PROCESSES THAT SHAPE THE SURFACE OF EARTH

Noble M.A.
United States Geological Survey, Menlo Park, California, USA

Keywords: landform evolution, plate tectonics, active margin, convergent margin, subduction, hot spots, erosion, weathering, chemical dissolution, acid rain, glacier, moraine, ice age, river, flood plain, drainage basin, sediment transport, dust storm, ocean processes, flocculation, turbidity current, debris flow, canyon formation, alluvial fan, coastal bluff, continental shelf, continental slope, canyon formation, seafloor, ocean basin, seamount, mid-ocean ridge, climate change, human impact

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Summary

Earth's surface exhibits an endless variety of morphological forms. High mountain ranges, vast deserts, abyssal plains, islands, deep canyons and seafloor trenches abound. This morphology is not static. Even as weathering reduces mountains to small hills and rivers carry mountain sediments to the ocean, the heat engine inside the earth causes uplift processes that create new mountains along continental boundaries. Convection currents in Earth's interior cause old seafloor to melt as it is carried beneath continental margins even as new seafloor is created along the spreading centers at mid-ocean ridges. Coastal barrier islands lose sediments and are eroded at one end, while accretion processes cause the islands to grow at the other, effectively moving an entire island to a different location. Earth's surface is in dynamic equilibrium. A variety of competing processes erode and reduce all surface elevations, whether they are on a continental landmass or on the seafloor, while others rebuild Earth's surface elevations. If Earth

were static, weathering processes would eventually transport all continental material into ocean basins. Oceans would cover the globe.

Water is a major factor in the processes that shape Earth’s surface. The abundance of water is not only a major contributor to weathering processes that erode the newly-built mountains, but without watertectonic processes themselves would be slowed, or even halted, because frictional forces would inhibit the collisions between oceanic and continental plates. Water as rain erodes mountains and coastal cliffs. Water in the form of rivers excavates large canyons. Water in the form of glaciers creates fjords, lake basins and even modifies Earth’s continental shelves. Water as ocean waves or currents moves barrier islands, erodes the seafloor and carries sediment to ocean basins. Tectonic processes, the presence of water, and human impacts together combine to shape the Earth as we know it.

1. Introduction: Earth in a Dynamic Balance

Earth, a primarily spherical heavenly body, is composed of four main layers. The solid core is the innermost layer. A liquid outer core, the second layer, surrounds it. The two together constitute Earth's thickest sequence of layers, 45% of Earth's radial depth. The mantle, roughly 2900 km thick, is the third layer. It accounts for most of the remaining material. The fourth layer, the crust, is the strong outer shell of Earth. It is relatively stiff, brittle, and very thin compared to the other layers. With a thickness of about 40–60 km under the continents and about 6 km beneath the ocean basins, the crust accounts for less than 0.02% of Earth's radius. Yet this thin shell is of utmost importance. It is Earth’s surface, the shell upon which life dwells. The crust is the interface between the solid earth and the oceanic and atmospheric envelopes that cover and surround it.

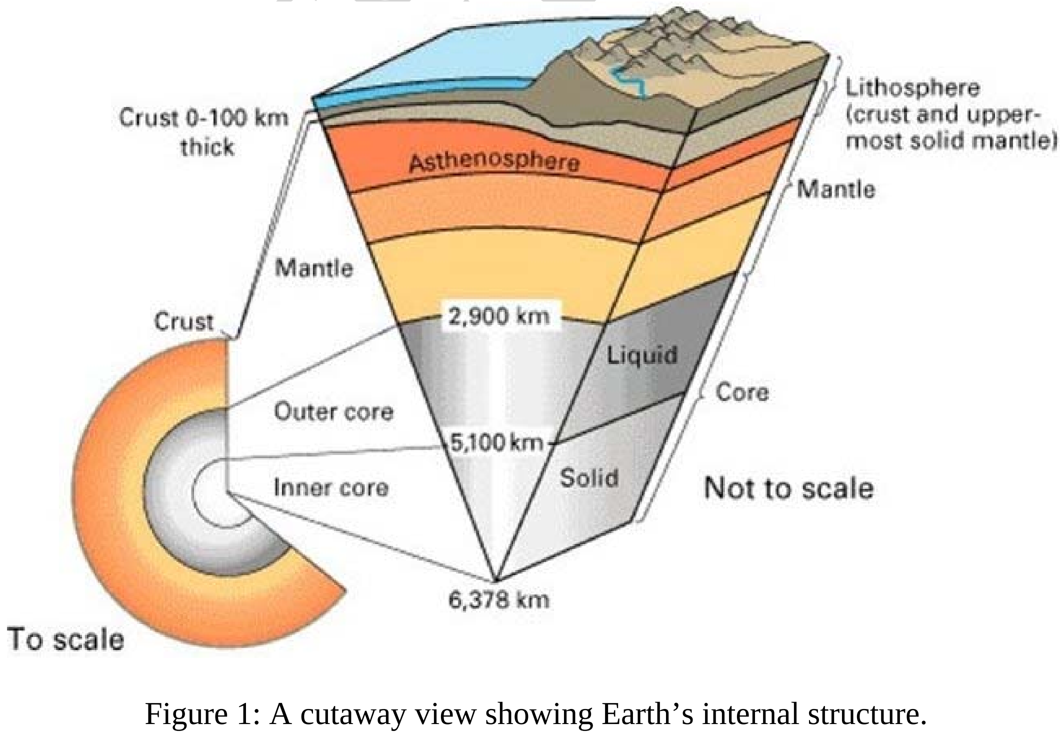

Figure 1: A cutaway view showing Earth’s internal structure.

From Kious W.J. and Tilling R.I. (1996). This Dynamic Earth: The Story of Plate Tectonics, 77 pp. Washington, DC: US Geological Survey.

The crust and the uppermost highly viscous portion of the mantle together comprise Earth's lithosphere, which is 80–100 km thick. Density or buoyancy forces cause the lighter lithosphere to float above the deeper, denser portions of the mantle. Tectonic forces move sectors (or plates) of the lithosphere across Earth’s surface. The top portions of the lithosphere are composed mainly of light felsic or granitic rocks. Denser ultramafic rocks are found lower in the lithosphere. The lightest rocks are primarily found near the surface of Earth's crust; they form the continental landmass. It is this land that humans are most familiar with because we walk and live on it. The remaining 70% of Earth's crust is primarily composed of denser rock that floats over the mantle at lower elevations than continental rock. Because Earth has an abundance of liquid water, extensive oceans cover this low-lying crust. Both surfaces, the continental land and the seafloor, exhibit an endless variety of morphological forms. High mountain ranges, large valleys, deep abyssal plains, canyons, and deep trenches abound.

The distributions of continental land and seafloor are constantly changing. Weathering and other surficial processes erode Earth's surface. Over geologic time, mountains are reduced to small hills. Rivers carry soils from eroded mountains and vast plains to the sea. Some of these rivers carve deep canyons as they flow across Earth's surface. Eventually, large amounts of continental materials are deposited in the ocean basins. It is estimated that sediment is delivered to the oceans at a rate which is causing the mean level of the continental crust to be lowered by 0.3 m every 9000 y. Eventually, if Earth were static, erosional processes would transport all continental material into oceanic basins. Former continental landmasses would be gradually lowered to sea level. Oceans would cover the continents in perhaps as short a period as 25 million years. Waves would attack the drowned continents, further eroding them until the highest topography would be more than 80 m below the ocean surface. If coral reefs continued to exist, they would be the only lands above sea level. From space, a view of Earth would show mainly clouds and oceans.

However, Earth is not static. Earth is a dynamic balance of processes that not only demolish and rebuild the surface relief (elevation), but also demolish and rebuild the total amount (volume) of continental crust available to cover the planet. The heat engine in Earth's interior drives powerful convection currents in the mantle. Earth’s thin, rigid crust is brittle and breaks like a cake of dried mud. The crust fractures into lithospheric plates that move in slow, relative motion. Plates split and move apart, creating new seafloor as the denser material from deep within Earth rises to the surface between the separating parts. Plates also collide. Along some continental margins, such as along the west coast of North America and virtually the entire length of western South America, tectonic forces cause the heavier oceanic crust and lithosphere layers to be subducted landward and under the continents. The continental landmasses are compressed and uplifted. New mountain ranges, such as the Andes, are created. Some of the sediment that was eroded from continental landmasses and deposited on the seafloor is pulled into the subduction zone by the sinking oceanic slab. Sedimentary material can be scraped off and plastered to the submerged edge of the continent, potentially creating new areas of land out of older material. However, on a global scale, most of the oceanic sediment is subducted with the sinking oceanic lithosphere and, with it, recycled to the mantle. This process, called sediment subduction, is an important part of Earth's dynamic balance. Sediment subduction, like erosion, serves to remove crust material from Earth's surface and recycle it to the mantle. Subsequently, igneous (volcanic) processes recreate that crust.

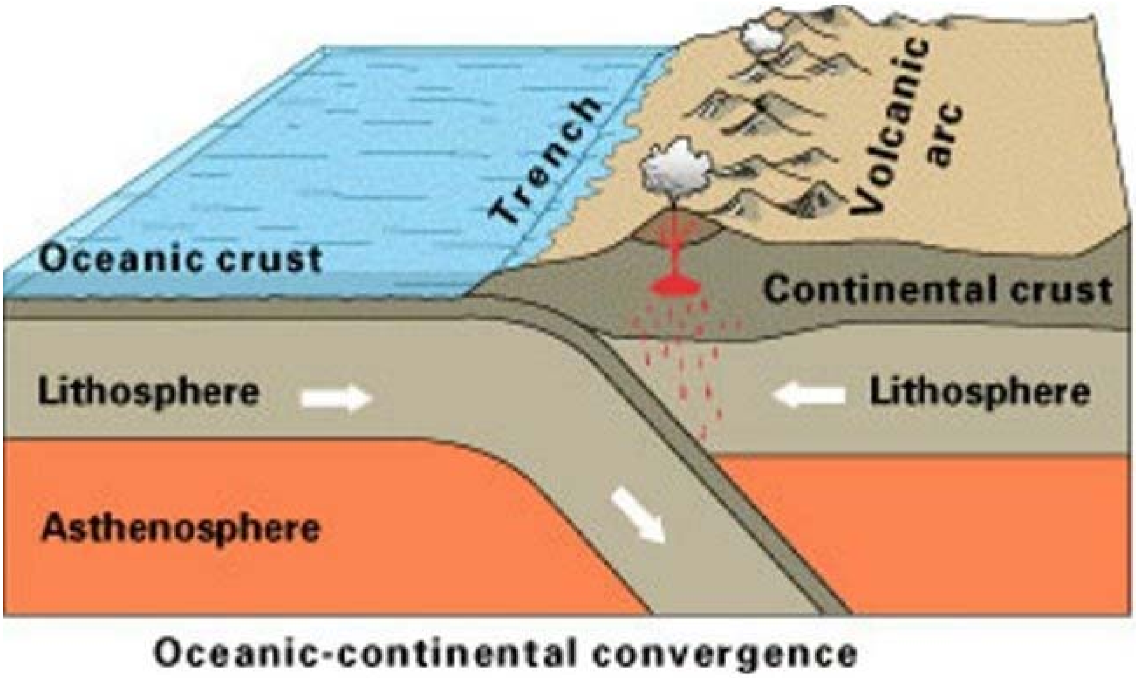

Figure 2: The convergence between an oceanic and a continental plate
From Kious W.J. and Tilling R.I. (1996). This Dynamic Earth: The Story of Plate Tectonics, 77 pp. Washington, DC: US Geological Survey.

This is the key to Earth's dynamic balance. Continental crust is weathered, eroded, transported, and eventually dispersed within ocean basins. Tectonic processes concentrate, reincorporate, and return much of the dispersed material to continental landmasses along active plate boundaries. During the past several hundreds of millions of years, Earth has neither gained nor lost continental crustal mass. During this same time period, scores of major mountain systems have formed and been eroded to low levels. Hence, even though it has been four billion years since Earth was formed, continents still exist, even though much of the continental materials have been eroded and recycled over time.

2. Plate Tectonics

Earth's interior is hot. Radioactive decay and the residual heat left over from its formation 4.6 billion years before present causes Earth's surface and its interior to be in motion. The mobile rock beneath the rigid, but fragile plates that make up Earth's lithosphere forms convection cells. Hotter material rises toward the surface, spreads laterally at midocean spreading centers, or ridges, then cools and sinks back into the depths at subduction zones. The pull of the cooled edges of the plates sinking beneath the continents helps drive the spreading process at midocean ridges, such as the Mid-Atlantic Ridge. Because the spreading ridges are relatively hot, they rise to depths much higher than the mean ocean floor. Their height enables them to push the plates sideways. Hence, mantle convection in combination with the pull of the sinking lithospheric slab and the push of the spreading ridge act together to drive the global motion of lithospheric plates. The plates move slowly. Their speed is measured in centimeters per year, roughly the same rate that fingernails grow. But the motions, though slow, are inexorable. They drive the contacts between plates that produce fundamental structures on Earth's surface, such as the elongate mountain belts of folded rock and chains of majestic arc volcanoes.

One of the more dramatic and visible morphologies on Earth is formed where moving plates drive two continents into collision. The Indian and Eurasian plates started to collide 40–50 million y BP. As the two continents collide, they buckle and thrust up high mountain ridges. The Himalayan Mountains, which stretch nearly 3000 km along the India–Tibet border, are pushed up about one cm each year by this collision. The rugged Himalaya rise nearly 9 km above sea level. This ongoing collision has doubled the thickness of the associated continental crust, causing an uplift of nearby continental lands. The Tibetan Plateau, which lies on the Eurasian plate to the north and east of the Himalayan range, has been lifted to a mean elevation of 4600 m. The Alps of southern Europe were formed by the similar plate-driven collision between Africa and Europe.

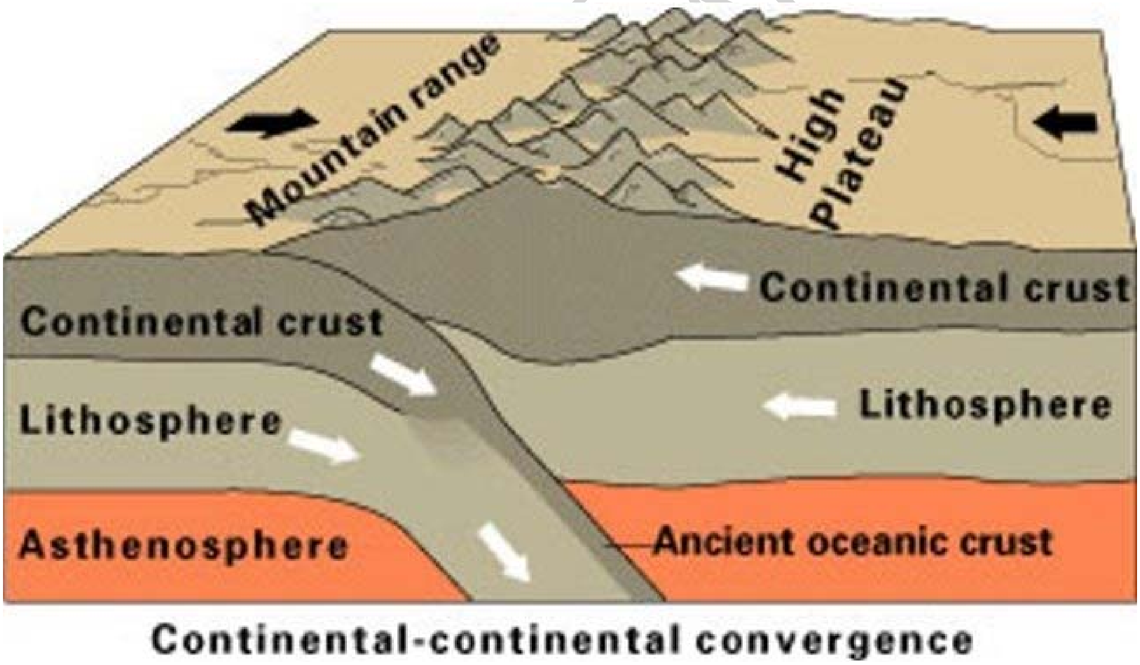

Figure 3: The convergence between two continental plates
From Kious W.J. and Tilling R.I. (1996). This Dynamic Earth: The Story of Plate Tectonics, 77 pp. Washington, DC: US Geological Survey.

Other common topographic structures are created when plates composed primarily of continental materials slowly collide with oceanic plates at subduction zones (see Figure 2). The denser and much lower oceanic plate is subducted under the continental crust.

As the oceanic crust subducts, it injects water and ocean sediments into the upper mantle. At a depth of about 100 km, the presence of the subducted water causes the warm, viscous mantle to melt and send columns of molten rock, or magma, toward Earth's surface. The molten material either cools beneath the surface to form granitic bodies or plutons, or it rises to the surface and erupts to form arcuate chains of volcanoes. One such chain is the commonly labeled "Ring of Fire" that girds much of the rim of the Pacific Basin. Arc volcanoes, including those in Japan, the Aleutian Islands, the Andes, New Zealand, and the Kingdom of Tonga, rebuild Earth’s surface above the subduction zone. The eruptions of Mt. Pinatubo in the Philippines and Mt. St. Helens in North America are typical of the violence associated with these arc volcanoes. So, as sediment subduction returns continental material to the mantle, arc volcanism brings new volumes of Earth’s crust to the surface and builds mountains above the same subduction zone.

In the subduction process, oceanic trenches and mountains form as the oceanic plate melts and the continental crust buckles. Off the west coast of South America, the oceanic Nazca Plate is being subducted under the continental portion of the South American Plate, creating the deep Peru–Chile trench. The compression from the collision of the two plates causes the Andes Mountains to be thrust up as the continental portion of the South American Plate overrides the Nazca plate. One additional and very important tectonic process operates at subduction zones. The action of the oceanic crust sliding beneath the continents at subduction zones erodes the basal rocks of the overlying continent and transfers this material to the sinking oceanic plate and thus, to the mantle. This process is called subduction erosion.

Deep oceanic trenches are created when two oceanic plates converge. In contrast to the joint buckling and upthrust associated with the convergence of two continental plates, one oceanic plate will override the other. The Marianas Trench, which lies along the western rim of the Pacific Ocean, is being created as the fast-moving Pacific plate collides with the Philippine plate. This collision is creating a trench which is, at 11 000 m, deeper than the highest mountain of the Himalaya is tall. The subduction processes associated with oceanic plate convergence create volcanoes that form chains called island arcs. The Aleutian Trench and Aleutian Archipelago arc system is typical of the form created by oceanic plate convergences.

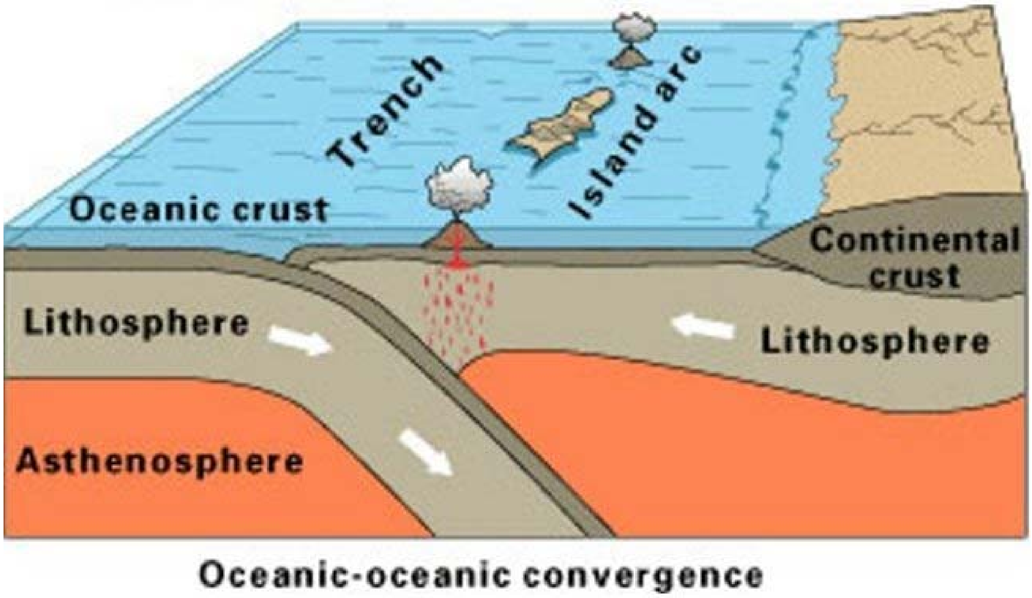

Figure 4. The convergence between two oceanic plates
From Kious W.J. and Tilling R.I. (1996). This Dynamic Earth: The Story of Plate Tectonics, 77 pp. Washington, DC: US Geological Survey.

The mantle also provides new igneous rocks to the continents away from subduction zones. New crust is created at hot spots, which are quasi-stationary or slow-moving thermal plumes rising through the mantle. These localized sources of high-heat energy partially melt the overlying continental plate, creating magma that is lighter than the surrounding rock. The magma rises and ultimately erupts, either creating a new volcano or contributing mass to an existing volcano. After countless eruptions, volcanoes initially located under the sea emerge and become islands or island chains. The Hawaiian Islands were formed in this manner. The movement of the Pacific Plate is carrying the active volcanoes on the islands of Hawaii past the hot spot and a new potential island is forming in its wake. A small volcano, called Loihi, is currently erupting under the sea. It may eventually grow to become the next island in the Hawaiian Island chain. Hot spots may also form under continental land. Yellowstone, a national park in the northwestern United States that contains large hot-water geysers and other thermal features, lies above a thermal plume in the mantle. Iceland lies above another. The mantle can also plate a layer of basaltic magma along the base of our continents, in particular at locations where they are being pulled or rifted apart.

(An expanded discussion of plate tectonics and landform evolution is found in Volcanic and Magmatic Rocks and Plate Tectonics and Landform Evolution.)

3. Weathering

Tectonic processes form the basic structure, or shape, of Earth. But the abundance of water, and its ability to change from a solid to a liquid or gas in normal temperature ranges, is a major contributor to processes that alter Earth's surface. Without an abundance of water, the tectonic processes themselves would be slowed or halted because frictional forces would inhibit the collisions between oceanic and continental plates. Water provides the basic lubricant that allows plates to slide over each other and eventually melt in subduction zones. Water is also an excellent solvent for many materials, and, in its several phases, is a weathering agent that ameliorates and tears down the very surfaces created by tectonic processes.

3.1. Chemical Weathering

Chemical weathering is a primary mechanism of erosion—the decay and physical fragmentation of rock. In general, the smaller the rock, the more surface area that is available for attack, the faster erosion proceeds. Rock surfaces that are exposed to water decay at enhanced rates. This process is analogous to rust forming on the exposed surfaces of bridges, common garden tools, and nails. Rusting is a chemical process. Water and oxygen combine to convert iron into its oxidized form, ferric iron. The rust is structurally weak. It crumbles and is swept from the original object, which eventually disappears.

Water assists in erosive processes because, as a polar molecule, it is a good solvent for many materials. The water molecule's charge distribution is asymmetric. This gives it a weak electronic attraction to solid surfaces, which enhances water's ability to interact with other materials. Gases also dissolve in water. Solutions of carbon dioxide dissolved in water are familiar to many people. The bubbles in common soft drinks are made when pressurized carbon dioxide is pumped into the sugary liquid. If carbon dioxide is dissolved in water in the atmosphere, a new compound, carbolic acid, is fabricated. This relatively weak acid will not burn one's skin, but it is strong enough to dissolve rocks it comes in contact with over long periods of time.

A stronger dissolved acid is formed when fossil fuels such as coal and oil are burned in industrial areas. Incineration of these materials has been and may still be responsible for up to half the volume of sulfur dioxide emitted to the atmosphere. Natural sources such as volcanoes, sea spray, rotting vegetation, and plankton emit the rest of the sulfur dioxide. Once sulfur dioxide reaches the atmosphere, it oxidizes into a sulfate ion. This ion is then transformed into sulfuric acid when it joins with hydrogen atoms in the air. The resultant compounds fall back to earth as an acid rain (See enhanced mobility of trace elements under acid rain conditions in articles on Biogeochemical Cycling of Micronutrients and other Elements.)

Both carbolic and sulfuric acids weather exposed stones and building materials. Even solid granites succumb to weathering processes. Inscriptions on gravestones, intended to last forever, are eventually worn away. Feldspar, a component of granite, weathers into chalky, clayey minerals such as kaolinite, which can become soft enough to be gouged with a sharp stick. The original crystal lattice of feldspar and quartz no longer holds together, and the granite boulder crumbles. The resulting kaolinite clay can be used to make pottery and china.

The chemical weathering of rock forms several types of clay besides kaolinite. All these clay materials have a sheet structure. Smectite is the main clay product formed in part by the weathering of volcanic ash, though kaolinite is the clay mineral formed from ash in acidic environments. Illite is typically created when sediments are weathered in temperate regions. The sheet structure of clays makes them easily cleavable, or slippery, when they have a high water content. If you park off to the side of a clay road in the volcanic Hawaiian Islands during a rainstorm, you can easily become mired in the gooey mud when the watery clay slides out from under the car wheels. Cliffs containing a high proportion of smectite slide as the smectite adsorbs water during rainstorms.

Feldspar and other silicates that weather comprise a large portion of the igneous and metamorphic rocks upon Earth's surface. One third of the sediments on Earth are made of the clay materials derived from chemical weathering processes. Rivers and streams eventually carry these soils from the rocky promontories and high mountains to the fertile plains and ocean basins that make up the majority of Earth's surface. *(See Clay minerals in Mineralogy.)*

Rocks buried in moist soil weather faster than rocks exposed to dry air because ground water and its associated dissolved acids enhance the chemical reactions necessary for weathering. In moist soils, rocks such as granites are continually exposed to corrosive acid–water solutions; they decay into clays. Some of the acid content of soils is produced by bacterial organisms or by plant roots. These living agents participate directly in chemical weathering through metabolic processes and through production of organic acids when the organic matter decays. Both the bacteria and the plant roots produce carbon dioxide during respiration, causing organic matter to oxidize and carbon dioxide to be released. The amount of carbon dioxide dissolved in soils can be an order of magnitude more than is found in rainwater, making acidic soils an efficient weathering agent for rocks.

Weathering does not proceed at the same rate in all climates. Monuments last longer in the arid desert because water, an essential component of chemical weathering, is not abundant. Chemical weathering processes are also slowed in the Antarctic, where it is cold. Rocks and other materials decay relatively quickly in tropical climates, which are both wet and warm. The speed of chemical reactions increases as the temperature rises. Bacteria and plants also grow faster in the tropics, making more carbon dioxide available for chemical reactions as the temperature rises.

3.2. Chemical Dissolution

Many chemical weathering processes produce the fine clays that form an essential element of our soil. However, other chemical processes actually dissolve rock. Large caves with many passageways and chambers are created when rainwater laced with carbonic acid dissolves limestone. The columnar stalactites and stalagmites often present in these caves are created when water that is super-saturated with calcium carbonate slowly seeps through the ceiling of the cave. Because limestone dissolves faster than silicates, the chemical weathering of limestone accounts for a large portion of weathered rock on Earth's surface.

3.3. Mechanical Erosion

Not all materials are susceptible to chemical weathering: man-made glass is resistant to the processes. Old bottles are found in quiescent environments long after tin cans have disintegrated. However, glass is very susceptible to mechanical weathering; it breaks when rocks collide with it.

Mechanical erosion, the physical breaking and fracturing of rock, increases the rate of chemical erosion. Large, unbroken rocks have few surfaces for chemical weathering to act on. Fragmented rocks, with their larger surface to volume ratios, succumb more quickly to weathering processes. Water, in its liquid and solid forms, again plays a major role in the physical weathering and fragmentation of rock. In high mountain ranges, in temperate climates, or in any region of Earth where temperatures vary around the freezing point of water (around 0°C), water in its liquid form flows into small crevices and cracks in rock. When temperatures drop below freezing, water cools and initially contracts,abruptly expanding as it freezes. When it freezes, water is strong enough to wedge fractures open, fragmenting and cracking the rock in the process. The thaw–freeze cycle has an effect similar to that of a wedge being driven into a log to make kindling. The log splits along a cleaving plane. During warm periods, the ice melts and water sinks deep into the rock crevices. If the temperature lowers, the water refreezes and forces the rock faces further apart. The erosional consequences caused by the melting and refreezing of water are easily seen in mountainous areas. Bedding plains or joints in rock are split by ice, creating the rockfalls and talus slopes commonly found at the base of sheer rock faces. In particular, sandstone breaks into sheets along bedding planes. Massive rocks, like granite, split at joints or at regularly spaced cracks along the joints. Chemical and bacterial processes weather the exposed rock surfaces. Plants root in the newly opened rock fractures, forcing them to widen. These combined processes enhance the inevitable disintegration of the rocky surfaces. Other common modes of mechanical weathering, including wind erosion, erosion by glaciers, by rivers carrying sediment, and by waves along coasts, will be discussed in subsequent sections of this article.

(See Glacial and Periglacial Processes.)

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Biographical Sketch

Marlene Noble, presently a physical oceanographer at the US Geological Survey, did not begin her career as a marine scientist. The focus of her undergraduate work at the University of Washington was physics. She went on to complete a master’s degree in physics at Princeton University in 1972. She then transferred to the Massachusetts Institute of Technology because she wanted to change her career path and enter the emerging field of coastal oceanography. She left MIT in 1975 with a master's degree in physical oceanography to take a job with the US Geological Survey (USGS) in Woods Hole, Massachusetts. The USGS was just starting a coastal ocean program that focused on determining how sediments and associated pollutants moved over the northeastern US shelves. While working for the USGS, she completed her PhD at the University of Rhode Island in 1983. She then transferred to the USGS offices on the west coast of the US to expand her research programs. While at the USGS, she has developed many cooperative research projects with universities and outside agencies that have the ultimate goal of understanding and predicting the structure and dynamics of currents and the associated processes that transport resuspended sediment and pollutants in diverse environments: estuaries, continental shelves and slopes, submarine canyons, and deep ocean seamounts. She has been an invited member or chairperson of various research advisory panels that evaluate physical oceanographic or sediment and pollutant transport programs in the coastal ocean. She has been the Ocean Sciences editor of EOS, Transactions of the American Geophysical Union, for the past three years and is presently an associate editor for Estuaries.