GLACIERS AND GLACIAL EROSIONAL LANDFORMS

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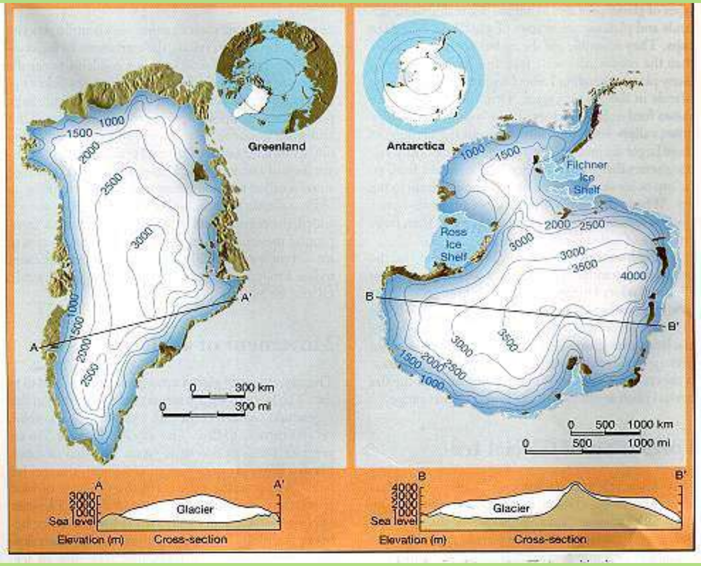
GLACIER AND ICE CAPS

Glacier is an extended mass of ice formed from snow falling and accumulating over the years and moving very slowly, either descending from high mountains, as in **valley glaciers**, or moving outward from centers of accumulation, as in **continental glaciers**.

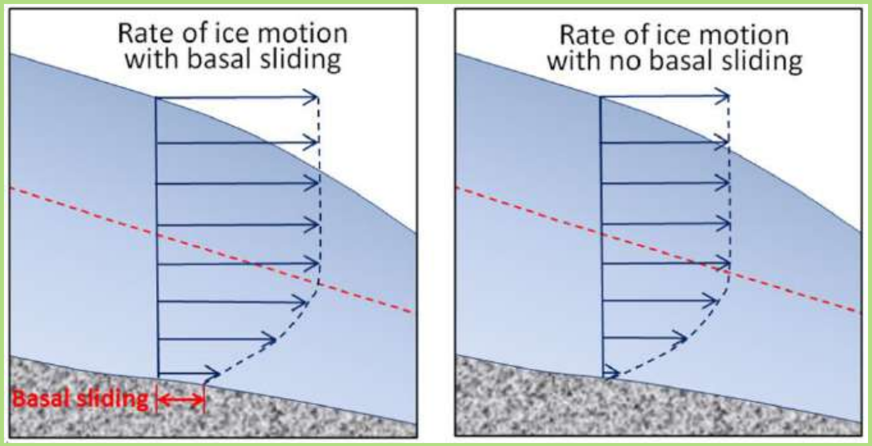


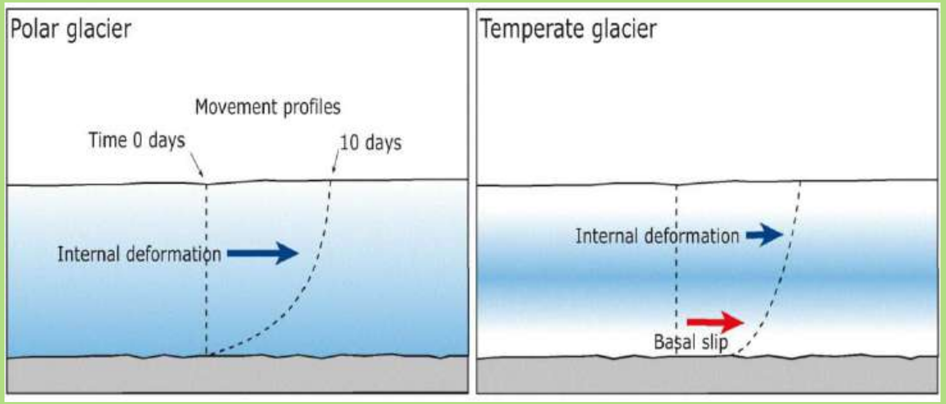
- **Ice Cap** - less than 50,000 km^2.
- **Ice Sheet** - cover major portion of a continent.
- Ice thicker than topography.
- Ice flows in direction of slope of the glacier.
- Greenland and Antarctica - 3000 to 4000 m thick (10 - 13 thousand feet or 1.5 to 2 miles!)

FORMATION AND MOVEMENT OF GLACIERS

- Glaciers begin to form when **snow** remains in the same area year-round, where enough snow accumulates to transform into **ice**. Each year, new layers of snow bury and compress the previous layers. This compression forces the snow to re-crystallize, forming grains similar in size and shape to grains of sugar. Gradually the grains grow larger and the air pockets between the grains get smaller, causing the snow to slowly compact and increase in density. After about two winters, the snow turns into **firn**—an intermediate state between snow and glacier ice. At this point, it is about two-thirds as dense as water. Over time, larger ice crystals become so compressed that any air pockets between them are very tiny. In very old glacier ice, crystals can reach several inches in length. For most glaciers, this process takes more than a hundred years.

Once the glacier becomes heavy enough, it starts to move. There are two types of glacial movement, and most glacial movement is a mixture of both:
Internal deformation, or strain, in glacier ice is a response to shear stresses arising from the weight of the ice (ice thickness) and the degree of slope of the glacier surface. This is the slow creep of ice due to slippage within and between the ice crystals. The rate of internal deformation is greatest at the base of the glacier where pressures are at a maximum. This type of flow can occur in both polar and temperate glaciers
Basal slip occurs when the glacier rests on a slope. Pressure causes a small amount of ice at the bottom of the glacier to melt, creating a thin layer of water that causes the glacier to slide down the slope. Loose soil underneath a glacier can also cause basal slip.





basal slip: when a thin layer of water builds up at the ice-rock interface and the reduction in friction enables the ice to slide forward.
enhanced basal creep: ice squeezes up against a large (>1m wide) bedrock obstacle the increase in pressure causes the ice to plastically deform around the feature. When a glacier moves, it is like a flowing river. That's because the layers of ice are very flexible under great pressure. The upper layers are more brittle. layers can fracture and form huge cracks that sometimes get covered by fresh snow.

regelation flow: when ice presses up against a small (<1m wide) bedrock obstacle, and rather than deforming the ice melts and re-freezes on the lee side where pressure is lower. This process only occurs around obstacles that are small enough to enable the latent heat released by lee side re-freezing to be effectively conducted to stoss side and promote further melting.

Warm based glaciers

These are known as **temperate glaciers** and are found in lower latitudes such as the Alps mountain range. Due to the lower latitude, the temperature around the glacier allows the ice to move relatively rapidly. The process of movement is largely through **basal slippage**. Liquid meltwater plays a significant role in this process, provided by surface ice melting and being conveyed through the glacier via internal meltwater tunnels. In addition, as the glacier slides downslope it further increases the temperatures at the base due to friction and pressure. The subglacial ice layer can then melt and the resulting water will increase the rate of flow of the glacier by lubricating the contact between the lowest ice layers and the basal rock with meltwater. Where this process occurs some glaciers can move up to 3 metres per day. When the seasons change and there is less melting, the glacier will refreeze to the basal rock and months later, when the temperature warms up again, the glacier will pluck material away from the base and this will cause increased erosion as the glacier moves downhill once more.

Cold based glaciers:

These are found in higher latitudes and have less seasonal variation in temperature than those found in the lower latitudes. Meltwater is far less a presence. These glaciers still move but due to **internal deformation/flow** rather than basal slippage. They freeze to the bedrock and do not experience the same melting, but the role of gravity and pressure exerted by ice accumulation at the source causes the glacier to move. They may only move up to 2cm per day. The ice crystals within the glacier orientate themselves into the same direction as the ice slowly moves out from source regions.

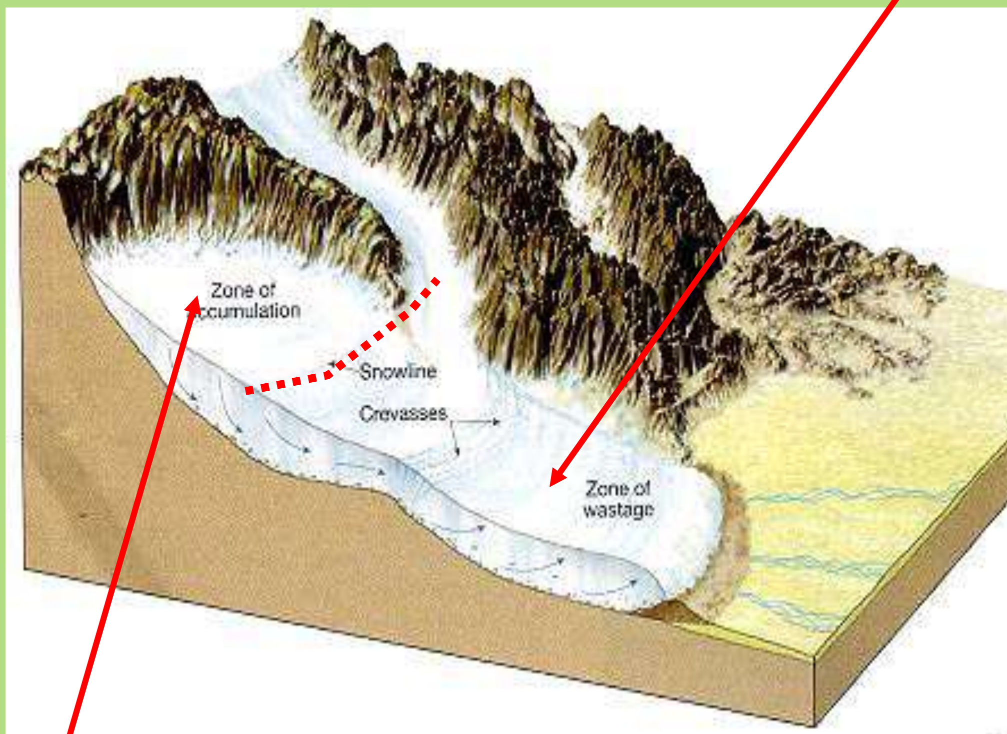
Glacial surges are spectacular increases in velocity during which rates of flow may reach 10 to 100 times their normal value, whereas, glaciers usually flow at 3-300m a-1, surging glaciers move at speeds of 4 to 12kma-1. Some surges may trigger rapid advance of the snout. For instance, when Bruarjokullin Iceland, surged the snout moved forward 45km at a rate of 5m every hour. The precise cause of surging is unknown,but it is generally, considered to be caused by enhanced basal sliding triggered by the build-up of meltwater at the ice/rock interface.

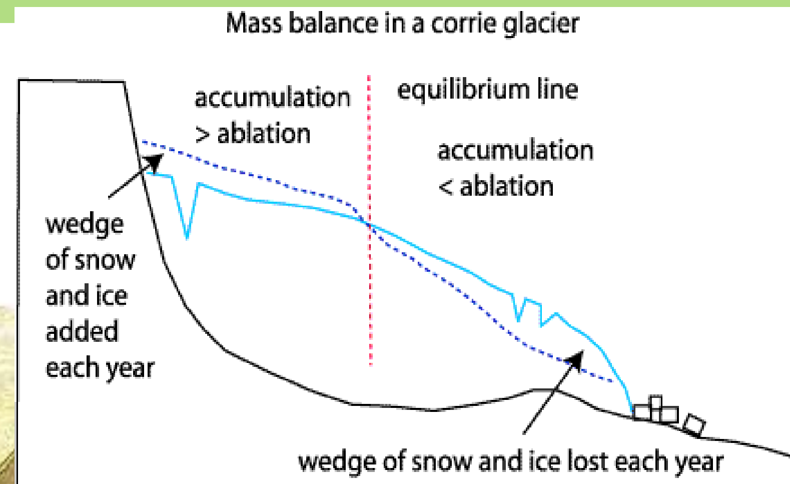
Hole-in-the-Wall Glacier knocked over trees when it surged in 1941, crossing terrain not covered since the eighteenth century. Hole-in-the-Wall Glacier is located in the coastal mountains of southeast Alaska

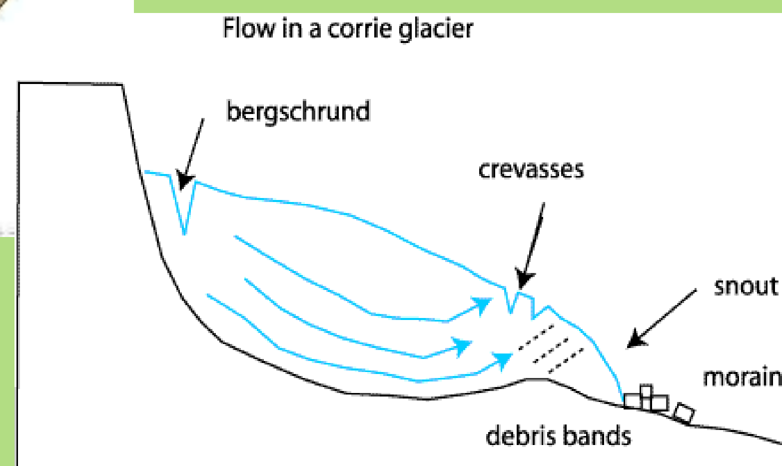
Columbia Glacier, located in the Chugach Mountains of Alaska, surges periodically. This photograph from 1909 shows the terminus of the glacier knocking over trees as it advanced.

Glacier System

Zone of ablation (wastage)
(more melting than snowfall)







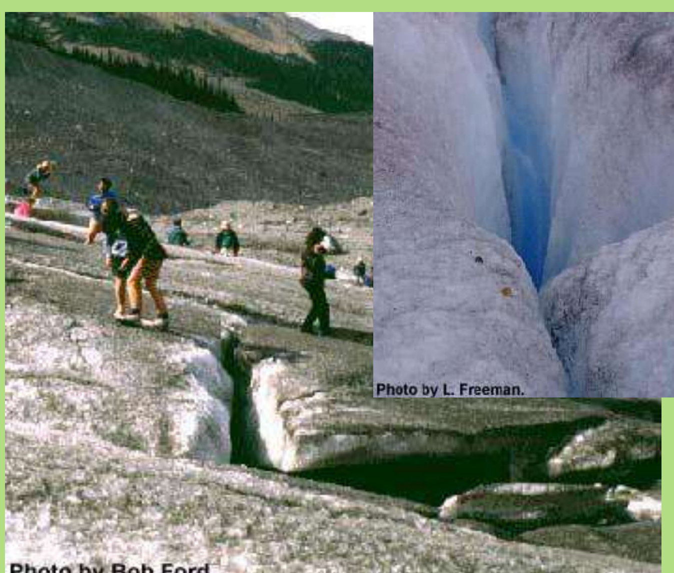
Zone of accumulation
(more snow falls then melts per year)


Equilibrium line


Equilibrium line

Crevasse

A crack in the upper 30 meters (100 feet) of a glacier. Ice in approximately the upper 30 meters of glaciers tends to be brittle and as the glacier flows, cracks develop. In general, crevasses rarely extend much deeper than 30 meters because below this depth the ice is too plastic and any surficial cracks close.



Bergschrund

These form when a crevasse or ***wide , curved*** crack opens along the headwall of a glacier; most visible in the summer when covering snow is gone.

Glacial Erosion Processes

Plucking/Quarrying

As the glacier moves, friction causes the bottom of the glacier to melt this water freezes into joints in the rock. When the glacier moves again the rock is pulled away or 'plucked' from the base of the valley.

Abrasion

Rock pieces that have been plucked away and carried by the glacier (moraine) act like sandpaper scraping away at the valley bottom and sides.

Freeze – thaw or frost shattering

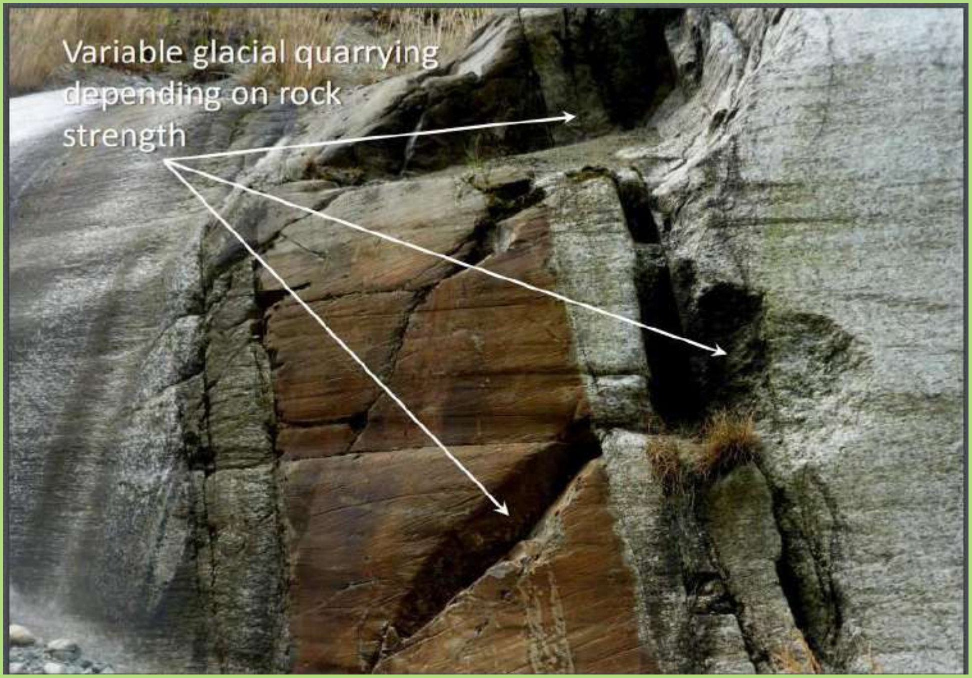
Water enters into cracks in the rock over time it freezes and repeatedly thaws putting large amounts of pressure on the rock – eventually this will force the rock to break apart or shatter.

Landforms created by mountain glacial erosion

Polished Rocks , Grooves and Striations
Corries-Arêtes-Pyramidal Peaks (Horns)
Tarns
U Shaped Valleys or glacial troughs
Glacial Stairways- Riegels
Paternoster Lakes
Truncated Spurs
Hanging Valleys
Crag and Tail
Fjords

Glacial Processes

Glacial Quarrying/Plucking • Removal of large pieces from bedrock • Starts with fracturing (may or may not be initiated by glacial processes) • Water pressure changes may be important • Freeze-thaw cycles are probably not important but freezing of water due to P changes are • The presence of basal cavities is important



Plucking occurs at the base of the glacier as the ice drags along an uneven surface. The weight and moving force
of the ice will break the bedrock and incorporate the fragments into the glacier. They will be transported down slope
until they are deposited

Abrasion: Plucking removes rocks and by itself creates changes in the landscape, but plucking also contributes to the second process of glacial erosion, known as **abrasion**. Abrasion is defined as the erosion that occurs when particles scrape against each other. The enormous weight of the glacier, along with rocks and sediment plucked up and clinging to its belly scratch and carve the rock surface below. It's almost as if the moving glacier is sanding the rocks with abrasive sandpaper. As the glacier sands the rock, it leaves behind long scratches that form in the direction of the glacialmovement called **glacial striations**.

abrasion rate affected by:
basal contact pressure, basal ice velocity concentration & supply of rock fragments removal of glacial flour

Polished Rocks and Striations

These rocks were embedded in the ice at the bottom of a glacier. As the glacier moved over bedrock it was rocks like these that cut the parallel grooves. In the process these rocks tumbled and rolled becoming <u>SCRATCHED</u> *and* <u>POLISHED.</u>

<u>SCRATCHED</u> and <u>POLISHED</u> boulders are evidence of glacial erosion.

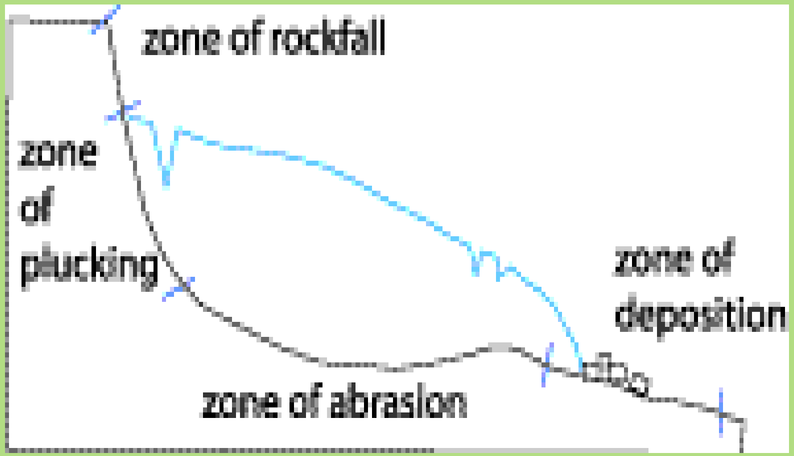
As glaciers flow, the rocks embedded in the ice cut deep PARALLEL GROOVES in the bedrock beneath. When the glaciers melt these parallel grooves remain as evidence that the glaciers were there.

Above more parallel grooves and scratches in exposed bedrock.

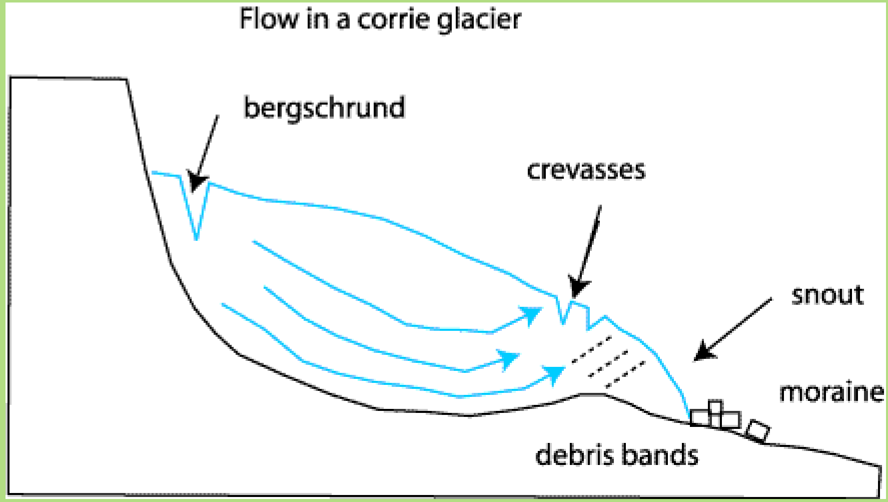
Cirque

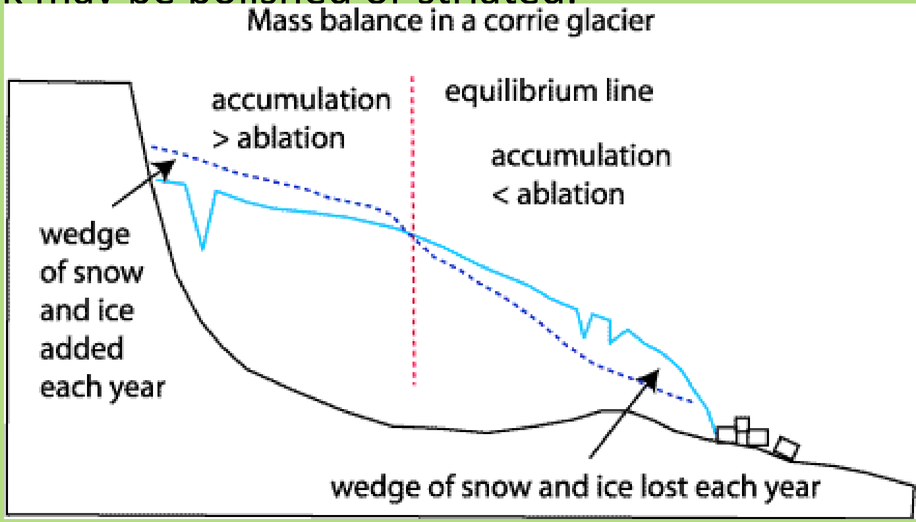
Cirque is a semi-circular, amphitheatre shaped basin with steep headwalls at the head of a valley glacier and formed due to glacial erosion.

- **Tarn**
- A small mountain lake especially
- one that collects in a cirque basin behind
- risers of rock material or in an ice gouged
- depression.

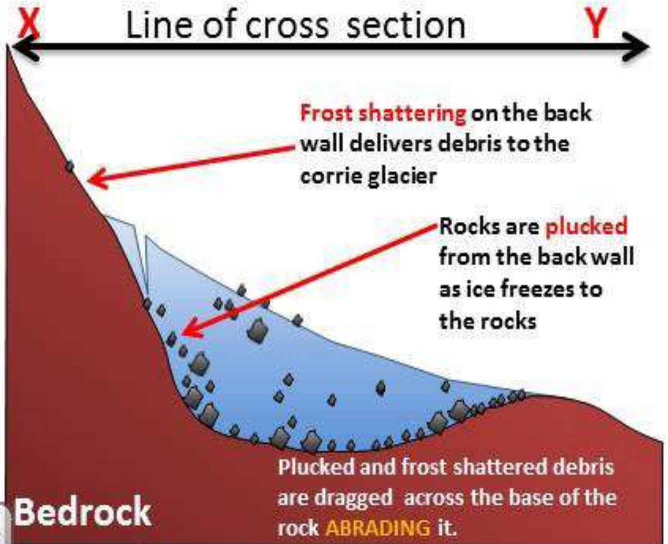


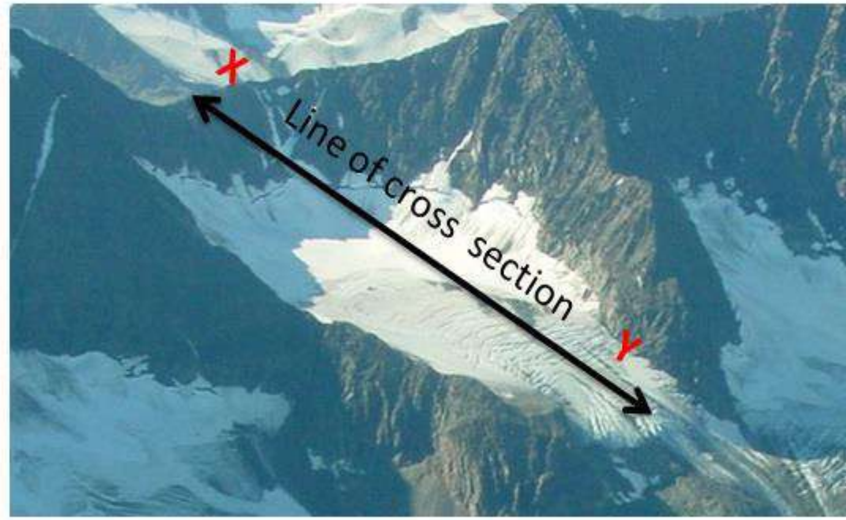
If the former glacier did not fill the corrie then its headwall was exposed to frost shattering and rock fall above the ice. This part of the rock wall is typically riven by deep gullies and has lots of loose rock. Below the rock surfaces may be fresher and sharp-edged but large slabs and sockets are evident where the glacier has been frozen on to the rock wall and pulled away or *plucked* blocks from the headwall. The smoothest slabs occur towards the base of the headwall and probably continue beneath the scree cover. Here abrasion has been active and the rock may be polished or striated.

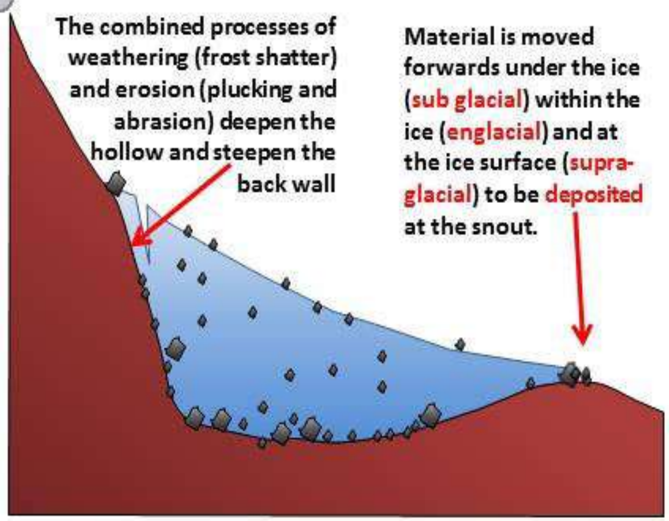




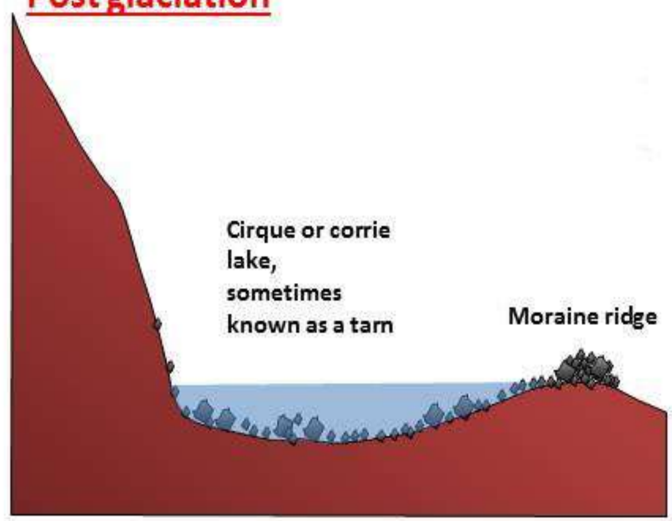
The formation of Corries







Post glaciation



Englacial debris is former surface debris that has been covered by subsequent snow falls

By Rob Gamesby

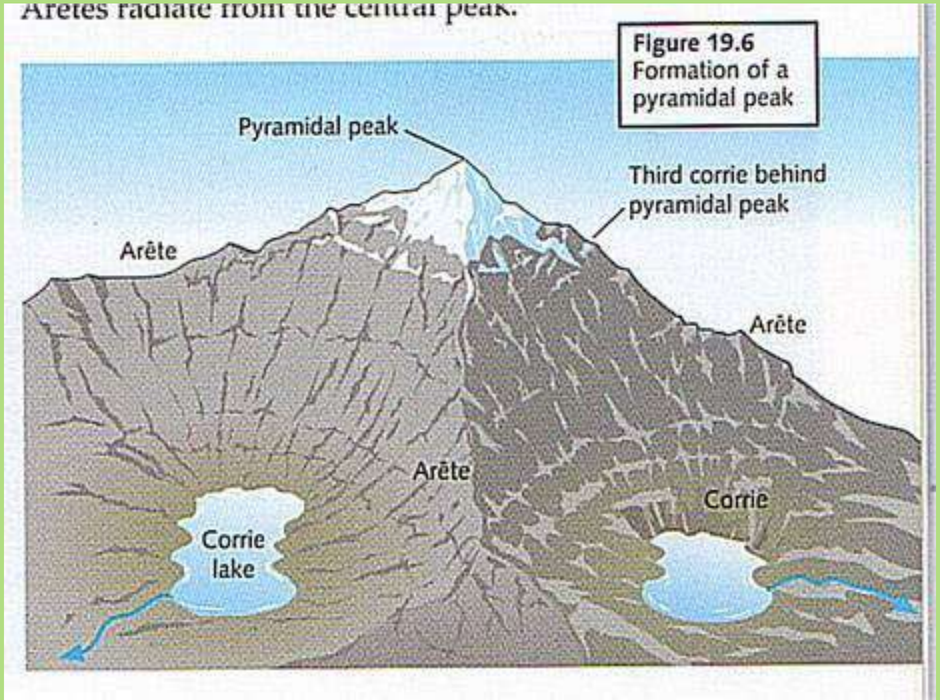
http://www.coolgeography.co.uk

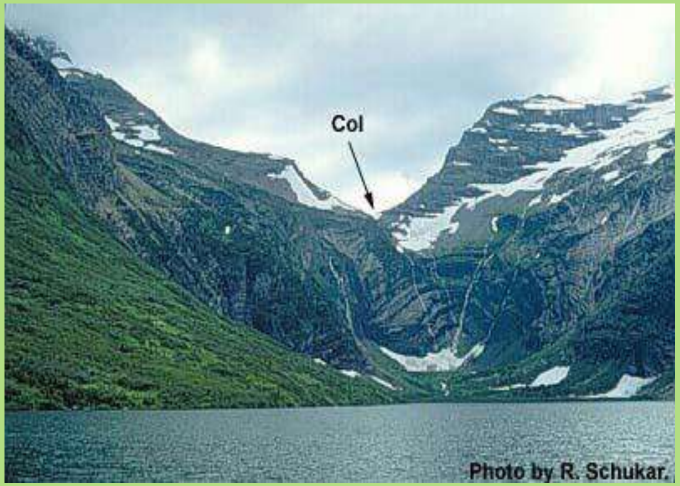
Theories of Cirque formation

One of the most popular theories of cirque formation is the one provided by **W.D. Johnson** in 1904. This theory is popularly known as the *Bergschrund theory*. A *bergschrund* is a large crevasse at the back of a cirque glacier separating it from the backwall. The theory emphasises the importance of the process of basal sapping or plucking by freeze-thaw at the base of the bergschrund. Temperature in the bergschrund in summer season is generally above the freezing point during the day while it falls below the freezing point at night. The repeated freezing and thawing of water in the rock crevices is an effective means of rock disintegration. According to him, the cirque owes its origin to this basal sapping. However, several scholars have challenged this theory. Although the importance of headwall shattering by freeze-thaw is accepted by all, but it is doubtful whether this process occurs at a large scale at the base of the bergschrunds. According to Bowman, bergschrunds are not always present in cirques and many of them failed to reach bedrock. According to him, the cirque headwall could develop without bergschrund through the plucking and abrasion actions of glacial ice.

W.V. Lewis modified the bergschrund theory of cirque formation and his presentation is known as the *Meltwater theory*. According to him, much of the water in the bergschrund is derived from either summer rain or the melting of snow high above the bergschrund. Such water could seep down narrow cracks far below the limits of the deepest bergschrunds, freeze in the rocks and shatter them. In this manner the headwall will be undermined and become steeper. The rock fragments thus produced get imbedded in the moving ice and increase the rate of abrasion on the rock floor of the cirque. **W.R.B. Battle** also argued that temperature variations in the bergschrunds are too small to cause alternate freeze-thaw process. Such action is more likely only in the upper parts of the open bergschrunds. Explanation for the over-deepened floors of the cirques has been provided by the *Rotational Slip Hypothesis* of Lewis. He suggested that abrasion by rotationally moving ice is the principal mechanism for the grinding of the rock basin and the perpetuation of the rock threshold

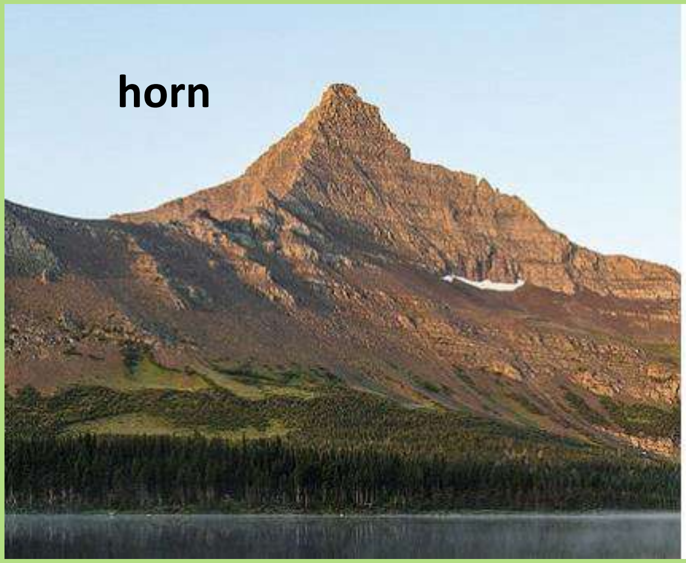
An **arete** is a knife-edged ridge often found at the back of a corrie or separating two glaciated valleys. **Aretes** are often extremely narrow features. A typical **arete** forms when erosion in two back-to-back corries causes the land in between to become even narrower. If three or more corries have formed on a mountain, erosion may lead to the formation of a single peak rather than a ridge. This is called a **pyramidal peak.**





An **arête** is a thin, jagged crest that separates—or that once separated—two adjacent glaciers. These rugged ridgelines often look like serrated knives or saw blades, with steep sides and a sharp crest. The low points on the serrated surface are known as ***cols***. Cols act as spillways for the ice and occur where glacier action has eroded the rock sufficiently to overtop it.

Horns are pointed peaks that are bounded on at least three sides by glaciers. They typically have flat faces that give them a somewhat pyramidal shape and sharp, distinct edges,eg Matterhorn



GLACIAL TROUGHS

The V-shaped valley seen to the right is typical of stream or water erosion. As the stream flows, it's 'cutting tools' which are the rocks and stones it carries, cut deeper and deeper into the streambed forming a V-shape.

If the climate gets colder and the valley fills with ice the glacier will rip rocks from the sides as well as the bottom of the valley. This will widen the valley and change it's shape.

To the left is a wide U-shaped valley which is typical of glacial erosion.

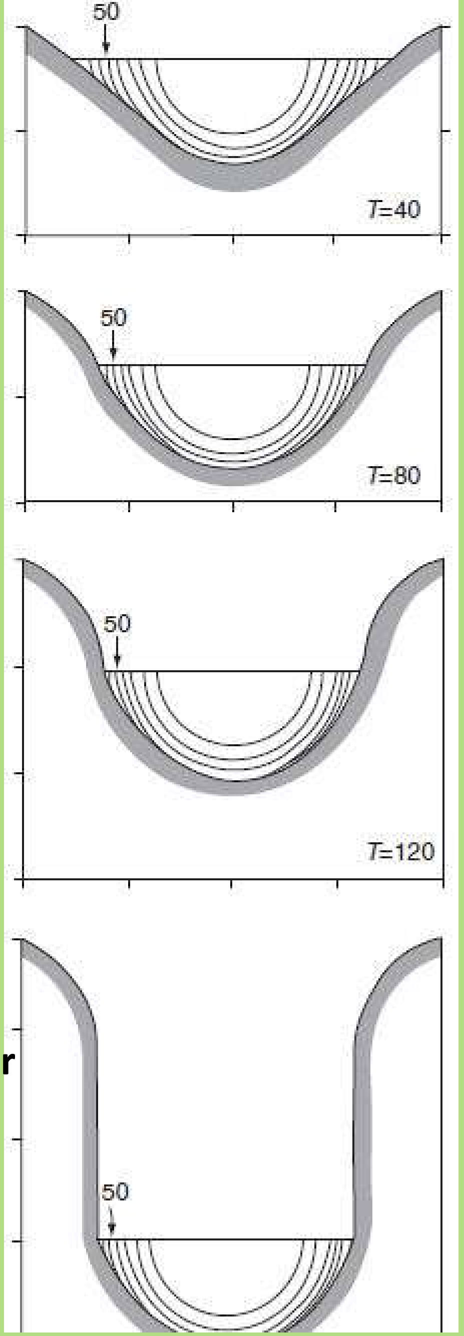
V-shaped = streams

U-shaped = glaciers

Glacial troughs range in size from hundred-meter scale troughs in mountain regions to the largest fjords with lengths of several hundred kilometers and maximum depths of a few thousand meters. A number of researchers have emphasized the need to combine this with the depth/width ratio (form ratio; Graf, 1970) with values for measured cross-sections ranging from 0.1to 0.45 (Li etal.,2001; Benn andEvans,2010). Extremely shallow glacial troughs with depth/width ratios less than 0.02. have been identified on the northeastern Tibetan Plateau based on digital elevation model analysis(Heyman etal.,2008).

Glacial trough in the Jotunheimen mountains, central Norway

Glacial erosion remolding a V-shaped valley into a glacial trough (Harbor, 1992). In an ideal V-shaped valley, the basal ice velocity(shown as percentage of maximum with 10% interval lines),and thus the erosion rate,is higher some distance up the valley side. This causes widening of the lower parts of the valley and development of a U-shaped parabolic cross-section.



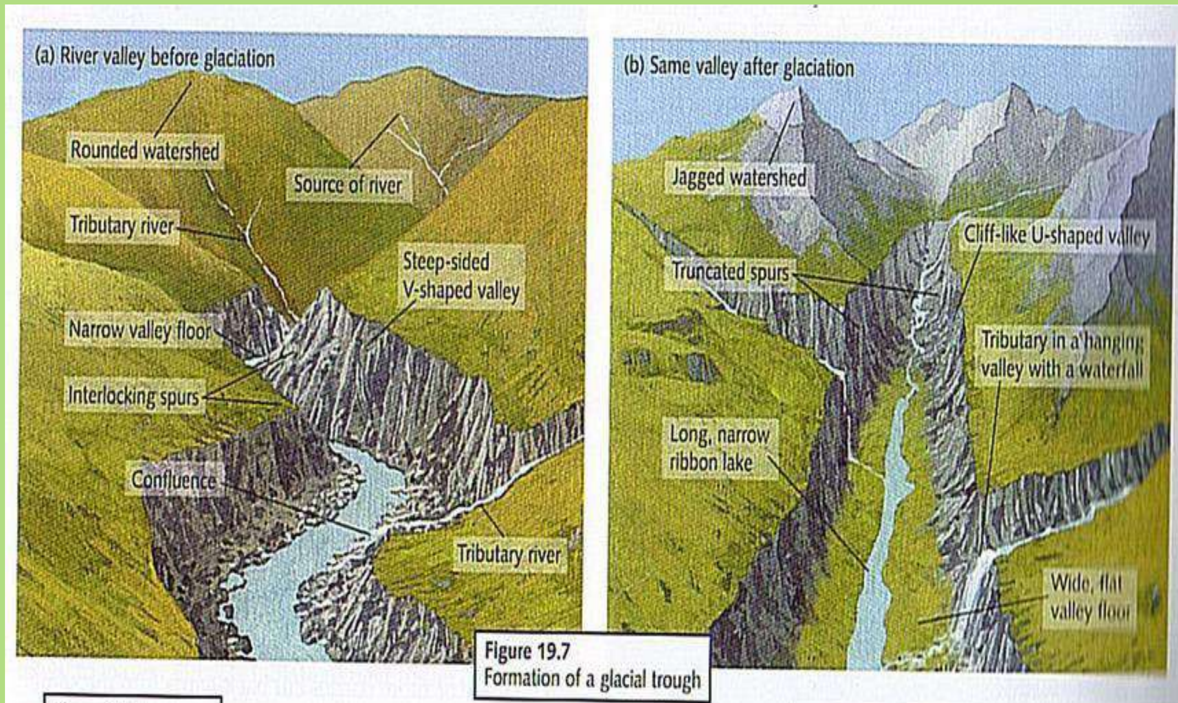
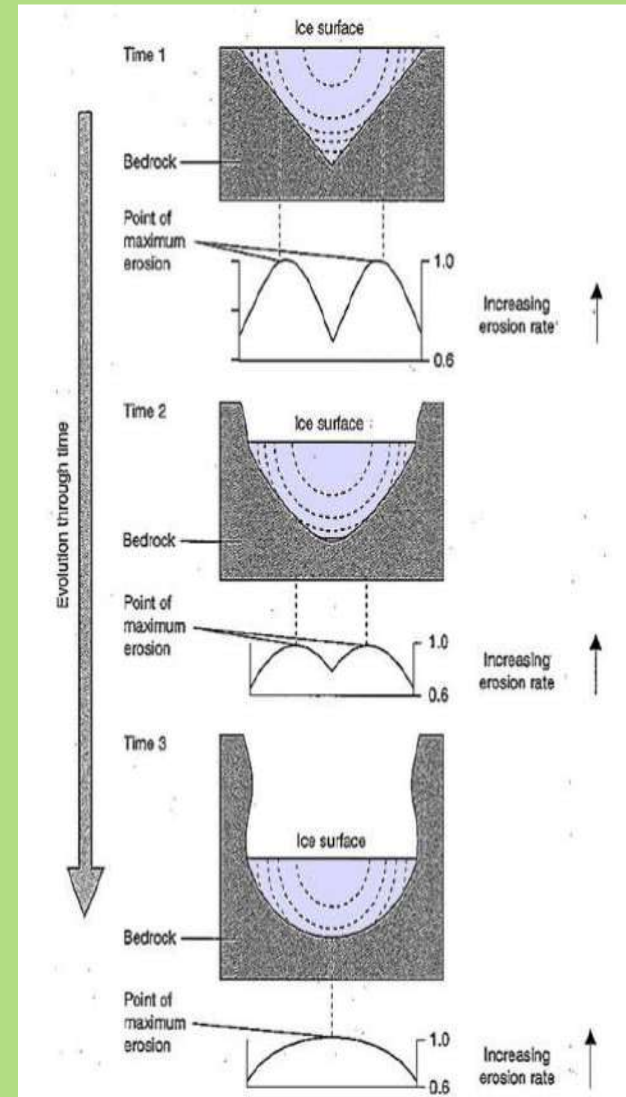


Figure 19.7
Formation of a glacial trough



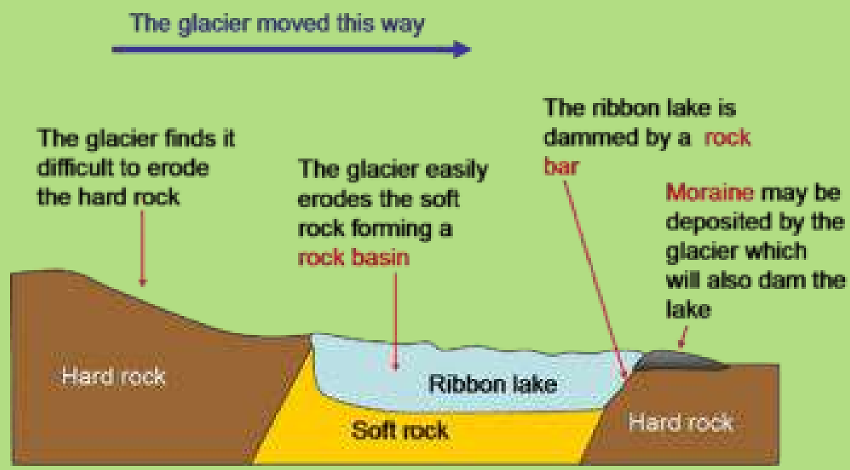
After Bennett and Glasser, 2009

The longitudinal profile of a former mountain (or valley) glacier is often subdivided into numbers of giant steps often with overdeepened hollows between. This profile is known as a *glacial stairway*. The flattish sectors are known as *treads*, and the steep parts are known as *risers*; the rock bar at the crest of the rise is sometimes called the *threshold* or *riegel* (an Alpine term). (Stamp, 1961). Where the overdeepened treads are undrained, there are rock-cut depressions or partly moraine dammed pools, and these occur in series. They are known as *paternoster lakes*, an allusion to a string of prayer beads.

glacial stairway The long profile of a glacial trough: it is characterized by alternating rock bars (riegels) and rock basins, giving the impression of a stairway. The structure is attributed to variations in the erosive power of ice, or to the influence of rock jointing.

A **riegel** (from German, literally *crossbar*) is a transverse ridge of bedrock that has been exposed by glacial erosion. Riegels are also known as rock bars, thresholds, and verrous. They are found in glaciated valleys, and are often associated with waterfalls and zones of rapids when streams are present. When multiple riegels are stacked in a series they are referred to as a glacial stairway.
Most riegels can be identified by having smooth faces on the up-valley sides, while the down-valley sides show signs of having been plucked (eroded by the removal of rocks and blocks from the bedrock).

A **ribbon lake** is a long and narrow, finger-shaped lake, usually found in a glacial trough. Its formation begins when a glacier moves over an area containing alternate bands of hard and soft bedrock. The sharp-edged boulders that are picked up by the glacier and carried at the bottom of the glacier erode the softer rock more quickly by abrasion, thus creating a hollow called a rock basin. On either side of the rock basin, the more resistant rock is eroded less and these outcrops of harder rock are known as rock bars, which act as dams between which rainwater may accumulate after the retreat of the ice age, filling up the rock basin and creating a ribbon lake.

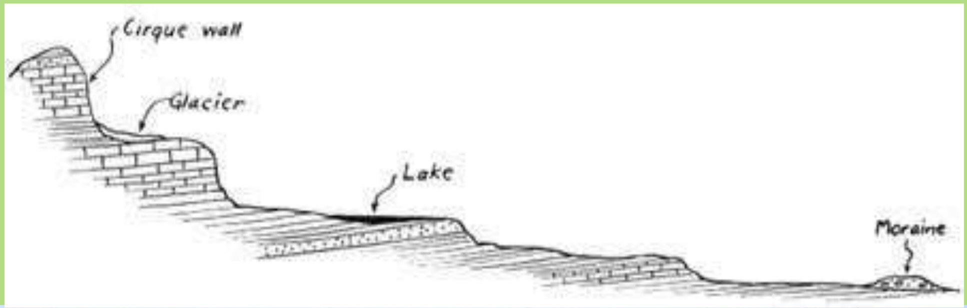


Windermere in the Lake District

The **Finger Lakes** are a group of 11 long, narrow, roughly north–south lakes in an area called the Finger Lakes region in Central New York

Glacial Lakes

A **glacial lake** is a lake with origins in a melted glacier. They are formed when a glacier erodes the land, and then melts, filling the hole or space that it has created.

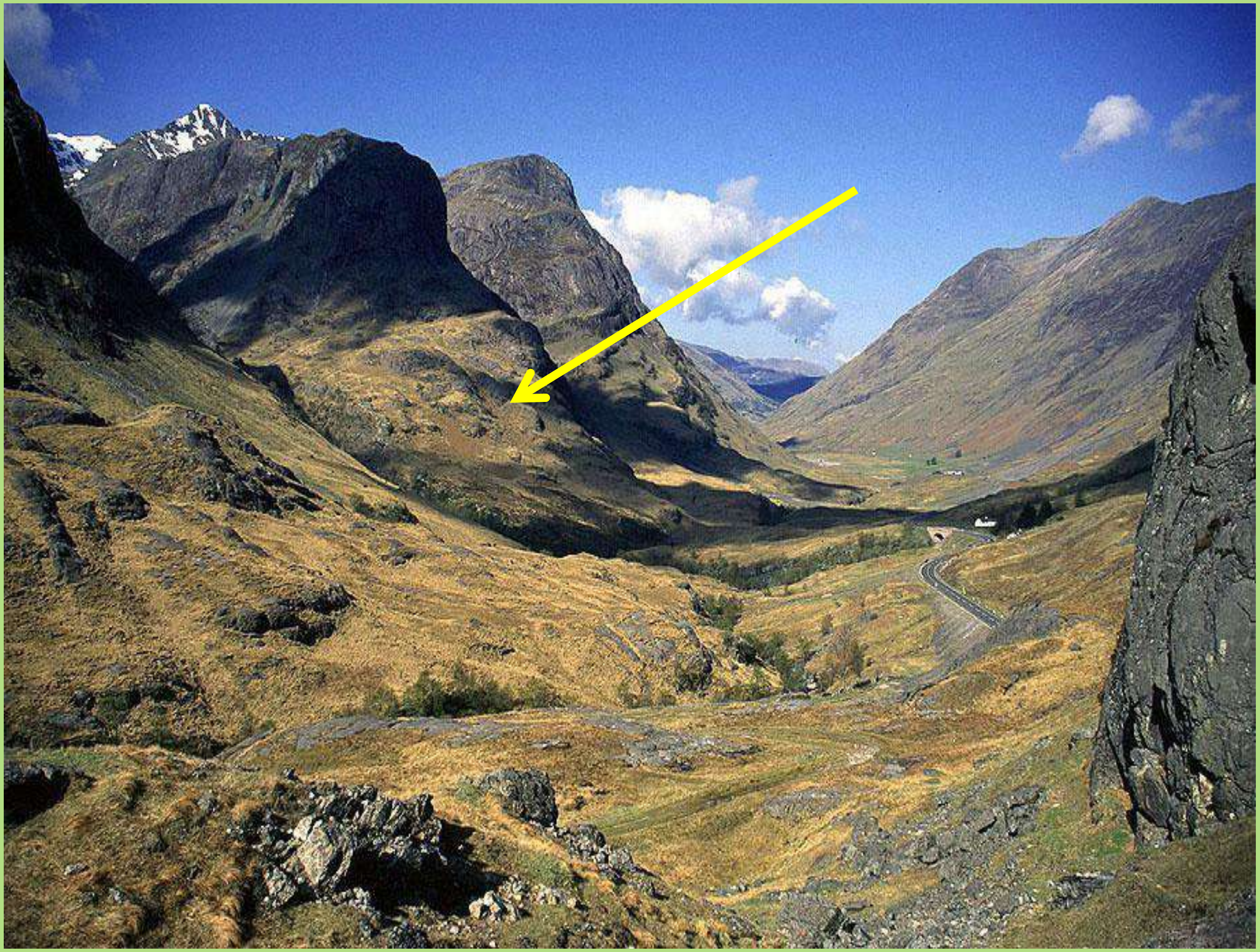


The Great Lakes as seen from space. The Great Lakes are the largest glacial lakes in the world.

Paternoster Lakes

- Paternoster Lakes :One of a series of small, circular stair-stepped lake formed in individual rock basins aligned down the course of a glaciated valley.

Truncated Spurs



**Occur where a glacier carves its way though rock, cutting off
the edges of interlocking spurs.**

Hanging Valley

- Hanging valleys are often associated with valley glaciers, joining the main valley along its sides.
- They are the product of different rates of erosion between the main valley and the valleys that enter it along its sides. The floors of the tributary valleys are eroded and deepened at a slower rate than the floor of the main valley, so the difference between the depths of the two valleys steadily increases over time. The tributaries are left high above the main valley, hanging on the edges, their rivers and streams entering the main valley by either a series of small waterfalls or a single impressive fall.
-

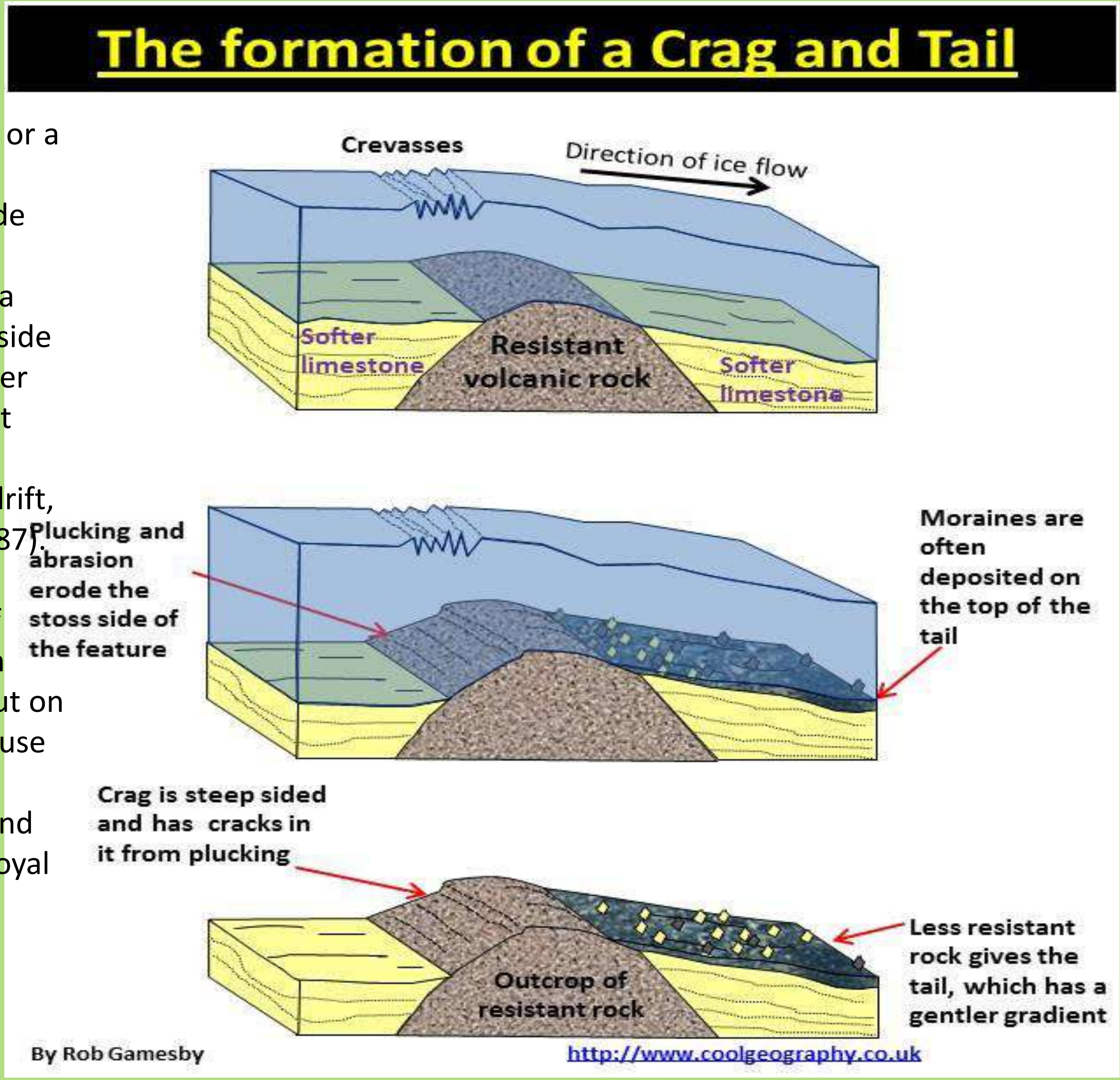
Crag And Tail

Landform developed by glacial erosion of rocks on unequal resistance. The crags are cliffs developed in near-cylindrical masses of strong rock. The tail is formed in softer rocks sheltered from erosion in its lee.

FIG. 82.—Section of the form of hill in the Lowlands of Scotland known as 'Crag and Tail.' *a*, 'Crag' of basalt or other eruptive rock. *b*, 'Tail' of softer rocks which have been worn away from around the hard igneous mass. *c*, Hollow often found in front of the crag. *d*, Covering of drift.

- The basal layers of the Pleistocene ice sheets were forced to deform around large bedrock obstructions. The quickening of flow and the high stresses on the up-ice side of the hill led to the erosion of crescent-shaped depression in front of the hill. The sides of the hill were over-steepened and crags were formed. In the lee of the rock boss, the velocity of glacier flow and the effective pressure on the glacier bed was reduced. This allowed the preservation of relatively softer rock but the sheltering effect diminished with distance from the crag and so the tail tapers away from the hill. A thin layer of till was probably deposited as the ice thinned during deglaciation.

Crag-and-tail -- An elongated ridge or hill, or a drumlin-like feature, having a steep stoss side sculptured in hard consolidated rock and a smooth elongated lee side occasionally cut in softer weathered bedrock but more commonly composed of a tail or drift, usually till (Dionne, 1987). The most prominent landmark of the city of Edinburgh is Edinburgh Castle, which stands out on the urban skyline because of its location on an elongate bedrock mound (Castle Rock and the Royal Mile)



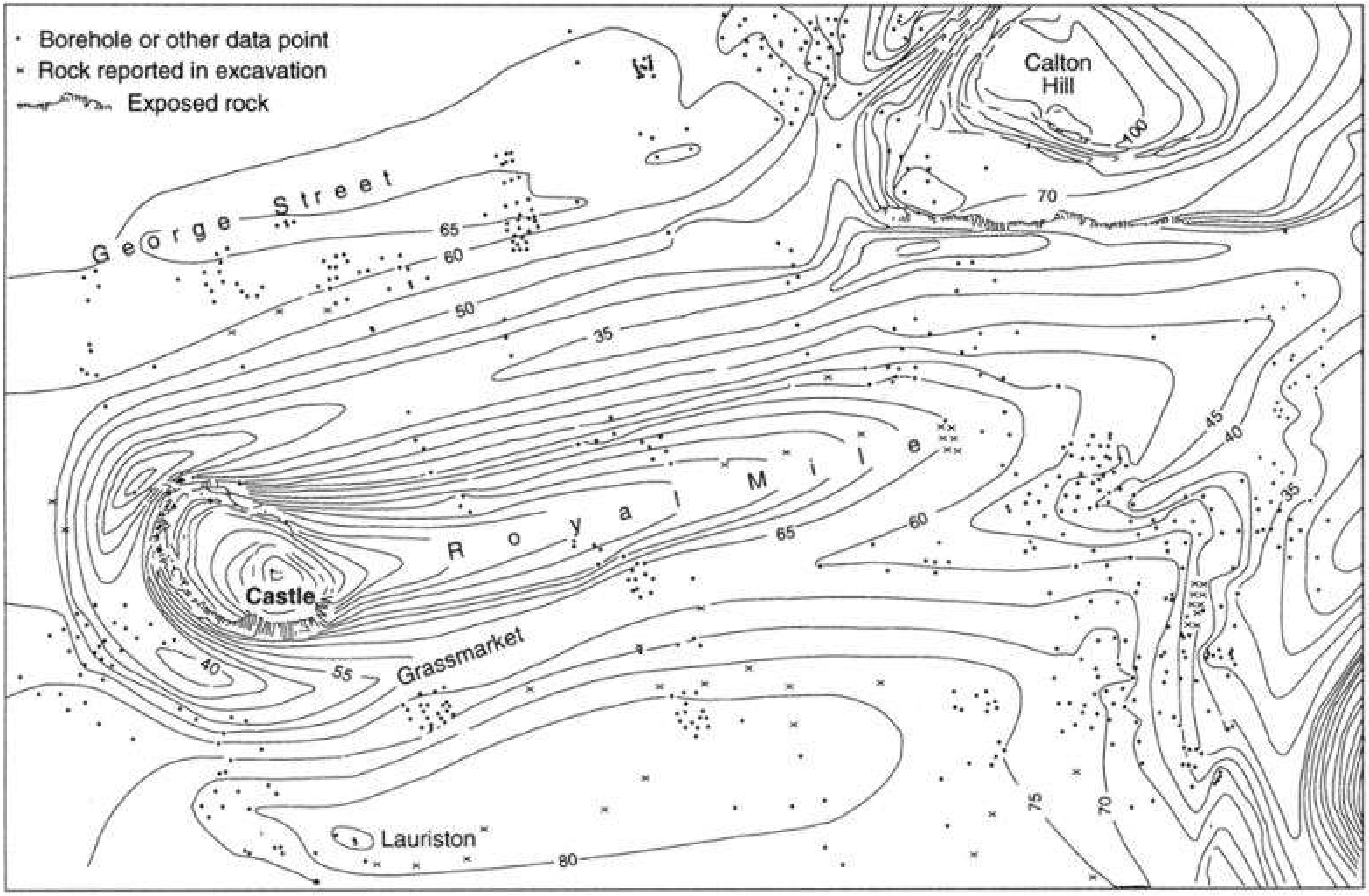


Figure 3: Bedrock contours of the Edinburgh Castle crag-and-tail after Sissons (1971). Note the horseshoe shaped depression which has been eroded on the up-ice side of the Castle Rock crag. Remember that various amounts of till have been deposited over these features and so these bedrock contours do not represent the present day land surface.

CRAG-AND-TAIL

A landform consisting of a rock hill and tapering ridge which is produced by selective erosion and deposition beneath an ice sheet. They range in scale from tens of metres to kilometres in length, with the tail pointing in the down-ice direction. The hill, or crag, is usually of strong rock that has resisted glacial erosion and forms an obstruction to the ice producing a `pressure shadow´ in its lee. This extends in a down-ice direction in proportion to the ice velocity and thickness and creates a gradually tapering zone of minimal erosion or even a cavity. Although often similar in appearance there are two types of crag-and-tail dependent upon the composition of the tail and processes that led to its formation. Erosional crag-and-tails consist of a highly resistant rock crag that protected less resistant bedrock in its lee from the full force of glacial erosion. The tail in this type consists of bedrock. Depositional crag-and-tails were formed by the inflow of glacial sediments into a cavity produced in the lee of the rock obstruction, and hence have tails composed of unconsolidated sediments. These tend to be smaller in scale. In practice it is hard to differentiate between these two types as they may both have glacial sediments at the surface of the tail. The significance of these landforms is that in common with SUBGLACIAL BEDFORMS they record former directions of ice flow and indicate that the ice was at pressure melting point, which permitted sliding at the bed.

Reading

Benn, D.I., and Evans, D.J.A., 1998: *Glaciers and Glaciation*. London: Arnold.

Fjords

- Fjords are found along some steep, high-relief coast-lines where continental glaciers formerly flowed into the sea. They are deep, narrow valleys with U-shaped cross sections that often extend inland for tens or hundreds of kilometres and are now partially drowned by the ocean. These troughs are typical of the Norwegian coast, but they also are found in Canada, Alaska, Iceland, Greenland, Antarctica, New Zealand. The floor and steep walls of fjords show ample evidence of glacial erosion. The long profile of many fjords, including alternating basins and steps, is very similar to that of glaciated valleys. Toward the mouth, fjords may reach great depths, as in the case of Sogn Fjord in southern Norway where the maximum water depth exceeds 1,300 metres. At the mouth of a fjord, however, the floor rises steeply to create a rock threshold, and water depths decrease markedly.

If the U-shaped depression carved by the glaciers reaches all the way to the sea it is often referred to as a ‘fjord

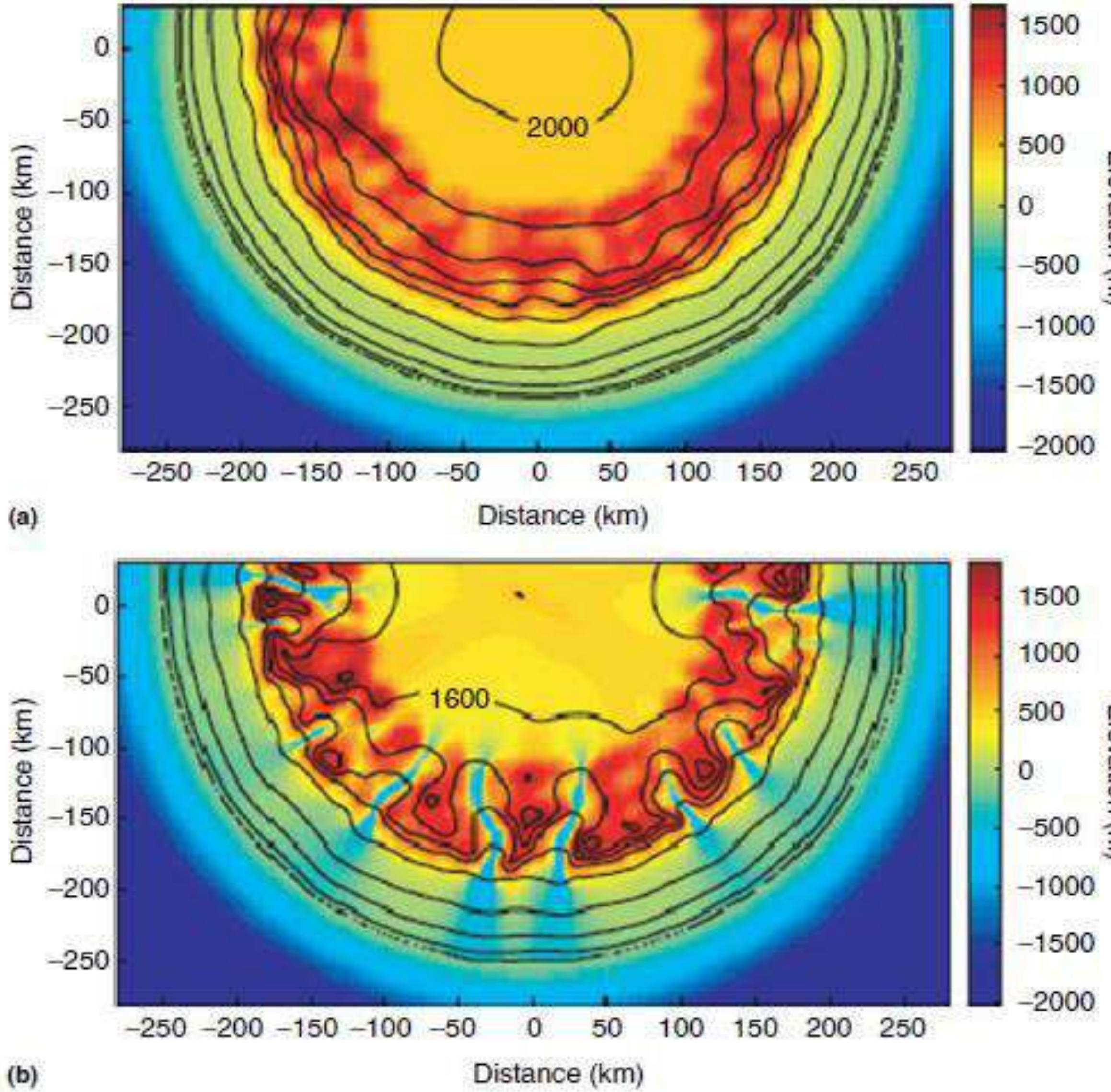
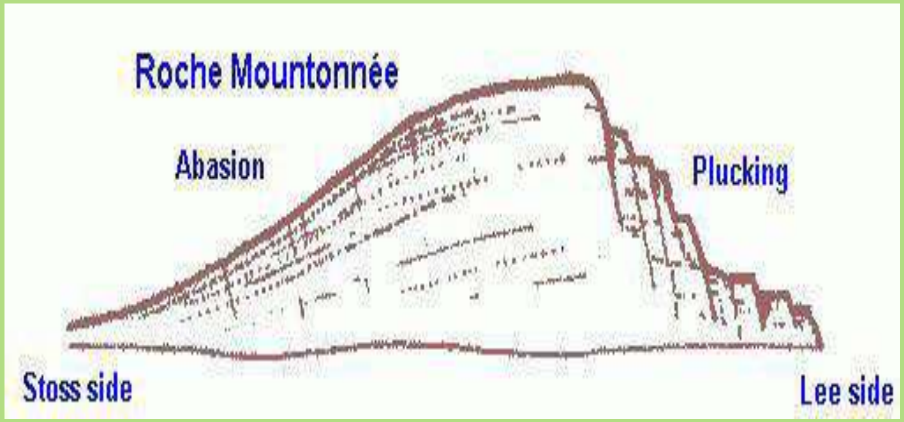
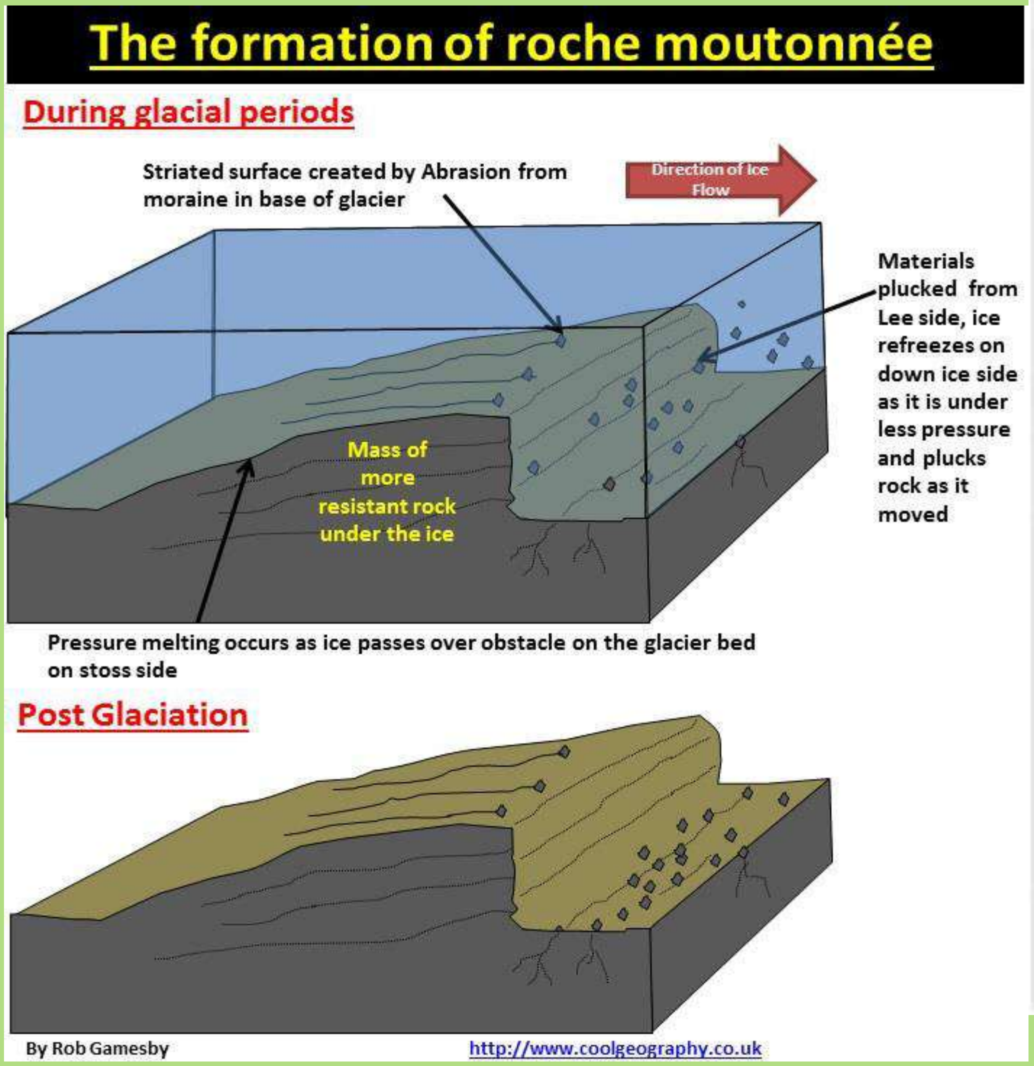


Figure 10 Simulated formation of fjords by topographic steering of ice. Reproduced from Kessler, M.A., Anderson, R.S., Briner, J.P., 2008. Fjord insertion into continental margins driven by topographic steering of ice. Nature Geoscience 1, 365–369: (a) Initial non-glacial topography with a mountain range separating a low relief high elevation area and the sea; (b) Topography after 1.2 million years of ice sheet glaciation. The topographic steering of ice over/through the mountain range into the ocean, with highest ice flow and erosion in the lower regions of the mountains, has created deeply incised glacial troughs and fjords.

Roche Mountonnee



These structures are bedrock knobs or hills that have a gently inclined, glacially abraded, and streamlined stoss side (*i.e.,* one that faces the direction from which the overriding glacier impinged) and a steep, glacially plucked lee side. They are generally found where jointing or fracturing in the bedrock allows the glacier to pluck the lee side of the obstacle. In plan view, their long axes are often, but not always, aligned with the general direction of ice movement. **Former glacier basal thermal regime**: both the abraded stoss side and the plucked lee side of roches moutonnées require the former presence of sliding ice and meltwater. The presence of roches moutonnées means therefore that the ice masses that progressively shaped these bedrock hills were warm based, with ice at the glacier bed above its pressure melting point. The valley-floor roches moutonnées reflect the passage of thick, fast-moving and sliding ice streams.



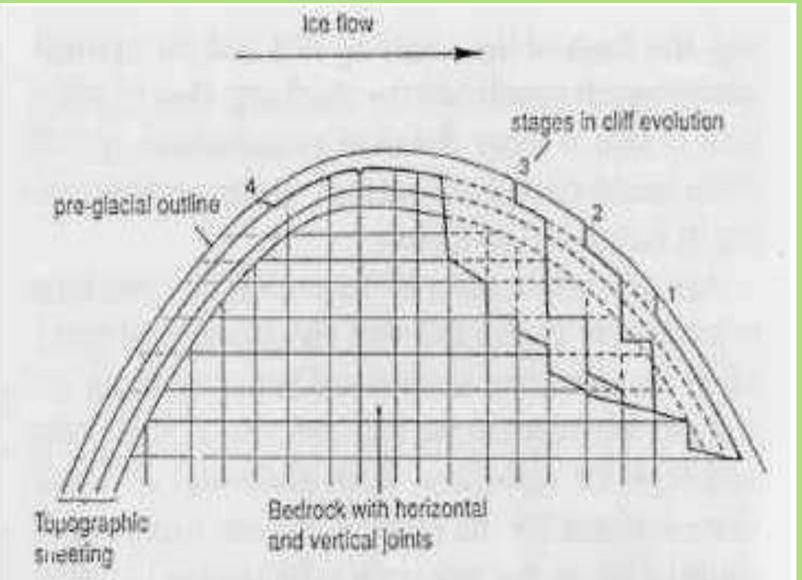


Fig. 11. A model of the evolution of roches moutonnées in Upper Deeside.
Stage 1: Lee side surface slabs removed, exploiting topographic sheeting.
Stage 2: Vertical faces migrate up ice with depth limited by depth of crack propagation.
Stage 3: Continued back wearing and successive cycles of deepening.
Stage 4: Staircase cliff. The top of the roche moutonnée may have been lowered by abrasion.

The 18th-century Alpine explorer [Horace-Bénédict de Saussure]() coined the term *rôches moutonnées* in 1786. He saw in these rocks a resemblance to the [wigs]() that were fashionable amongst French gentry in his era

Whaleback is *a bedrock knoll smoothed and rounded on all sides by a glacier (Bennett and Glasser, 1996)*

As a continental glacier expands, it strips the underlying landscape of the soil and debris accumulated at the preglacial surface as a result of weathering. The freshly exposed harder bedrock is then eroded by abrasion and plucking. During this process, bedrock obstacles are shaped into streamlined “whaleback” forms,

Whalebacks are bedrock knolls that have been smoothed and rounded on all sides by a glacier. Individual whalebacks may be slightly elongated in the direction of ice flow, although the structural attributes of the bedrock (e.g., joints, bedding planes and foliations) may dramatically affect the morphology of their overall form. Whalebacks tend to have low height to length ratios. They are relatively high (1-2 m) in comparison to their length (1.5-3 m). Striations and other small-scale features of glacial abrasion may be superimposed on any surface of a whaleback. Striations on whalebacks are often continuous along the entire length of the whale-back. From this it is possible to infer that there were no basal cavities around the whaleback during its formation and the ice was everywhere in contact with

Nunataks are rocky islands that are surrounded by flowing glacier ice. As the glaciers surrounding a nunatak come together, a medial moraine composed of rockfall from the nunatak often marks their confluence. These are residual features oContinental Glaciial Erosion

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