

MINERAL AND ROCK CHARACTERISTICS RELATED TO HAZARDS

The following section outlines the characteristics of many common rocks, especially as they relate to geological hazards. Earthquakes and landslides are among the processes that break down rocks to smaller particles, which are then transported downstream in flowing water. The strength of rocks, therefore, affects when a fault will break and how strong the associated earthquake will be, when a hillside will slide and in what way, and how easily big boulders are broken down to be transported in streams. Whether rocks are at or near Earth's surface or deep beneath the surface also matters.

Rocks at least a few kilometers below the surface are warm or even hot. They are under high pressure because of the load of rocks and sediments above them. Like ice in a glacier, they may be brittle at the surface but deform plastically deep below under such loads. Hard rocks at the Earth's surface may break during an earthquake or collapse in a landslide. Those same rocks, warmer and persistently stressed at depth, may slowly flow. Some hard taffy seems rigid or brittle if you bite it hard; if you bite more gently and slowly, it bends and flows. Like warm tar, rocks may flow when stressed by tectonic movements. Many rocks deform more easily if they are soaked with water. We discuss these differences in more detail in the separate chapters in which they are most relevant.

Geologists classify rocks into three basic groups: igneous, sedimentary, and metamorphic. We focus on their descriptive characteristics here.

Igneous Rocks

Igneous rocks are those that solidify from molten magmas. Those that crystallize slowly deep underground are called **plutonic** rocks; they generally show distinct mineral grains that are easily visible to the unaided eye. Their grains interlock with one another because some grains crystallize first at high temperature within the magma; others crystallize later at somewhat lower temperatures, filling in the spaces between earlier-formed grains so the grains are in direct contact with no spaces in between. Most igneous rocks are massive—that is, they show little or no orientation of their grains. In a few cases, where the magma was moving as it crystallized, the grains may show parallel-oriented

grains. If the magma crystallized within a kilometer or so of the Earth's surface, gases dissolved in the magma separate as steam bubbles that are trapped between the straight sides of the grains. Such rocks contain cavities bounded by the straight sides of the mineral grains that grew in the magma.

Volcanic rocks are formed when a magma reaches the Earth's surface. If the magma has low viscosity and contains little gas, it may pour out as a lava flow. If it is highly viscous and contains significant dissolved gas, it is likely to blast out as loose particles of volcanic ash. If the ash settles while still hot, its particles may fuse together to form a solid rock. Alternatively, loose ash that sits around for hundreds or thousands of years may become cemented into solid rock because water dissolves the surfaces of particles and then precipitates along their contacts, cementing them together. Blasting ash out of the vent typically chills the shreds of magma so quickly that minerals cannot crystallize into grains; the particles are glass. Volcanic rocks and processes are described in some detail in Chapters 6 and 7 on volcanic rocks.

Sedimentary Rocks

Sedimentary rocks form at the Earth's surface by deposition or precipitation from water or sometimes wind. Weathering processes break down rocks into particles that are transported downslope into streams, lakes, and ultimately the ocean. Loose particles are described as sediments. Chemicals dissolved from the surfaces of sediment grains that are in contact with water for hundreds to millions of years again precipitate to form cements that bind the grains together to form solid sedimentary rocks. Individual rocks of sand-sized grains, for example, become sandstone, and mud-sized grains become mudstone or shale. Where water in a lake or ocean contains large amounts of dissolved constituents, those chemicals may concentrate further by evaporation in a warm environment and precipitate to form chemical sedimentary rocks such as limestone. Marine animals such as clams and coral may take in chemicals dissolved in the water to precipitate them in their shells. Tiny corals often form colonies that precipitate enough calcium carbonate to build whole coral reefs that fringe coastlines in warm-water environments.

Metamorphic Rocks

Metamorphic rocks begin as sedimentary or igneous rocks but have been buried well beneath the Earth's surface, where they are subjected to higher temperatures and pressures. Heated mineral grains react with one another and with water along their boundaries to form new metamorphic minerals. If sediment grains were not interlocking, the new grains grow to interlock with one another. If the rock undergoing metamorphism is sufficiently deep where it becomes soft and plastic, it often flows in response to tectonic stresses and its mineral grains become oriented. This is one of the distinctive characteristics of many metamorphic rocks. Because a few igneous rocks such as some granites, show such orientation, there can be uncertainty and debate as to whether such a rock is actually igneous or metamorphic. Where sedimentary or igneous rocks are locally heated by contact with an intruding magma, the resulting rock becomes a contact metamorphic rock. Because most contact metamorphic rocks are not buried deeply enough to flow and take on mineral orientation, they are most commonly massive.

Weak Rocks and Strong Rocks

Most people think of shale as weak and granite as strong, and in a general way that is quite true. Shale, which is a sedimentary rock that forms when clay-rich muds compact and dry out, splits easily into thin sheets that may crumble in your hand. Shale in a hillside may crumble and slide when the load of the slope above pushes on a shale layer. If the platy sheets of the shale are oriented parallel to the slope, then the shale may split easily and slide on those sheets. Pieces of shale eroded by a stream crumble to tiny fragments as other rocks tumble against them. The tiny scraps are easily picked up by the swirling currents and carried far downstream. In a fault zone, a large mass of shale is so easily broken that it cannot build up a large enough stress to cause a large earthquake.

Granite, on the other hand, consists of interlocking grains of hard minerals, quartz, and feldspars. Granite in a hillside is so strong that it rarely fails unless it is exposed in a vertical cliff. Then it may collapse in a rockfall if the cliff is oversteepened or if cracks in the granite fill with water that freezes and expands. Boulders of granite that fall into a stream may tumble along the bottom in high water, but as the water level falls the stream is not energetic enough to move them. They often collect in place to form a steeper gradient and rapids. A large mass of granite in a fault zone does not easily break. Stress on the rocks on opposite sides of the fault needs to build up to a high level before the fault slips. When it does it may produce a large earthquake.

Many igneous rocks such as granite, and many metamorphic rocks such as quartzite and gneiss, which are formed by heating at high temperatures far below the Earth's sur-

face, can be considered strong. Many sedimentary rocks such as shale or sands in which the grains are not cemented together are weak. As used here, strong rocks are hard to break. They do not collapse as easily in landslides or rockfalls; they do not erode as easily in streams. Rock strength also depends on whether the rock contains weak layers or many fractures.

Common Rock-Forming Minerals

To understand the makeup and behavior of rocks, we need to keep clear the distinction that **elements** such as oxygen, silicon, iron, and aluminum combine chemically to form **minerals** such as quartz, feldspars, and micas. Groups of minerals go together to form **rocks** (►Figure A2-1). Some of the more common rocks are discussed below.

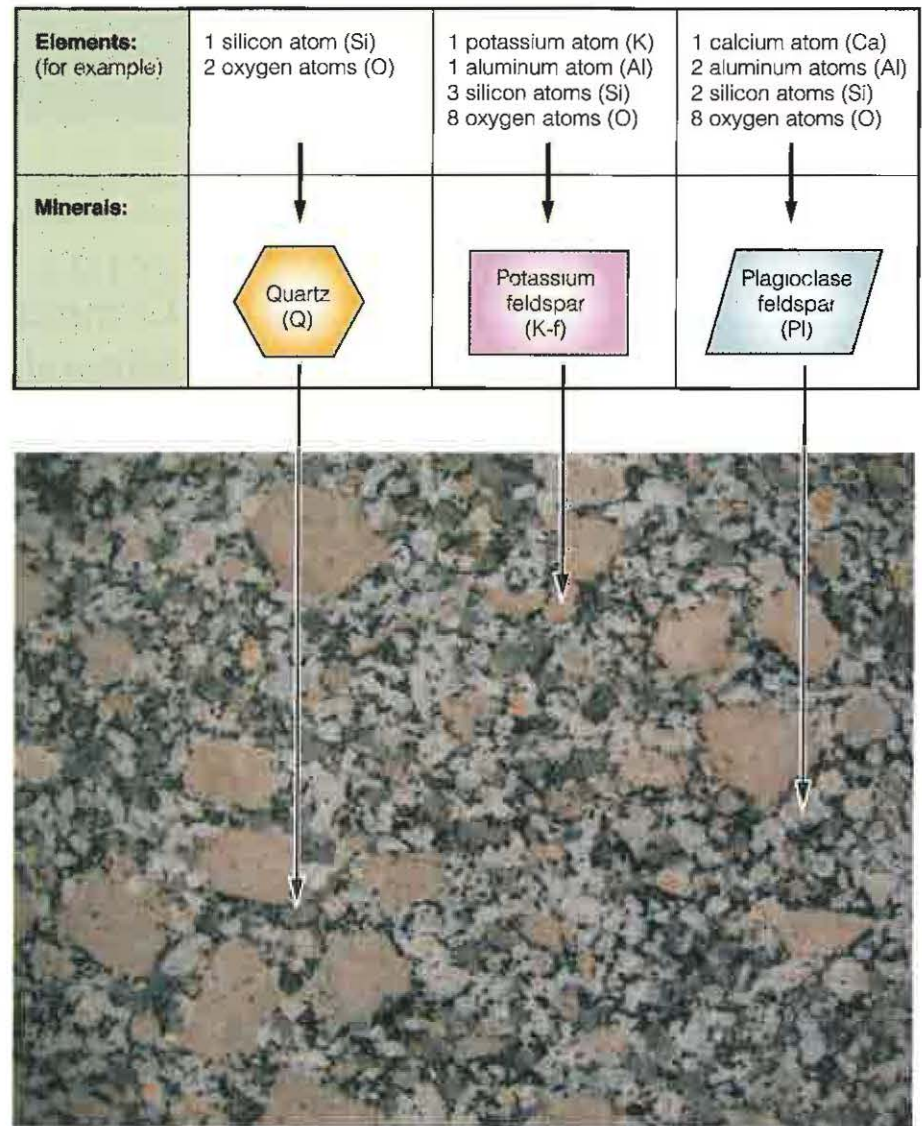
Rocks are agglomerations of grains of individual minerals. Mineral grains are individual crystals of chemical compounds (Figure A2-1). Each type of mineral has a crystalline structure controlled by the size and electrical charge on the atoms of its elements. Although there are literally thousands of different minerals, only a handful are common rock-forming minerals, and those are formed from only a few elements. Some grew to form igneous rocks by crystallization from high temperature melts or magmas. Shale, sandstone, and most other sedimentary rocks were formed by the disintegration of other rocks, followed by erosion and deposition of the sediment. In most cases, the grains are later cemented together to form a solid rock. Some sedimentary rocks grow by precipitation from cold, watery solutions. After deep burial under other rocks, some sedimentary rocks are subjected to the high pressure of other rocks on top and heat up to form metamorphic rocks. Elements in some minerals in the hot rocks diffuse into nearby minerals and react with them to form new metamorphic minerals.

Most minerals are recognizable by their visible properties. The abundant elements (and their standard chemical abbreviations) in most rocks are: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), and potassium (K).

Rocks dominated by light-colored minerals are themselves light-colored or **felsic**. Rocks dominated by dark-colored minerals are themselves dark-colored or **mafic**. See ►Figure A2-2. Distinctive properties of the common minerals are listed in Table 2-1. Figure A2-2 shows that igneous rocks range from pale to dark. The rock names are arbitrary divisions that permit us to talk about them efficiently without full descriptions.

We use various terms to describe the characteristics of rocks and minerals. Colors are described, as you might expect, in terms of gray, yellow, brown, red, and green, but most colors are imposed by small amounts of iron oxides that are hydrated to varying degrees. Those shades of color

► **FIGURE A2-1.** Elements combine chemically to form minerals. Combinations of minerals make rocks.



are less important than how light or dark the color is. The darkness of the color often reflects the amount of iron in the rock; that also often relates to other aspects of rock composition as well. The **cleavage** of a mineral refers to the flat breakage surfaces that are controlled by the mineral's internal arrangement of atoms. The most obvious example is the prominent cleavage of mica flakes. Other minerals such as feldspar have two different orientations of cleavages. Rocks can also have cleavage because of the parallel orientation of flat or elongate mineral grains. Prominent examples include slate or schist in which small to larger grains of micas control the platy breakage of the rock. The **hardness** of a rock is technically the ease with which you can scratch it, such as with the tip of a pocket knife. Hard rocks are those that contain large amounts of hard minerals such as quartz and feldspars that cannot easily be scratched with a knife. Those that contain large amounts of soft minerals

such as micas or calcium carbonate minerals can be easily scratched and are described as soft. The ease of breakage of a rock or mineral is not hardness but brittleness. A poorly cemented sandstone, for example, might be hard because it contains lots of grains of quartz; but it also might be brittle or crumbly because the grains are not well cemented together. Most limestones are soft but not brittle or crumbly.

The characteristics and strength of a rock depends in large part on the minerals that it contains, and the nature of a mineral depends on the chemical elements and their arrangement within the mineral.

Four oxygen atoms surround each silicon atom in a tetrahedral arrangement; six oxygen atoms surround each aluminum atom to make an octahedral array (► Figure A2-3). Those sheets stacked like the pages of a book and more or less weakly bonded together are the basic components of the

Table A2-1 The Common Rock-Forming Minerals and Their Main Properties

Mineral	Main Elements*	Properties
Quartz		Generally, medium to pale gray as grains in rocks, commonly white in veins that fill fractures in rocks Typically glassy looking Especially hard (cannot scratch with a knife), no flat cleavage surfaces Abundant in granite, rhyolite, sandstone, schist, gneiss Pale colors: white, pinkish, beige Hard, with flat cleavage surfaces in two directions at 90 degrees
Potassium feldspar	K, Al	Abundant in granite and rhyolite Pale colors: white, pale gray, sometimes a bit greenish Hard with flat cleavage surfaces in two directions at 90 degrees
Plagioclase feldspar	Na, Ca, Al	Abundant in granite, gabbro, and most other igneous rocks Dark brown or black flakes, almost golden if weathered
Biotite (dark mica)	K, Al, Mg, Fe	Soft (can easily scratch with a knife), has one shiny, smooth cleavage direction Biotite can amount from 5% to 20% of granite and more than 50% in metamorphic rocks such as mica schist
Muscovite (white mica)	K, Al	Yellowish white flakes, soft Has one shiny, smooth cleavage direction Generally less abundant than biotite but can make up more than 10% of a granite and more than 50% of a schist
Clay	Al and often Mg, Ca, Na, K	Microscopic flakes similar to micas but much softer and weaker Make up highly variable amounts of soils Some clay minerals take on water when wet and make a soil susceptible to landsliding (see descriptions of important clay minerals below)
Hornblende (an amphibole)	Ca, Mg, Fe, Al	A major component of shale. See Figures A2-3 to A2-5 Dark green or black Short rod-shaped grains Two shiny cleavage surfaces at 60-degree directions to one another Can amount to 10% to 20% in granite and similar rocks, commonly ~50% in a metamorphosed basalt rock called <i>amphibolite</i>
Pyroxene	Ca, Mg, Fe, Al	Dark green, dark brown, or black Short stubby grains Two less prominent cleavage surfaces at 90 degrees
Olivine	Mg, Fe	Occurs primarily in dark-colored rocks, most abundant in gabbro Green, glassy looking, hard Generally occurs in dark-colored rocks, especially in basalt and gabbro

*In addition to silicon and oxygen.

clay minerals. Between these negatively charged combination sheets, some clays have positively charged atoms or ions such as sodium or calcium that hold the sheets together.

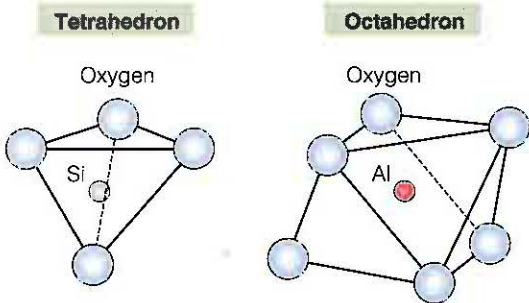
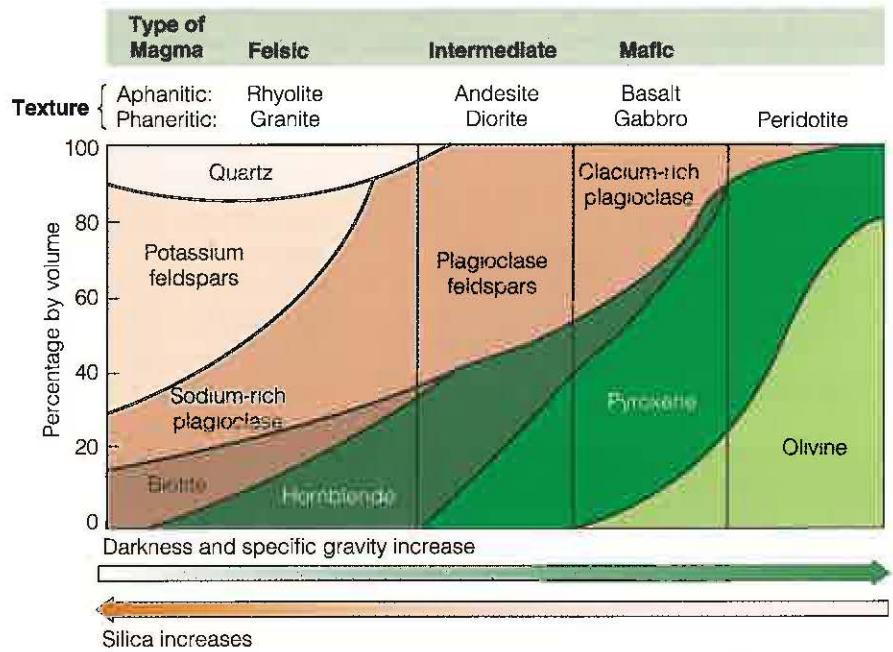
Kaolinite is the simplest clay. It consists of alternating sheets of silicon tetrahedra and aluminum octahedra (► Figure A2-4). Although they have no overall charge, the layers are weakly positive on one side and weakly negative on the other. These positive and negative charges weakly bind the structure together, resulting in extremely soft crystals.

Kaolinite does not absorb water between its layers and does not expand and contract as it wets and dries. It generally forms through weathering in especially wet and warm environments. Kaolinite commonly forms deep soils, some considerably more than 100 meters deep. Because it is so weak, it is frequently involved in landslides.

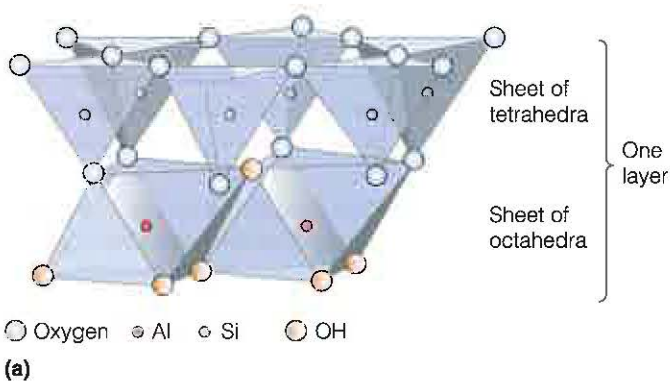
Smectite is a group of complex clay minerals that has silicon, aluminum, and magnesium sheets bound together to make combination layers. Loosely bound atoms of water



► **FIGURE A2-2.** Percentages of minerals in common igneous rocks. Aphanitic rocks have grains that are too small to see without a magnifier; phaneritic rocks are distinctly grainy looking.

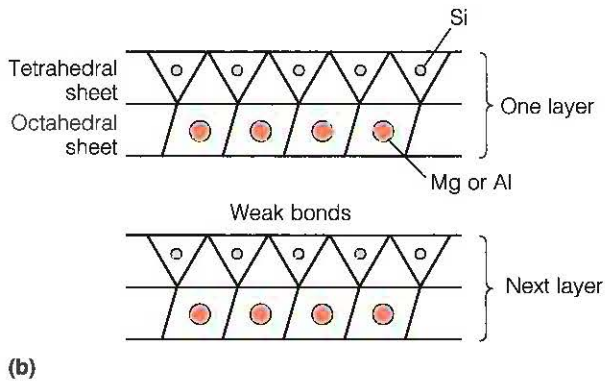


► **FIGURE A2-3.** Atomic arrangement of the main building blocks in clay minerals. Oxygen atoms surround either silicon or aluminum atoms.



and sodium or calcium bind the sheets together (► Figure A2-5). When the clay gets wet, water seeps between the layers. Then the clay swells to become plastic and structurally extremely weak. Smectite generally forms through weathering in a dry environment, especially in volcanic ash.

Many of the sedimentary formations that lie beneath the High Plains just east of the Rocky Mountains are rich in smectite. Soils developed on them become extremely slippery when wet; they are highly unstable and likely to slide. If this slimy mineral did not exist, landslides would be much less abundant. Because it swells when it gets wet, smectite also wreaks havoc with houses that are built on soils containing this mineral (see Chapter 9's section on swelling soils).



► **FIGURE A2-4.** (a) Kaolinite-type structure in some clays. (b) The Kaolinite-type structure in some clays consists of sheets of tetrahedra and octahedra. Compare the tetrahedra (inverted triangles here) and octahedra. Oxygen atoms are at each corner.

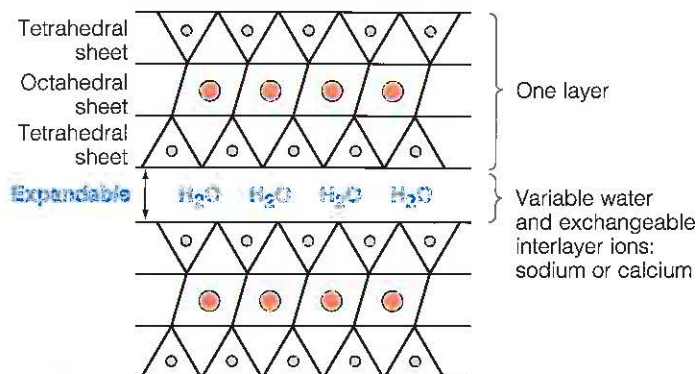


FIGURE A2-5. In the smectite structure, the interlayer cations (positive-charged atoms) are sodium or calcium that can be replaced by water. This causes the interlayer space to expand and the clay to swell.

Common Rocks

Granite

Granite, a common igneous rock (► Figures A2-1 and A2-6), is found primarily in mountainous areas such as the Rockies and Appalachians and in deeply eroded “basement” rocks such as those of eastern Canada and of the Adirondacks of New York. It is light-colored, grainy, and strong. It breaks to form sharp edges but typically weathers to rounded corners on outcrops. It crystallized from molten magma well below the Earth’s surface to form strongly interlocking grains. Its minerals include abundant plagioclase and sometimes potassium feldspar, moderately abundant quartz, and small amounts of micas or hornblende. Diorite is a darker, less common rock that is otherwise similar to granite. When granite magma reaches the surface to erupt in a volcano, it solidifies as fine-grained rhyolite.

Gabbro

Gabbro (► Figure A2-7) is a coarse-grained igneous rock that crystallizes underground in large masses from the same magma that erupts at the surface as basalt lavas. It is medium to dark gray in color and strong. Early crystallizing grains of dark pyroxene often settle in the magma to form black layers as in the photo. Gabbro is not common.



(a)



(b)



(c)

FIGURE A2-6. Granite is a light-colored, grainy, massive, strong, and hard igneous rock with few fractures.



(a)



(b)

► **FIGURE A2-7.** (a) Gabbro is a darker-colored, grainy, massive, strong, and hard igneous rock with few fractures. (b) In some cases, early crystallized dark grains of pyroxenes settle out to form dark layers.

Rhyolite

Rhyolite (► Figure A2-8) is a common, light-colored, fine-grained volcanic rock that has the same composition as granite but which solidified at the surface. It can be white, pink, yellow, or pale green, the color provided by superficial amounts of various iron oxides. Most rhyolite is ash and rather easily eroded, though vertical cliffs are not uncommon. Vertical fractures are well spaced and permit large slabs to break off as dangerous rockfalls. The sample at the bottom shows fragments of pumice.



(a)



(b)



(c)

► **FIGURE A2-8.** Rhyolite is a light-colored, fine-grained, massive, generally soft igneous rock with few fractures. (a) If crystallized at shallow depths below the surface, rhyolite may be hard. (b) Pieces of pumice (slightly darker) may be surrounded by fine-grained ash. (c) Pieces of pumice are frothy with gas holes formed in the rising magma as pressure on it decreased.



(a)



(b)

► **FIGURE A2-9.** Andesite is a medium-colored, fine-grained, massive igneous rock with few fractures. Its composition and characteristics are intermediate between those of basalt and rhyolite.

Andesite and Dacite

Andesite (► Figure A2-9) is a volcanic rock with color and characteristics that are intermediate between those of rhyolite and basalt. Its color ranges from gray to pinkish gray, green, or brown. Some andesites contain larger grains of white plagioclase (as in the photo) or greenish black hornblende or pyroxene. Andesite forms strong, hard lava flows but weak ash.



(a)



(b)

► **FIGURE A2-10.** (a) Basalt is a dark-colored, fine-grained, massive igneous rock with few fractures. Its composition is equivalent to that of gabbro. (b) Basalt with gas holes and green crystals of olivine.

Dacite is a paler volcanic rock, related to andesite, and intermediate in composition and appearance between andesite and rhyolite.

Basalt

Basalt, the most common volcanic rock, is low in silica and typically forms lava flows. It is usually black but can be slightly brownish or greenish. Most basalts are fine-grained and massive (► Figure A2-10a); some are full of steam holes





► **FIGURE A2-11.** Some shales or mudrocks are marked by mudcracks that formed as wet mud dried and shrank.

► see Figure A2-10b. Some basalts contain larger dark grains of black pyroxene or green olivine. Basalt forms strong, widespread lava flows but less abundant and weak cinder piles.

Shale and Mudstone

Shale and **mudstone** are dried mud or mudrocks; some even show ripple marks or mudcracks as in ► Figure A2-11. These rocks range widely in color from medium to dark gray, red, green, yellow, and brown. Shale is almost as soft and flaky as the clay-rich mud that forms it. Mudstone is more massive and much stronger; it contains lots of tiny grains of quartz and feldspar. Shale may form thick layers on gentle slopes or thin layers between stronger sedimentary rocks such as sandstone or limestone. Shale and its lightly metamorphosed equivalent, slate, form thin plates that break easily and make weak slopes and weak layers between rocks that easily fail in landslides.

Sandstone

As its name implies, **sandstone** (► Figure A2-12) is made of sand grains—generally quartz but sometimes with feldspar. Its color ranges from white to yellow, brown, red, or green. It may be rather weak if in thin layers with weak rocks in between or lightly cemented. It may be strong if well-cemented or if metamorphosed to interlocking grains, in which case it is called *quartzite*.

Limestone

Limestone (► Figure A2-13) is calcium carbonate, soft to scratch but strong. It dissolves slowly in rainwater to form ragged rock surfaces and underground caverns but does



► **FIGURE A2-12.** Sandstone is made of grains of sand cemented together to make a solid rock.



► **FIGURE A2-13.** Light-colored limestone with a rough surface.

not erode easily. Its color is commonly pale gray, often weathering to a soft-looking but a rough and sandy-feeling surface. Dissolution of limestone under soil is the most common cause of sinkholes.

Slate

Slate (► Figure A2-14) is lightly metamorphosed, strongly compressed shale. It is somewhat harder but still splits fairly easily into flat sheets. Those sheets lie flat on steep slopes and facilitate sliding. Its color is most commonly dark gray or green.



(a)



(b)

► **FIGURE A2-14.** (a) Slate, a lightly metamorphosed but strongly compressed mud rock, breaks into thin plates or flakes that make weak slopes that are subject to landsliding. (b) An outcrop view from the Sierra Nevada northwest of Sacramento, California.

Schist

Schist (► Figure A2-15) is a strongly metamorphosed shale or slate. The grains range from 1 to several millimeters across. Mica-rich varieties are weak and prone to sliding on steep slopes. Schist splits into flat sheets; those and individ-



► **FIGURE A2-15.** Shiny micas in this schist are slightly wavy because of deformation after metamorphism. The little lumps are dark red garnets.



► **FIGURE A2-16.** Gneiss is similar to schist but contains pale layers that are dominated by light-colored feldspars alternating with dark mica-rich layers. Some were heated to high enough temperatures to melt and thus produce the pale granite layers.

ual mica grains lie flat and facilitate sliding in translational landslides. The sample in Figure A2-15 contains dark red garnets.

Gneiss

Gneiss (► Figure A2-16) is a generally hard and strong highly metamorphosed rock. It consists of white grains of feldspar, glassy quartz, generally some micas, and sometimes hornblende or garnet. It is characterized by distinct thin layers dominated by dark grains separated by layers of light-colored grains. Gneiss forms bold cliffs that break into slabs or blocks like granite.



Serpentinite

Serpentinite (► Figure A2-17) is a low-grade metamorphic rock that forms by hydration of rocks from the Earth's mantle, dark rocks originally consisting of olivine and some pyroxene. It generally rises toward the Earth's surface along fault zones, where it can be found in a wide range of shades from medium green to black. Serpentinite is weak, soft, slippery, and creates high risk of landslides. Its weakness and presence in fault zones leaves it strongly deformed. Often only larger blocks of serpentinite remain in a thoroughly sheared matrix, as in the outcrop photo. Serpentinite is found in mountainous areas of western and eastern North America and to a minor extent in areas of basement metamorphic rocks.

Rocks, Landscapes, and Hazards

In summary, hard, strong rocks such as granite, gabbro, gneiss, much basalt, and some andesite and sandstone do not erode easily. In cool climates, they form steep slopes, rocky cliffs, and narrow canyons. In dry climates, weathering and formation of clays on the surfaces of feldspar grains in granites causes gradual disintegration of the rocks to form sandy soils that erode easily when it rains. Cliffs of these rocks are prone to rockfalls. In warm, moist climates, they may weather to soft clays. Fractures in these rocks are typically spaced at decimeters to meters; those fractures help drain water, keeping slopes relatively dry.

Rhyolite can be quite hard and resistant to erosion if the rock solidified at high temperature to fuse the grains together. More often it settles out of the air as cold ash that is not well stuck together; if it is not later cemented, it erodes easily.

Limestone is soft in the sense that it is easy to scratch with a knife. However, where it forms thick layers, limestone tends to be strong and forms prominent cliffs. It dissolves slowly in rainwater near the water table to form underground caverns. Where cavities above these grow sufficiently large near the surface, the ground may collapse to form sinkholes, sometimes taking roads or houses down with them.

Especially soft and crumbly rocks such as shale, slate, and mica schist break up and erode easily to form gentle slopes. They are prone to landsliding because water does not drain out easily and the flat sheets slide easily past one another. Where layers of shale separate layers of stronger rocks, their flat planes form prominent zones of weakness. Where those weak zones slope nearly parallel to a hillside, large masses of rock can be prone to sliding. Serpentinite is simply a slope-failure disaster waiting to happen.



(a)



(b)



(c)

► **FIGURE A2-17.** (a) Dark, thoroughly sheared serpentinite typically contains somewhat bigger but still weak lumps shown in this 5-meter-wide outcrop. (b,c) Small samples that show the typical smooth, curving surfaces formed by shear.