

Encyclopedia of Geography

Rock Weathering

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Weathering is the in situ alteration, by disintegration or decomposition, of rocks and minerals. By weathering, rocks and minerals reach a new equilibrium (chemical, pressure, and/or thermal) with the surface environment. Disintegration refers to the in situ mechanical production of smaller particles without chemical change, while decomposition refers to chemical alteration that results in both smaller particles as well as dissolved ions. Mechanical and chemical weathering are convenient subdivisions for discussion, though it is understood that the mechanical and chemical weathering processes are symbiotic and often inseparable.

Weathering is of vital importance to numerous Earth systems (and is therefore a subject for trans-disciplinary study). Weathering is one of several geomorphic processes, as weathering alone or in conjunction with other geomorphic processes is responsible for creating and modifying landforms. In petrology, weathering is a key function of the rock cycle, in which all the major rock types exposed on Earth's surface are ultimately vulnerable to weathering. Sediments, and sedimentary rock, could not exist without weathering first, and weathering is a primary means of recycling Earth materials. Soil is another feature that directly depends on weathering, as the mineral proportion of soil derives entirely from weathering by-products. Last, and of recent scientific attention, weathering is seen as an important function of biogeochemical cycles, as weathering is one of the true interfaces between all of Earth's geosystems (land, water, air, and life). Weathering plays a role in liberating or sequestering elements and in transferring these elements between biota, air, and water.

Types of Weathering

Mechanical Weathering

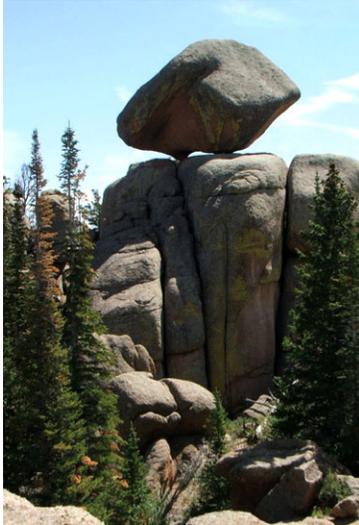
Mechanical weathering involves physical forces (compressive, tensile, and shear) that cause rocks and minerals to fracture (i.e., exceed the limit of plastic deformation). A number of physical forces are present in terrestrial environments.

Cryostatic pressure involves the compressive stress due to the expansion of water ice. Sometimes referred to in many writings as “frost” weathering, the process is not limited to the presence of frost crystals. Water ice is unique in its tendency to expand on the change of state from liquid to solid. Typically, liquid water works into the voids of existing rock weaknesses such as cracks, sutures, bedding, voids, or mineral or grain boundaries. In the confined spaces of the rock weakness, ice crystal growth exerts considerable pressure, forcing the rock or mineral apart. As the rock weakness void grows, confined pressures decrease, and the ability to continue cryostatic weathering decreases. Intense or prolonged stress will eventually completely separate the fragments. The products of cryostatic weathering are angular rock fragments, frequently observed in alpine, subarctic, and arctic regions.

Cryostatic pressures can be emphasized in environments with diurnal freeze-thaw cycles, in which ice crystal growth, melting, and regrowth allow repeated physical force. Freeze-thaw cycles are expected in temperate or midlatitude climates, though in polar areas rock surfaces exposed to sunlight can reach above-freezing temperatures even in winter. Cryostatic weathering is suspected on Mars in locations where water is or has been present.

Like ice, *expansion and growth of other crystals* in confined spaces also exerts compressive pressure to cause or enlarge fractures. Iron minerals, calcite, and expansive clays are examples of crystal growth weathering. However, salt (any of the alkaline minerals, including NaCl) is the chief and most common example cited and observed. Salt can enter the [p. 2478 ↓] rock or mineral by way of solution in water. As water evaporates, the salt is left behind and will expand as it crystallizes. Similar to ice, salt weathering will produce angular shards of by-product rock. Salt weathering is prevalent in arid and semiarid climates, where rapid evaporation is more apt to leave salt precipitates within the surface rocks rather than flushed by solution into deeper soil or ground-water. Salt weathering may be prevalent in polar deserts, where lack of liquid precipitation allows salts to accumulate at or near the surface. Thus, what is often assumed to be ice weathering may in fact be attributed to salt. Salt weathering is also seen in coastal areas, where sprays from waves can move inland up to several kilometers by way of atmospheric transport. Stone conservationists have noted salt weathering on building stones. Salt sources in urban areas include atmospheric aerosols, streets and sidewalks, and mortars.

A tor, near Crow Creek, southeastern Wyoming. Existing joints are widened by mechanical weathering such as ice, while chemical weathering results in disintegration and rounding. Lichens growing on much of the rock surface enhance chemical weathering. Erosion of weathered material leaves the spectacular remnant boulders.



Source: Courtesy of Jeffrey Pope

Hydrostatic pressure is exerted by thin water films in small pores and fractures. Almost always present even in dry environments, hydrostatic pressure may be responsible for prying apart microfractures in rock. Water microfilms can exist in the presence of subfreezing temperatures, such that liquid water may in fact be responsible for some of the weathering attributed to ice.

Rapid or extreme temperature changes are believed to create variations in the volume of rocks or minerals themselves. Rock expansion due to heating and rock contraction due to cooling may therefore exert compressive and tensile forces, respectively. There is some debate as to how much plastic deformation a rock will tolerate before fracture, thus a debate about how important temperature changes can be toward weathering. Still, most experts would agree that temperature changes have at least some impact. The critical factor pertains to diurnal temperature change. Diurnal ranges of 40°C

per day are not uncommon in deserts, while surface changes of 20°C per hour are possible in temperate continental climates. *Thermal* weathering is a term applied to environments of extreme heat, for instance, on dark rocks in tropical deserts or in proximity to fires. *Cryogenic* weathering pertains to environments of extreme cold.

Pressure unloading involves a volume adjustment of rocks formerly under considerable mass and pressure. Most rocks (apart from surface-cemented or solidified volcanic rock) are produced [p. 2479 ↓] deep in the crust under immense pressures. When erosion exposes these rocks to the surface, the atmosphere exerts pressure at #1/1,000,000th that of the crustal interior. Rock will then expand somewhat plastically to a point where a brittle fracture occurs. Unloading fractures tend to occur just below the rock surface and parallel or concentric to the surface. Slabs of rock millimeters to meters in thickness spall off (often aided by gravity and water). Landforms resulting from pressure unloading often appear dome shaped (e.g., Half Dome in Yosemite, Sugarloaf in Rio de Janeiro), with “onion” layers of slabs yet to fall.

Biomechanical processes of plant roots and animals are specialized weathering agents. A common image of tree roots attached to rock crevasses suggests the tenacity of plants and their ability to fragment rock. In reality, roots take advantage of preexisting fissures, and the physical pressure of root growth has been shown to be negligible except in soft and fragile rocks. Fine roots are known to expand and contract due to variable moisture content, and this may be a factor in mechanical weathering at smaller scales. Most likely, the very active chemical environment of roots contributes a synergistic weathering environment.

There are a few instances of weathering by animals. A species of desert-dwelling snails consume endolithic lichens and, in so doing, also consume parts of the rock substrate at appreciable rates. Species of bivalve mollusks are known to bore small holes into rock by a combination of chemical excretions and physical consumption of the mineral material. Other rock- and soil-dwelling animals (earthworms, insects, etc.) may similarly attack rocks by a combination of mechanical or chemical means, though the subject is poorly researched.

Chemical Weathering

Chemical weathering involves the decomposition of rocks and minerals at the elemental or molecular level by means of chemical reaction with exogenic weathering agents. Rather than attacking structural weaknesses as mechanical weathering does, chemical agents attack weak molecular bonds, removing elements to solution, consequently weakening the mineral and rock fabric. Chemical weathering therefore removes material in the form of ions and promotes further decomposition of rock by means of granular disintegration (between crystals or particles).

Solution, or congruent dissolution, is the simplest form of chemical weathering. It involves water in the complete solution of the mineral into aqueous ions without precipitation of secondary minerals in the solution process. Water is all that is necessary for solution weathering, though acids and organic chelates can greatly enhance the solution potential. Calcium carbonate (calcite), calcium sulfate (gypsum), and silica (quartz) are examples of minerals that are subject to solution weathering. of these, quartz is the least soluble by several orders of magnitude—a testament to its resistance, though not permanence, in the terrestrial environment.

Hydrolysis or incongruent dissolution is sometimes referred to as complexing, and rightly so. The complete process takes place in several steps with intermediate by-products and precipitates. Hydrolysis refers to the H^+ ion available in aqueous acids, carbonic acid being common in the terrestrial environment by way of naturally acidic rain, though organic acids are also important in soils and surface water, and sulfuric acid can be present near hydrothermal areas and in the presence of old mines (“acid mine drainage”). Polluted air in industrial and urban areas may contain both sulfuric and nitric acids, and acid precipitation may drift by prevailing winds into pristine regions. The weathering of aluminosilicate minerals (such as feldspars and micas), the most common in Earth's crust, is most apt to be from hydrolysis. The process yields dissolved cations (such as potassium, sodium, and calcium), silicic acid, silica precipitates, and clay minerals (such as kaolinite, illite, and smectite). High-resolution electron microscopy of minerals attacked by acid reveal incipient molecule-sized etch pits, while more extensive weathering results in a skeletal lattice of remnant mineral (see

photomicrograph image). An ultimate residual of aluminosilicate hydrolysis is aluminum oxide, Al

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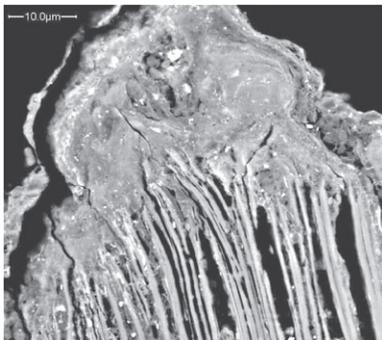
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, a stable mineral known as bauxite that is highly resistant to further weathering. Both bauxite and kaolinite are valuable economic minerals, the former for aluminum metal and the latter for a variety of ceramic, paper, and medicinal materials.

[p. 2480 ↓]

Photomicrograph, from backscatter scanning electron microscope, of a weathered biotite mineral, illustrating microscale chemical weathering. Hydrolysis dissolves and opens the crystal layers, while silica and dissolved rock varnish are seen infiltrating as precipitates near the mineral surface.



Source: Photomicrograph courtesy of Dr. Ronald Dorn, Arizona State University

Hydration is a relatively simple absorption of water molecules into the mineral, which disrupts the crystalline structure (and creates a new mineral). Hydration causes an increase in volume and mechanical pressure. Hydrated micas are partially responsible for granular disintegration of coarse-grained igneous and metamorphic rocks. Hydrated shrink-swell clays achieve similar stresses. Amorphous glass (e.g., silica glazes and obsidian) can also hydrate and decompose. *Dehydration* is the removal of water

molecules under hyperaridity or high temperatures (such as extreme wildfires). Dehydration leads to a collapse of the mineral structure and a decrease in volume.

Oxidation is a chemical process by which mineral ions are lost due to the introduction of an oxygen ion in the presence of water. Iron is the most common subject of oxidation, and iron-bearing minerals such as the amphiboles, pyroxenes, olivine, and biotite are vulnerable. Removal of Fe^{2+} (ferrous iron) combines with the oxygen ion to form Fe^{3+} (ferric iron), a much less soluble ion that precipitates easily. Resultant by-products of the reaction include hydrous and oxidized minerals of iron such as hematite, limonite, and goethite. Rocks containing iron-bearing minerals first exhibit reddish or brown halos around the minerals, while more complete oxidation can tint the entire rock (see rock weathering photo). Oxidized iron-rich cements account for the red color in many sandstones, and iron mineral residues are responsible for rubification in soils.

Chelation is a complex chemical process by which metallic ions are selectively removed in the presence of organic substances. Large organic acid molecules (such as ethylene diamine tetraacetic acid [EDTA] and amino acids) are examples of chelating agents and, unlike hydrolysis reactions, attach to the metallic ions through numerous (rather than single) bonds. Chelates, by way of decomposed organic material or within the roots of plants, aid in the release of nutrients to plants. Lichens are thought to have strong chelating agents, one factor that allows these pioneering symbiotic plants to use bare rock for sustenance. Lichens are responsible for the creation of incipient soils and soluble ions in environments that are lacking in other chemical weathering agents.

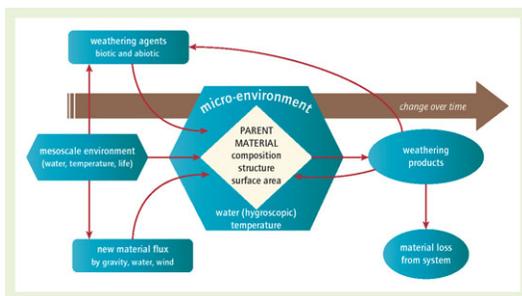
The Geography of Weathering and Weathering Factors

The extent and intensity of rock weathering is moderated by a number of factors ([Figure 1](#)). Many of these factors are highly geographic in nature; hence, weathering has a real variability from small to large scales.

Time, Scale, and the Geomorphic System

Weathering is among the slowest of geomorphic processes; considerable time elapses before significant modifications to the landscape occurs. Weathering over a given time produces a weathering rate. Rates of weathering vary considerably due to the availability of weathering agents, nature of the parent material, and environmental parameters, most relevant at small scales. Weathering is generally not a straight-line and constant process over time but more usually a decaying [p. 2481 ↓] rate over time until reaching an equilibrium state, consistent with any chemical and physical reaction. There are some instances where weathering rates may increase over shorter durations of time—for instance, when dissolution opens up greater surface area to attack, resulting in more and faster weathering. However, this also reaches an eventual equilibrium. Weathering rates are most likely to be polycyclic and metastable, not unlike most geomorphic systems.

Figure 1 Relationships of environmental and microscale factors relevant to the weathering system



Source: Author.

Weathering rates are well studied around the world as they give an indication of landscape evolution and environmental change. In some cases, weathering rates are so well established that they can reliably indicate elapsed time and hence can be used as a relative and occasionally calibrated numeric dating method. Examples of these applications include the width of stone weathering rinds (see granitic stone photo), the

diameter of tafoni and rock basins, and the proportional abundance of less weatherable minerals in sediments and soils. Most often, significant geomorphic modification is a synergistic combination of weathering with other geomorphic processes (the [p. 2482 ↓] combined process referred to as *denudation*). Erosion is capable of exerting larger landscape modifications when preconditioned by weathering, in which weathering weakens and softens the rock prior to erosion. Landscapes are sometimes referred to as “weathering limited,” meaning that the efficacy of erosion and transport is held back by slower rates of weathering, or “transport limited,” in which weathering is aggressive but erosion is not capable of keeping pace by removing the weathered material. Weathering and transport limits are frequently cited in support of tectonic and climatic models for landscape evolution, though relief, lithology, vegetation, and land use are equally relevant.

A granitic stone exhibiting a well-developed weathering rind. Orange tint is from oxidation; the rind itself is indurated with secondary silicate precipitates derived from hydrolysis. Width of the rind can be correlated to the exposure age.



Source: Photo by author; rock courtesy of M. Anderson

Tafoni, or honeycomb weathering, on a sandstone wall in arkosic sandstone near Cañon City, Colorado. Multiple weathering agents and factors include salts, water, microclimate, and petrology. Size and shape exhibit qualities of self-organization.



Source: Author

Landscapes dominated by weathering processes (but helped by other geomorphic processes) are some of the most dramatic on Earth. Examples include the deep regoliths of the Brazilian shield; the tower karst of Guilin, China; and remnant tors and inselbergs in Dartmoor (England), East Africa, and Australia. In mountainous landscapes, the work of weathering is less recognizable but still highly significant. Owing to the increased exposure of fresh, unaltered rock, new mountain ranges promote rapid weathering and the addition of a heavy solute load to the surrounding streams and rivers. Studies in the Rocky Mountains and Scandinavia attest to high levels of chemical weathering despite cooler temperatures. A recent (though contested) theory suggests that very active orogeny in the late Cenozoic Era (e.g., Himalayas) allowed increased chemical weathering and profligated an atmospheric drawdown of carbon dioxide, perhaps decreasing the greenhouse effect enough to trigger climate change. At smaller scales, weathering at focused points and with aggressive agents can cause significant modification over shorter time periods. These myriad small-scale

landforms reflect a diversity of interacting processes, type localities, and odd names—for instance, *gnammas* (rock basins), *tafoni* (honeycomb-like hollows), *karren* (solution channels), and *hoodoos* (rock pinnacles). Small-scale weathering forms are the product of differential weathering and erosion and sometimes exhibit process positive feedback as well as self-organized geometry (see tafoni photo).

[p. 2483 ↓]

Not limited to the natural environment, small-scale weathering is also a matter of concern in the case of buildings, and the processes and mitigation of damage in them are an important focus of research.

Petrology, Mineralogy, and Geologic Structure

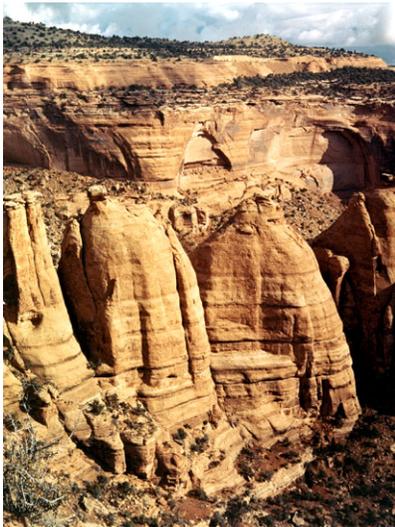
Weathering is easiest and proceeds fastest along rock and mineral weaknesses, these weaknesses being the product of rock and mineral formation and crustal stresses. Rock and mineral weakness is a factor across scales, from submicrometers to many kilometers. Minerals have a range in resistance to weathering owing to both crystal structure and composition. This attribute translates up in scale to the composition of the rock and to lithologic differences.

Fractures present avenues of weakness as well as paths of contact with weathering agents. Fractures are present at the smallest scales, within mineral grains. At the largest scales, networks of fractures (including fault zones) allow fluids to penetrate and create greater surface area. Quarries are ideally situated in rock outcrops relatively devoid of fractures, minimizing the chances for weathering and easing the ability to remove large intact slabs of workable stone.

Over larger scales, the variation in lithology (by composition or structure) would factor into variations in weathering and erosion rates, resulting in differential landscapes of landforms resistant to positive relief and less resistant to negative relief. Resistant landforms (such as bornhardts, inselbergs, buttes, tors) have been described as having

a more resistant composition compared with the surrounding rock, fewer fractures, or both.

Colorado National Monument, Colorado. Weathering away of the protective caprock of the overlying Kayenta Formation has produced rounded tops on all but the left-hand shaft, which is still protected by the Kayenta.



Source: U.S. Geological Survey

Source of Weathering Agents, Climate and Biotic Influences

The abundance and efficacy of weathering agents is a factor in the geography of weathering (Figure 1). Concentration of weathering agents will yield faster weathering rates and more intense weathering. Because of the ubiquity of water in almost all terrestrial environments (possible exceptions in hyperarid deserts, though the [p. 2484 ↓] persistence of this condition over weathering timescales is debatable), chemical weathering is nearly always available. At least one type of mechanical weathering is

present in terrestrial environments. Again, variation of weathering agents is evident at changing scales. For example, at regional scales, increased precipitation, perhaps aided by enhanced levels of atmospheric acid, may account for increased chemical weathering (evident in increased solute load in streams). Certain biomes would be more conducive to increased levels of organic acid (e.g., pine barrens or sphagnum bogs). Certain climate regions are more favorable for mechanical weathering (e.g., due to freeze-thaw cycles or salt). Variations in weathering agents at centimeter-to-meter scale account for differential weathering. Individual plants (e.g., lichens, trees) can locally enhance the chemical weathering environment. Microclimatic difference can influence temperatures and the availability of water and organisms. Small-scale declivities in the land or rock walls can concentrate weathering agents as well as influence the microenvironment. In contrast, small-scale armoring (rinds, rock coatings) protects rock from weathering by retarding the access of chemical agents or indurating the rock against mechanical stresses. Finally, the efficacy of weathering agents can decline over time as the material evolves from higher to lower weathering potential.

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See also

- [Biota and Soils](#)
- [Geomorphology](#)
- [Rill Erosion](#)
- [Sedimentary Rock](#)
- [Soil Erosion](#)
- [Soils](#)
- [Wind Erosion](#)

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