Deserts and Glaciers

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Note: all images used are sourced from Earth: Portrait of a Planet by Stephen Marshak.

1 Deserts

1.1 Introduction

Deserts are landscapes that are classified as having very little precipitation, regardless of the temperature. They cover around 25 percent of the land surface. Though you may at first imagine deserts as vast seas of sand dunes, they are a diverse group of landscapes. Some deserts are covered in sand, and some have very little. Some deserts may even have snow instead. Despite their often barren appearance, they are full of exciting geological features and processes.

1.2 Types of Deserts

1.2.1 Subtropical Desert

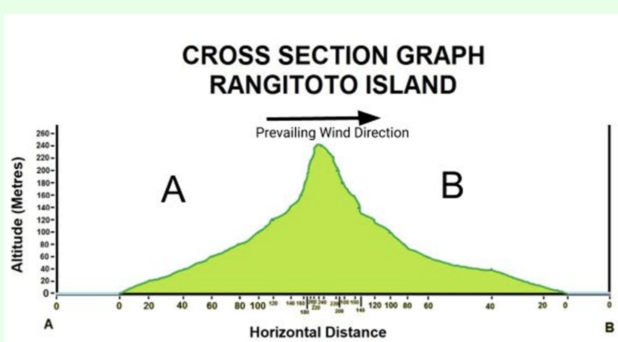
These types of deserts are found on or around 30 degrees north and south of the equator. This is due to the Hadley cell, which causes humid air to rise at the equator, and dry air to descend around 30 degrees. The land underneath where the Hadley cell descends gets very little moisture, and in fact, the hot dry air increases evaporation, taking water away from the region. An example of this type of desert is the Sonoran desert.

1.2.2 Rainshadow Deserts

These kinds of deserts occur due to air losing its moisture when it passes over a mountain range. When moisture-laden air from the ocean hits a coastal mountain range, the air rises and cools, causing it to lose most of its moisture. This means that the windward side of the mountain can host lush forests. When the air reaches the other side of the mountain, the leeward side, it is hot and dry. When this air descends and flows across the land, it creates a desert. Examples include the eastern Washington desert.

Example 4.1 (2020 USESO Open Exam)

Using the figure below of Rangitoto Island, New Zealand, answer the following question.



Compared to "A", the "B" side of the island is likely to be:
A. Hotter and drier

B. Colder and wetter
C. Hotter but similar in humidity
D. Colder but similar in humidity

Solution: The answer is A. Due the air having to rise over the mountain, most of its moisture will precipitate on side A, leaving side B drier. The only answer choice with this option is A.

1.2.3 Coastal Deserts

Cold ocean currents parallel to the coast cool the air above the surface of the ocean, reducing the amount of moisture it can hold. The cold layer of air is also bounded above by a warmer layer, not affected by the cold ocean current. This means that when the cold air flows over the land, it is trapped to the surface. The surface is therefore exposed to almost no moisture, leading to some of the driest deserts in the world. An example would be the Atacama desert in Chile caused by the Humboldt current.

1.2.4 Continental Interior Deserts

These kinds of deserts are often found in the interior of continents. They are formed due to the air reaching them having traveled over a large amount of land, causing the air to lose most of its moisture. It eventually loses so much moisture that the area it is flowing over becomes a desert. An example is the Gobi desert.

1.2.5 Polar Deserts

The areas inside the arctic and antarctic circles get very little precipitation due to the polar high, where subsiding air from the Polar cell produces calm weather. Additionally, cold air cannot hold much moisture, meaning that little precipitation forms, leading to the formation of a desert.

1.3 Wind Features

1.3.1 Desert Varnish

Desert Varnish is a dark rusty brown coating of iron oxides, manganese oxides, and clay that coats the surfaces of rocks in the desert. The current theory on its formation predicts that when dust collects on rocks, microbes, in the presence of moisture, can extract elements from the dust and precipitate oxides. This process relies on dust staying on the rocks for long periods of time, which is not possible in other climates due to rain washing it away.

1.3.2 Lag Deposits and Desert Pavements

A lag deposit forms when the wind blows away the finer sediments, leaving the heavier materials, such as pebbles and cobbles, to collect at the surface. This process was how desert pavements were thought to have formed, but recent studies suggest that instead of sediment being blown away, sediment collects under the deposit at the top and slowly pushes it up, forming a stony surface. Over time, the stones break and crack and settle into a jigsaw-like arrangement.

1.3.3 Deflation

Deflation is the process by which the height of the surface is reduced due to sediment being continuously blown away. In many cases, the roots of plants can stabilize the soil around them, stopping them from blowing it away. Over time, this can lead to the plants becoming elevated relative to the ground around them. This can be seem in Figure 1.

Figure 1: Deflation has removed the soil in the area except for the soil being held on to by plant roots.

1.3.4 Wind Abrasion

When wind picks up large amounts of sediment, it can essentially act as a sandblaster, eroding anything in its path. Individual rocks can become flattened and smoothed on whatever side is facing the wind. If the rock changes position and direction, a new face will be exposed to the wind. These rocks, which have been faceted by the wind, are known as **ventifacts**. In places where a hard layer overlies a soft layer, a **yardang** can form due to the softer lower layers being eroded faster than the harder layers above.

Figure 2: An example of a yardang.

1.3.5 Loess

Loess is a clastic sedimentary rock that is formed from the deposition of silt or clay-sized sediment. Loess, or similar deposits, cover around 10 percent of the earth's surface. They are formed downwind of dune systems since they are lighter and can stay as suspended load for longer.

1.4 Water Features

1.4.1 Calcrete

In the desert, heavy rains can leach ions and clay particles down into the soil, but due to the low amount of rain, they cannot percolate all the way out, and collect in a layer below the surface. This layer is able to cement the rocks and clasts around it, forming a hard sedimentary rock. When the matrix is made from calcite, it is called calcrete or caliche.

1.4.2 Alluvial Fans and Bajadas

When water flows out of the canyon into a flat plain, a conical wedge of sediment, called an alluvial fan, can form. They grow in sections, with active distributaries building up a certain section before the channel switches. The process is similar to how rivers form deltas. Because alluvial fans are highly permeable, they can absorb much of water coming out the canyon during a flood. When many alluvial fans from different canyons merge and overlap they form bajadas. In other words, they are rows of continuous sediment, formed by fluvial processes, found at the base of cliffs.

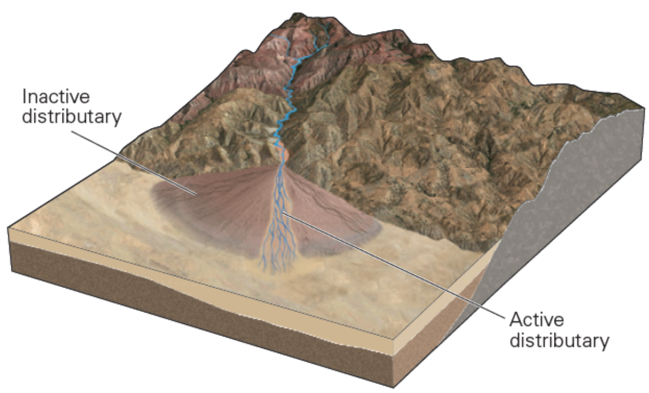


Figure 3: Formation and growth of an alluvial fan.

1.4.3 Playas and Salt Lakes

A playa is an exposed lake bed found in arid areas that is rich in clay and various salts. It is formed in basins where water temporarily collects. Because there is no outlet, any salts that flow in stay trapped there as lake water evaporates, building up over time. If there is enough salt, a salt flat can form, which is what happened in northwestern Utah with the Bonneville Salt Flats. If the water does not evaporate or enter the ground, it can stay there permanently, forming a salt lake. The same forces that make a playa salty act here. The best example of a salt lake is the Great Salt Lake, which is also in Utah.

1.5 Other Features

1.5.1 Scarps

Scarps or cliffs are very common in desert landscapes. Their erosion comes in many forms, and forms some of the most beautiful structures in the world, from the arches of Arches National Park to the mesas and buttes of Monument Valley. The erosion of a cliff and the shape that it takes, depends a lot on the type of rock that forms it. Large vertical pieces of continuous rock form tall cliffs, while alternating layers of hard and soft rock form a step-like pattern. If there happens to be a layer of weak shale, it can form a almost continuous slope, since all the layers are very likely to erode away. Debris at the base of the cliff is referred to as talus. When talus accumulates, it formed a gently sloping plain called a pediment, which grows in size the more the scarp retreats.

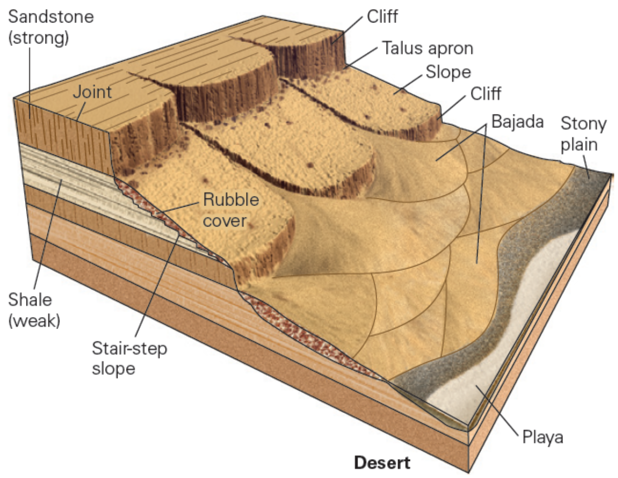


Figure 4: The different types of scarps and the sediments that their erosion forms.

Many times, the erosion forms large flat-topped hills. There are three types.

- Mesas - The largest of the three. Their top is several square kilometers big.
- Butte - The middle size is called a butte. It is not as big as mesas, being around one or two square kilometers, and sometimes less.
- Chimney - The smallest of the three. Buttes are eventually called chimneys when their height is larger than the area of their top. Chimneys are known as hoodoos in the American Southwest.

1.5.2 Cuestas, Hogbacks, and Inselbergs

A cuesta is a ridge of resistant rock that is tiled at an angle and consequently sticks out of the ground. These ridges are often produced by tectonic activity, as anticlines, synclines, or by faulting. One side of the cuesta has a slope while the other side is a scarp. The angle of the sloping side is called the dip slope because it has the same angle as the bed dip. When a cuesta is nearly vertical it forms a hogback. In some cases, these mountainous features or mountain ranges themselves get eroded from all sides, until they form basically an island of rock in the desert. These are called inselbergs, which translates from German into island rock.

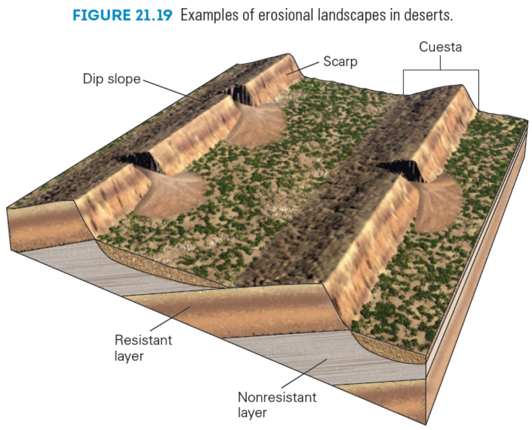


Figure 5: A cuesta and its dip slope.

1.6 Types of Dunes

- Barchan - Where sand is relatively scarce and the wind blows steadily in one direction, crescent-shaped dunes with the tips pointing downwind.
- Star - If the wind approaches a dune from multiple directions, it forms a star dune. Each time the wind shifts, it tries to make a new dune over the existing ones, and this process leads to a multi-lobed dune.
- Transverse - Where there is enough sand to bury the ground and there are moderate winds, sand piles into multiple wave-like shapes that are perpendicular to the wind.
- Parabolic - If the wind breaks through a transverse dune, it makes the tips of the crescent point in the direction the wind is going.
- Longitudinal - When there is abundant sand a strong steady wind, dunes can form in long lines parallel to the direction of the wind.

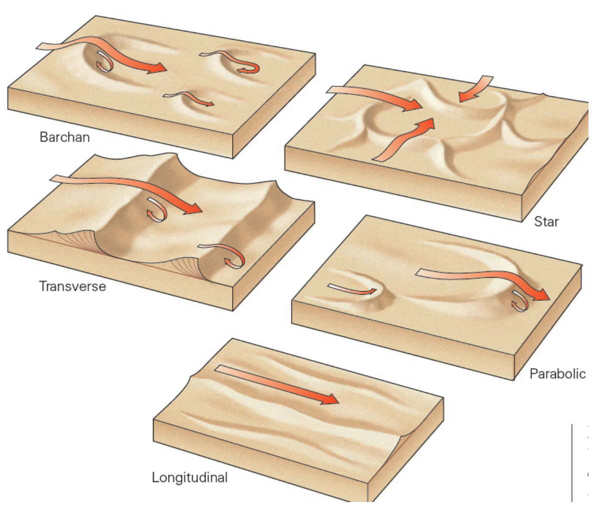


Figure 6: Types of dunes.

1.7 Closing

Deserts are a landscape that are always changing and evolving. The wind and water sculpt a beautiful landscape. Even though the ecology of deserts is not earth science, we should still acknowledge the complex ecosystems that have emerged in these barren lands. Our relationship with deserts is also changing, as we expand into them and they expand into us. The better we understand deserts, the better our ability to adapt to our changing world.

2 Glaciers

2.1 Introduction

Glaciers are massive sheets of ice that form in places where snow is able to accumulate over time. As long as year on year, more snow accumulates than is melted, a thick layer of ice will form. As it keeps growing it will try to start flowing downslope, forming a glacier. Glaciers also have interesting features in their morphology. The first is called a crevasse, which is a deep crack that forms on the surface of glaciers. They can be anywhere from a few inches to tens of feet wide. Another important feature is a moulin, which is a tall vertical shaft that drains flowing meltwater from the surface of a glacier to its base. Glaciers also have two zones, the zone of accumulation, where mass is accumulated, and the zone of ablation, where mass is lost. The zone of accumulation is upstream and the zone of ablation is downstream.

2.2 Types of Glacial Ice

As snow in glaciers slowly accumulated and gets buried deeper and deeper, it changes form. When snow first falls, it is 90 percent air, and by the time it becomes blue glacial ice, it has only 20 percent ice. A process known as pressure solution is responsible for this compaction. When ice is put under pressure, there is melting at points of contact. The water formed from this goes into the air pockets and is deposited as ice.

- Loose Snow - 90 percent air
- Granular Snow - 50 percent air
- Firn - 25 percent air
- Fine-grained ice - 20 percent air, smaller crystals
- Coarse-grained ice - 20 percent air, larger crystals

2.3 Types of Glaciers

2.3.1 Alpine Glaciers

These glaciers, also known as mountain glaciers form in or around mountain ranges and generally flow from high elevations to low elevations. There are 4 types of alpine glaciers.

- Cirque Glacier - These form when ice builds up in cirques, bowl-shaped depressions carved out by glaciers.

- Mountain Ice Caps - These are mounds of ice that cover the peaks and ridges of a mountain range.
- Valley Glaciers - These are glaciers that form in the valleys between mountains and flow down its slope. When a valley glacier flows out over the sea, it is considered a tide water. The portion sticking into the ocean is known as an ice tongue.
- Piedmont Glacier - When a valley glacier reaches the end of the valley, it fans out onto the plain.

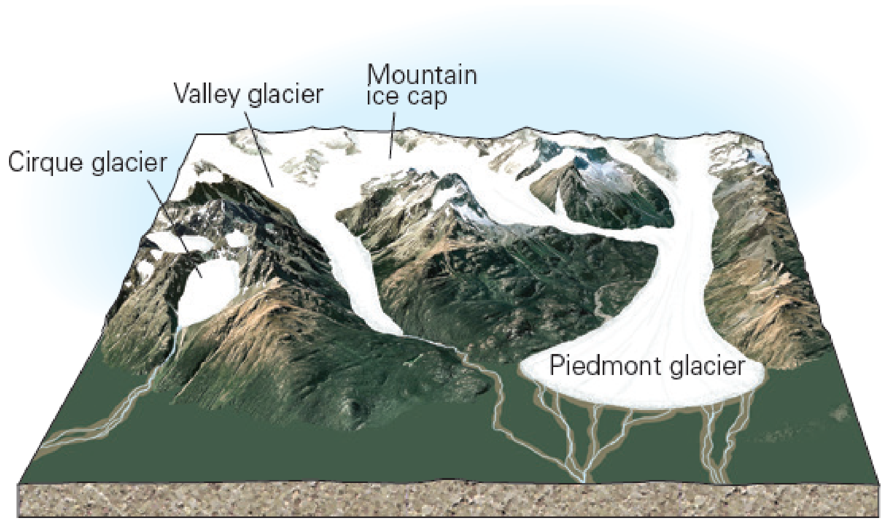


Figure 7: Types of alpine glaciers.

2.3.2 Continental Glaciers

These are vast ice sheets that cover thousands of square kilometers of continental crust. They are found in Greenland and Antarctica. These ice sheets flow outwards, decreasing in height as you get to the edge of it. At the edge, they can divide into multiple lobes. When a continental glacier flows into the sea over sea ice, it is known as an ice sheet. Due to the sheer weight of continental glaciers, they push and compress the ground underneath them, lowering the land height. When these glaciers eventually melt away or recede, the land begins the process of isostatic rebound. The lithosphere, which was deformed to accommodate the weight of the ice, is able to rise. More detail on isostasy can be found in other geosphere handouts.

2.3.3 Temperate Glaciers

These glaciers are glaciers that are in places where some of the ice can melt. The water can collect at the base of the glacier. For this reason, these glaciers are also called wet-based glaciers.

2.3.4 Polar Glaciers

These glaciers are found in regions where the ice cannot melt. Due to this, no water will collect at the base of the glacier, leading them to be called dry-based glaciers.

2.4 Movement of Glacial Ice

As stated earlier, the ice in a glacier flows. Below a depth of 60 meters in a glacier, the ice moves using plastic deformation, where the ice crystals change shape or new ice crystals form replacing old ones. Above 60 meters, the ice is too brittle to flow, and forms cracks when stress acts upon it, which is how crevasses form. The depth of 60 meters in glaciers is called the brittle-plastic deformation. This allows the ice in the glacier to flow and is the main type of flow in dry-based glaciers since there is no film underneath them between the ice and bedrock. Wet-based glaciers on the other hand move by a process called basal sliding, where a wet slurry at the base of the glacier reduced friction between the ice and the bedrock, allowing the whole glacier to slide. Due to increase friction and pressure at the bottom, ice in the middle of a glacier flows the fastest, dragging above layers with it at the same rate. All of this means that glaciers usually have flow rates between 10 to 300 meters per year.

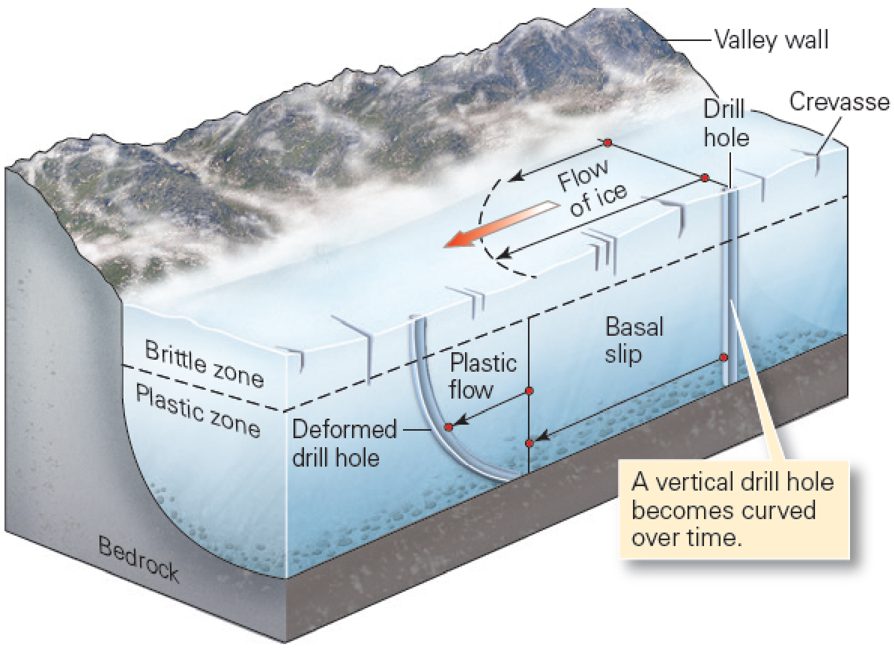


Figure 8: Flow of ice within a glacier.

2.5 Erosional Features

Glaciers can carve the landscape through which they flow in multiple ways. The first is a process called glacial plucking. It occurs when ice that had frozen around a rock at the base or sides of the glacier begins to move, pulling the rock off of the substrate and bringing it with it. Once such clasts become embedded in the ice, they turn the glacier into a rasp. Just as sanding wood makes sawdust, a glacier "sands" the ground underneath it, producing very fine sediment known as rock flour. Glaciers are so effective at eroding mountains that geologists refer to this phenomenon as the glacial buzz saw. This is one of the factors that contribute to keeping the maximum height of mountains down.

2.5.1 Polishing and Striations

Glaciers can both smooth out a rock and cause indentations and other irregularities. Sand embedded in the glacier can make rocks that have glacially polished surfaces. When bigger clasts are dragged against a rock, instead of polishing it, they leave glacial striation, which are indented lines in the rock. When even bigger clasts strike the ground, they leave indentations of shattered rocks called chatter marks.

Figure 9: Striations and Chatter Marks.

2.5.2 Mountain Features

If a glacier is above the top of a mountain then it is able to round it out and make it smooth. If the top of the mountain is higher than the top of the glacier, then you get rugged and jagged features, which are listed below.

- Cirque - A bowl-shaped depression formed at the head of a glacier due to the fracturing of rock above it, caused by the freeze and thaw cycle. The rocks fall and get carried away by the glacier.
- Arete - An arete is a sharp ridge formed between two cirques.
- Horn - The sharp peak of the mountain caused by being surrounded by at least 3 cirques. The most famous example of a horn in the world is Matterhorn, which lies on the French-Swiss border.
- Tarn - A lake formed from glacial melt water that accumulates at the base of a cirque.

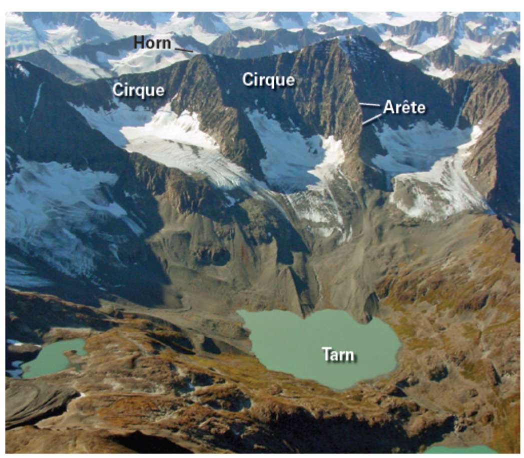


Figure 10: Erosional features of a glacier.

2.5.3 Roche Moutonnee

When a glacier moves over hilly terrain, it can create asymmetrical hills called roche moutonnee. They have a gentle slope on one side and a steep slope on the other. This forms because the gentle slope is upstream and is therefore smoothed by abrasion, while the downstream steeper slope is eroded using plucking, which will lead to a steeper slope.

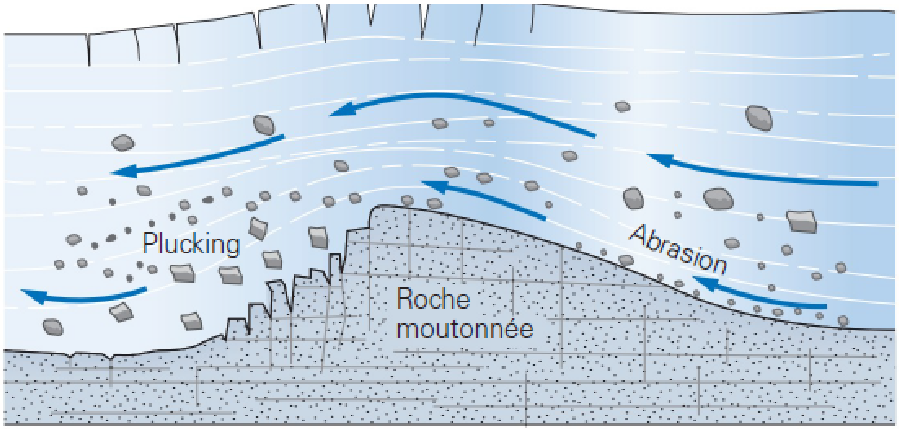


Figure 11: Formation of a Roche Moutonee.

2.5.4 Glaciers and Valleys

Valley glaciers are responsible for some of the world's most beautiful scenery, from Yosemite to the Alps. These glaciers start off in the mountains, and as time passes they grow and flow down into the preexisting river or stream valley. Because of the size and shape of a glacier, it is able to turn the v-shaped valley caused by flowing water and turn it into a U-shaped valley. This means that the valley is deepened and has flat sides. When the ice finally melts, this deepening means that the valley sits well below the valleys flowing into it. These side valleys are called hanging valleys. Glaciers also cut the spurs between side valleys, leading to the spurs abruptly ending when they hit the main valley. These are called truncated spurs. When a glacial valley floods with water it is called a fjord. Fjords can be either freshwater or saltwater depending on where they are, but the majority are saltwater.

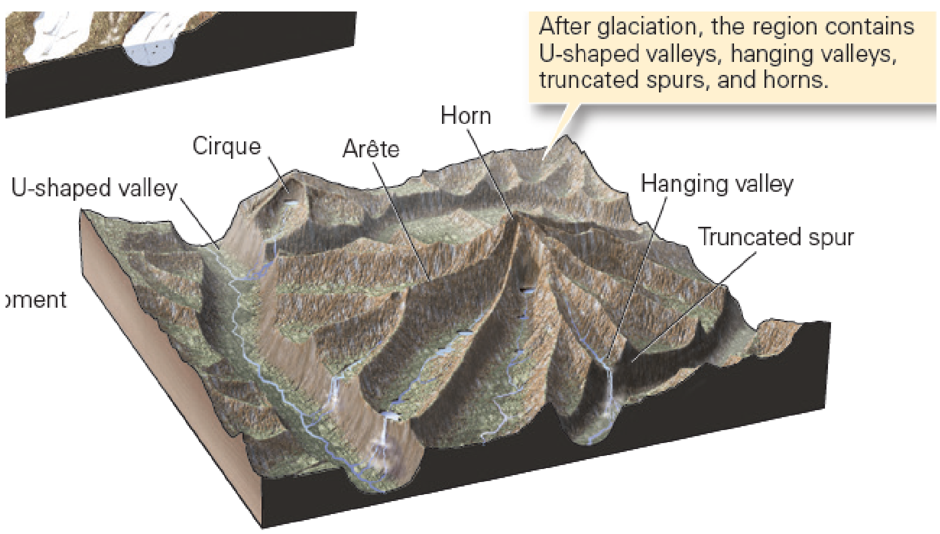


Figure 11: Erosional features of a glacier in a valley.

2.6 Depositional Features

Sediment deposited by glaciers is called glacial drift. It can either be stratified or unstratified.

2.6.1 Glacial Sedimentary Deposits

- Till - Sediment transported a glacier that is deposited at the side of the glacier. The sediment has not been sorted
- Erratics - Large boulders that have been dropped by a glacier during its retreat.
- Glacial Outwash - Till from the toe of a glacier that is carried away by meltwater. Forms braided streams in outwash plains.
- Loess - Sediment made from fine silt and clay particles picked up by katabatic winds (strong winds produced by cold, dense air atop plateaus; see the 'Air Pressure and Winds' handout) and carried downwind of the glacier and deposited in thick layers.
- Kames - A circular mound of often stratified sediment deposited by water flowing on the surface of a glacier.
- Eskers - A long mound of sediment that runs roughly parallel to the direction of glacier movement or roughly perpendicular to the face of the glacier. It forms when sediment accumulates in the tunnels used by water to flow out from underneath the glacier. When the glacier retreats, this sediment is exposed, forming eskers.

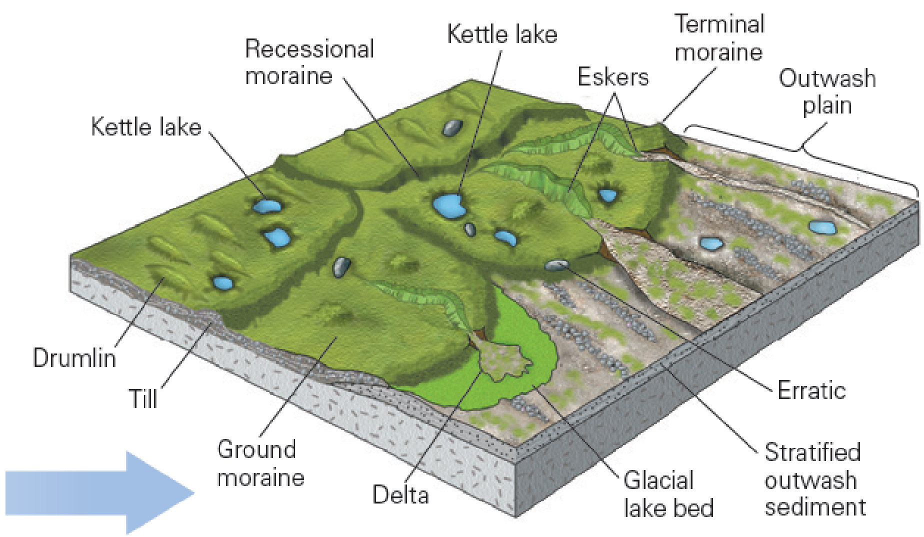


Figure 12: Depositional features of a glacier.

Types of Moraines

- Terminal Moraine - A deposit of sediment that forms at the very end of a glacier parallel to the glacier face. The location of a terminal moraine can tell you the maximum extent of glaciation.
- Recessional Moraine - These are moraines that occur perpendicular and behind terminal moraines. They form during a temporary halt in glacial retreat, allowing a moraine to be formed.
- Ground Moraine - When a glacier has a fast retreat, it leaves behind till in a thin hummocky layer. If the glacier starts to advance again, it can then form these sediments that it previously deposited into **drumlins**, which are streamlined elongated hills that align with the direction of glacier flow. They have a gentle downstream slope and a more steep upstream slope.

- Lateral Moraine - A moraine that forms from sediment deposited on the side of a glacier. Lateral moraines lie parallel to the direction of the glacier movement.
- Medial Moraine - When two glaciers merge together, the lateral moraines of each join together, leaving a wall of sediment in the middle of the glacier. This wall of sediment is known as a medial moraine. By the time you get to the toe of a glacier, it can have many medial moraines in it, indicating how many glaciers have been combined to form it.

Kettle Lakes - These lakes are formed when a retreating glacier drops chunks of ice that embed themselves in the ground and then melt. This leaves a hole in the ground that is filled with water, which is a lake.

2.7 Ice ages and their causes

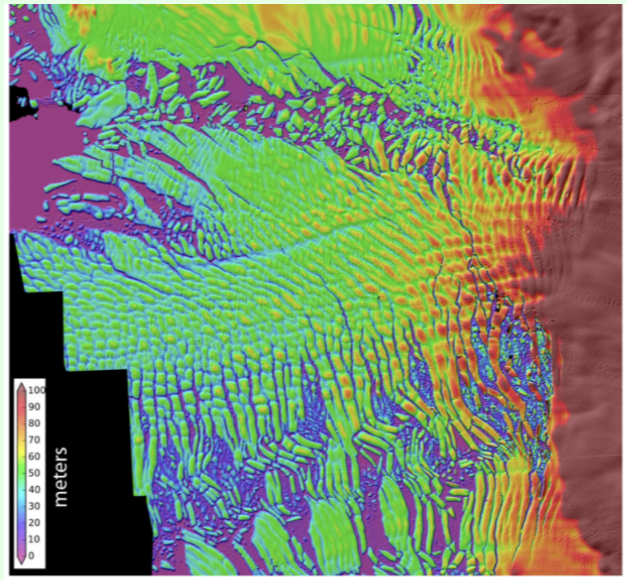
One of the main long-term causes of an ice age is the low levels of CO2 and other greenhouse gases in the atmosphere. One of the short-term causes of an ice age is the Milankovitch cycle, in which the earth's eccentricity, tilt, and precession change over time. The planet is colder when eccentricity and tilt are higher. When the planet starts to cool, ice accumulates and the albedo increases, further cooling the planet. Another positive feedback loop that occurs shuts off thermohaline circulation. Due to cooler temperatures, less water is evaporated, making the oceans less salty, and stopping or slowing down a large part of the thermohaline circulation, which means that higher altitudes don't get warm water from the tropics, making them colder and further increasing albedo.

2.8 Closing

Glaciers and their melting have the ability to control the direction and severity of the climate crisis. How much their meltwaters affect thermohaline circulation, and how much the reduction in albedo heats up the earth. We need to preserve these beautiful landscapes, and gaining a better understanding of them is one of the best ways to try and save them and minimize the effects of their melting.

Example 2.1 (2022 USESO Camp Hydrosphere Exam)

The figure below illustrates the fracturing ice shelf of the Thwaites Glacier to the right (color indicates elevation). Warming waters also contribute to sea level rise by inducing ice melt. Briefly describe how ice shelf break up can lead to the acceleration of Thwaites.



Solution: The breakup of the ice shelf is thought to remove the 'buttressing' effect that prevents greater ice flow, especially because ice shelves like the one from Thwaites are held in place by an embayment. In short, Buttressing, in short, describes the contribution of upstream ice towards 'holding back' a glacier and slowing its flow. The ice shelf is inhibiting the glacial ice from flowing because it is held in place, but as the ice shelf starts to fall apart, the buttressing effect is removed.

Example 2.2 (2022 USESO Camp Hydrosphere Exam)

Despite melt from the Greenland ice sheet significantly contributing to global sea level rise, little local sea level rise has been observed at the Greenland coast so far. Describe two reasons why this may be. (Hint: both relate to gravity.)

Solution: First, since the Greenland Ice Sheet is rapidly losing mass, the land mass uplifts by isostatic rebound. As global mean sea level rises, uplifting land experiences less local sea level rise than land that is static or undergoing subsidence. Second, the loss of mass decreases the gravitational attraction of water towards Greenland.