

Outline #3 Glacial Deposits and Landforms

Glaciation: the modification of the land surface by the action of glacier ice.

Glacial Erosion:

-Small-Scale Features: glacial grooves and striations, crescentic gouges, asymmetrical landforms

-Landforms of Glaciated Mountains: cirques, tarns, aretes, horns
glacial valleys, fjords.

-Landforms Associated with Ice Caps and Ice sheets: abrasional features,
streamline forms (drumlins and rock drumlins)

Glacial Deposits:

-Glacial Drift: sediment deposited directly by glaciers or indirectly by meltwater in streams, in lakes, and in the sea.

-Till

-Glacial-marine drift

-Stratified Drift

-Deposits of Active Ice

-ground moraine

-end moraine (includes terminal and lateral moraines)

-medial moraine

-erratics and boulder trains

-outwash (outwash plain, terraces)

-proglacial lakes and deltas

-Deposits of Stagnant Ice

-Ice-contact stratified drift

-kame

-kame terraces

-kettle lakes



Glaciated terrains represent some of the most beautiful landscapes in the world. Yosemite National Park, California is a classic alpine glaciated landscape.



Glacial erosion is accomplished by three major processes: abrasion, crushing and fracturing, and quarrying (or plucking) of joint blocks.



Glacial grooves and striations are preserved on quartzite bedrock overrun by the Puget ice sheet.



EROSION PROCESSES

Erosion occurs under a glacier through several processes:

1. Abrasion: scratching action
2. Plucking or quarrying: removal of large fragments from the substrate
3. Moving meltwater: abrasion, corrasion, and dissolution

Abrasion

Glacier ice cannot directly abrade other rocks, unless they are softer, like talc or gypsum, because its hardness is low (2 to 3 at -15°C , on Mohs' scale), even in cold glaciers. It needs rock fragments embedded in its base to abrade (Fig. 4.1). With

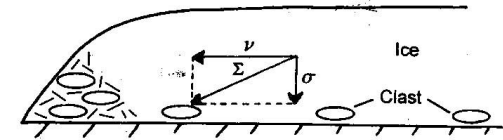


FIGURE 4.1 Schematic cross section of a glacier showing conditions necessary for abrasion. Abrasion occurs when the combined forces of weight (σ) and movement (v) of a glacier push a clast against the bedrock or against another clast, as indicated by the vector sum $\Sigma = v + \sigma$.

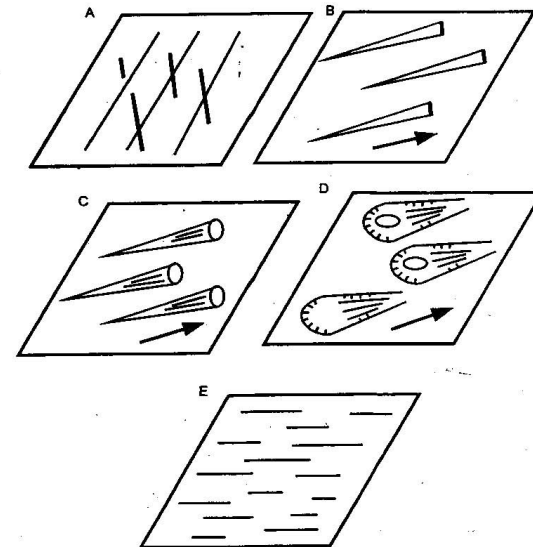


FIGURE 4.3 Diagrams of selected small-scale glacial-erosional features. (A) Two sets of striae. The heavier, deeper ones can persist when additional, but shallower, abrasion (striae) occur. (B) Wedge-shaped striae. (C) Nailhead striae. (D) Rat-tail striae are composite features showing convex upstream erosion in front of still-existing or removed obstructions, and tail furrows. (E) Polished surface made by numerous small scratches on the surface of hard rocks. These are generated by small clasts like silt grains.



Factors Affecting Glacial Abrasion

1. Presence of debris within basal ice.
2. Basal sliding rate.
3. Movement of debris towards base of glacier (polished material less erosive).
4. Ice thickness: the greater the thickness of the ice, the greater the vertical pressure on the abrasive particle. If thickness is too great friction increases and ice flows around the particle.
5. Basal water pressure: the presence of basal water can both reduce the effective pressure on particles at the glacier bed and increase basal sliding.
6. Relative hardness of debris and bedrock.
7. Debris particle size and shape.
8. Efficient removal of fine debris (largely by meltwater).

Frictional Shear at the Bed of a Glacier

Ice thickness determines the normal stress at the interface between glacial debris and substrate at the base of the glacier.

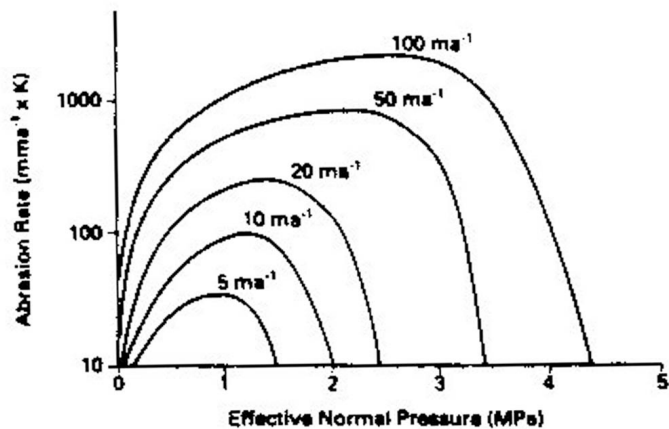
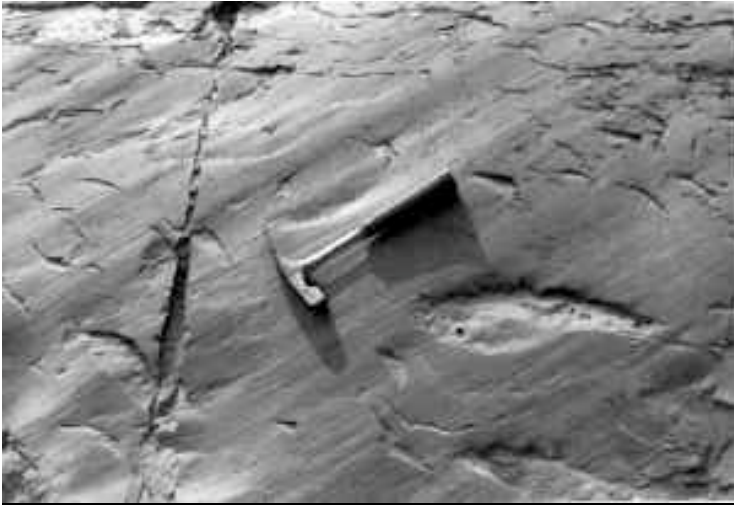
For warm-based glaciers this stress is reduced by basal water pressure.

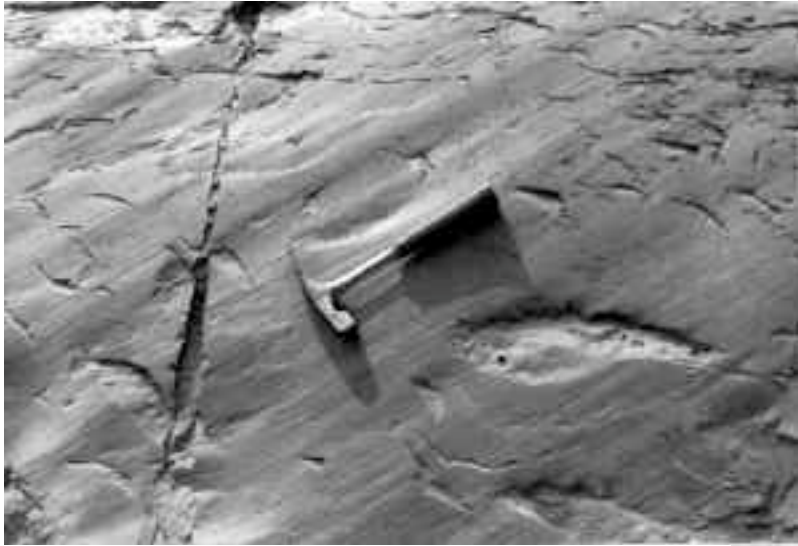
The basal frictional shear (F) is given by:

$$F = A_c \mu (vh - \pi)$$

Where: A_c : is the area of contact, μ : coefficient of friction, v : unit weight of the ice, h : ice thickness, and p : basal water pressure.

As the effective basal pressure increases, the rate of abrasion for any given sliding velocity increases until frictional resistance becomes so high that ice will flow over the particle (abrasion reduced).

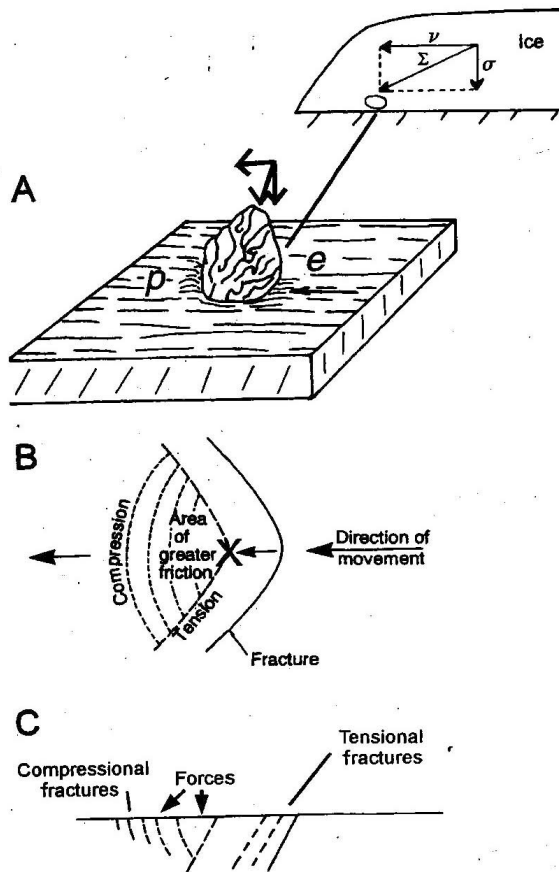




Fracture of Bedrock

Fracturing of bedrock beneath glacial ice can only occur where large blocks, contained in the ice, are force against the underlying bedrock surface.

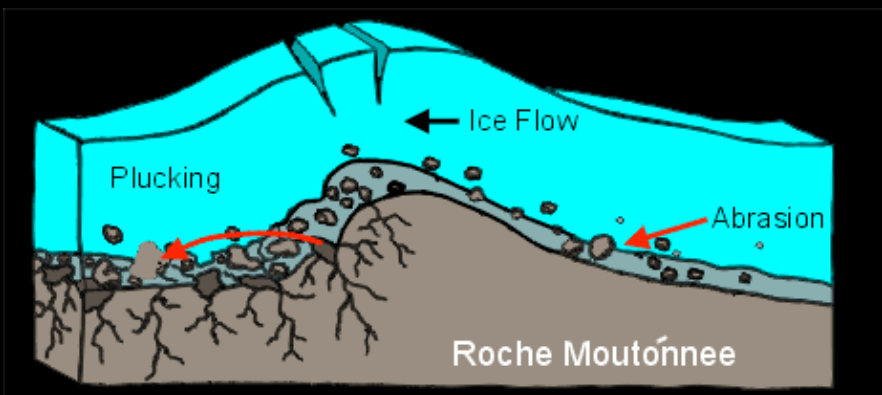
Crescentic gouges and chatter marks result from pressure fracturing by the pointed corner of an entrained large clast held in the ice. The ice pressure against a large block produces high stress that is concentrated into a small area, which permits fracturing of the bedrock.



The chatter marks may be oriented up or down related to ice flow direction. The angle of contact between the pointed block and the fracturing face controls their relative orientation.



Asymmetric (stoss and lee) landforms are characteristic of glacially eroded landscapes. They range in size from several meters, such as the small scale roche moutonnees, in front of Franz Josef glacier, New Zealand (upper left image), to several kilometers, such as the large *flyggberg* defining Mt. Erie on Fidalgo Island, Washington. They have a smooth, abraded up-glacier side and an over-steepened, plucked, down-glacier side. Ice flow direction is from right to left in these images.



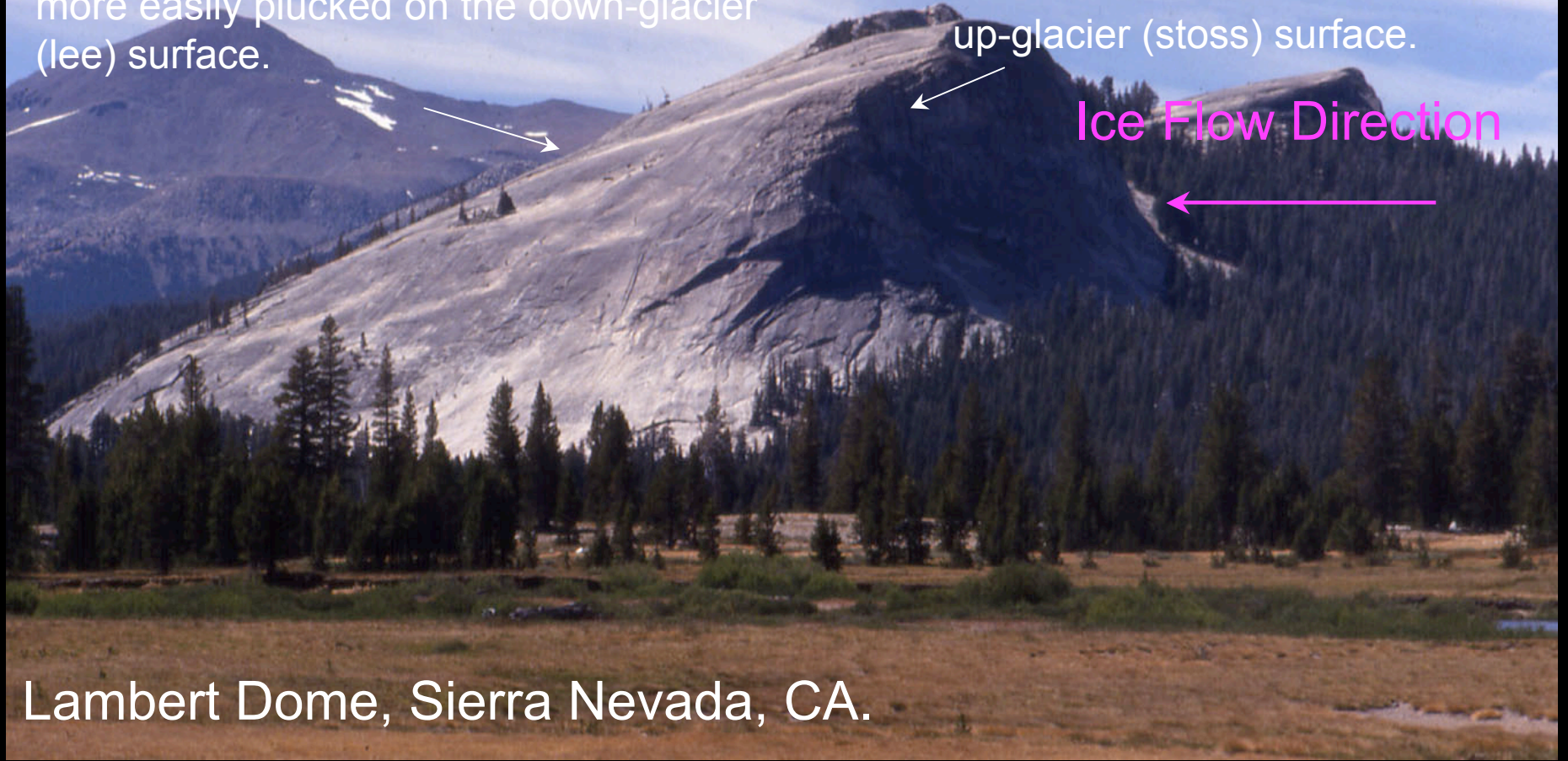
Basal ice pressure decreases as the glacier flows over the bedrock knob. Melting temperature is increased and meltwater may refreeze and enhance frost wedging of jointed bedrock. Weakened joint blocks are more easily plucked on the down-glacier (lee) surface.

Basal ice pressure increases as glacier flows over pre-existing bedrock knob. Melting temperature is lowered and abrasion rate increases on the up-glacier (stoss) surface.

Ice Flow Direction

Lambert Dome, Sierra Nevada, CA.

Asymmetric landforms, such as Lambert Dome in the Sierra Nevada, likely result from pressure differences beneath the glacier as the ice flows over a bedrock knob.





Meltwater Abrasion

Fine silts (glacial flour) suspended in glacial meltwater can also polish bedrock under conditions of high pressure. This polished surface in the Sierra Nevada, CA was polished by melt water abrasion.

Note, that unlike surfaces polished by glacial ice, this surface lacks striations, indicative of abrasion by ice.

Debris Entrainment and Transport

- Effective glacial erosion can only occur if debris is entrained and transported away by the ice.
- The grain size of debris ranges between fine silts and clays to very large boulders.
- Subglacial debris is transported along the base of the glacier, englacial debris within the glacier, and supraglacial debris constitutes material that falls on the ice surface from rock falls.

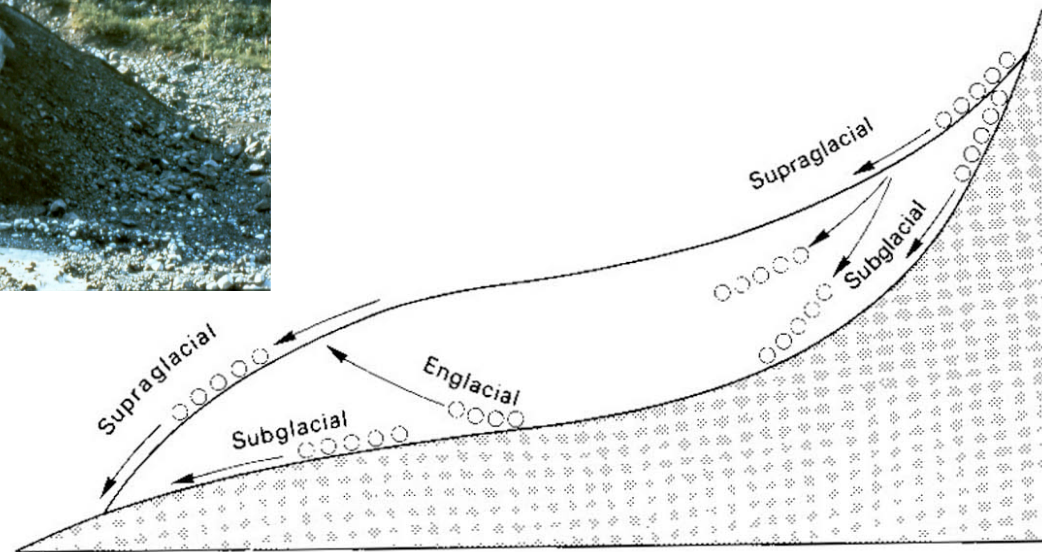
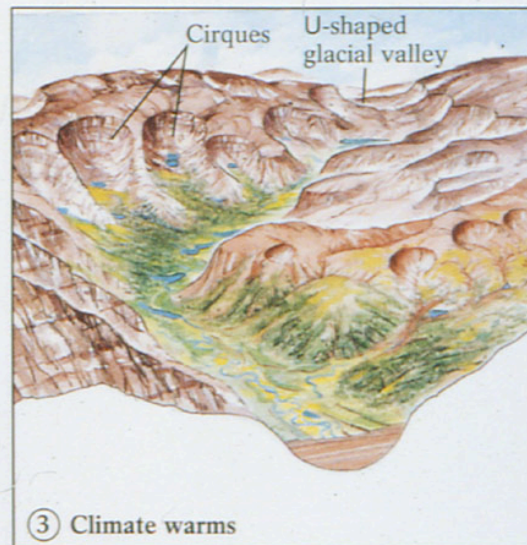
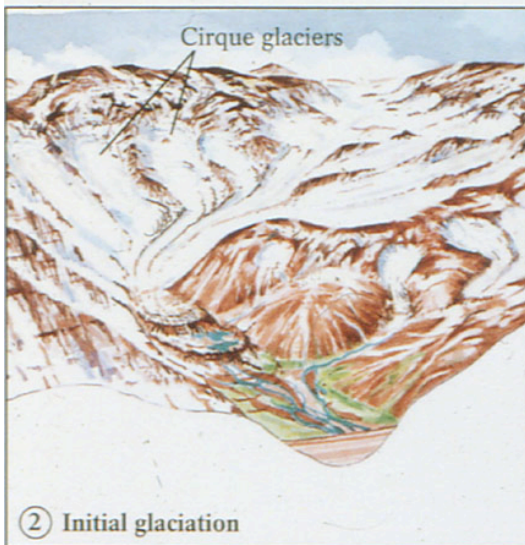
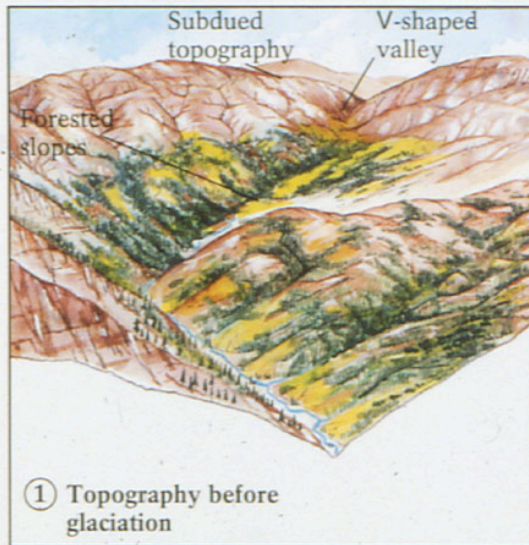


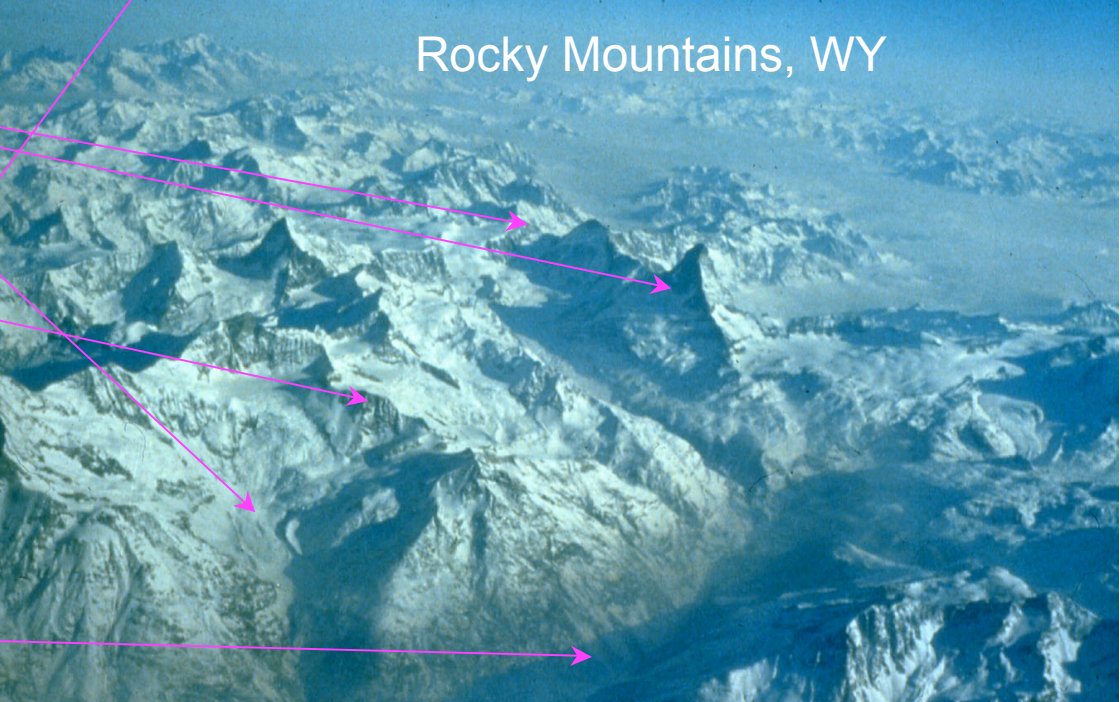
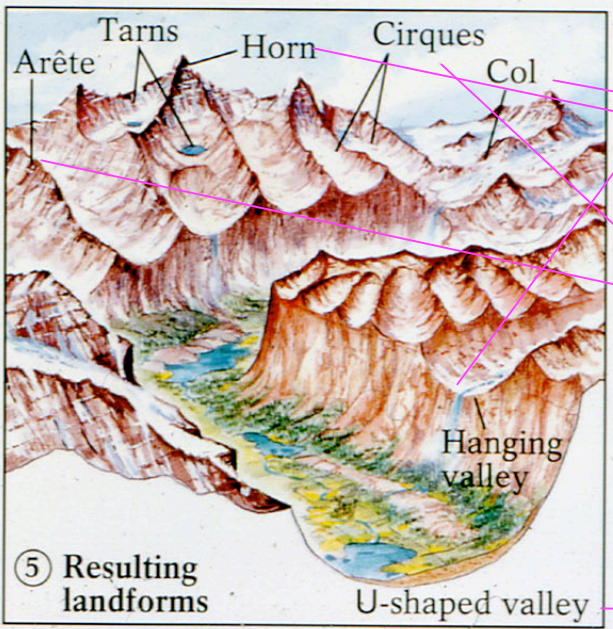
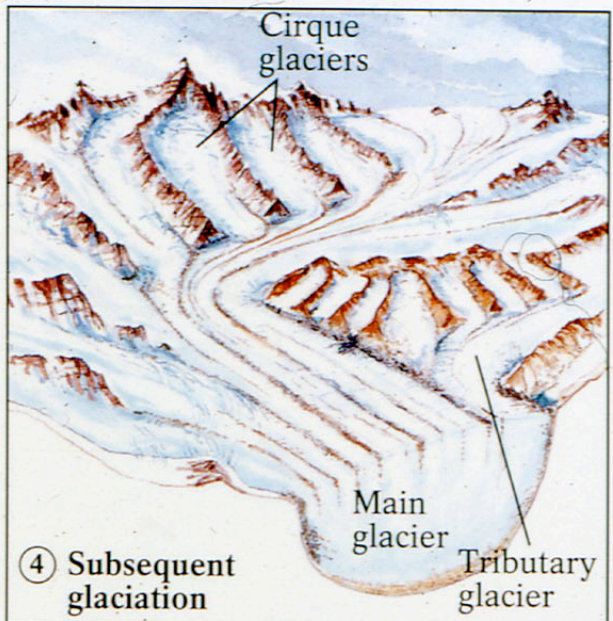
Fig. 11.11 Schematic illustration of travel paths of debris transported by valley glaciers.

Alpine Glacial Erosion

Transformation of V-shaped valleys eroded by streams and weathering processes during non-glacial climates to U-shaped glaciated valleys occurs over multiple glacial-interglacial cycles.

Glacially eroded alpine landscapes have U-shaped cross profiles, lakes typically filling the erosion depressions. Tributary valleys are hanging and the alpine topography is characterized by erosional cirques, horns, sharp-crested aretes and cols.







Fjord Landscapes

Deep glaciated valleys that have been eroded adjacent to coastlines are now occupied by marine waters following deglaciation and eustatic sea level rise.

Sognefjord, Norway is over 1500 m deep to its rock floor and covered with up to 200 m of sediment.

The deep erosion of fjords, similar to Sognefjord, occurs over multiple glacial cycles.

Why are glaciated valleys U-shaped?

Ice pressure >100 kPa acts like a plastic. Velocity profiles and pressure differences beneath the ice reflect its plasticity and erosion of valley results in U-shaped profile.

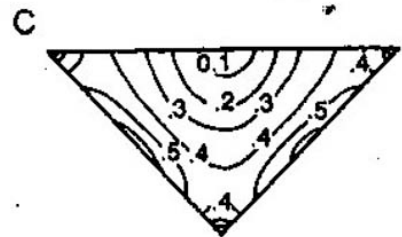
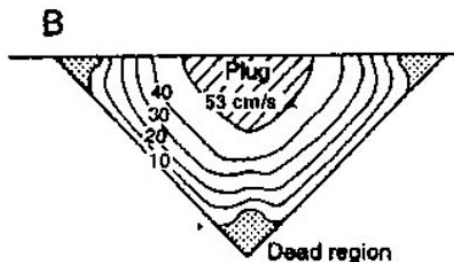
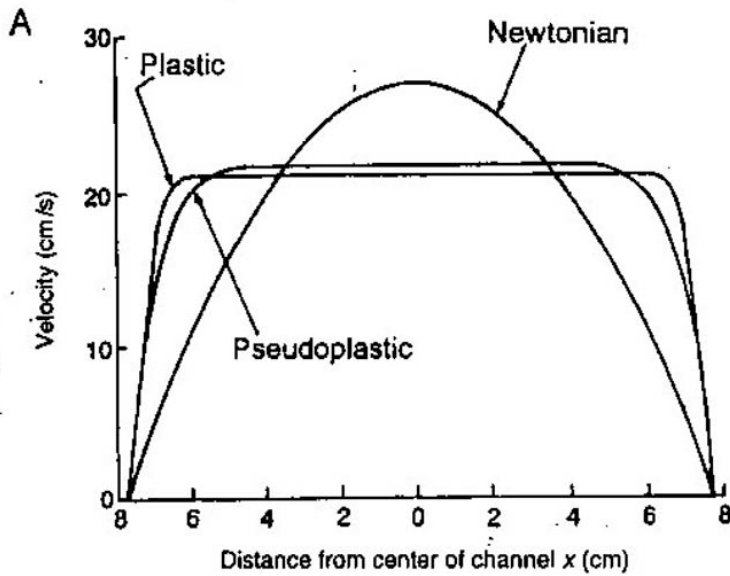


FIGURE 4.16 Development of a U-shaped valley by a glacier. (A) Plan-view pattern of different substances (Bingham = plastic material; pseudoplastic = akin to ice; Newtonian = akin to water). (B) Cross section of theoretical velocity gradients of a pseudoplastic material in a V-shaped valley — steep velocity gradients (contour lines closer together) toward the sidewalls. Note that no movement occurs at the bottom and levees are where fluid is lost. (C) Cross section showing pressure gradients — highest in correspondence with the steepest velocity gradients (units are dimensionless). (After unknown, please check website for update.)





Cirques (Corrie) Formation

Cirques depressions are developed by a combination of periglacial processes and glacial erosion.

Cirques consist of a bowl-shaped depression which extends from a steep headwall to a low lying rim.

Wind-blown snow is an important component enhancing their development.

Firn banks develop in suitable depressions and enlarged by frost-wedging and mass movement.

Deepening proceeds until the firn turns to ice which begins to flow. The cirque floor is deepened by glacial abrasion and enlarged by retreat of its headwall.

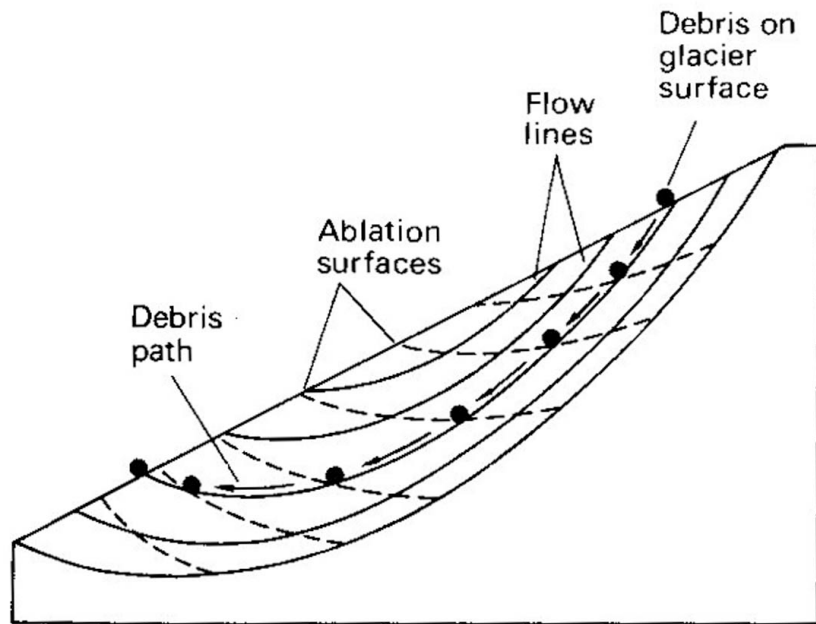
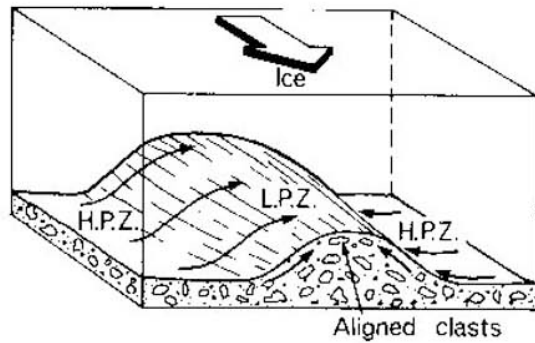
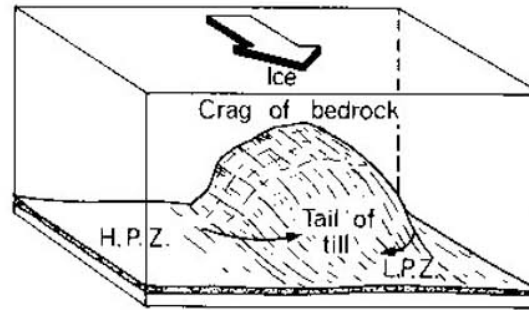


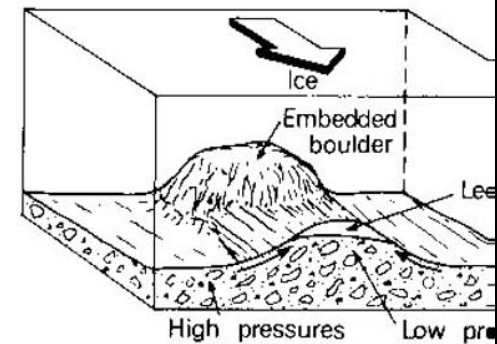
Fig. 11.14 Schematic longitudinal section through a cirque glacier. Note the form of the flow lines and the path taken by debris which falls on to the glacier surface.



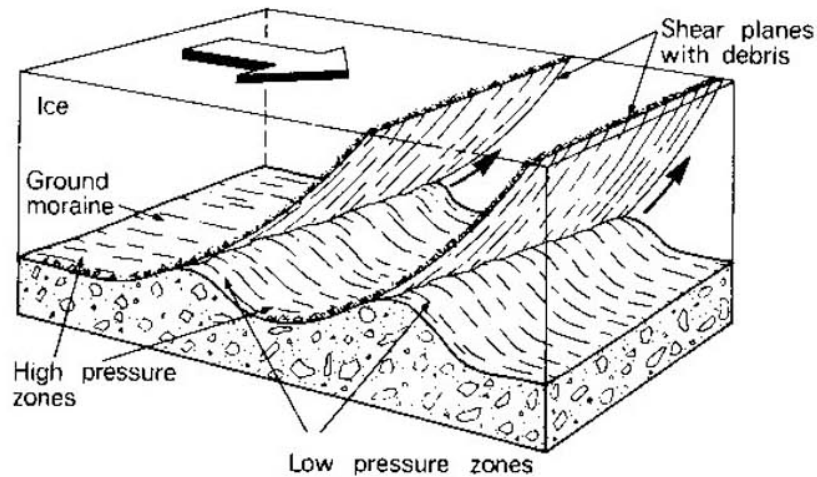
(a) DRUMLIN



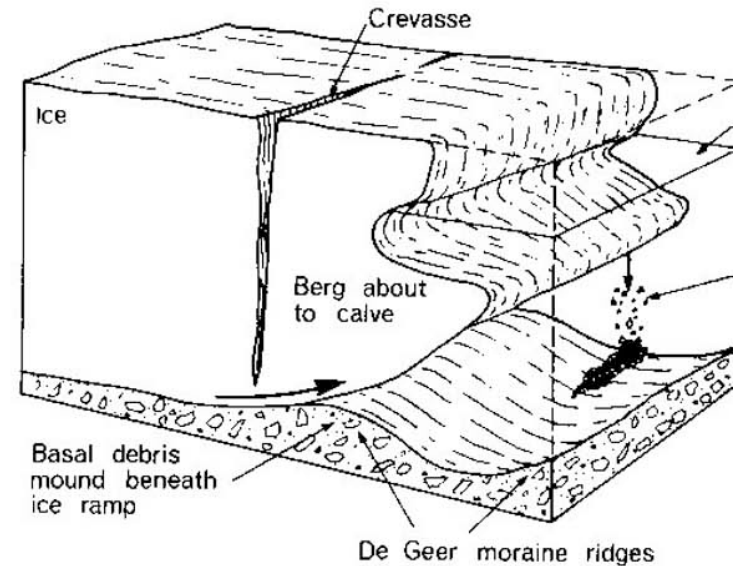
(b) CRAG AND TAIL



(c) FLUTED MORAINE

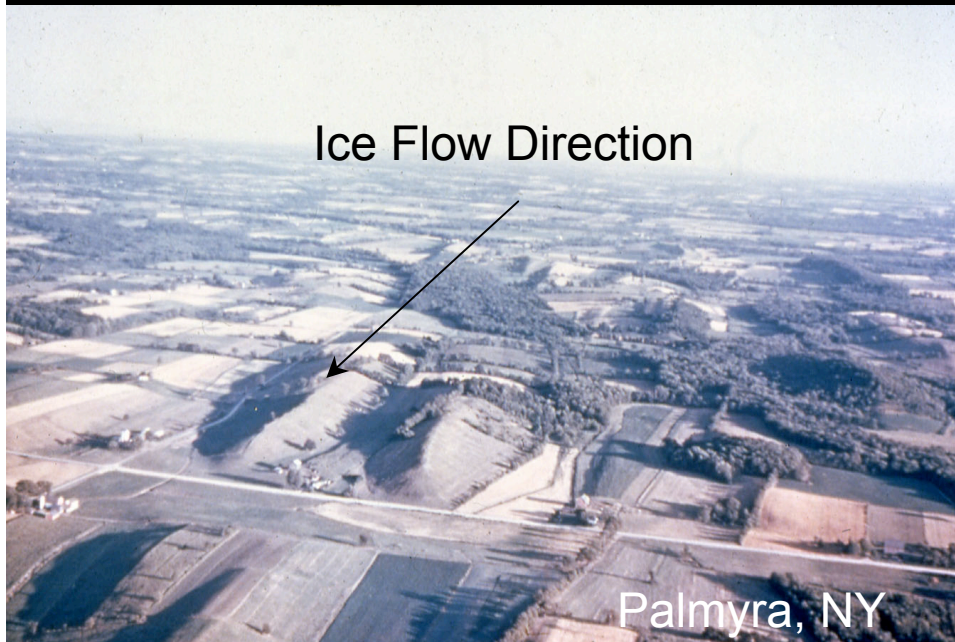


(d) ROGEN MORAINE

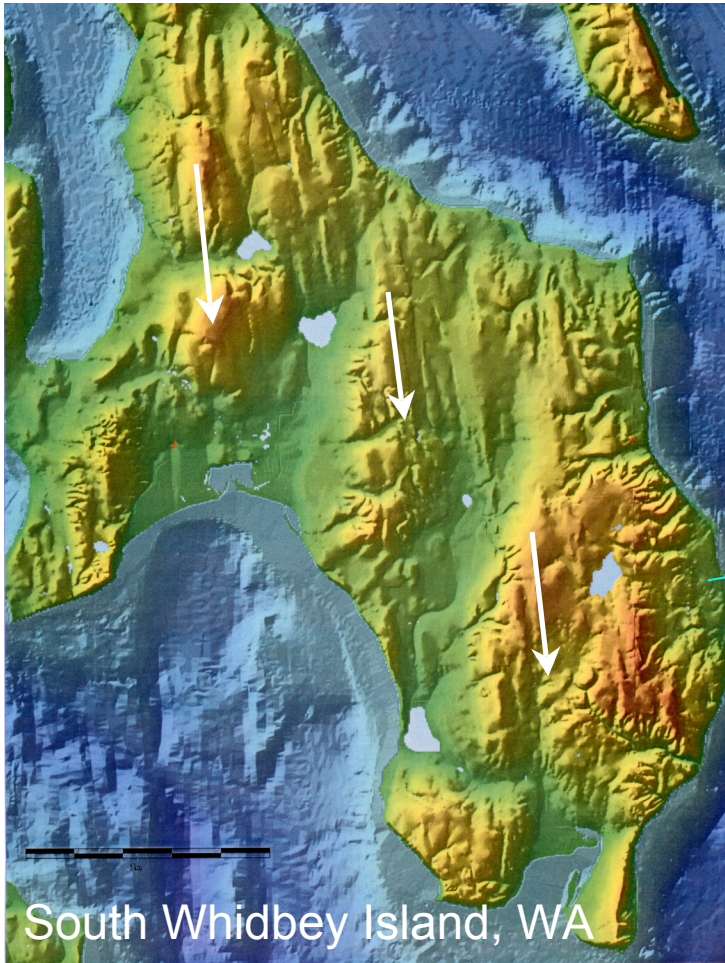


(e) DE GEER MORAINE

Fig. 15.19 Formation of glacial depositional landforms. (a) Drumlin. (b) Crag and tail, (c) Fluted moraine deposition in an ice and water pressure at the bed of the glacier where pressure zones are parallel to the direction of ice movement. (d) One rogen moraine is that it develops where shear stresses, transverse to direction of movement, are relieved. (e) De Geer moraine thought to form in lakes where grounded ice calves and debris accumulates at the ice margin.



- Drumlins have a morphology like an inverted spoon (steep slope facing up ice).
- **Dimensions:** (variable) 100m to 7km length, 50 m to 2 km width, 5-30 m height.
- **Composition:** Internal composition may include a core of rock, glacial fluvial sediment, moraine or older till. Most drumlins have a carapace of lodgment till.
- **Distribution and Orientation:**
 1. oriented parallel to glacial flow.
 2. Drumlins occur fields that trend parallel to flow.
 3. Drumlin spacing is uniform and may range from 100 m to 1000 m.
 4. Drumlins usually occur behind large moraine complexes.
 5. Drumlins are deposited by both ice sheets and valley glaciers.

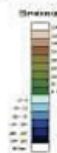


South Whidbey Island, WA

Drumlinoid features are prevalent within the Puget Lowland. Dimensions vary but they all parallel ice flow direction. There is no unifying theory likely to explain all observed drumlinoid landforms, as they are likely polygenetic features.



Lake Tapps, WA



Puget Sound

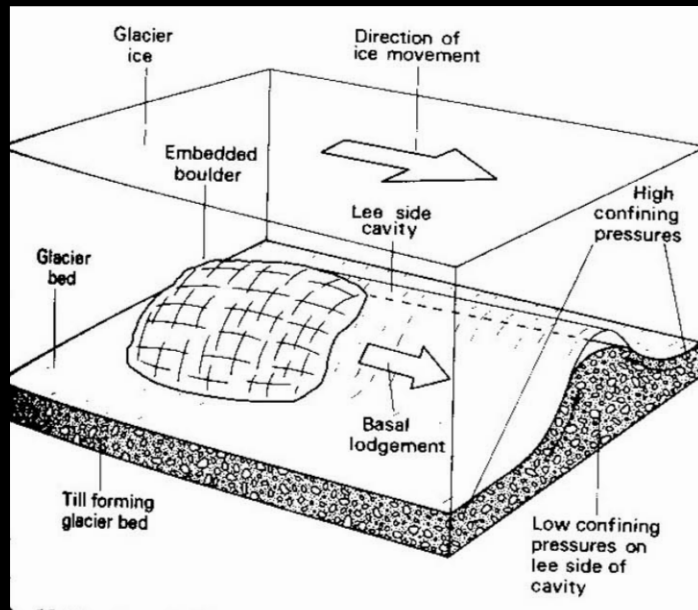
By David W. Brown, Todd Ringstad, Hans-Ulrich Ang, Sakai Yukio

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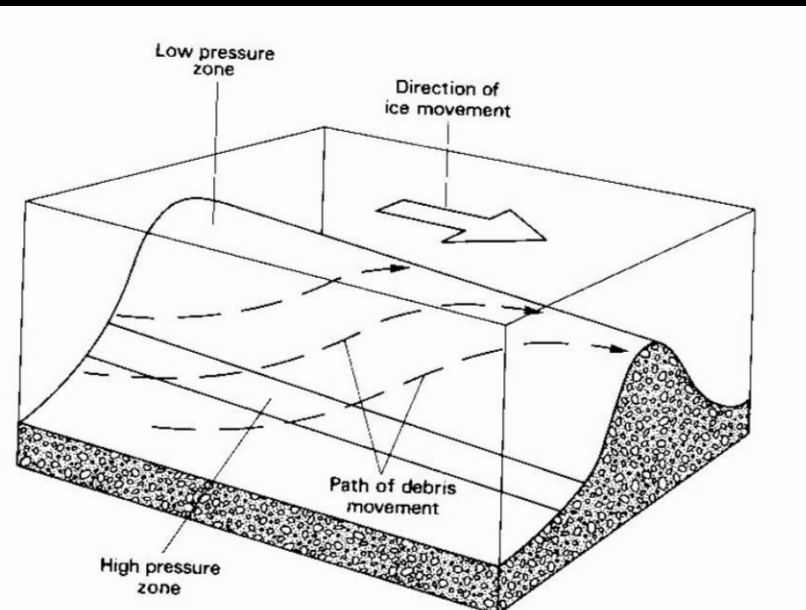


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Flute Theory



Subglacial Streamlining



Flute theory of drumlin formation proposes that a low pressure zone or cavity exists in the lee of an obstacle, such as an embedded boulder or sediment core. Till is deposited or molded into this cavity.

Subglacial streamlining of obstacles create resistance to glacial flow. Drumlins accrete till slowly in the low pressure zones and erode in areas of high pressure (i.e., troughs between drumlins).

Subglacial Meltwater Theory (Shaw, 1989; Sharp 1987)

Giant Bedform Hypothesis: Drumlins are sculpted from sediment into streamlined forms by a catastrophic meltwater discharge event (Shaw, 1989).

Fluvial Infillings of Subglacial Cavities: Sharp (1987) contends that some drumlinoid forms result from glacial-fluvial infilling of subglacial cavities.

Differential Erosion/Deposition within a Deformable Heterogeneous Bed (Boulton, 1987)

Deformable sediment flows around and is deposited onto cores of less deformable rock or sediment (drained stratified sediment over consolidated till).

Subsole deformation and deposition is greatly influenced by pore water pressure.

Deposition occurs where water can drain from the bed, such as on permeable sediment.

Where pore water pressure is high subsole deformation is promoted.



Crag and tail



Edinburgh is built on a crag and tail

Crag and Tail Features

Crags are formed when a glacier overruns an resistant bedrock “plug” and differentially erodes the softer surrounding material.

Following erosion of the softer material the resistant bedrock stands in relief. Frequently the crag protects the softer material lying down glacier and tapered ridge or fan forms a tail on the lee side.

Edinburgh Castle, Scotland is constructed on the bedrock knob of a crag and tail feature that formed while Great Britain was overrun by the British Ice Sheet.

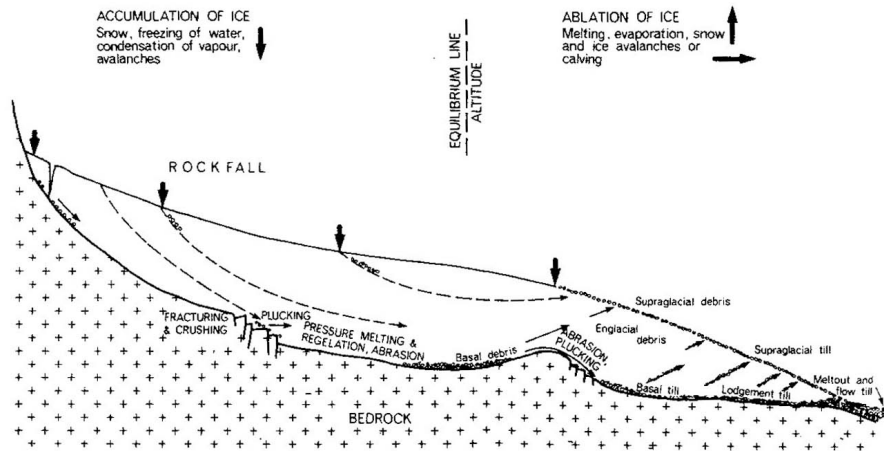


Fig. 15.11 Processes acting on and within a glacier.

Glacial Deposition

Sediment and ice crystals within a glacier are transported along imaginary flow lines. *Till* is defined as glacial sediment directly deposited by ice. *Moraines* are the landforms composed of till.

Flow lines which start at the head- or side-walls move downward and sediment is transported in the same basal layer with material plucked or abraded from the bed of the glacier.

The *sole* of the glacier is typically 1-2 m thick and loaded with rock and debris.

The sole of the glacier is sheared up to the glacier surface, where material is deposited along the front of the glacier as an end moraine.

Till is being deposited at the front of an ablating glacier and forms a terminal moraine.



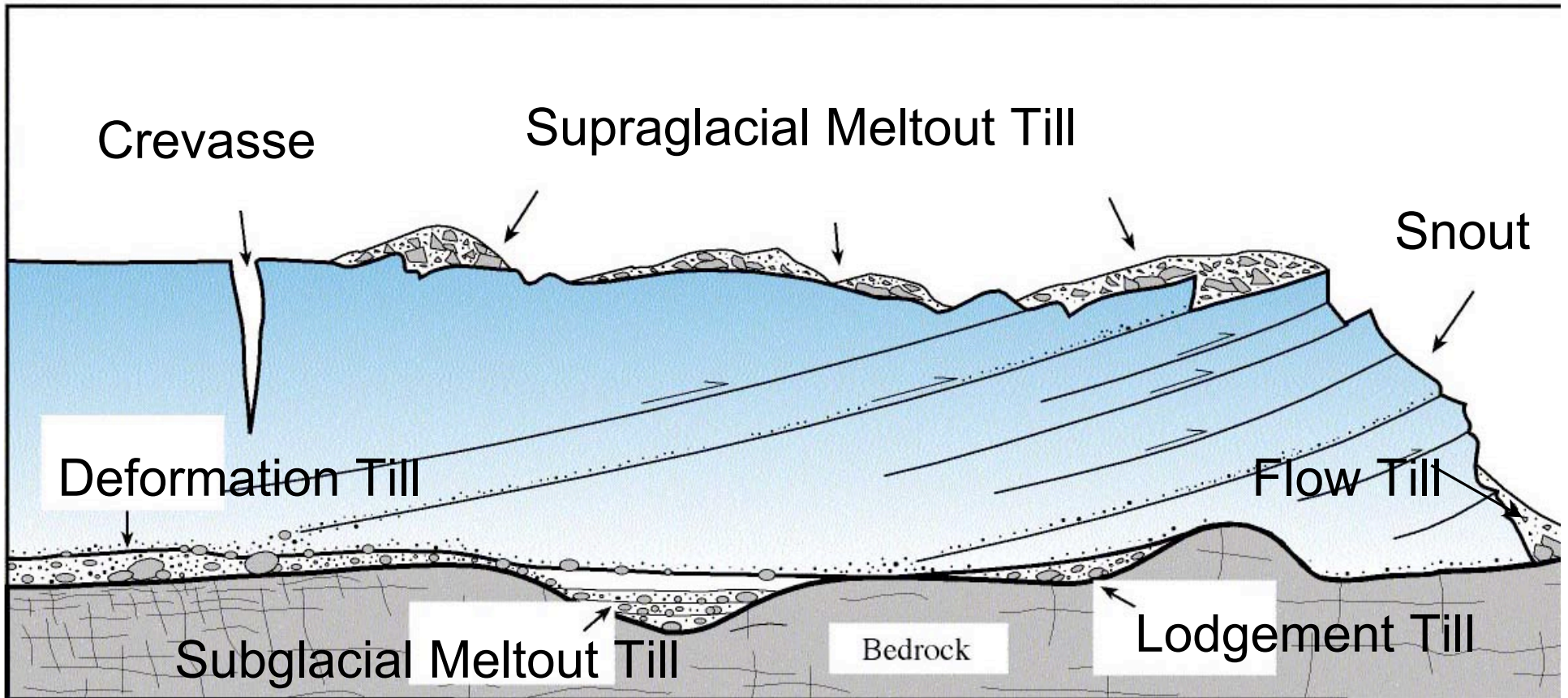


Properties of Till

Till is sediment deposited directly by ice.

Tills are highly variable deposits, but usually have some characteristics in common:

1. Poor sorting
2. Lack of stratification (crude stratification with flow tills).
3. Mixture of lithologies
4. Clasts may have abraded facets and striations
5. Preferred orientation of particles (basal tills)
6. May be compacted if deposited beneath ice
7. Overlies striated rock or sediment basement
8. Predominantly subangular due to combination of fracturing and rounding by abrasion



Mechanisms of Deposition

Subglacial: undermelt, basal lodgement, basal flowage.

Supraglacial: meltout and flowage

Marginal: dumping and pushing

*Diagram taken from the British Society for Geomorphology

Mechanisms of Subglacial Till Deposition

1. **Undermelt:** involves the deposition of till through melting of the underlying ice. This can be facilitated by geothermal heat, frictional heating, or increasing pressure and melting as ice flows over a topographic obstruction.
2. **Basal Lodgement:** glacier smears predominantly fine material on the glacier bed. Lodgement of subglacial debris occurs when the frictional resistance between the transported particle and the bed becomes so great that the ice will no longer move the particle as it flows around it. Clasts within basal lodgement till tend to be oriented with their long axes parallel to ice flow (till fabric).
3. **Basal Flowage:** involves the squeezing of unconsolidated water soaked debris into basal ice concavities and the streamlining of till by overriding ice (i.e., fluted moraines).



Mechanisms of Marginal Till Deposition



1. **Dumping:** involves the deposition of supraglacial and englacial debris by meltout along a stable glacier margin.



2. **Pushing:** existing sediment can be pushed by an actively advancing glacier and deposited when the glacial advance stops, or overridden and recycled towards the snout as englacial and supraglacial debris. A small push moraine formed in the Chiatovich Creek Valley, CA during the last glaciation.

Mechanisms of Supraglacial Till Deposition

1. **Meltout:** involves the deposition of till through melting of the glacial surface. It is most active in the snout of warm-based glaciers where up to 20 m of ablation can occur in a year. The two images shown on the left show (Fig. a.) meltout (ablation) till being deposited at the terminal zone of a surging glacier and (Fig. b.) ablation till forming the hummocky surface of previously glaciated valley in the White Mountains, CA.

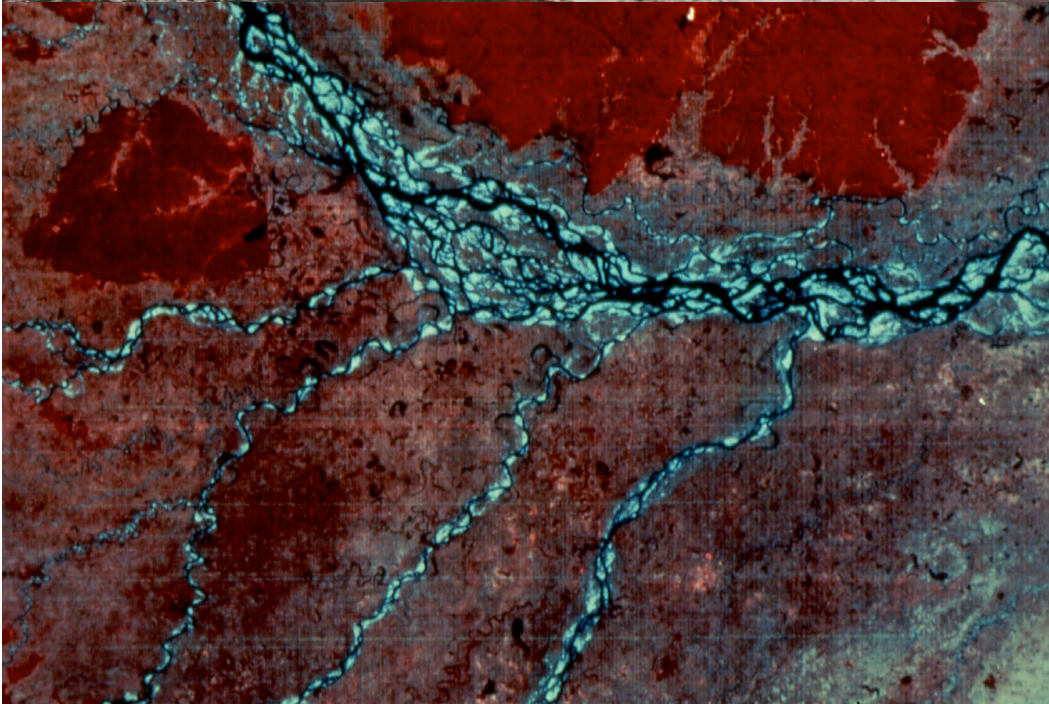


2. **Supraglacial Flowage:** involves the movement down the ice surface of the debris-rich upper layers of the glacier where melting rates and presence of water are high. The flow ranges from creep to saturated flow. A flow till is shown overlying lodgement till deposited by the Puget Lobe ice sheet on Whidbey Island (Fig. c.).



Nisqually Valley, Mt. Rainier,
WA.

Meltwater from glaciers is an important transport agent for reworking and depositing sediment beyond the glacier. Outwash tends to be well-sorted, stratified and generally contains rounded clasts. Grain-size is related to transport distance from the glacier margin. The ice front is proximal to the outwash train shown in the above image.



Outwash streams are typically braided because of their high sediment loads and variable discharge rates.

Braided streams are created when discharge of water cannot transport its bed load

When there is a decrease in stream velocity sediment is deposited on at the base of the channel creating multiple bars. The bars separate the channel into multiple smaller channels creating the braided appearance.

Braided channels commonly form as sediment choked mountain streams flow onto a lower gradient, such as the Brahmaputra River flowing from the Himalayas to the Ganges delta (shown on left image).



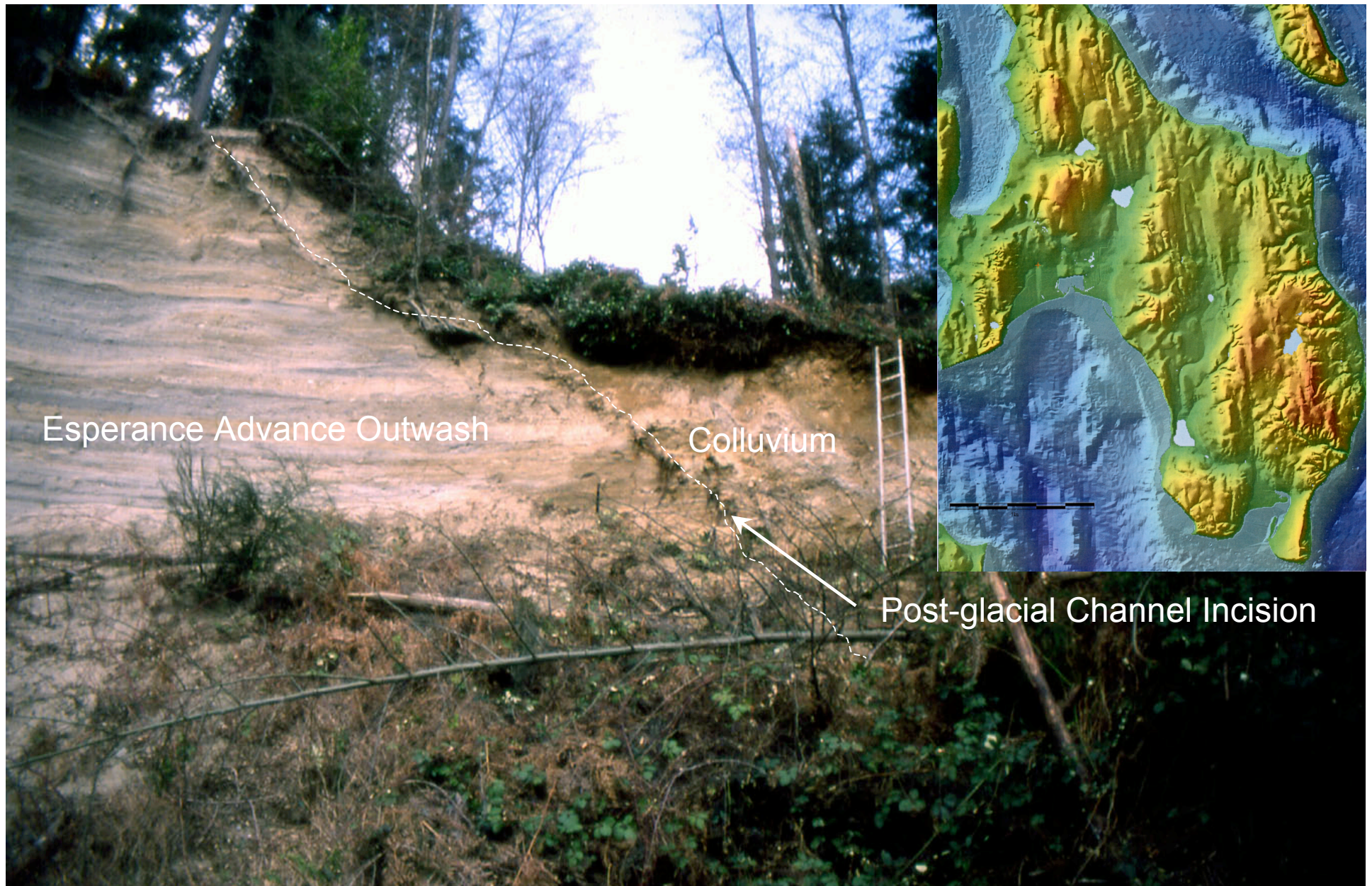
Esperance Outwash Sand

The Esperance outwash sand was deposited by the Puget Lobe during its advance into the Puget Lowland.

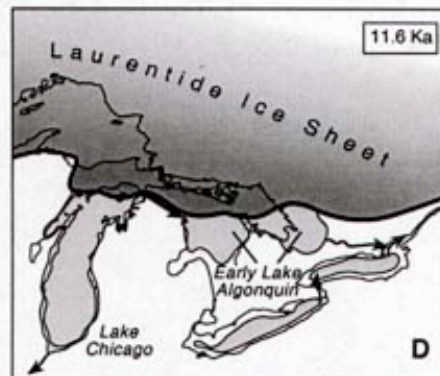
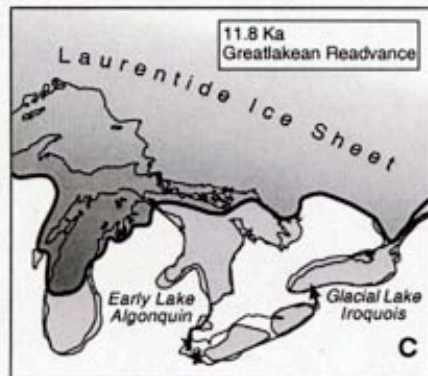
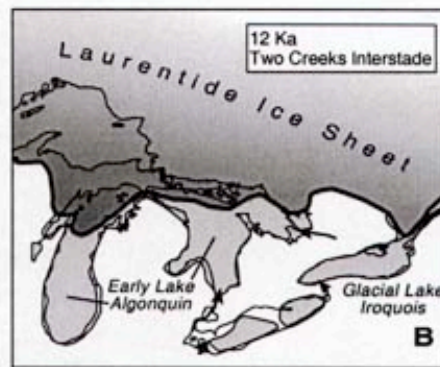
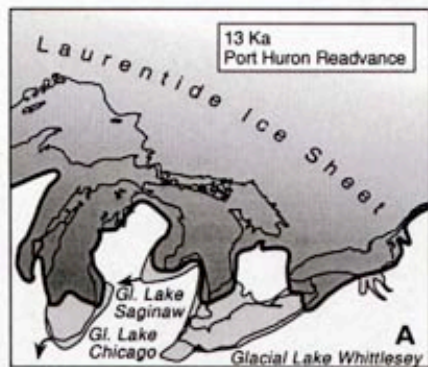
The advance outwash consists of well-sorted sand and fine gravels and is found at elevations from near sea level to over 375 feet. It was likely graded as a broad outwash plain in front of the advancing ice.

Sedimentary structures such as cross-beds, cut and fill features are common within braided stream deposits.





Well-sorted advance outwash sand was prograded into a broad outwash plain in front of the advancing Puget Lobe. Post-glacial channels were incised by ground water sapping following deglaciation.

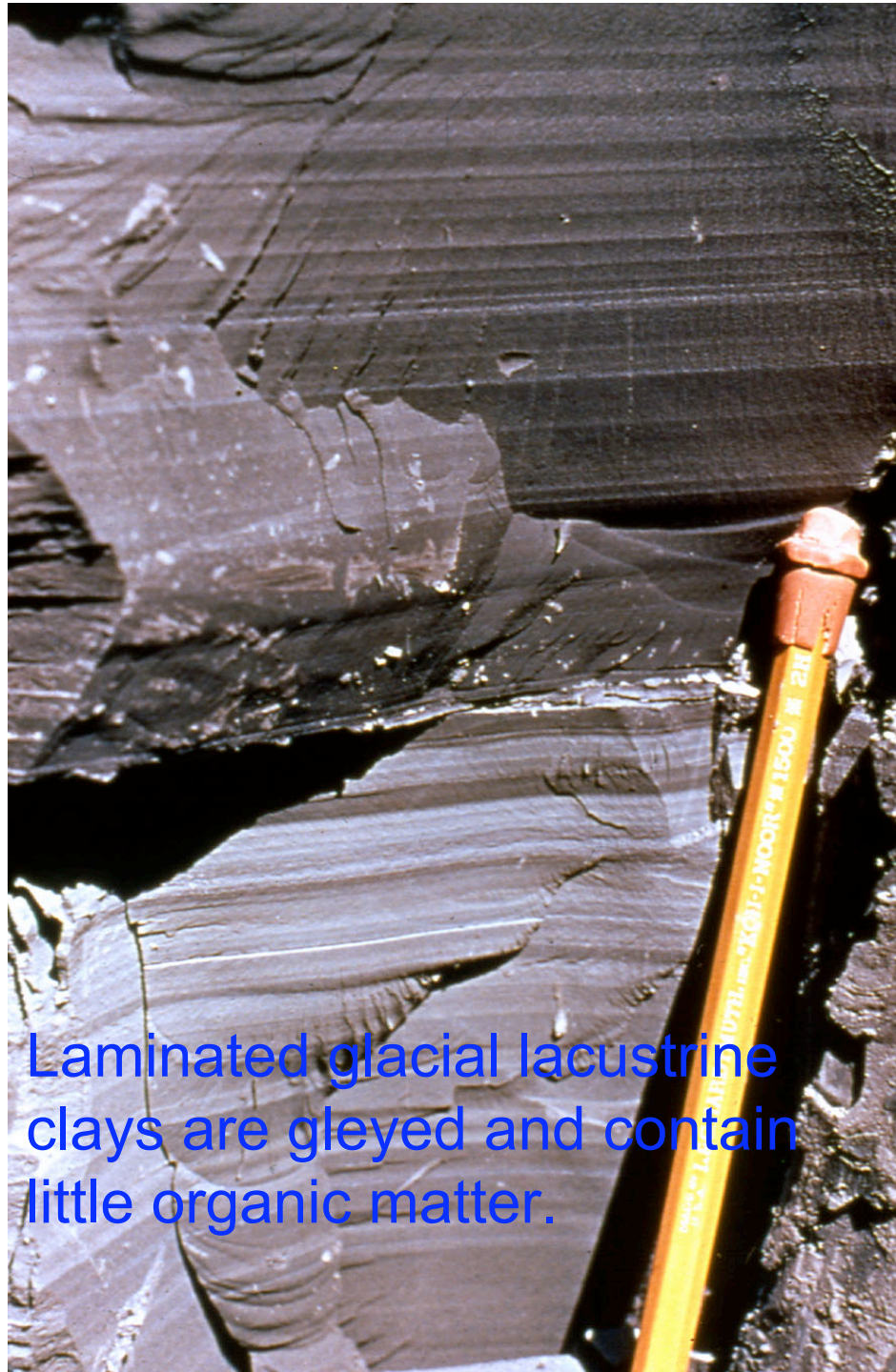


Glacial Lacustrine Sediment

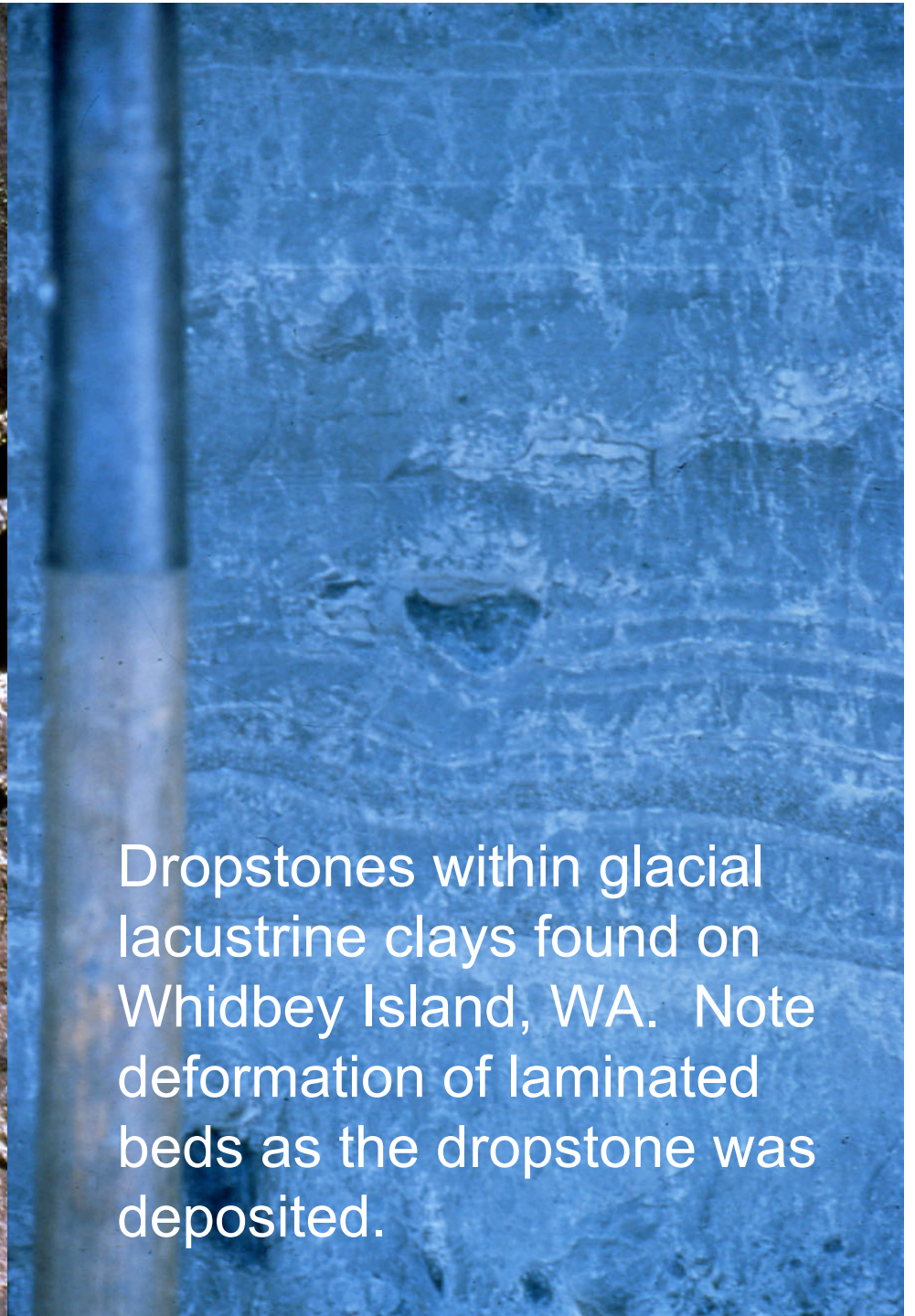
Similar to the Puget Lowland, a system of proglacial lakes formed as the Laurentide Ice Sheet retreated from the Great Lake basin.

Glacial lacustrine sedimentation veneered much of the isostatically depressed topography following deglaciation.





Laminated glacial lacustrine clays are gleyed and contain little organic matter.



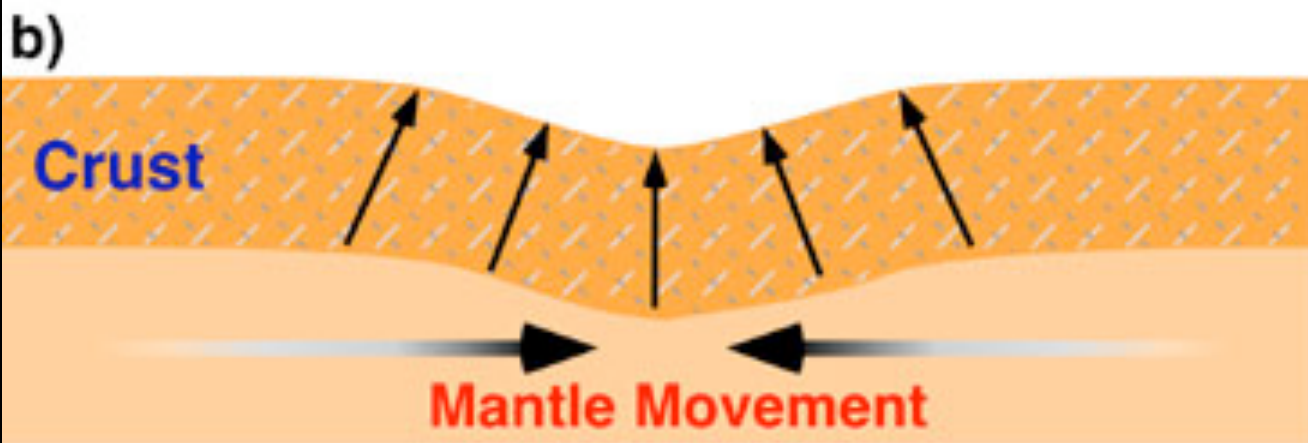
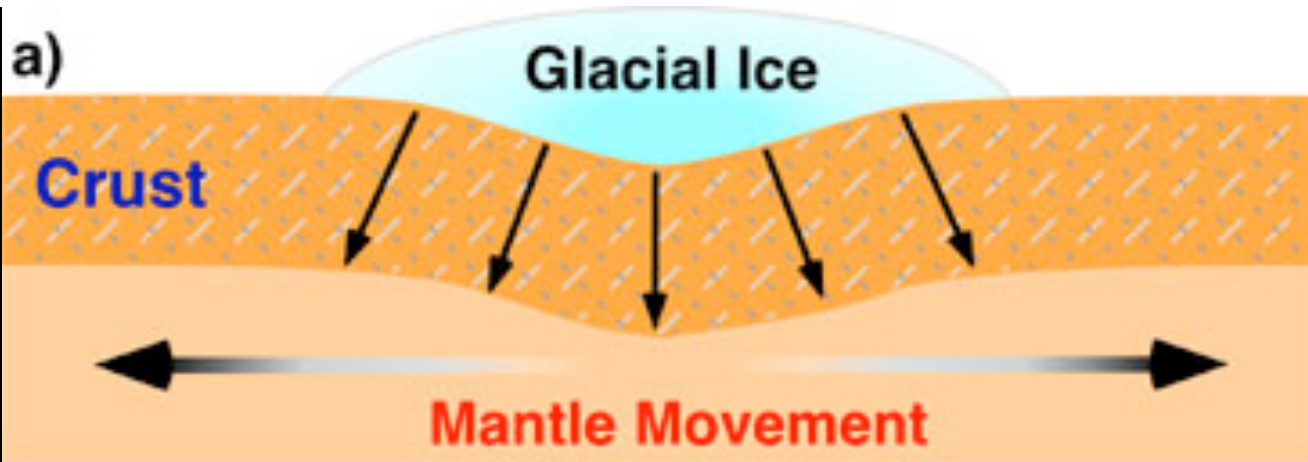
Dropstones within glacial lacustrine clays found on Whidbey Island, WA. Note deformation of laminated beds as the dropstone was deposited.



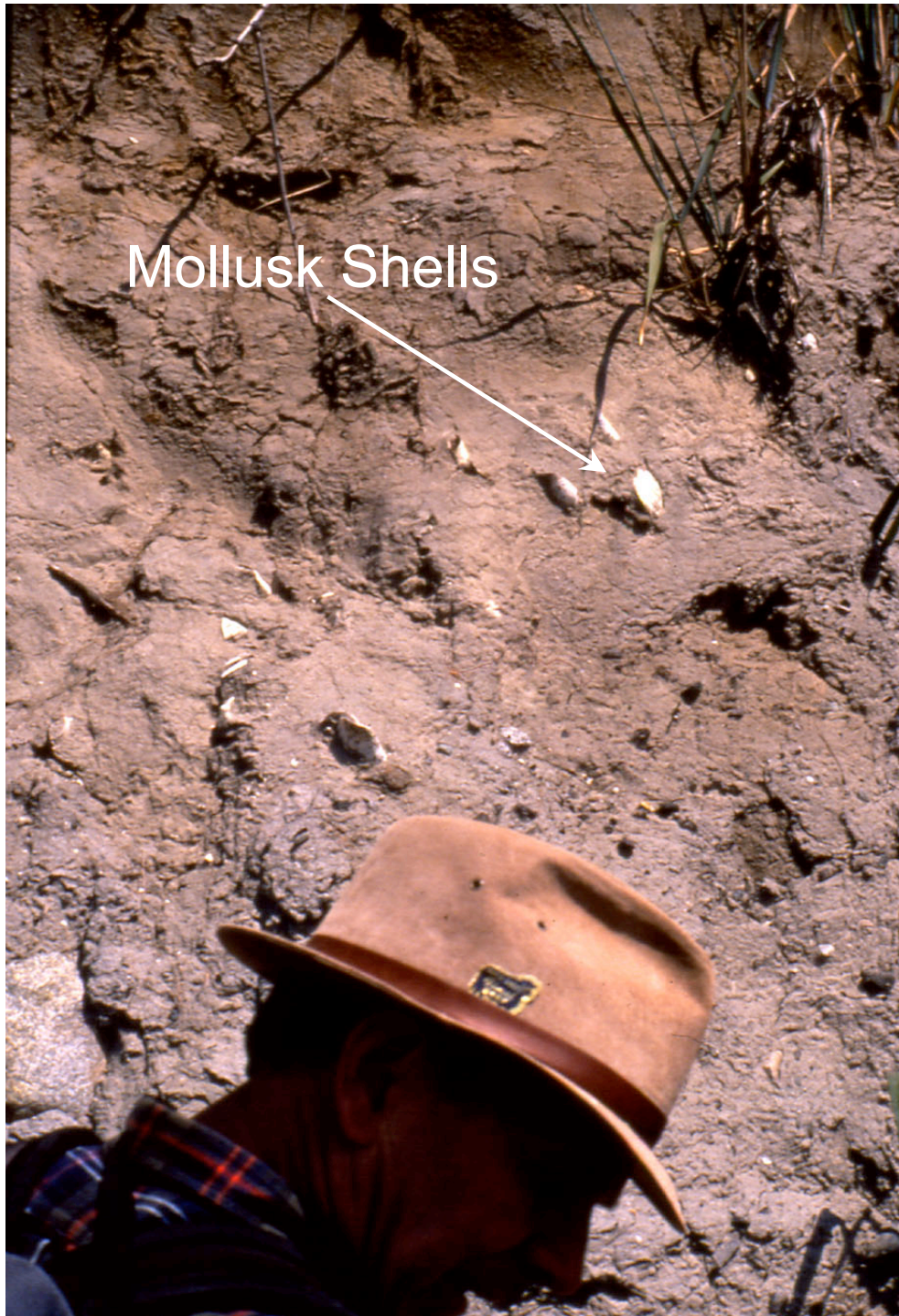
Glacial marine drift (GMD) sedimentation occurs where tidewater glaciers calve into a marine embayment and sediment is deposited on the sea floor as ice bergs melt and turn over. During the last glaciation the Puget Lobe retreated into a calving embayment following the opening of the Strait of Juan de Fuca ~15,000 years ago.



GMD deposits are found in locations within the Puget Lowland that lie north of Seattle where isostatic uplift has been great enough to preserve the deposits above modern sea level.



Isostatic depression and uplift related to ice loading and unloading on the lithosphere.



Mollusk Shells

Glacial Marine Drift (GMD)

GMD has characteristics similar to till in that it is poorly sorted, unstratified and contains faceted, subangular clasts.

Marine shells may be present in some GMD deposits. GMD was deposited at progressively higher elevations in a northerly trend within the Puget Lowland. Why do you think this is case?

The GMD shown on the left is located at Double Bluff on Whidbey Island.

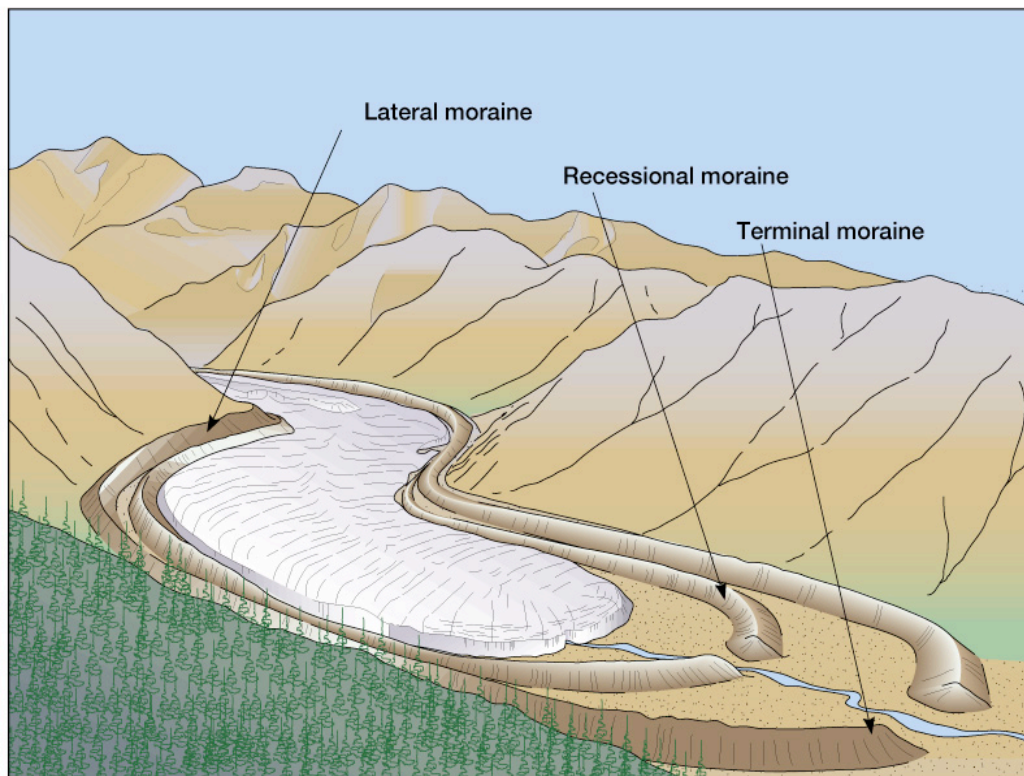
Shell ages provide minimum deglaciation ages for the Puget Lobe from this region.



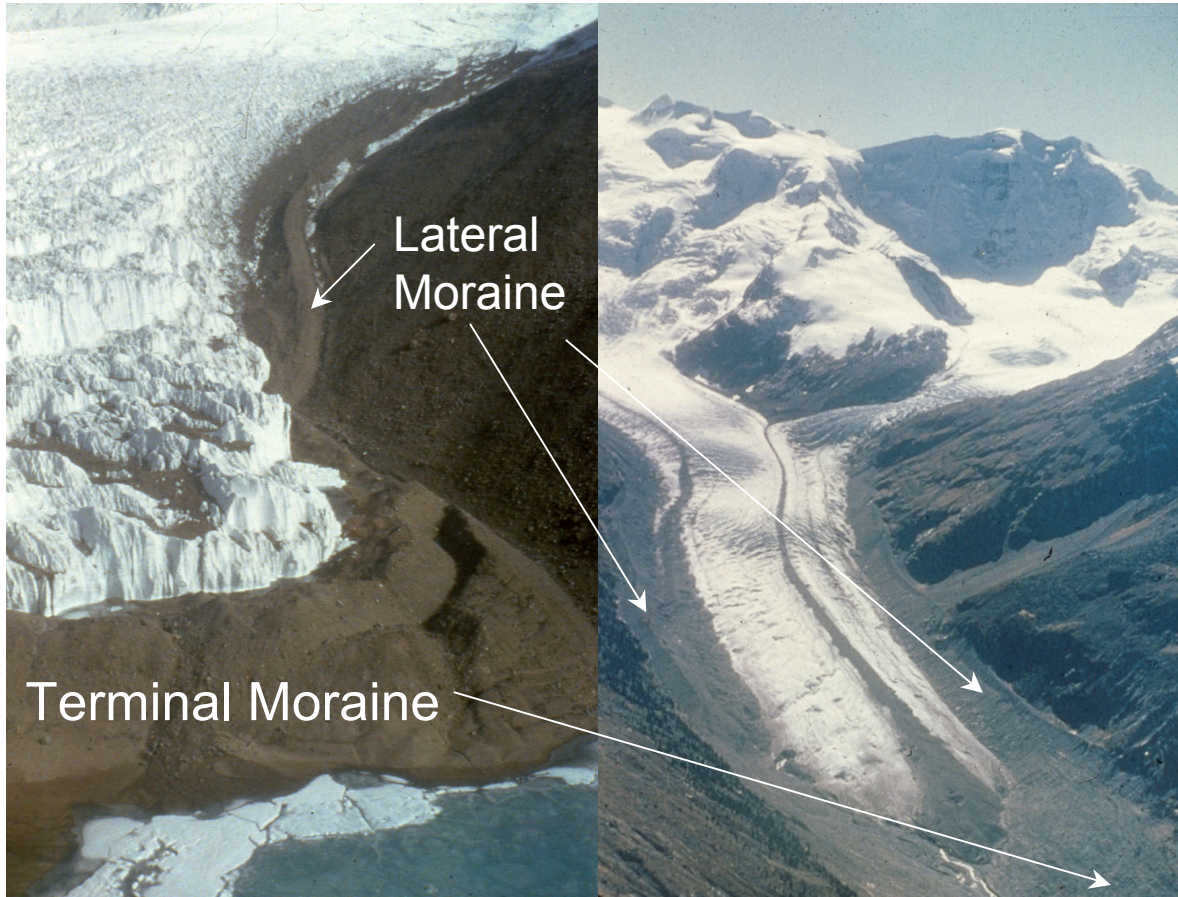
Fig. A.



Fig. B.



Moraines are landforms formed along the margins of glaciers by ablation of debris (Fig. A.) or bulldozing action of ice, as in the case of *push moraines* (Fig. B). Moraines are classified according to their position relative to the glacier during deposition. Moraines are largely composed of till



Hummocky ground moraine in the White Mountains, CA.

End moraines are deposited along the *lateral* and *terminal* margins of a glacier. Following retreat of the glacier the preserved end moraines are useful to determine the glacier prior position. The highest elevation of a glacier's lateral moraine system is often close to its ELA.

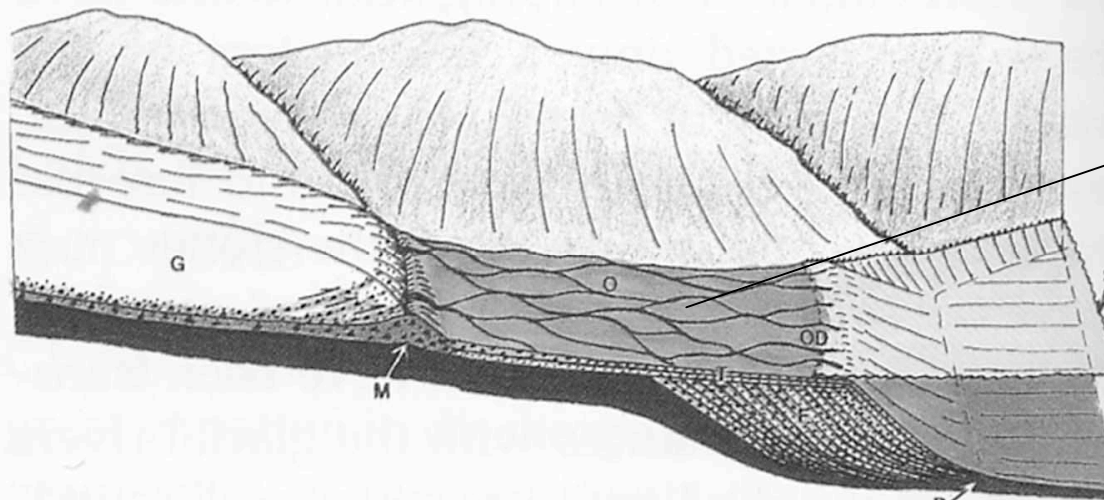
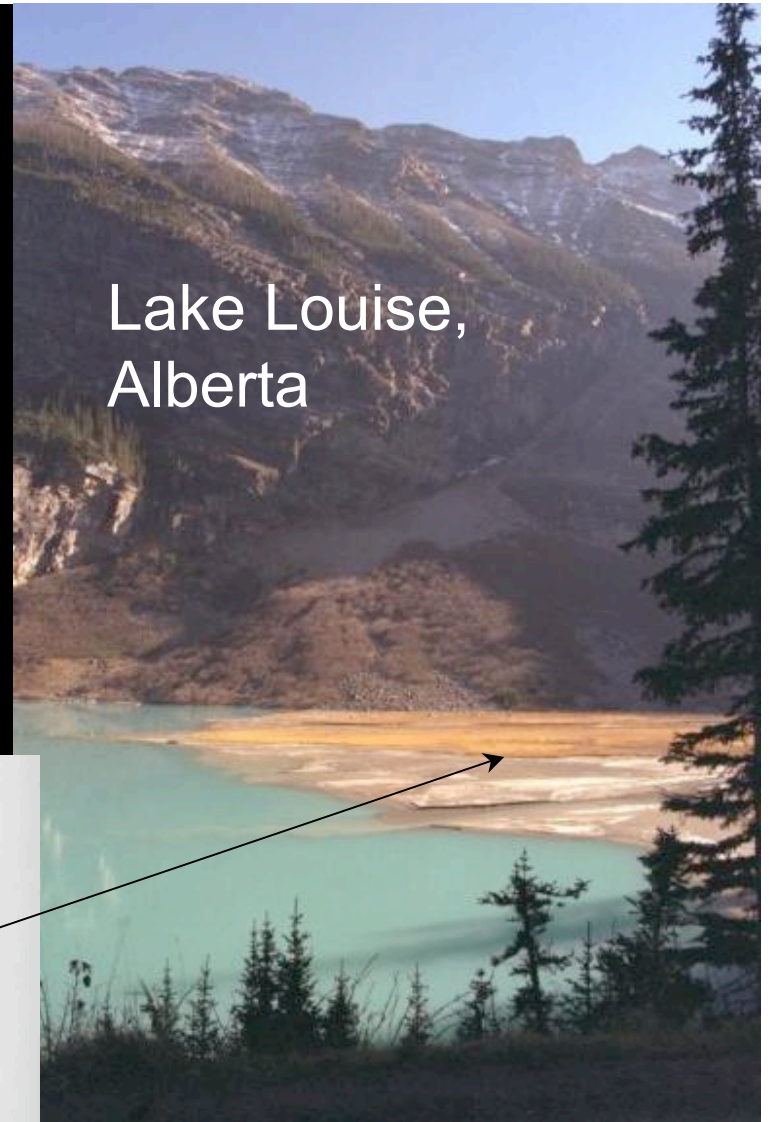
Ground moraine is deposited as a veneer over the landscape as a glacier retreats from a region. Ground moraine deposition results in a hummocky landscape and consists predominantly of ablation till.

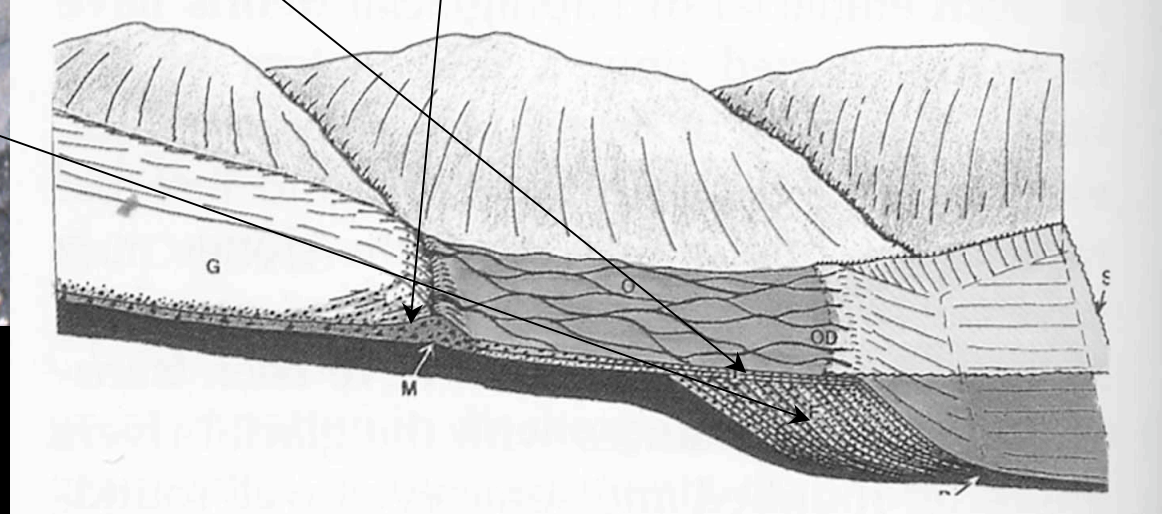
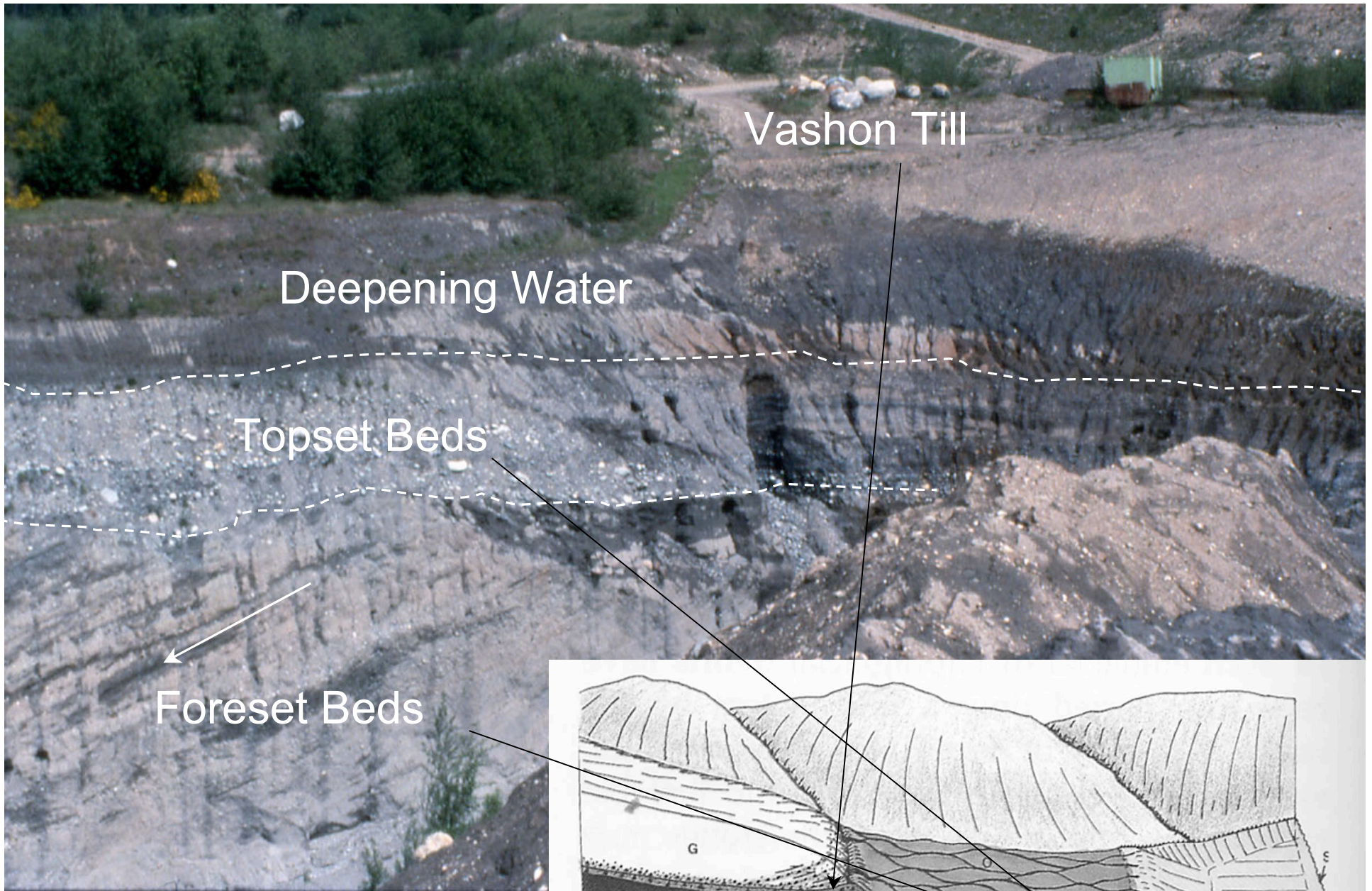


Medial moraines form when lateral moraines of two tributary glaciers coalesce. When the glacier retreats how would you recognize medial moraines.

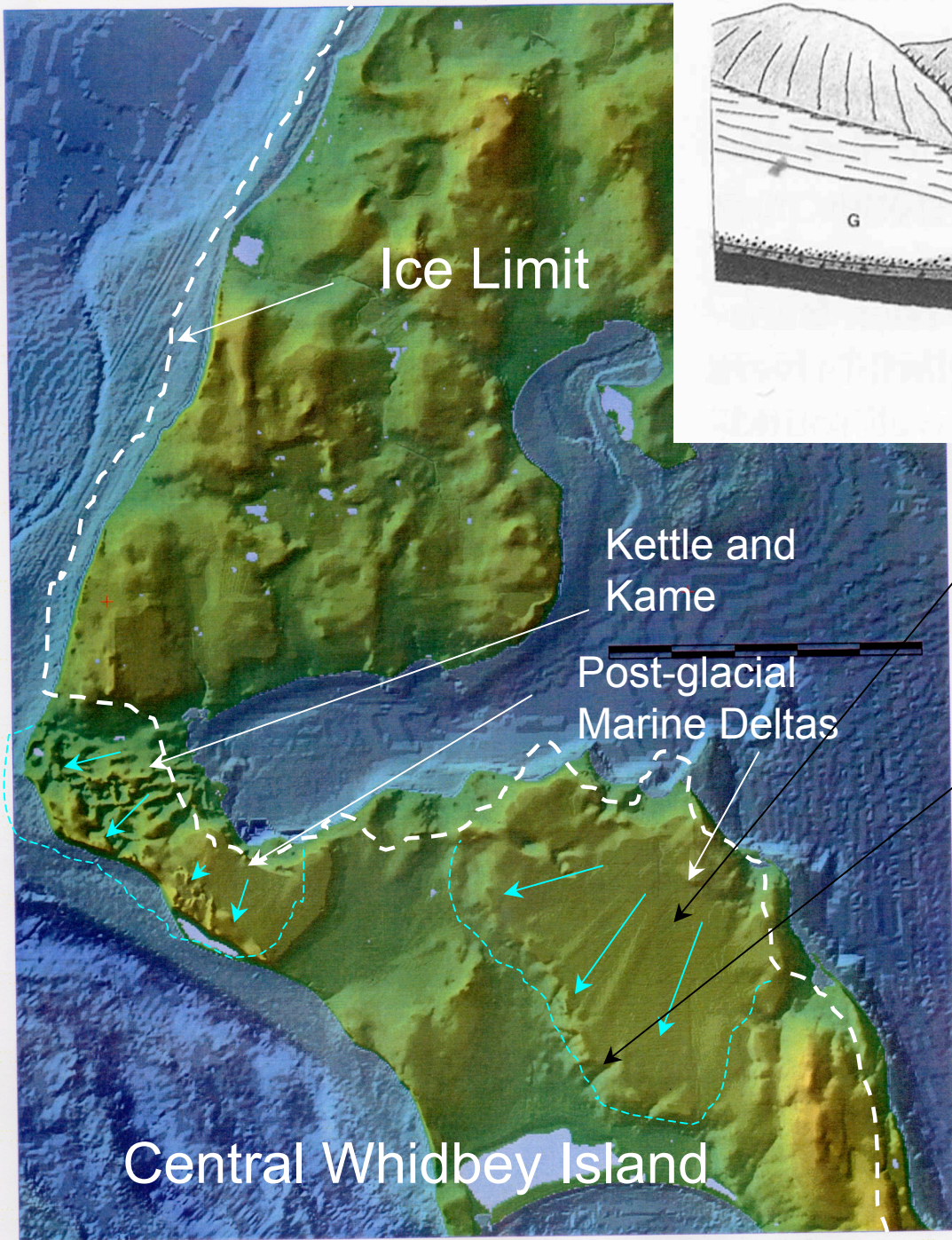
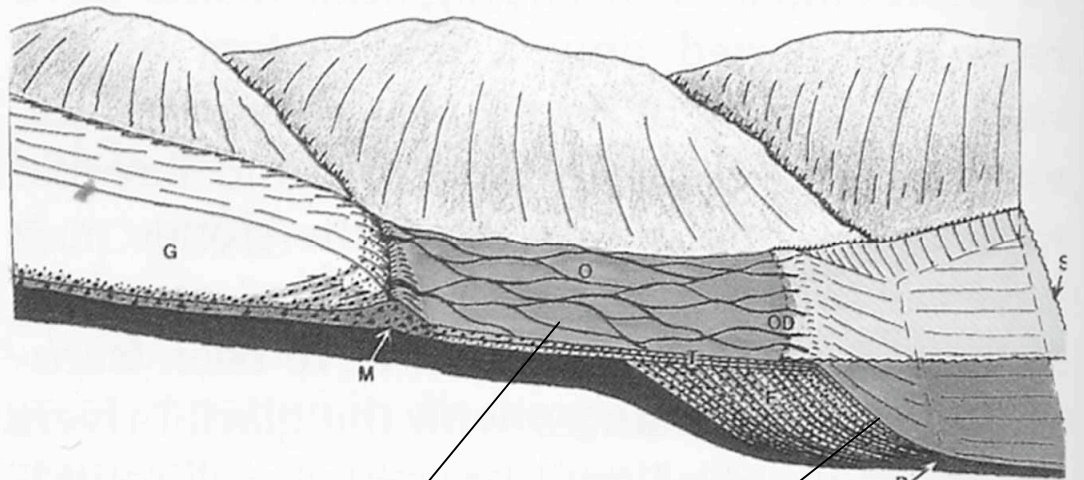
Proglacial Deltas

Proglacial deltas form where glacial meltwater streams flow into a still body of water such as lake or a marine embayment. The topset beds are prograded to the elevation of the lake or sea level. The foreset beds dip in the direction of stream flow.





Proglacial delta prograded into Glacial Lake Sammamish.



Two post-glacial marine deltas are preserved near Coupeville, WA on central Whidbey Island. The deltas were prograded to the marine high-stand (near 200 feet above modern sea level) approximately 15,000 years ago. Black arrows point to the outwash plain prograded to sea level and delta front. The foreset beds have been exposed in gravel pits here.

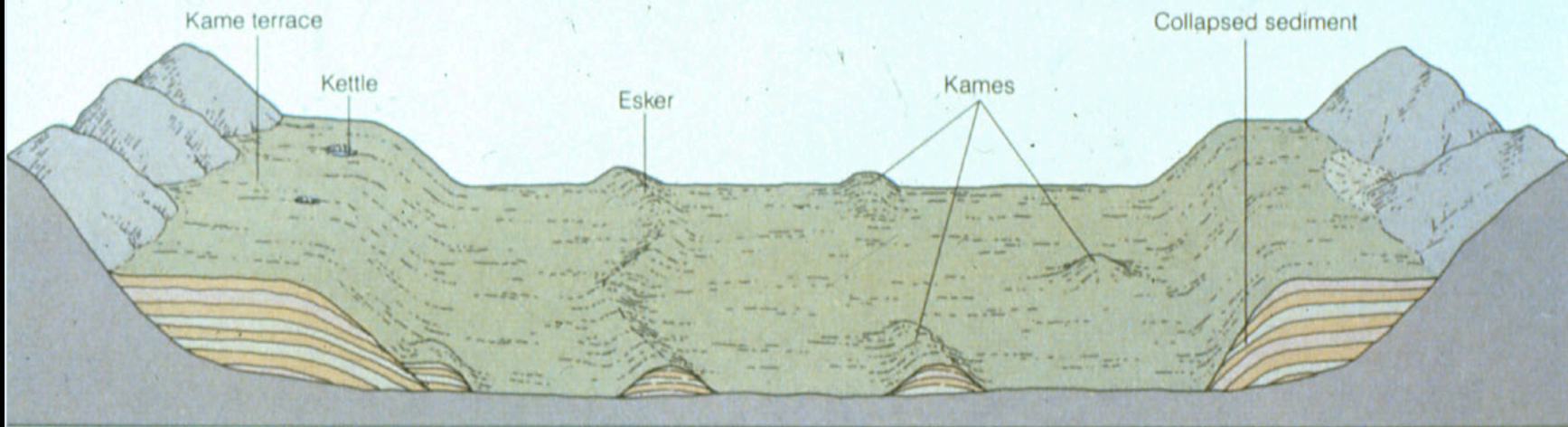
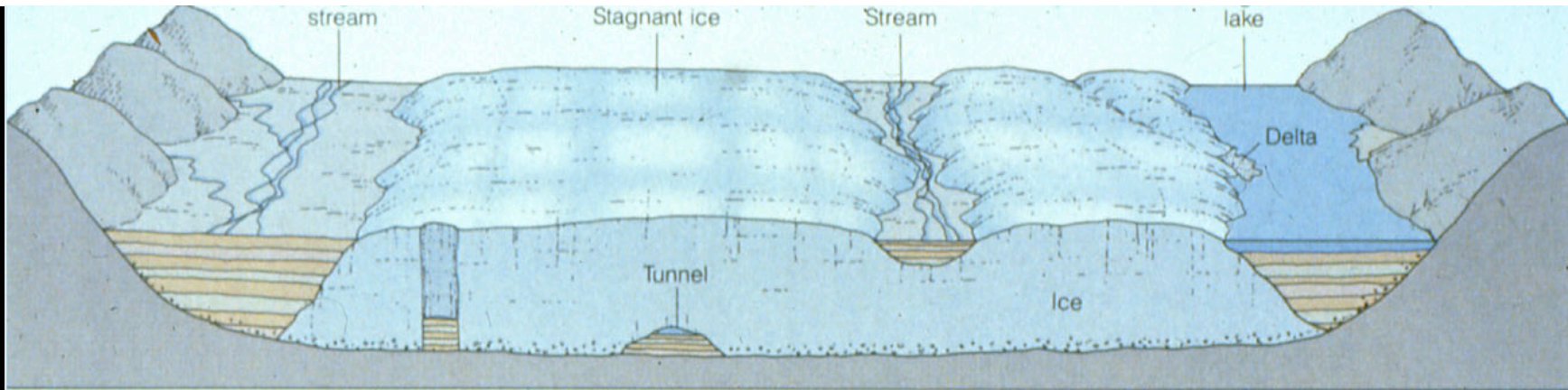
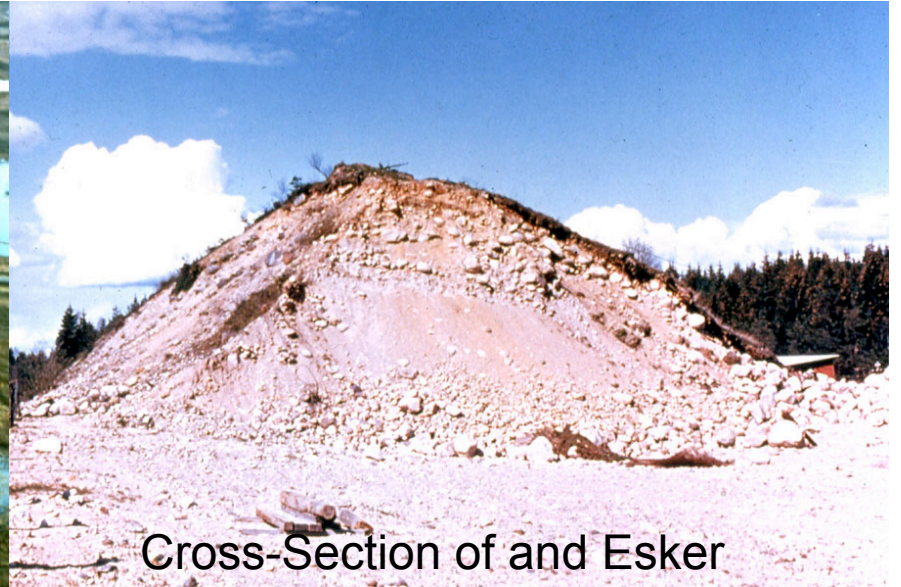
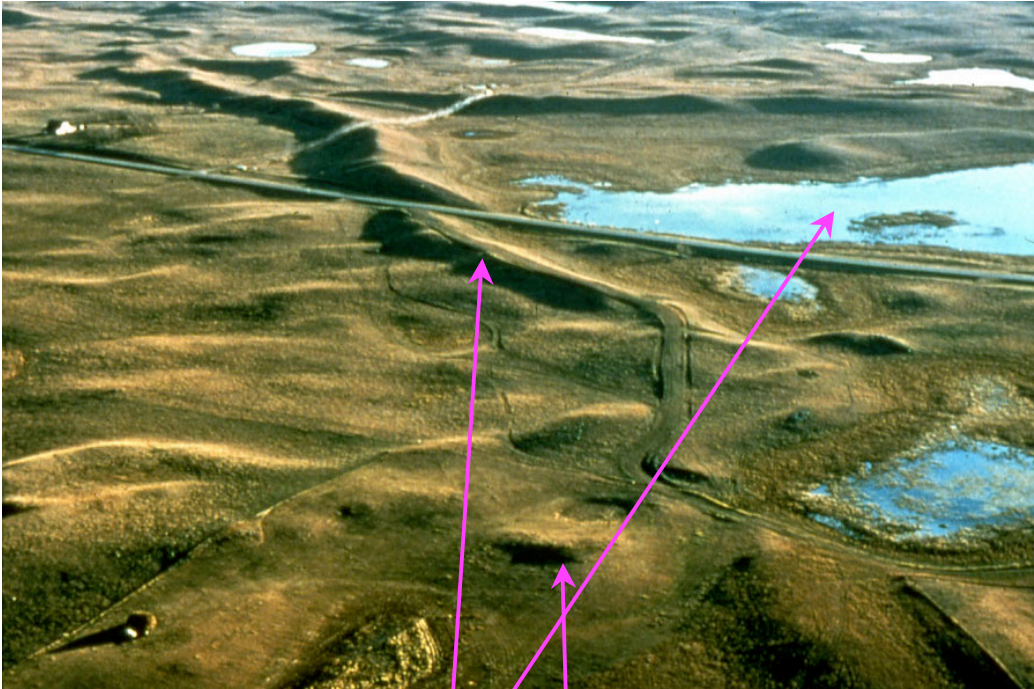


FIGURE 12.19 Origin of ice-contact stratified drift associated with stagnant-ice terrain. (a) Nearly motionless melting ice furnished temporary retaining walls or bodies of sediment deposited chiefly by meltwater streams and in meltwater lakes. (b) As ice melts, bodies of sediment slump, creating kettle-and-kame topography.

Landscapes of stagnant ice are dominated by ice-contact stratified drift (ICSD).



Cross-Section of and Esker

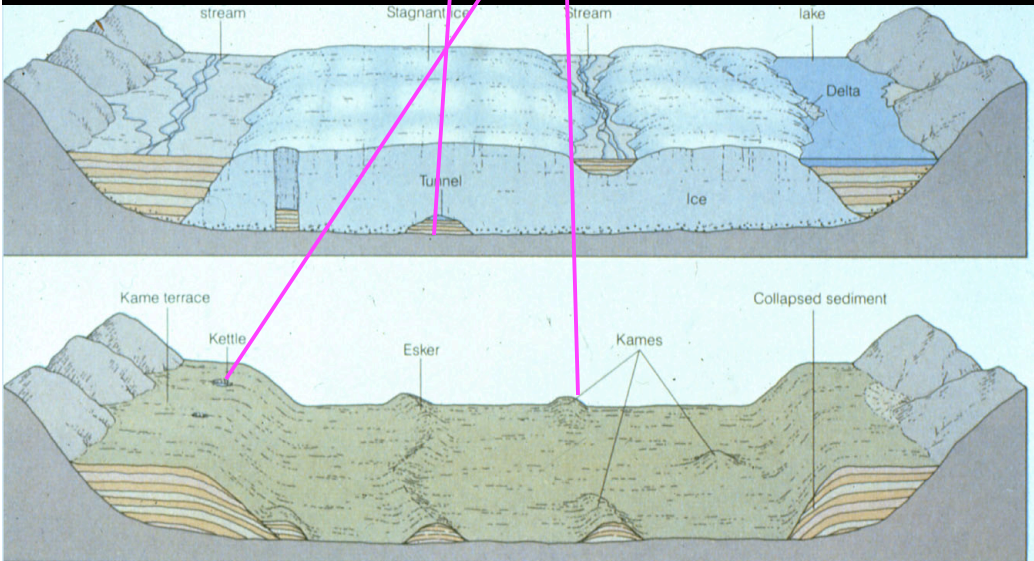


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Eskers form when stratified outwash is deposited within subglacial tunnels along the bed of the glacier. As the ice melt away a sinuous esker is preserved on landscape. Eskers are often used for road beds because they tend to be well-drained and elevated above the landscape.

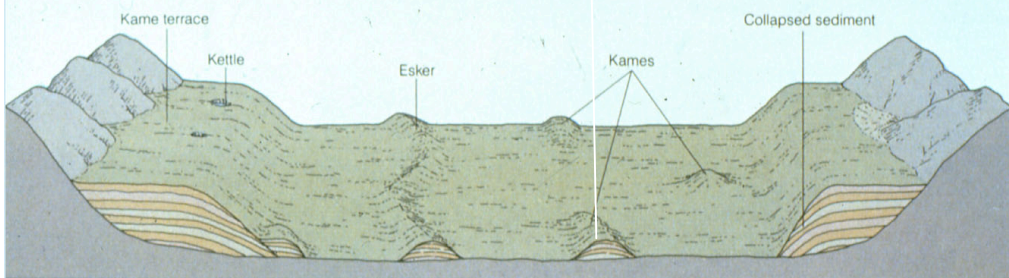
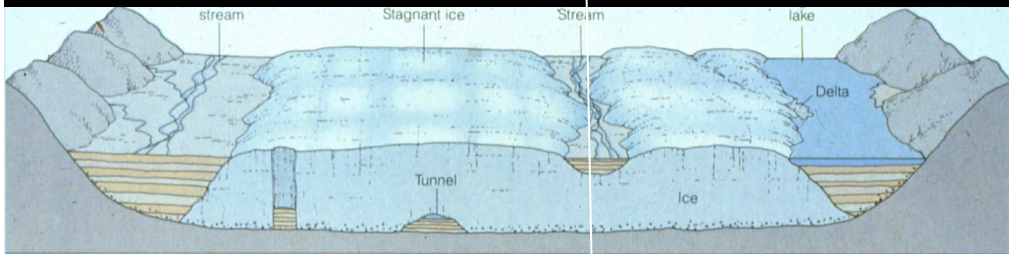
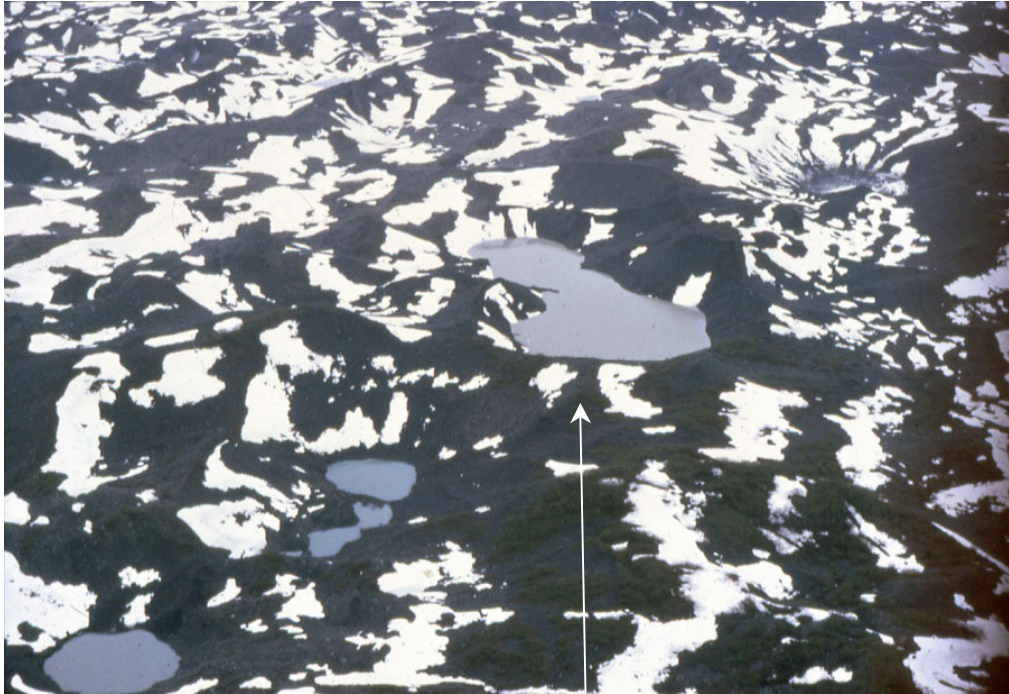
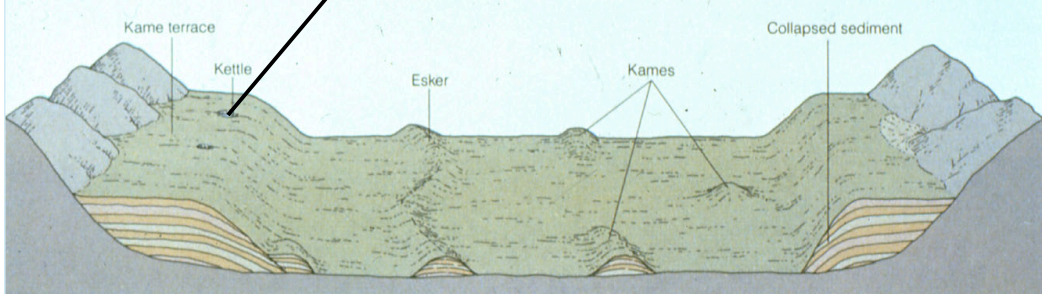
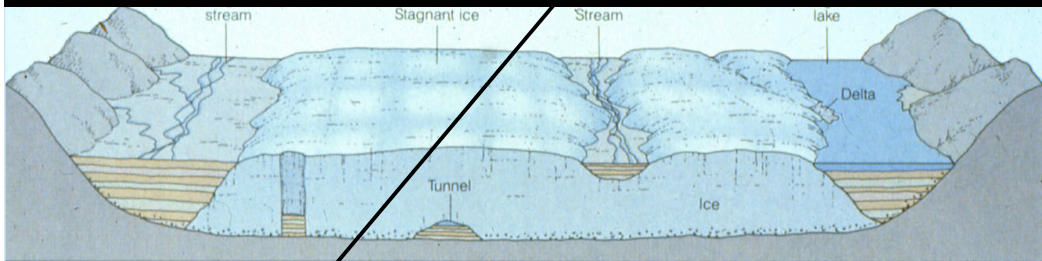


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Kames form when sediment is deposited on the ice surface and is subsequently lowered onto landscape as the glacier melts away. Kames

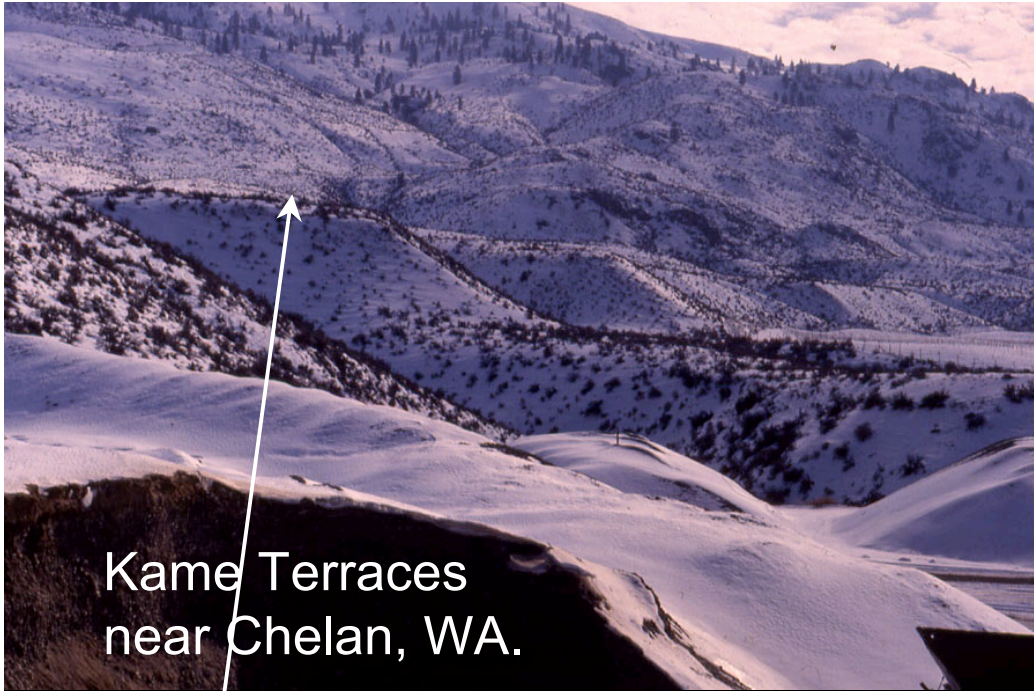


Kame feature stand in relief on the deglaciated landscape. Deformation structures related to ice contact are associated with Kame features.



Kettle lakes form when a stagnant ice body is buried by outwash. As the stagnant ice ablates, collapse structures form leaving depressions on the landscape. If the kettle depressions intersect the local water table, then a kettle lake forms.

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Kame Terraces
near Chelan, WA.

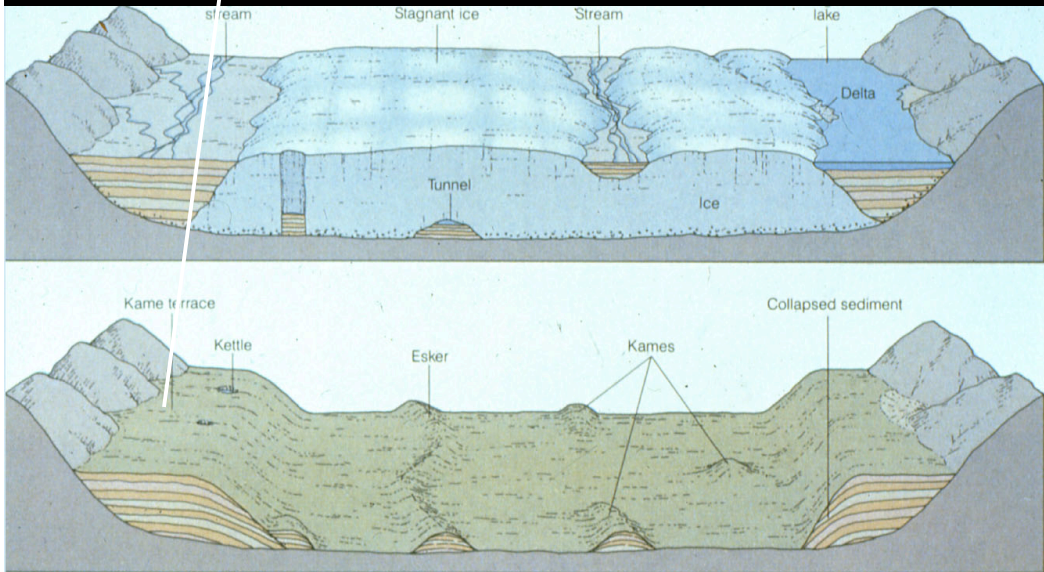


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Kame terraces form when outwash streams deposit sediment marginally to the glacier. As the ice ablates the ice-contact face of the terrace slumps and the original surface is preserved as a kame terrace. Multiple kame terraces may be preserved along the margins of an ablating ice body.