What constitutes a glacier? How is glacier ice formed?

- **Outline #2 Glaciers and Glaciation**

- **Glaciers and the Cryosphere**

- **Forms of Glaciers**
  - **-Mountain Glaciers**
  - **-Ice Caps**
  - **-Ice Sheets**
  - **-Ice Shelves**

- **Glacier Temperature Profiles**
  - **-pressure melting point**
  - **-temperate (warm base) glaciers**
  - **-polar (cold base) glaciers**
  - **-subpolar glaciers**

- **Snowline:** lower limit of perennial snow

- **Changes in Mass within Glaciers**
  - **-Mass Balance:** measure of the change in the total mass /year.
  - **-Accumulation and Ablation:** the addition and loss of mass to a glacier.
  - **Equilibrium Line:** level on glacier where net loss of mass = net gain.
  - -grounded versus calving glaciers

- **Movement of Glaciers**
  - **-Internal Flow**
  - **-Basal Sliding**
  - **-Crevasses**
  - **-Velocities and Flow Direction**
  - **-Glacial Surges**

Glacier ice starts out as accumulated snow with a density of 50-70 kg/m^3. It is gradually converted to firn (density ~400 kg/m^3), and eventually glacial ice (density ~900 kg/m^3), through a process of compaction and recrystallization.

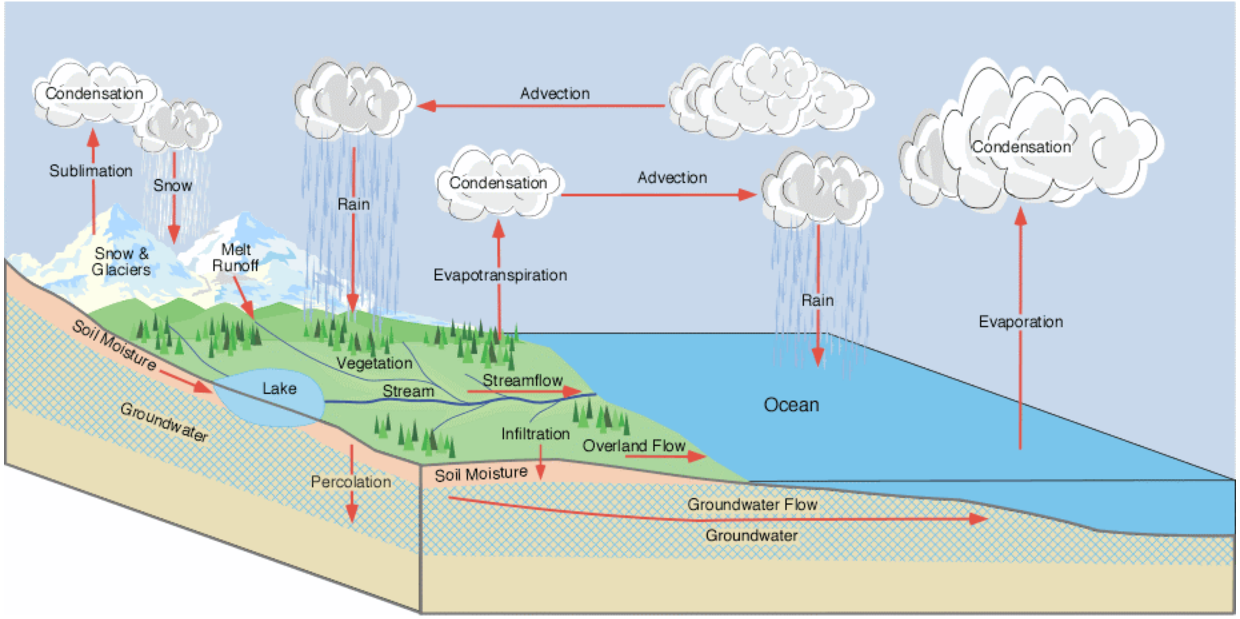
Formation of true glacial ice is only achieved when most of the void spaces are eliminated from the ice because of the overlying pressure.

Accumulation layers are still preserved in the upper portion of the glaciers.

Where temperatures fluctuate around the freezing temperature (0°C) the transition from snow to firn to ice is completed in 1-5 years and occurs in the upper few meters.

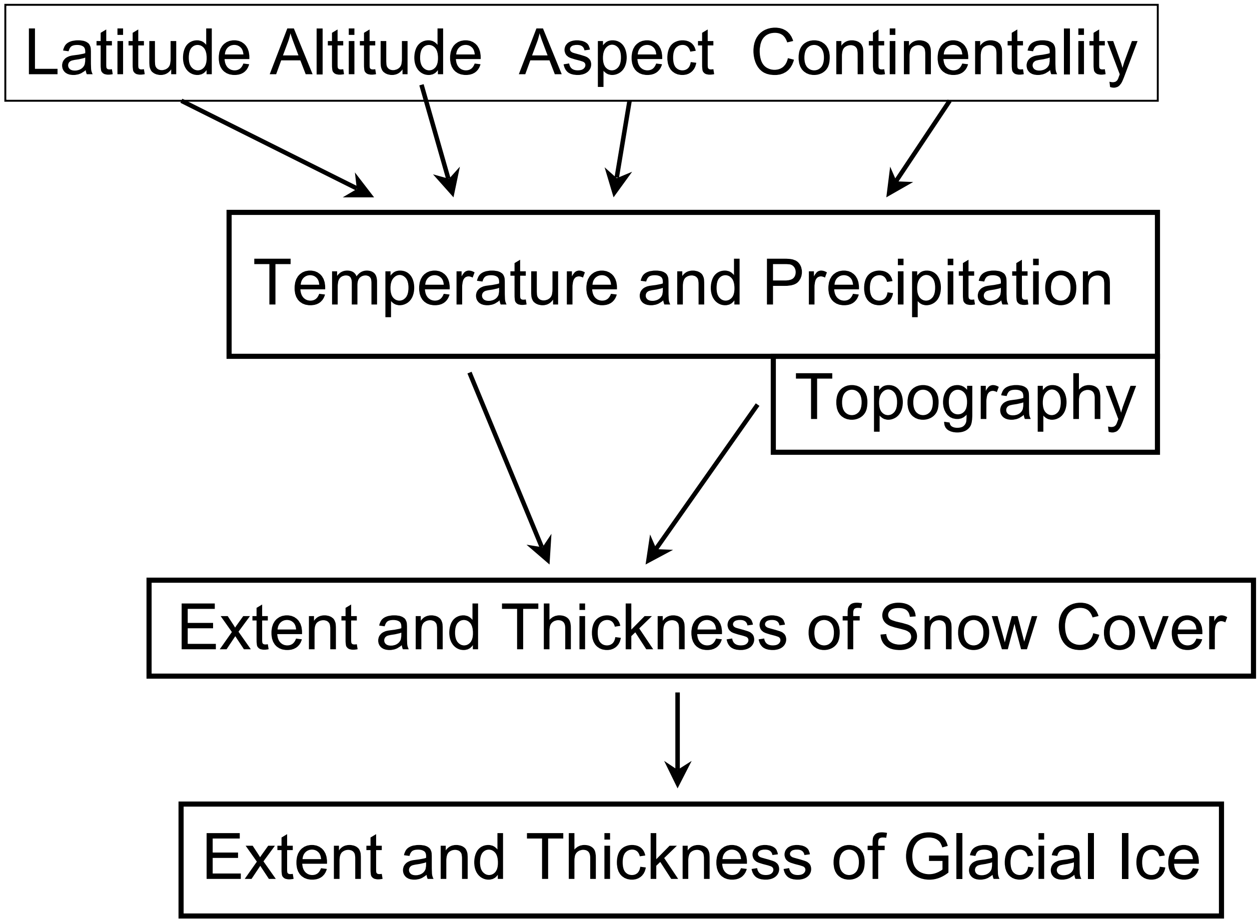
In extreme polar climates, like central Antarctica (temperatures -30 to -80°C), the conversion process may take as long as several 1000 years and may extend to depths of 100 to 200 meters.

Why are glaciers so important to the Earth’s water budget?



Reservoir	Percent of Total
Oceans	97.25
Ice Cap/Glaciers	2.05
Groundwater	0.68
Lakes	0.01
Soil Moisture	0.005
Atmosphere	0.001
Streams/Rivers	0.0001
Biosphere	0.00004

Major Factors Controlling Glaciers



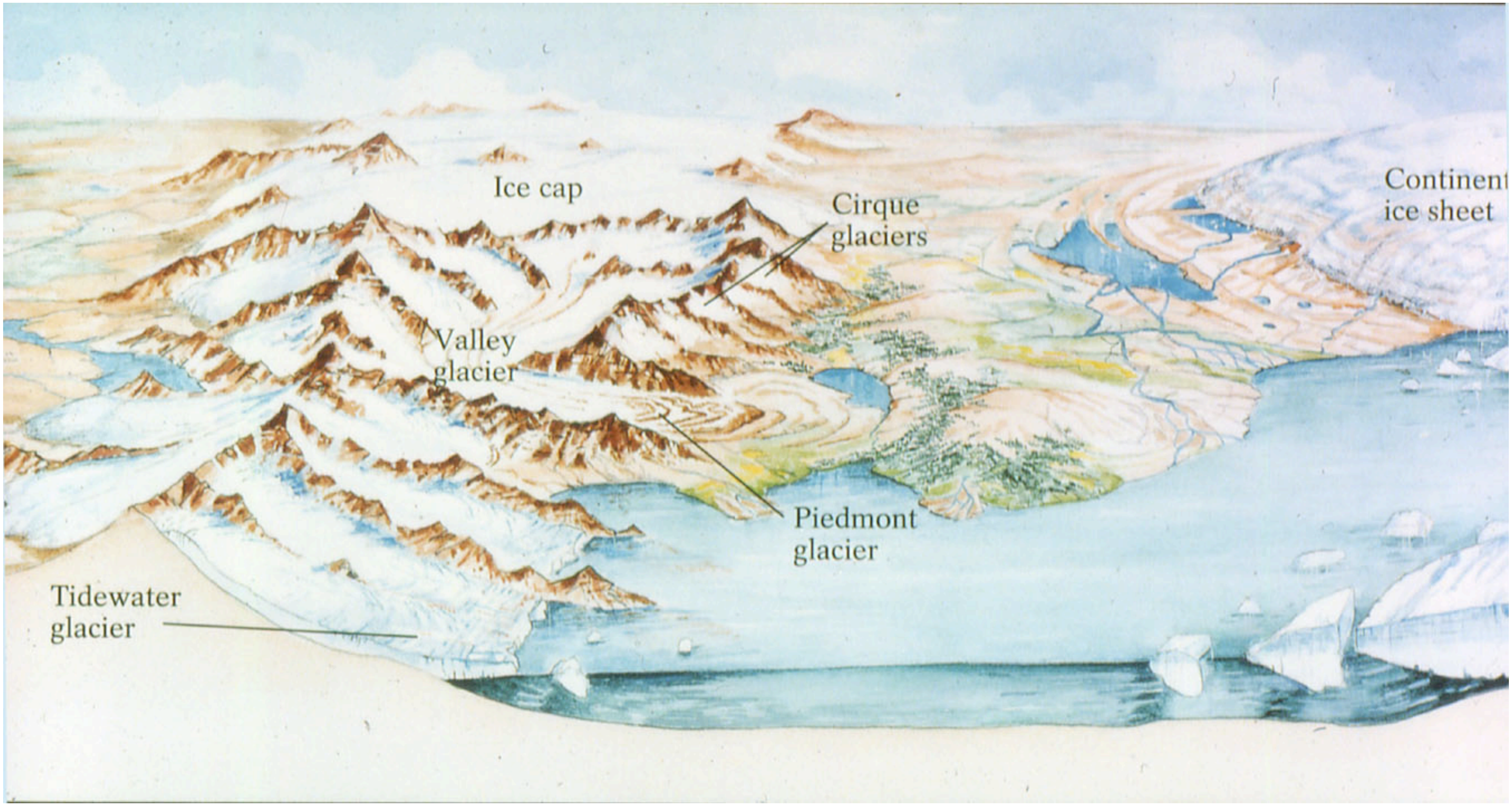
Latitude Altitude Aspect Continentality

Temperature and Precipitation

Topography

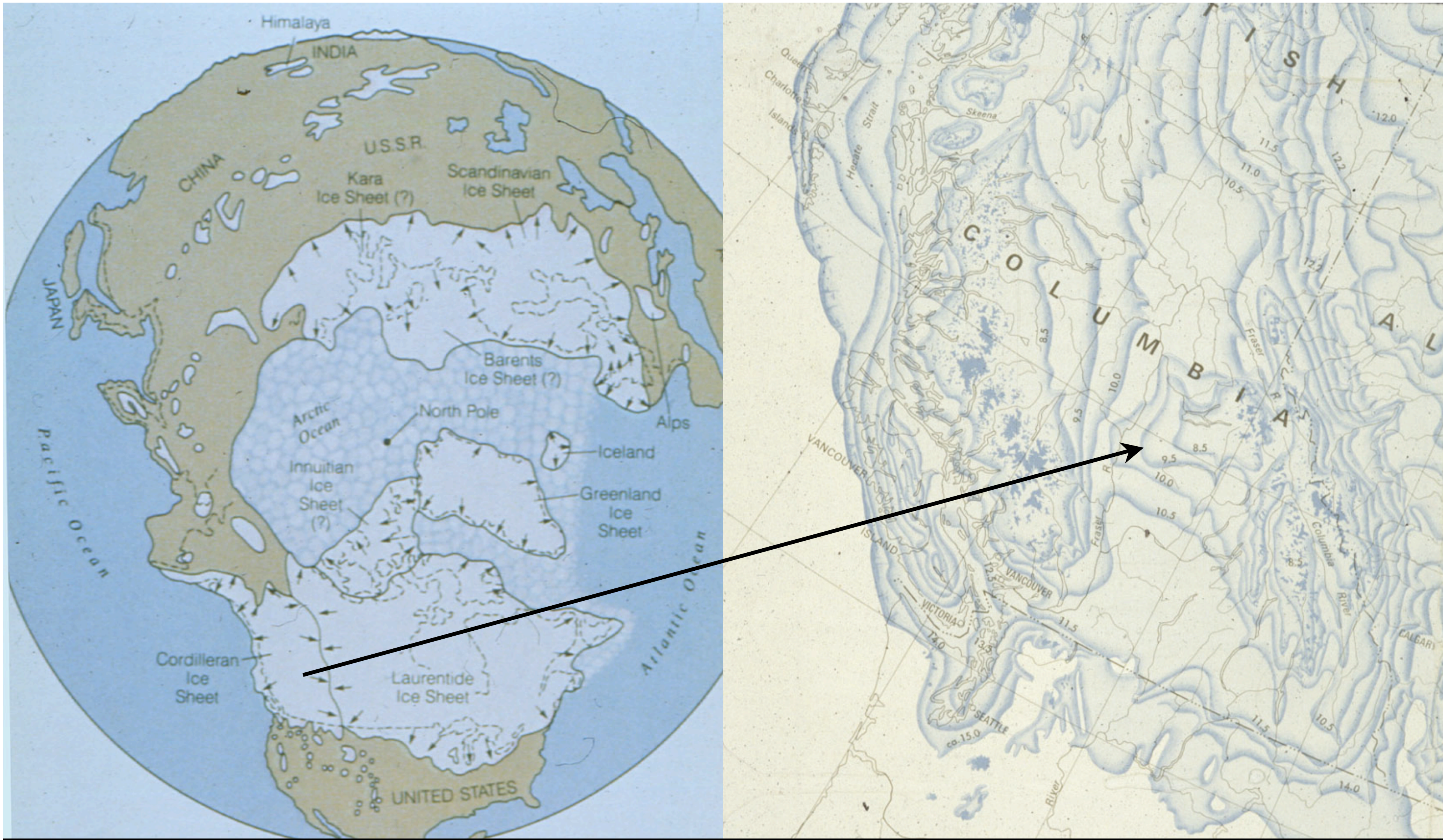
Extent and Thickness of Snow Cover

Extent and Thickness of Glacial Ice



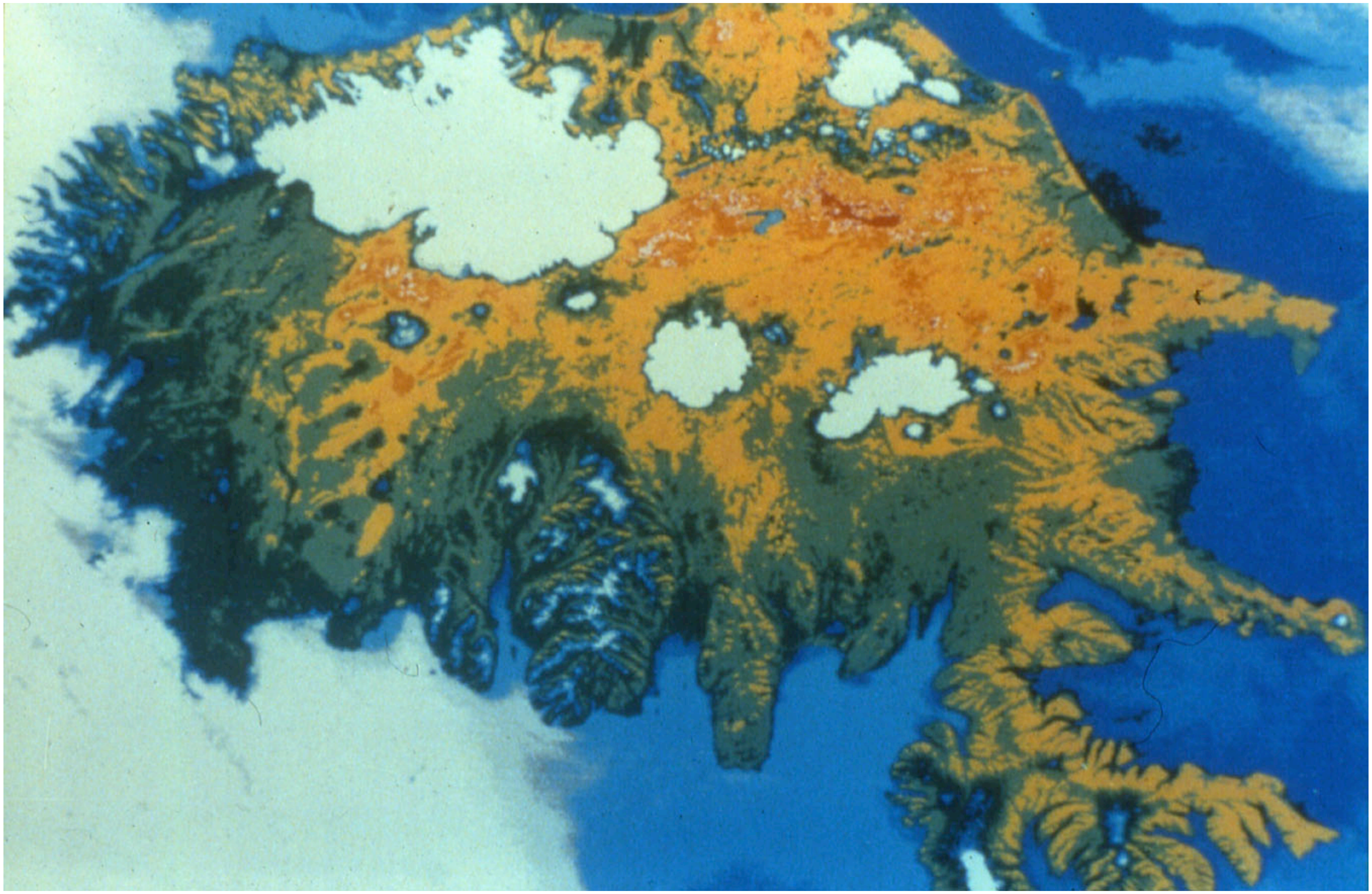
Glaciers are classified into two major subdivisions: 1. those unconstrained by topography (i.e., ice sheets and ice caps), and 2. those constrained by topography (i.e., cirque, valley, piedmont and tidewater glaciers).

Large ice sheets, such as those found on Antarctica and Greenland flow radial outward from their highest elevations (domes) and overwhelm the underlying surface topography.

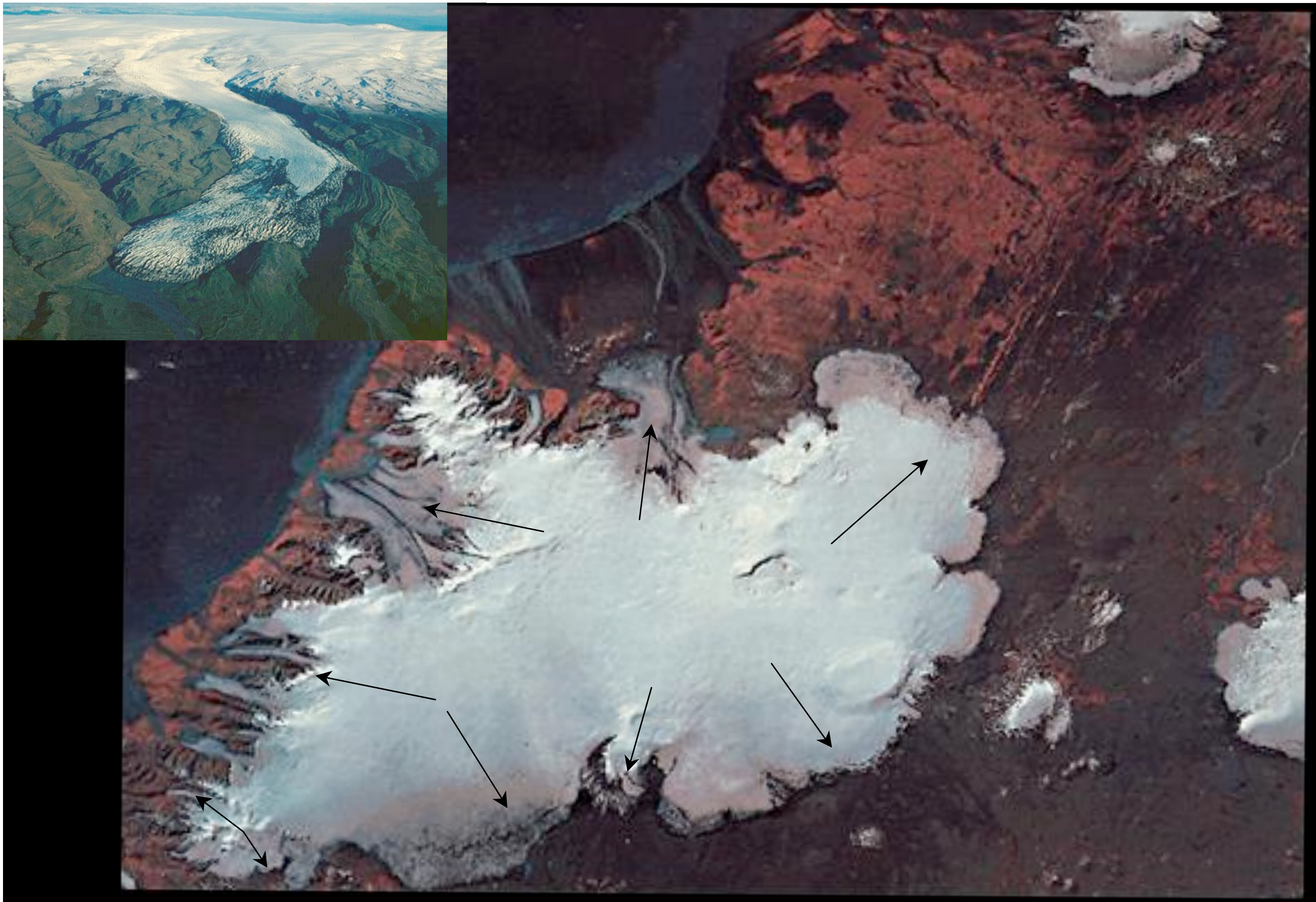


Large ice sheets grew and expanded over the northern land masses of North America and Eurasia during the last glaciation (25-13 k.y.). The ice sheets reached thicknesses of over 4000 m in their central domes overwhelming the underlying topography.

Ice shelves are floating sheets that are not grounded to a moraine complex on the sea floor.



Modern ice caps exist in Iceland and high elevation mountains in Alaska. During the last glaciation many high mountain ranges in the mid-latitude area of the world possessed ice caps that fed valley glacier systems (e.g., North Cascades, Sierra Nevada).



Ice caps are not constrained by topography below their central domes. Ice flow (shown by black arrows tends to be radial. Note that outlet glaciers flow northward from the Icelandic ice cap towards the Arctic Ocean.

Outlet glaciers within Denali National Park are fed from an ice field near the summit.

Modern cirque glaciers typically occupy cirque depressions eroded during times of more extensive glaciation.

As climatic conditions begin to cool, snow accumulates and is converted to glacial ice. Glacial ice within protected cirques begins to advance within pre-existing stream valleys.

The modern glacier shown on the image to the left is actually retreating, as evidenced by the preserved end moraine lying above and outside it present limit.

Valley glaciers within the St. Elias Mountains, Alaska have coalesced into a major trunk glacier. Medial moraines form where tributary glaciers coalesce with the main glacier.

Tidewater glaciers terminate in a marine embayment. Much of their mass is lost by calving (producing ice bergs) along their respective terminal positions.

Piedmont glaciers, such as in Alaska, form when constrained valley glaciers flow onto level plain. The ice rapidly decelerates and thins. Deformation flow structures form as the ice decelerates because of decreasing slope gradient.

Glaciers can only form at or above the lower limit of perennial snow, or the *snowline*. The snowline rises from near sea level in polar latitudes to over 5000 m in the tropics. The annual mass balance (net accumulation - net ablation) is strongly controlled by environmental factors (largely climatic) that occur over a given water year.

Where would you place the annual snow line on Mt. Rainier during the 1990-91 (year the image was taken) water year?

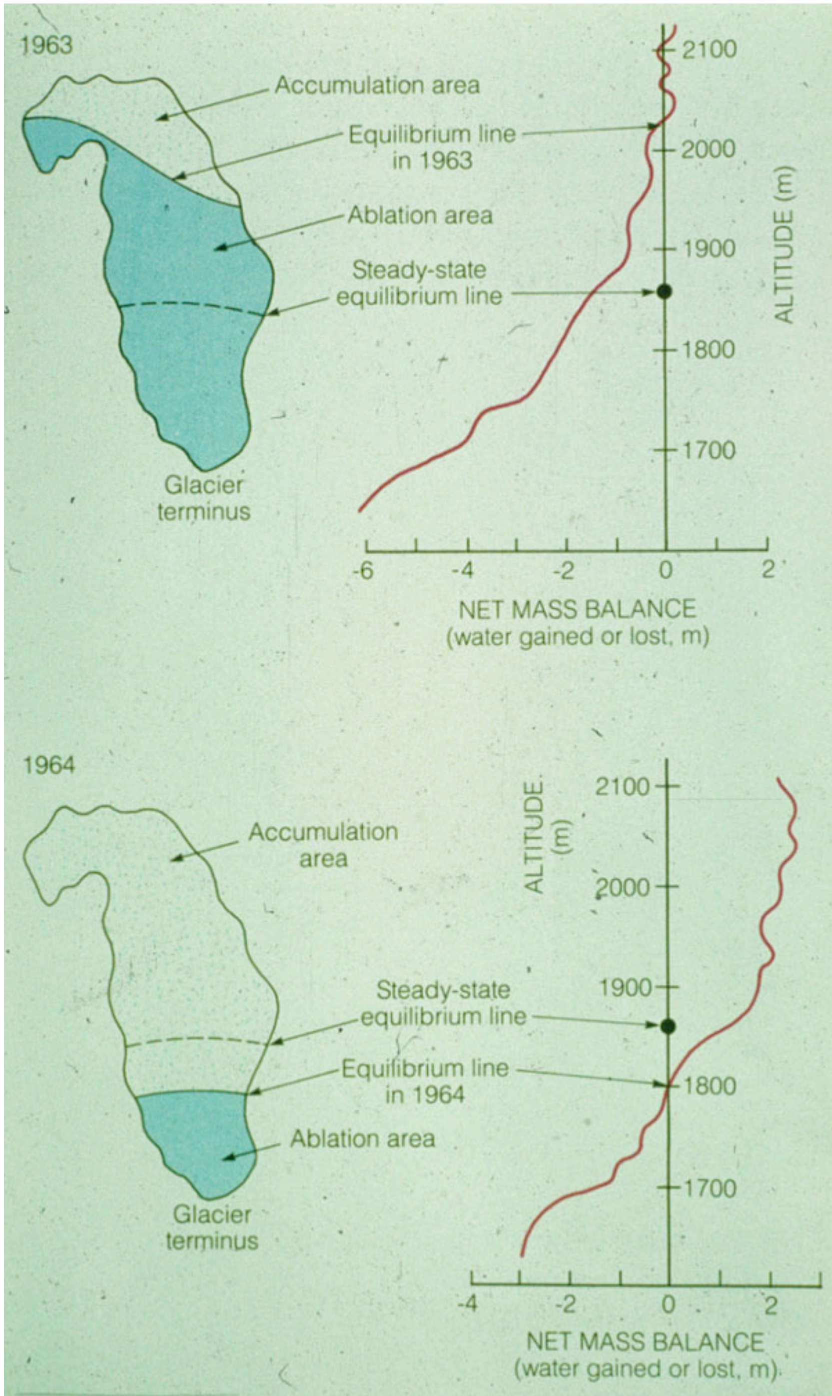
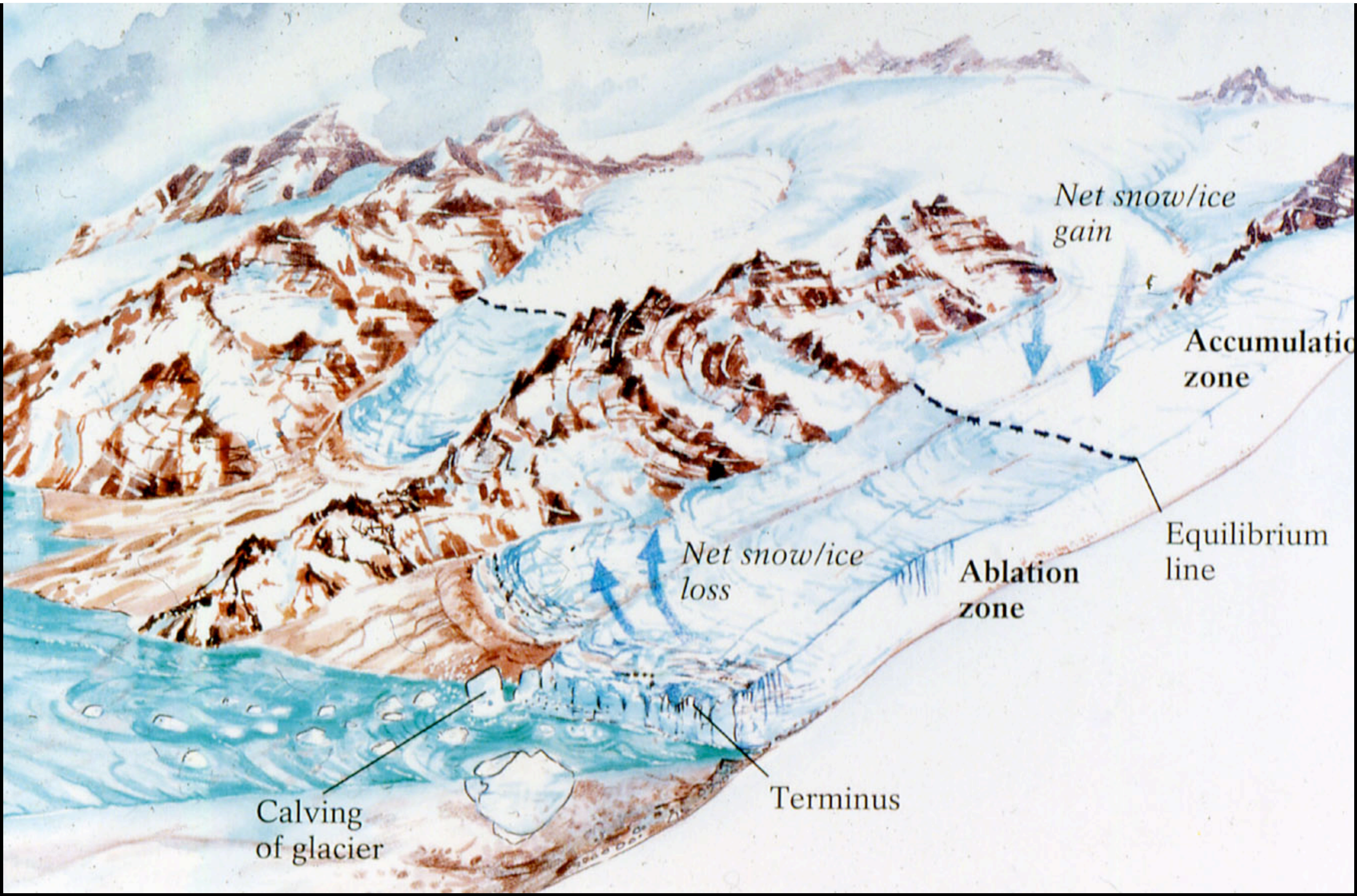


FIGURE 11.12

Net mass balance data for water years 1963 and 1964 for Carbon Glacier, Mt. Rainier.

Note that 1963 was a much drier year than 1964, when the annual ELA altitude was lower than the steady-state ELA.



The equilibrium line on a glacier separates the accumulation zone (positive mass balance) from the ablation zone (negative mass balance). What effect would climatic cooling have on the steady-state equilibrium line altitude (ELA) for a glacier.

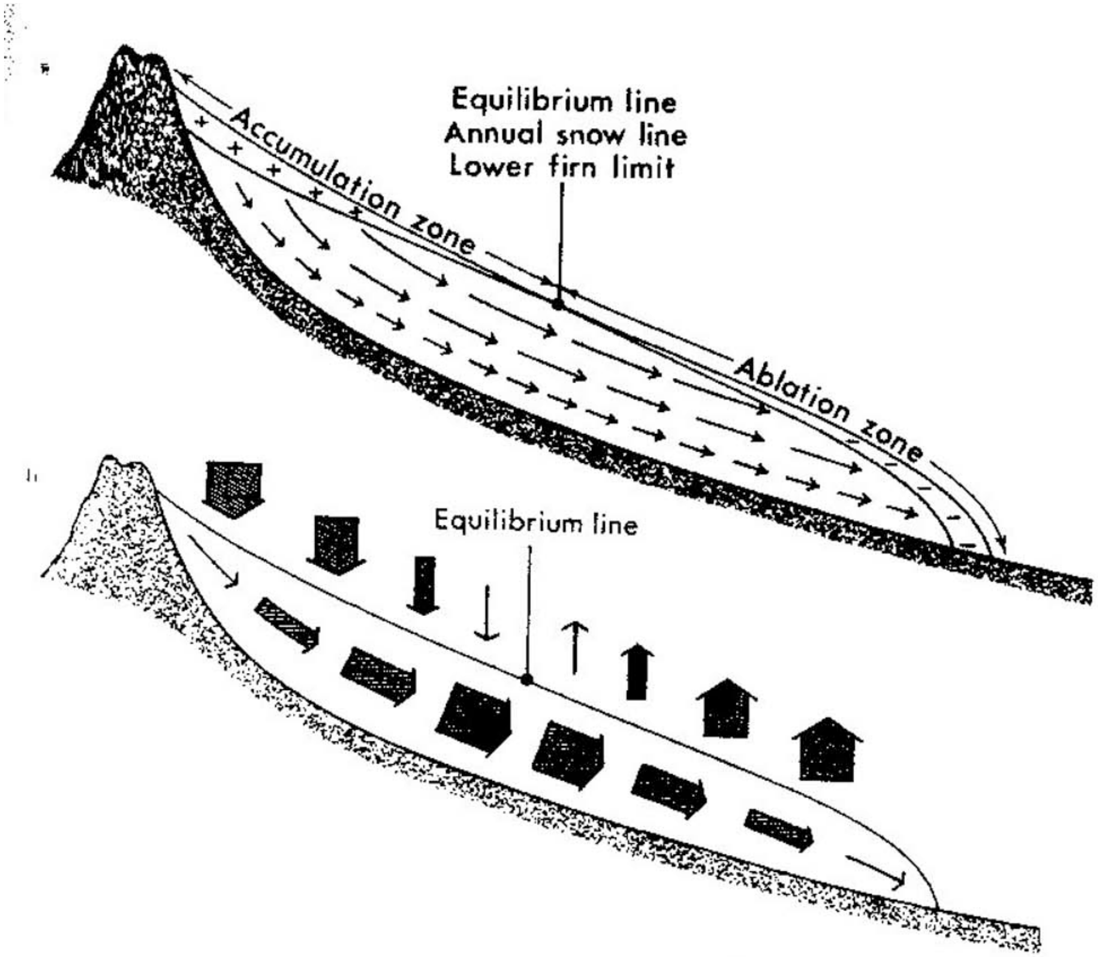
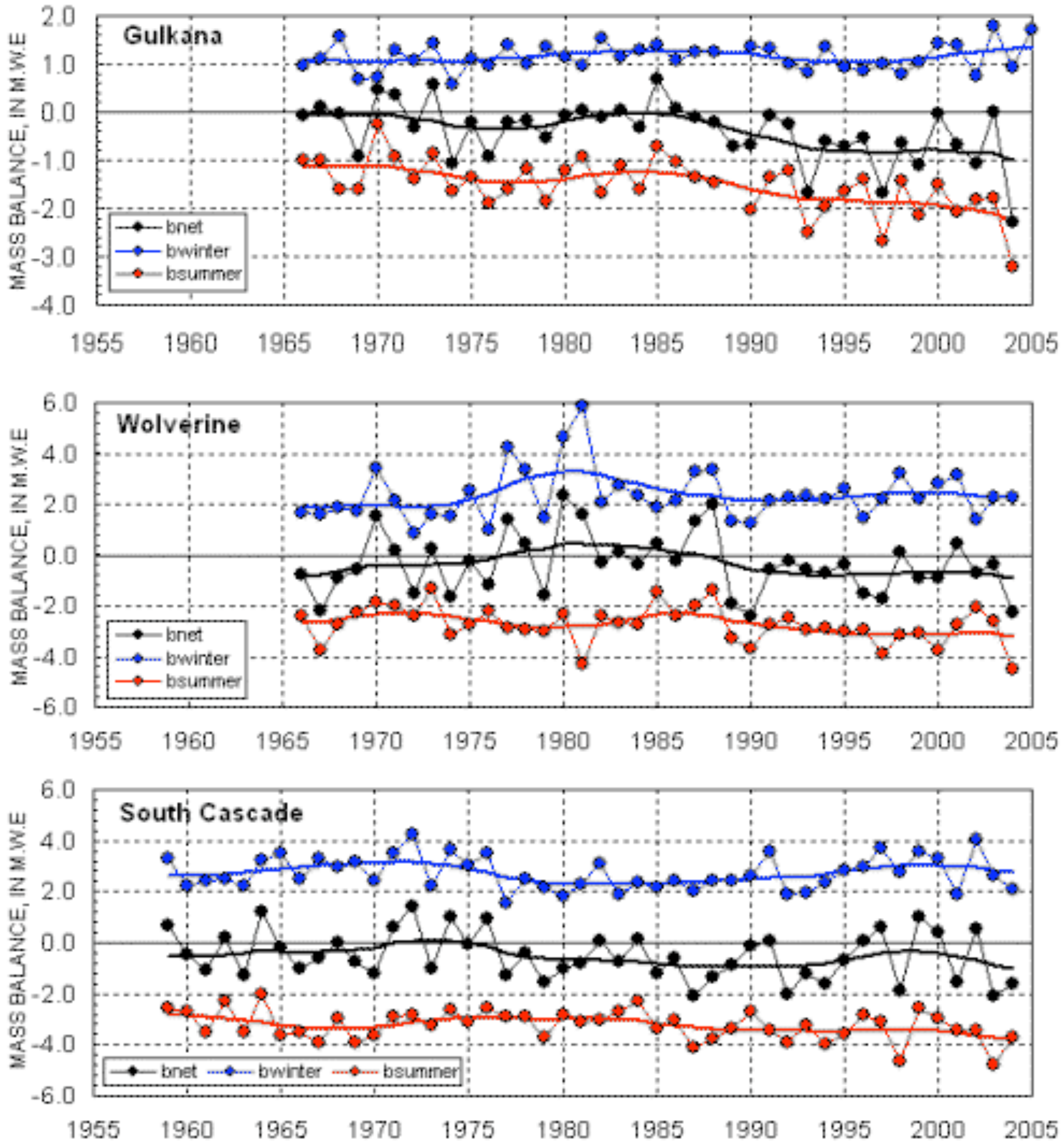


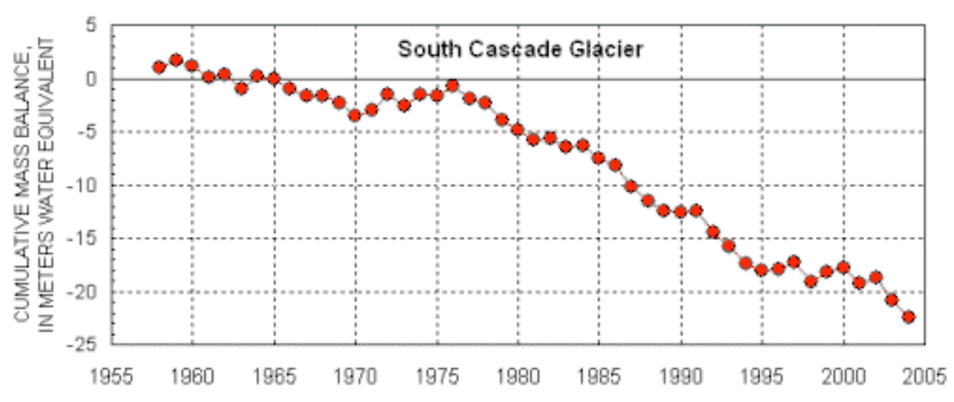
Fig. 15.9 (a) Long profile of a valley glacier showing the zones of accumulation and ablation separated by the equilibrium line, and the resulting flowlines of the ice. In (b) the magnitude of gains, losses, and transfers of ice along the glacier are indicated.



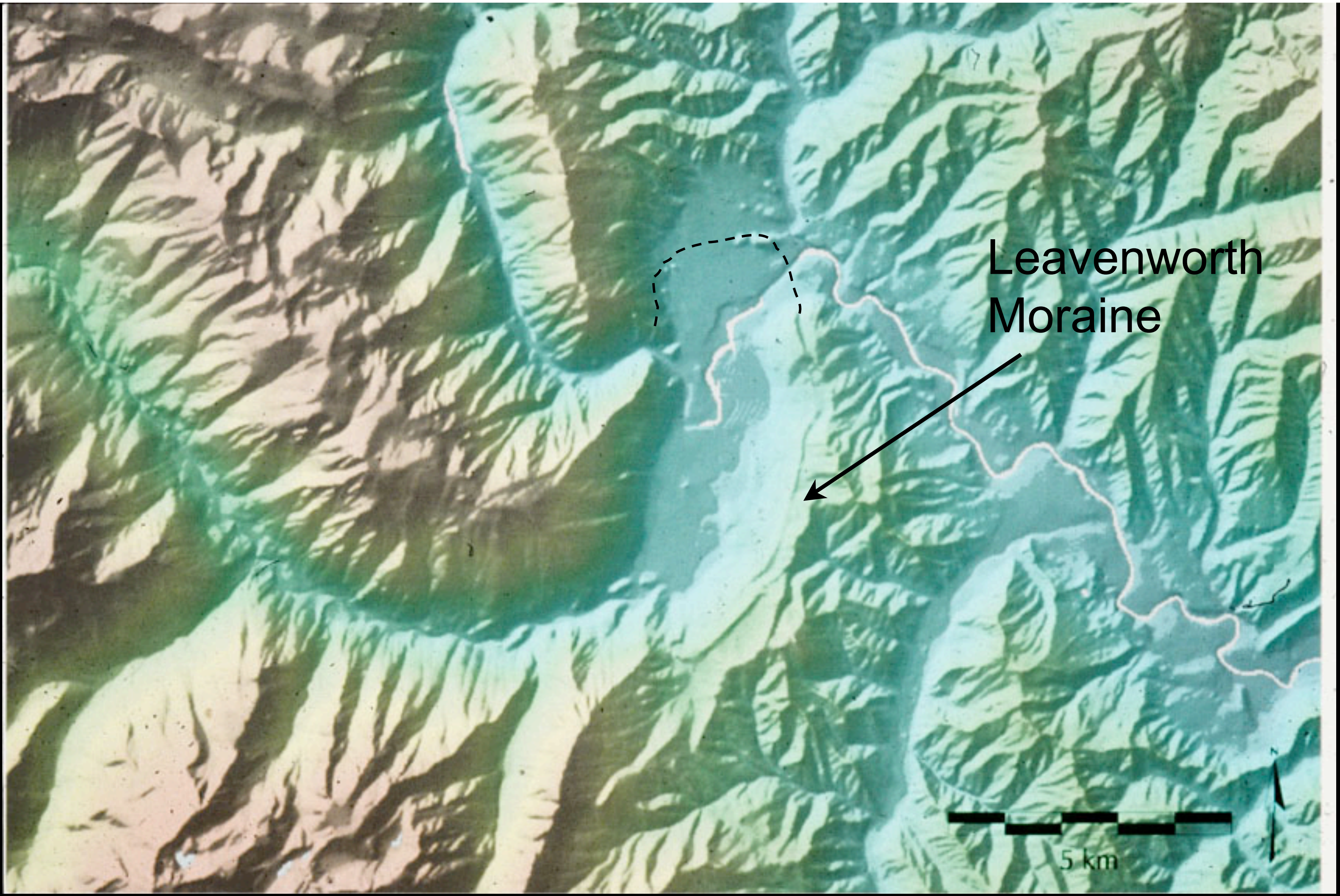
Mass balance data from three glaciers within the U.S. Note that the net mass balance (shown by black points) has been decreasing since the data has been collected for all three locations.

Note the difference between the annual mass balance of a glacier versus the long-term mass balance of a glacier.

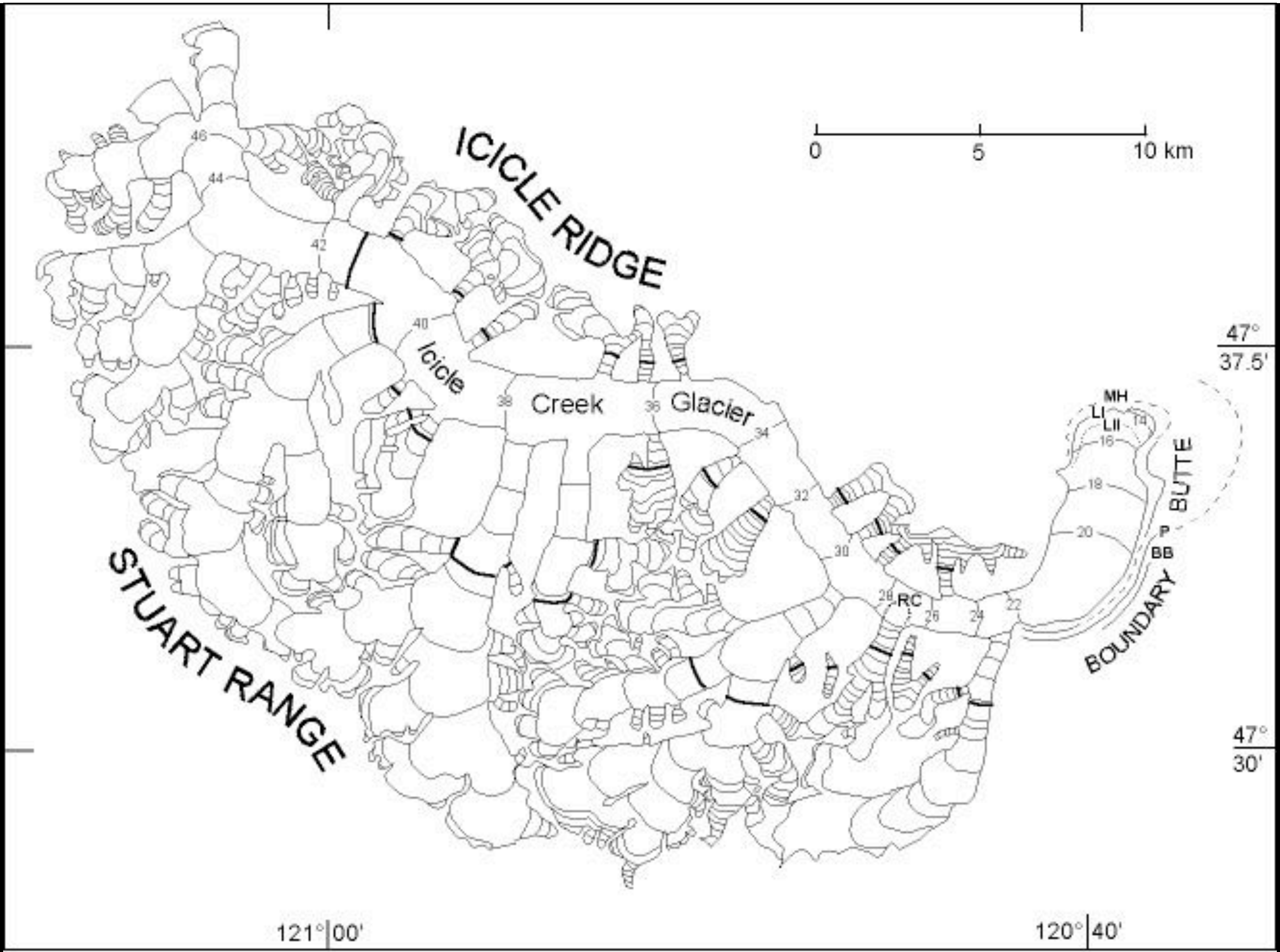
Which data are more useful for long-term water budget planning?



The terminal position of the South Cascade glacier, WA have retreated several kilometers up-valley since 1928. Most alpine glaciers around the world have been retreating since the end of Little Ice Age near the mid-19th century and currently have negative mass balances. Retreat rates have increased in the last several decades.



DEM of Icicle Creek Drainage, East Cascades, Washington. Paleo-ice reconstructions of the Late Pleistocene glacier can be used to determine paleo-ELA reconstructions. Paleo-ELA reconstructions can be used to infer the Late Pleistocene temperature depression.



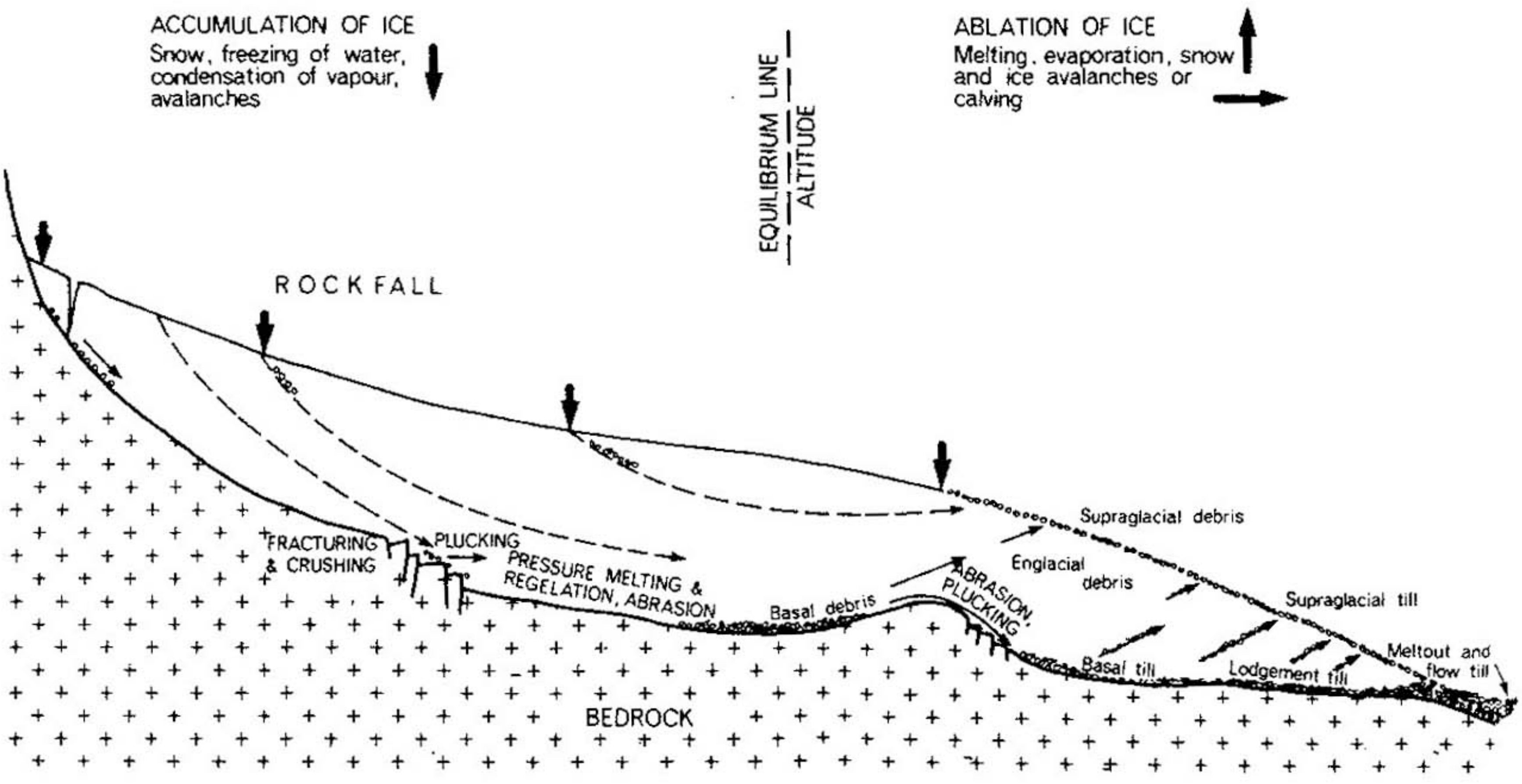
Equilibrium line reconstruction (shown as thick black line) of the Icicle Creek glacier during the last glaciation (Leavenworth Glaciation). Ice limit defined by end moraine and cirque headwall positions (Porter and Swanson, 1999).

Factors Controlling Temperature of Ice

- Solar radiation
- Heat transfer due to latent heat of freezing of meltwater
- Geothermal heat flux
- Internal friction
- Simple Temperature Profile (stationary and constant thickness:

$$(dT/dh) = (T_s - T_b)/h$$

Where: T-temperature, h-height, Ts-surface temperature, basal temperature



Processes acting on and within a glacier are controlled by its surface and interior temperatures.

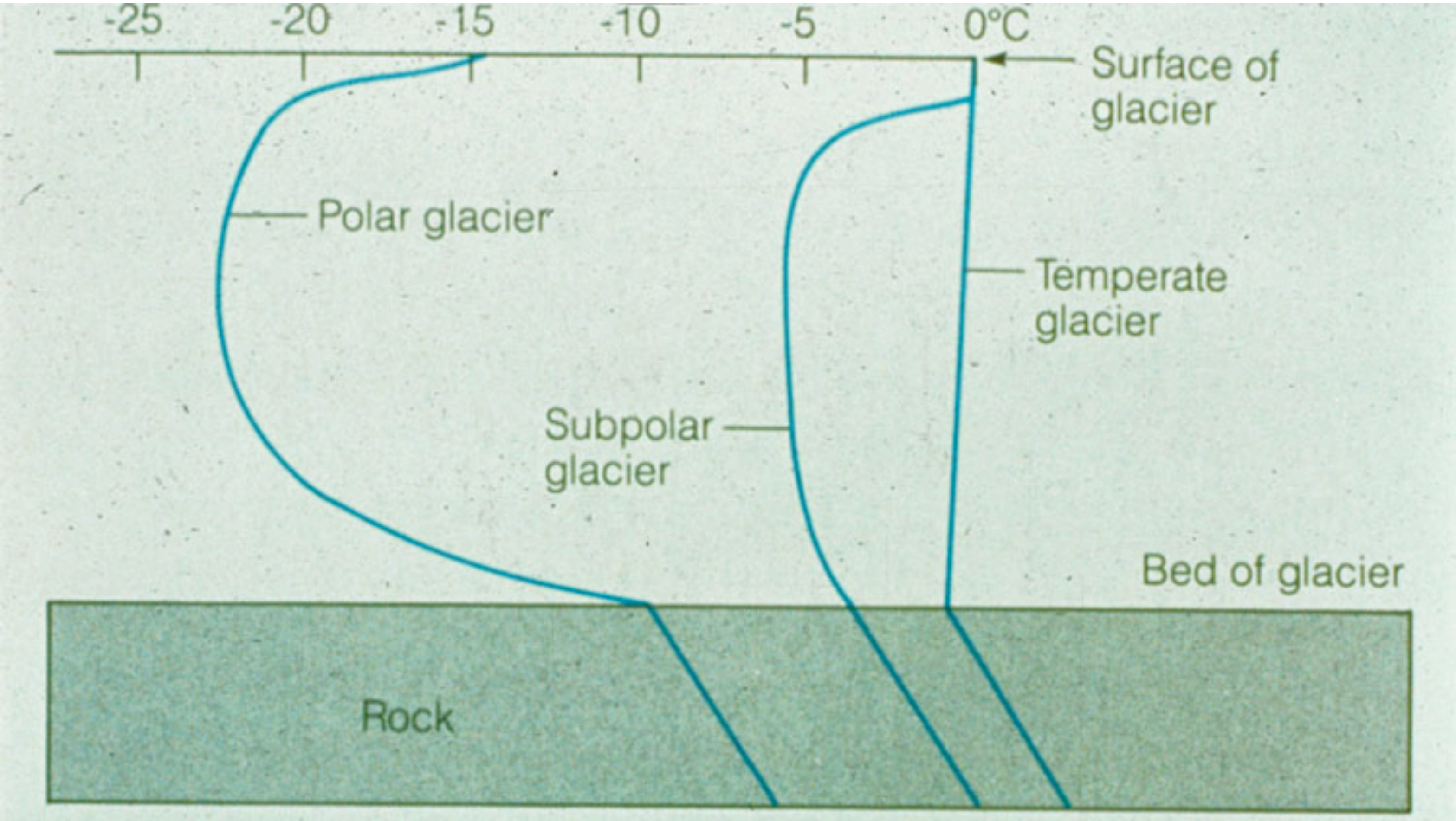
Pressure Melting Temperature

- Freezing point of water decreases as pressure increases (1°C/14 MPa).
- The melting temperature at the base of the Antarctic ice sheet is about -1.6° C under a pressure of 20 MPa.

- Pa pascal= 1 (Nm^{-2}) To convert to millibars (mb) multiply 100. Newton (N) is the force required to give a mass of 1kg an acceleration of $1ms^{-2}$.

Ice Temperature Influences

- 1. **Ice thickness-** controls stress and temperature at the base of the ice.
- 2. **Surface Temperature-** varies with altitude (temperature decreases between 0.6°-1.0°C/100 m rise in elevation.
- 3. **Accumulation rate-** controls the rate at which accumulating firn is transported downward (high rates=lower basal temps.).
- 4. **Ice velocity-** influences the rate of transport of colder ice to lower parts of the glacier.
- 5. **Geothermal heat-** and 6. **Frictional heat-** are concentrated near the base of the ice.

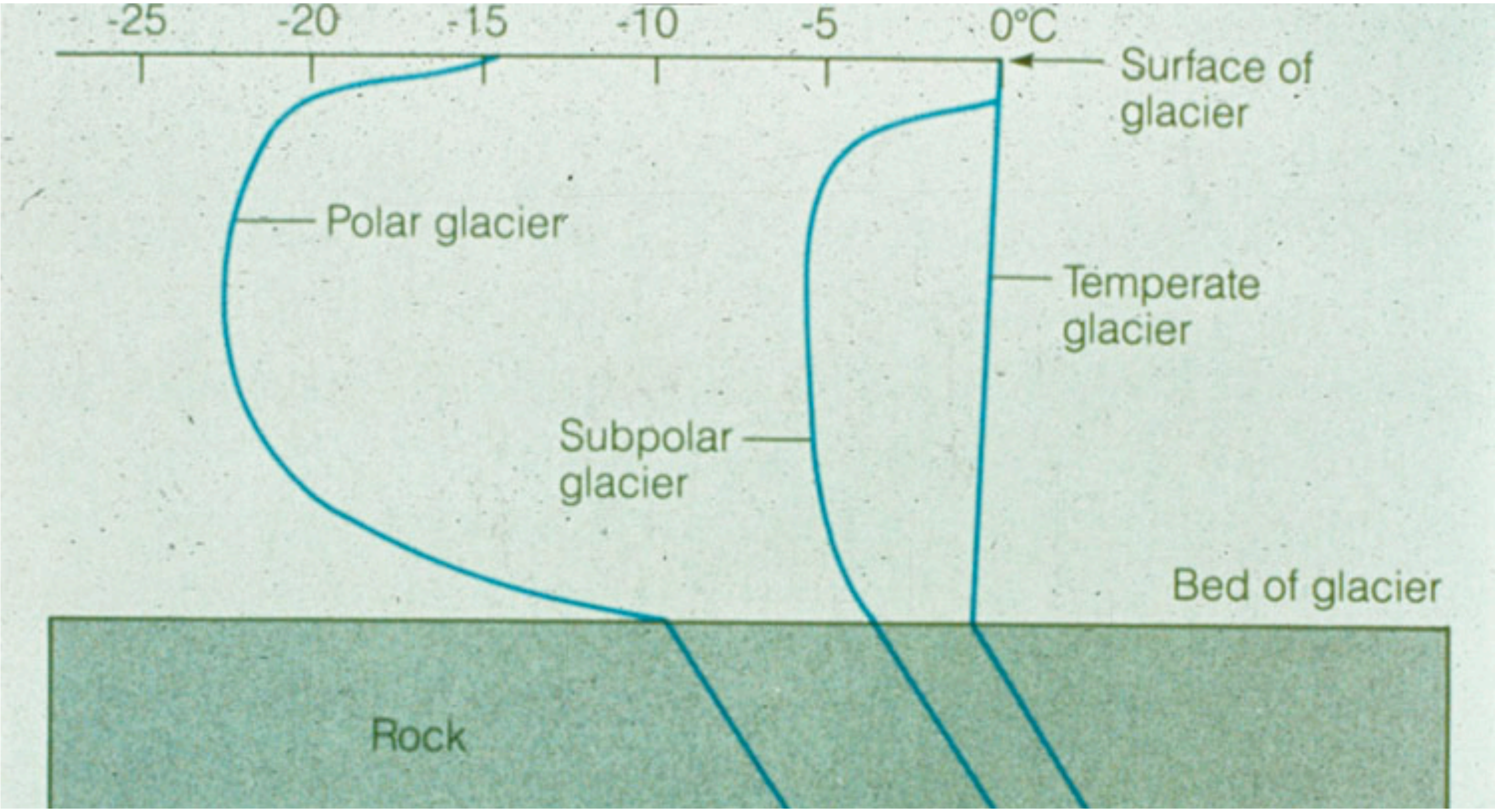


-Temperate (warm-based) glaciers are generally at or near the pressure-melting temperature throughout their profile.

-Surface layer may freeze to 10 m during winter.

-High meltwater discharge.

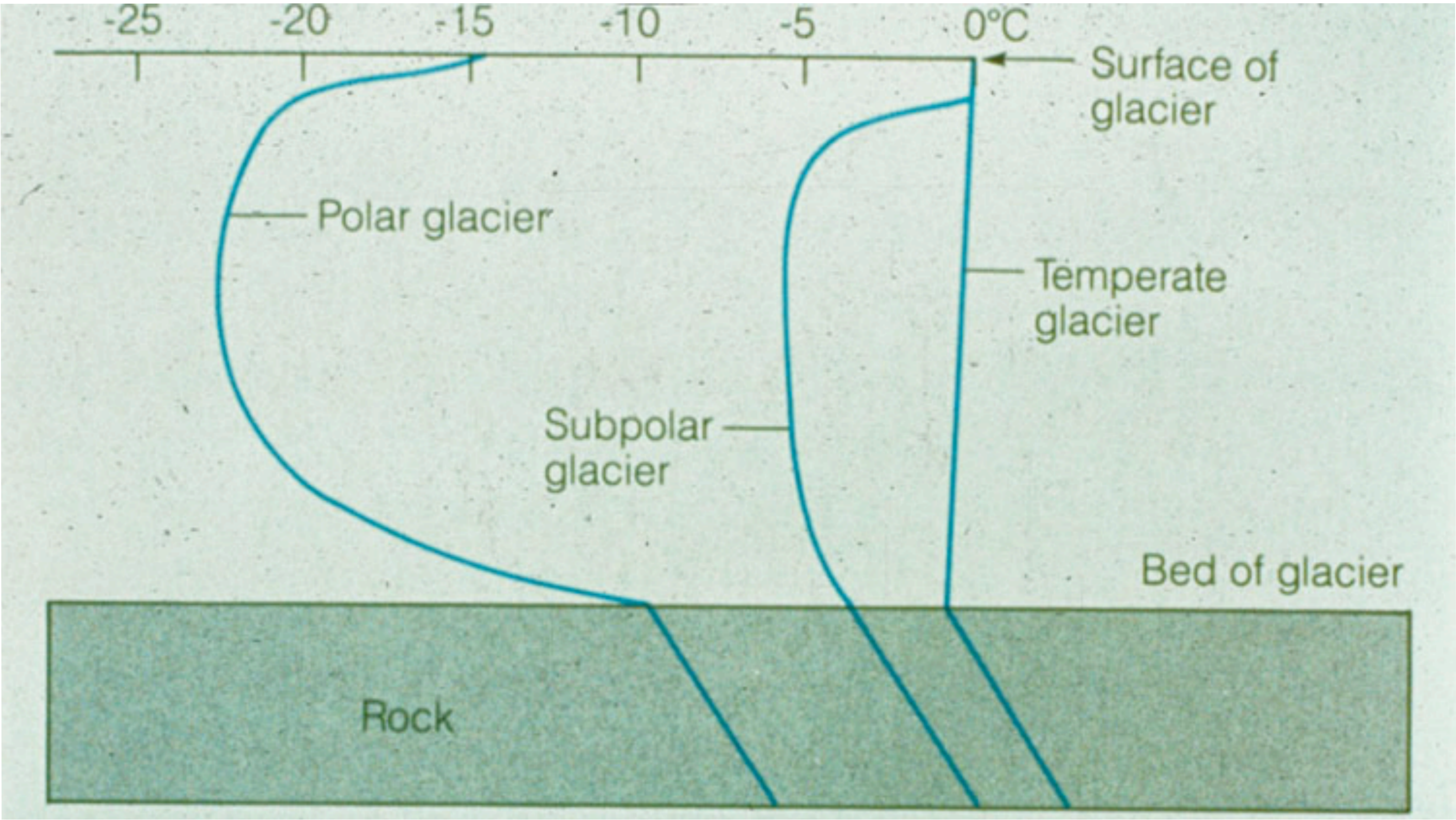
-Most erosive of glaciers types because of basal sliding.



-Subpolar glaciers contain both warm and cold ice.

-Ice may contain some water in summer months.

-Tend to show characteristics of warm-based (temperate) glaciers within interior profile and cold-based (polar) near the exterior margins.

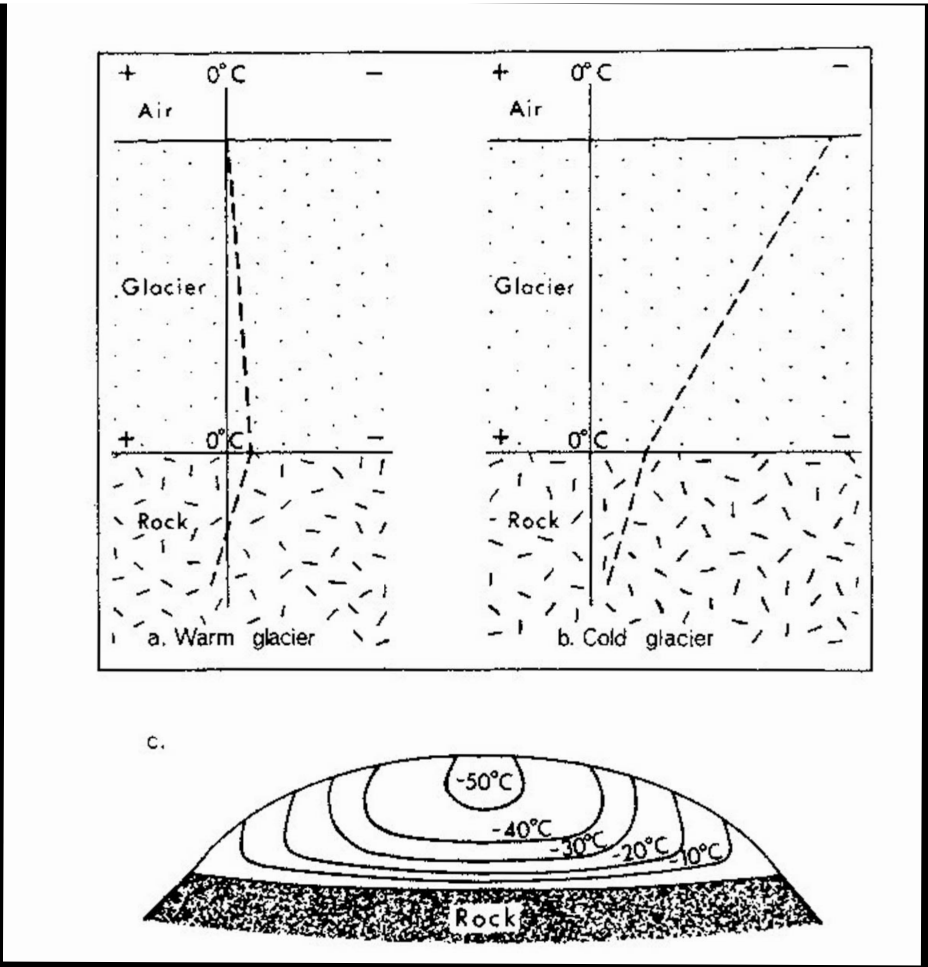


-Polar glaciers contain largely cold ice.

-Ice may contain very little liquid water.

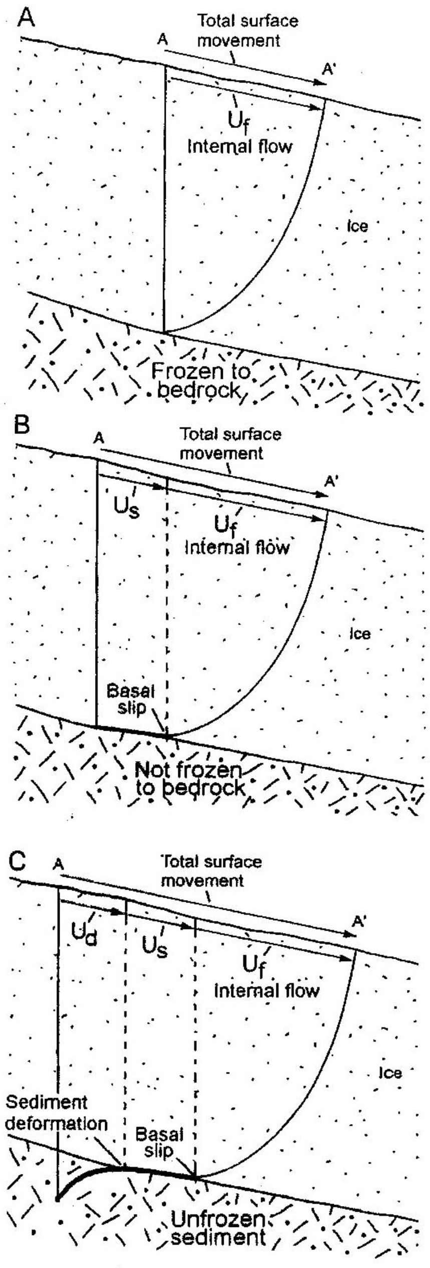
-Glacier ice frozen to its bed and flows largely by internal flow.

-Low erosion capability of ice.

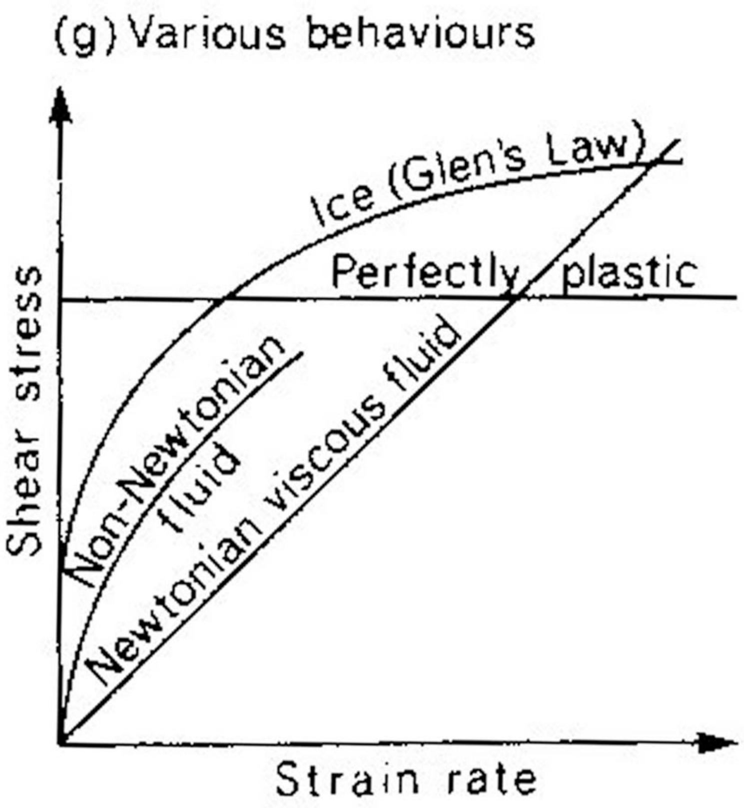


The temperature of a warm-based glacier is close to 0° C throughout (a). The temperarture in a cold-based glacier is well below 0° C and increases towards the base because of frictional and geothermal heat (b). In a cold-based ice sheet the temperatures are lowest at the summit of the dome and increase towards the base and periphery.

Movement of Glaciers



1. Movement of individual ice crystals past one another is possible in the snow and firn zones.
2. Internal slippage between ice crystals (creep). Depends upon the shear stress and temperature of the ice.
3. Slippage of glacier over bedrock occurs only in glaciers with ice at the pressure melting point. Overpressured water at base of glacier reduces friction between ice and bedrock. Accounts for up to 90% movement in warm-based glaciers.
4. Soft, deformable, water-saturuated sediments at the bases of glaciers can also enhance basal sliding.
5. Movement of water downslope internally transfers material downslope as the water refreezes into ice.



Internal flow is the result of the weight of the overlying ice and gravity acting down the surface slope of a glacier.

Ice does not behave as a perfect plastic. Under stress levels <100 kPa crystals of ice have no yield stress and will deform under any magnitude of applied stress (like a viscous fluid).

If the stress level is increased to >100 kPa, the strain rate increases, and the behavior approximates a plastic material.

The predicted rate of deformation (Glen's Flow Law) depends not only on the shear stress, but also on the temperature of the ice

Glen's Flow Law

the applied stress (τ) to strain rate (ε)

$$\varepsilon = A\tau^n$$

Where: A is a temperature dependent constant, n has values from 1.3 to 4.5 with a mean of about 3.0.

Glen’s Flow Law

(the applied stress (τ) to strain rate (ε)

$$\varepsilon = A\tau^n$$

Where: A is a temperature dependent constant, n has values from 1.3 to 4.5 with a mean of about 3.0.

If ice is subjected to stresses of >100 kPa, it is assumed to act as a perfect plastic material, which deforms in proportion to the stress of the overburden of ice.

The basal shear stress of a glaciers with parallel sides can be calculated from:

$$\tau_b = \gamma ice.h.\sin\beta$$

Where: τ_b is the basal shear stress (kN/m^2)

γice is the unit weight (9.0 kN/m^3)

h is the ice thickness (m)

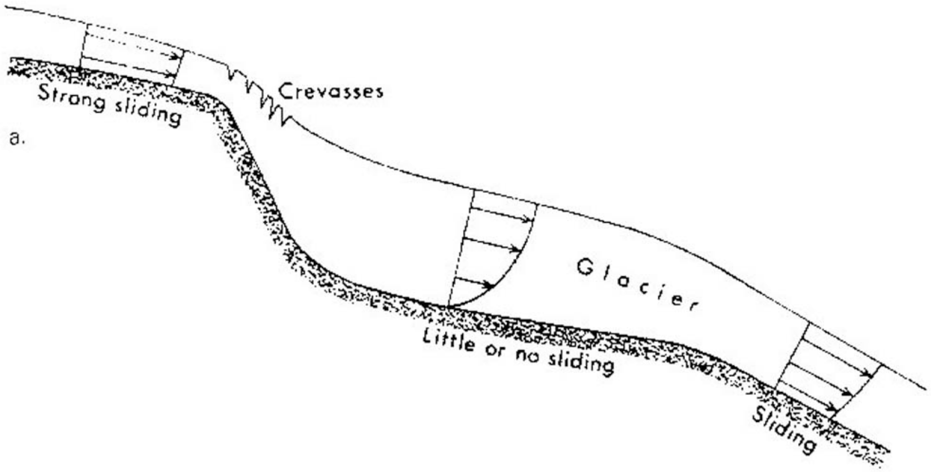
β is the slope of the glacier surface (degrees).

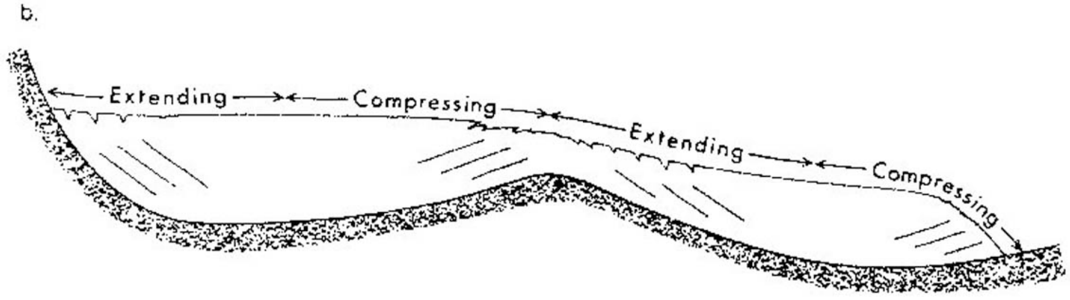
Calculating Ice Thickness

When τ_b is equal to the assumed plastic yield stress of ice (τ_c), 100 kPa, sliding would begin at the base of the glacier and ice thickness and basal shear stress could not increase further.

The thickness of the ice may be calculated as a function of surface slope:

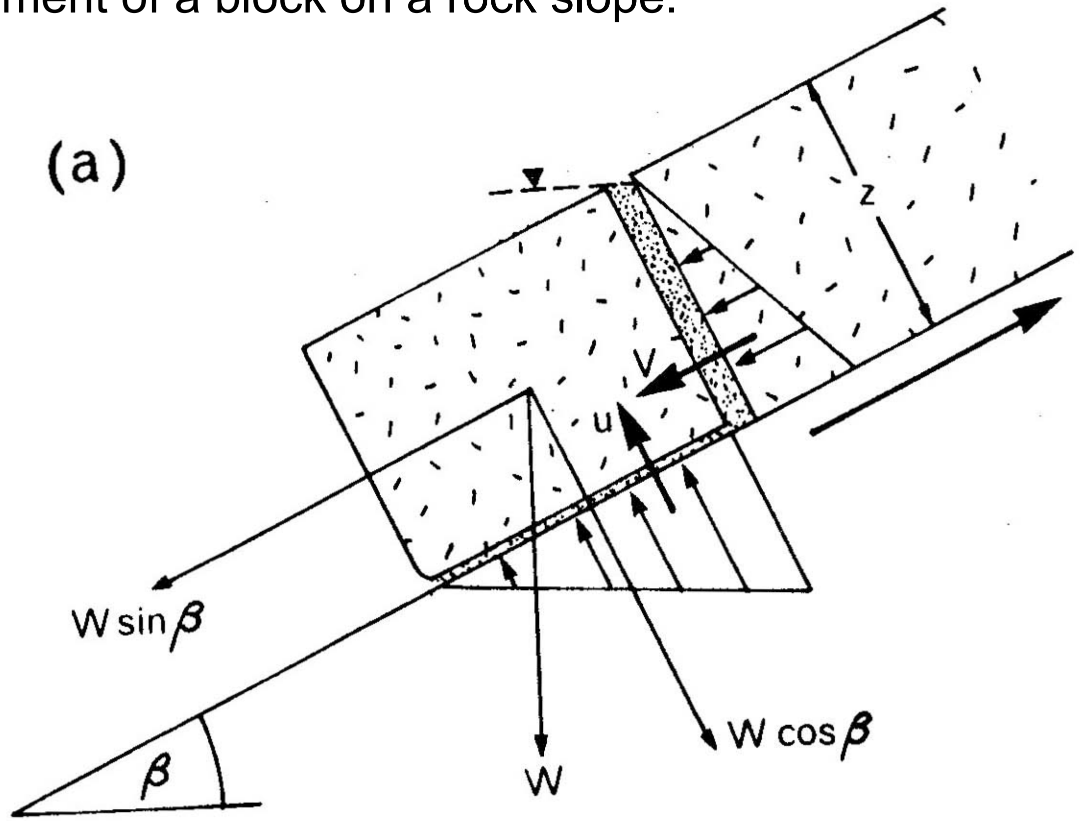
$$h = \gamma\text{ice}.\sin\beta/\tau_c$$





Plasticity implies the $h.\sin\beta$ is a constant and is validated by field measurements. It has been shown that where the glacier bed steepens, the glacier thins, develops crevasses and increases in velocity by sliding (extending flow). Where the bed flattens, or becomes concave, the ice thickens, undergoes thrust faulting, and decreases in velocity (compressing flow).

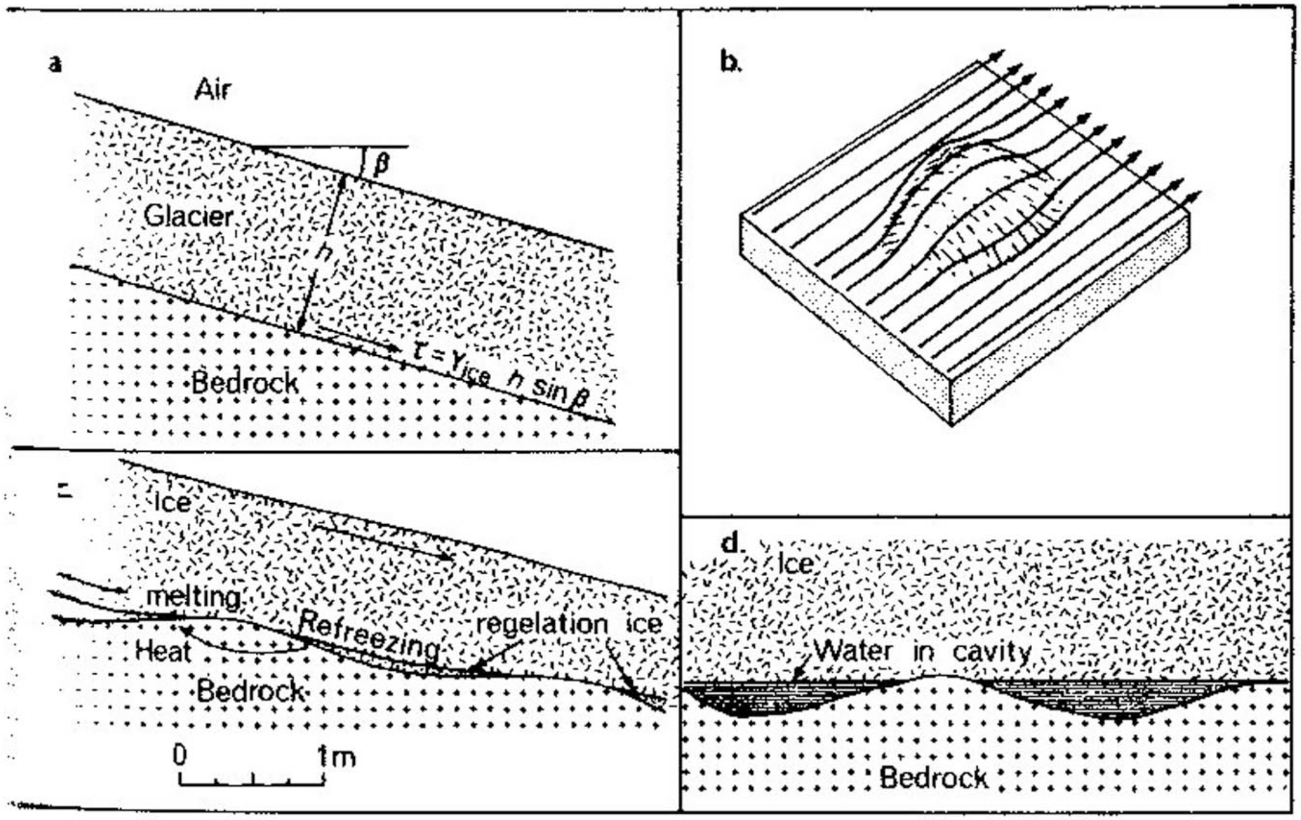
Movement of a block on a rock slope.



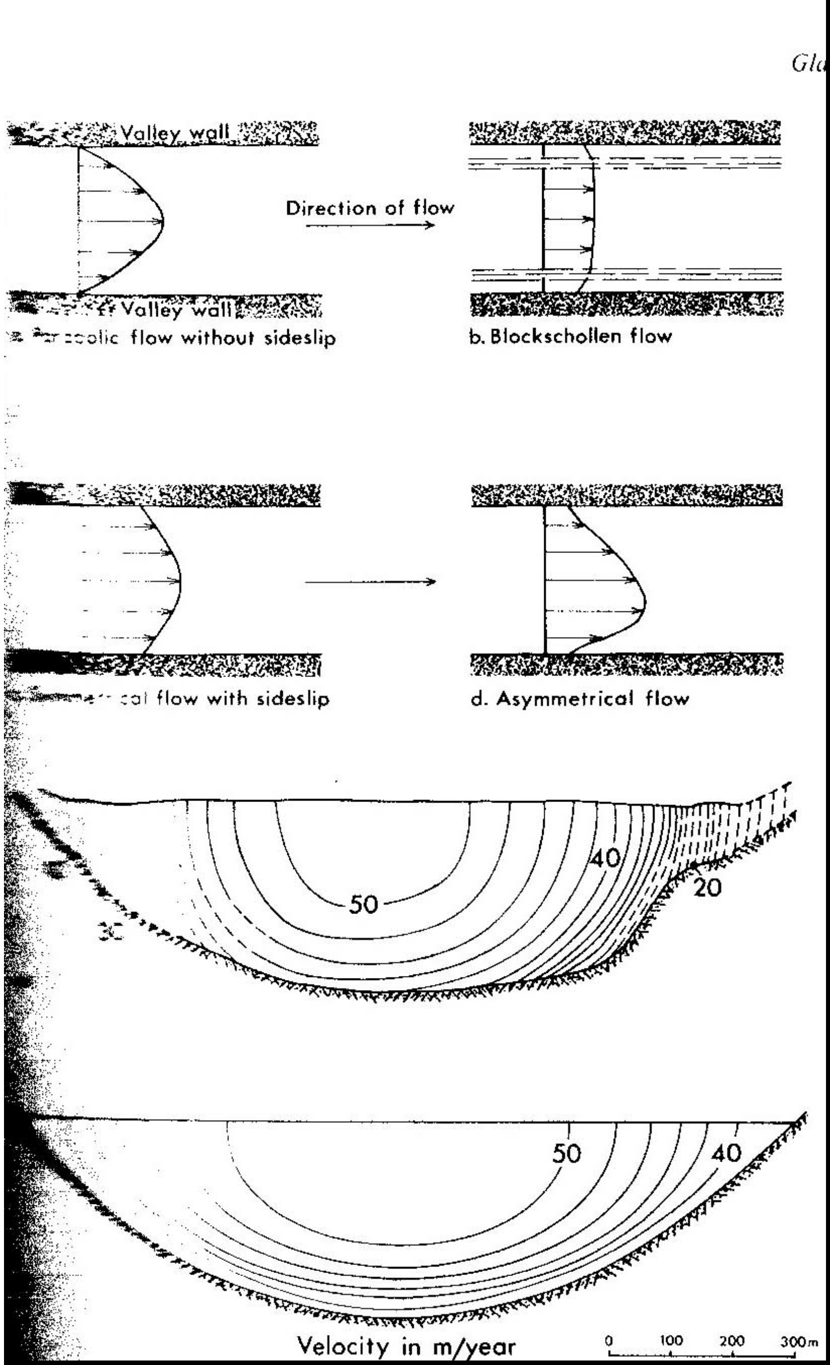
Driving Forces: $W\sin\beta + V$

Resisting Forces: $c_j (W\cos\beta - U)\tan\phi$

Where: W-weight of block, V-weight of joint water, c_j-cohesion along the base of the block, U-water pressure along base of block, and ϕ–angle of internal friction.



At the base of a glacier, where ice is at the pressure melting point, the ice is separated from the bedrock by a film of water. The film reduces the friction and ice can slide. If the water is under high pressure (p), the effective basal stress will be (γice.h - p). Zero values of (γice.h - p) occur when the ice is completely detached and may occur when a glacier surges.



In a valley or alpine glacier flow velocities of ice are strongly controlled by frictional resistance at the base and along the sidewalls.

Ice velocity is greatest in the center and near the surface of the glacier.

Flow lines project downward in the accumulation area and upward in the ablation area.

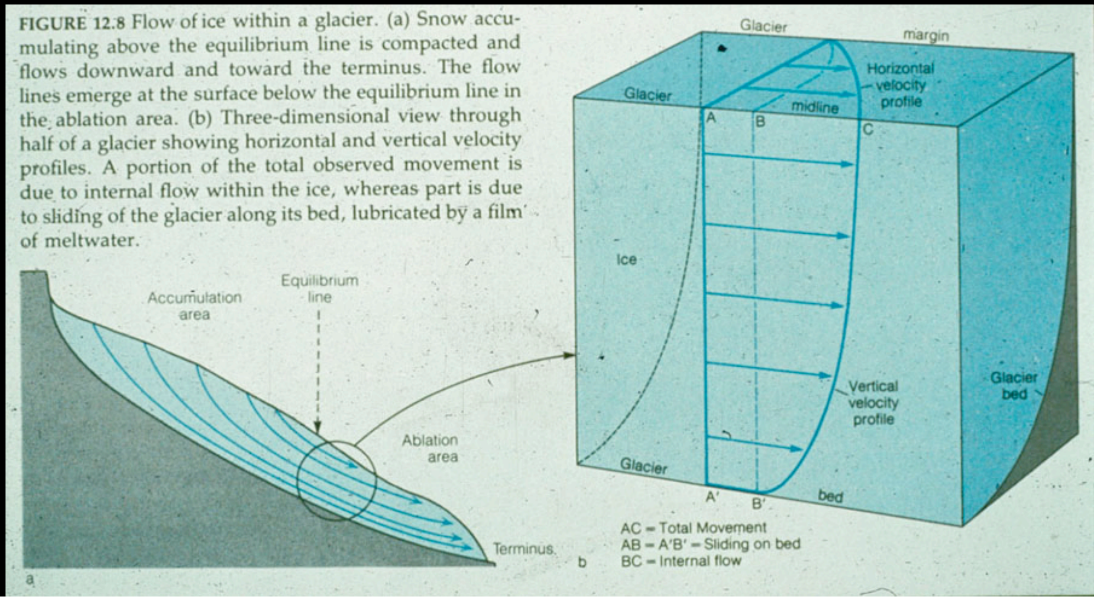
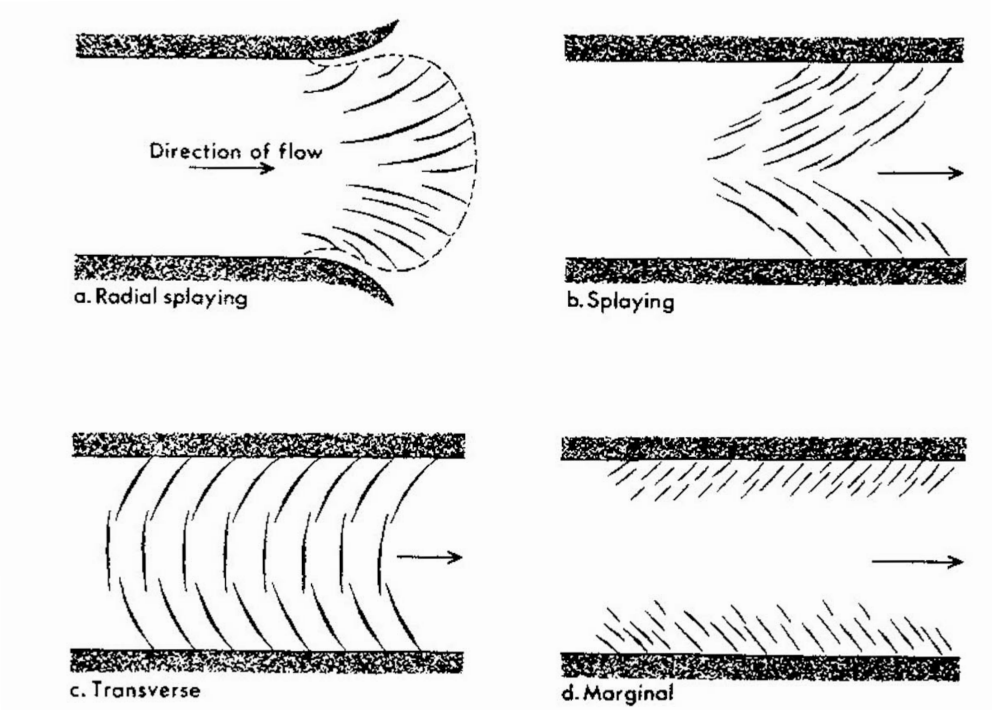


FIGURE 12.8 Flow of ice within a glacier. (a) Snow accumulating above the equilibrium line is compacted and flows downward and toward the terminus. The flow lines emerge at the surface below the equilibrium line in the ablation area. (b) Three-dimensional view through half of a glacier showing horizontal and vertical velocity profiles. A portion of the total observed movement is due to internal flow within the ice, whereas part is due to sliding of the glacier along its bed, lubricated by a film of meltwater.



Where stretching of the glacier exceeds 1% per year crevasses tend to form.

Crevasses vary in width between a few centimeters to 10’s of meters.

Crevasses rarely extend to depths below 40 m because the fracture closes due to internal flow (creep).

Crevasses commonly form as ice flows over steepening topography and extends.

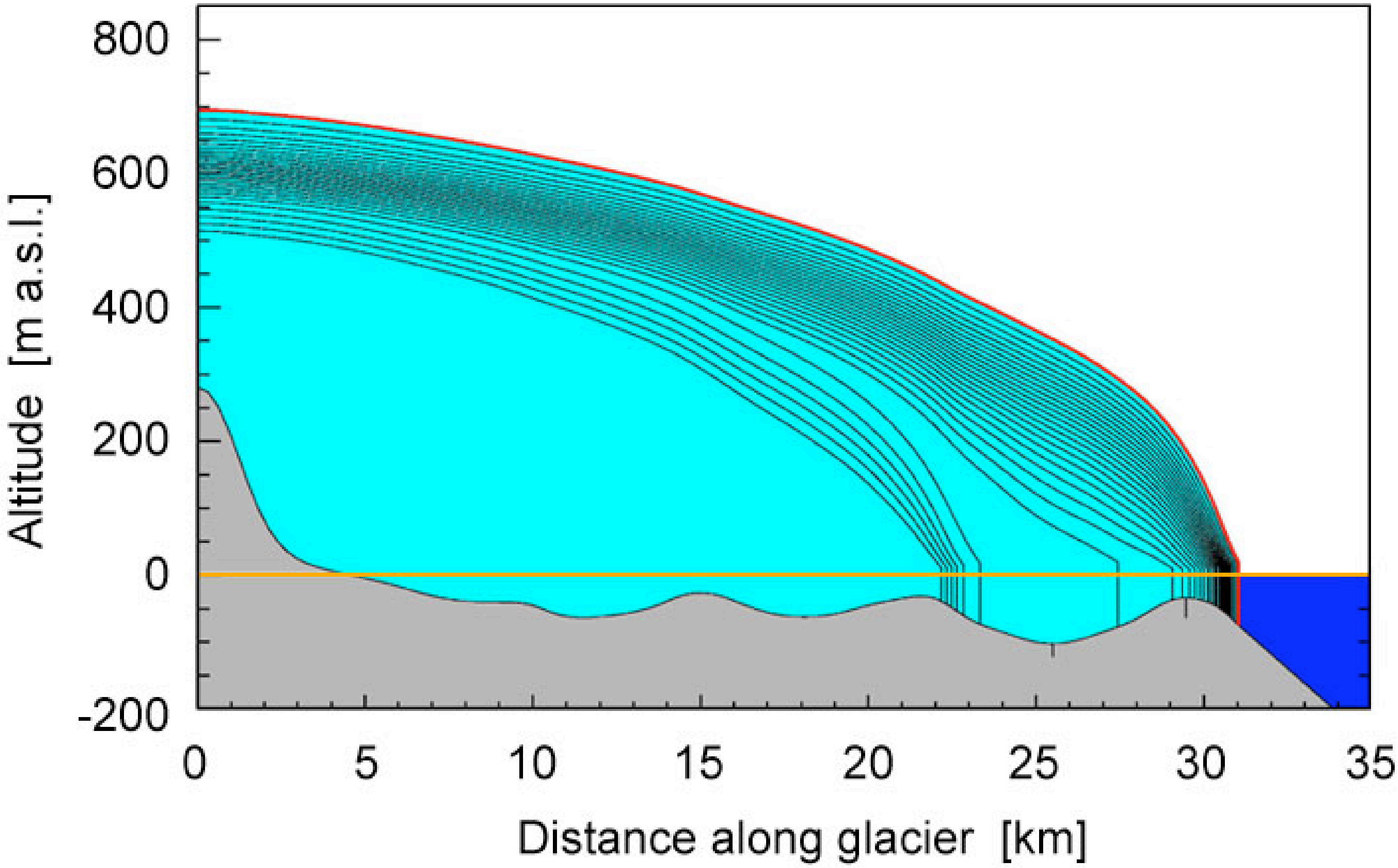
Crevasses also form as ice flows onto an open plain or in response to variations in slope of the base or the side walls.

At the base of an ice fall crevasses close and ice reforms. The reformed ice may have a wave-like form that bows down valley. The wave form is called an *ogive.* The wave form is produced from ice which has crossed the ice fall during the accumulation season. The depression between ogives correspond to ice which has crossed the ice fall during the ablation season.

Within ice falls developed at steep sections, the ice may divide into blocks or pinnacles called *seracs.*

Tide water glaciers advance slowly into their fjords as they build their submarine moraine shoal. The moraine protects the ice front from relatively warm marine waters and stablilizes the glacier.

During the retreat of a tidewater glacier, the glacier first begins to thin in the terminal zone until it is no longer grounded on its moraine. Retreat then becomes very rapid, as the glacier front becomes exposed to warm marine waters.



The retreat rate of calving glaciers is strongly related to water depth of the calving embayment. This image was produced by the Laboratory of Hydraulic, Hydrolgy and Glaciology, ETH Zurich, 2006).

What is Glacial Surging?

- Rapid flow over a short time (active stage) followed by long periods of no movement (quiescent stage)
- Maximum velocities 10x more than quiescent stage
- During active stage ice is moved from upper area (reservoir) to the snout (ice-receiving)
- Active and quiescent cycles usually consistent, but every surging glacier has their own cycle length
- Amount of ice in accumulation zone affects surging
- 4% all glaciers are surging glaciers
- Temperate and cold glaciers both are subject to surge
- Glaciers of surge type appear to occur mostly on sedimentary rocks

Variegated Glacier, AL

- **Features of Glacial Surging**
- Heavy crevassing
- Ice velocities increase and fluctuate
- Transfer of large volumes of ice
- The snout may advance (few km's in few months)
- Large amounts of melt water released
- Thrusting in the ice occurs at the surge front

- # Causes of Glacier Surging

Rigid Bed Hypothesis

- Glacier lies on rigid bed of rock
- Water drains at base through tunnels and drains to the snout
- The tunnels eventually closes/collapse trapping water and building pressure
- Basal sliding increases and friction is less
- Glacier separates from its bed and cavities begin to join
- Joining cavities results in water discharges easily and surge stops.

Soft Deformable Bed Hypothesis

- Ice resting on soft unconsolidated cement
- Drainage through permeable sediments under the ice
- Permeability is reduced and ice thickens
- Pressure builds up and glacier begins to flow
- Sediments return to permeable and surging ends