Weathering, Erosion, Soil, and Mass Wasting

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1 Introduction

The landscape of Earth seems relatively constant when viewed from a human timescale. However, Earth's surface is constantly being reshaped by the processes of weathering and erosion. A key idea to note for the following guide is the difference between the two processes. **Weathering** refers to the breakdown of materials without displacement while **erosion** refers to the displacement of materials after being broken. Weathering causes erosion to more readily occur and erosion exposes new material to be weathered. **Mass wasting** refers to a rapid type of erosion that is caused by the action of gravity. The following guide will overview the basic mechanics of each process, but keep in mind that other types of weathering, erosion, and mass wasting not covered in this handout also exist.

2 Weathering

Weathering is the process in which surface materials are broken down. This is caused by mechanical and chemical means.

2.1 Mechanical Weathering

Rocks weather mechanically in four principal ways: frost wedging, salt wedging, sheeting, and biological action.

- **Frost/Ice wedging** is weathering due to the forces of ice expansion. Frost wedging occurs because water expands up to 9% as it freezes. When water enters cracks in a rock and freezes, this expansion causes new fractures to form and new cracks to become larger. This type of weathering breaks down larger rocks into smaller rocks.

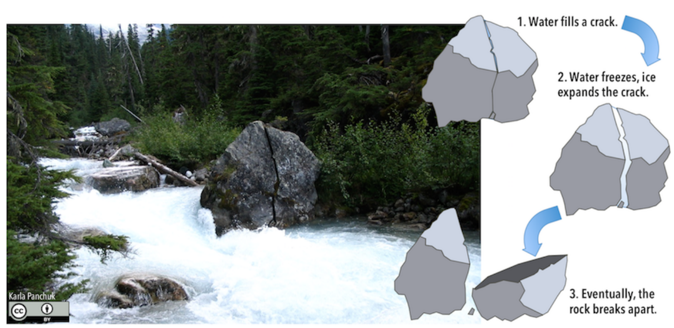


Figure 1: A rock that has undergone Ice wedging

- A secondary process, **frost heave**, also occurs by this same mechanism. Water trapped in fractures or rock pores freeze and draw more water, forming an ice lens. These lenses grow and push rock above them, weakening the material.

- **Salt wedging** occurs in the same way as frost wedging. Dissolved salts are carried by water into fractures in rocks. As the water begins to evaporate, the salts precipitate out of solution and crystallize. The formation of these crystals fragment rocks in a similar manner as ice.

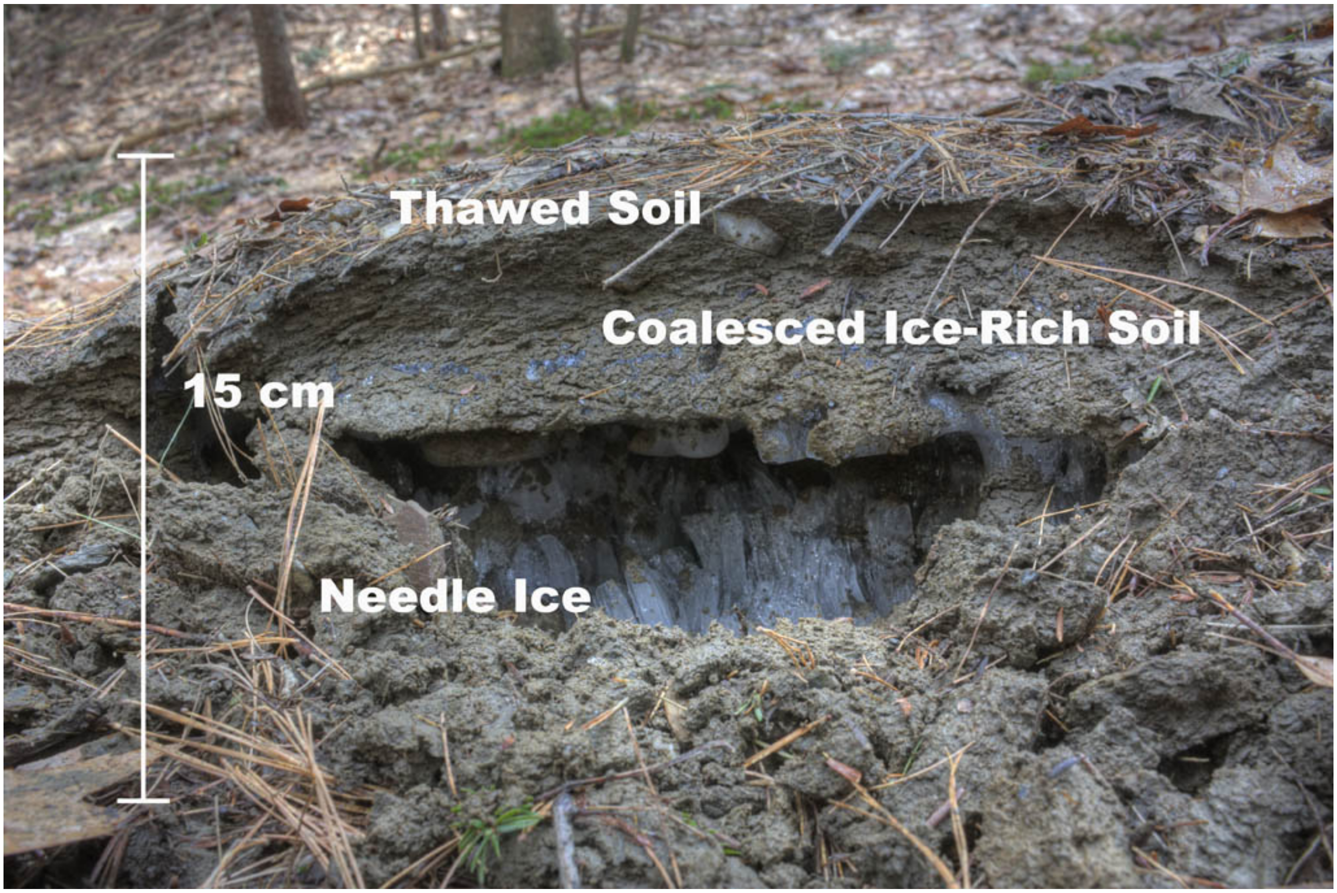


Figure 2: A labelled diagram of Frost Heave showing the different layers

Figure 3: Image of the effects of salt wedging

- **Sheeting** is when rocks fracture in sheets, peeling like onion layers. This is because as masses of typically granitic rock are gradually exposed to the surface through the erosion of layers above them, the confining pressure on them is reduced. This allows the rock to bound back and expand, fracturing them into slabs. This produces structures called exfoliation domes.

- **Biological action** contributes significantly to weathering as well. Plant roots and burrowing

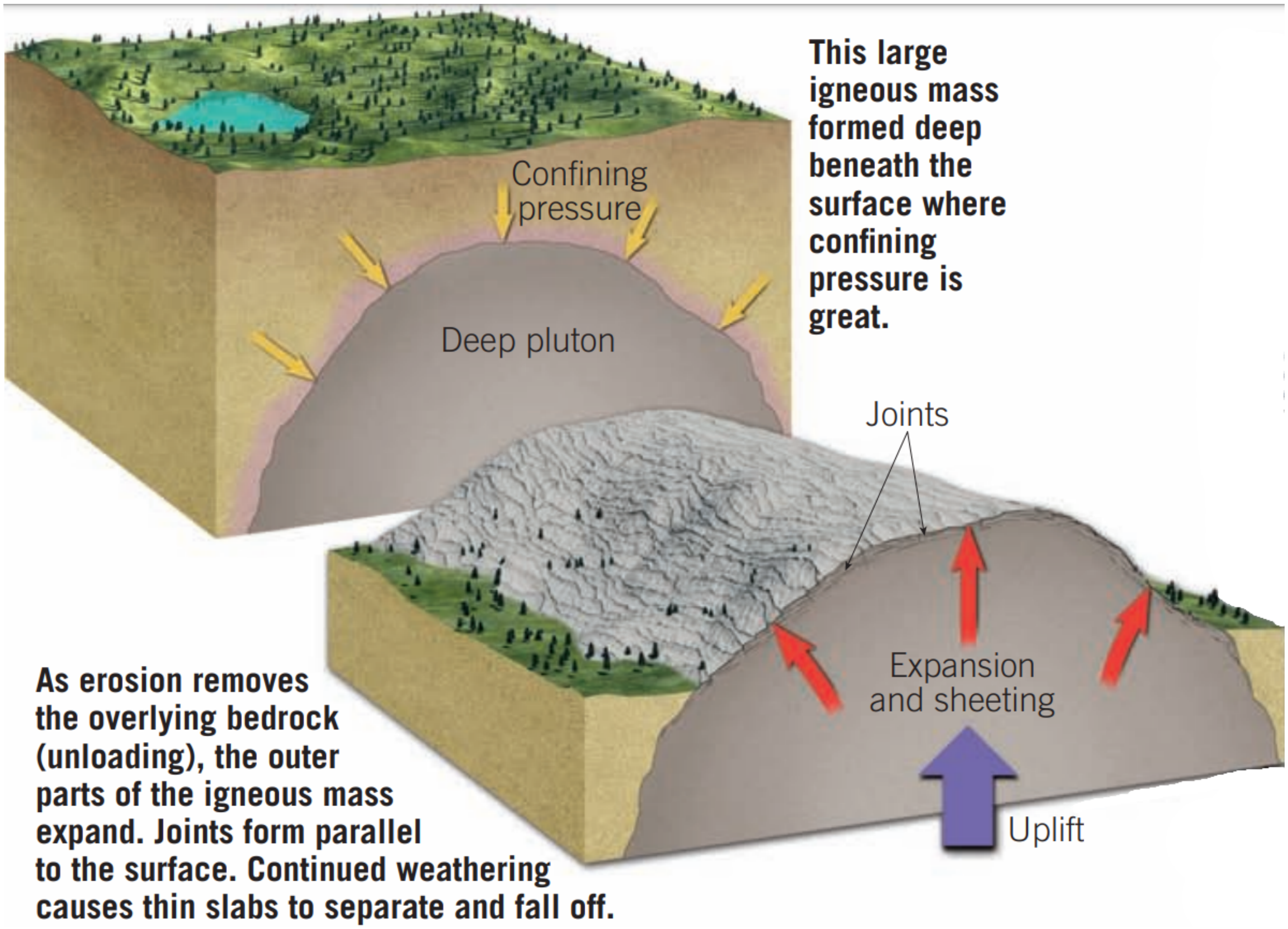


Figure 4: Sheeting of a Pluton (Tarbuck, Edward J. Earth Science)

animals split rock. Biological processes produce acids that, along with decaying material, can enter such cavities and expose rocks to chemical attack.

2.2 Chemical Weathering

- Chemical weathering occurs primarily through acids carried in water. However, biological acids contribute to this form of weathering as mentioned above.
- As water reacts with carbon dioxide in the atmosphere, it produces **carbonic acid** through the following reaction:

$$H_2O + CO_2 \longrightarrow H_2CO_3$$

- Carbonate rocks such as limestone varieties and dolostone are weakly effervescent (they will react) in carbonic acid, leading to weathering.
- Silicates in igneous rocks can also be weathered by carbonic acid, although they will not effervesce. An example of this is the weathering of plagioclase feldspar, the most common crust mineral, shown by the following reaction:

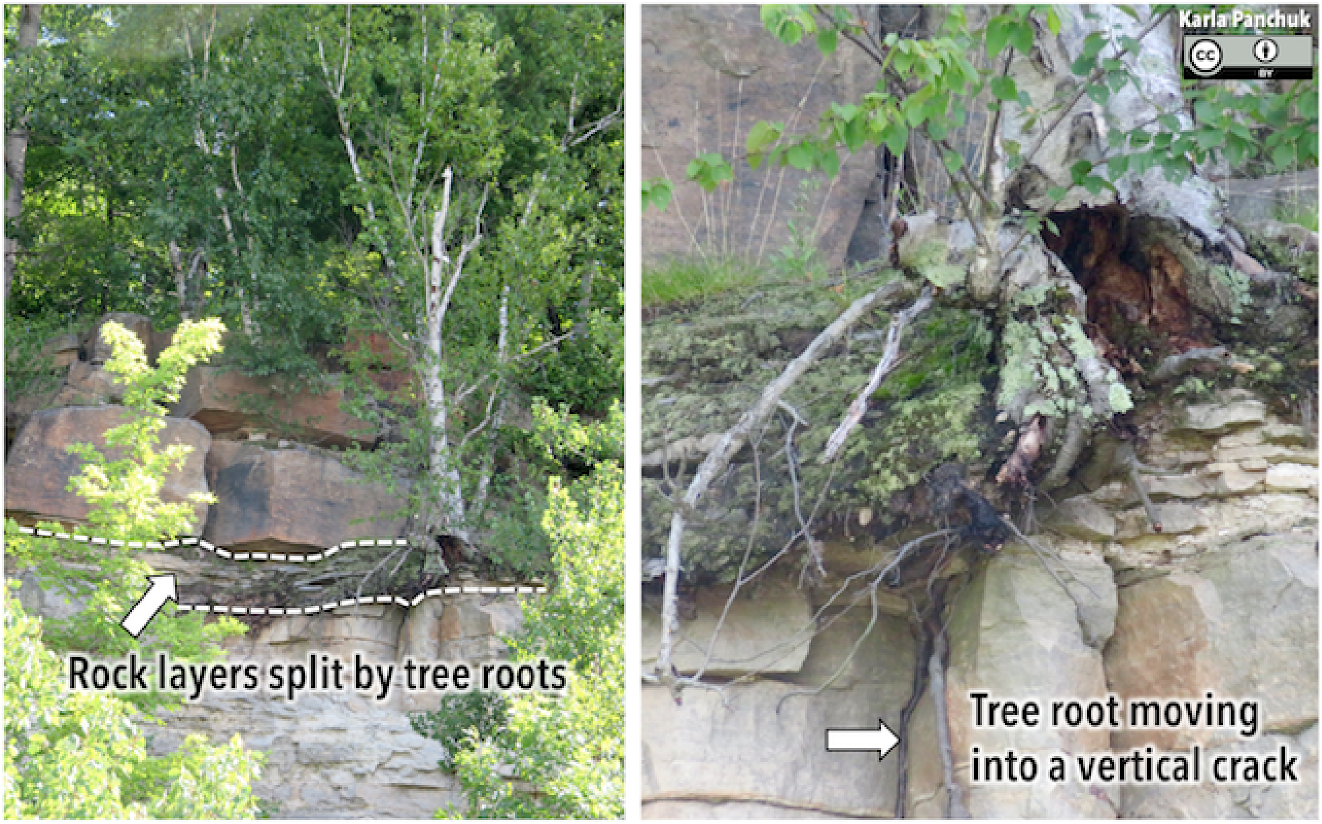


Figure 5: An example of root wedging in exposed strata

Example Felsic Mineral Hydrolysis (Feldspar) $2\,CaAl_2Si_2O_8 + 2\,H_2CO_3 + O_2 \longrightarrow 2\,Al_2Si_2O_5(OH)_4 + 2\,Ca^{2+} + 2\,{CO_3}^{2-}$ Example Mafic Mineral Hydrolysis (Olivine) $Fe_2SiO_4 + 4\,H_2CO_3\ + 4\,HCO_3 + H_4SiO_4$ Note: this weathering can also lead to the creation of other minerals like hematite from basalt weathering $2\,Fe^{2+} +\ + 2\,H_2O + 4\,HCO_3 + 4\,H_2CO_3$

- As shown by the above reaction, the weathering of silicates like feldspar through hydrolysis results in the creation of clay minerals such as kaolinite, along with dissolved ions. These ions are carried away by water and supplement soil or are carried into waterways. Carbonate ion and calcium ions produced by chemical weathering can result in the creation of new calcite.

2.2.1 Carbonate - Silicate cycle

The carbonate silicate cycle is also known as the inorganic carbon cycle, and it describes the long-term transformation of silicate rocks to carbonate rocks by weathering and sedimentation, and the transformation of carbonate rocks back into silicate rocks by metamorphism and volcanism.

- The cycle is the primary control on carbon dioxide levels over long timescales, as it regulates the balance between atmospheric carbon dioxide and dissolved carbon in the oceans.
- The cycle involves several physical and chemical processes, such as:

  - Carbonic acid formation: Rainwater and gaseous carbon dioxide react to form carbonic acid, a weak acid that can dissolve silicate and carbonate rocks.
  - Silicate weathering: Carbonic acid reacts with silicate minerals, such as calcium silicate, to produce dissolved ions, such as calcium and bicarbonate, and dissolved silica. This process removes carbon dioxide from the atmosphere and transfers it to the oceans.
  - Carbonate precipitation: Dissolved calcium and bicarbonate ions combine to form calcium carbonate, a solid mineral that can precipitate out of seawater or be incorporated into the shells and skeletons of marine organisms, such as corals and foraminifera. This process sequesters carbon in the form of carbonate rocks or biogenic sediments.
  - Subduction and metamorphism: Carbonate rocks or biogenic sediments can be subducted into the mantle along with oceanic crust at convergent plate boundaries. Under high pressure and temperature, they undergo metamorphic reactions that release carbon dioxide and water back into the mantle or the atmosphere through volcanism.

- The cycle is influenced by several factors that affect the rate of weathering, precipitation, subduction, and volcanism, such as:
  - Sea level: Changes in sea level can expose or submerge more land area, affecting the amount of silicate rocks available for weathering and the amount of carbonate rocks available for subduction.
  - Topography: Changes in topography can alter the erosion rate, runoff rate, and surface area of silicate rocks, affecting their weathering rate and the transport of dissolved ions to the oceans.
  - Lithology: The composition and structure of silicate rocks can affect their susceptibility to weathering and their dissolution rate. For example, basaltic rocks are more easily weathered than granitic rocks.
  - Vegetation: Plants can enhance silicate weathering by producing organic acids, increasing soil acidity, increasing root penetration, increasing water retention, and reducing erosion. Plants can also reduce atmospheric carbon dioxide by photosynthesis.
  - Solar forcing: Changes in solar radiation can affect the global temperature, which can affect the solubility of carbon dioxide in seawater, the rate of photosynthesis by marine organisms, and the rate of volcanism by thermal expansion or contraction of the crust.

Example (2022 USESO Geosphere Exam, Section II, #1)

While uncommon, wollastonite ($CaSiO_3$) is a simple mineral that exemplifies a pattern of silicate weathering. The chemical equation for this weathering is as follows:

$$2\,H_2O + CO_2 + CaSiO_3 \longrightarrow 2\,HCO_3{}^- + Ca^{2+} + SiO_2$$

(A) The carbon produced from silicate weathering is transported into the ocean. Marine organisms cannot use the bicarbonate produced directly from weathering, yet are able to incorporate the carbon into calcium carbonate. What chemical change must bicarbonate undergo?

(B) A significant amount of carbon dioxide enters the ocean where it reacts with water to form carbonic acid (H_2CO_3). How might an increase in carbonic acid inhibit the reaction that forms calcium carbonate as described in part (A)?

Solution A: Organisms can only use carbonate (${CO_3}^{2-}$), not bicarbonate (HCO_3) to create calcium carbonate ($CaCO_3$). For bicarbonate to become carbonate, an H^+ ion needs to be removed.

Solution B: Carbonic acid increases ocean acidity, therefore increasing the concentration of H^+. This means that bicarbonate is less likely to lose an H^+ ion since the conditions of equilibrium are less favorable, preventing the formation of carbonate and therefore, calcium carbonate.

2.2.2 Why do minerals change?

- Minerals change depending on their environment because certain environments will be more favorable kinetically, chemically, or thermodynamically for chemical reactions. Different environments may also introduce new reactants such as acids to minerals, leading to unique changes.
- The reason clay is formed is because in comparison to the reacting silicates, clay minerals are far more stable on Earth's surface. Likewise, the weathering of silicates is determined primarily by their formation environment. Materials higher on the Bowen's reaction series like olivine and pyroxene are formed at conditions extremely different to those on Earth's surface. Therefore, they will more readily weather.
- On the other hand, quartz is extremely resistant to weathering and does not react with carbonic acid. As silicates around quartz grains weather, the quartz is released from their constituent rocks. This quartz can be left behind in soil or transported away by water. This is the primary method by which sand is formed.
- Weathered silicates will be visibly less glassy-looking and have clay minerals on their surface. Chemical weathering also occurs through oxidation.
- Minerals lower on Bowen's reaction series are more stable than minerals higher on the series. This is because minerals lower on the series have a higher proportion of silicon and oxygen in their structure, which makes them more resistant to chemical weathering than minerals higher on the series. The minerals that form at the cooler end of the discontinuous series are richer in silicon and oxygen and poorer in metal cations. Therefore, the minerals at the cooler end are also more dominated by covalent bonds over ionic bonds

Example (2021 USESO Open Exam, Section I, #25)

A geologist encounters a large granite outcrop and examines the various minerals included in the matrix. When the geologist visits the outcrop much later, which of the following minerals would have weathered the most since her previous visit?

(A) Quartz (B) Orthoclase Feldspar (C) Biotite

(D) Muscovite (E) All of the minerals would have weathered the same amount

Solution: C. Relative to all other options, biotite is ranked the highest on Bowen's reaction series, meaning it formed at temperatures and conditions most different to those on Earth's surface. This makes it weather more readily than stable minerals like quartz.

2.3 Rates of Weathering

- Rocks do not weather evenly on all their surfaces. As the composition of rocks varies, so do their rates of weathering. As previously mentioned, some rocks like limestone will readily weather in weak acids while other rocks are more resistant to wear. This can cause unusual structures to form on the surface where remnants of weathered rock form pillars, stacks, or other phenomena.
- As rocks fracture and split, more surface area is exposed to the elements. Fragmented rocks will weather much more rapidly than solid rocks for this reason. Weathering will follow the lines of least resistance for this reason, meaning they will follow structures like joints and connected pores.

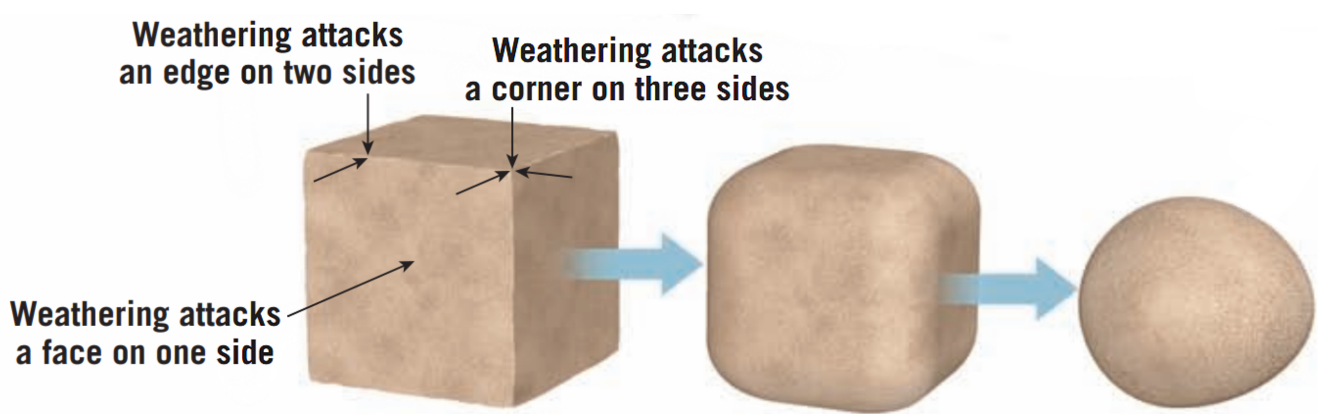


Figure 6: Spheroidal Weathering (Tarbuck, Edward J. Earth Science)

- Rocks do not weather at the same rate on different surfaces. On edges, rocks can be weathered from two faces. On corners, they are exposed on three faces. This causes angled pieces to gradually smooth, approaching the shape of a sphere, in a process aptly named **spheroidal weathering**.

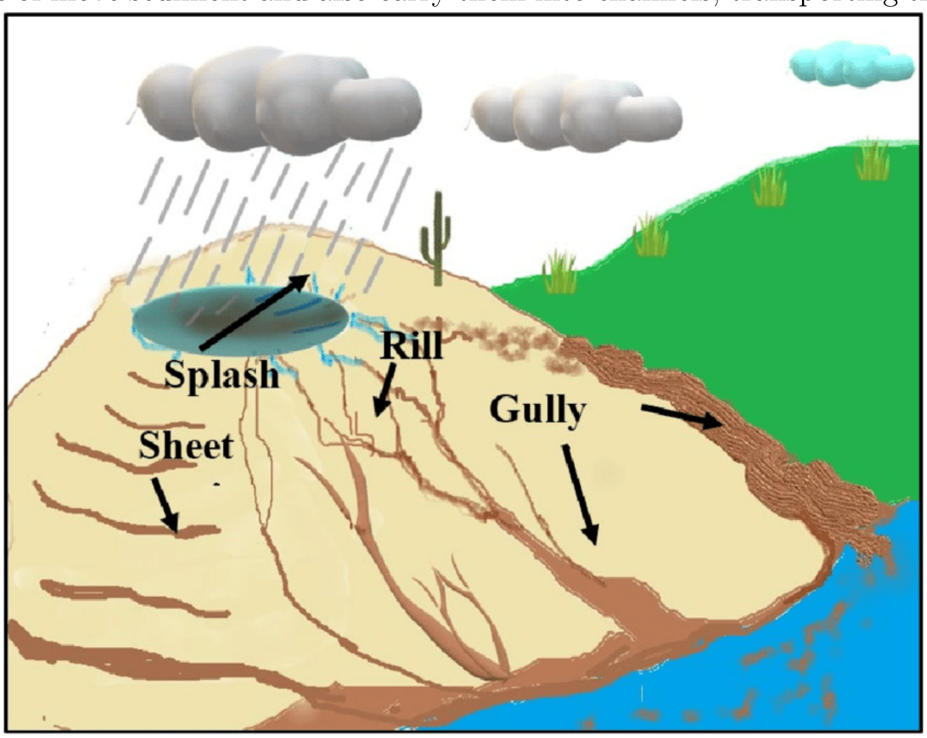
3 Erosion

Erosion is the process by which broken material is transported away. This transport occurs primarily by water, and to a lesser degree, by wind and glaciers.

3.1 Water Erosion

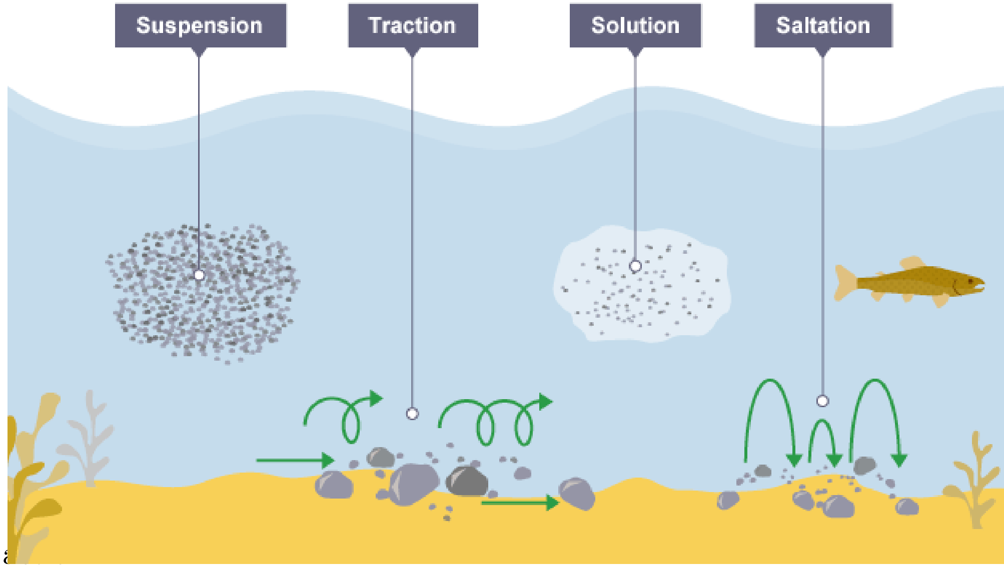
Erosion is mainly caused anywhere there is running water. On exposed surfaces, erosion takes place during precipitation events and occurs through the following methods: splash, sheet, rill, and gully erosion.

- **Splash erosion** refers to the displacement of soil by the impact of raindrops. Rain falls with enough force to lightly crater soil and dislodge it, making it more susceptible to further removal.
- **Rill erosion** is the removal of soil through small channels called rills. Rainwater flows into these channels and carries sediment with it, removing them further from their source.
- **Gully erosion** is extremely similar to rill erosion. Gullies can be thought of as larger channels fed by several rills. Like rills, they carry sediments away from their source.
- **Sheet erosion** refers to erosion by sheets of water flowing over the surface. This occurs when infiltration cannot accommodate all of the water, causing a sheet of runoff to form. These sheets of move sediment and also carry them into channels, transporting them further.



A diagram of the different types of soil erosion by water

Erosion occurs more noticeably through the action of streams, forming extensive floodplains of eroded sediment. Erosion occurs here through the following methods: attrition, abrasion, solution,



and hydraulic a

- **Attrition** refers to the grinding of material in streams from suspended sediments. As the stream carries particles, these particles erode each other through collisions, becoming smaller over time.
- **Abrasion** refers to the scouring of the stream bed by its bedload. When sediment runs over bedrock, it scrapes and smooths it down, eroding the stream bed.
- **Solution** refers to the dissolution of alkaline material. As previously mentioned, water carries a slight concentration of dissolved acids such as carbonic acid, causing rocks like limestone to weakly react. These reactions weaken and erode beds.
- **Hydraulic action** refers to erosion caused by the force of moving water. When water strikes beds or banks, air becomes trapped in fractures, enlarging cracks and promoting erosion.

3.2 Other Types of Erosion

- Wind erosion plays a minor role in erosion. Its effects are only marginal in comparison to water. However, the force of wind along with suspended particles can cause erosion after sustained periods. Changes from this type of erosion will be most noticeable when the surrounding rocks are weak or soft.
- Glaciers also cause a significant transport of sediments. As glaciers move, they drag tons of sediment along their bases. This sediment can be transported even further when the glacier begins to melt, washing out its carried material into floodplains and rivers.

3.3 Factors of Erosion

- Since erosion happens mainly by water, any process increasing precipitation or runoff will directly increase the rates of erosion. For example, climate change causes more extreme precipitation events to occur, increasing the rates of erosion. Urbanized locations with low ground permeability also promote more runoff, increasing sheet erosion.

- The topography of an area also may increase its susceptibility to erosion. For example, slopes will have shallower soils since they are more susceptible to erosion by gravity.
- The presence of plant life is extremely important to slowing erosion. Plant roots bind soil together and prevent it from being eroded. This causes arid regions with little vegetation such as deserts to be extremely prone to erosion since there is little in the way to hold material together.

4 Soil

4.1 Soil formation

Soil formation, also known as pedogenesis, is the process of soil genesis as regulated by the effects of place, environment, and history. It involves five fundamental factors: parent material, climate, topography, organisms, and time.

- Parent material is the initial state of the solid matter making up a soil. It can consist of consolidated rocks or unconsolidated deposits such as volcanic ash, glacial tills, or organic matter. Parent materials influence soil formation through their mineralogical composition, their texture, and their stratification. For example, dark-coloured rocks can produce soils with a high content of iron and clay minerals, while light-coloured rocks can produce soils that are low in iron and contain different clay minerals.
- Climate affects soil formation by influencing the rate of weathering, the amount and distribution of precipitation, the temperature regime, and the type and activity of soil organisms. Climate also determines the vegetation cover and the type of organic matter added to the soil. For example, warm and humid climates can accelerate weathering and leaching, resulting in acidic and infertile soils, while cold and dry climates can slow down weathering and leaching, resulting in alkaline and fertile soils.
- Topography or relief refers to the shape and slope of the land surface. It affects soil formation by influencing the drainage, erosion, deposition, and exposure to sunlight and wind. Topography also creates local variations in climate and vegetation. For example, steep slopes can enhance erosion and drainage, leading to shallow and coarse-textured soils, while gentle slopes can favour deposition and water retention, leading to deep and fine-textured soils.
- Organisms include plants, animals, microorganisms, and humans that affect soil formation. Plants contribute organic matter and nutrients to the soil through their roots and litter. Animals mix and redistribute the soil through their burrowing and grazing activities. Microorganisms decompose organic matter and release carbon dioxide, water, and nutrients. Humans alter soil formation by modifying the vegetation cover, cultivating the land, adding fertilizers and pesticides, and constructing buildings and roads. For example, grasses can increase the organic matter content and porosity of the soil, while trees can lower the pH and increase the acidity of the soil. Earthworms can improve the aeration and aggregation of the soil, while termites can create tunnels and mounds that affect the soil structure. Bacteria can fix nitrogen from the air and make it available to plants, while fungi can form symbiotic

associations with plant roots and enhance their nutrient uptake. Farmers can enrich or deplete the soil fertility by applying manure or harvesting crops, while urban developers can seal or compact the soil by paving roads or erecting buildings.

- Time is the duration of all the processes that lead to soil formation. The longer a soil has been forming, the more developed and differentiated it becomes. Soil formation is a continuous process that can take from a few years to thousands of years depending on the intensity of the factors and the type of parent material. For example, soils formed on recent volcanic ash can be young and poorly developed, while soils formed on ancient rocks can be old and well developed. Soils formed on river alluvium can be renewed periodically by flooding events, while soils formed on glacial tills can be stable for long periods of time.

4.2 Soil structure

Soil is a complex and dynamic natural resource that supports life on Earth. Soil has different layers, called horizons, that vary in their physical, chemical and biological properties. These horizons are the result of soil formation processes, such as weathering, leaching, accumulation and biological activity, that operate over long periods of time. The soil profile is the vertical sequence of horizons in a specific location. Soil profiles can differ greatly depending on the climate, vegetation, parent material and human activities of the area. The following is a summary of the structure of soil and its different horizons, based on at least 10 different sources.

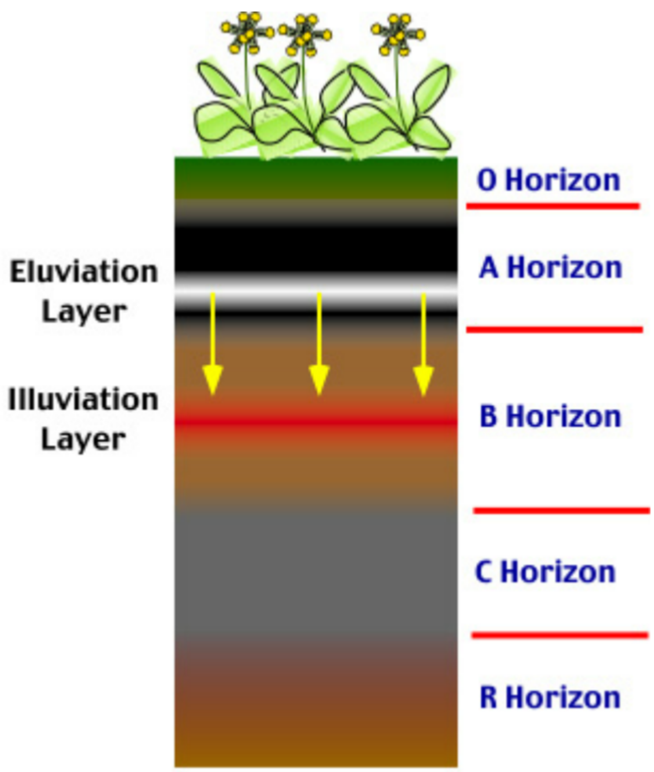
- The O horizon is the organic layer at or near the soil surface. It consists mainly of plant and animal residues, such as litter, humus, dung and bones, that are in various stages of decomposition. The O horizon is important for nutrient cycling, water retention and erosion control. It is usually found in forested or grassland areas, but may be absent or thin in cultivated or arid lands. The O horizon may be further divided into Oi, Oe and Oa subhorizons, depending on the degree of decomposition of the organic matter.

- The A horizon is the mineral layer at or near the soil surface that has been mixed with some organic matter. It is usually darker in color than the lower horizons due to the presence of humus. The A horizon is the zone of maximum biological activity, where most plant roots, microorganisms and soil animals are found. It is also the zone of maximum leaching, where water and dissolved substances move downward through the soil profile. The A horizon may lose clay, iron, aluminum and other minerals to the lower horizons, resulting in a process called eluviation.

- The E horizon is the mineral layer below the A horizon that has been leached of clay, iron, aluminum and other minerals, leaving behind a concentration of resistant minerals, such as quartz. The E horizon has a pale or bleached appearance due to the loss of color from these minerals. The E horizon is common in acidic soils under coniferous forests or heathlands, where organic acids enhance the leaching process. It may also form under grasslands or cultivated lands with high rainfall and low evaporation rates. The E horizon may be absent or indistinct in many soils.

- The B horizon is the mineral layer below the E horizon that has been enriched with clay, iron, aluminum and other minerals that have been translocated from the upper horizons by water. This process is called illuviation. The B horizon may also show evidence of other soil formation processes, such as accumulation of organic matter, carbonates, gypsum, silica or soluble salts; formation of hard or cemented layers; or alteration of color or structure by weathering. The B horizon is usually more dense and less permeable than the upper horizons. It may have various subhorizons depending on the type and degree of accumulation or alteration.

- The C horizon is the mineral layer below the B horizon that has not been significantly affected by soil formation processes. It consists mainly of unconsolidated or partially consolidated parent material from which the upper horizons have developed. The C horizon may show some evidence of weathering or biological activity, but less than the B horizon. The C horizon may have different textures and colors depending on the origin and composition of the parent material.
- The R horizon is the bedrock layer below the C horizon that is hard and consolidated. It may consist of igneous, metamorphic or sedimentary rocks that have not been weathered or broken down by soil formation processes. The R horizon may be exposed at the surface in some areas due to erosion or tectonic movements. The R horizon may influence the properties and development of the overlying soil horizons by providing parent material, water flow, or heat.



5 Mass Wasting

Mass wasting is a form of erosion caused by gravity affecting rock or unconsolidated sediments. It can be triggered after heavy precipitation or earthquakes, or result as a product of continued weathering.

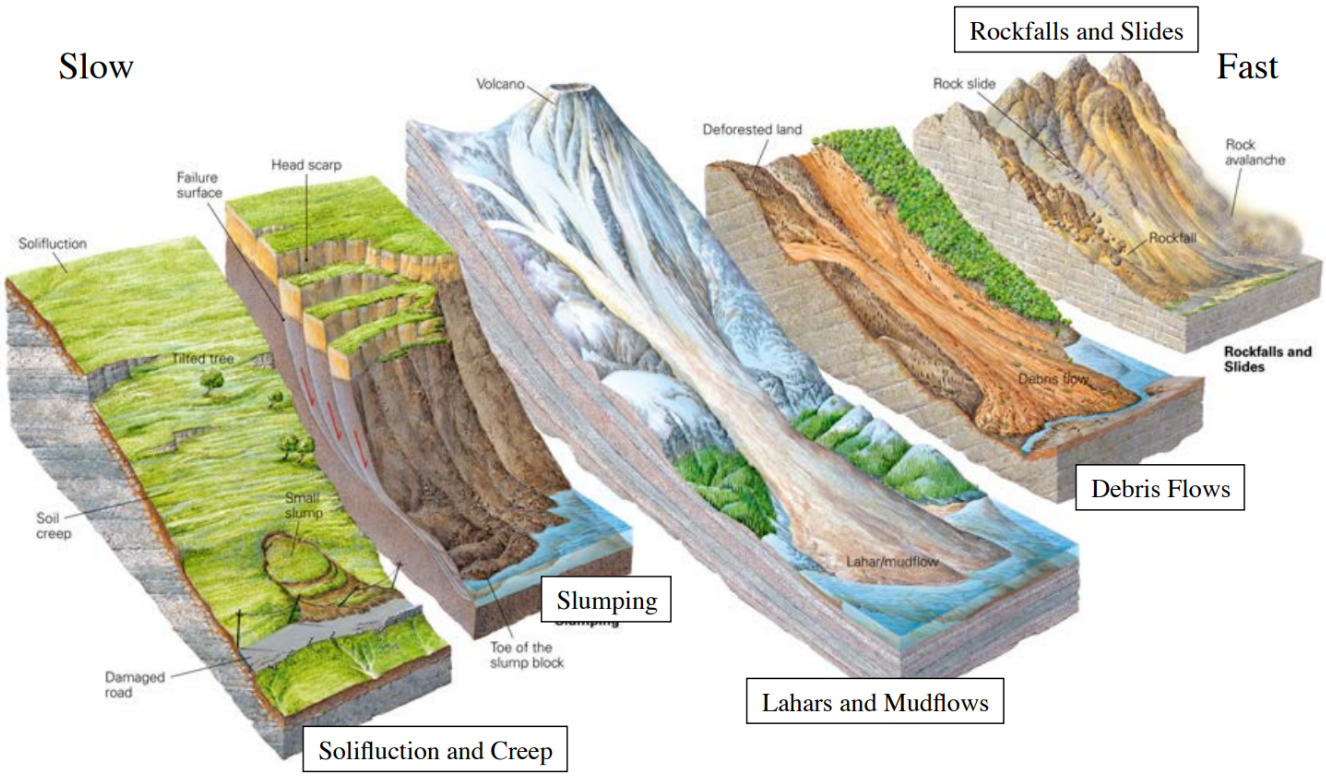


Figure 7: Mass Wasting Types (Marshak, Portrait of a Planet 5th Edition)

5.1 Causes of Mass Wasting

- Mass wastage can be caused after heavy precipitations saturate surface materials. This increases the material's weight and reduces its cohesion from friction. While a slight degree of saturation may increase cohesion of sediment, oversaturation causes it to flow.
- Since mass wasting is caused by gravity, steepening a slope makes it easier for mass wasting to occur. This can occur by stream action, wave action, or by human activities. The maximum angle material can remain stable is called the **angle of repose**. When this angle is exceeded, mass wasting occurs to return to the angle of repose. Smaller sediment has a lower angle of repose.
- As mass wasting is a form of erosion, the presence of plant life will also affect the stability of slopes threatened by mass wasting. Roots will bind and anchor surface material to bedrock, preventing mass wasting from occurring.

5.2 Rapid Wastage

The rates of mass wasting vary on the type of waste and suspended particles can cause erosion after sustained periodside, debris flow, and earthflow.

- **Slump** refers to the downslope movement of material along a curved surface. Slump typically occurs because of steep slopes in which material at the base of the slope gives way and allows the rest of the slope to move downwards.

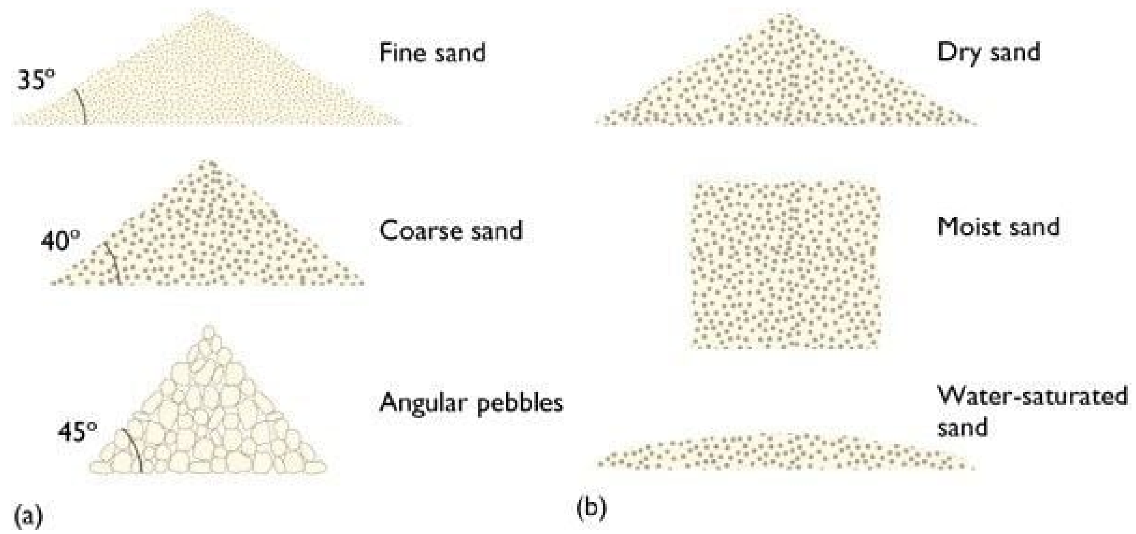


Figure 8: An illustration of different angles of repose for different materials

- **Slides** are events in which parts of the slope are completely separated from their base and fall down a slope. The specific name of the slide depends on the material that fell. For example, falling bedrock is termed a rock slide while falling soil is termed a debris slide. Rockslides are common where jointing is prevalent.
- **Debris flows** refer to the flow of soil that contains a large volume of water. They can sometimes be called mudflows when lacking larger sediments and typically occur in mountains. Arid regions have optimal conditions for making debris flows since the lack of vegetation allows for material to easily erode and coagulate together. This also means debris flows form in channels. These flows have significant force, pushing and crushing obstacles in their path.
- A type of debris flow formed on the slopes of volcanoes is a **lahar**. A lahar is made of mainly volcanic ash and other regolith materials.
- **Earthflows** are visually similar to debris flows. However, instead of in channels, earthflows form on hills. Furthermore, where debris flows typically form in drier areas, earthflows occur in humid places. They can occur rapidly during earthquakes because of liquefaction, where ground materials lose their cohesion because of shaking.
- Mass wasting also occurs in the ocean through turbidity currents. Along the continental shelf, unstable material can break off and cleave the continental slope, accumulating on the abyssal plain and adding to the continental rise. The sediment deposited from these flows and can be lithified into turbidites.

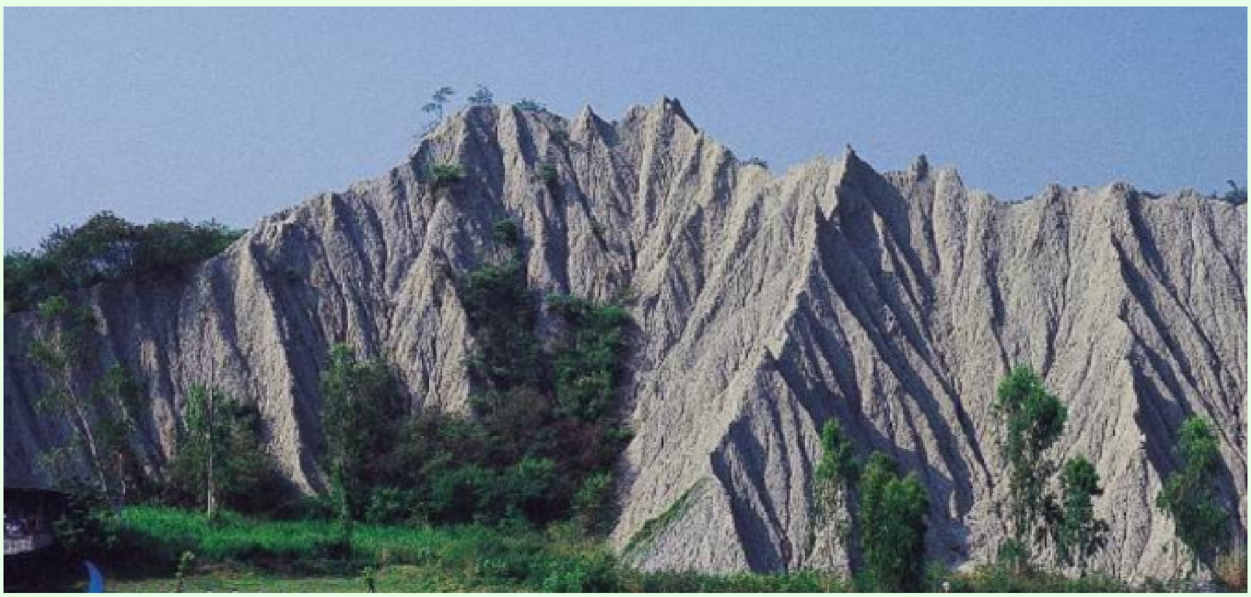
5.3 Slow Wastage

Mass wasting can also happen slowly over years rather than in single events. Two types of slow mass wasting are as follows: creep and solifluction.

- **Creep** refers to the slow movement of material over time. Thermal expansion and contraction by changing seasons is the main cause, sped up by soil saturation and biological disturbances.
- **Solifluction** refers to the slow movement of saturated material downhill. Solifluction frequently occurs in areas of low ground permeability, trapping water in the surface layer.

Example (2009 IESO Written Test, #38)

The figure below shows the typical hill slopes developed on a massive mudstone bedrock. Two major processes could have contributed to erosion in this area and one of them is sheet wash. Please identify the other major process.



(A) Debris Flow (B) Rockfall (C) Rill Erosion

(D) Channel Cutoff (E) River Bank Erosion

Solution: C. When looking at the hillslope, there are clear lines in which rill-like channels are present. Some other clues to this answer would be the presence of standing vegetation, the lack of a present stream, the fact that mudstone is impermeable which leads to runoff, and the fact that sheet wash is another form of runoff.

6 Closing

Most of the processes covered in this handout are pretty similar and can be hard to memorize individually. Take it slow, try to understand the concepts and causes first. Hope this guide is helpful to your studying!

6.1 Further Resources

A great place to explore further is by reading the most recent versions of either *Earth Science* by Edward J. Tarbuck, Frederick K. Lutgens or *Earth: Portrait of a Planet* by Stephen Marshak, or *Open Geology*: https://opengeology.org/textbook/5-weathering-erosion-and-sedimentary-rocks/.