The specific type of clay mineral produced by hydrolysis depends on the composition of the preexisting mineral and other substances that may be present and active in the water. Because water is the weathering agent, hydrolysis is not limited to rocks that are exposed at the surface, but can occur in the subsurface through the action of soil and groundwater; in tropical humid climates, it can decay rock to a depth of 30 meters (100 ft) or more.

The chemical weathering process of hydrolysis differs from the physical weathering process of hydration, in which water molecules join and leave a substance, causing it to swell and shrink without changing its inherent chemical formula. Both weathering processes, however, may involve clay minerals because those clay-sized substances are often the product of hydrolysis, and many clay minerals swell and shrink substantially during hydration and dehydration.

### Variability in Weathering

How and why types and rates of weathering vary, at both the regional and local spatial scales, are of particular interest to physical geographers. In addition to climate, the type of rock (lithology) and the nature and amount of fractures or other weaknesses in it are major influences on the effectiveness of the various rock weathering processes. How specific rocks weather in different natural settings is important for explaining the amount and formation of regolith, soil, and relief, but it also impacts the cultural environment because weathering affects building stone as well as rock in its natural setting.

### Climate

In almost all environments, physical and chemical weathering processes operate together, but usually one of these categories dominates. Although water plays a role in all but two of the physical weathering processes, it is essential for all types of chemical weathering. Also, chemical weathering increases as more water comes in contact with rocks. Chemical weathering, then, is particularly effective and rapid in humid climates (Fig. 15.16). Most arid regions have enough moisture to allow some chemical weathering, but it is much more restricted than in humid climates. Arid regions typically receive sufficient moisture for physical weathering by salt crystal growth and the hydration of salts. Abundant salts, high humidity, and contact with seawater make salt weathering processes very effective in marine coastal locations.

The other principal climatic variable, temperature, also influences dominant types and rates of weathering. Most chemical reactions proceed faster at higher temperatures.

Low-latitude regions with humid climates consequently experience the most intense chemical weathering. In the tropical rainforest, savanna, and monsoon climates, chemical weathering is more significant than physical weathering, soils are deep, and landforms appear rounded. Although chemical weathering is somewhat less extreme in the mid-latitude humid climates, its influence is apparent in the moderate soil depth and rounded forms of most landscapes in those regions. In contrast, the landforms and rocks of both arid and cold regions, where physical weathering dominates, tend to be sharper, angular, and jagged, but this depends to some extent on rock type, and rounded features may remain in an arid landscape as relics from prehistoric times when the climate was wetter (Fig. 15.17). Comparatively low rates of chemical weathering are reflected in the thin (or absent) soils found in arid, subarctic, and polar climatic regimes. We have already noted the role of daily temperature ranges in weathering processes, including thermal expansion and contraction weathering in arid climates and freeze–thaw weathering in areas with cold winters.

Air pollution that contributes to the acidity of atmospheric moisture accelerates weathering rates. Extensive damage has

---

**FIGURE 15.16**

This diagram of weathering regions summarizes the relationships between climate and weathering processes. Physical weathering is most active where temperature and rainfall are both low. Chemical weathering is most active in regions of high temperature and rainfall. Most world regions experience a combination of both physical and chemical weathering.

In which weathering region would we find a site that has an annual mean temperature of 5°C (41°F) and an annual rainfall of 100 centimeters (40 in.)?
already occurred in some regions to historic cultural artifacts made of limestone and marble (metamorphosed limestone), both containing calcium carbonate (●Fig. 15.18). Because many of the world’s great monuments and sculptures are made of limestone or marble, there is a growing concern about weathering damage to these treasures. The Parthenon in Greece, the Taj Mahal in India, and the Great Sphinx in Egypt are examples of structures made of rock where pollution-induced chemical solution, and related growth and hydration of salts, are damaging and rotting away monument surfaces.

Rock Type

Wherever many different rock types occupy a landscape, some will be more resistant and others will be less resistant to the weathering processes operating there. Because erosion removes weathered rock fragments more easily than large, intact rock masses, areas of diverse rock types undergo differential weathering and erosion; easily eroded rocks exhibit more extensive effects of weathering and erosion than the resistant rocks.

A rock that is strong under certain environmental conditions may be easily weathered and eroded in a different environmental setting. Rocks that are resistant in a climate dominated by chemical weathering may be weak where physical weathering processes dominate, and vice versa. Quartzite is a good example. It is chemically nearly inert and harder than steel, but it is brittle and can be fractured by physical weathering. Shale is chemically inert but mechanically weak. In humid regions, limestone is highly susceptible to carbonation and solution, but under arid conditions, limestone is much more resistant. Granitic outcrops in an arid or semiarid region resist weathering. However, the minerals in granite are susceptible to alteration by oxidation, hydration, and hydrolysis, particularly in regions with warm, humid conditions. Accordingly, granitic areas are often covered by a deeply weathered regolith when they have been exposed to a tropical humid environment.

Structural Weaknesses

In addition to rock type, the relative resistance of a rock to weathering depends on other characteristics, such as the presence of joints, faults, folds, and bedding planes that make rocks susceptible to enhanced weathering. Sandstone is only as strong as its cement, which varies from soluble calcium carbonate to inert and resistant silica. In general, the more massive the rock, that is, the fewer the joints and bedding planes it has, the more resistant it is to weathering.

The processes of volcanism, tectonism, and rock formation produce fractures in rocks that can be exploited by exogenic processes, including weathering. Joints can be found in any solid rock that has been subjected to crustal stresses, and some rocks are intensely jointed (●Fig. 15.19). Joints and other fractures that commonly develop in igneous, sedimentary, and metamorphic rocks represent zones of weakness that expose more surface area of rock, provide space for flow or accumulation of water, collect salts and clay minerals, and offer a foothold for plants (●Fig. 15.20). Rock surfaces along fractures tend to experience pronounced weathering. Chemical and physical weathering both proceed faster along any kind of gap, crack, or fracture than in places without such voids.
Because joints are sites of concentrated weathering, the spatial pattern of joints strongly influences the landforms and the appearance of the landscapes that develop. Multiple joints that parallel each other form a joint set, and two sets, each composed of multiple parallel joints, will cross each other at an angle (● Fig. 15.21). Joints divide rocks into many different configurations, most commonly resembling blocks or columns, which are often visible in the topography. Over time, preferential weathering and erosion in crossing joint sets leave rock in the central area between the fractures only slightly weathered while the rock near the fractures acquires a more rounded appearance. This distinctive, rounded weathered form, known as spheroidal weathering, develops especially well on jointed crystalline rocks, such as granite (● Fig. 15.22). Spheroidal weathering is a result that can occur from the interaction of many weathering processes; it does not refer to a specific weathering process. Once a rock becomes rounded, weathering rates of spheroidal outcrops and boulders decrease because there are no more sharp, narrow corners or edges for weathering to attack, and a sphere exposes the least amount of surface area for a given volume of rock.

**Topography Related to Differential Weathering and Erosion**

In the previous chapter, we learned that structural upfolds (anticlinal) do not always form topographic ridges and that structural downfolds (synclines) do not always form topographic valleys. The reason for this stems from the resistance of the folded rock units to the weathering and erosion processes. If resistant rocks are found in the center of a syncline, they will eventually create a topographic high regardless of the structural downfold. Weak rocks, even when forming an anticline, are too easily attacked by weathering and erosion to exist in the landscape as a topographic high for very long. Variation in rock resistance to weathering...
exerts a strong and often highly visible influence on the appearance of landforms and landscapes. Given sufficient time, rocks that are resistant to weathering and erosion tend to stand higher than less resistant rocks. Resistant rocks stand out in the topography as cliffs, ridges, or mountains, while weaker rocks undergo greater weathering and erosion to create gentler slopes, valleys, and subdued hills.

An outstanding example of how differential weathering and erosion can expose rock structure and enhance its expression in the landscape is the scenery at Arizona’s Grand Canyon (● Fig. 15.23). In the arid climate of that region, limestone is resistant, as are sandstones and conglomerates, but shale is relatively weak. Strong and resistant rocks are necessary to maintain steep or vertical cliffs. Thus, the stair-stepped walls of the Grand Canyon have cliffs composed of limestone, sandstone, or conglomerate, separated by gentler slopes of shale. At the canyon base, ancient resistant metamorphic rocks have produced a steep-walled inner gorge. The topographic effects of differential weathering and erosion tend to be more prominent and obvious in landscapes of arid and semiarid climates. In these dry environments, chemical weathering is minimal, so slopes and varying rock units are not generally covered under a significant mantle of soil or weathered rocks. In addition, vegetation typically does not mask the topography in arid regions as it does in humid regions.

Another example of differential weathering and erosion can be seen in the Appalachian Ridge and Valley region of the eastern United States (● Fig. 15.24). The rock structure here...
FIGURE 15.23
The Grand Canyon of the Colorado River in Arizona is a classic example of differential weathering and erosion in an arid climate. Weathering, mass wasting, and erosion work together to make differences in rock structure and strength visible in the landscape. Rock layers of varying thickness and resistance result in a distinctive array of cliffs formed by strong rocks and slopes formed by less resistant rocks.

FIGURE 15.24
A satellite image of Pennsylvania’s Ridge and Valley section of the Appalachians clearly shows the effects of weathering and erosion on folded rock layers of different resistance. Resistant rocks form ridges, and weaker rocks form valleys. Can you see how the topography of the Ridge and Valley section influences human settlement patterns?

Consists of sandstone, conglomerate, shale, and limestone folded into anticlines and synclines. These folds have been eroded so that the edges of steeply dipping rock layers are exposed as prominent ridges. In this humid climate region, forested ridges composed of resistant sandstones and conglomerates stand up to 700 meters (2000 ft) above agricultural lowlands that have been excavated by weathering and erosion out of weaker shales and soluble limestones.