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Earth's Dynamic Systems: Erosion

The Sculpting of Earth's Surface

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Introduction

Erosion is the quiet machinery of the planet's surface: the set of processes — flowing water, wind, ice, gravity, and the sea — that wear rock and soil away from one place and carry it somewhere else. Its partner is deposition, the arrival of that same material downstream, downhill, or down-current. Together the pair reshape every landscape on Earth, from the V-shaped young valleys of steep mountains to the slow subsidence of river deltas. Two contrasts organize the whole subject. Weathering breaks rock in place; erosion carries the pieces away — a distinction that sounds trivial until you realize the transport is what sculpts landforms.

And natural erosion has a human-amplified twin: agriculture, deforestation, roads and urban sprawl have multiplied soil-erosion rates many times over their geological baseline, which is why soil is now treated as a finite, mismanaged resource rather than a given. This book follows the subject in the order it grew. Early chapters cover the recognition of erosion as a process, from the first disputes over how valleys form to the Dust Bowl's hard demonstration of what plow and drought can do together. The middle chapters lay out the mechanics — how raindrops detach soil, how rills become gullies, how coasts, glaciers and gravity each take their turn, and how vegetation holds the system together.

Later chapters take up measurement and prediction (the universal soil loss equation and its descendants), the engineering and land-use practices that limit erosion, and what a changing climate and a rising sea are doing to the rates.

Chapter 1: The Discovery of Erosion

Water and wind erosion are the two primary causes of land degradation; combined, they are responsible for about 84% of the global extent of degraded land, making excessive erosion one of the most significant environmental problems worldwide. Intensive agriculture, deforestation, roads, anthropogenic climate change and urban sprawl are amongst the most significant human activities in regard to their effect on stimulating erosion.

However, there are many prevention and remediation practices that can curtail or limit erosion of vulnerable soils. Rainfall, and the surface runoff which may result from rainfall, produces four main types of soil erosion: splash erosion, sheet erosion, rill erosion, and gully erosion. Splash erosion is generally seen as the first and least severe stage in the soil erosion process, which is followed by sheet erosion, then rill erosion and finally gully erosion (the most severe of the four).

In splash erosion, the impact of a falling raindrop creates a small crater in the soil, ejecting soil particles. The distance these soil particles travel can be as much as 0.6 m (2.0 ft) vertically and 1.5 m (4.9 ft) horizontally on level ground. If the soil is saturated, or if the rainfall rate is greater than the rate at which water can infiltrate into the soil, surface runoff occurs.

If the runoff has sufficient flow energy, it will transport loosened soil particles (sediment) down the slope. Sheet erosion is the transport of loosened soil particles by overland flow. Rill erosion refers to the development of small, ephemeral concentrated flow paths which function as both sediment source and sediment delivery systems for erosion on hillslopes. Generally, where water erosion rates on disturbed upland areas are greatest, rills are active.

Flow depths in rills are typically of the order of a few centimetres (about an inch) or less and along-channel slopes may be quite steep. This means that rills exhibit hydraulic physics very different from water flowing through the deeper, wider channels of streams and rivers. Gully erosion occurs when runoff water accumulates and rapidly flows in narrow channels during or immediately after heavy rains or melting snow, removing soil to a considerable depth.

A gully is distinguished from a rill based on a critical cross-sectional area of at least one square foot (roughly 0.1 square metre). Extreme gully erosion can progress to formation of badlands. These form under conditions of high relief on easily eroded bedrock in climates favorable to erosion. Conditions or disturbances that limit the growth of protective vegetation (rhexistasy) are a key element of badland formation.

Valley or stream erosion occurs with continued water flow along a linear feature. The erosion is both downward, deepening the valley, and headward, extending the valley into the hillside, creating head cuts and steep banks. In the earliest stage of stream erosion, the erosive activity is dominantly vertical, the valleys have a typical V-shaped cross-section and the stream gradient is relatively steep. When some base level is reached, the erosive activity switches to lateral erosion, which widens the valley floor and creates a narrow floodplain.

The stream gradient becomes nearly flat, and lateral deposition of sediments becomes important as the stream meanders across the valley floor. In all stages of stream erosion, by far the most erosion occurs during times of flood when more and faster-moving water is available to carry a larger sediment load. In such processes, it is not the water alone that erodes: suspended abrasive particles, pebbles, and boulders can also act erosively as they traverse a surface, in a process known as traction.

Bank erosion is the wearing away of the banks of a stream or river. This is distinguished from changes on the bed of the watercourse, which is referred to as scour. Erosion and changes in the form of river banks may be measured by inserting metal rods into the bank and marking the position of the bank surface along the rods at different times. Thermal erosion is the result of melting and weakening permafrost due to moving water.

It can occur both along rivers and at the coast. Rapid river channel migration observed in the Lena River of Siberia is due to thermal erosion, as these portions of the banks are composed of permafrost-cemented non-cohesive materials. Much of this erosion occurs as the weakened banks fail in large slumps. Thermal erosion also affects the Arctic coast, where wave action and near-shore temperatures combine to undercut permafrost bluffs along the shoreline and cause them to fail.

Annual erosion rates along a 100-kilometre (62-mile) segment of the Beaufort Sea shoreline averaged 5.6 metres (18 feet) per year from 1955 to 2002. Most river erosion happens nearer to the mouth of a river. On a river bend, the longest least sharp side has slower moving water. Here deposits build up. On the narrowest sharpest side of the bend, there is faster moving water so this side tends to erode away mostly.

Rapid erosion by a large river can remove enough sediments to produce a river anticline, as isostatic rebound raises rock beds unburdened by erosion of overlying beds. Shoreline erosion, which occurs on both exposed and sheltered coasts, primarily occurs through the action of currents and waves but sea level (tidal) change can also play a role. Hydraulic action takes place when the air in

a joint is suddenly compressed by a wave closing the entrance of the joint. This then cracks it.

On-site impacts include decreases in agricultural productivity and (on natural landscapes) ecological collapse, both because of loss of the nutrient-rich upper soil layers. In some cases, this leads to desertification. Off-site effects include sedimentation of waterways and eutrophication of water bodies, as well as sediment-related damage to roads and houses.

Wave pounding is when the sheer energy of the wave hitting the cliff or rock breaks pieces off. Abrasion or corrasion is caused by waves launching sea load at the cliff. It is the most effective and rapid form of shoreline erosion (not to be confused with corrosion). Corrosion is the dissolving of rock by carbonic acid in sea water. Limestone cliffs are particularly vulnerable to this kind of erosion.

Attrition is where particles/sea load carried by the waves are worn down as they hit each other and the cliffs. This then makes the material easier to wash away. The material ends up as shingle and sand. Another significant source of erosion, particularly on carbonate coastlines, is boring, scraping and grinding of organisms, a process termed bioerosion. Sediment is transported along the coast in the direction of the prevailing current (longshore drift).

When the upcurrent supply of sediment is less than the amount being carried away, erosion occurs. When the upcurrent amount of sediment is greater, sand or gravel banks will tend to form as a result of deposition. These banks may slowly migrate with the longshore current over time, alternately protecting and exposing parts of the coastline. Where there is a bend in the coastline, quite often a buildup of eroded material occurs forming a long narrow bank (a spit).

Armoured beaches and submerged offshore sandbanks may also protect parts of a coastline from erosion. Over the years, as the shoals gradually shift, the erosion may be redirected to attack different parts of the shore. Erosion of a coastal surface, followed by a fall in sea level, can produce a distinctive landform called a raised beach. Chemical erosion is the loss of matter in a landscape in the form of solutes. Chemical erosion is usually calculated from the solutes found in streams.

Anders Rapp pioneered the study of chemical erosion in his work about Kärkevagge published in 1960. Formation of sinkholes and other features of karst topography is an example of extreme chemical erosion. Glaciers erode predominantly by three different processes: abrasion/scouring, plucking, and ice thrusting. In an abrasion process, debris in the basal ice scrapes along the bed, polishing and gouging the underlying rocks, similar to sandpaper on

wood.

Scientists have shown that, in addition to the role of temperature played in valley-deepening, other glaciological processes, such as erosion also control cross-valley variations. In a homogeneous bedrock erosion pattern, curved channel cross-section beneath the ice is created. Though the glacier continues to incise vertically, the shape of the channel beneath the ice eventually remain constant, reaching a U- shaped parabolic steady-state shape as we now see in glaciated valleys.

Scientists also provide a numerical estimate of the time required for the ultimate formation of a steady-shaped U-shaped valley—approximately 100,000 years. In a weak bedrock (containing material more erodible than the surrounding rocks) erosion pattern, on the contrary, the amount of over deepening is limited because ice velocities and erosion rates are reduced.

Glaciers can also cause pieces of bedrock to crack off in the process of plucking.

In ice thrusting, the glacier freezes to its bed, then as it surges forward, it moves large sheets of frozen sediment at the base along with the glacier. This method produced some of the many thousands of lake basins that dot the edge of the Canadian Shield. Differences in the height of mountain ranges are not only being the result tectonic forces, such as rock uplift, but also local climate variations.

Scientists use global analysis of topography to show that glacial erosion controls the maximum height of mountains, as the relief between mountain peaks and the snow line are generally confined to altitudes less than 1500 m. The erosion caused by glaciers worldwide erodes mountains so effectively that the term glacial buzzsaw has become widely used, which describes the limiting effect of glaciers on the height of mountain ranges.

As mountains grow higher, they generally allow for more glacial activity (especially in the accumulation zone above the glacial equilibrium line altitude), which causes increased rates of erosion of the mountain, decreasing mass faster than isostatic rebound can add to the mountain. This provides a good example of a negative feedback loop. Ongoing research is showing that while glaciers tend to decrease mountain size, in some areas, glaciers can actually reduce the rate of erosion, acting as a glacial armor.

Ice can not only erode mountains but also protect them from erosion. Depending on glacier regime, even steep alpine lands can be preserved through time with the help of ice. Scientists have proved this theory by sampling eight summits of northwestern Svalbard using Be10 and Al26,

showing that northwestern Svalbard transformed from a glacier-erosion state under relatively mild glacial maxima temperature, to a glacier-armor state occupied by cold-based, protective ice during much colder glacial maxima temperatures as the Quaternary ice age progressed.

These processes, combined with erosion and transport by the water network beneath the glacier, leave behind glacial landforms such as moraines, drumlins, ground moraine (till), glaciokarst, kames, kame deltas, moulins, and glacial erratics in their wake, typically at the terminus or during glacier retreat. The best-developed glacial valley morphology appears to be restricted to landscapes with low rock uplift rates (less than or equal to 2mm per year) and high relief, leading to long-turnover times.

Interplay of glacial erosion and tectonic forcing governs the morphologic impact of glaciations on active orogens, by both influencing their height, and by altering the patterns of erosion during subsequent glacial periods via a link between rock uplift and valley cross-sectional shape. At extremely high flows, kolks, or vortices are formed by large volumes of rapidly rushing water.

Kolks cause extreme local erosion, plucking bedrock and creating pothole-type geographical features called rock-cut basins. Examples can be seen in the flood regions result from glacial Lake Missoula, which created the channeled scablands in the Columbia Basin region of eastern Washington. Wind erosion is a major geomorphological force, especially in arid and semi-arid regions.

It is also a major source of land degradation, evaporation, desertification, harmful airborne dust, and crop damage—especially after being increased far above natural rates by human activities such as deforestation, urbanization, and agriculture. Wind erosion is of two primary varieties: deflation, where the wind picks up and carries away loose particles; and abrasion, where surfaces are worn down as they are struck by airborne particles carried by wind.

Deflation is divided into three categories: (1) surface creep, where larger, heavier particles slide or roll along the ground; (2) saltation, where particles are lifted a short height into the air, and bounce and saltate across the surface of the soil; and (3) suspension, where very small and light particles are lifted into the air by the wind, and are often carried for long distances. Saltation is responsible for the majority (50-70%) of wind erosion, followed by suspension (30-40%), and then surface creep (5-25%).

Mass wasting is an important part of the erosional process and is often the first stage in the breakdown and transport of weathered materials in mountainous areas. It moves material from higher elevations to lower elevations where other eroding agents such as streams and glaciers can then pick up the

material and move it to even lower elevations. Mass-wasting processes are always occurring continuously on all slopes; some mass-wasting processes act very slowly; others occur very suddenly, often with disastrous results.

Foods such as fresh fruits, ketchup and pickled food in vinegar have been implicated in causing acid erosion. Frequency rather than total intake of acidic juices is seen as the greater factor in dental erosion; infants using feeding bottles containing fruit juices (especially when used as a comforter) are therefore at greater risk of acid erosion. Saliva acts as a buffer, regulating the pH when acidic drinks are ingested. Drinks vary in their resistance to the buffering effect of saliva.

Studies show that fruit juices are the most resistant to saliva's buffering effect, followed by, in order: fruit-based carbonated drinks and flavoured mineral waters, non-fruit-based carbonated drinks, sparkling mineral waters; mineral water being the least resistant. Because of this, fruit juices in particular may prolong the drop in pH levels. A number of medications such as chewable vitamin C, aspirin and some iron preparations are acidic and may contribute towards acid erosion.

Certain drugs can cause hyposalivation (low quantity or quality of saliva) which is considered a risk factor for acid erosion. Intrinsic dental erosion, also known as perimolysis, is the process whereby gastric acid from the stomach comes into contact with the teeth. This is often secondary to conditions such as anorexia nervosa, bulimia nervosa, gastroesophageal reflux disease (GERD) and rumination syndrome. Dental erosion can also occur by non-extrinsic factors.

There is evidence linking eating disorders with a range of oral health problems including dental erosion, caries and xerostomia. Reduced salivary flow rate, a common symptom of bulimia, predisposes an individual to dental erosion due to increased vulnerability to the effects of acidic food and drinks. Self-induced vomiting increases the risk of dental erosion by a factor of 5.5 compared to healthy controls. Lesions are most commonly found on the palatal surfaces of the teeth, followed by the occlusal and then the buccal surfaces.

The main cause of GERD is increased acid production by the stomach. This is not exclusive to adults, as GERD and other gastrointestinal disorders may cause dental erosions in children. Acid erosion often coexists with abrasion and attrition. Abrasion is most often caused by brushing teeth too hard. Any frothing or swishing acidic drinks around the mouth before swallowing increases the risk of widespread acid erosion. Sucking citrus fruits can also contribute to acid erosion.

In-vivo studies are advantageous in assessing erosion directly from the patient's mouth. There are numerous signs of dental erosion, including changes in appearance and sensitivity. One of the physical changes can be the colour of teeth. Dental erosion can lead to two major tooth colour change - the first being a change of colour that usually happens on the cutting edge of the central incisors. This causes the cutting edge of the tooth to become transparent.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.