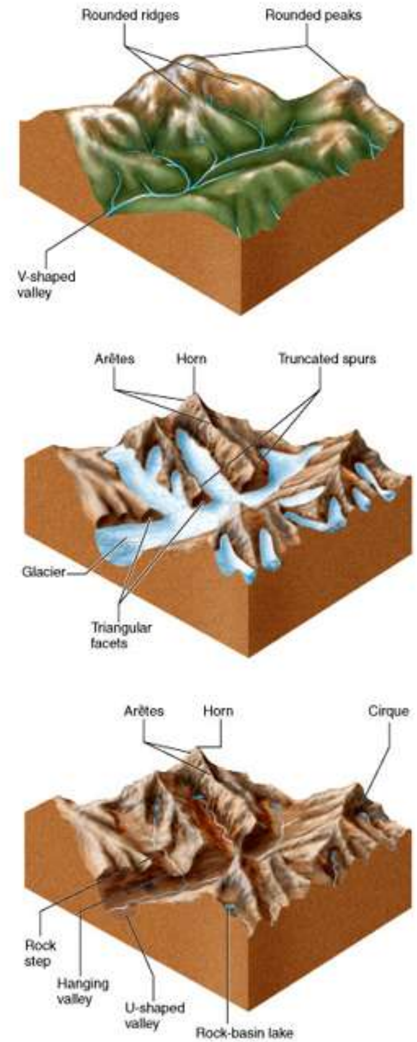
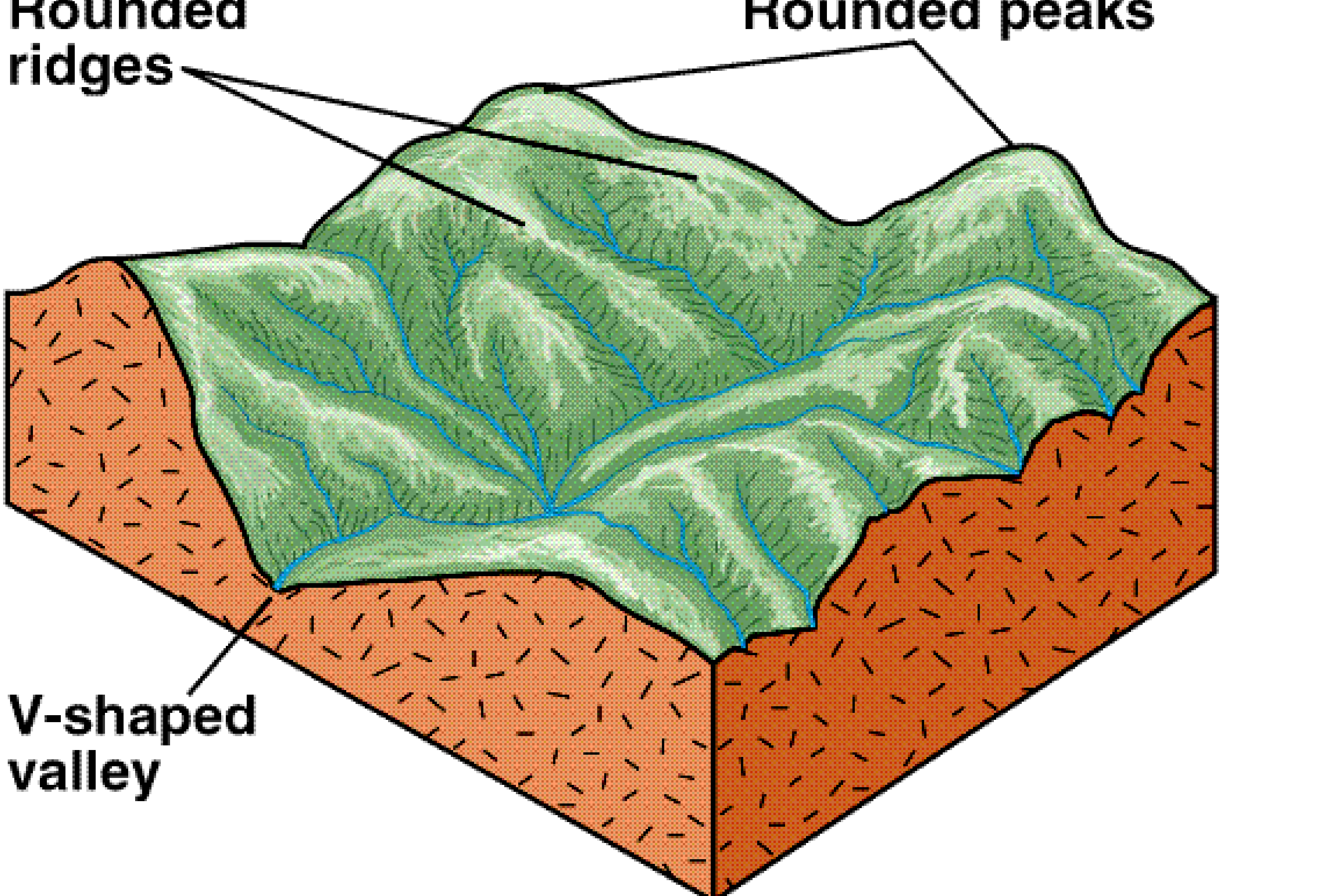
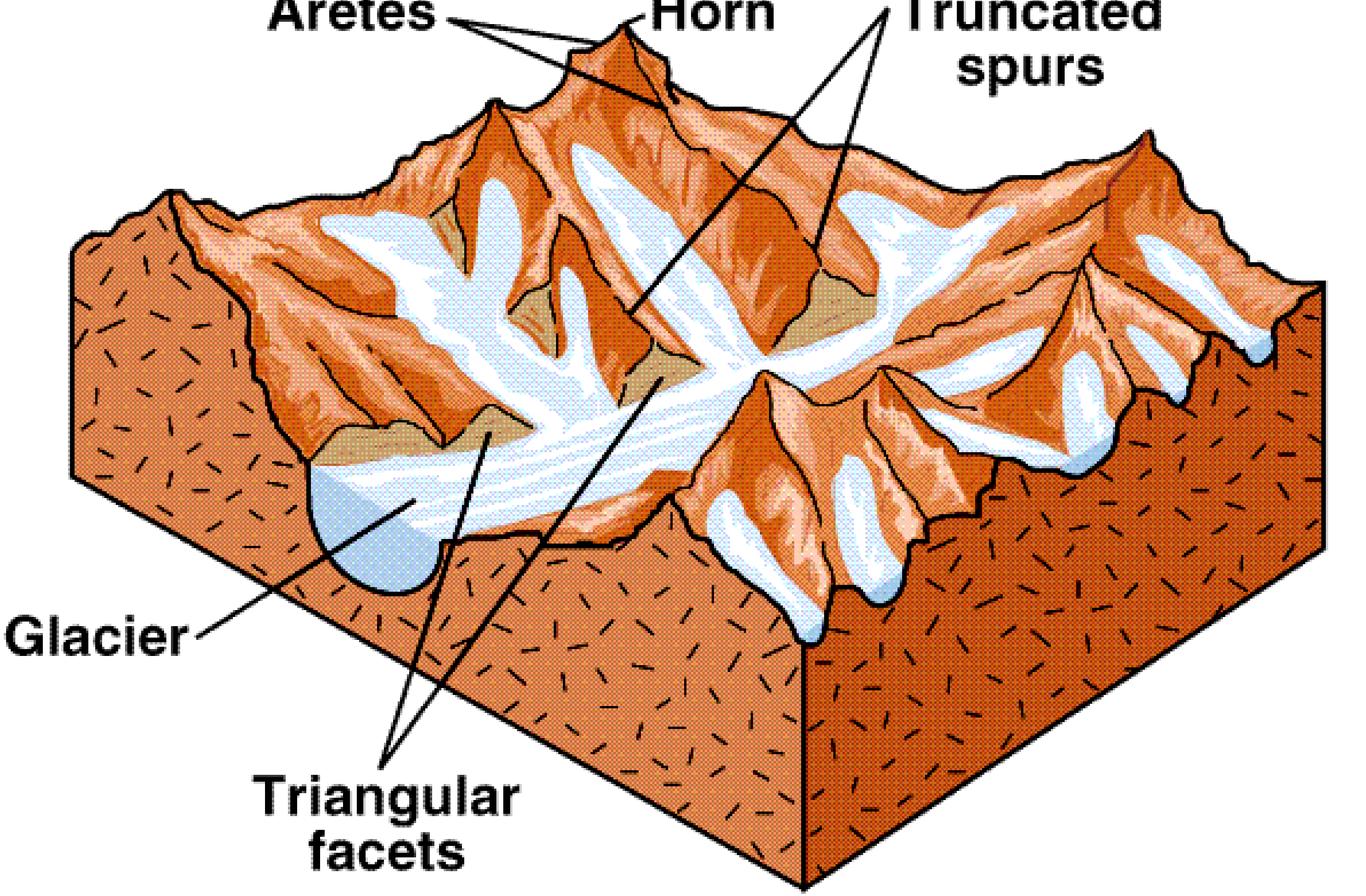


Mountain Landscape before Glaciation



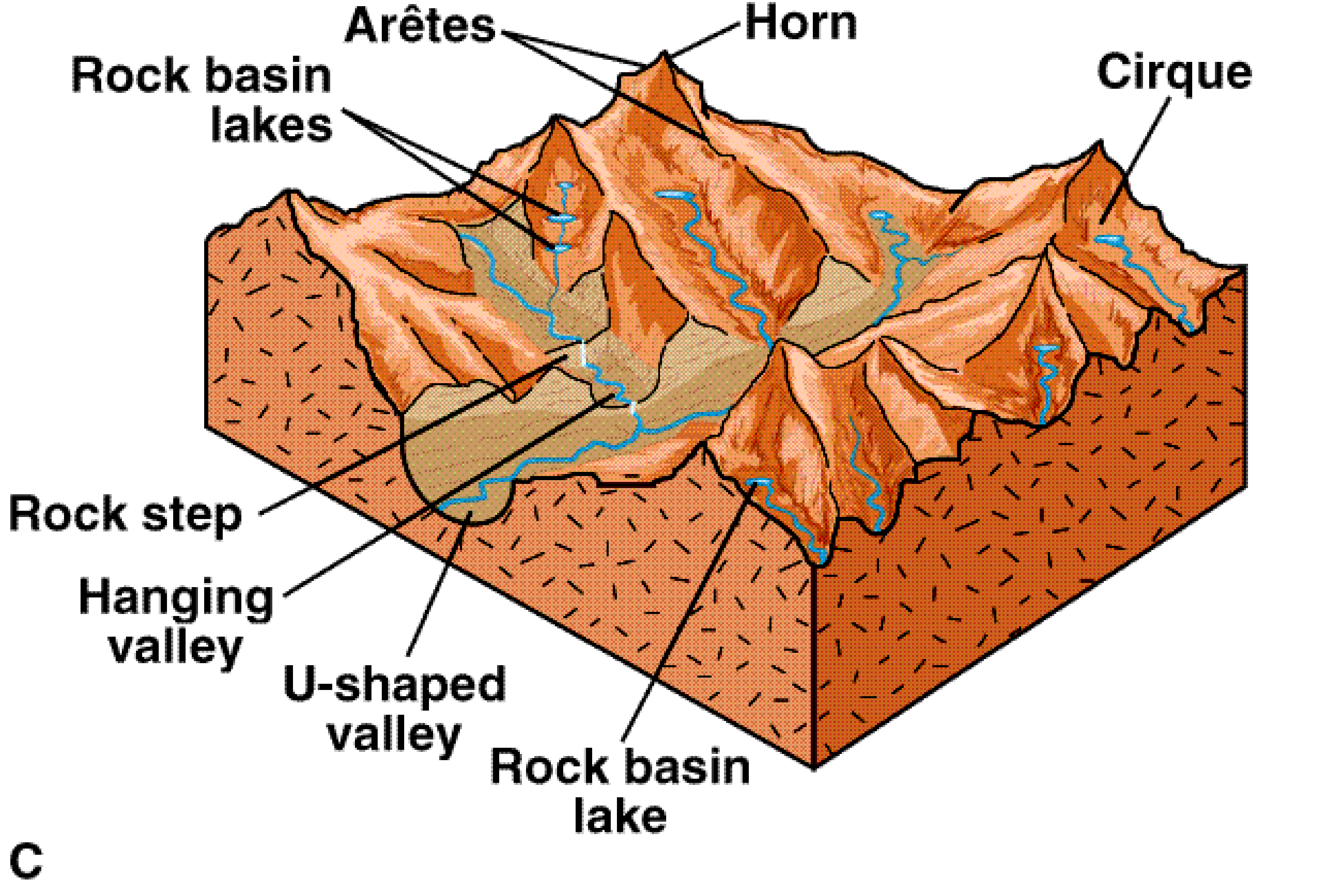
A

Mountain Landscape during Glaciation



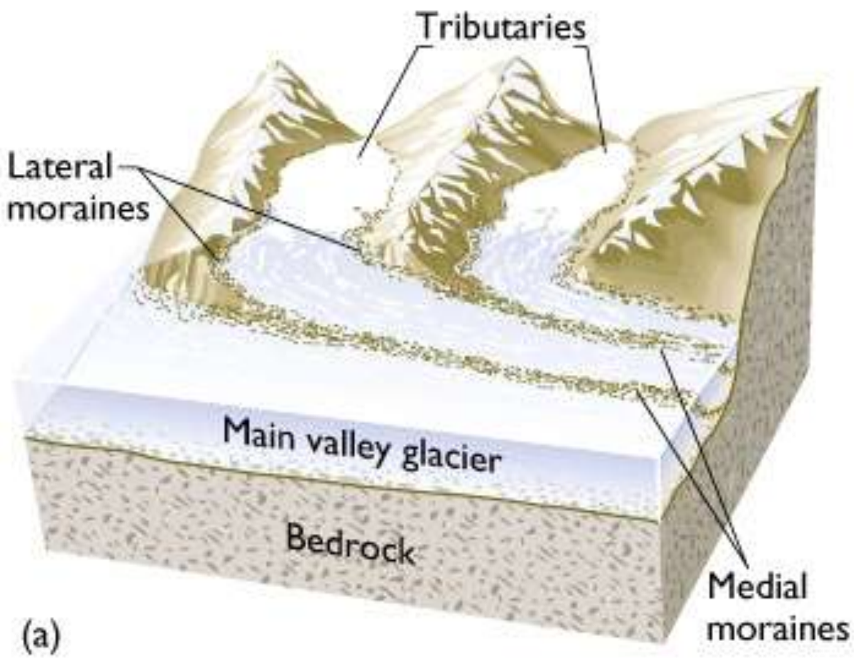
B

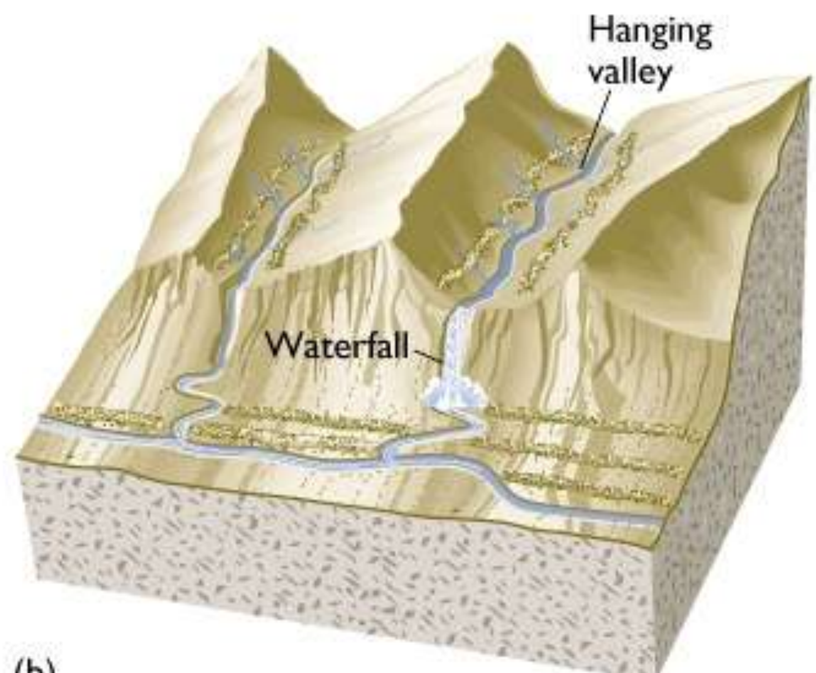
Mountain Landscape after Glaciation

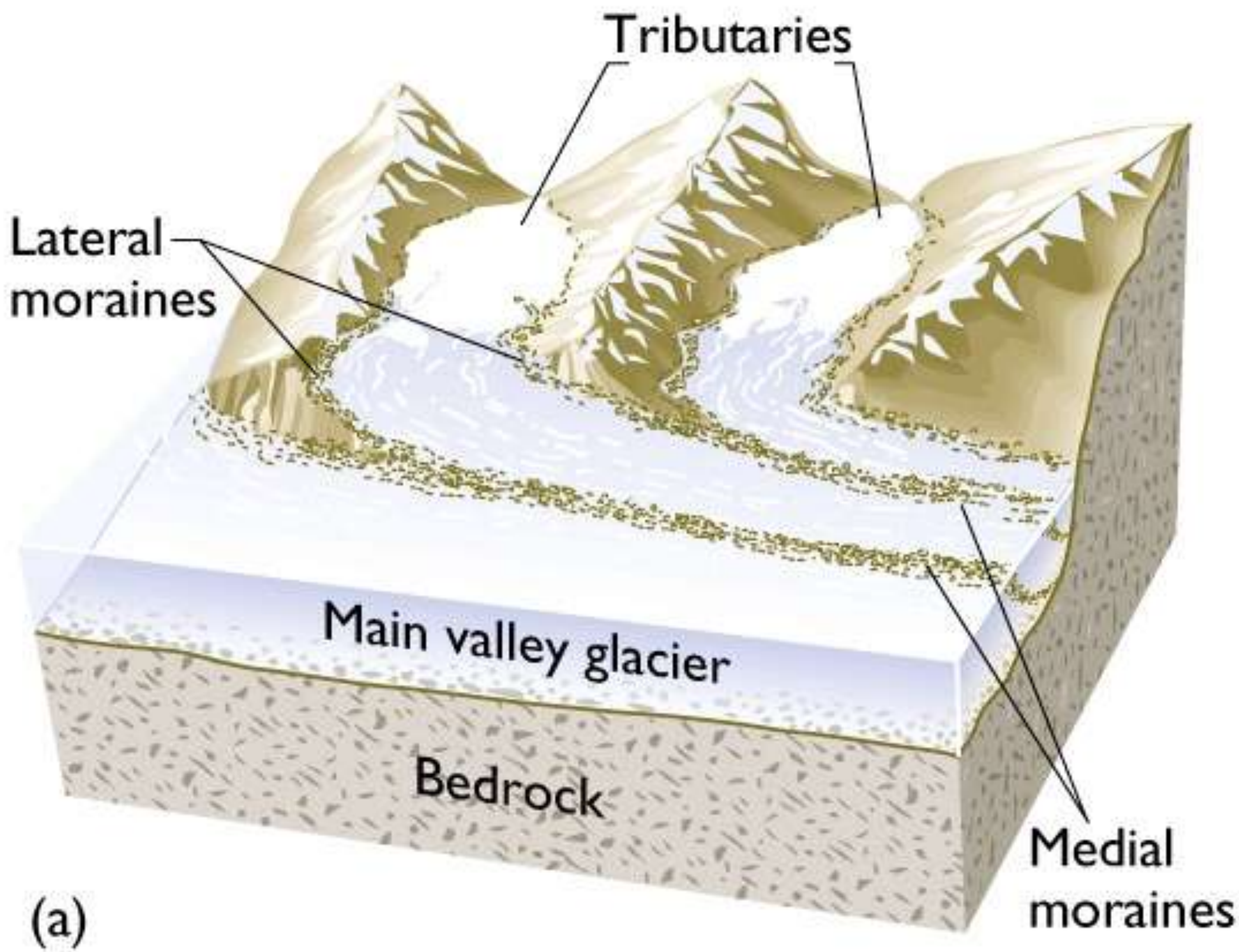


Erosional Landscapes Associated with Alpine Glaciation

- *Cirque*- at head of valley glacier
  - Rock steps
- Rock basin lakes
  - Pater Noster Lakes – string of beads
- Horn
- Arete- sharp ridge

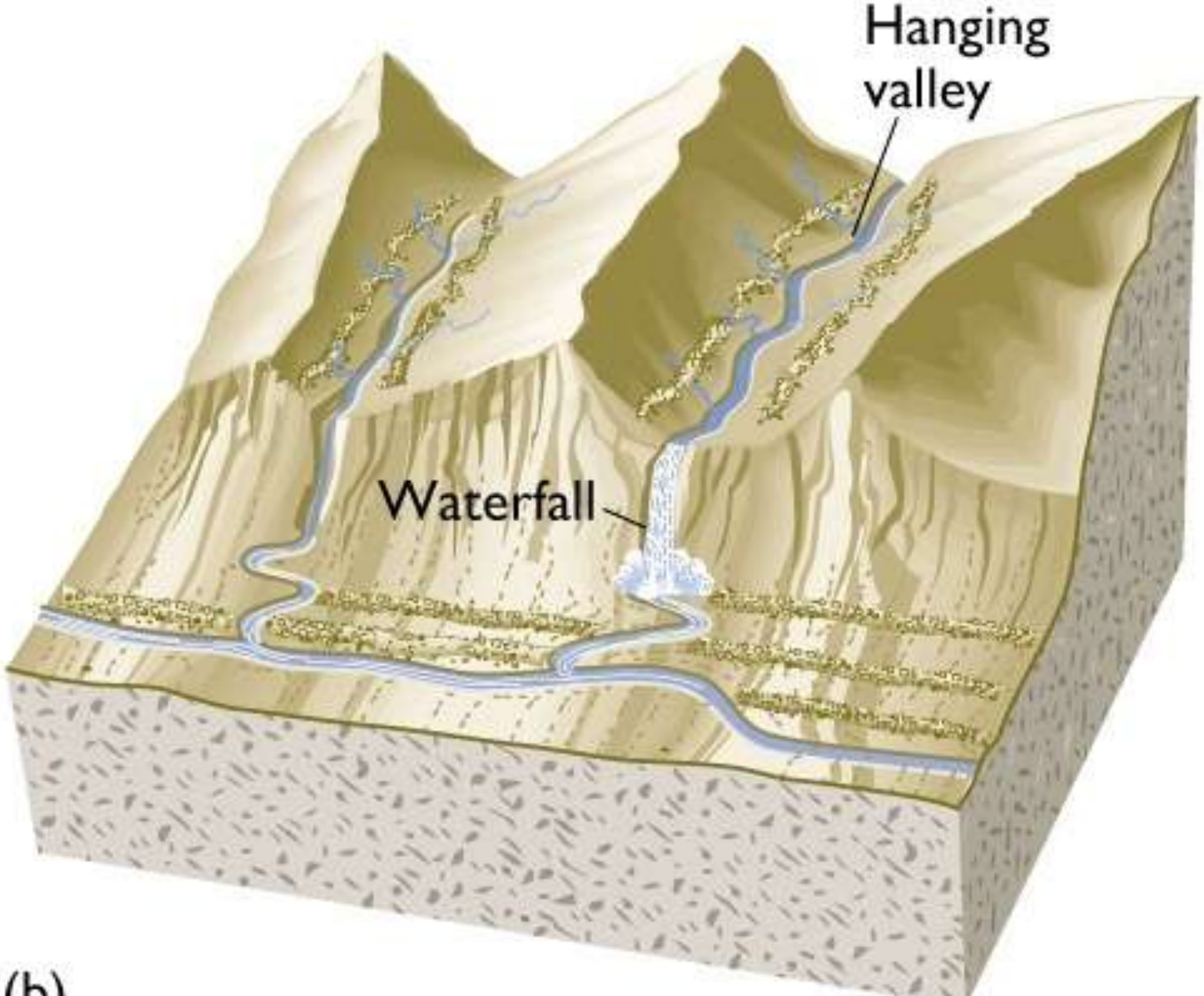

Tributaries
Lateral moraines
Main valley glacier
Bedrock
Medial moraines
(a)


Hanging valley
Waterfall
(b)


Tributaries
Lateral moraines
Main valley glacier
Bedrock
Medial moraines
(a)

Erosional landforms

- Cirques, U-shaped valleys - distinctive of ice action

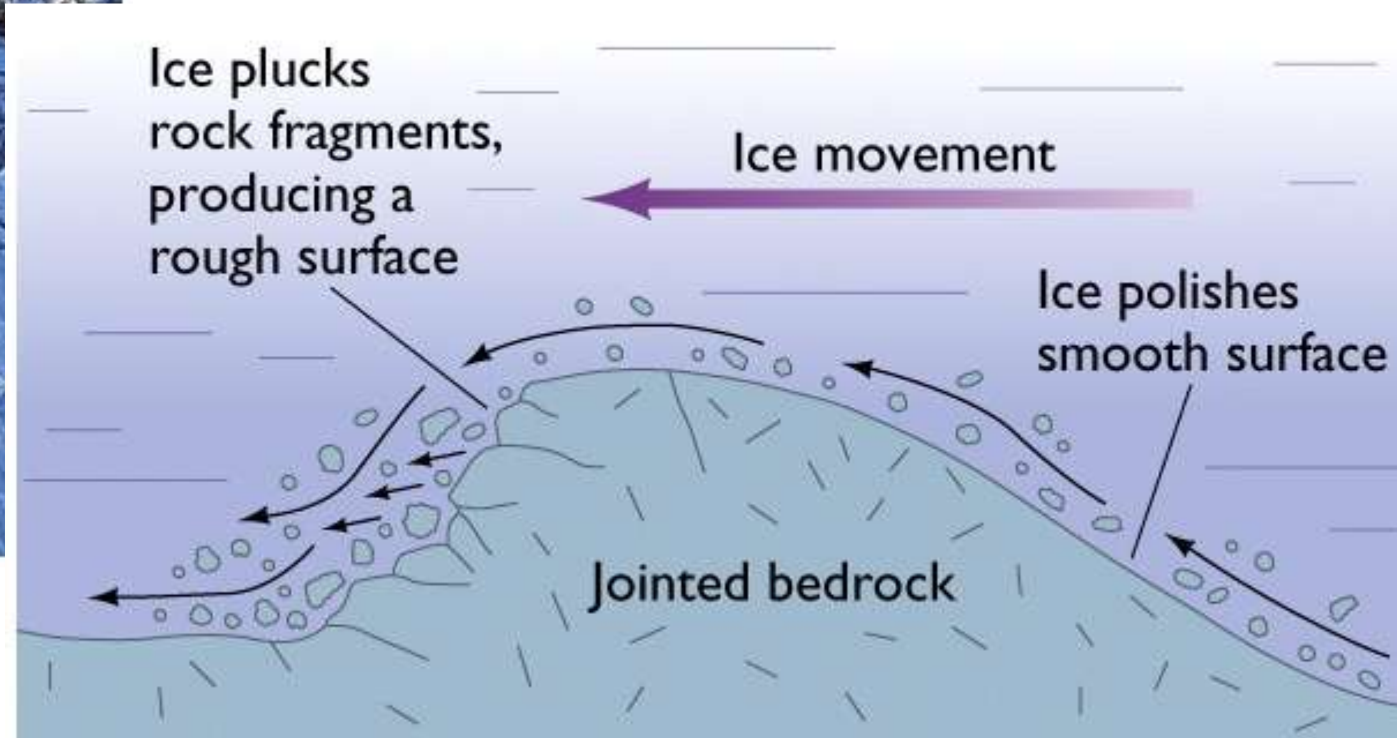


(b)

Fjords – partially drowned glacial valleys

Erosion under glaciers

- Removes unconsolidated material
- Plucks, polishes, and scratches (striations) the rock surface

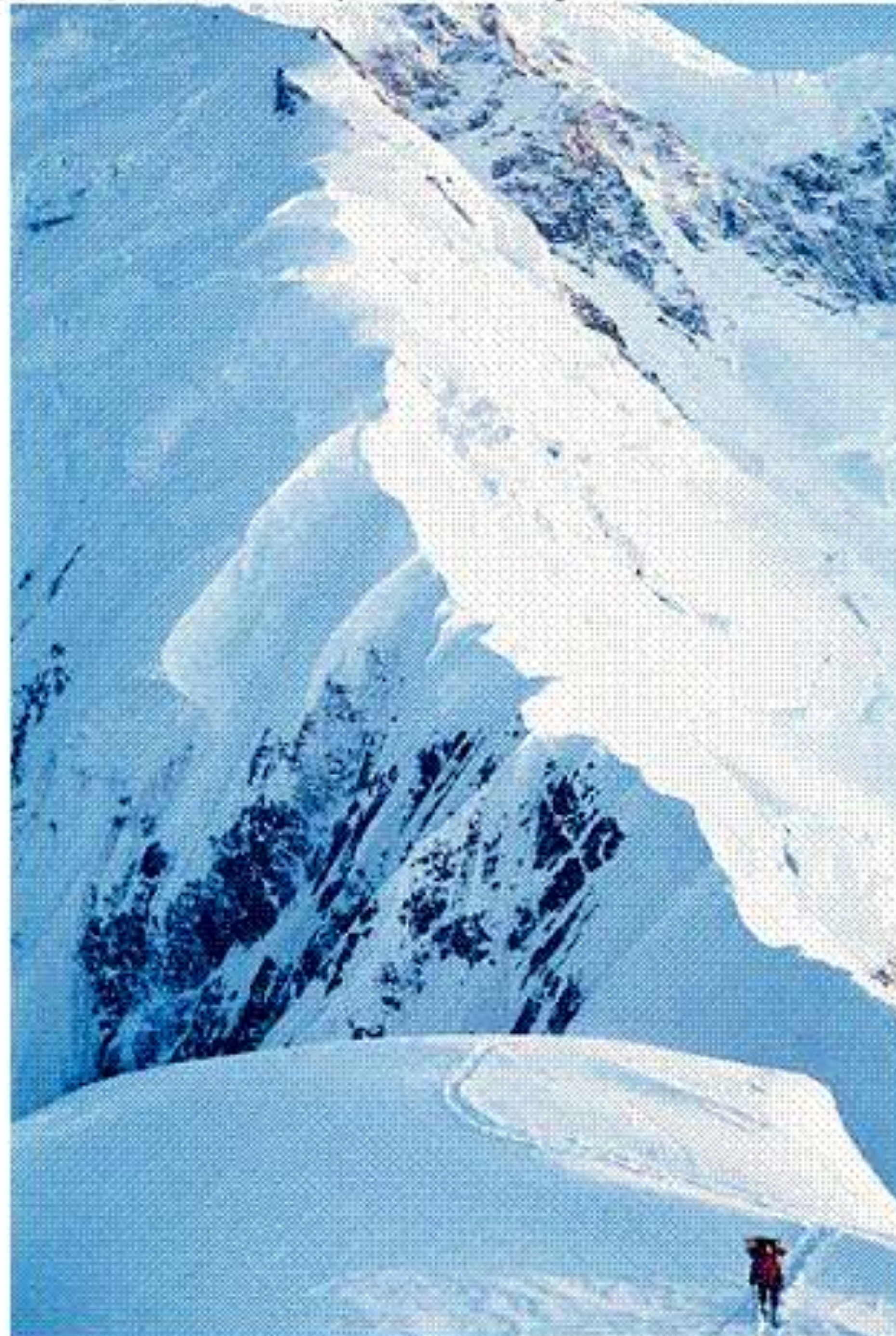


Cirque Occupied by Small Glacier

Erosional Landscapes Associated with Continental Glaciation

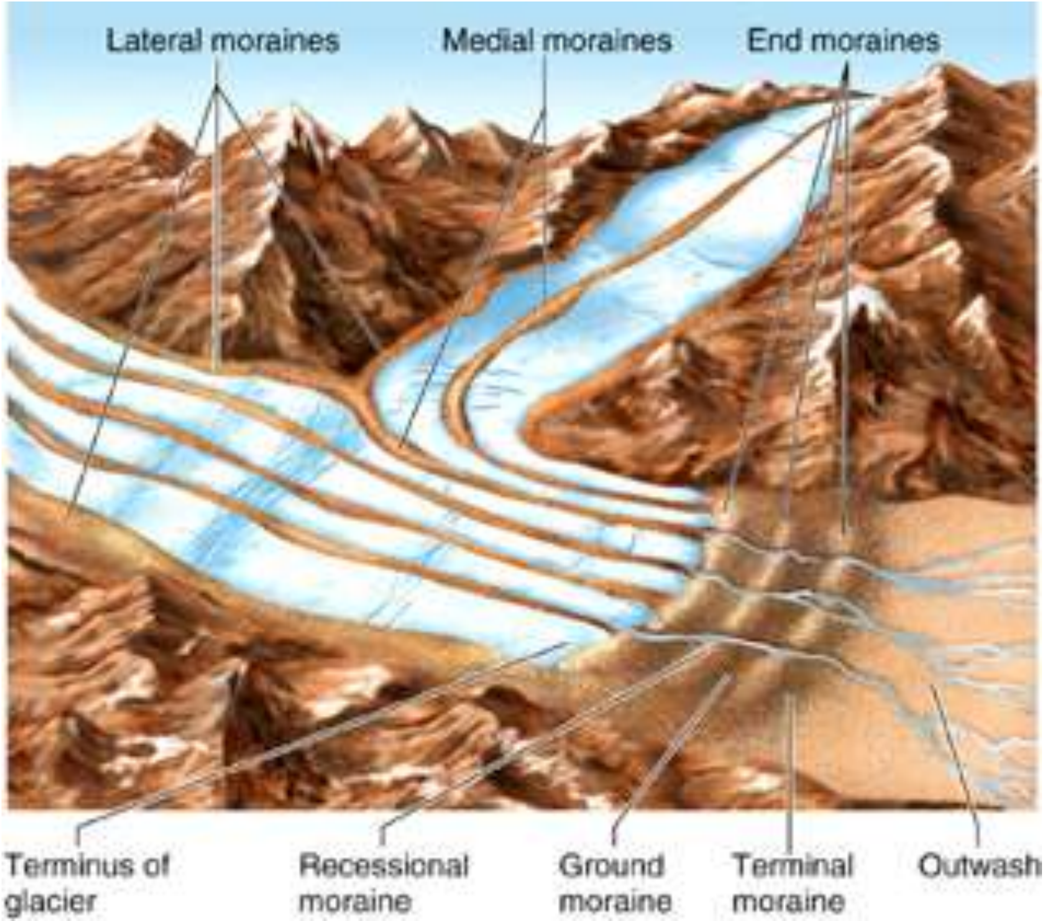
- Grooved and striated bedrock
  - Grooves may be channels
- Rounded hills & mountains

Arête on Mount Logan, Canada



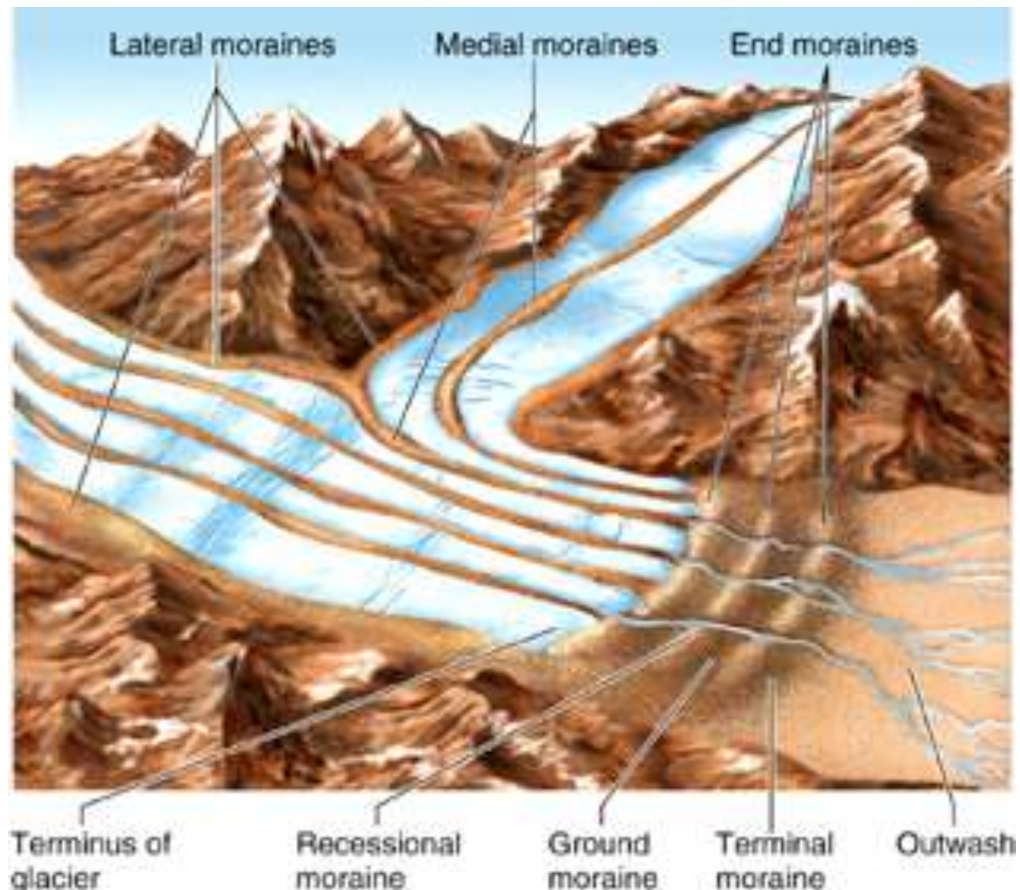
Glacial Deposition

- General name for unsorted, unlayered glacial sediment is ***till***
  - Deposits of till left behind at the sides and end of a glacier are called *lateral*, *medial* and *end moraines*, respectively
    - *Lateral moraines* are elongate, low mounds of till that form along the sides of a valley glacier

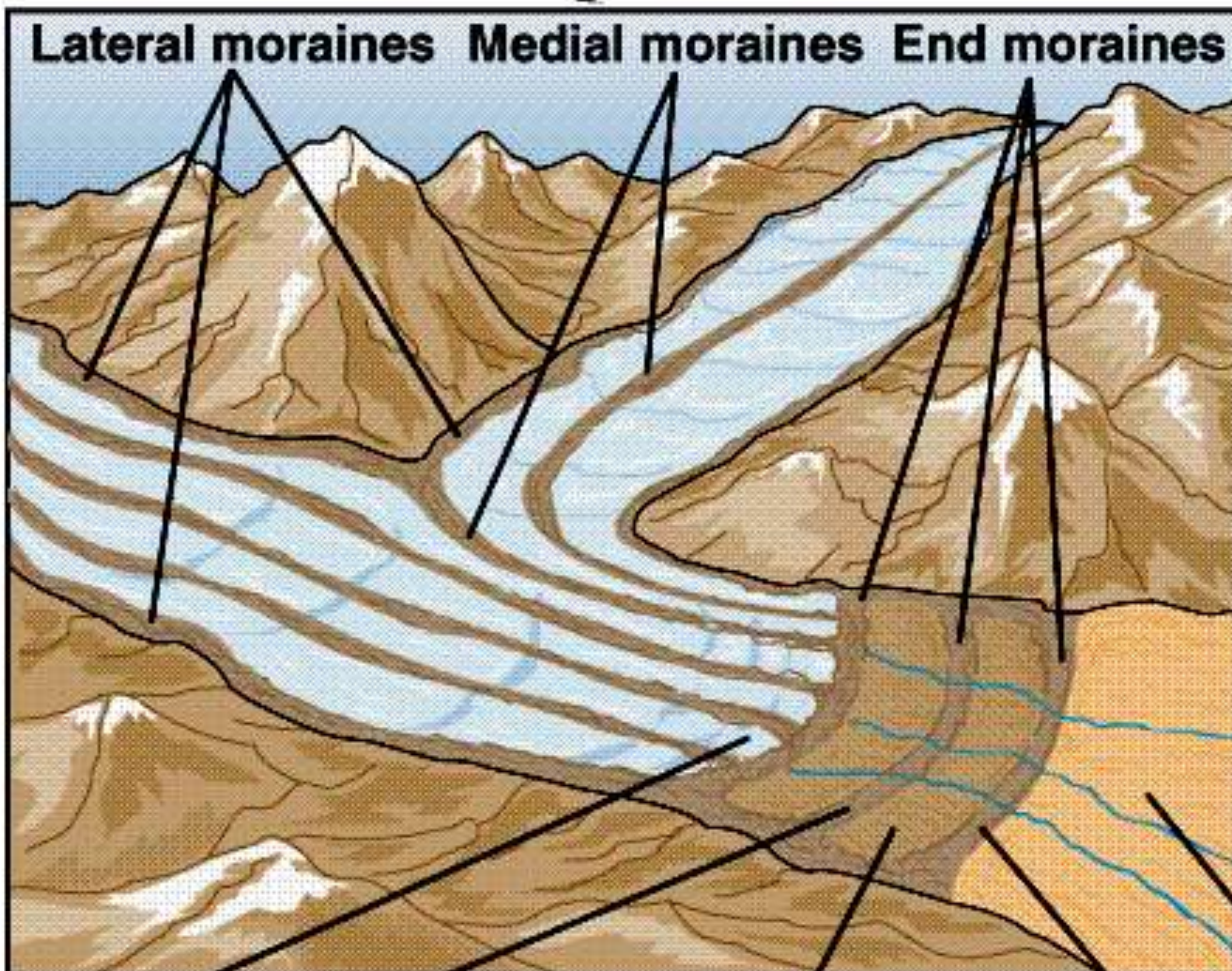


Glacial Deposition

- the sides of a valley glacier
    - *Medial moraines* form when tributary glaciers come together and adjacent lateral moraines get trapped between the two flowing ice streams
    - *End moraines* are ridges of till piled up along the front end of a glacier
    - Successive end moraines left behind by a retreating glacier are called *recessional moraines*



Moraines Associated with Valley Glaciers



Medial and Lateral Moraines

Lateral moraine

fiord

Glacial Deposition

- Till
  - Unsorted debris
- Erratic
- Moraine- body of till
  - Lateral Moraine
  - Medial Moraine- where tributaries join
  - End moraine-
    - Terminal
    - Recessional
  - Ground moraine
  - Drumlin

Glacial Deposition

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Glacial Deposition

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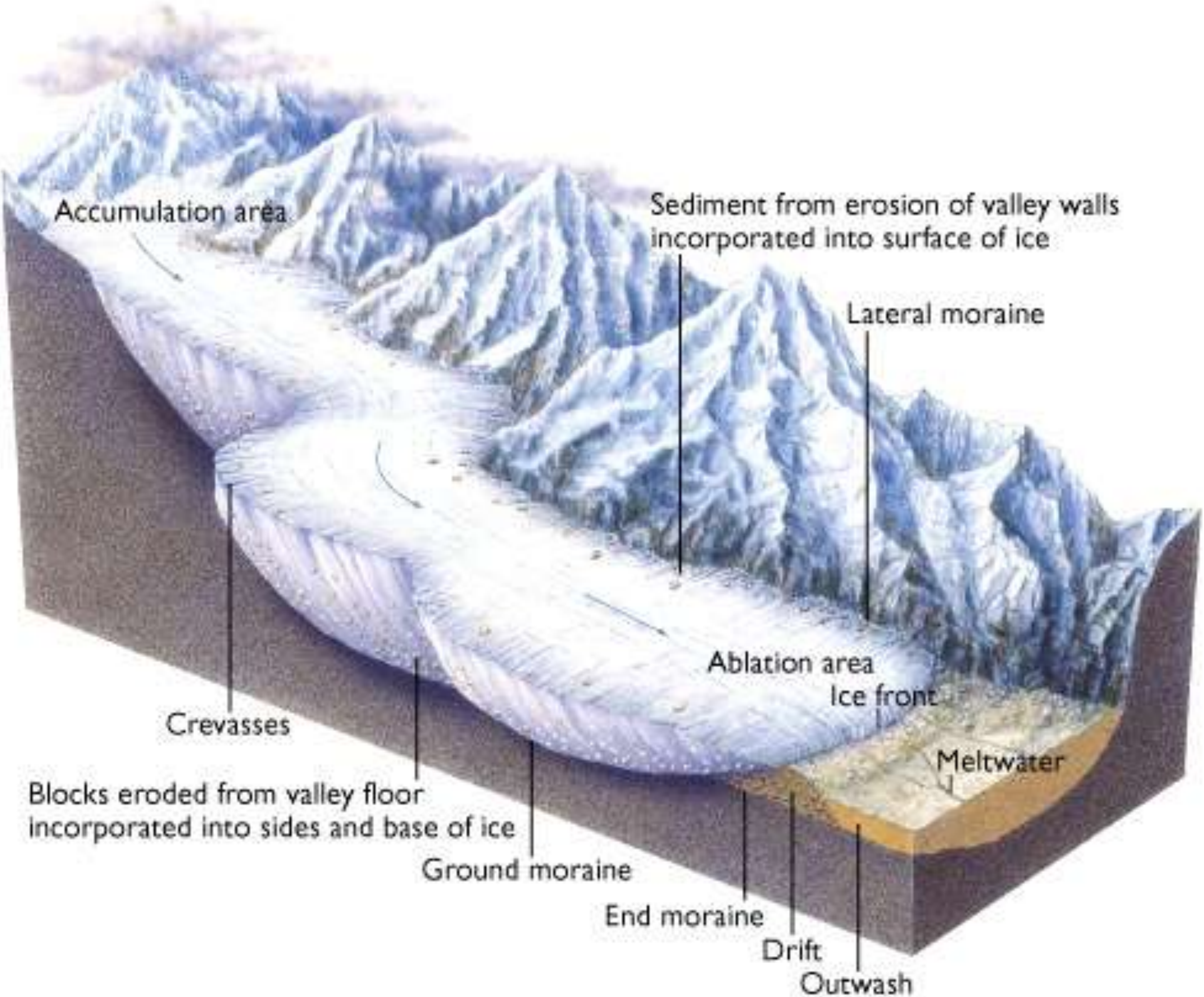

Accumulation area
Sediment from erosion of valley walls incorporated into surface of ice
Lateral moraine
Ablation area
Ice front
Meltwater
Crevasses
Blocks eroded from valley floor incorporated into sides and base of ice
Ground moraine
End moraine
Drift
Outwash

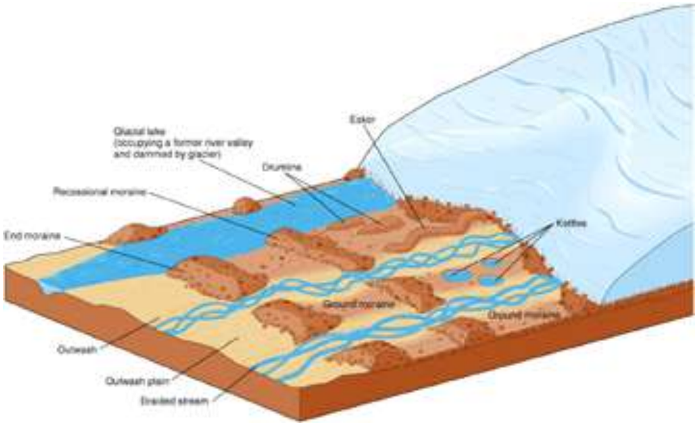
Glacial Deposition

- Outwash
  - Stream-deposited sediment
    - sorted
  - Braided streams typical
  - Esker
  - Kettle
- Glacial lakes
  - Varves

Glacial Deposition

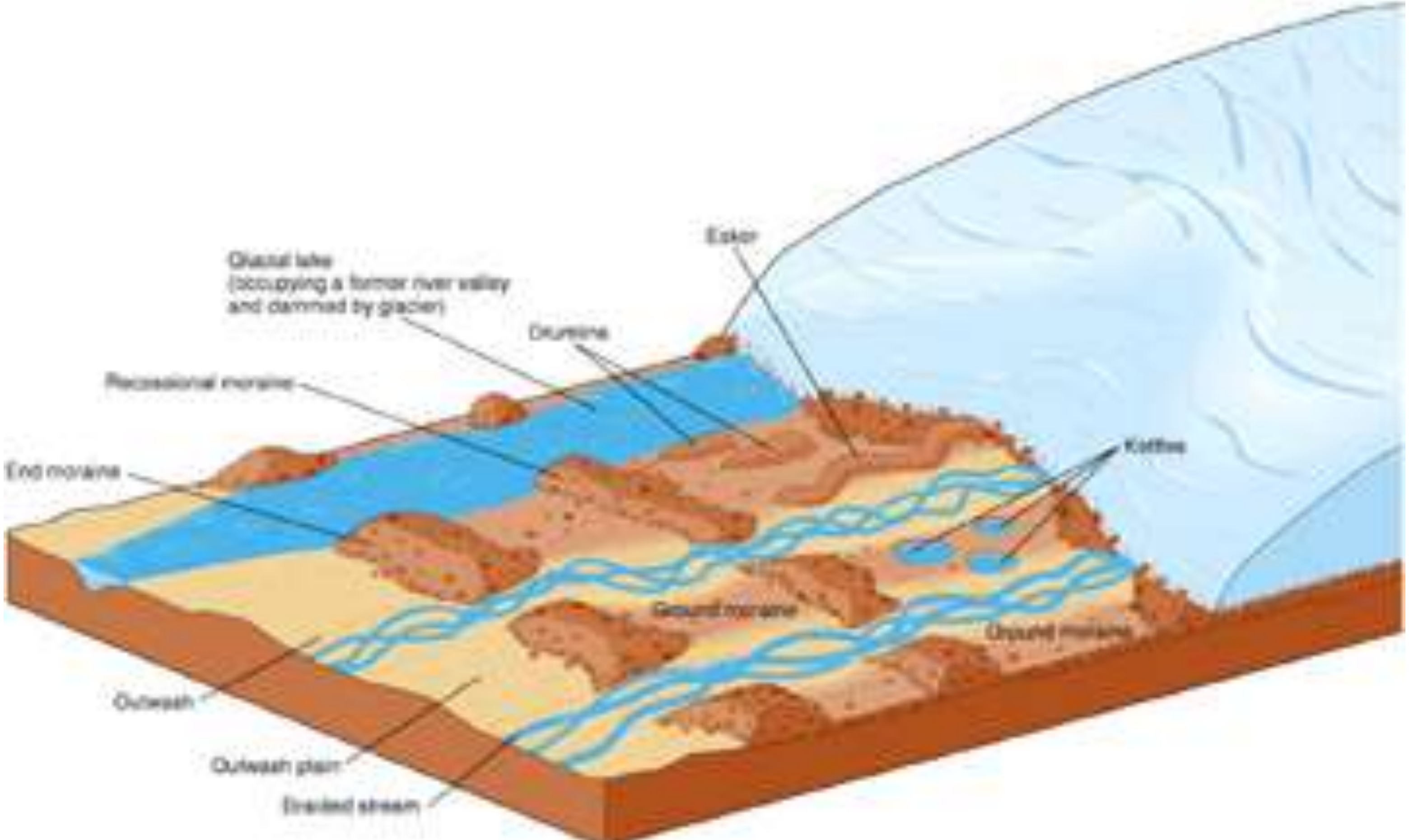
glacial outwash

- Sediment-laden streams emerging from the ends of glaciers have *braided* channel patterns
- Outwash deposits and landforms include *eskers* – snake-like ridges of former under glacier stream
- *kettles* and
- *kames*
- Annual variations in sediments deposited in glacial lakes produces paired layers known as *varves*, which can be counted like tree rings

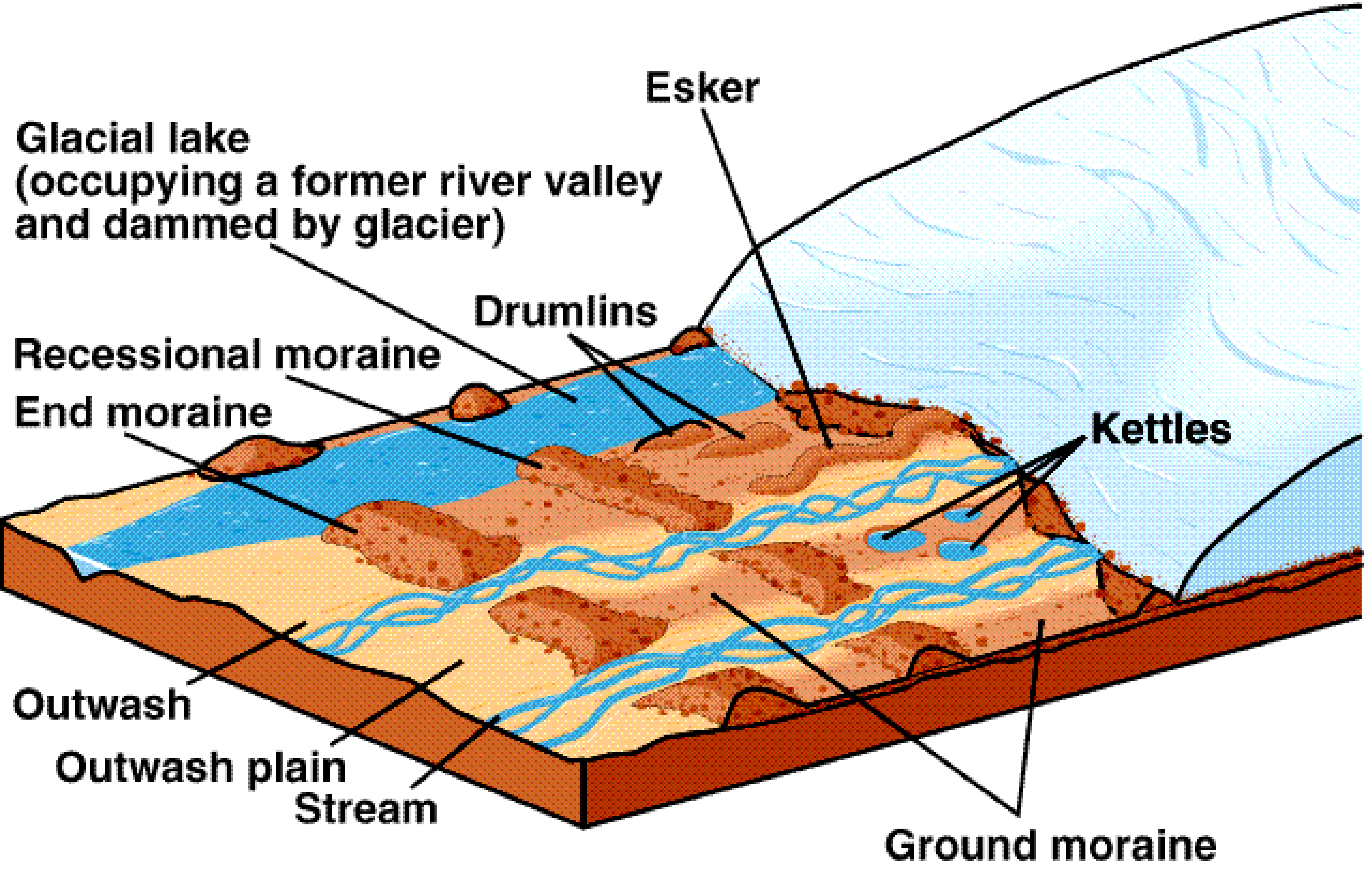


Glacial Deposition

- Large amounts of *liquid water* flow over, beneath and away from the ice at the end of a glacier
- Sediment deposited by this water is known as *glacial outwash*



Receding Ice Sheets and Deposition

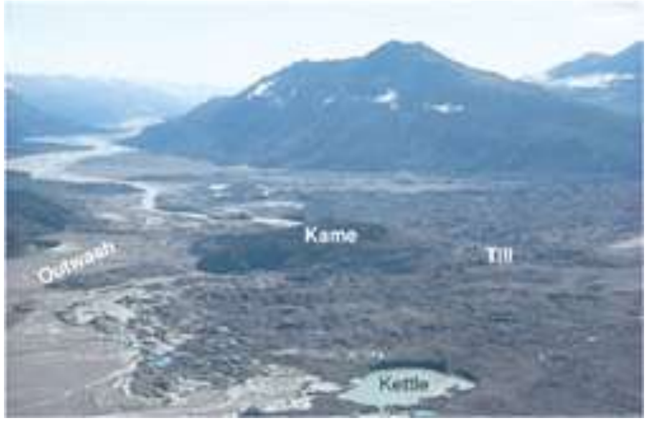


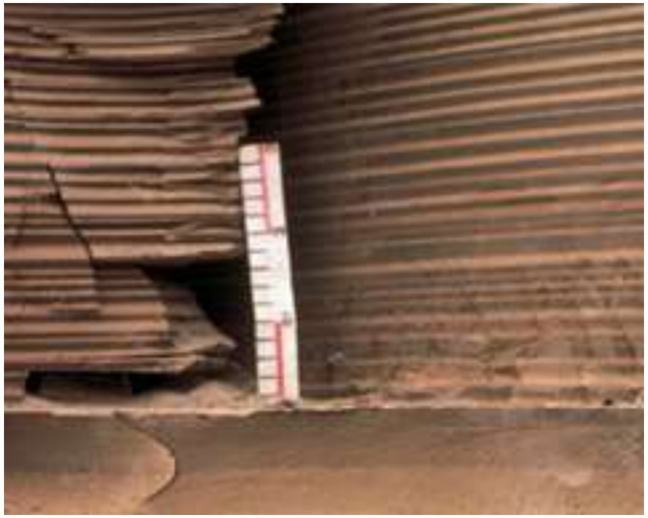
A Kettle and Outwash

Drumlins and other features . . .

Glacial Deposition

- Large amounts of *liquid water* flow over, beneath and away from the ice at the end of a glacier
- Sediment deposited by this water is known as *glacial outwash*
- Sediment-laden streams emerging from the ends of glaciers have *braided* channel patterns
- Outwash deposits and landforms include *eskers*, *kettles* and *kames*
- Annual variations in sediments deposited in glacial lakes produces paired layers known as *varves*, which can be counted like tree rings



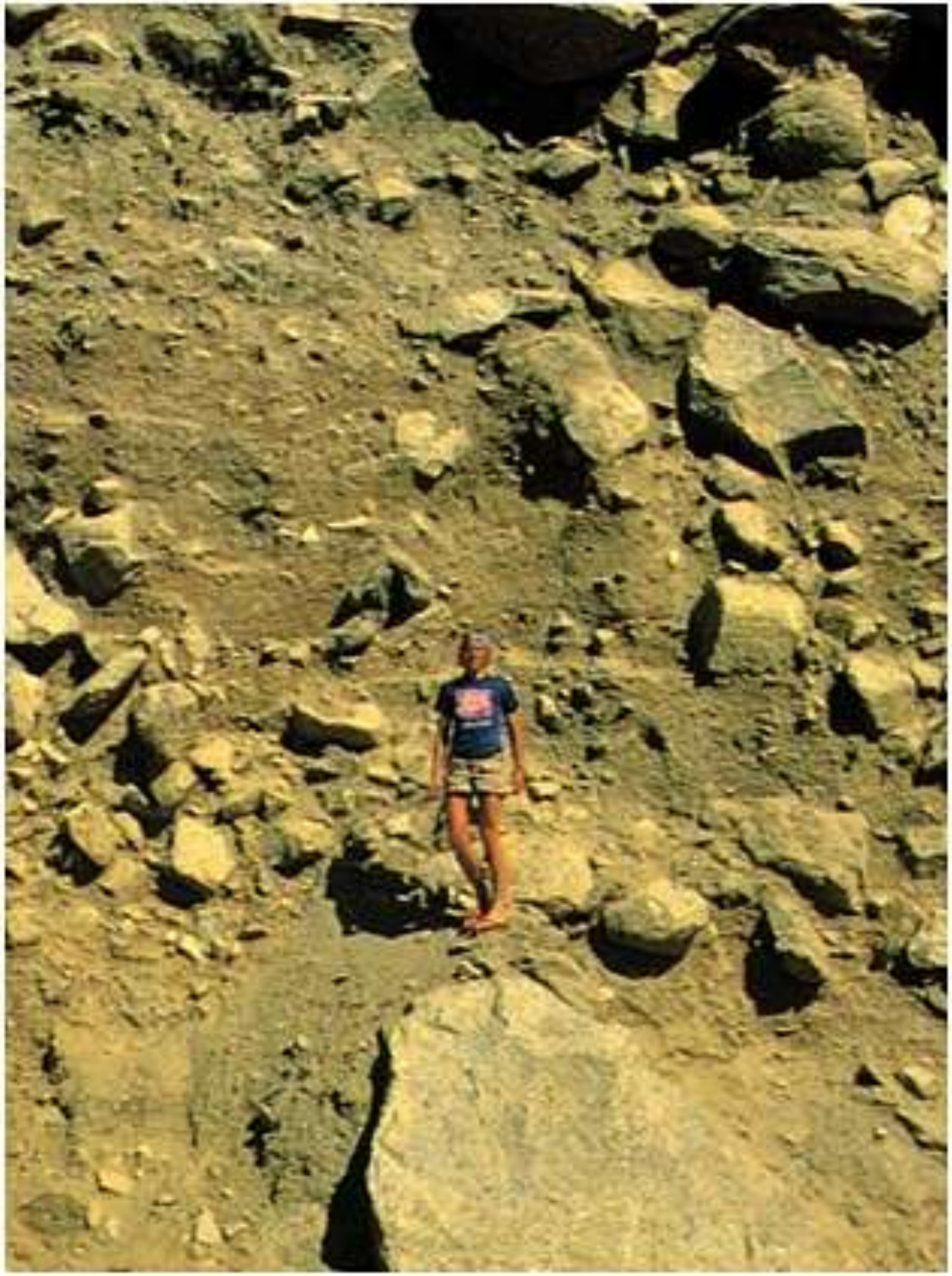


Glacial lake sediments

- Delicately banded ("varved") sediments record annual variations in sedimentation - no bioturbation

Glacial Drift

- "Drift" is the general term for glacial sediments
- Till is unsorted glacial material
- Why unsorted?

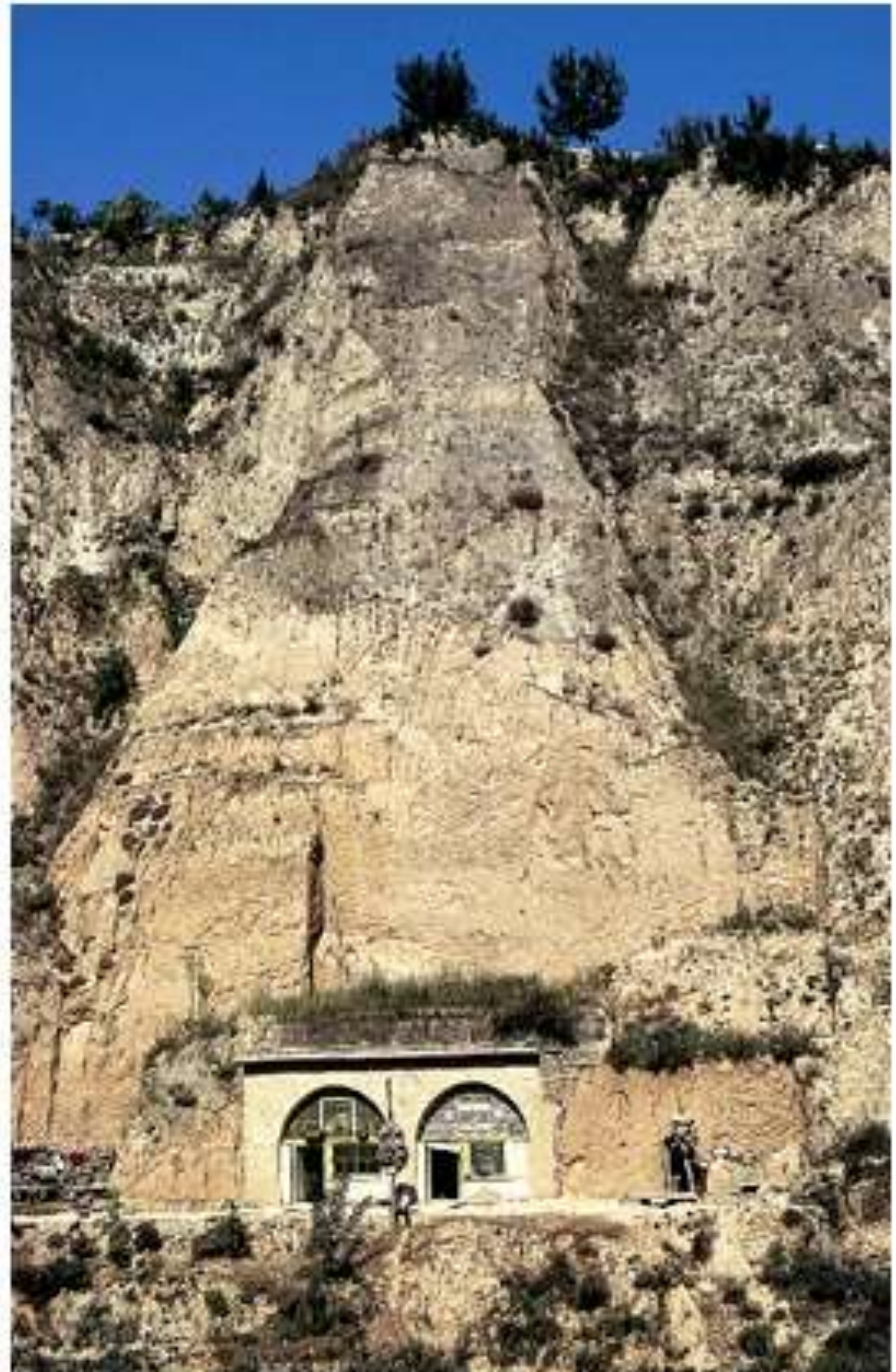


Varieties of glacial sediment (drift)

- Till
  - Unstratified, poorly sorted glacial drift deposited directly by melting ice
  - Has clay, sand, and boulders; boulders known as *erratics*
- Outwash
  - Stratified, well sorted drift deposited by meltwater streams; may be crossbedded
- Loess
  - Wind-sorted material, generally reworked from outwash

Loess

- Accumulations of wind-blown silt and dust
- Especially abundant in the Pleistocene (ice ages) — why?



Giant Ripples of Gravel

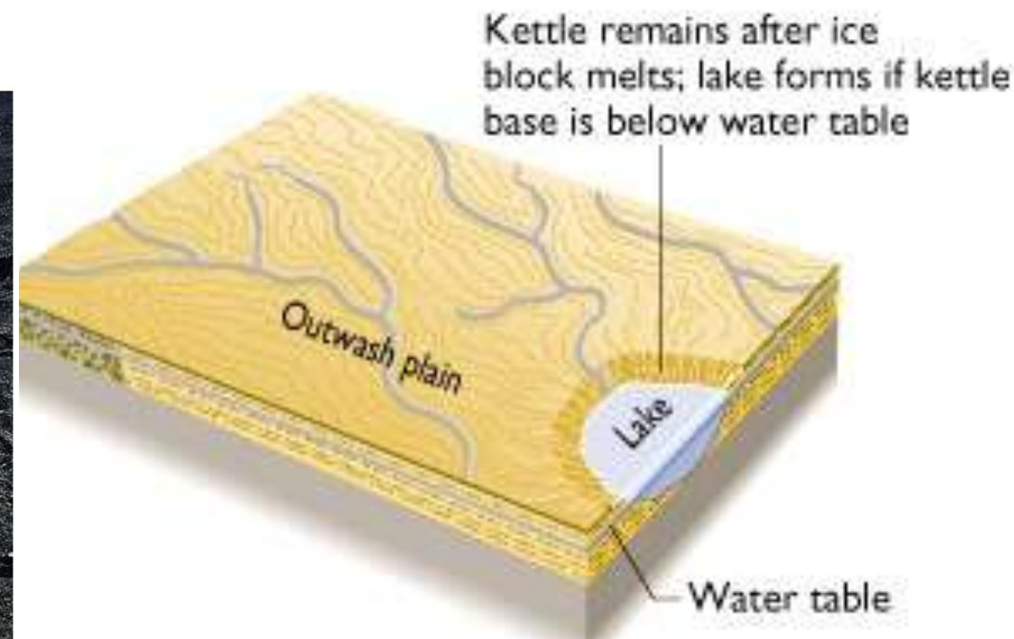
Post-glacial depositional features

Formation of kettles →

- Kames
  - Small hills of sand and gravel dumped near edge of ice
- Kettles
  - Steep-sided hollows or undrained depressions
  - Land of 10,000 Lakes

(a) During ice melting

Kames and kettles

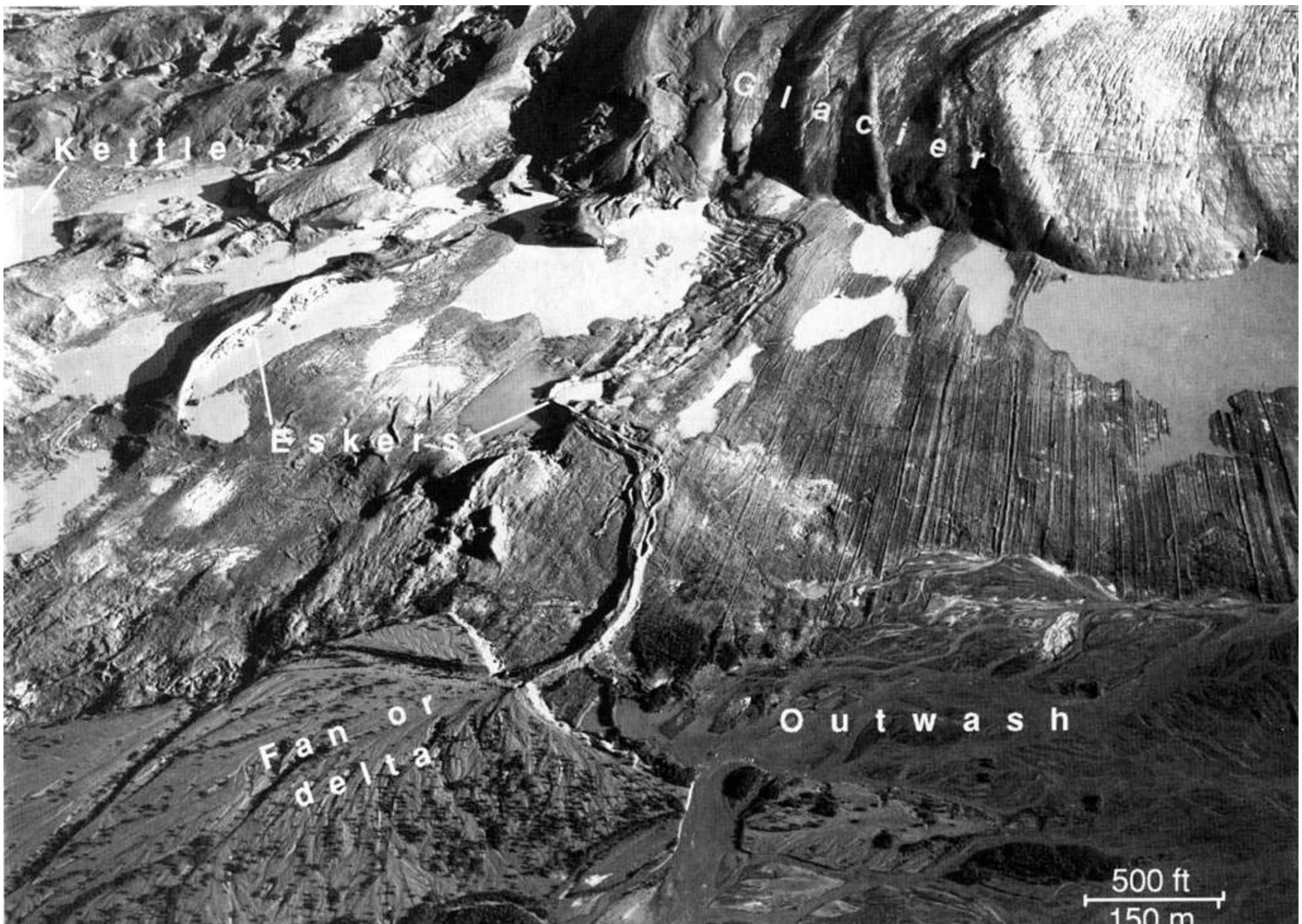


After complete deglaciation

Eskers

Eskers — subglacial streambeds

- Eskers are stream deposits that form under glaciers; melt water flows at the base and moves sediment, often uphill relative to current topography! *Why?*



Theory of glacial ages

- Northern Europe & North America heavily glaciated
  - Peak of glaciation 18,000 years ago

Direct Effects of Past Glaciation

- Large-scale glaciation of North America during the most recent ice age produced the following effects:
  - Most of the soil and sedimentary rocks were scraped off of underlying crystalline rock in northern and eastern Canada, and future *lake basins* were gouged out of the bedrock
  - Extensive sets of *recessional moraines* were left behind by retreating ice sheets in the upper midwestern U.S. and in Canada

Glacial Ages

- In the early 1800s, past extensive glaciation of Europe was first hypothesized
  - Hypothesis was initially considered outrageous, but further observations by *Louis Agassiz* (initially a major opponent of the hypothesis) in the Swiss Alps found much supporting evidence
  - Agassiz traveled widely in Europe and North America, finding more and more supporting evidence, eventually leading to the *theory of glacial ages*
- Theory of glacial ages states that *at times in the past, colder climates prevailed during which much more of the land surface of Earth was glaciated than at present*
  - Most recent glacial age was at its peak only 18,000 years ago

Effects of Past Glaciation

- Glacial ages
- Direct effects in North America
  - Scoured much of Canada
  - Cut Great Lakes
  - Deposited till & flattened Midwest
  - Extensive alpine glaciation in mountains

Great Lakes

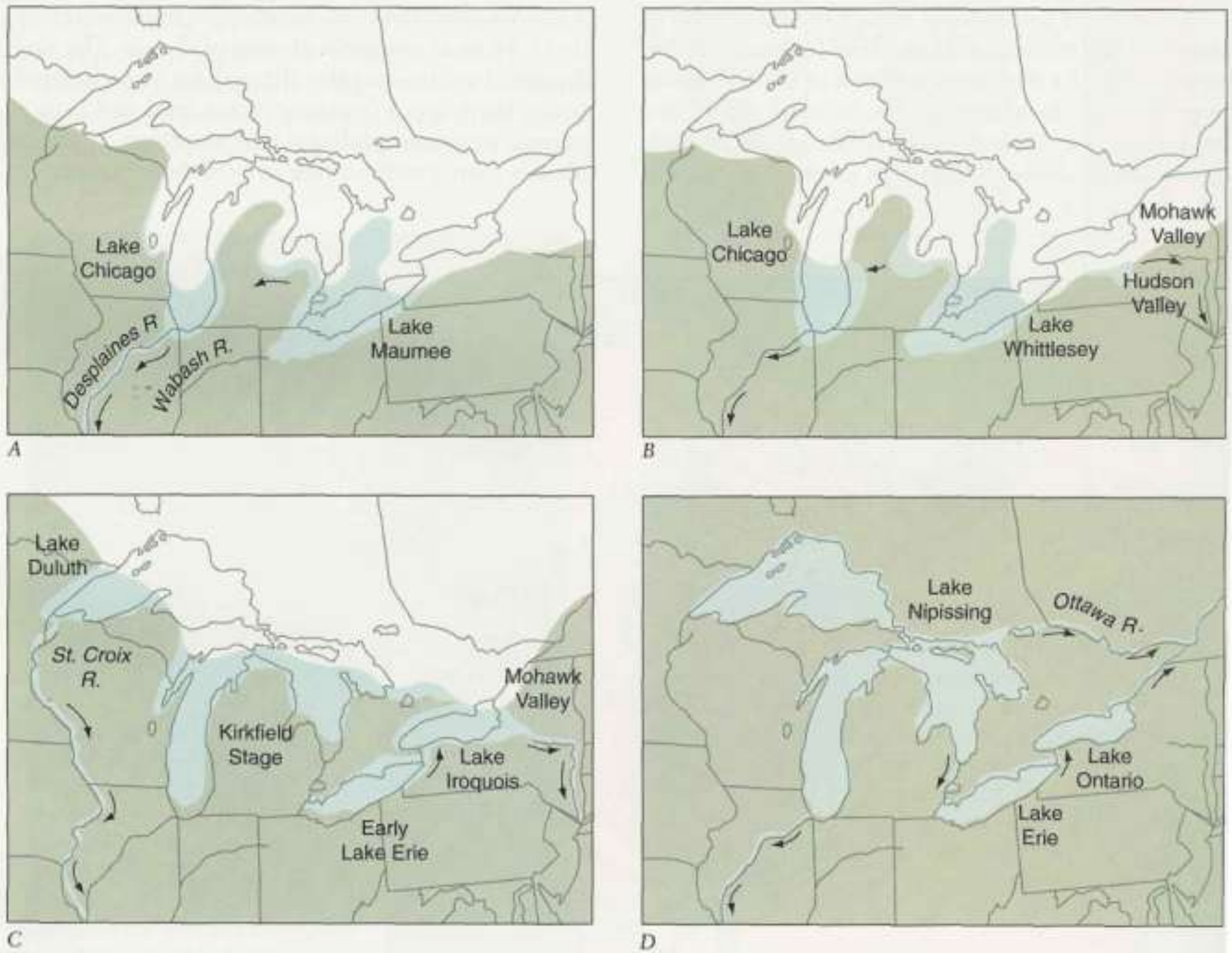


FIGURE 13-47 **Continental glaciers moved into low-lying areas and scoured them deeper. As they retreated northward, meltwater filled the depressions to form the Great Lakes.** (*Courtesy of Thompson, G.R. and Turk, J. 1977,* Modern Physical Geology, *Philadelphia: Saunders College Publishing.*)

Effects of Glacial Ages

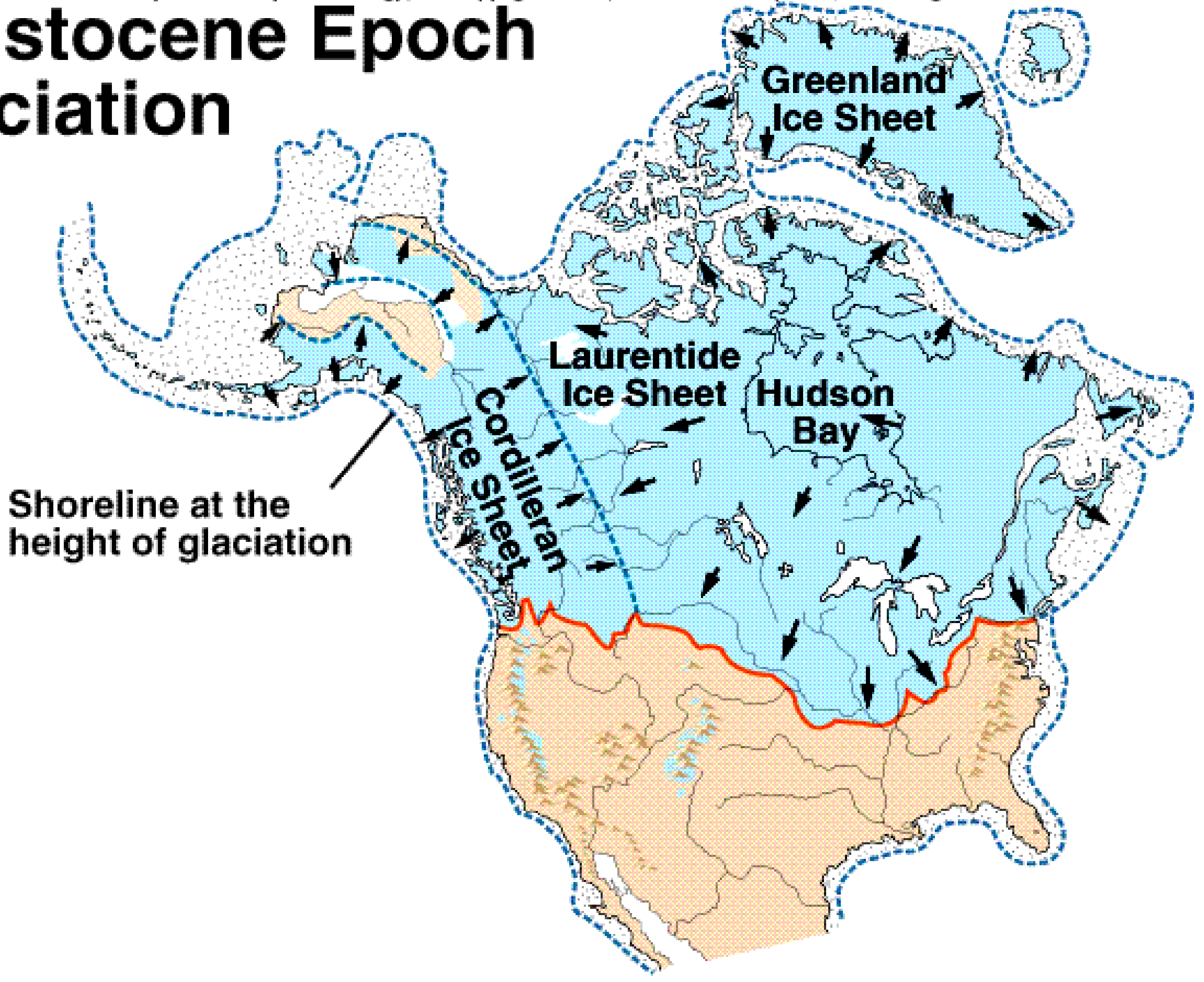
- Indirect effects
  - Pluvial lakes
  - Lowering of sea level
    - *Fiord*
  - Crustal rebound
- Evidence for older glaciation
  - *Tillite*
  - Late Paleozoic glaciation
    - Evidence for a supercontinent
  - Precambrian glaciation

Indirect Effects of Past Glaciation

- Large *pluvial lakes* (formed in a period of abundant rainfall) existed in closed basins in Utah, Nevada and eastern California
  - Great Salt Lake is a remnant of the much larger pluvial *Lake Bonneville*
  - Huge floods emanated as ice-dammed lakes (e.g., *Lake Missoula*) drained catastrophically
- *Sea level* was significantly *lowered* by large amounts of water locked up into ice sheets, allowing stream channels and glaciers to erode valleys below present-day sea level
  - *Fiords* are coastal inlets formed by drowning of glacially carved valleys by rising sea level

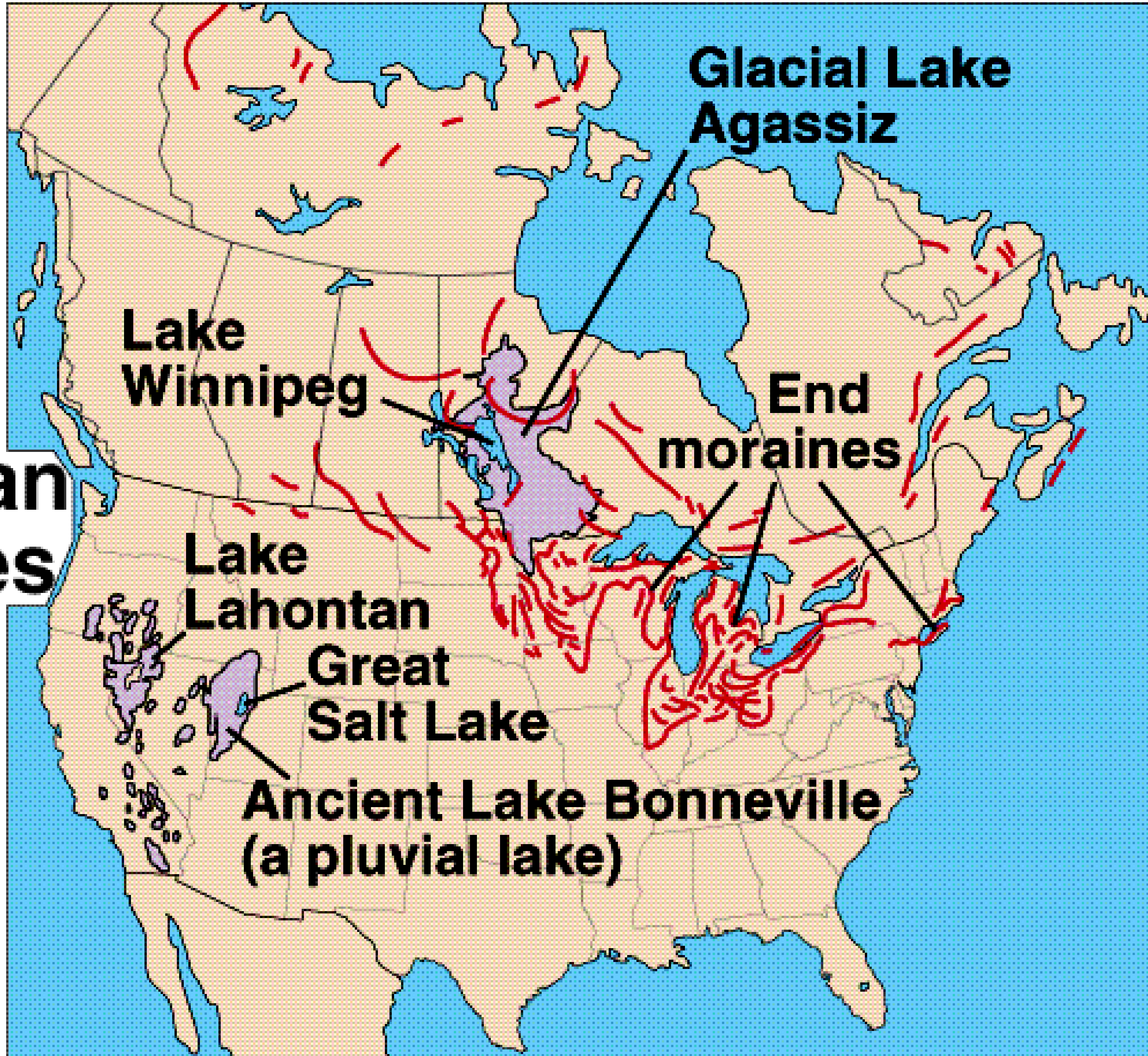
Giant gravel ripples formed during draining of Lake Missoula

Pleistocene Epoch Glaciation




Scandanavia
North Pole
Greenland
British Isles
Hudson
Bay

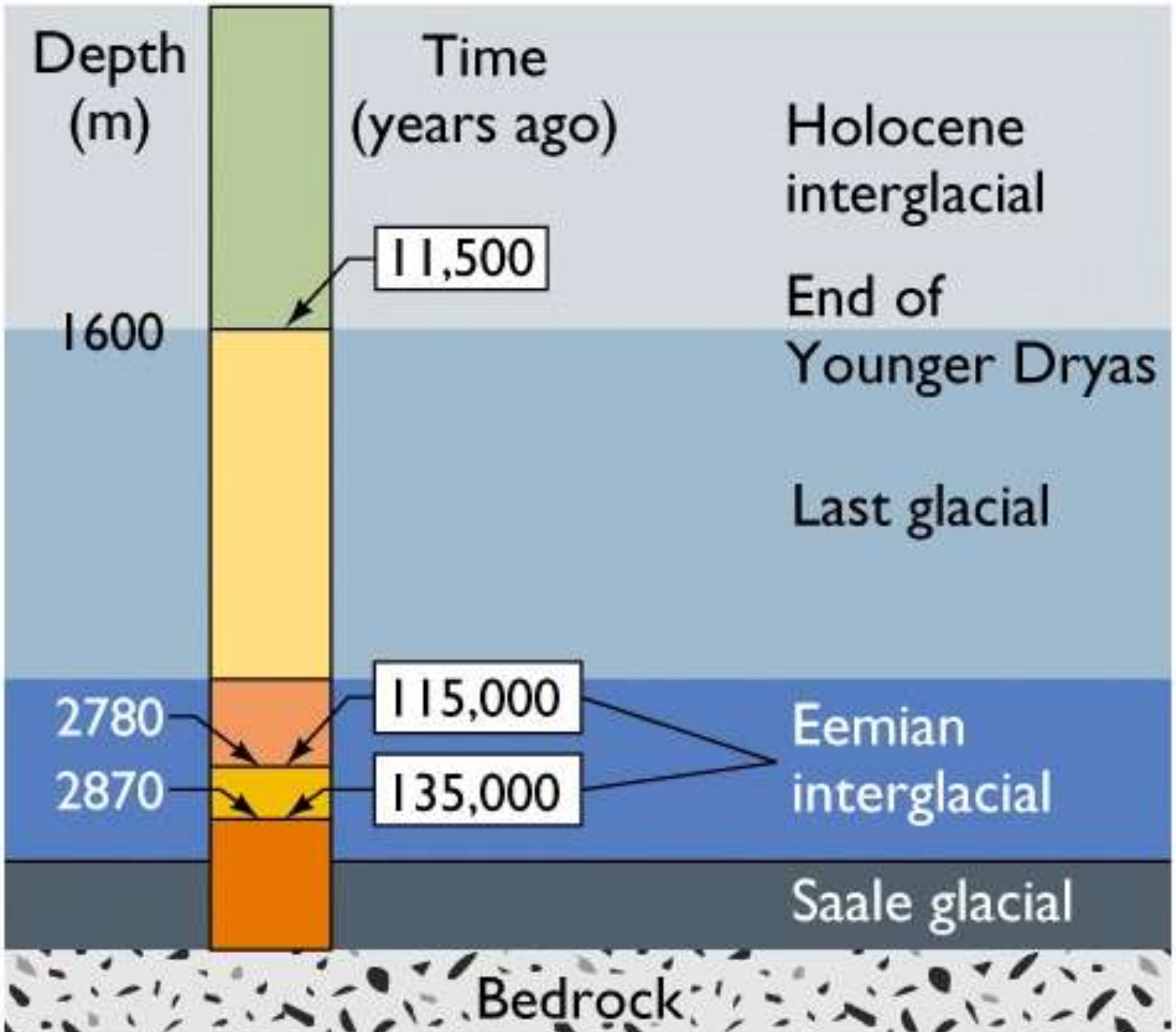
North American Moraines and Pluvial Lakes



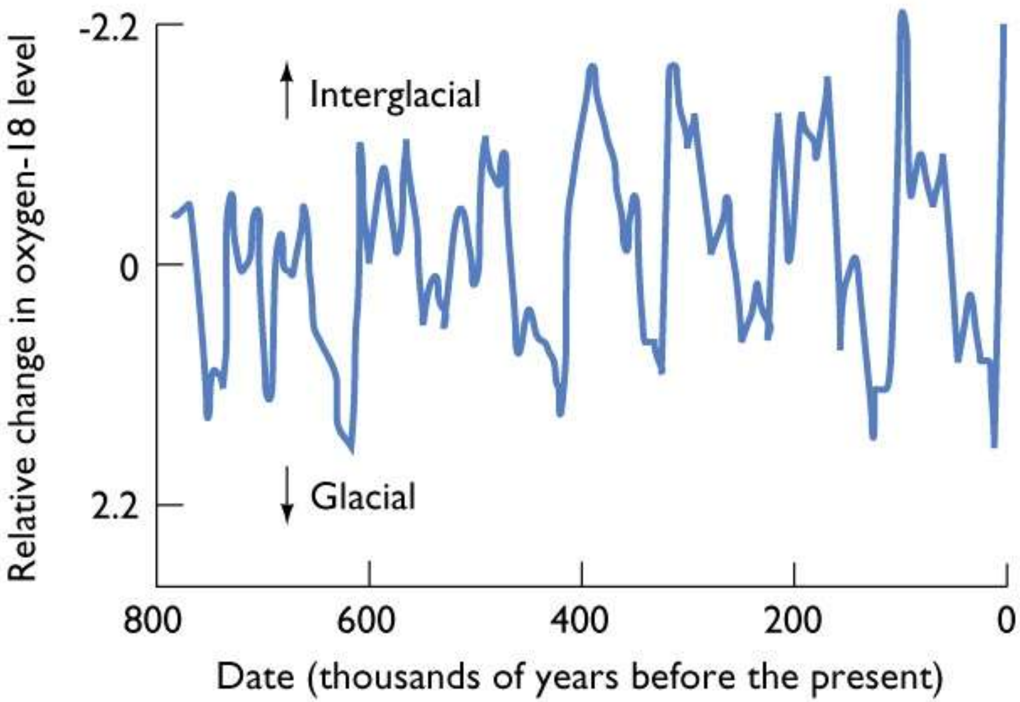
Ice cores - access to glacial records

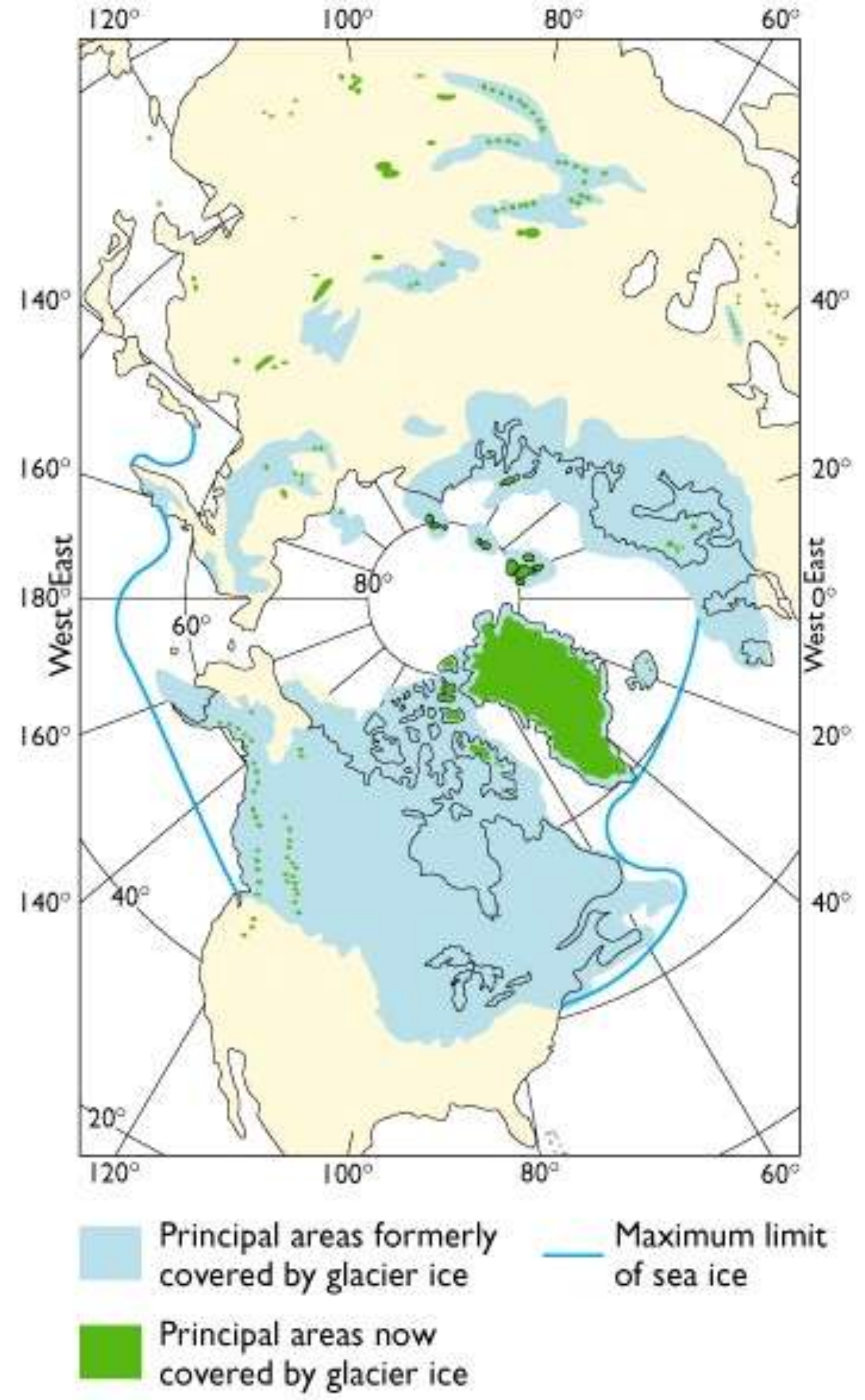
- Antarctica and Greenland
- U of A studies

Glacial stratigraphy - a record of the last 250,000 years



Pleistocene glaciation (Ice Ages)





Quaternary Period
(Pleistocene and Recent epochs)

- Evidence for glaciation
- Climate change
- Temperature changes with time
- Effects of glaciation
- Future glacial and interglacial stages

Europe till

Figure 16.2 Distribution of the drift or Diluvium containing erratic boulders associated with unsorted "boulder clay" over Europe and long considered to have been drifted in by icebergs during the biblical Flood. After 1840, it was attributed to glacial transport. *(Adapted from L. J. Wills, 1951,* A Palaeogeographical atlas; *by permission of Blackie and Son Ltd.)*

N. America climate change

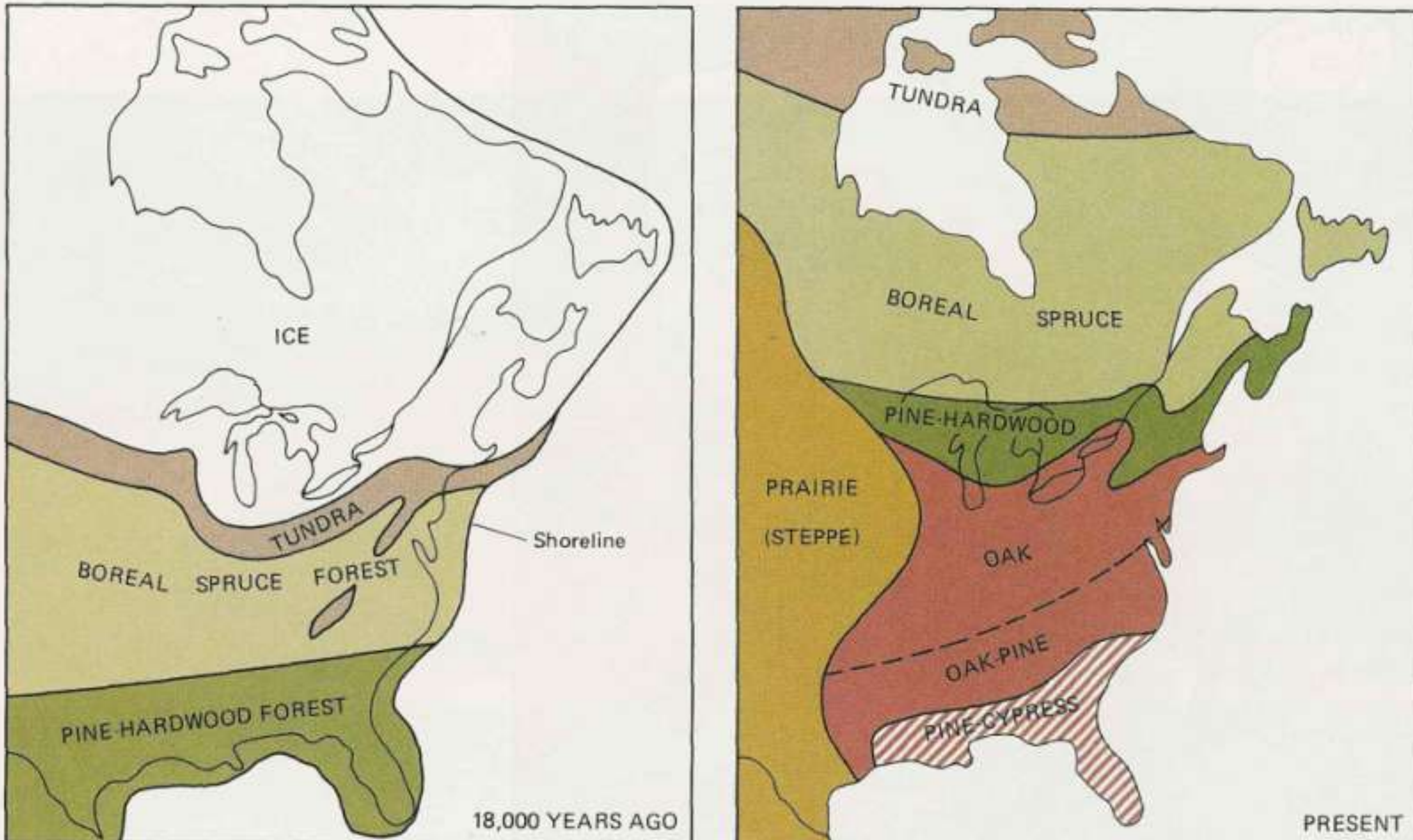


Figure 16.23 Effects of climate change on plant communities of eastern North America during the last maximum ice advance (Woodfordian) *(left)*, compared with modern native vegetation *(right)*. Past distribution at left is based largely upon studies of fossil pollen distributions. *(Adapted from Mayewski et al., 1981, in* The last ice sheets: *Wiley, pp. 67–178; Delcourt and Delcourt, 1984:* Natural History, *v. 93, no. 9, p. 24;* Goode's world atlas: *Rand McNally.)*

Europe climate change

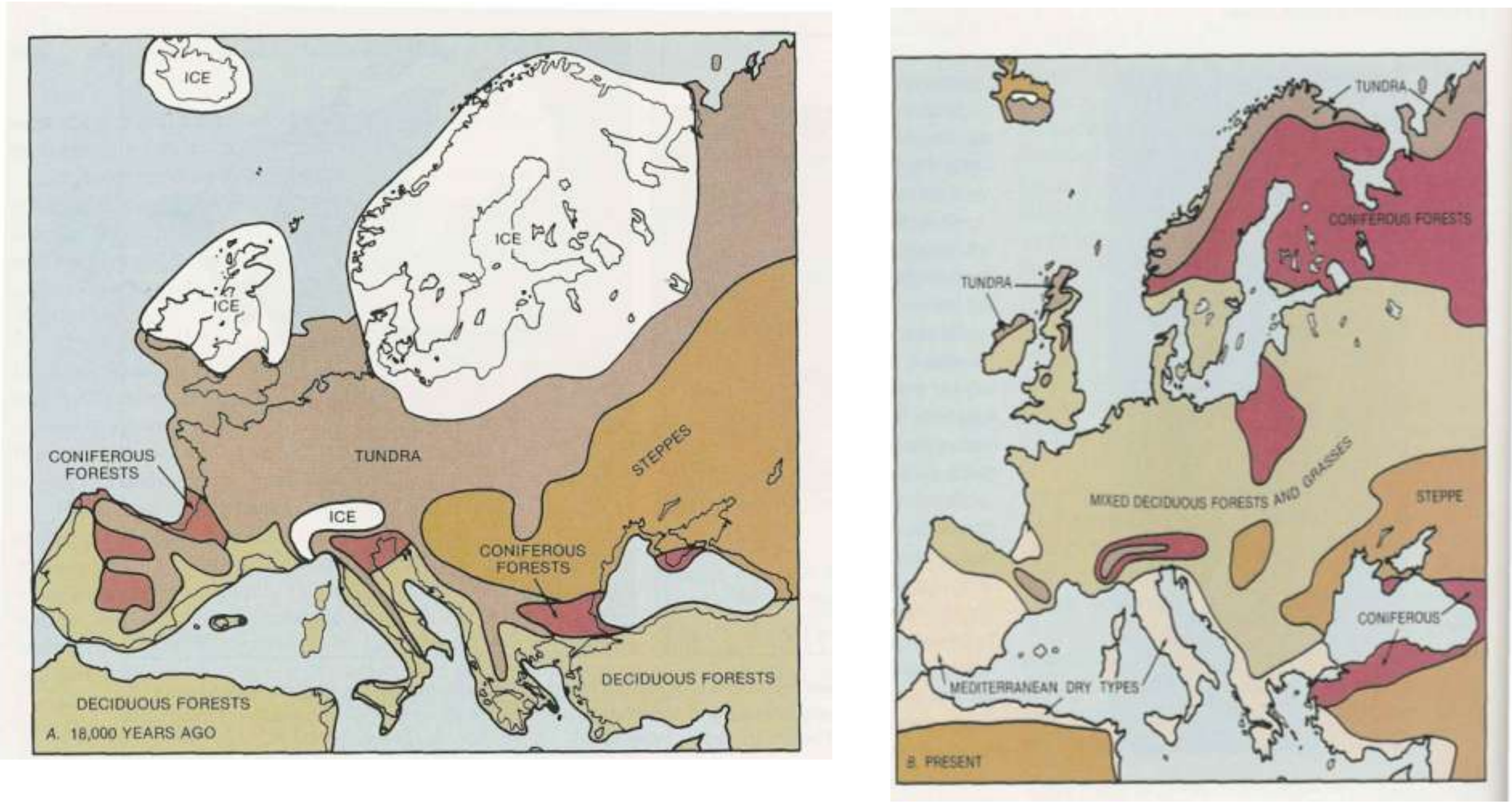


Figure 16.25 Effects of climatic changes on plant communities of Europe during the last maximum ice advance about 18,000 years ago (A), compared with native vegetation of modern Europe (B). (A adapted from Brinkmann, 1960, Geological evolution of Europe: *Ferdinand Enke*; Wills, 1951, A Palaeogeographical atlas: *Blackie & Son Ltd.*; B after *Goode's world atlas: Rand McNally Corp.*)

Climates of 18,000 yrs ago

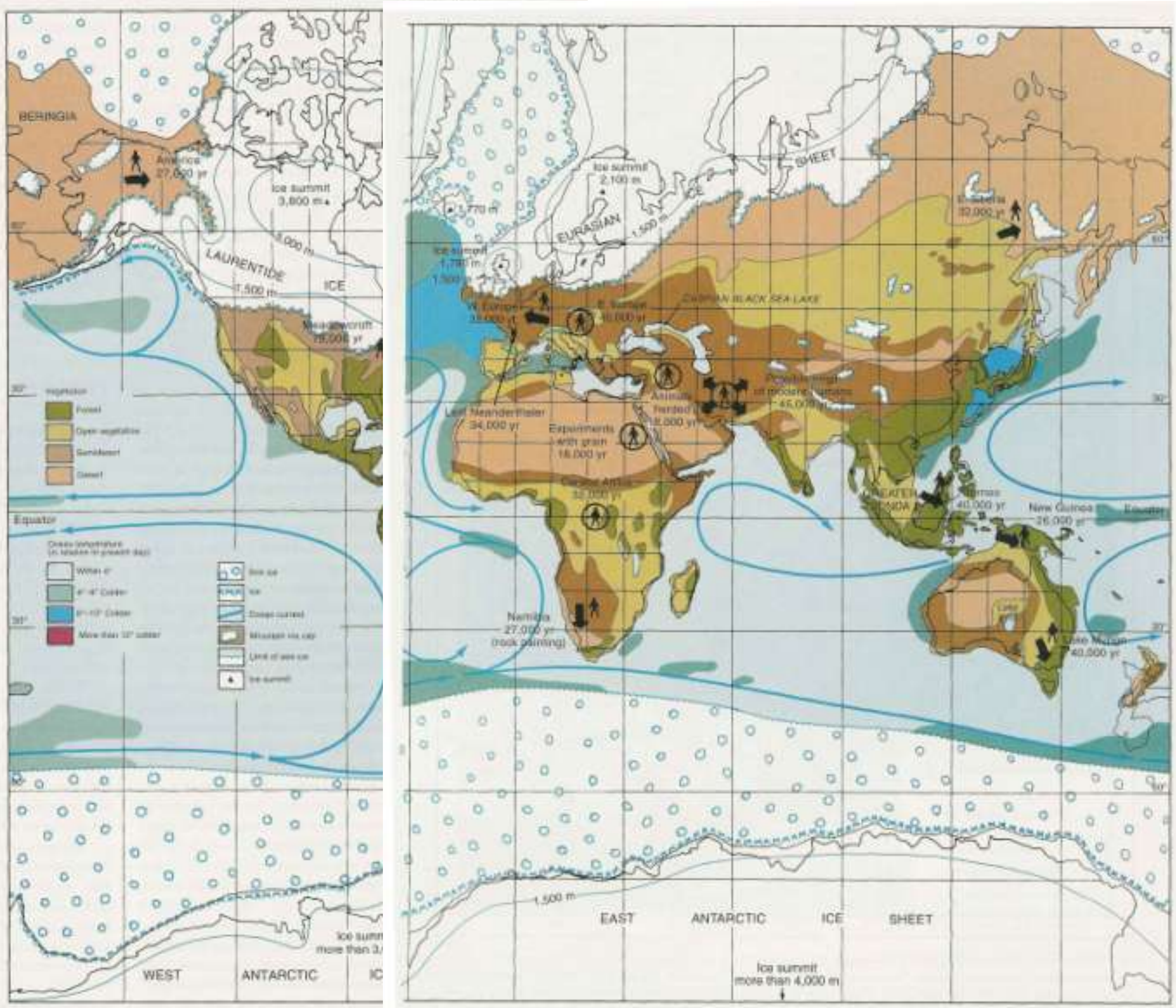
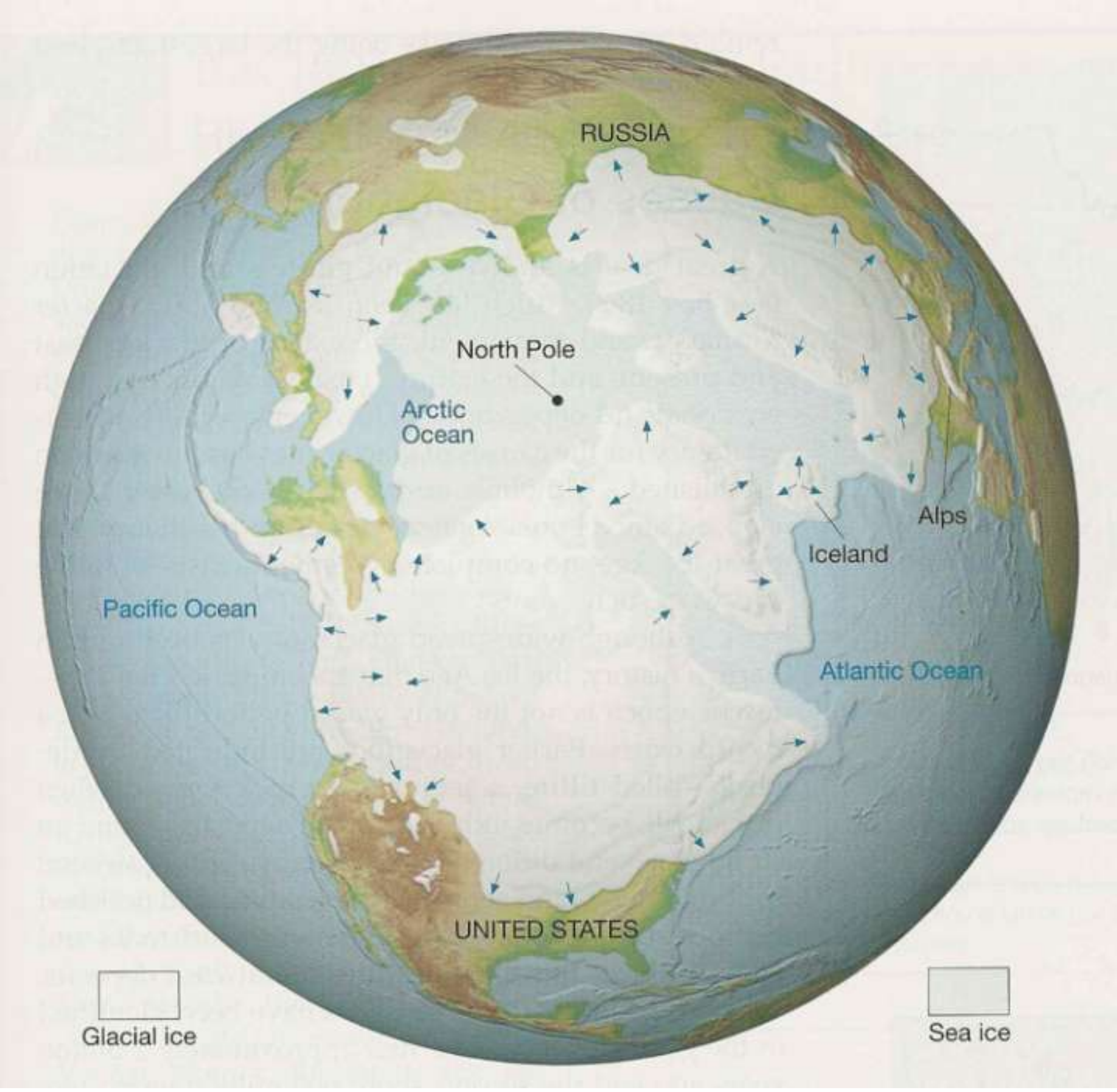


Figure 16.3 Map of global climate during the last glacial maximum 20,000 years ago. Note how far each of the ice sheets extended toward the equator, both on land and in the ocean. This changed the oceanic circulation patterns and caused all the other temperate climatic belts to shift to lower latitudes. The tropical belt did not cool, but it did shrink in size. The effect on climate was surprising. Note how the Sahara region and the western United States, which are now deserts, were once wet and fertile. Expanded glaciers also locked up so much seawater that much of the continental shelf was exposed, enlarging the coastal plains of many regions. Important migration of humans and cultural breakthroughs are also shown. *(Modified from N. Calder, 1983, Timescale, Viking, New York.)*

Pleistocene maximum glaciation



Pleistocene paleo-geography

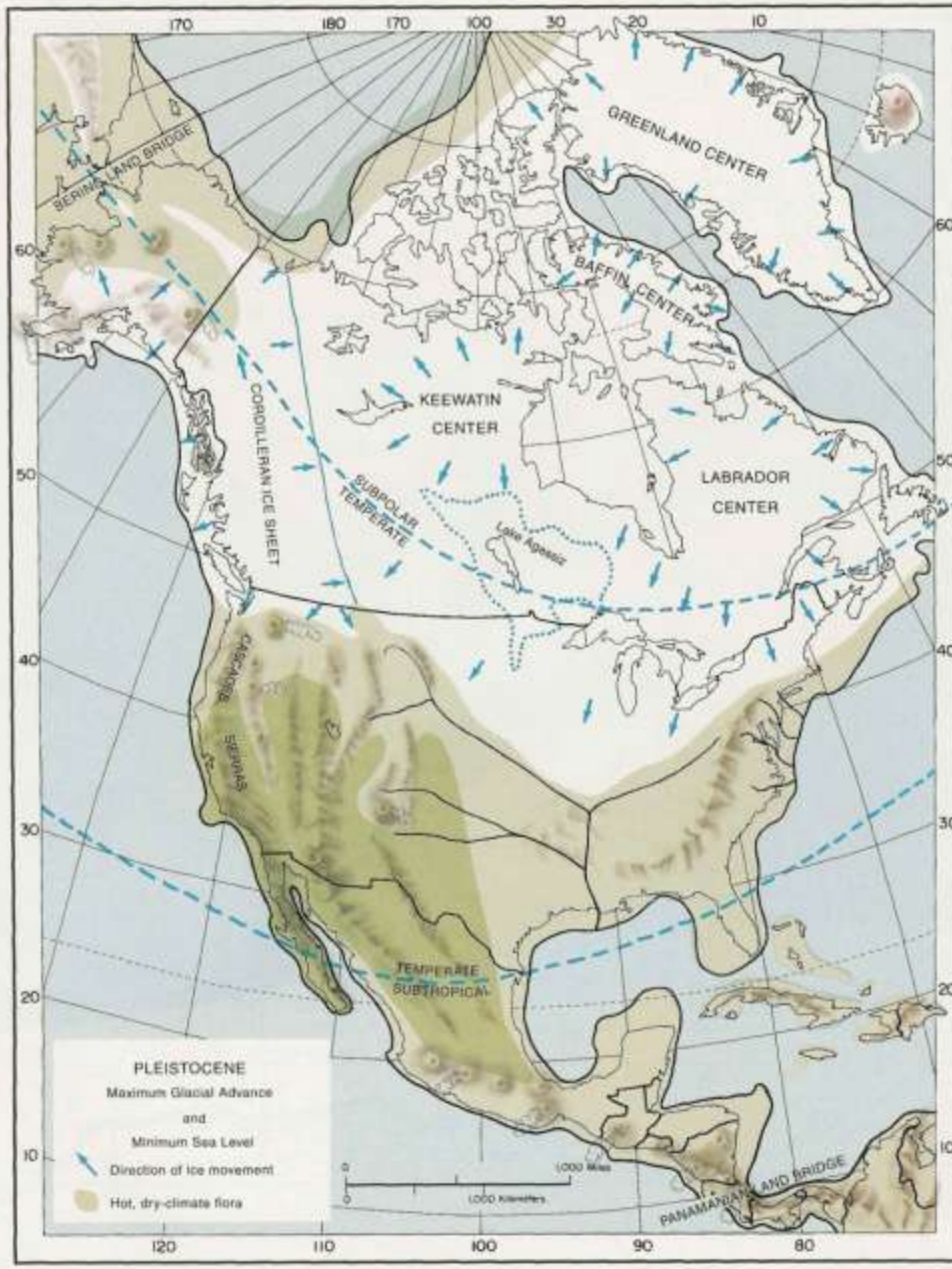


Figure 16.4 Pleistocene paleogeography of North America showing maximum ice advance and retreat of the sea, immediate postglacial Lake Agassiz, Cascade and other volcanoes, and late Pleistocene desert floras in the southwest. Joining of Cordilleran ice caps with main Canadian Shield cap in western Canadian plains blocked migrations of organisms to and from Asia during glacier advances. Note Bering and Panamanian land bridges.

Post-glacial uplift

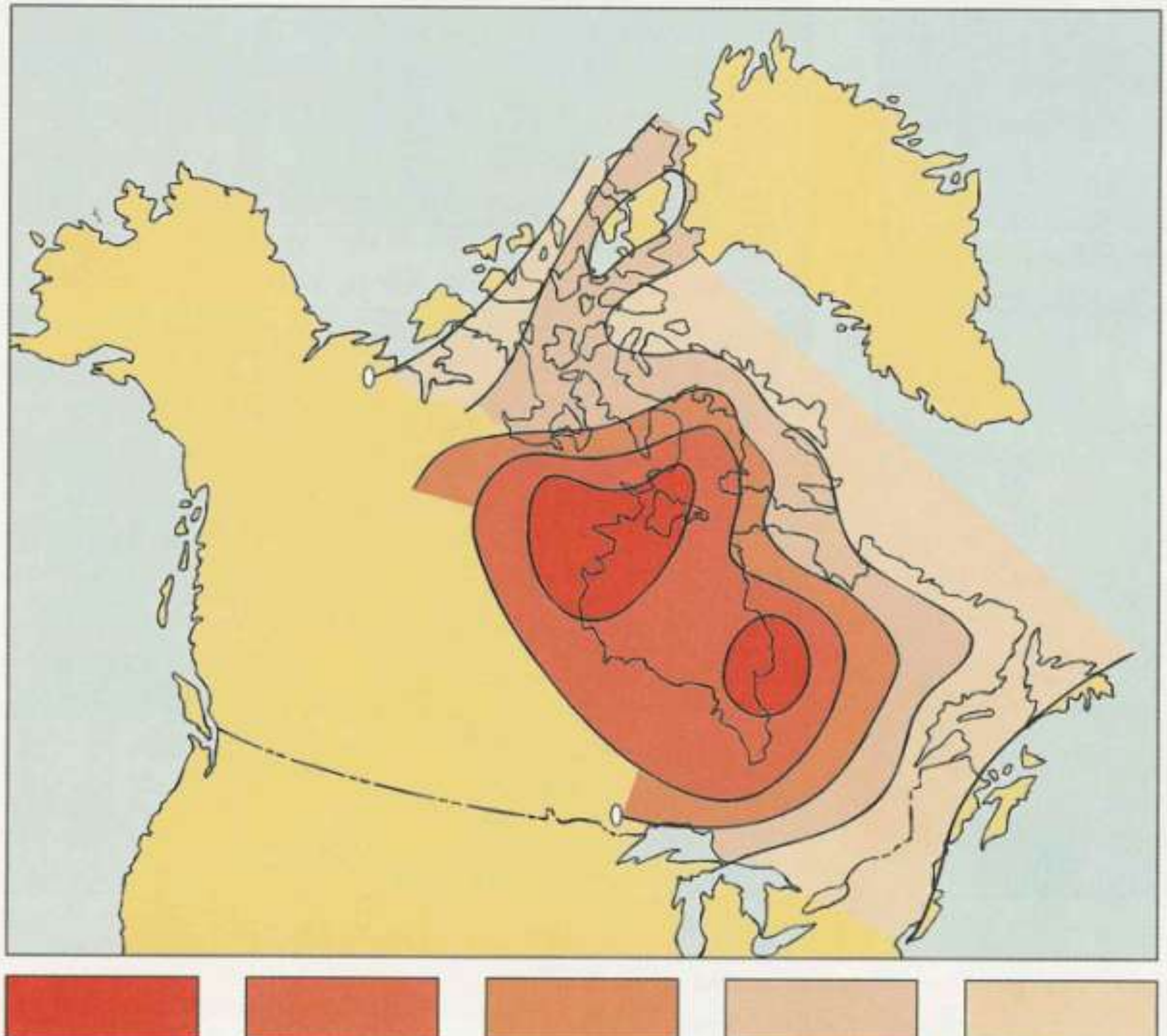
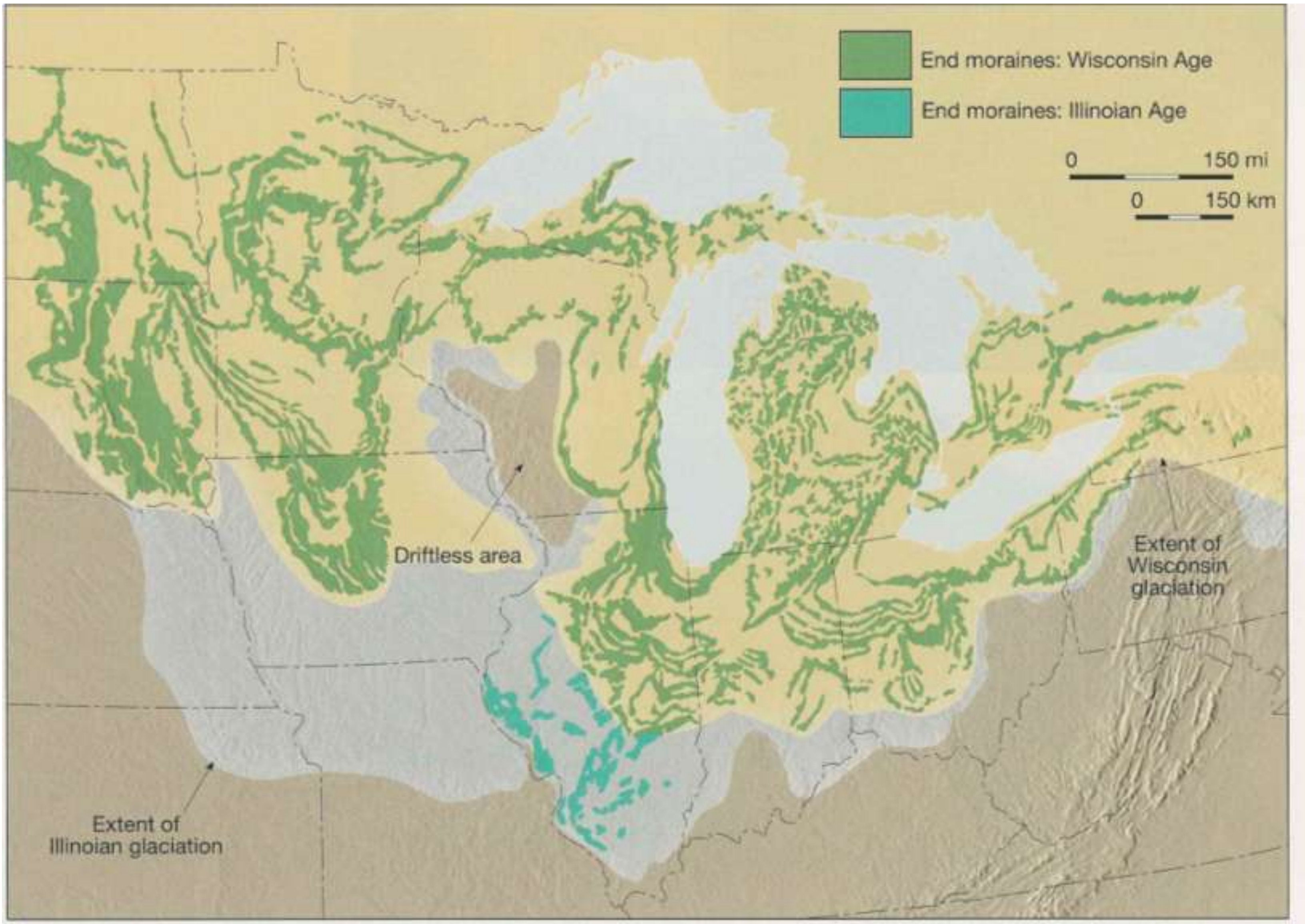


FIGURE 13-46 Postglacial uplift of North America, determined by measuring elevation of marine sediments 6000 years old. (*Simplified and adapted from Andrews, J. T. 1969.* The pattern and interpretation of restrained, postglacial and residual rebound in the area of Hudson Bay, *in* Earth Science Symposium on Hudson Bay, Ottawa, *1968, Canadian Geological Survey Paper 68–53, p. 53.*)

US end moraines



IGURE 18.23 End moraines of the Great Lakes region. Those deposited during the most recent (Wisconsinan) stage are most prominent

Finger Lakes, NY

Pluvial – lakes in the West

▲ **FIGURE 18.30** Pluvial lakes of the Western United States. (After R. F. Flint, *Glacial and Quaternary Geology*, New York: John Wiley & Sons)

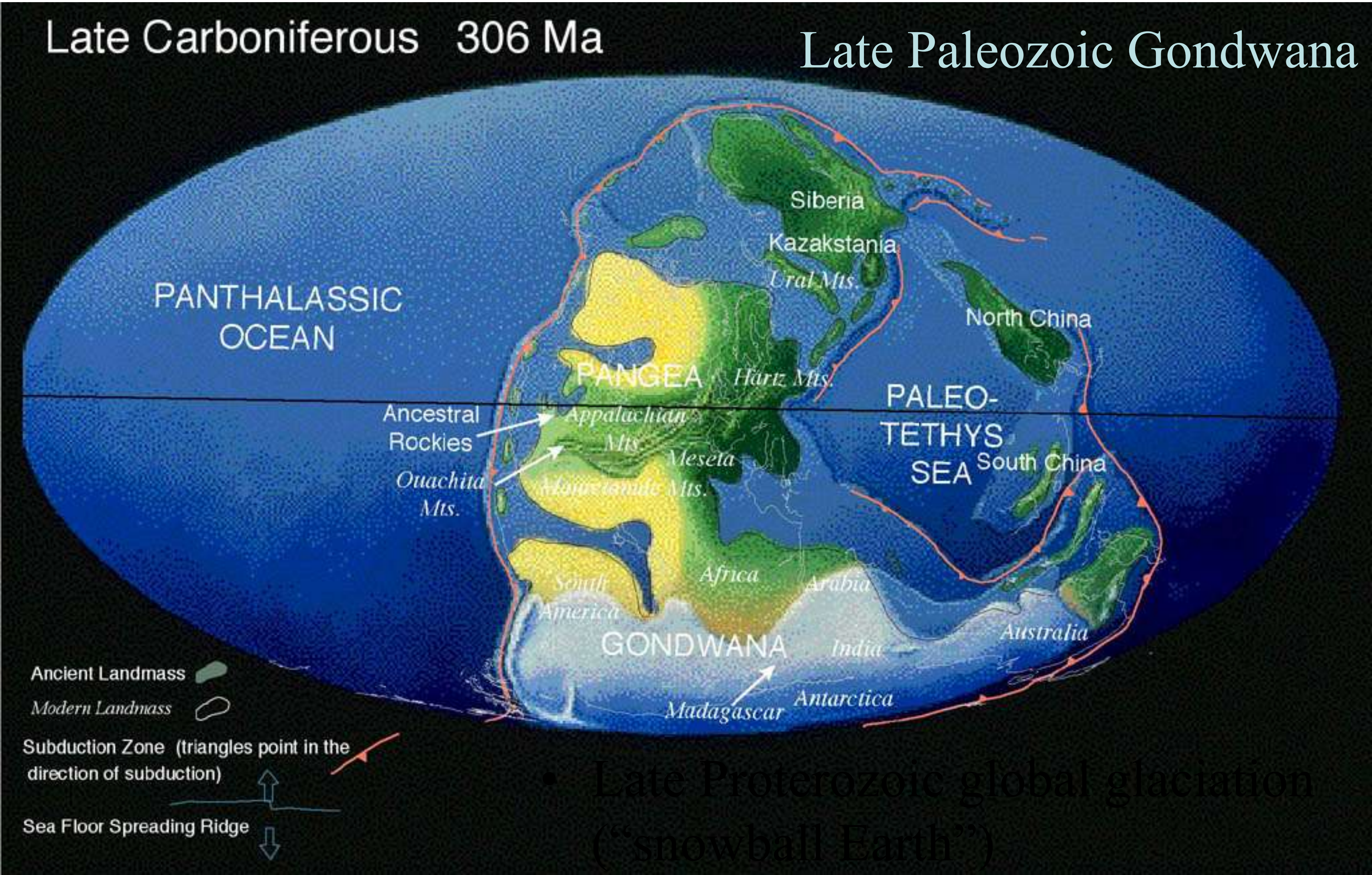
Evidence for Older Glaciation

- Rocks called *tillites*, lithified glacial till, have distinctive textures that suggest emplacement of sediments by glaciers
  - Unsorted rock particles including angular, *faceted* and *striated* boulders
- In some areas, old tillites directly overlie *polished* and *striated* crystalline rocks
- *Tillites* formed during the late Precambrian and late Paleozoic eras exist in portions of the southern continents
- Late Paleozoic *tillites* from South Africa, Australia, Antarctica and South America indicate that these landmasses were once joined - strong evidence supporting *Theory of Plate Tectonics*

Ancient glaciations

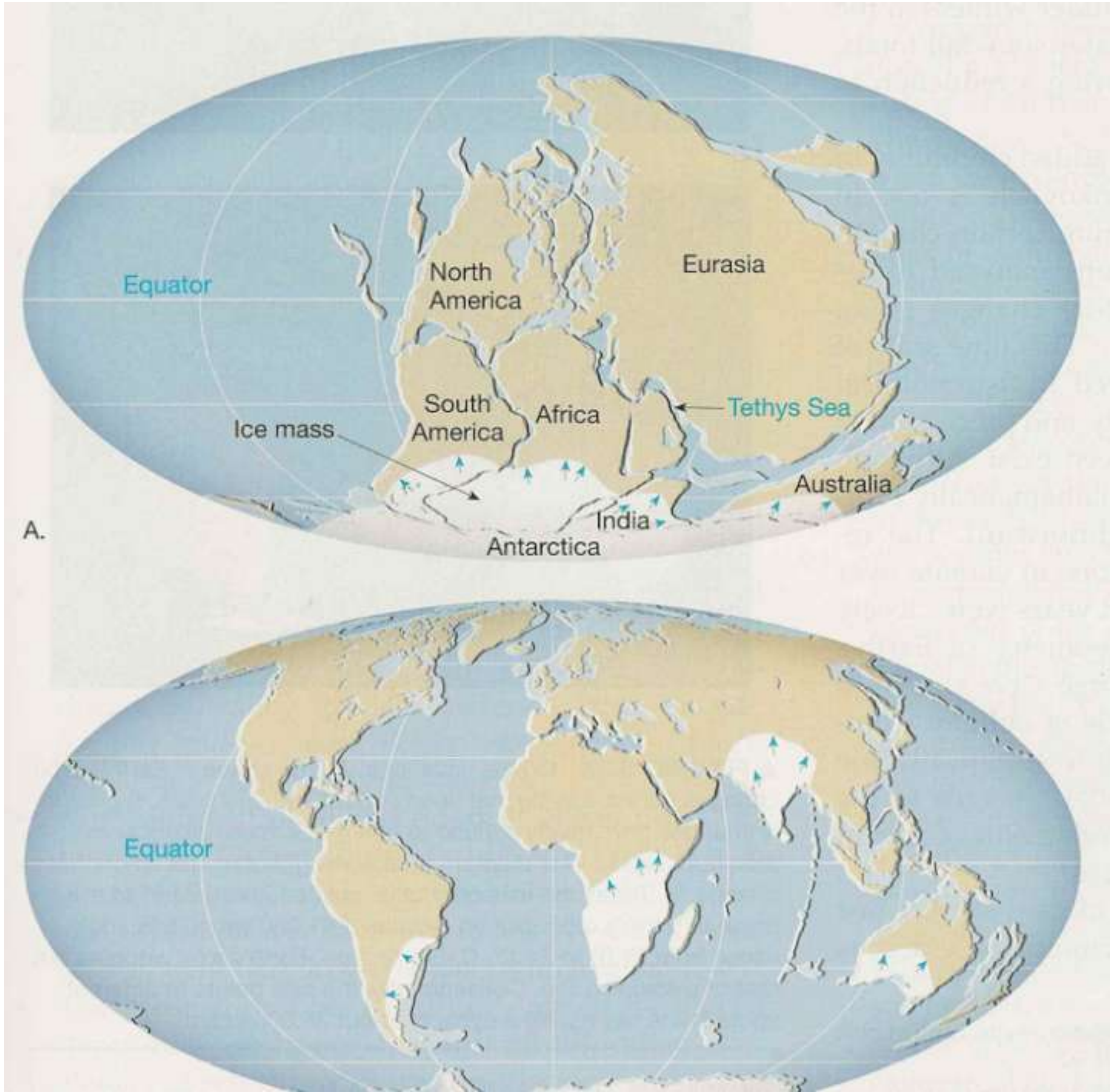
"Tillites" in the geologic record

Late Paleozoic Gondwana



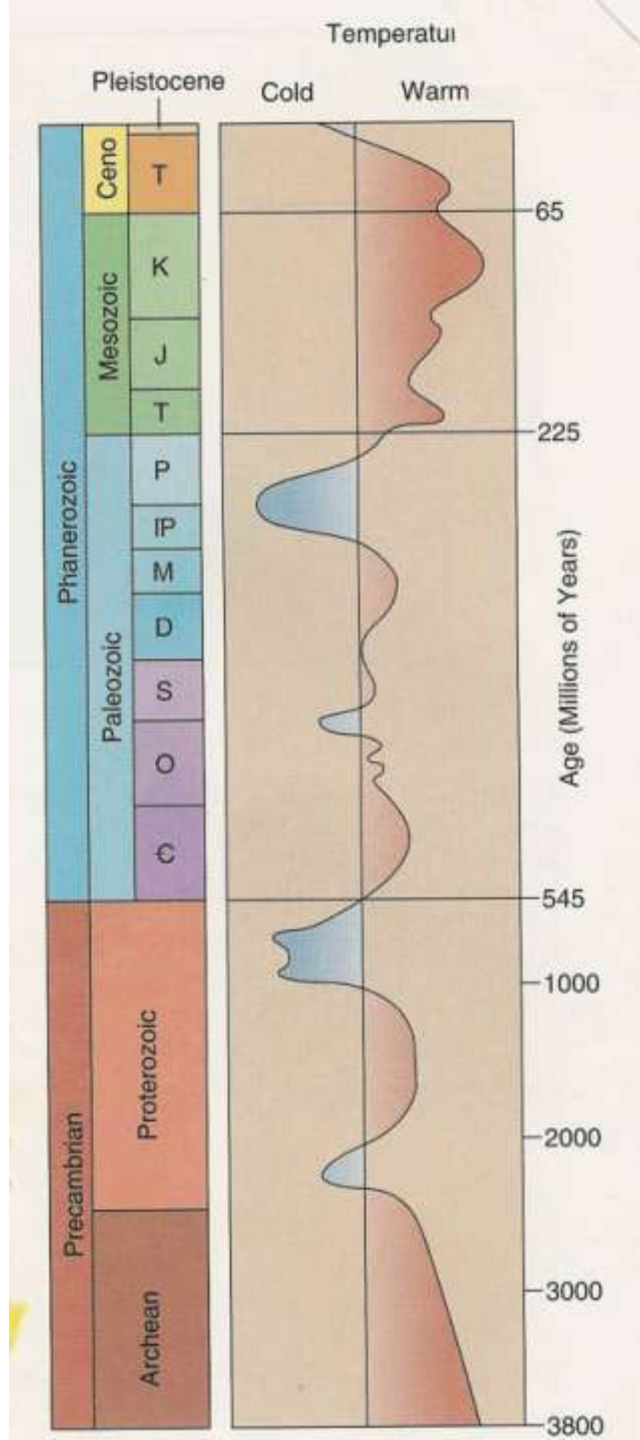
- Late Proterozoic global glaciation ("snowball Earth")

Permian Ice Age



Glaciation through Geologic time

Figure 14.37 Several periods of glaciation have been identified in Earth's long history that may record changes in the surface temperature. The graph shows one estimate of relative temperature changes with time. The curve shows when temperatures were higher (to the right) or lower (to the left) than today.



Evidence for Older Glaciation

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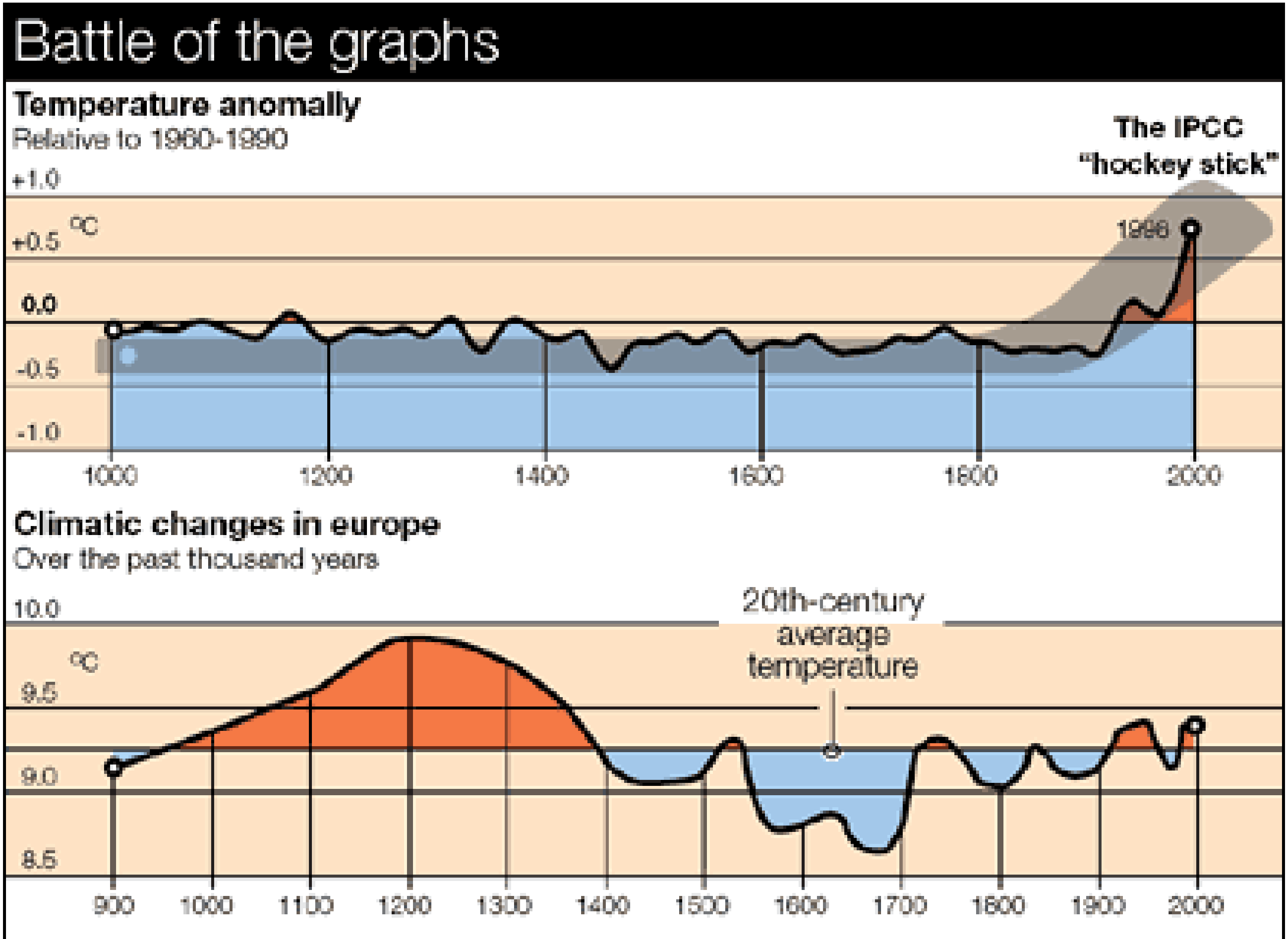
- Late Paleozoic *tillites* from South Africa, Australia, Antarctica and South America indicate that these landmasses were once joined - strong evidence supporting *Theory of Plate Tectonics*

Controversial science



Temperature change, 5500 years

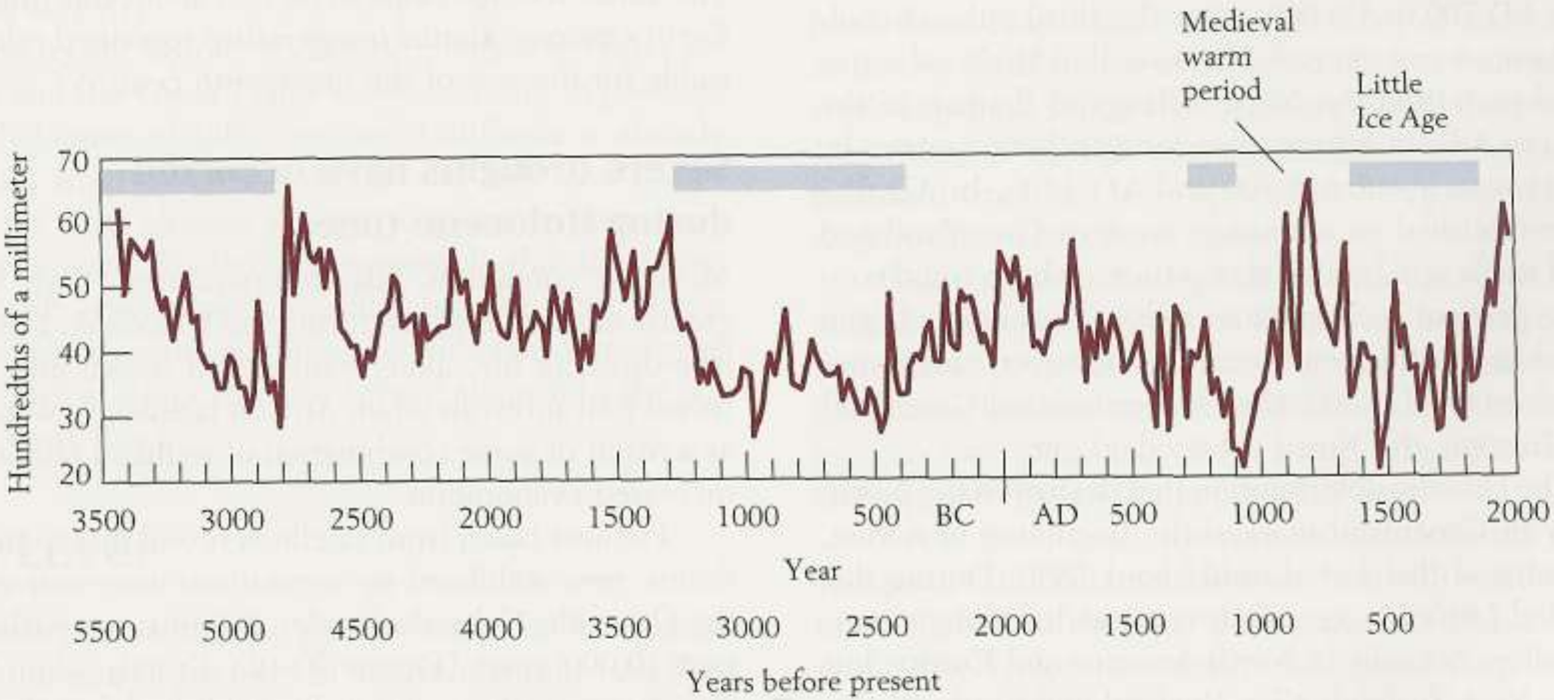


Figure 20-10 Cold intervals of the past 5500 years recorded by widths of annual growth rings in bristlecone pines near the upper tree line of the White Mountains of California. (Data from V. C. La Marche, in H. H. Lamb, *Climate History and the Modern World*, Routledge, London, 1995.)

Last 10,000 yrs temperature

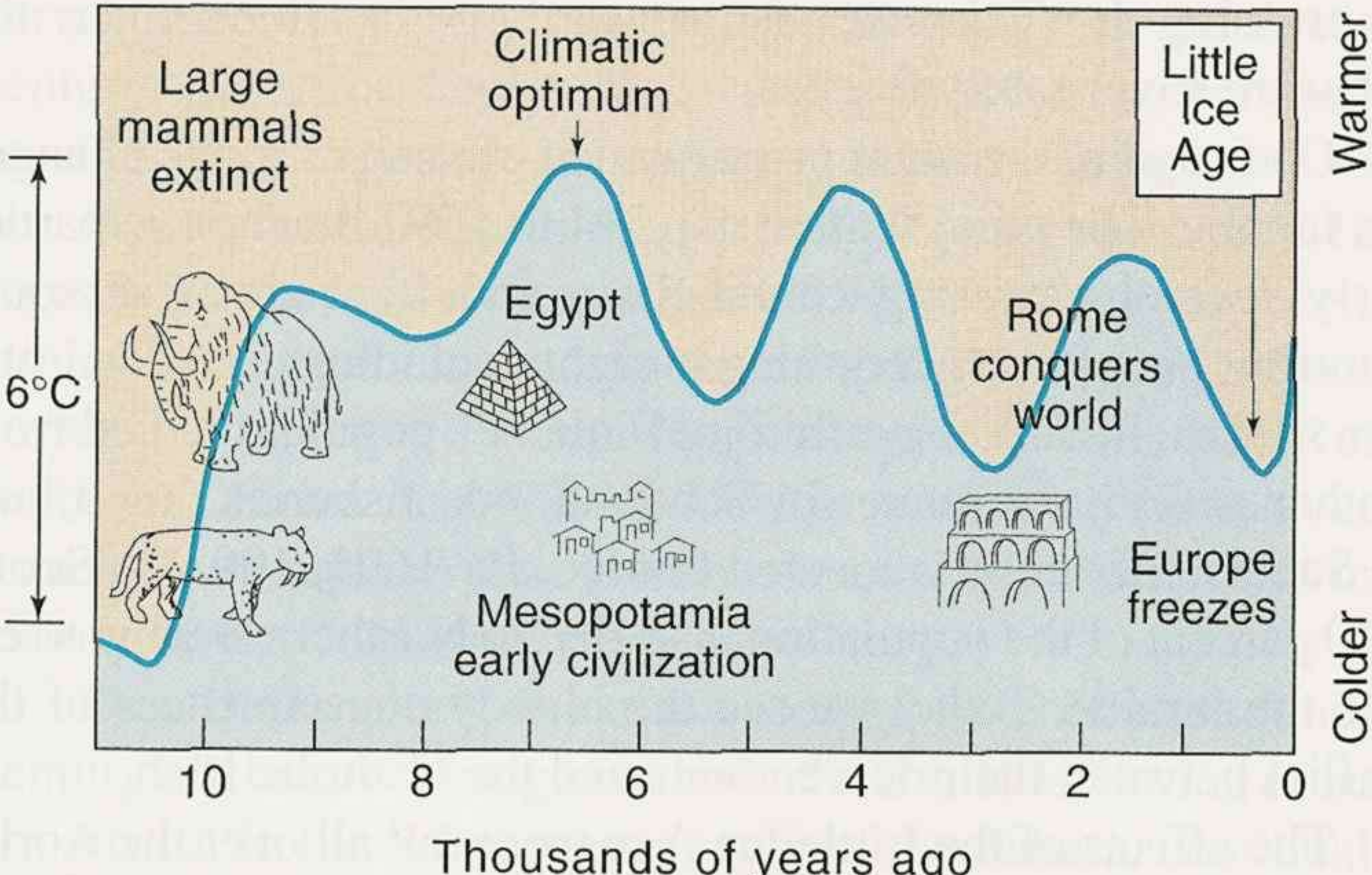
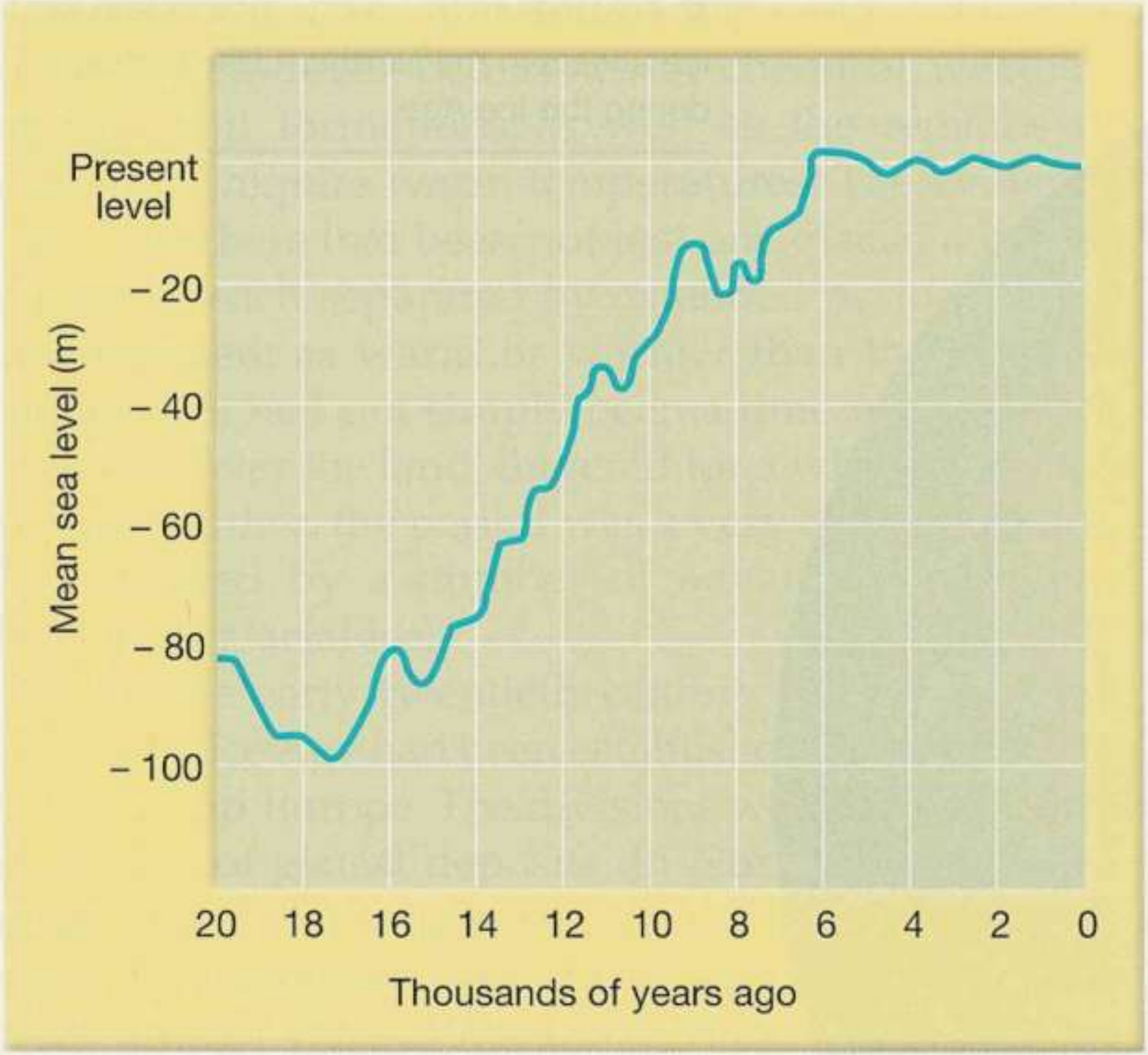


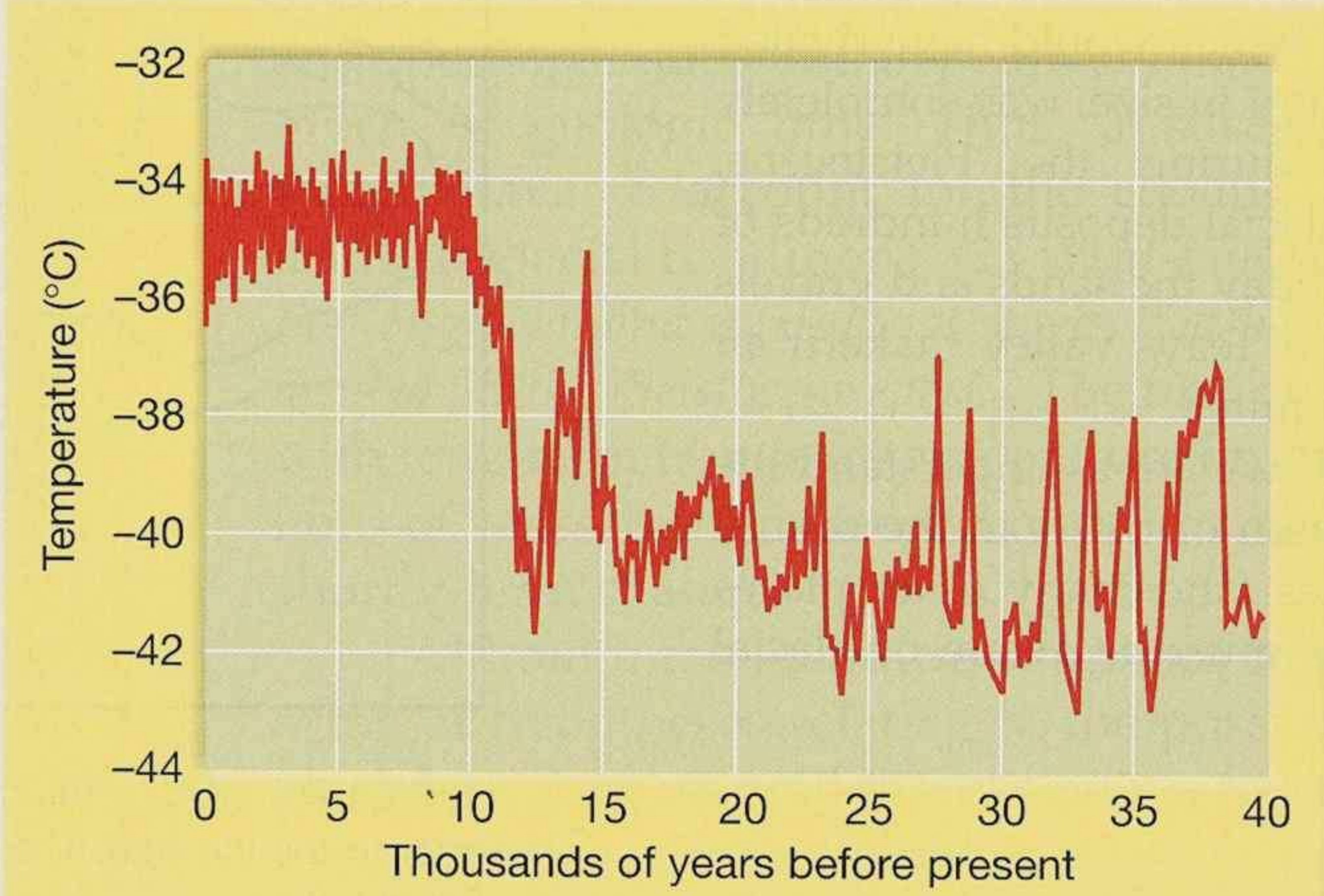
Figure 16.35 The effects of climatic cycles on the past 10,000 years of human history.

Temperature curve – 20,000 yrs



▲ **FIGURE 18.29** Changing sea level during the past 20,000 years. The lowest level shown on the graph represents the time about 18,000 years ago when the most recent ice advance was at a maximum.

40,000 yrs temp change



▲ **FIGURE 18.E** This graph showing temperature variations over the past 40,000 years is derived from oxygen isotope analysis of ice cores recovered from the Greenland ice sheet. *(After U.S. Geological Survey)*

Climate Change 160,000 yrs

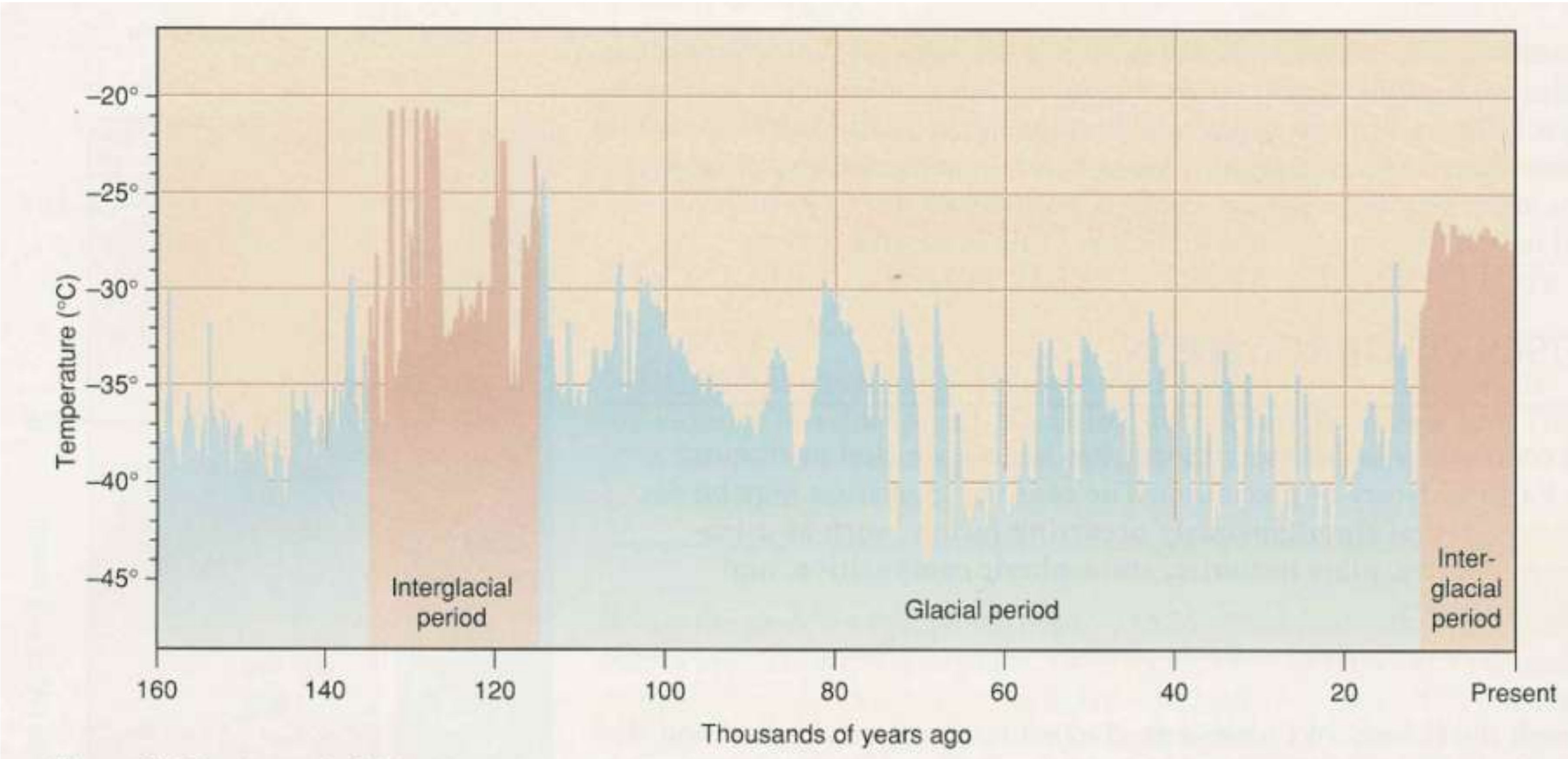


Figure 14.38 A record of climatic change during the last 160,000 years was assembled from studies of ice cores from Greenland's glacier. It shows that the normal pattern of change involves numerous rapid fluctuations in temperature—not only during glacial periods, but throughout interglacial periods as well. The stable warm temperature of the present interglacial period is distinctly abnormal.

1,000,000 years temperature change

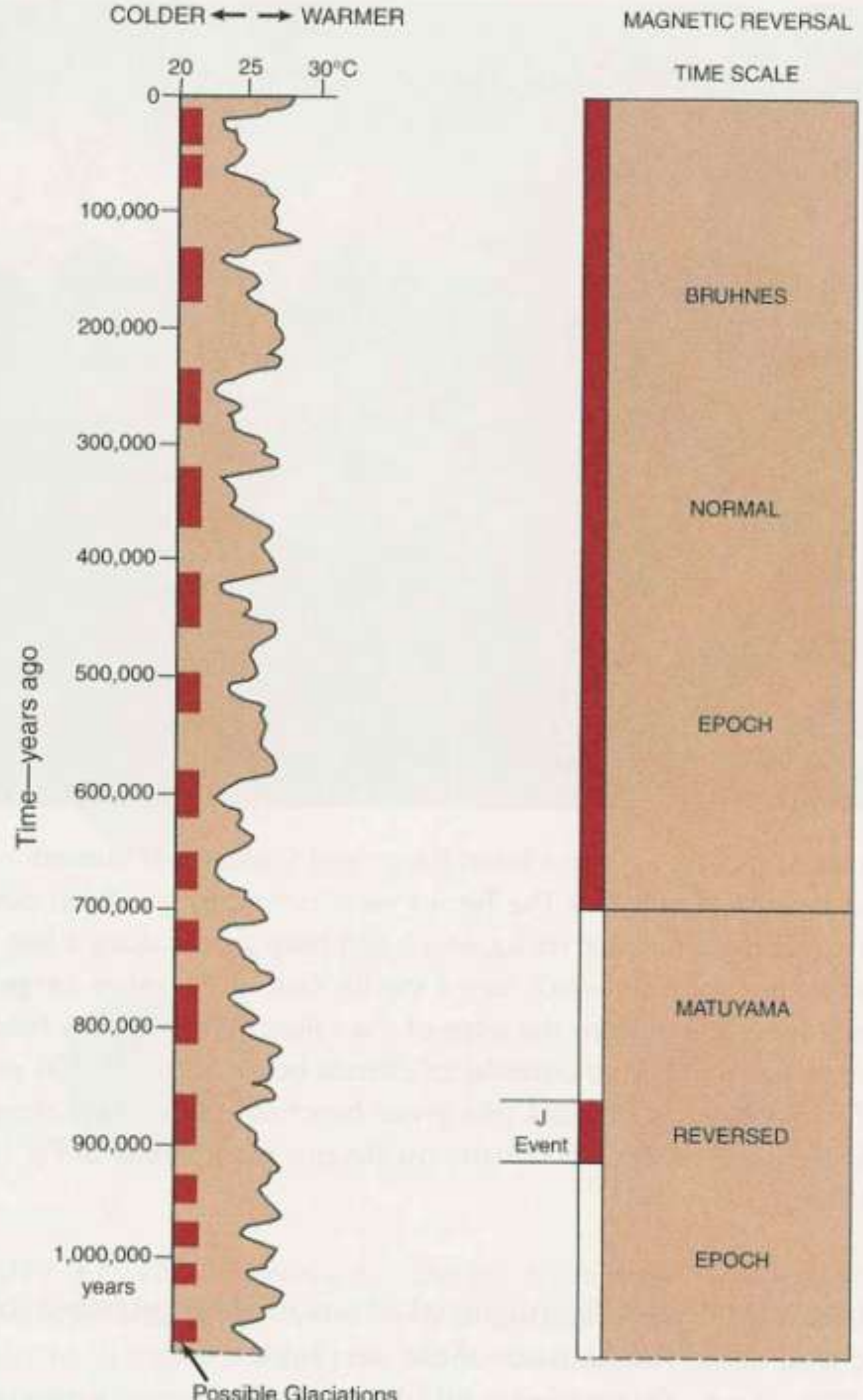


Figure 16.16 Late Pleistocene standard marine paleotemperature curve *(left)* based upon oxygen-isotope analyses of calcium carbonate in microfossil shells from deep-sea cores of three oceans. Magnetic polarity measurements on the same cores *(right)* and limited isotopic dating of cores provide a time scale. Note that, for the last 600,000 years, cold intervals had a periodicity of about 100,000 years; from then back to about 1.4 million years, the period was about 40,000 years (J—Jaramillo brief normal polarity event). *(Adapted from Emiliani and Shackleton, 1974: Science, v. 183, pp. 511–514; and Shackleton and Opdyke, 1976:* Geological Society of America Memoir 145, *pp. 449–464.)*

Carbon dioxide, last 100,000,000 years

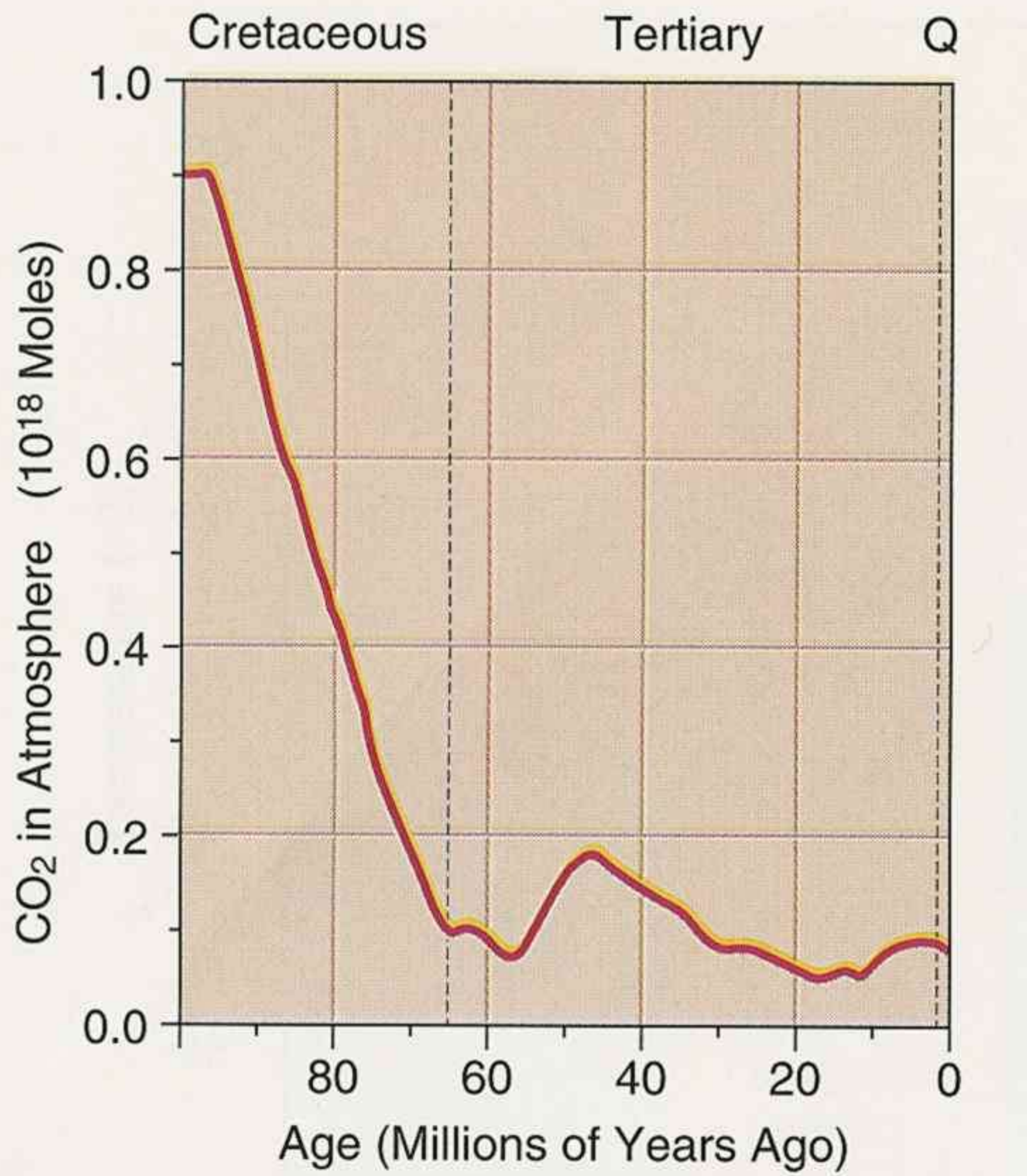


Figure 14.40 The abundance of carbon dioxide in Earth's atmosphere has declined dramatically during the last 100 million years. Loss of this important greenhouse gas may have allowed Earth to cool enough for glaciers to accumulate.

Glacial and Interglacial stages

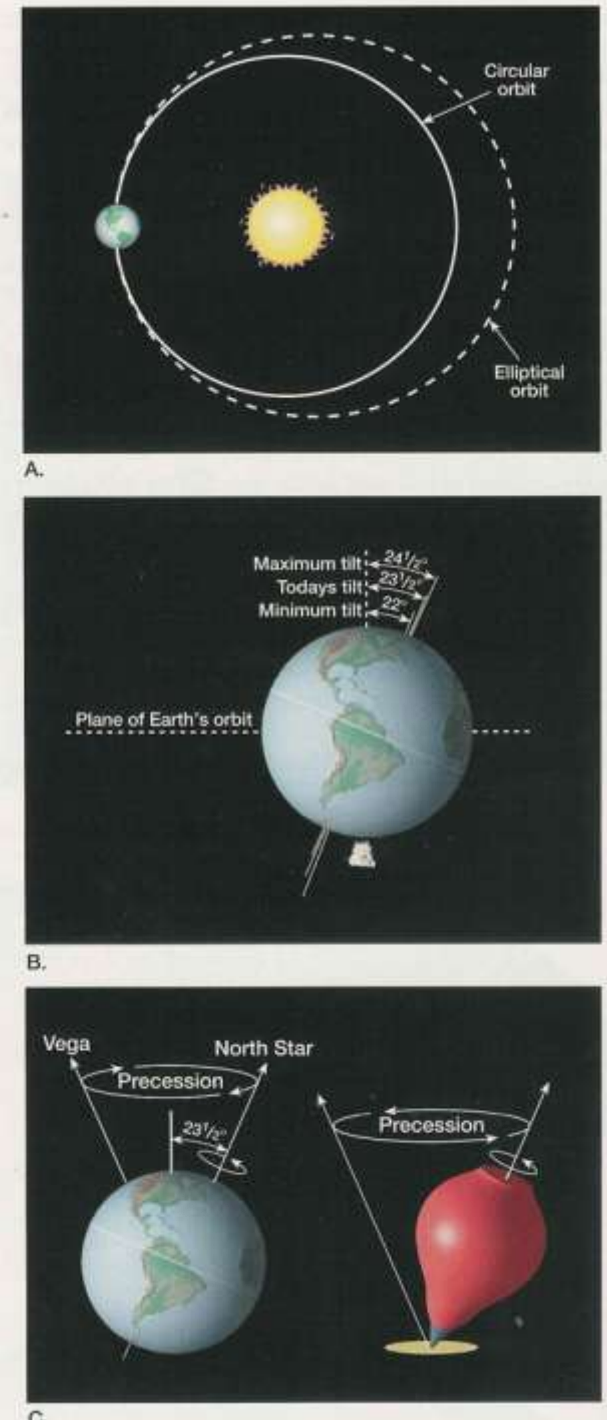
TABLE 13–2 Classic Nomenclature for Glacial and Interglacial Stages of the Pleistocene Epoch

NORTH AMERICA	ALPINE REGION	YEARS BEFORE PRESENT
		—10,000
WISCONSIN	Würm	
		—75,000
Sangamon	Riss-Würm	
		—125,000
ILLINOIAN	Riss	
		—265,000
Yarmouth	Mindel-Riss	
		—300,000
KANSAN	Mindel	
		—435,000
Aftonian	Günz-Mindel	
		—500,000
NEBRASKAN	Günz	
		—1,800,000
Pre-Nebraskan	Pre-Günz	

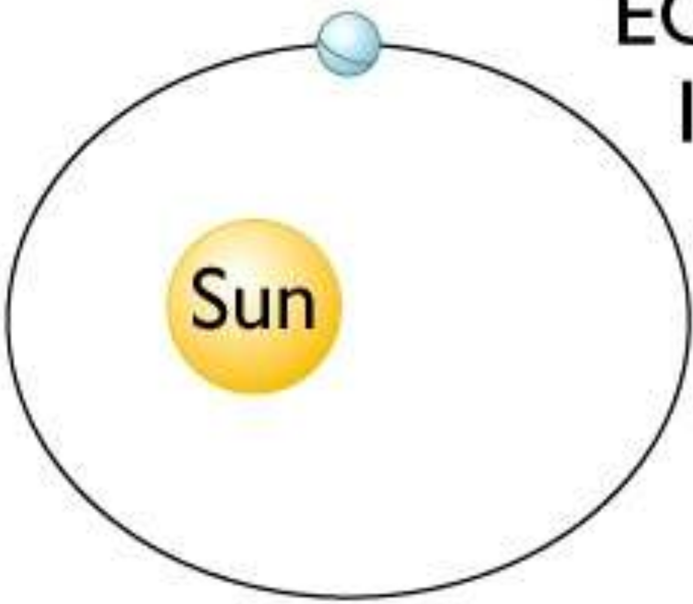
In North America, the glacial stages are Nebraskan, Kansan, Illinoian, and Wisconsinian. These terms correspond approximately to the Günz, Mindel, Riss, and Würm in Europe.

Milankovitch causes of glaciation

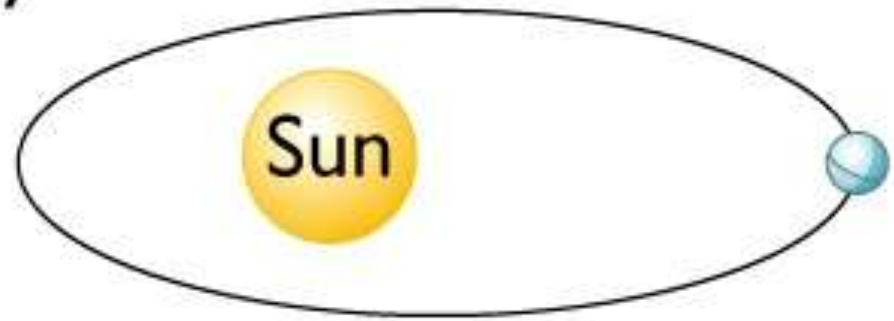
▲ **FIGURE 18.32** Orbital variations. **A.** The shape of Earth's orbit changes during a cycle that spans about 100,000 years. It gradually changes from nearly circular to one that is more elliptical and then back again. This diagram greatly exaggerates the amount of change. **B.** Today the axis of rotation is tilted about 23.5° to the plane of Earth's orbit. During a cycle of 41,000 years, this angle varies from 21.5° to 24.5°. **C.** Precession. Earth's axis wobbles like that of a spinning top. Consequently, the axis points to different spots in the sky during a cycle of about 26,000 years.



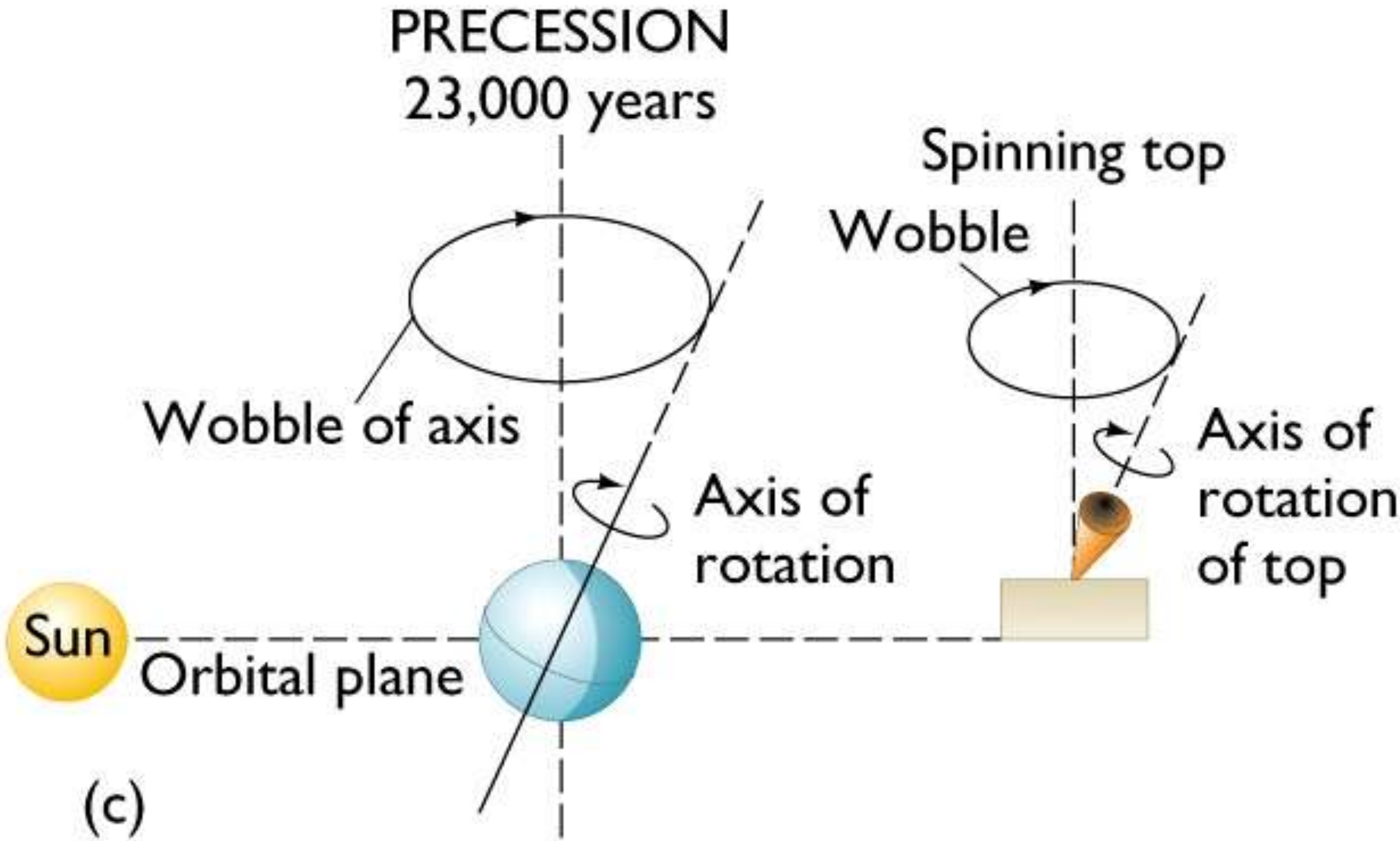
ECCENTRICITY
100,000 years



Low eccentricity



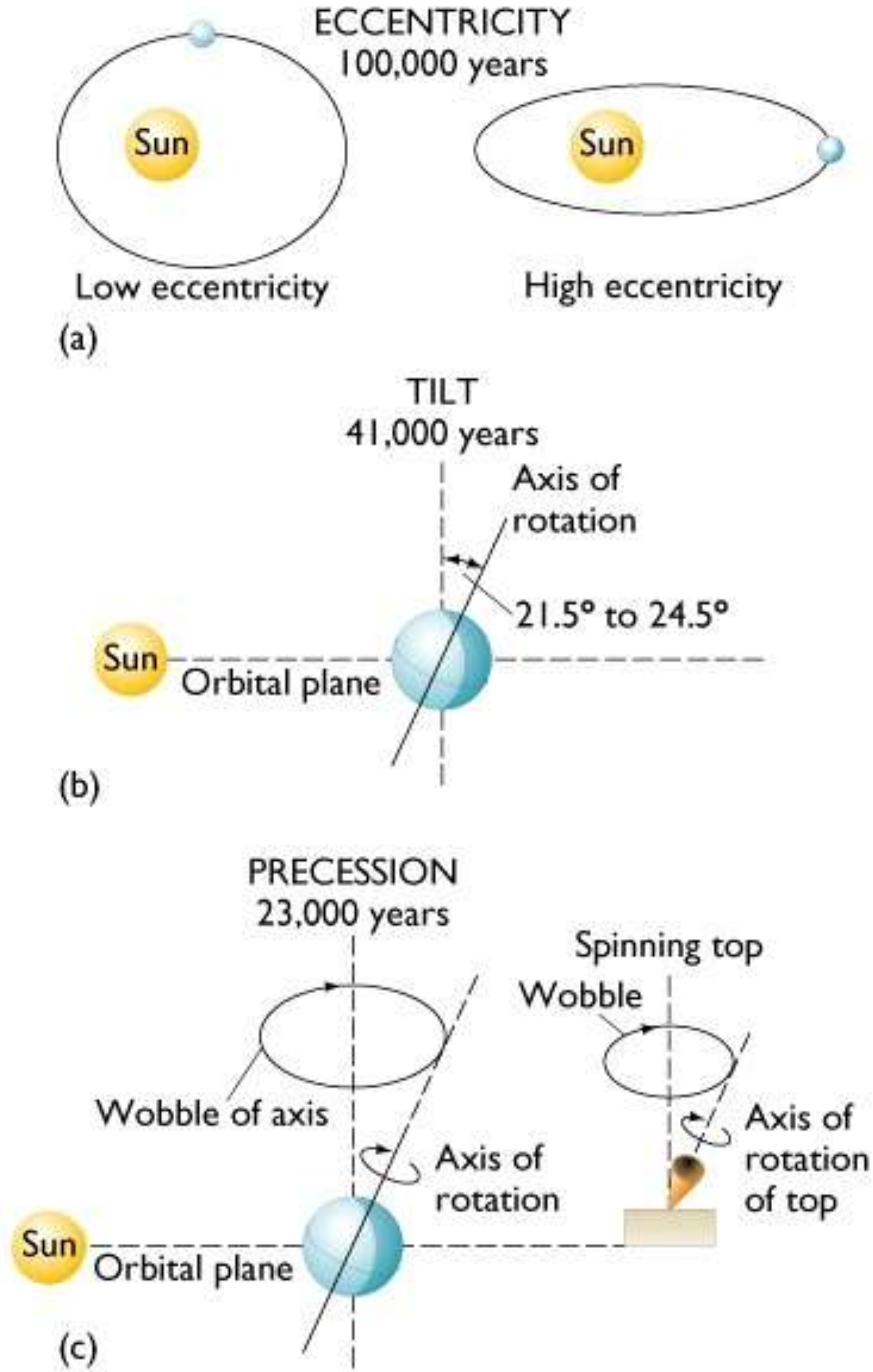
High eccentricity


PRECESSION
23,000 years
Spinning top
Wobble
Wobble of axis
Axis of rotation
Axis of rotation of top
Sun
Orbital plane
(c)

Orbital forcing of climate

- Periodic changes in
  - The eccentricity of the Earth's orbit
  - The tilt of the axis of rotation, and
  - The precession (wobble) of the Earth's axis of rotation

change solar heating and trigger ice ages



Milankovitch curves

Table 16.2 Milankovitch Orbital Factors

Parameter	Relative Variation	Approximate Periods
Eccentricity of the orbit (ellipticity)	0.017–0.053	100,000 years
Tilt of the axis (obliquity)	21½–24½°	41,000 years
Precession of the axis (wobble)	0–360°	23,000 years

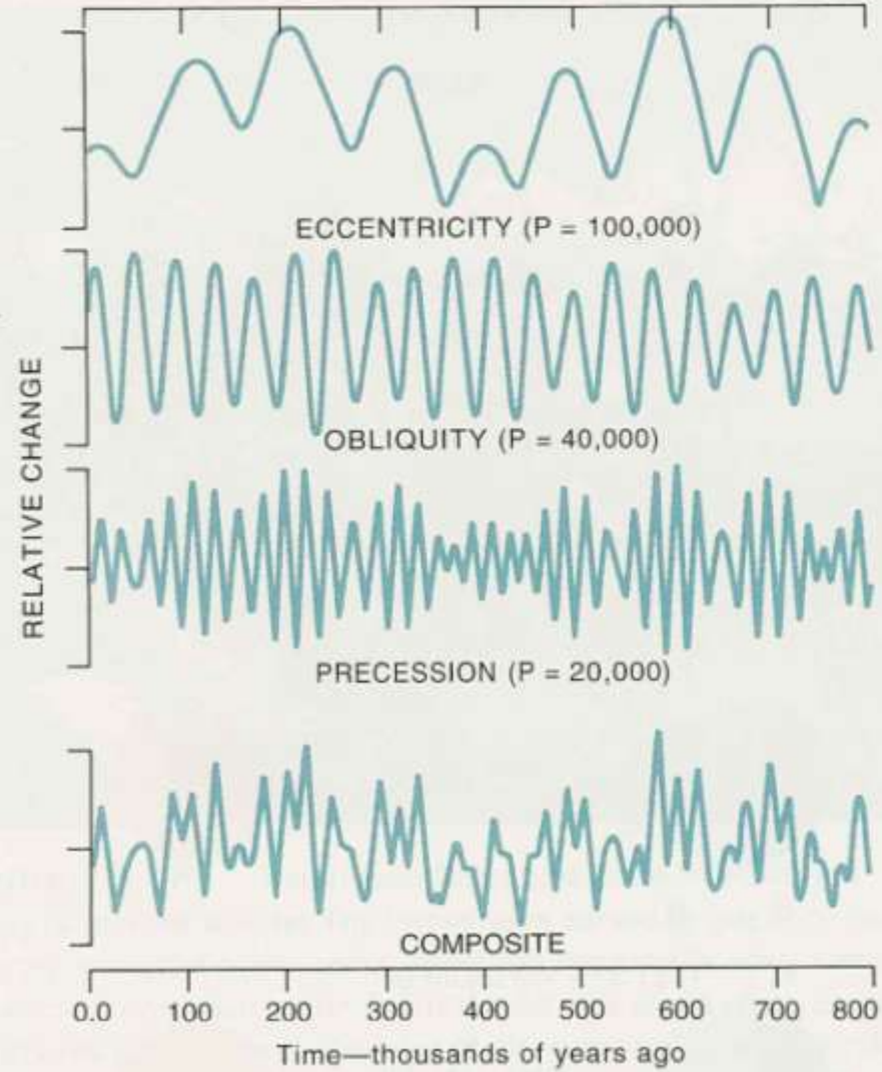


Figure 16.20 Variations in the Milankovitch orbital factors, eccentricity of the earth's orbit, obliquity of the axis, and precession of the equinoxes. The different approximate periods (P) for each of these factors are indicated (see Table 16.2), and a composite curve shows the result of adding all three curves together. *(Adapted from Berger, 1976:* Celestial Mechanics, *v. 15, pp. 53–74.)*

Milankovitch curves

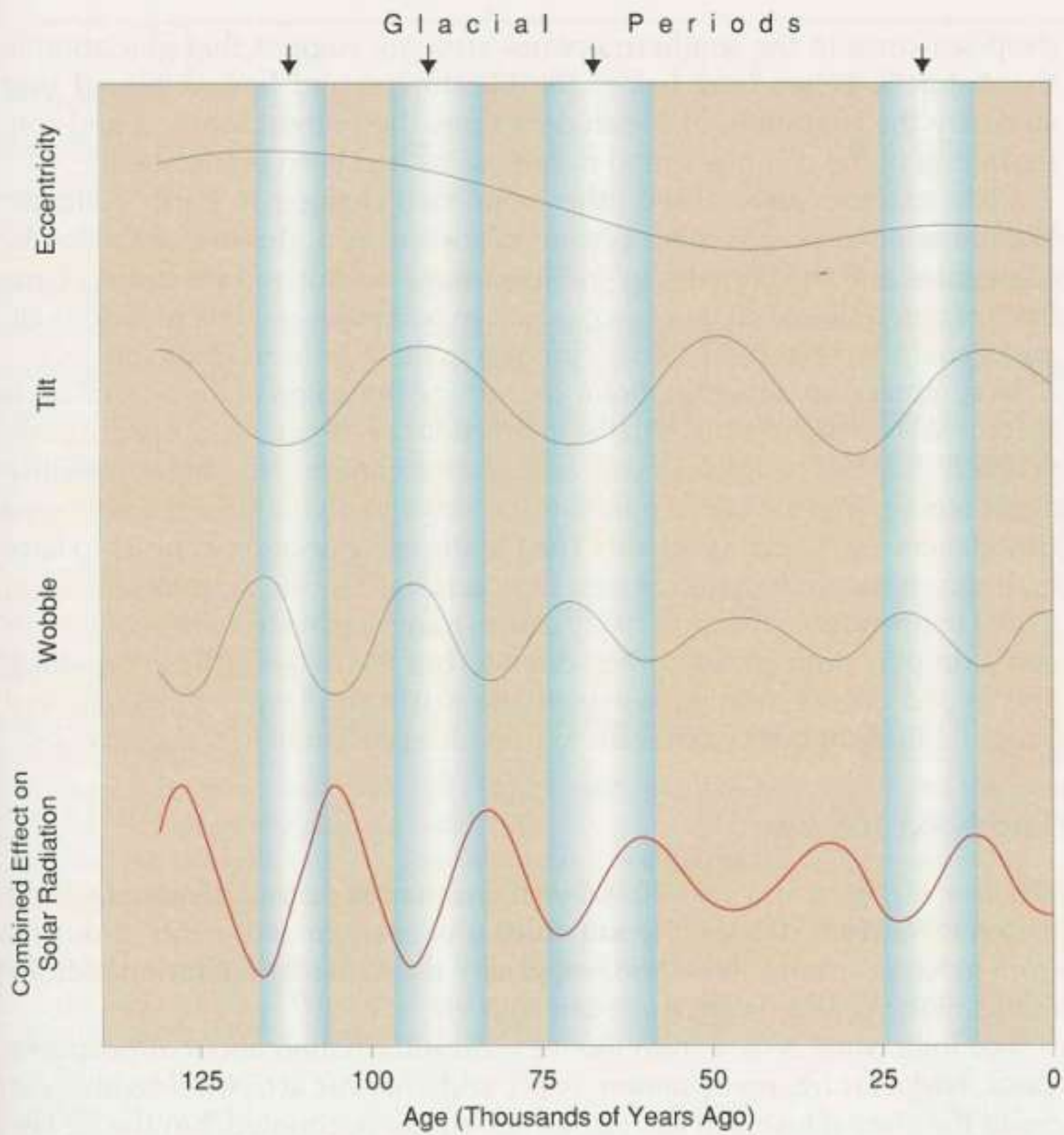


Figure 14.39 Milankovitch climate cycles are caused by periodic changes with time in Earth's orbital elements, including (top) orbital eccentricity, (middle) obliquity or tilt of the spin axis, (bottom) precession or wobble of the spin axis. When all of these cycles are added together (lowermost), they affect the seasonal differences in temperature on Earth. The total solar radiation at 65° N is shown as an example. The principal periods of glaciation as defined from the continents, seafloor sediments, and polar ice cores are also shown.

Terrace formation

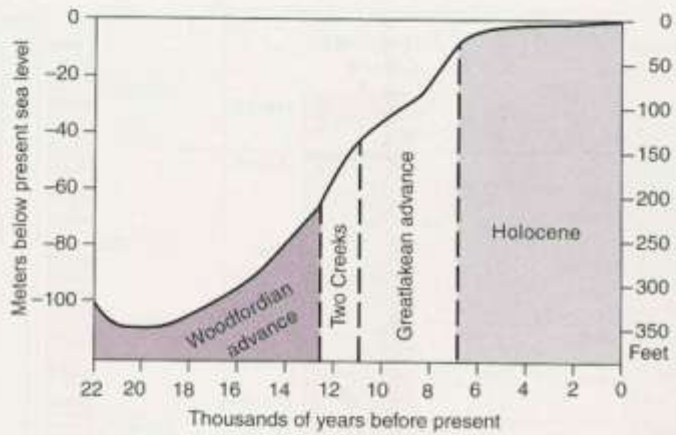


Figure 16.10 Curve representing the last rise of sea level to its present position in late Pleistocene time (compare Table 16.1).

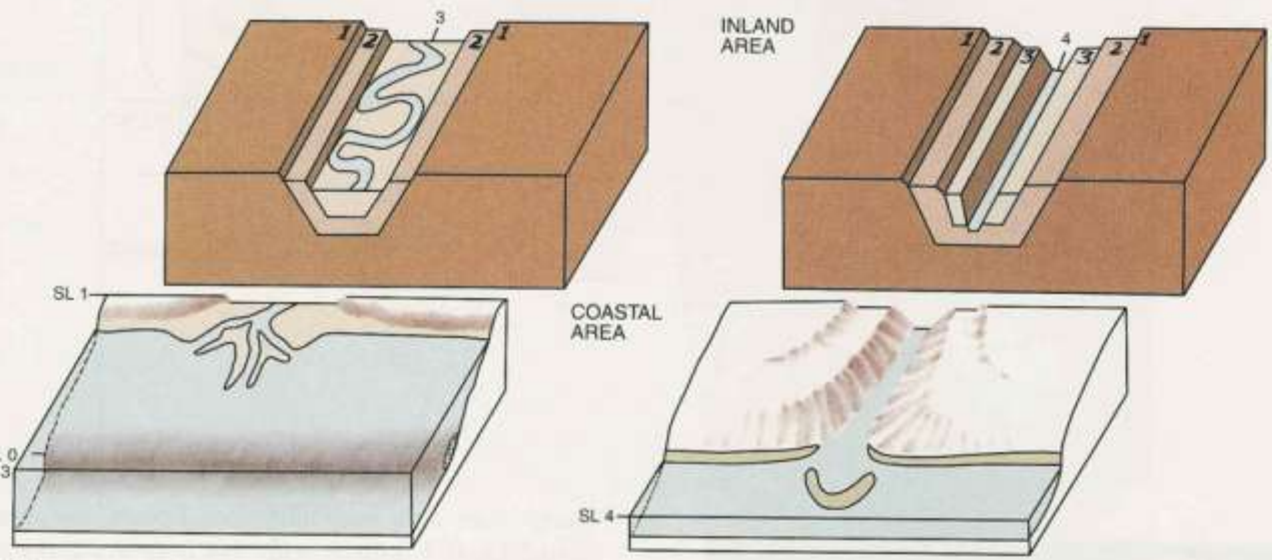


Figure 16.11 Effects of sea-level changes on river valleys and coastlines. Sea levels and river terraces are numbered from oldest to youngest *Left:* Initial drop of sea level (SL 0) caused cutting of main valley and formation of now submerged shore features; a rise, then a second fall, and a second rise also are recorded. The final rise (3) produced a branching delta, present beaches, and valley alluvium. *Right:* Recent drop in sea level (SL 4) caused downcutting into all previous valley alluvium and seaward migration of crescentic delta bar and left several high terrace levels reflecting earlier events. *(Adapted from* Scientific American, *The Bering Strait land bridge, W. G. Haag, January, 1962; Copyright © 1962 by Scientific American, Inc.; used by permission.)*

Coastline when glaciers all melt

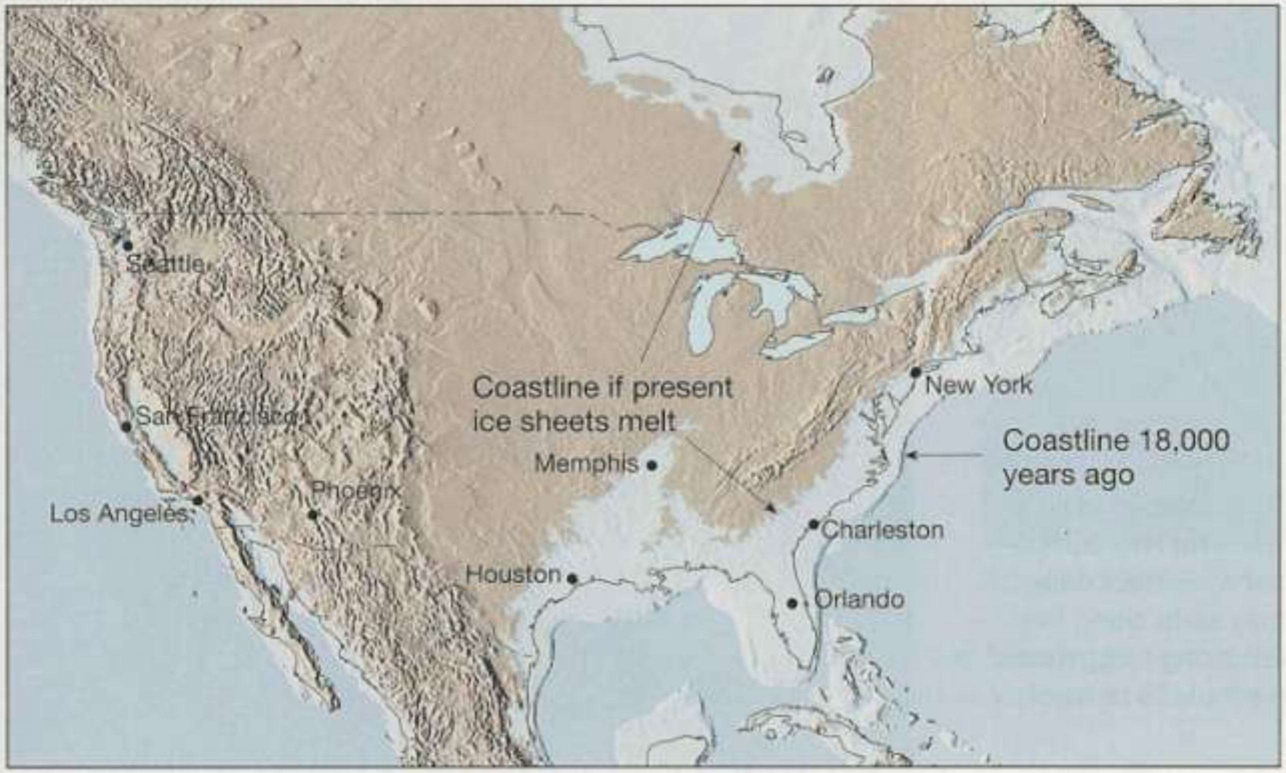


FIGURE 18.6 This map of a portion of North America shows the present-day coastline compared to the coastline that existed during the last ice age (18,000 years ago) and the coastline that would exist if present ice sheets on Greenland and Antarctica melted. (After R. H. Dott, Jr., and R. L. Battan, *Evolution of the Earth*, New York: McGraw Hill, 1971. Reprinted by permission of the publisher.)

Glacial and Interglacial stages

TABLE 13–2 Classic Nomenclature for Glacial and Interglacial Stages of the Pleistocene Epoch

NORTH AMERICA	ALPINE REGION	YEARS BEFORE PRESENT
		—10,000
WISCONSIN	Würm	
		—75,000
Sangamon	Riss-Würm	
		—125,000
ILLINOIAN	Riss	
		—265,000
Yarmouth	Mindel-Riss	
		—300,000
KANSAN	Mindel	
		—435,000
Aftonian	Günz-Mindel	
		—500,000
NEBRASKAN	Günz	
		—1,800,000
Pre-Nebraskan	Pre-Günz	

In North America, the glacial stages are Nebraskan, Kansan, Illinoian, and Wisconsinian. These terms correspond approximately to the Günz, Mindel, Riss, and Würm in Europe.