



10 Weathering

A new building gradually deteriorates. The paint chips and peels, wood dries and splits, and even brick, building stone, and cement eventually decay and crumble. Left alone, most buildings decompose into a pile of rubble within a few hundred years. This process of natural decay is called weathering. Weathering is a general term describing all of the changes that result from the exposure of rock materials to the atmosphere.

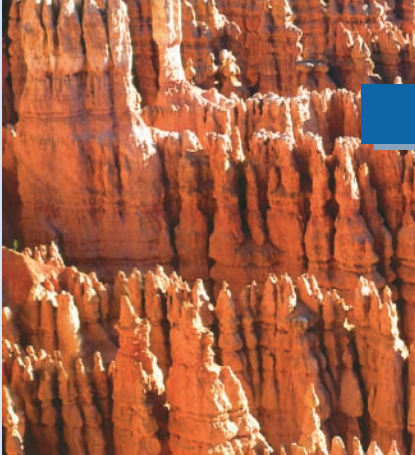
The spires and columns of Bryce Canyon National Park in Utah vividly show how weathering modifies a rock body. Once a solid mass of sedimentary rock, these spires and columns were largely created by the gradual decomposition of rock by reactions with water and air. The loose material fell downslope and was eventually carried away by streams. Here, weathering is controlled by vertical joints and by differences in the various layers of colorful sedimentary strata. The intersecting joint systems produce a series of columns that are modified during weathering into an infinite variety of forms by different bedding characteristics. Take a moment to study this photograph. Can you see that the columns are aligned in rows parallel to joint systems? Can you recognize certain horizons in the



sedimentary strata that weather much more rapidly than others? Can you see joint systems being enlarged by weathering to separate the rocks into columns? Weathering has produced this remarkable landscape, but the effects of weathering can be seen everywhere.

From a geologic point of view, weathering is important because it transforms the solid bedrock into small, decomposed fragments and prepares those fragments for removal by the agents of erosion.

It would be difficult to overemphasize the importance of weathering to humans. Without weathering, Earth would be forbidding indeed. The continents would be bare, hard rock, for no soil cover could develop; consequently, Earth would be devoid of plant and animal life. In addition to producing the soil on which agriculture depends, weathering produces some other very practical products. Sand, gravel, and clay deposits are the indirect results of weathering. Practically all aluminum ore, most iron ore, and some copper ore are formed and concentrated by weathering. Consequently, it is important for us to understand this important component of Earth's systems.



MAJOR CONCEPTS

1. Weathering is the breakdown and alteration of rocks at Earth's surface through physical and chemical reactions with the atmosphere and the hydrosphere.
2. Physical weathering is the mechanical fragmentation of rocks from stress acting on them. Ice wedging may be the most important type.
3. Chemical weathering involves chemical reactions with minerals that progressively decompose the solid rock. The major types of chemical weathering are dissolution, acid hydrolysis, and oxidation.
4. Joints and fractures facilitate weathering because they permit water and gases in the atmosphere to attack a rock body at considerable depth. They also greatly increase the surface area on which chemical reactions can occur.
5. The major products of weathering are spheroidal rock forms, a blanket of regolith, and dissolved ions. Soil is the upper part of the regolith—a mixture of clay minerals, weathered rock particles, and organic matter.
6. Climate and rock type greatly influence the type and rate of weathering.

The Nature of Weathering

To appreciate how geologic processes erode the surface of Earth, and how the landscape evolves, one first needs to understand the nature of weathering—the disintegration and decomposition of rocks. By definition, weathering is different from erosion. Weathering involves only the breakdown of rock, whereas erosion involves the removal of debris produced by the breakdown. In reality, however, weathering and erosion are intimately involved with one another. Weathering disintegrates solid rock and produces loose debris. Erosion by running water, wind, and ice removes the debris and exposes fresh rock, which is then weathered, and the cycle continues. The results of weathering are seen everywhere, from the debris along hill slopes to decomposed monuments of antiquity (Figure 10.1).

Like metamorphism, its counterpart deep within the crust, weathering reflects adjustments of rocks exposed to a new environment. Minerals in rocks are in equilibrium with where they originate (in terms of temperature, pressure, and chemical environment, for example). If they are exposed to a different environment, the elements in minerals will slowly adjust to different forms that are stable under the new conditions. In weathering, rocks adjust and are altered to forms more stable at low pressure, low and fluctuating temperatures, and the chemical environment



(A) Weathering is especially obvious on old monuments in Europe. Here, most of the details on the gargoyles of the Notre Dame Cathedral in Paris have been erased by weathering.



(B) Weathering is apparent from the fallen debris on many slopes. Here the resistant sandstone butte is shrinking as weathering separates fragments that fall and accumulate at the base of the cliff.

FIGURE 10.1 The effects of weathering are seen whenever rocks are exposed. These photographs show typical examples.

with abundant water that prevails at Earth's surface. Thus, metamorphic rocks and igneous intrusions are generally most susceptible to weathering.

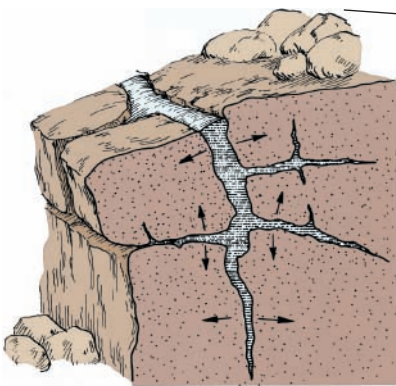
Weathering, then, involves a multitude of physical, chemical, and biological processes, but two main types of weathering are recognized: (1) **physical weathering** and (2) **chemical weathering**. Physical (or mechanical) weathering breaks the rock mass into small particles. It is strictly a physical process involving no change in chemical composition. Chemical weathering alters the rock by chemical reactions between elements in the atmosphere and those in the rocks. Most geologists believe that chemical weathering is most important in terms of total amount of rock breakdown. In most places, however, the two processes work together, each facilitating the other, so that the final product results from a combination of the two processes.

PHYSICAL WEATHERING

Physical weathering is the breakdown of rock into small fragments by physical processes without a change in chemical composition. No chemical elements are added to, or subtracted from, the rock. The most important types of physical weathering are ice wedging and sheeting, or unloading.

Ice Wedging

Figure 10.2 includes a simple diagram showing how **ice wedging** breaks a rock mass into small fragments. Water from rain or melting snow easily penetrates cracks, bedding planes, and other openings in the rock. As it freezes, it expands about 9%, exerting great pressure on the rock walls, similar to the pressure produced by driving a wedge into a crack. Eventually, the fractured blocks and



(A) Ice wedging occurs when water seeps into fractures and expands as it freezes. The expanding wedge forces the rock apart and produces loose, angular fragments that move downslope by gravity and accumulate at the base of the cliff as talus cones.



(B) The effects of ice wedging in the Teton Range in Wyoming are seen in both the rugged surface of the mountain peaks and the accumulation of fragmented debris at the base of the cliff. The rock that forms the mountain range is a massive granite cut by numerous fractures. Ice wedging, controlled in part by the fractures, produces the sharp, angular texture of the mountain peaks. The debris derived from ice wedging has accumulated in conical slopes near the base of the cliff. (Courtesy of U.S. Department of Agriculture)

FIGURE 10.2 Ice wedging is an important type of physical weathering in areas where temperatures rise above and fall below the freezing point.

How does physical weathering break down a mass of solid rock into small fragments?

What is the difference between sheeting and stratification?

bedding planes are pried free from the parent material. The stress generated each time the water freezes is approximately 110 kg/cm^2 , roughly equivalent to that produced by dropping a 98-kg ball of iron (about the size of a large sledgehammer) from a height of 3 m. Stress is exerted with each freeze, so that, over a period of time, the rock is literally hammered apart.

Ice wedging occurs under the following conditions: (1) when there is an adequate supply of moisture; (2) where preexisting fractures, cracks, or other voids into which water can enter occur within the rock; and (3) where temperatures frequently rise and fall beyond the freezing point. Temperature fluctuation above and below the freezing point is especially important because pressure is applied with each freeze. In areas where freezing and thawing occur many times a year, ice wedging is far more effective than in exceptionally cold areas, where water is permanently frozen. Ice wedging thus occurs most frequently above the timberline. It is especially active on the steep slopes above valley glaciers, where meltwater produced during the warm summer days seeps into cracks and joints and freezes during the night (Figure 10.2).

The process of ice wedging has been known for years, and more than 100 years ago, ice wedging was used in some quarrying operations. Workers would drill a series of holes along the line of a desired cut and fill them with water. The expansion accompanying freezing would split the rock apart almost as cleanly as modern methods.

In arid regions, the growth of salt crystals in pores and cracks can also pry apart rock. The crystals grow by evaporation of the salt-laden spray that accumulates in the fractures of rocks exposed along the shores of salty lakes or the sea. This process is vividly expressed in the shattering of fence posts near the shore of the Great Salt Lake (Figure 10.3).

Sheeting

Rocks formed deep within Earth's crust are under great confining pressure from the weight of thousands of meters of overlying rocks. As this overlying cover is removed by erosion, the confining pressure is released, and the buried rock body tends to expand. The internal stresses, set up by expansion, can cause large fractures, or expansion joints, parallel to Earth's surface (Figure 10.4). The result is known as **sheeting**. It can be observed directly in quarries, where the removal of large blocks is sometimes followed by the rapid, almost explosive expansion of the quarry floor. A sheet of rock several centimeters thick may burst up, and at the same time, numerous new parallel fractures will appear deeper in the rock body. The same process occasionally causes rock bursts in mines and tunnels, when the confining pressure is released during the tunneling operation. It can also be seen in many valley walls and in excavations for roads, where rock slumping, due to sheeting, can cause serious highway problems.

Other Types of Physical Weathering

Animals and plants play a variety of relatively minor roles in physical weathering. Burrowing animals, such as rodents, mechanically mix the soil and loose rock particles, a process that facilitates further breakdown by chemical means. Pressure from growing roots widens cracks and contributes to the rock breakdown. Lichens can live on the surface of bare rock and extract nutrients from its minerals by ion exchange; the presence of lichens, therefore, results in both physical and chemical alteration of the minerals. These processes may seem trivial, but the work of innumerable plants and animals over a long period of time adds significantly to the disintegration of the rock. Although dismissed by some geologists, recent evidence is mounting that thermal expansion and contraction of the rock caused by daily or seasonal temperature changes may also be an effective process of physical weathering.



FIGURE 10.3 Growth of salt crystals has shattered these fence posts near the shore of the Great Salt Lake, Utah. Salty groundwater seeps into the wood, and, as it evaporates, salt crystals grow, expand, and break apart the wood fibers.



Talus

The products of physical weathering are best seen in high mountain country, where ice wedging dominates and produces a large volume of angular rock fragments. This material commonly accumulates in a pile at the base of the cliffs from which it was derived. Because most cliffs are notched by steep valleys and narrow ravines, the fragments dislodged from the high valley walls are funneled through the ravines to the base of the cliff, where they accumulate in cone-shaped deposits known as **talus cones** (Figure 10.5).

Talus cones are built up by isolated blocks loosened by physical weathering. The blocks commonly fall separately, as almost any mountain climber can testify, but large masses of the material on steep slopes may be moved by an avalanche. Earthquakes may also suddenly activate large numbers of blocks loosened by many seasons of ice wedging.

In the example shown in Figure 10.5, all of the talus has accumulated since the last ice age, which terminated 10,000 to 15,000 years ago. This is a considerable amount of material produced by physical weathering alone.

FIGURE 10.4 **Sheeting in granite** of the Sierra Nevada occurs as erosion removes the overlying rock cover and reduces the confining pressure. The bedrock expands, and large fractures develop parallel to the surface. Ice wedging may subsequently enlarge the fractures.



Talus Cones

CHEMICAL WEATHERING

Chemical weathering is the breakdown of minerals by chemical reactions with the atmosphere or hydrosphere. The three main types of chemical reactions are (1) dissolution, (2) hydrolysis, and (3) oxidation.

During chemical weathering, rocks are decomposed, the internal structure of the minerals is destroyed, and new minerals are created. Thus, there is a significant change in the chemical composition and physical appearance of the rock.

Dissolution

Dissolution is a process whereby a mineral passes completely into solution, like salt dissolving in water. Some minerals dissolve directly in water and the ions are **leached**, or flushed away. Halite (salt) is perhaps the best-known example. It is extremely soluble, surviving at Earth's surface only in the most arid regions. Gypsum



FIGURE 10.5 **Talus cones** are piles of rock debris that accumulate at the base of a cliff as the result of rockfall. Most rock fragments in talus cones are produced by ice wedging as here in the Canadian Rockies. (Courtesy of L. F. Hintze)

is less soluble than halite but is also easily dissolved by surface water. Few, if any, large outcrops of these minerals occur in humid regions. This kind of dissolution happens because water is one of the most effective and universal solvents known. The structure of the water molecule requires the two hydrogen atoms to be positioned on the same side of the larger oxygen atom. The molecule thus has a concentration of positive charges on the side with the two hydrogen atoms, balanced by a negative charge on the opposite side. As a result, the water molecule is polar and behaves as a tiny magnet would. It acts to loosen the bonds of the ions at the surface of minerals with which it comes into contact. Because of the polarity of the water molecule, practically all minerals are soluble to some extent in water, but those with ionic, rather than covalent, bonds are more easily dissolved.

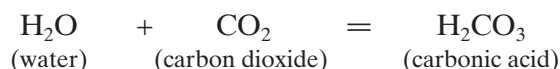
Acid Hydrolysis

The most common dissolution reactions involve slightly acidic water. Carbonic acid (H_2CO_3) is common in natural environments and forms when water combines with carbon dioxides. This reaction takes place in the atmosphere and in the root zones of plants where carbon dioxide is released into the soil. In addition, bacteria in the soil combine oxygen with decaying organic materials to make carbonic acid. Consequently, water seeping through organic remains becomes more and more acidic and its effectiveness as a weathering agent continually increases. Other acids are also produced by plant activity and by bacterial decay of plant and animal remains. The result is seen dramatically in regions such as the Great Lakes area, where rivers flow through bogs and marshes and the organic acids stain the water yellowish brown. Human activities have also produced acids that contaminate surface waters, including sulfuric acid and nitric acid in acid rain and sulfuric acid from mining coal or sulfide minerals. The effects of these acids are seen in the corrosion of buildings and acidification of lakes and rivers and occasionally in the destruction of their biota.

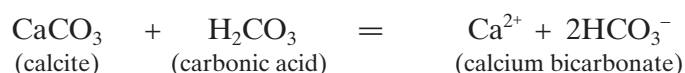
What are the products of chemical weathering?

Hydrolysis is a chemical reaction wherein water and another substance both decompose into ions; the OH^- ion groups with one of the fragments and the H^+ ion with another fragment. As you examine the following reactions, observe how the H^+ and the OH^- ions are derived from splitting water molecules. Hydrolysis can occur in pure water, but in the natural world it usually accompanies reactions with acids; thus, this kind of reaction between a mineral and an acid is usually called *acid hydrolysis*.

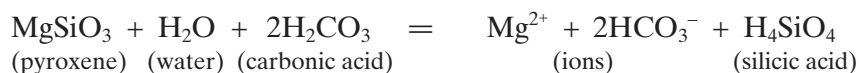
To simplify what is a far more complex series of reactions, we will illustrate weathering reactions involving calcite and carbonic acid. In pure water, calcite is not very soluble. But water with carbonic acid is capable of dissolving much more calcite than is pure water. Carbonic acid forms when rainwater combines with carbon dioxide in the atmosphere or the soil by the reaction:



This acid may then react with calcite to form calcium and bicarbonate ions in solution. This reaction may be expressed as follows:



Some silicate minerals may also dissolve, although not as readily as calcite. For example, pyroxene will slowly dissolve when it is in contact with acidic waters according to the following reaction:

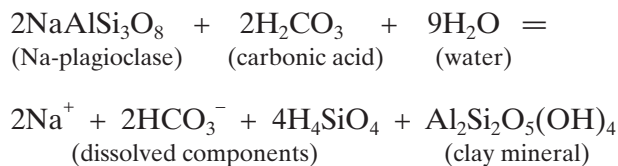


Acid Hydrolysis and Secondary Minerals

Another important kind of hydrolysis reaction involves the formation of new minerals, in addition to the dissolved ions. You might think of this as a kind of partial solution, with some ions going into solution and being carried away at the same time as a new mineral forms. During chemical weathering, these new minerals are almost all *hydrated*—that is, they have water in their structures. The water is not merely absorbed, as by a sponge, but actually incorporated as OH^- ions into the atomic structure of the new mineral (Figure 10.6). Most silicate minerals, especially those containing aluminum, do not simply dissolve in water. Instead, they react to form a new mineral and free ions.

A good example of the production of secondary minerals is the chemical weathering of feldspar. As you recall from previous chapters, feldspar is an abundant mineral in a great many igneous, metamorphic, and sedimentary rocks. It is therefore important to understand how feldspars weather and decompose to make clay minerals. In turn, these clay minerals are transported and deposited to form the most abundant sedimentary rock, shale (or, strictly speaking, mudrocks).

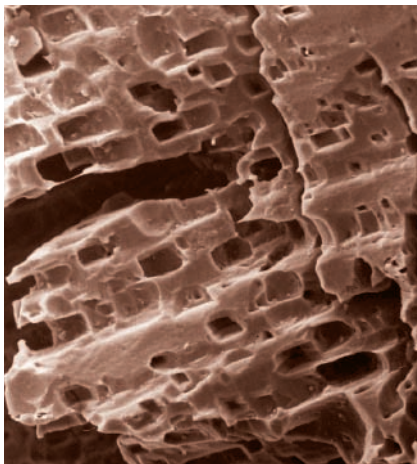
If plagioclase feldspar, the most common silicate mineral in the crust, comes in contact with water containing carbonic acid, the following general reaction takes place:



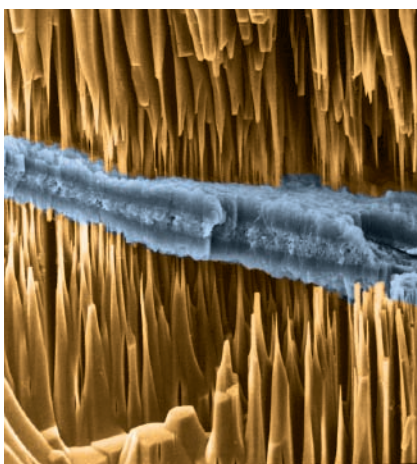
This reaction is simplified; it actually takes several steps to form clay. This clay mineral does not contain sodium, which was present in the original feldspar. The new mineral also has a new crystal structure, consisting of sheets of silicate

What are the major chemical reactions in weathering?

How are natural acids formed?



(A) Weathering creates small rectangular pits in plagioclase feldspar. The shapes of the pits are controlled by the internal arrangement of ions in the mineral's framework structure.



(B) Weathering corrodes amphibole to make long needles or cones of residual material controlled by the chain structure of the ions in the mineral. A thin vein of clay (purple) formed at the expense of the amphibole.

FIGURE 10.6 Chemical weathering of minerals can be seen with an electron microscope. The magnification is about 3000 times. (Courtesy of E. Berner and R. A. Berner)

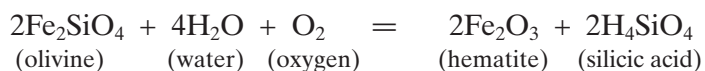
tetrahedra that form submicroscopic crystals (see Figure 3.15). The Na^+ ion is dissolved in the water. Silica is also released from the minerals and goes into solution in the water as a weak acid (H_4SiO_4). The water may then carry the dissolved components away from the site of reaction. For example, the sodium eventually accumulates in ocean water as dissolved salt. As a result of weathering reactions like this, the shales that form from the accumulation of such clays are poor in sodium, compared with their igneous precursors.

Potassium and calcium feldspars go through similar weathering reactions to produce clays, but K^+ ions are largely retained in the soil by absorption and become important nutrients for plants. When the plants die, the potassium is returned to the soil. Many of the Ca^{2+} ions released by weathering are transported to the oceans, but they eventually react with dissolved CO_3^{2-} to form carbonate minerals. These two processes leave seawater rich only in Na^+ .

The effects of chemical weathering of minerals are clearly seen with a scanning electron microscope and are truly remarkable (Figure 10.6). Rectangular etch pits develop on weaknesses in the crystal structure of plagioclase, shown here at a magnification of 3000 times. As weathering proceeds, the pits grow and merge to destroy the fabric of the rock containing the feldspar. A macroscopic example of the effects of chemical weathering can be seen in the fragments of ancient granite columns that were partly buried in the mud of the Nile floodplain (Figure 10.7). Weathering destroyed the delicate carvings in the monuments as feldspar converted to clay minerals.

Oxidation

Oxidation is the chemical combination of oxygen, in the atmosphere or dissolved in water, with one mineral to form a completely different mineral in which at least one of the elements has a higher oxidation state (higher ionic charge). Of the elements that have variable charges, iron is the most important in weathering reactions on Earth. In most silicates, iron is present as Fe^{2+} , but in the presence of Earth's modern oxygen-rich atmosphere, Fe^{3+} is the favored oxidation state. Therefore, oxidation is especially important in the weathering of minerals that have a high iron content, such as olivine, pyroxene, and amphibole. Oxidation of silicates is commonly accompanied by hydrolysis and partial solution. In the case of olivine, the reaction is as follows:



In this reaction, the iron in silicate minerals unites with oxygen to form the mineral hematite (Fe_2O_3). Hematite is deep red, and if it is dispersed in sandstone or shale, it imparts a red color to the entire rock. Limonite [$\text{FeO}(\text{OH})$] is another common weathering product. It is formed by oxidation combined with a reaction with water.

Concluding Notes

By carefully examining the reactions above and Tables 10.1 and 10.2, you should be able to detect a general pattern for chemical weathering. Most alkali (e.g., Na and K) and alkaline earth (e.g., Ca and Mg) elements are removed into solution by weathering reactions (Table 10.1) and eventually become enriched in seawater (Table 10.2). On the other hand, the solid mineral residue becomes enriched in Al, Si—incorporated in clays—and Fe—incorporated in oxides. These minerals are stable in the surface environment.

Figure 10.8 lists common minerals in order of their susceptibility to chemical weathering. This is a powerful example of how the materials in Earth's systems are constantly changing toward equilibrium. Minerals at the top of the list weather



FIGURE 10.7 A column of granite from a temple in Lower Egypt fell over and its right side was partially buried for hundreds of years. Moisture in the soil facilitated hydrolysis and altered much of the feldspar to clay. The left side of the column was exposed only to the dry atmosphere and remained fresh and unaltered for more than 2000 years.

easily and rapidly; those at the bottom weather slowly and are resistant to change. Note that the order shown for igneous silicate minerals corresponds to their typical temperature of formation. Thus, olivine weathers more readily than plagioclase and plagioclase more readily than muscovite. Moreover, these minerals commonly weather to form minerals found low on the list—minerals that are stable at the cool, wet, oxygen-rich surface of the planet.

Inasmuch as feldspars and other silicate minerals that weather into clay constitute a large percentage of igneous and metamorphic rocks, an enormous amount of clay has been produced by the weathering of these minerals throughout geologic time. It has been calculated that sediment and sedimentary rocks have an average thickness of 3 km throughout the ocean basins, 5 km on the continental shelves, and 1.5 km on the continents. Because clay makes up about one-third of all sedimentary rocks, the total amount of clay would form a layer almost 2 km thick if spread uniformly over the entire surface of Earth.

We have considered physical and chemical weathering as separate processes, but in nature they are inseparable because many types of weathering processes are usually involved in the weathering of any outcrop. Mechanical fracturing of a rock increases the surface area, where chemical reactions take place, and permits deeper penetration of reactive fluids that cause chemical decomposition. Chemical decay in turn facilitates physical disintegration. One process may dominate in a given area, depending on the climate and rock composition, but physical and chemical weathering processes generally attack the rock at the same time.

WEATHERING OF MAJOR ROCK TYPES

The weathering of rocks is influenced by a number of variables, such as the mineral composition, the texture of the rock, and the climate in which weathering occurs. Differential weathering is a result of differences in the rates of weathering.

Weathering is influenced by so many factors that it is difficult to make a meaningful generalization concerning the weathering of specific rock types. Limestone, for example, may weather and erode into a soil-covered valley in a humid climate, whereas the same formation forms a cliff in an arid climate. Similarly, a well-cemented quartz sandstone may be extremely resistant to weathering, whereas a sandstone with a high clay content is likely to be soft and weak and weather rapidly.

TABLE 10.1 Weathering Reactions for Common Minerals				
Original Mineral	General Formula	Weathering Reactions	Dissolved Ions	Residual Minerals
Gypsum	CaSO ₄ •2H ₂ O	Dissolution by water	Ca, SO ₄	
Halite	NaCl	Dissolution by water	Na, Cl	
Olivine	(Mg,Fe) ₂ SiO ₄	Oxidation		Fe oxides
		Dissolution by acid	Mg, Fe	
Pyroxene	Ca(Mg,Fe)Si ₂ O ₆	Oxidation		Fe oxides
		Dissolution in acid	Mg, Fe, Ca	
Amphiboles	NaCa(Mg,Fe) ₅ AlSi ₇ O ₂₂ (OH) ₂	Oxidation		Fe oxides
		Partial solution by acid	Na, Ca, Mg	Clay
Plagioclase	NaAlSi ₃ O ₈ to CaAl ₂ Si ₂ O ₈	Partial solution by acid	Na, Ca	Clay
K-feldspar	KAlSi ₃ O ₈	Partial solution by acid	K	Clay
Muscovite	KAl ₃ Si ₃ O ₁₀ (OH) ₂	Partial solution by acid	K	Clay
Biotite	K(Mg,Fe) ₃ AlSi ₃ O ₁₀ (OH) ₂	Oxidation		Fe oxides
		Partial solution by acid	K, Mg	Clay
Quartz	SiO ₂	Resists dissolution		
Calcite	CaCO ₃	Dissolution by acid	Ca	
Dolomite	CaMg(CO ₃) ₂	Dissolution by acid	Mg, Ca	
Pyrite	FeS ₂	Oxidation	SO ₄	Fe oxides

Why is seawater so rich in sodium, calcium, and magnesium?

Mineral composition is of prime importance. Some minerals, such as quartz, are very stable and remain essentially unaltered for long periods of time; others, such as olivine and the feldspars, are very unstable and begin to decompose almost immediately (Figure 10.8). The texture of the rock is also very significant because of its influence on **porosity** and **permeability**, which govern the ease with which water can enter the rock and attack the mineral grains. Precipitation and temperature are the chief climatic controls, but weathering will be influenced not only by the total rainfall, but also by the distribution of precipitation through time, percent of runoff, and rate of evaporation. Therefore, a given rock will respond to weathering in a variety of ways, but in general the major rock groups weather in a characteristic fashion.

Granite is a massive homogeneous rock composed of feldspar, quartz, and mica, with minor amounts of other minerals. It forms at high temperatures, in considerable depth, and under great pressure, so it is out of physical and chemical equilibrium when exposed at Earth’s surface. For example, the release of pressure resulting from the erosion of the overlying rocks produces expansion joints, which aid in the development of exfoliation.

TABLE 10.2 Contribution of Weathering to Water Compositions (in parts per million)				
Component	Rain-water	River Water	Ground-water	Ocean Water
HCO ₃ ⁻	0.5	58	93	28
SO ₄ ²⁻	2	11	32	905
Cl ⁻	1	7	5	19,400
Ca ²⁺	1	15	27	412
Mg ²⁺	0.5	44	6	1,290
Na ⁺	1	6	9	10,800
K ⁺	0.5	2	1	380
Fe ²⁺		0.6	1.6	0.1
Si ⁴⁺		6	18	2

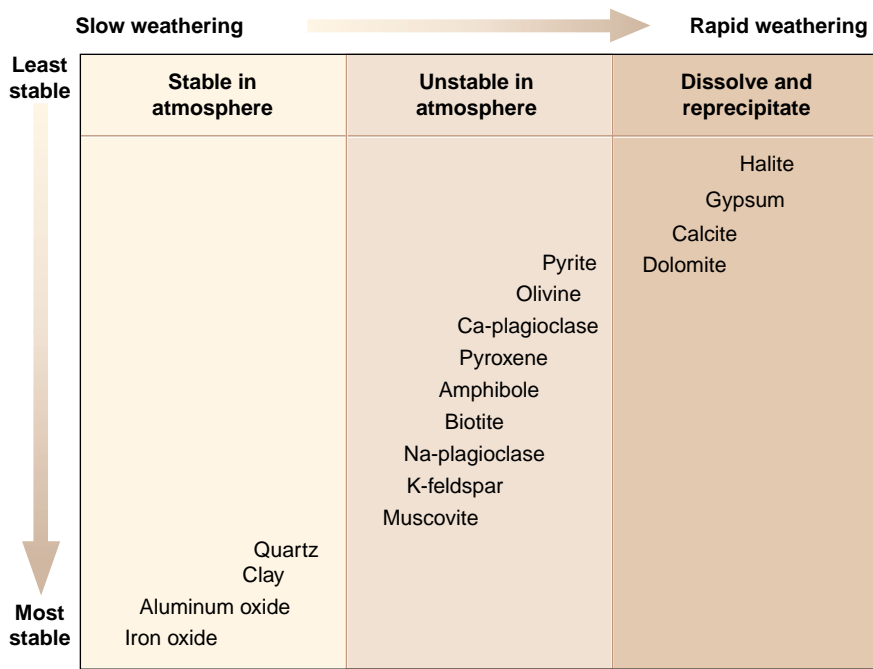


FIGURE 10.8 Relative susceptibility to weathering varies widely among common minerals found at Earth's surface. Minerals at the top of the diagram react to form minerals near the bottom that are stable at low temperatures and pressures and in the presence of abundant water and oxygen. The ultimate weathering products of many rocks are clays, quartz, and oxides of aluminum and iron.

Feldspars weather rapidly by chemical reaction with water and are altered to various clay minerals. Calcium plagioclase is least resistant, followed by potassium feldspars. Mica weathers somewhat more slowly than most feldspars but is easily attacked along its cleavage planes by water, and oxidation of iron and ion exchange are common. Micas alter, with little change in structure, to chlorite and clay minerals. In contrast, quartz is very resistant to both chemical and physical weathering and remains essentially unaltered as the other minerals are decomposed. Therefore, it constitutes the most significant particle or fragment produced by the weathering of a granite.

Basalt is a fine-grained rock composed mostly of feldspar, olivine, and pyroxene. The surface of a basalt flow is generally vesicular and very porous, and the interior of the rock body is commonly broken by a system of columnar joints. Therefore, flows are highly permeable and susceptible to decomposition. Olivine, pyroxene, and calcium plagioclase—the most common minerals in basalt—are all highly susceptible to chemical weathering. Quartz is not present in basalt, so most minerals in this rock are eventually converted to clay and iron oxides. The ultimate weathering product is a red or brown soil.

Sandstone is composed mostly of quartz grains, with varying amounts of small rock fragments, feldspar, and clay minerals. The quartz in sandstone is highly resistant to chemical weathering, so chemical decomposition of the rock consists largely of an attack on the cement. The major cementing materials in sandstones are calcite, iron oxide, and quartz.

Limestone is composed mostly of the mineral calcite, although it generally contains some clay and other impurities. It is the most soluble of the common rock types, and (except in extremely dry climates) solution is the dominant weathering process. In most limestone regions in humid climates, solution activity enlarges joints and bedding planes and forms a network of caverns and caves; the limestone formations in such regions typically form valleys. In arid regions, where solution activity is at a minimum, limestones form cliffs.

Shale commonly weathers faster than most other rocks because it is fine-grained and soft. Because it contains a high proportion of clay, it has the ability to absorb and expel large amounts of water.

Why do various rock types weather in different ways?

Why do rocks weather at different rates?

Differential Weathering

As can be seen from the preceding brief descriptions, different rock masses, or different sections of the same rock, weather at different rates. This variation is known as **differential weathering**. It occurs on a broad scale, from the great sandstone ridges of the Appalachian Mountains to delicate etching of thin layers in sedimentary rock. The more-resistant zones stand out as ridges, and the weaker zones form depressions. Differential weathering can lead to the formation of unusual shapes and forms, such as the spindles and pinnacles in Bryce Canyon (see the chapter-opening photograph) or pits and caverns on a rock face. Differential erosion on dikes of igneous rocks can form trenches or walls, depending on whether the dike is harder or softer than the surrounding rock.

Differential weathering can be seen everywhere a rock is exposed. Study the photo of Bryce Canyon and you will notice that each layer has its own weathering characteristics. The white layers erode most rapidly and tend to form slender columns. The thicker beds of sand are more resistant, whereas the interbeds of siltstone and shale weather rapidly. Thus, the horizontal layers are etched into ridges and furrows, which are responsible for much of the beauty in this scene.

PRODUCTS OF WEATHERING

The major products of weathering are (1) rock bodies modified into spherical shapes; (2) a blanket of loose, decayed rock debris, known as regolith, of which soil is an important part; and (3) ions in solution.

Geometry of Weathered Rock Fragments

The breakdown of rocks and the shapes of most rock fragments are inherited from patterns of joints, bedding, cleavage, and other planes of structural weakness in the parent rock material. The best way to appreciate how joints, bedding planes, and other planes of weakness influence the geometry of rock fragmentation is to compare and contrast outcrops of several rock types and consider the shape of the fragmented material that weathering has produced (Figure 10.9).

Importance of Fractures and Joints. Almost all rocks are broken into a system of fractures that greatly influence the weathering of rock bodies in two ways. First, they effectively cut large blocks of rock into smaller ones, thereby increasing the surface area where chemical reactions take place. The importance of joints in weathering processes can be appreciated by considering the amount of new surface area produced by jointing. Consider, for example, a cube of rock that measures 10 m on each side (Figure 10.10). If only the upper surface of the cube were exposed and the rock were not jointed, weathering could attack only the exposed top surface of 100 m². If the block were bounded by intersecting joints 10 m apart, however, the surface area exposed to weathering processes would be 600 m². If three additional joints cut the cube into eight smaller cubes, the surface exposed to weathering would be 1200 m². If joints 1 m apart cut the rock, 6000 m² of rock surface would be exposed. Obviously, a highly jointed rock body weathers much more rapidly than a solid one. The breakdown of a rock along a system of jointing planes is known as **joint-block separation**. Figure 10.9A shows a basalt flow that broke into hexagonal columns as it cooled.

Besides providing a larger surface area for chemical decomposition, joints also act as a system of channels through which water can more readily penetrate a rock body. Joints thus permit physical and chemical weathering processes to attack the rock from several sides, even hundreds of meters below the surface.



(A) Joint-block separation results when prominent fractures divide the rock into small blocks. The Devil's Post Pile in California is an excellent example, where columnar joints control the geometric patterns of rock breakup.



(B) Bedding-plane separation occurs along a bedding zone of weakness in sedimentary rocks and causes the rock to break up into slabs. Foliation in metamorphic rock causes similar type of weathering.



(C) Jointing is commonly the major type of structural weakness in granite and related rocks and causes the rock to break up into large blocks. Spheroidal weathering then rounds the edges of the fragments.



(D) Granular disintegration in granite is common, producing crumbly spheroidal boulders. The disintegrated material consists of feldspars weathered to clay and quartz grains. The dissolution of calcite cement in a sandstone also causes granular breakdown.

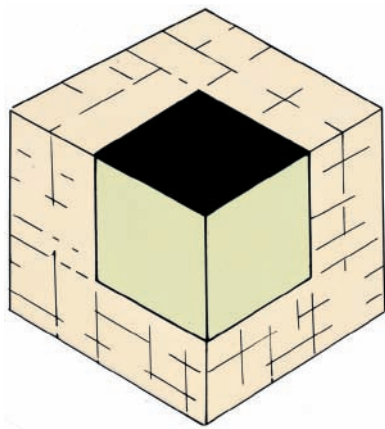


(E) Exfoliation occurs when the solid rock mass comes apart in a series of shells or plates that roughly conform to the shape of the outer surface. Exfoliation can occur on a very large scale, such as on this dome in Yosemite National Park, California, or on a very small scale, with the individual plates being only a millimeter or less thick.

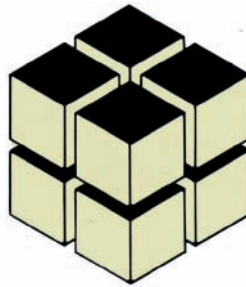


(F) Shattering occurs when a rock is subjected to severe stress that ruptures the rock into sharp, irregular, angular blocks. Ice wedging shatters rock outcrops in nature. Repeated cycles of heating and cooling may also cause shattering. Blasting bedrock with explosives produces shattering artificially.

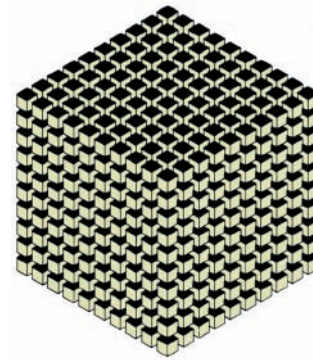
FIGURE 10.9 The geometric patterns of rock disintegration depend on the composition, texture, and structure (especially layers and joints) of the parent rock body.



(A) A surface of bedrock, 10 m long and 10 m wide, with no joints, exposes a total area of 100 m^2 to weathering processes. A set of joints 10 m apart would expose more rock to the atmosphere and would increase the surface area vulnerable to weathering to 600 m^2 .



(B) Three additional joints, dividing the block into eight cubes, would increase the surface area to 1200 m^2 .



(C) If joints 1 m apart cut the rock, the surface area exposed to weathering would be increased to 6000 m^2 .

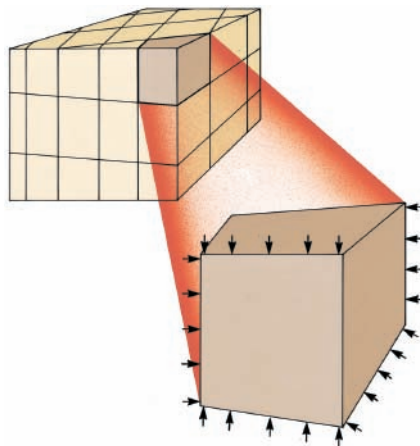
FIGURE 10.10 A system of joints cutting a rock body greatly increases the surface area exposed to weathering.

Spheroidal Weathering

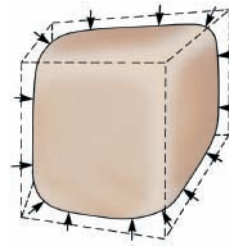
In the weathering process, there is a universal tendency for rounded (or spherical) surfaces to form on a decaying rock body regardless of the original shapes of the rock fragments. The sphere is the geometric form that has the least amount of surface area per unit of volume. A rounded shape is produced because weathering attacks an exposed rock from all sides at once, and decomposition is most rapid along the corners and edges of the rock (Figure 10.11). As the decomposed material falls off, the corners become rounded, and the block eventually is reduced to an ellipsoid or a sphere. Once the block attains this shape, it simply becomes smaller with further weathering. This process is known as **spheroidal weathering**.

Examples of spheroidal weathering can be seen in almost any exposure of rock (Figure 10.12). It can also be seen in the rounded blocks of ancient buildings and monuments. The original blocks had sharp corners and were fitted together with precision. The edges are now completely decomposed, and each block has assumed an ellipsoidal or spherical shape. In nature, spheroidal weathering is produced both at the surface and at some depth.

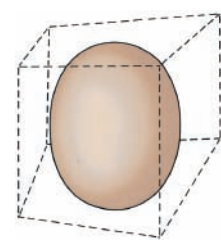
FIGURE 10.11 Spheroidal weathering occurs because the edges and corners of a joint block are easily decomposed.



(A) Joint systems cut a rock body into angular blocks.



(B) On each block, weathering proceeds inward from the joint face.



(C) The corners of the block are soon completely decomposed, so the weathered rock assumes a spherical or ellipsoidal shape.



FIGURE 10.12 Spheroidal weathering shapes natural outcrops like these jointed and weathered granite blocks from near Prescott, Arizona.

Exfoliation is a special type of spheroidal weathering in which the rock breaks apart by separation along a series of concentric shells or layers that look like cabbage leaves (Figure 10.9E). The layers, essentially parallel to each other and to the surface, develop by both chemical and physical means. Exfoliation may involve sheeting in rocks such as granite; if they are brought to the surface after deep burial, they have a tendency to expand upward and outward as the overlying rock is removed. In cold climates, ice wedging along the sheeting joints helps to remove successive layers gradually. The increase in volume of mineral grains associated with the chemical weathering of feldspar might also promote exfoliation. Exfoliation causes massive rocks, such as granite, to develop a spherical form characterized by a series of concentric layers ranging from boulders to a mountain.

Regolith

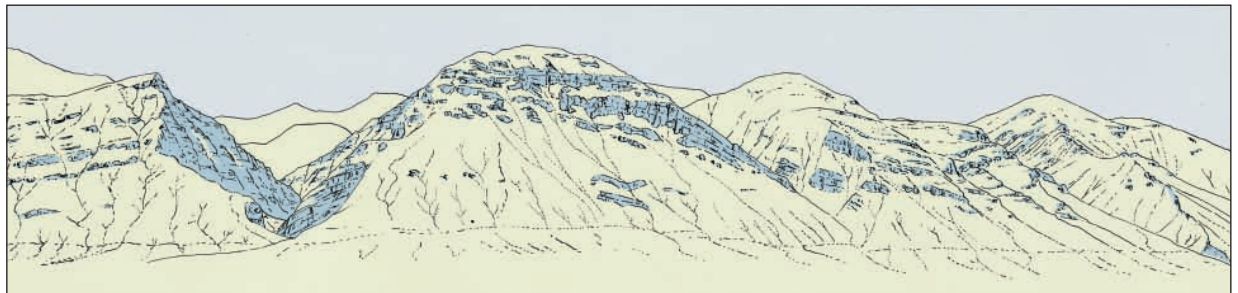
The results of weathering can be seen from the driest deserts and the frozen wastelands, to the warm, humid tropics. The most obvious product of weathering is a blanket of loose, decayed rock debris known as **regolith**, which forms a discontinuous cover over the solid, unaltered bedrock below it. The term *regolith* comes from the Greek work *rego*, meaning “blanket” (blanket rock). It is a layer of soft, disaggregated rock material formed in place by the decomposition and disintegration of the bedrock that lies beneath it. Within the regolith, the individual grains or small groups of mineral particles are easily separated, one from the other. The thickness of the regolith ranges from a few centimeters to hundreds of meters, depending on the climate, type of rock, and length of time that weathering processes have been operating. The transition from bedrock to regolith can be seen in road cuts and stream valleys.

Gravel, sand, silt, and mud deposited by streams, wind, and glaciers are sometimes referred to as transported regolith, in order to distinguish them from the residual regolith produced by weathering. Many types of transported regolith, or surficial deposits, have been identified, and we will learn more about them in later chapters dealing with rivers, glaciers, and wind.

A regional view of the regolith and its relationship to bedrock is given in Figure 10.13. The photograph shows exposures of bedrock limited to certain areas of resistant limestone and sandstone strata, which form discontinuous cliffs along the upper part of the mountain front. On the steep canyon walls, little soil is retained, and bedrock is exposed from the base to the top of the canyon. The sketch in (B) was made from the photograph and outlines the rock outcrops. In (C), the out-



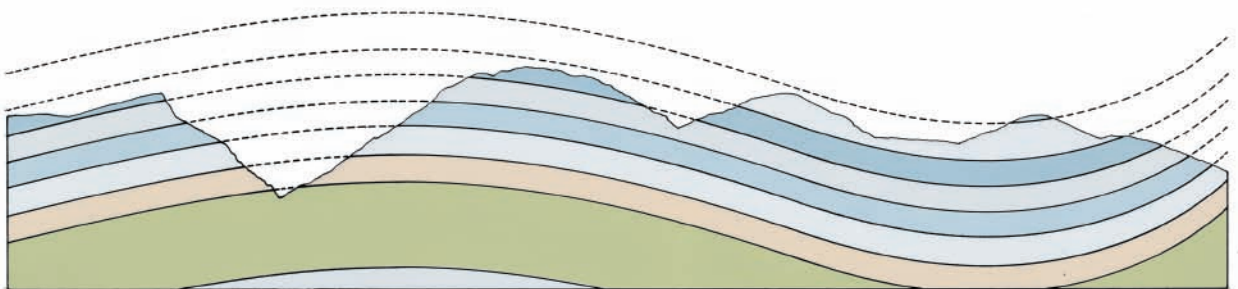
(A) The Wasatch Range in central Utah displays contrasting areas of bedrock and regolith.



(B) Outcrops of bedrock appear in cliffs and canyons. Slopes are covered with regolith.



(C) The discontinuous blanket of regolith almost completely covers some formations, while others are exposed as discontinuous cliffs. Outcrops of bedrock form "holes" in the regolith cover.



(D) The structure of the bedrock consists of rock layers warped into broad folds, some of which are cut by canyons. Compare with (A).

FIGURE 10.13 The relationship between bedrock and regolith is depicted in the photograph and diagrams.

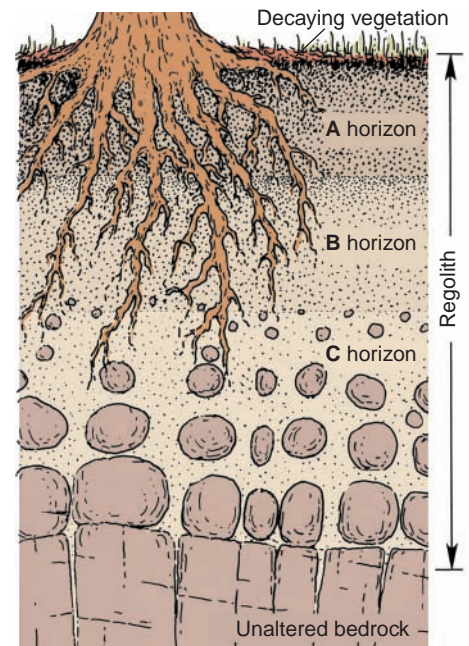


FIGURE 10.14 A soil profile for a temperate climate shows the transition from bedrock to regolith through a sequence of layers, or horizons, consisting of successively smaller fragments capped by a dark layer of decomposed organic material.

cropping bedrock is not shown, so the regolith appears as a thin, discontinuous blanket with “holes” where bedrock is exposed. Sediment fills the valley in the foreground, but the regolith there is not shown in the diagram. If you carefully study the pattern of exposed bedrock areas (B), you can see that the strata are warped into broad folds, shown in (D), which form the internal structure of the mountains.

Soil

The uppermost layer of the regolith is the **soil**. It is composed chiefly of small particles of rock, new minerals formed by weathering, plus varying amounts of decomposed organic matter. Soil is so widely distributed and so economically important that it has acquired a variety of definitions, and you should be aware that the term, as used by engineers, geologists, farmers, and soil scientists, has somewhat different definitions.

The transition from the upper surface of the soil down to fresh bedrock is a **soil profile**, which shows a rather systematic sequence of layers, or **horizons**, distinguished by composition, color, and texture. These are shown in Figure 10.14 for a humid temperate climate. The **A horizon** is the topsoil layer, which often is visibly divided into three layers: A_0 is a thin surface layer of leaf mold, especially obvious on forest floors; A_1 is a humus-rich, dark layer; and A_2 is a light, bleached layer. The **B horizon** is the subsoil, which contains fine clays and colloids washed down from the topsoil. It is largely a zone of accumulation and commonly is reddish in color. The **C horizon** is a zone of partly disintegrated and decomposed bedrock. The individual rock fragments are often weathered, spheroidal boulders that may be completely decomposed. The C horizon grades downward into fresh, unaltered bedrock.

Several special kinds of soils are worth noting here. The major soil orders are described in Table 10.3 and their distribution is shown in Figure 10.15. Some soils are noteworthy because they are ore deposits. For example, aluminum does not migrate far during weathering, and, in fact, it may be concentrated as a residual deposit as other elements are removed. The enrichment may be great enough to form aluminum ore—bauxite. Iron is also insoluble in the presence of dissolved oxygen

What is the ultimate origin of soil?

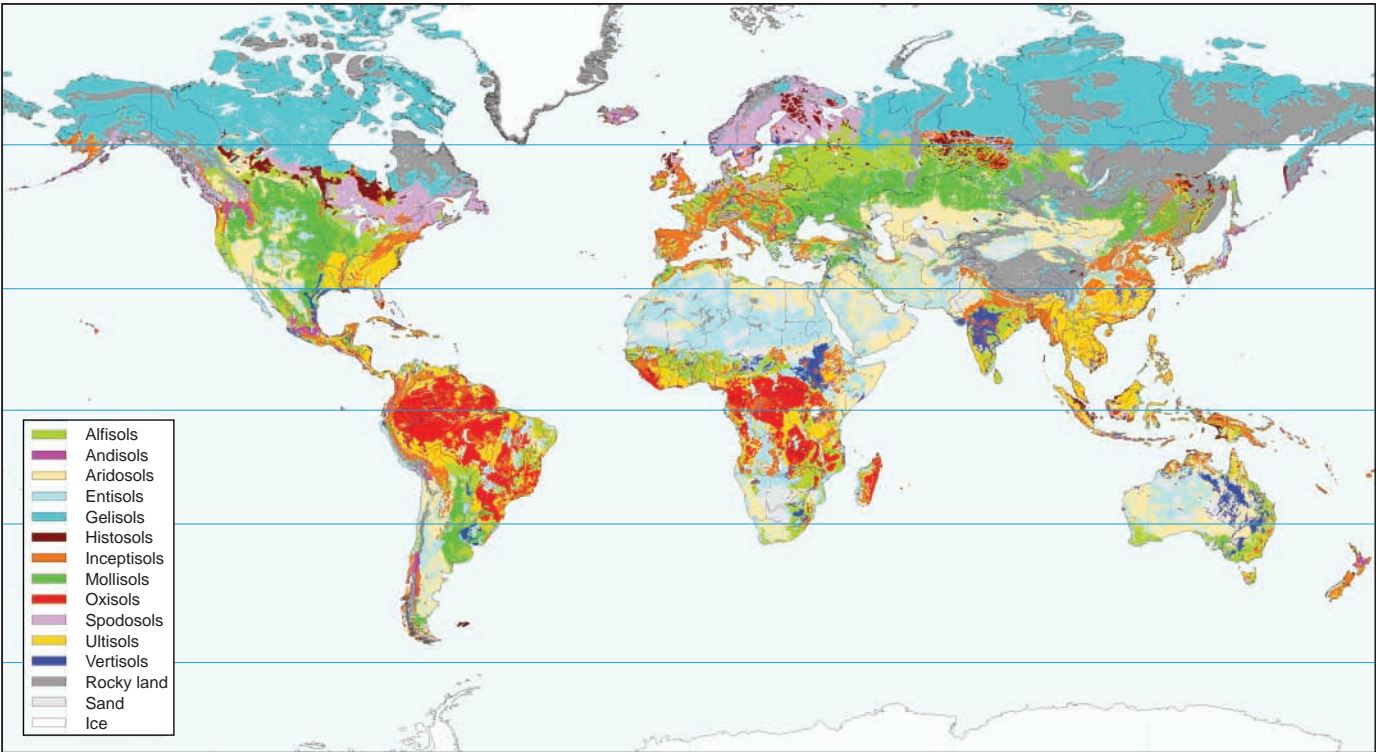


FIGURE 10.15 Principal soil types of the world are shown on this map. The various soils are classified based on obvious physical characteristics including organic matter and clay content, the degree of nutrient depletion, soil chemistry, and origin or age of the soil. See Table 10.3 for a description of the major features of each type of soil. Note the strong control of climate on soil types. (Modified after U.S. Department of Agriculture)

TABLE 10.3 Major Types of Soil

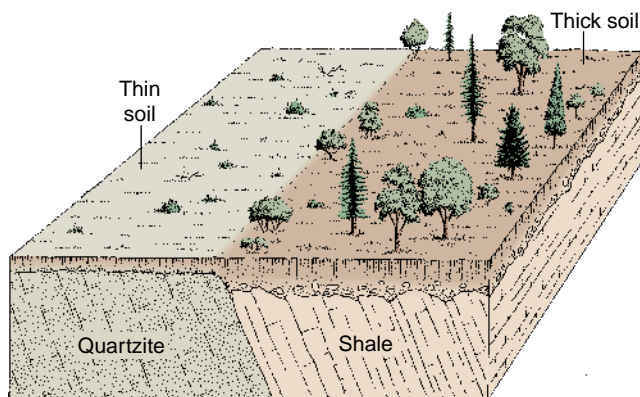
Soil Order	General Characteristics	Typical Geographic or Geologic Setting
Andisols	Soils that form by weathering of volcanic parent material	Common in volcanic areas like Japan, Alaska, and Pacific Northwest
Entisols	Only slightly weathered with minimal development of soil horizons. Similar to parent material	Young surfaces, slopes, and sand dunes
Aridisols	Thin A and B horizons with little organic matter Carbonate deposits (caliche) common in B horizon	Arid regions
Gelisols	Soils with a dark organic surface layer underlain by permafrost	Arctic regions of North America and Russia
Histosols	Dark soils dominated by decomposed organic matter	Typically in poorly drained low-lying areas
Inceptisols	Well developed A horizon, but little clay. Still retain weatherable minerals.	Relatively young surfaces or resistant bedrock
Mollisols	Dark organic-rich A-horizon. Nutrient-rich parent material.	Common in grasslands of stable platforms in temperate climates
Alfisols	Thin A horizon and clay and nutrient-rich B horizon	Semi-arid to humid climates; good agricultural soil
Spodosols	Strongly leached A-horizon with aluminum and iron-rich B-horizon	Coniferous forests in cool temperate climates
Vertisols	Clay-rich soils that shrink when dry and swell when wet	Tropical regions with wet and dry seasons
Oxisols	Deeply weathered with oxidized iron apparent in B horizon Red or yellow	Humid tropical to subtropical regions of low relief
Ultisols	Highly weathered clay-rich B horizon with high concentrations of aluminum and low in nutrients	Warm, humid regions; with fertilizer they can be used for agriculture

and also accumulates in soils. Intensely weathered soils are typically red because of the presence of secondary iron oxide minerals formed by weathering. Such residual laterites may also be enriched in other insoluble elements such as nickel and make ore deposits. (see Figure 10.18)

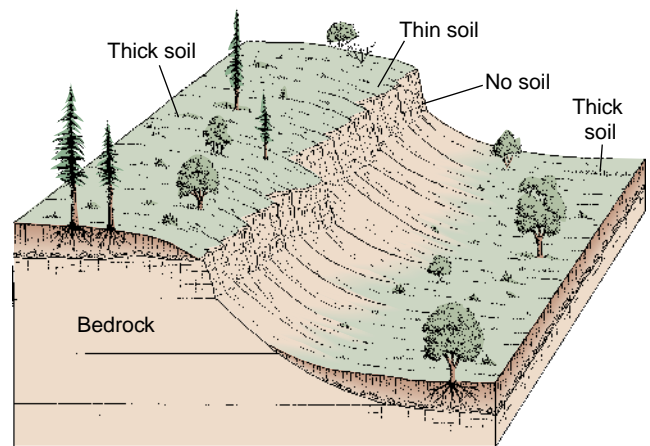
As do so many other aspects of weathering, the type and thickness of soil depend on a number of factors, the most important of which are parent rock composition, topography, and time. The mineral composition of the bedrock strongly influences the type of soil because the bedrock provides the chemical elements and mineral grains from which the soil develops. Pure quartzite, for example, contains 99% quartz and is extremely deficient in minerals that can weather to make clays. Its decomposition produces a thin, infertile soil poor in plant nutrients (Figure 10.16A).

Topography affects soil development because it influences the amount and rate of erosion and the nature of drainage. Flat, poorly drained lowlands develop a bog-type soil, rich in decomposed vegetation and saturated with water, whereas steep slopes permit rapid removal of regolith and inhibit the accumulation of weathered materials. Well-drained uplands are conducive to thick, well-developed soils (Figure 10.16B).

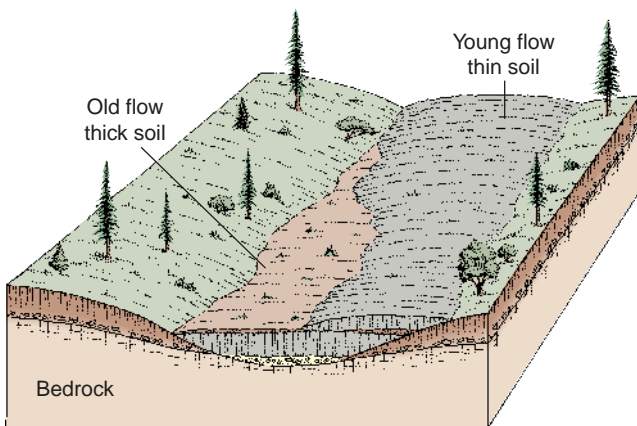
Time is important in soil development in that it takes time for physical and chemical processes to break down the bedrock. In Figure 10.16C, the young lava flow has a very thin, patchy soil, whereas the older flow has had time for a thick soil layer to develop.



(A) The influence of rock type is illustrated by the difference between a layer of quartzite and a layer of shale. Quartzite resists chemical decomposition, so the soils produced from it are thin and poorly developed. Shale is much more susceptible to chemical weathering and forms thicker soils.



(B) The influence of topography is apparent from the contrast between slope soils and valley soils. Thick soils can form on flat or gently sloping surfaces, but steep slopes permit only thin soils to develop.



(C) The influence of time can be seen in areas of volcanism. Thick soils have developed on old lava flows, in contrast to thin soils on younger flows.

FIGURE 10.16 Topography, rock type, and time also affect the thickness of soil.



FIGURE 10.17 Dissolved ions are one of the major products of chemical weathering. Here, along the margins of a salt pan in Death Valley, California, the salts once dissolved in river water accumulated in a shallow lake that then evaporated. The volume of salt in these evaporite deposits reveals the amount of dissolved materials.

Ions in Solution

The ions dissolved in water are almost invisible products of weathering. A chemical analysis of rainwater compared with river water illustrates the effectiveness of chemical weathering in dissolving and transporting many elements (Table 10.2). Fresh rainwater contains relatively little dissolved mineral matter, but surface water soon dissolves the more soluble minerals in the rock and transports ions away in solution (Figure 10.17). Each year the rivers of the world carry about 4 million metric tons of dissolved materials to the oceans (Table 10.2). It is not surprising, then, that seawater contains 3.5% (by weight) dissolved salts, most of which were derived from the continents by chemical weathering.

The major source of ions in solution are carbonate rocks. About 45% of the dissolved material in rivers is derived from carbonates, even though they constitute only about 16% of the continental area exposed to weathering. Evaporites are also made of very soluble minerals—salts of potassium, sodium, magnesium, chlorine, and sulfate. Despite the fact that they make up only about 1% of the area of the continents, fully 18% of the ions in solution in rivers appear to be derived from evaporites. If we consider only one constituent, about 80% of the chloride in the Amazon River comes from halite dissolution, not from the weathering of silicate minerals. Other rocks are much less soluble than carbonates and evaporites. Silicate rocks account for more than 80% of the land area but only about 35% of the dissolved constituents of river water. The effect of susceptibility of rock types to chemical weathering is the important factor here.

CLIMATE AND WEATHERING

Climate is the single most important factor influencing weathering. It determines not only the type and rate of weathering, but also the characteristics of regolith and weathered rock surfaces. Intense chemical weathering occurs in hot, humid regions and develops a thick regolith. Chemical weathering is minimal in deserts and polar regions.

Climate is of major importance in weathering because rainfall, temperature, and seasonal changes all directly affect the style and rates of weathering. The influence climate has on weathering is apparent in the striking contrasts of the soil in the tropics, deserts, and polar regions (Figure 10.18).

In physical weathering, perhaps the most important temperature changes are the ones that produce continual cycles of freezing and thawing that result in repeated expansion of water ice in the rock and soil, and thus mechanical fragmentation. The rate of chemical reactions (and biological activity) also tends to increase as temperature increases. Commonly, a 10°C increase in temperature doubles reaction rates.

Most chemical reactions, such as hydrolysis, dissolution, and oxidation, require the presence of water, so the total amount of precipitation in an area is clearly a major factor in weathering (Figure 10.15). But many factors such as the intensity of rain, seasonal variations, infiltration, runoff, and the rate of evaporation combine to influence weathering and weathered products in a given region.

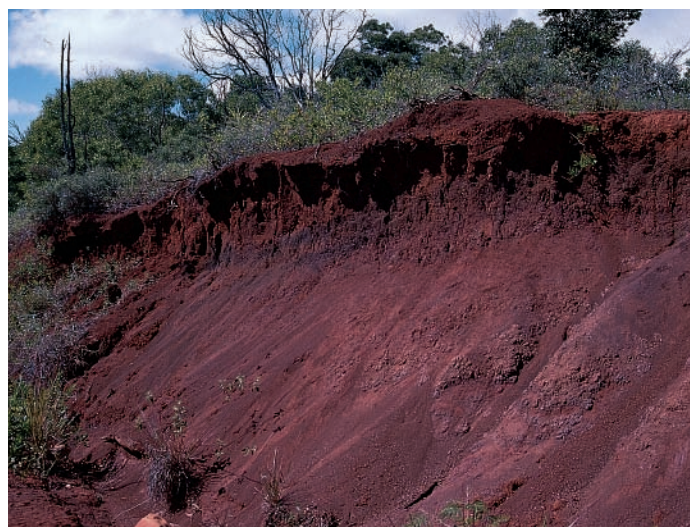
The extent and style of chemical weathering are not controlled entirely by temperature and total water supply; weathering may be greatly affected by other conditions. For example, many reactions are controlled by the water's acidity (hydrogen ion concentration), which is expressed as the pH value, ranging from 1 (acid) to 14 (alkaline). Iron, for example, becomes 100,000 times as soluble at pH 6 as it is at pH 8.5. Tropical climates typically support lush vegetation that yields organic acids. As a result, forested areas experience higher rates of chemical weathering than in otherwise similar areas that lack such growth. Some studies suggest weathering to be eight times as high as in forested areas as compared to nonforested areas, other things being equal. Moreover, high temperatures and abundant water can also increase the rate of bacterial activity, important in the production of acid.

The relative importance of various types of weathering under different climatic conditions (temperature and rainfall) is shown in Figure 10.19. High temperature and high precipitation cause intense chemical weathering. Physical weathering dominates in regions of low temperature and low rainfall. Perhaps the best way to appreciate the influence of climate on weathering is to consider variations in the types and thicknesses of soils from the equator to the poles, as shown in Figure 10.20. This diagram summarizes the relationships between the amount of chemical weathering and variations in precipitation and temperature.

In humid, **tropical climates**, extreme chemical weathering rapidly develops thick soils to depths greater than 70 m (Figure 10.20). In central Brazil, the zone of decayed rock is more than 150 m thick. Under such conditions, the feldspars are completely altered to clays, and all soluble minerals are leached out. Only the most insoluble materials (such as silica, aluminum, and iron) remain in the thick, red soil (Figure 10.18). These are not good soils for continued agriculture, because plant nutrients are leached away by the abundant rainfall. The high temperatures in tropical zones speed chemical reactions, so chemical decomposition is very rapid. Frost action, of course, is essentially nonexistent in the tropics, except on the tops of high mountains.



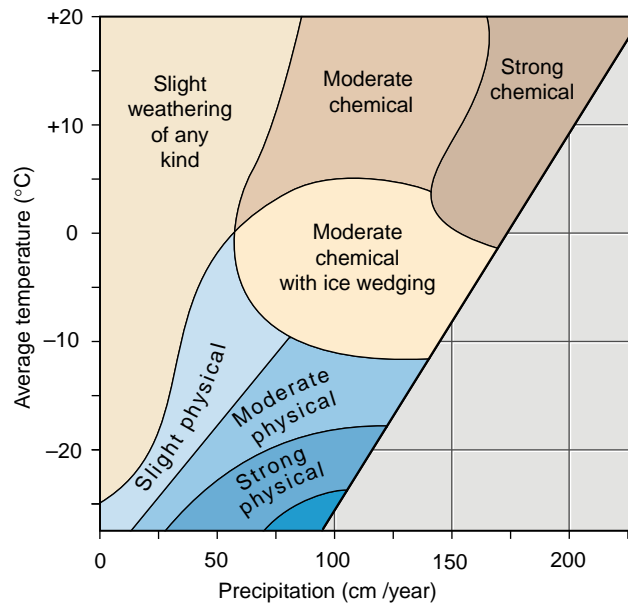
(A) Arctic weathering profile. Thin soils, with partly decomposed rock fragments, develop in polar regions. Physical weathering is dominant.



(B) Tropical weathering profile. Thick red (oxidized) soils develop in tropical regions. Chemical weathering dominates.

FIGURE 10.18 Climate is one of the important controls on the type of soil found in an area.

FIGURE 10.19 The relative importance of various types of weathering depends on temperature and rainfall. This diagram shows that strong chemical weathering occurs where both temperature and precipitation are high. Physical weathering is strongest where the mean annual temperature is between -10° and 10°C and precipitation is between 25 and 100 cm. Weathering is at a minimum where annual precipitation is below 25 cm.



In the low-latitude **deserts**, north and south of the tropical rain forests, chemical weathering is minimal because of the lack of precipitation. Moreover, organic matter is not abundant. Consequently, the soil is thin, and exposures of fresh, unaltered bedrock are common. Physical weathering is evident, however, in the fresh, angular rock debris that litters most slopes.

In the **temperate regions**, precipitation ranges from humid to subarid, and temperatures range from cool to warm. Both chemical and physical processes operate, and the soil and regolith develop to depths of several meters. The agricultural breadbaskets of the world are not in the tropics where soil is thickest, but in these temperate zones. Here, soils are moderately thick and have retained their nutrients. Moreover, temperate soils are commonly enhanced by added deposits of wind-blown dust.

In the **polar regions**, weathering is largely physical. Temperatures are too low for much chemical weathering, so the soil typically is thin and unproductive (Figure 10.18). It is composed mostly of angular, unaltered rock fragments. In permafrost zones (areas where water in the pore spaces of soil and rock is permanently frozen), the surface layer melts during the summer but freezes again in the winter. This unique condition produces polygonal ground patterns, which result from thermal contractions and the differential thawing and freezing.

Why are thin soils produced in both polar and desert regions?

RATES OF WEATHERING

The rate at which weathering processes decompose and break down a solid rock body depends on three main factors: (1) susceptibility of the constituent minerals to weathering, (2) climate, and (3) the amount of surface exposed to the atmosphere.

A consideration of the rate at which weathering proceeds is a good way to review its controlling factors. Rates of weathering can be calculated by measuring the amount of decay on rock surfaces of known age. Tombstones, ancient buildings, and monuments, for example, provide datable rock surfaces for estimating rates of weathering. These studies show that in some climates, several centimeters of rock can be decomposed in a few decades, whereas the same rock remains unaltered in other climates.

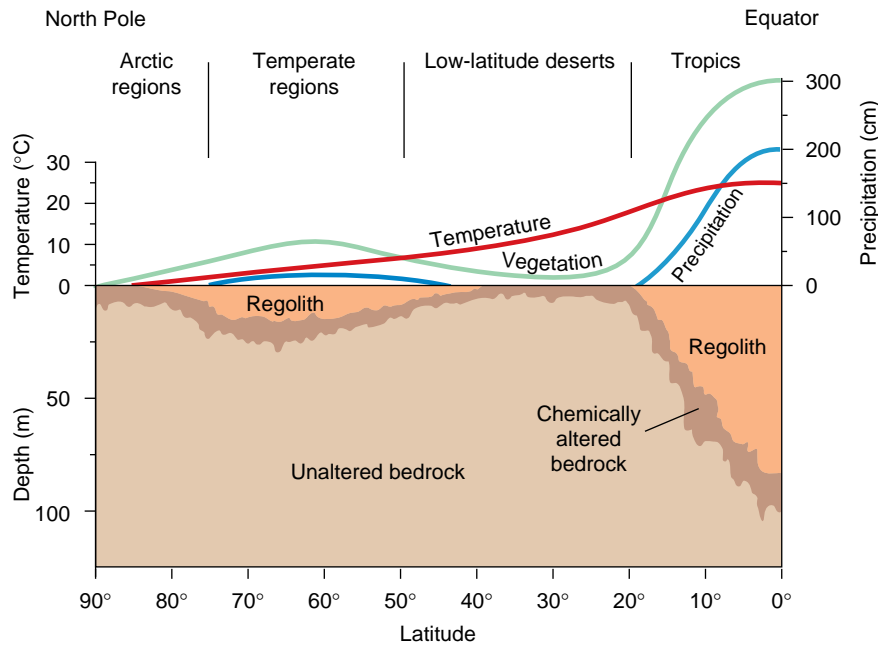


FIGURE 10.20 Climate controls the type and extent of weathering because of the combined effects of precipitation, temperature, and vegetation. (Other variables are also involved, such as those shown in Figure 10.16.) Weathering is most pronounced in the tropics, where precipitation, temperature, and vegetation reach a maximum. Conversely, a minimum of weathering is found in deserts and polar regions, where these factors are minimal. Compare this cross section with the map in Figure 10.15.

In places, rates of weathering have been measured on volcanic ash and basaltic lava flows that have been dated by radiometric means. For example, on the subtropical island of St. Vincent in the West Indies, a volcanic ash deposited 4000 years ago has weathered to produce a layer of clay soil 2 m thick. Soils have also formed on the ash deposits resulting from the 1883 eruption of the equatorial volcano Krakatua. Measurements made 45 years after the Krakatua eruption showed a new soil nearly 50 cm thick. Of course, the rates of weathering are much lower in polar climates and in the arid deserts.

The Egyptian pyramids provide an interesting example of rates of weathering in arid climates. The Great Pyramid of Cheops, near Cairo, was originally faced with polished, well-fitted blocks of travertine limestone. These blocks protected the rock in the pyramid core from weathering until the outer, polished layers were removed, about 1000 years ago, to build mosques in Cairo. Since then, without the rock facing, weathering has attacked all four main rock types used in the construction of the pyramid. The most least weathered rock in the pyramid is a granite, which today remains essentially unweathered. Also resistant is a hard, gray limestone, which still retains marks of the quarry tools used to carve its final shape. The shaly limestone and fossiliferous limestone used for other blocks, however, have weathered rapidly. Individual building blocks have weathered to spherical forms. Many of these blocks have a zone of decayed minerals as deep as 20 cm. Most of the weathered debris remains as talus on individual tiers and around the base of the pyramids. During the last 1000 years, the volume of weathered debris produced from the pyramid has been calculated to be 50,000 m³.

Near Saqqarah, Egypt, on older pyramids built nearly 4600 years ago, deeper weathering has occurred, with talus debris nearly covering the steps. Some of the smaller pyramids in the area are completely covered by their own weathered debris.

In Mexico, pyramids built nearly 2000 years ago have also been deeply weathered. Some were completely covered by their own weathered debris (see the *GeoLogic* essay on the next page).



Weathering of the Pyramids



When Europeans first entered the highland valleys of central Mexico, they found tree-covered mounds dotting the landscape. Eventually, archeologists discovered that these mounds were not natural at all, but were the weathered remnants of the buildings of a once great city. Teotihuacan was at its zenith about 400 AD but the city was abandoned and partially destroyed about 700 AD. In the photograph, you can see that the classic Mesoamerican architecture appears to be wonderfully preserved. But that is a popular misconception. The temples with their staircases, platforms and altars were restored after careful archeological work. Study the mounds to the left; the low rounded conical hills covered with grass and a few trees. These are the unrestored segments of the Teotihuacan complex.

Observations

1. After Teotihuacan was abandoned some 1300 years ago the buildings and monuments were left to decay as a result of weathering.
2. A regolith, in some places more than 1 m thick, topped the ruined structures. It consisted of decomposed rock fragments, clay, and organic material from plants that colonized the newly created soil.
3. Once angular building stones are now spheroidal, crumbly, and ill-fitting.
4. Numerous blocks of rock are scattered over the weathered structures.

5. Most of the delicate carvings in the solid rock are destroyed, only being preserved where collapse or overhangs had protected them from the attack by water and air.
6. Some of the temples have now been partially reconstructed, revealing their former grandeur. New stone was quarried and carefully placed to recreate the ancient buildings. But so extensive was the weathering that it was unclear how many steps ascend to the top of a temple or even how many wide platforms break the profile.

Interpretations

Considering the location, landscape, and present system of slopes, could the pyramids have been covered by deposition of sediment from running water, wind, or lakes? The principal conclusion you can draw from these observations is that the monuments were not covered with sediment transported in from some other area, but simply covered in their own weathered debris. Weathering is a rapid process capable of producing a regolith in only a few hundred years in a temperate climate. The products of weathering are spheroidal boulders, decomposed rock fragments, and soil.

KEY TERMS

A horizon (p. 265)	granular disintegration (p. 261)	permeability (p. 258)	soil profile (p. 265)
B horizon (p. 265)	horizon (p. 265)	physical weathering (p. 251)	spheroidal weathering (p. 262)
C horizon (p. 265)	hydrolysis (p. 255)	porosity (p. 258)	talus cone (p. 253)
chemical weathering (p. 251)	ice wedging (p. 251)	regolith (p. 263)	
differential weathering (p. 260)	joint-block separation (p. 260)	shattering (p. 261)	
dissolution (p. 253)	leach (p. 253)	sheeting (p. 252)	
exfoliation (p. 263)	oxidation (p. 256)	soil (p. 265)	

REVIEW QUESTIONS

1. List five ways in which the effects of weathering are expressed in natural outcrops of bedrock.
2. Discuss the processes involved in the most important types of physical weathering.
3. Which rock types are most susceptible to chemical weathering?
4. Discuss the chemical reactions involved in chemical weathering of feldspar.
5. Explain why joints are important in weathering processes.
6. How does soil originate?
7. Why are mudrocks (dominated by clay minerals) the most common sedimentary rocks?
8. Explain how rock types, topography, and time influence the types of soil produced by weathering.
9. Why is quartz sand so abundant in clastic sedimentary rocks?
10. What is spheroidal weathering?
11. Draw a schematic diagram showing variations in weathering from arctic regions to the tropics.
12. How do the pyramids of Egypt and Mexico provide information on rates of weathering?
13. Put these rock types in the order by which they would weather the fastest: granite, rock salt, gabbro, sandstone, mica schist, shale, serpentinite, and gypsum. Assume that the climate is humid and temperate.
14. Which rock type, limestone, granite, or basalt, would weather to form the most clay? Which would be most susceptible to oxidation?
15. Compare the soil map in Figure 10.15 with the climate map in Chapter 9. Comment on the distribution of different soil types in each of the major climates.

ADDITIONAL READINGS

- Berner, E. B., and R. A. Berner. 1996. *Global Environment: Water, Air, and Geochemical Cycles*. Upper Saddle River, N.J.: Prentice Hall.
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- Colman, S. M., and D. P. Dethier. 1986. *Rates of Chemical Weathering of Rocks and Minerals*. New York: Academic Press.
- Goldich, S. S. 1938. A study in rock weathering. *Journal of Geology* 46:17–58.
- Ollier, C. D., and C. Pain. 1996. *Regolith, Soils and Landforms*. New York: Wiley.
- Yotsu, E. 1988. *The Nature of Weathering*. Tokyo: Sozoshsha.

MULTIMEDIA TOOLS



Earth's Dynamic Systems Website

The Companion Website at www.prenhall.com/hamblin provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources



Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Slide shows about weathering of man-made structures
- Slide shows with examples of results of weathering, including talus cones
- Web links to more information about soils
- A direct link to the Companion Website