Earth’s Crust

Earth’s solid and rocky exterior is the crust, which is composed of a great variety of rocks that respond in diverse ways and at varying rates to Earth-shaping processes. The crust is the only portion of the lithosphere of which Earth scientists have direct knowledge, yet its related surface materials form only about 1% of Earth’s planetary mass. Earth’s crust forms the exterior of the lithosphere and is of primary importance in understanding surface processes and landforms. Earth’s deep interior components, the core and mantle, are of concern to physical geographers primarily because they are responsible for and can help explain changes in the lithosphere, particularly the crust, which forms the ocean floors and continents.

The density of Earth’s crust is significantly lower than that of the core and mantle, and ranges from 2.7 to 3.0 grams per cubic centimeter. The crust is also extremely thin in comparison to the size of the planet. The two kinds of Earth crust, oceanic and continental, are distinguished by their location, composition, and thickness (Fig. 13.5). Crustal thickness varies from 3 to 5 kilometers (1.9–3 mi) in the ocean basins to as much as 70 kilometers (43 mi) under some continental mountain systems. The average thickness of continental crust is about 32 to 40 kilometers (20–25 mi). The crust is relatively cold, rigid, and brittle compared to the mantle. It responds to stress by fracturing, wrinkling, and raising or lowering rocks into upwarps and downwarps.

Oceanic crust is composed of heavy, dark-colored, iron-rich rocks that are also high in silicon (Si) and magnesium (Mg). Its basaltic composition is described more fully in the next section. Compared to continental crust, oceanic crust is quite thin because its density (3.0 g/cm$^3$) is greater than that of continental crust (2.7 g/cm$^3$). Forming the vast, deep ocean floors as well as lava flows on all of the continents, basaltic rocks are the most common rocks on Earth.

Continental crust comprises the major landmasses on Earth that are exposed to the atmosphere. It is less dense (2.7 g/cm$^3$) and much thicker than oceanic crust. Where continental crust extends to very high elevations, such as in mountain ranges, it also descends to great depths below the surface. Continental crust contains more light-colored rocks than oceanic crust does, and can be regarded as granitic in composition. The nature of granite and other common rocks are discussed next.

Minerals and Rocks

Minerals are the building blocks of rocks. A mineral is an inorganic, naturally occurring substance represented by a distinct chemical formula and a specific crystalline form. A rock, in contrast, is an aggregate (collection) of various types of minerals or an aggregate of multiple individual pieces (grains) of the same kind of mineral. In other words, a rock is not one single, uniform crystal. The most common elements found in Earth’s crust, and therefore in the minerals and rocks that make up the crust, are oxygen and silicon, followed by aluminum and iron, and the bases: calcium, sodium, potassium, and magnesium. As you can see in Table 13.1, these eight most common chemical elements, out of the more than 100 known, account for almost 99% of Earth’s crust by weight. The most common minerals are combinations of these eight elements.

TABLE 13.1
Most Common Elements in Earth’s Crust

<table>
<thead>
<tr>
<th>Element</th>
<th>Percentage of Earth’s Crust by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen (O)</td>
<td>46.60</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>27.72</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>8.15</td>
</tr>
<tr>
<td>Iron (Fe)</td>
<td>5.00</td>
</tr>
<tr>
<td>Calcium (Ca)</td>
<td>3.63</td>
</tr>
<tr>
<td>Sodium (Na)</td>
<td>2.85</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>2.70</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>2.09</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>98.70</strong></td>
</tr>
</tbody>
</table>

Minerals

Every mineral has distinctive and recognizable physical characteristics that aid in its identification. Some of these characteristics include hardness, luster, cleavage, tendency to fracture, and specific gravity (weight per unit volume). Luster describes the shininess of the mineral. Cleavage signifies how the mineral tends to break along uniform planes, while fracture specifies the form of irregular breaks in the mineral. Minerals are crystalline in nature, although some crystals may only be evident when viewed through a microscope. Mineral crystals display consistent geometric shapes that express their molecular structure (Fig. 13.6). Halite, for example, which is used as table salt, is a soft mineral that has the specific chemical formula NaCl and a cubic crystalline shape. Quartz, calcite, fluorite, talc, topaz, and diamond are just a few examples of other minerals.

Chemical bonds hold together the atoms and molecules that compose a mineral. The strength and nature of these chemical bonds affect the resistance and hardness of minerals and of the rocks that they form. Minerals with weak internal bonds undergo chemical alteration most easily. Charged particles, that is, ions, that form part of a molecule in a mineral may leave or be traded for other substances, generally weakening the mineral structure and forming the chemical basis of rock weathering.

Minerals can be categorized into groups based on their chemical composition. Certain elements, particularly silicon, oxygen, and carbon, combine readily with many other elements. As a result, the most common mineral groups are silicates, oxides, and carbonates. Calcite (CaCO₃), for example, is a relatively soft but widespread mineral that consists of one atom of calcium (Ca) linked together with a carbonate molecule (CO₃), which consists of one atom of carbon (C) plus three atoms of oxygen (O). The silicates, however, are by far the largest and most common mineral group, comprising 92% of Earth’s crust.

Oxygen and silicon (Si) are the two most common elements in Earth’s crust and frequently combine together to form SiO₂, which is called silica. Silicate minerals are compounds of oxygen and silicon that also include one or more metals and/or bases. They are generally created when molten rock matter containing these elements cools and solidifies, causing the crystallization of different minerals at successively lower temperatures and pressures. Dark, heavy, iron-rich silicate minerals crystallize first (at high temperatures), and light-colored, lower density, iron-poor minerals crystallize later at cooler temperatures. The order of mineral crystallization parallels their relative chemical stability in a rock, with silicate minerals that crystallize later tending to be more stable and more resistant to breakdown. In rocks composed of a variety of silicate minerals, the dark, heavy minerals are the first to decompose, while the iron-poor minerals decompose later. Silica in its crystalline form is the mineral quartz, which has a distinctive prismatic crystalline shape. Because quartz is one of the last silicate minerals to form from solidifying molten rock matter, it is a relatively hard and resistant mineral.

Rocks

Although a few rock types are composed of many particles of a single mineral, most rocks consist of several minerals (Fig. 13.7). Each constituent mineral in a rock remains separate and retains its own distinctive characteristics. The properties of the rock as a whole are a composite of those of its various mineral constituents. The number of rock-forming minerals that are common is limited, but they combine through a multitude of processes to produce an enormous variety of rock types (refer to Appendix C for information and pictures of common rocks mentioned in the
Rocks are the fundamental building materials of the lithosphere. They are lifted, pushed down, and deformed by large-scale tectonic forces originating in the lower mantle and asthenosphere. At the surface, rocks are weathered and eroded, to be deposited as sediment elsewhere.

A mass of solid rock that has not been weathered is called **bedrock**. Bedrock may be exposed at the surface of Earth or it may be overlain by a cover of broken and decomposed rock fragments, called **regolith**. Soil may or may not have formed on the regolith (see again Fig. 12.13). On steep slopes, regolith may be absent and bedrock exposed if running water, gravity, or some other surface process removed the weathered rock fragments. A mass of exposed bedrock is often referred to as an **outcrop** (Fig. 13.8).

Geologists distinguish three major categories of rocks based on mode of formation. These rock types are igneous, sedimentary, and metamorphic.

**Igneous Rocks** When molten rock material cools and solidifies it becomes an **igneous rock**. Molten matter below Earth’s surface is called **magma**, whereas molten rock material at the surface is known specifically as **lava** (Fig. 13.9). Lava, therefore, is the only form of molten rock matter that we can see. Lava erupts from volcanoes or fissures in the crust at temperatures as high as 1090°C (2000°F). There are two major categories of igneous rocks: extrusive and intrusive.

Molten material that solidifies at Earth’s surface creates **extrusive igneous rock**, also called volcanic rock. Extrusive igneous rock, therefore, is created from lava. Very explosive eruptions of molten rock material can cause the accumulation of fragments of volcanic rock, dust-sized or larger, that settle out of the air to form **pyroclastics** (fire fragments), as a special category of extrusive rock (Fig. 13.10a). When molten rock beneath Earth’s surface, that is,
magma, changes to a solid (freezes), it forms intrusive igneous rock, also referred to as plutonic rock (after Pluto, Roman god of the underworld). Igneous rocks vary in chemical composition, texture, crystalline structure, tendency to fracture, and presence or absence of layering. They are grouped or classified in terms of their crystal size, or texture, as well as their mineral composition.

Rocks composed of small-sized individual minerals not visible to the unaided eye are described as having a fine-grained texture, while those with large minerals that are visible without magnification are referred to as coarse-grained. Extrusive rocks cool very quickly—at Earth surface temperatures—and are fine-grained as a result of the little time available for crystal growth prior to solidification. An extreme example is the extrusive rock obsidian, which has cooled so rapidly that it is essentially a glass (Fig. 13.10b). Large masses of intrusive rocks that solidify deep inside Earth cool very slowly because surrounding rock slows the loss of heat from molten magma. Slow cooling allows more time for crystal formation prior to solidification. Thin stringers of intrusive rocks and those that solidified close to the surface may cool rapidly and be fine-grained as a result.

The chemical composition of igneous rocks varies from felsic, which is rich in light-colored, lighter weight minerals, especially silicon and aluminum, to mafic, which is lower in silica and rich in heavy minerals, such as compounds of magnesium and iron (ma = magnesium and f = iron). Granite, a felsic, coarse-grained, intrusive rock, has the same chemical and mineral composition as rhyolite, a fine-grained extrusive rock. Likewise, basalt is the dark-colored, mafic, fine-grained extrusive rock equivalent to gabbro, a coarse-grained intrusive rock that cools at depth (Fig. 13.11).

Igneous rocks also form with an intermediate composition, a rough balance between felsic and mafic minerals. The intrusive rock diorite and the extrusive rock andesite (named after the Andes where many volcanoes erupt lava of this composition) represent this intermediate composition (see again Fig. 13.11).

Many igneous rocks are broken along fractures that may be spaced or arranged in regular geometric patterns. In the Earth sciences, simple fractures or cracks in bedrock are called joints. Although joints are common in all rock types, one way they develop in igneous rocks is by a molten mass shrinking in volume and fracturing as it cools and solidifies. Solidified lava flows in particular tend to have many fractures. Basalt is famous for its distinctive jointing, which commonly forms hexagonal columns of solidified lava. Devil’s Postpile in California and Devil’s Tower in Wyoming are well-known landforms that consist of hexagonal columns of lava formed by columnar joints (Fig. 13.12). Jointing in rocks of all types is also caused by regional stresses in the crust and can be a major influence in the development of landforms.

Sedimentary Rocks As their name implies, sedimentary rocks are derived from accumulated sediment, that is, unconsolidated mineral materials that have been eroded, transported, and deposited. After the materials have accumulated, often in horizontal layers, pressure from the material above compacts the sediment, expelling water and reducing pore space. Cementation occurs when silica, calcium carbonate, or iron oxide precipitates between particles of sediment. The processes of compaction and cementation transform ( lithify ) sediments into solid, coherent layers of rock. There are three major categories of sedimentary rocks: clastic, organic, and chemical precipitates.

Broken fragments of solids are called clasts (from Latin: clastus, broken). In order of increasing size, clasts may range from clay, silt, and sand (see again Fig. 12.7) to gravel, which is a general category for any fragment larger than sand (larger than 2.0 mm) and includes granules, pebbles, cobbles, and boulders. Most sediments consist of fragments of previously existing rocks, shell, or bone that were deposited on a river bed, beach, sand dune, lake bottom, the ocean floor, and other environments where clasts accumulate. Sedimentary rocks that form from fragments of preexisting rocks are called clastic sedimentary rocks.

Examples of clastic sedimentary rocks include conglomerate, sandstone, siltstone, and shale (Fig. 13.13). Conglomerate is a solid mass of cemented, roughly rounded pebbles, cobbles, and boulders...
Igneous rocks are distinguished on the basis of texture (mineral grain size) and mineral composition. Igneous rocks that cooled rapidly, such as those that cooled at and near the surface, have fine (small) crystals. Rocks that cooled slowly, typically in large masses deep beneath the surface, have a coarse crystalline texture (large mineral grains). Mineral composition can be mafic, silicic, or intermediate.

What is the difference between granite and basalt?

Large outcrops of fine-grained igneous rock can display hexagonal columnar jointing due to shrinkage as the molten rock matter cooled and solidified. (a) Devil’s Postpile National Monument, California. (b) Devil’s Tower National Monument, Wyoming.

Why are the cliffs shown in these photographs so steep?
the compaction of very fine-grained sediments, especially clays. Shale is finely bedded, smooth-textured, and has low permeability. It is also brittle and easily cracked, broken, or flaked apart.

Sedimentary rocks may be further classified by their origin as either marine or terrestrial (continental). Marine sandstones typically formed in nearshore coastal zones; terrestrial sandstones generally originated in desert or floodplain environments on land. The nature and arrangement of sediments in a sedimentary rock provide a great deal of evidence for the kind of environment in which they were deposited and the processes of deposition, whether on a stream bed, a beach, or the deep-ocean floor.

Organic sedimentary rocks lithified from the remains of organisms, both plants and animals. Coal, for example, was created by the accumulation and compaction of partially decayed vegetation in acidic, swampy environments where water-saturated ground prevented oxidation and complete decay of the organic matter. The initial transformation of such organic material produces peat, which, when subjected to deeper burial and further compaction, is lithified to produce coal. Most of the world’s greatest coal deposits originated between 300 and 354 million years ago during an interval of geologic time known as the Mississippian and Pennsylvanian Periods.

Other organic sedimentary rocks developed from the remains of organisms in lakes and seas. The remains of shellfish, corals, and microscopic drifting organisms called plankton sank to the bottom of such water bodies where they were cemented and compacted together to form a type of limestone, which typically contains fossils such as shells and coral fragments (Fig. 13.14).

At times in Earth history, dissolved minerals accumulated in ocean and lake water until saturation when it began to precipitate and build up as a deposit on the sea or lake bottom. Many fine-grained limestones formed as chemical sedimentary rocks in this manner from precipitates of calcium carbonate (CaCO₃). Limestone therefore may vary from a jagged and cemented complex of visible shells or fossil skeletal material to a smooth-textured rock. Where magnesium is a major constituent along with calcium carbonate, the rock is called dolomite. Because the calcium carbonate in limestone can slowly dissolve in water, limestone in arid or semiarid climates tends to be resistant, but in humid environments it tends to be weak.
Mineral salts that have reached saturation in evaporating seas or lakes will precipitate to form a variety of sedimentary deposits that are useful to humans. These include gypsum (used in wallboard), halite (common salt), and borates, which are important in hundreds of products such as fertilizer, fiberglass, detergents, and pharmaceuticals.

Most sedimentary rocks display distinctive layering referred to as stratification. The many types of sedimentary deposits produce distinctive strata (layers or beds) within the rocks. The bedding planes, or boundaries between sedimentary layers, indicate changes in energy in the depositional environment but no real break in the sequence of deposition (Fig. 13.15). Where a marked mismatch and an irregular, eroded surface occur between beds, the contact between the rocks is called an unconformity. This indicates a gap in the section caused by erosion, rather than deposition, of sediment. Within some sedimentary rocks, especially sandstones, thin “microbedding” may occur. A type of microbedding, called cross bedding, is characterized by a pattern of thin layers that accumulated at an angle to the main strata, often reflecting shifts of direction by waves along a coast, currents in streams, or winds over sand dunes (Fig. 13.16). All types of stratification provide evidence about the environment within which the sediments were deposited, and changes from one layer to the next reflect elements of the local geologic history. For example, a layer of sandstone representing an ancient beach may lie directly beneath shale layers that represent an offshore environment, suggesting that first this was a beach that the sea later covered.

Sedimentary rocks become jointed, or fractured, when they are subjected to crustal stresses after they lithify. The impressive “fins” of rock at Arches National Park, Utah, owe their vertical, tabular shape to joints in great beds of sandstone (Fig. 13.17).
Structures such as bedding planes, cross bedding, and joints are important in the development of physical landscapes because these structures are weak points in the rock that weathering and erosion can attack with relative ease. Joints allow water to penetrate deeply into some rock masses, causing them to be removed at a faster rate than the surrounding rock.

Metamorphic Rocks Metamorphic means “changed form.” Enormous heat and pressure deep in Earth’s crust can alter (metamorphose) an existing rock into a new rock type that is completely different from the original by recrystallizing the minerals without creating molten rock matter. Compared to the original rocks, the resulting metamorphic rocks are typically harder and more compact, have a reoriented crystalline structure, and are more resistant to weathering. There are two major types of metamorphic rocks, based on the presence (foliated) or absence (nonfoliated) of platy surfaces or wavy alignments of light and dark minerals that formed during metamorphism.

Metamorphism occurs most commonly where crustal rocks are subjected to great pressures by tectonic processes or deep burial, or where rising magma generates heat that modifies the nearby rock. Metamorphism causes minerals to recrystallize and, with enough heat and pressure, to reprecipitate perpendicular to the applied stress, forming platy surfaces (cleavage) or wavy bands known as foliations (Fig. 13.18). Some shales produce a hard metamorphic rock known as slate, which exhibits a tendency to break apart, or cleave, along smooth, flat surfaces that are actually extremely thin foliations (Fig. 13.19a). Where the foliations are moderately thin, individual minerals have a flattened but wavy, “platy” structure, and the rocks tend to flake apart along these bands. A common metamorphic rock with thin foliations is called schist.

**FIGURE 13.18**
Metamorphic rocks and foliations. Metamorphic foliations develop at right angles to the stress directions (arrows). (a) Layered rocks under moderate pressure. (b) Greater pressure can cause metamorphism and the development of platy foliations in rocks. (c) Stronger metamorphism can cause the foliations to widen into wavy bands of light and dark minerals.

How are foliations different from bedding planes?

**FIGURE 13.19**
Metamorphic rocks. (a) Slate, schist, and gneiss illustrate differences in metamorphism and the size of foliations. (b) Marble and quartzite are nonfoliated metamorphic rocks with a harder, recrystallized composition compared to the limestone and sandstone from which they were made.
Where the foliations develop into broad mineral bands, the rock is extremely hard and is known as gneiss (pronounced “nice”). Coarse-grained rocks such as granite generally metamorphose into gneiss, whereas finer-grained rocks tend to produce schists.

Rocks that originally were composed of one dominant mineral are not foliated by metamorphism (Fig. 13.19b). Limestone is metamorphosed into much denser marble, and impurities in the rock can produce a beautiful variety of colors. Silica-rich sandstones fuse into quartzite. Quartzite is brittle, harder than steel, and almost inert chemically. Thus, it is virtually immune to chemical weathering and commonly forms cliffs or rugged mountain peaks after the surrounding, less resistant rocks have been removed by erosion. The physical and chemical characteristics of rocks are important factors in the development of landforms.

The Rock Cycle  Like landforms, many rocks do not remain in their original form indefinitely but instead, over a long time, tend to undergo processes of transformation. The rock cycle is a conceptual model for understanding processes that generate, alter, transport, and deposit mineral materials to form different kinds of rocks (Fig. 13.20). The term cycle means that existing rocks supply the materials to make new and sometimes very different rocks. Whole existing rocks can be “recycled” to form new rocks. The geologic age of a rock is based on the time when it assumed its current state; metamorphism, or melting, and other rock-forming processes reset the age of origin.

Although a complete cycle is shown in Figure 13.20, many rocks do not go through every step of the rock cycle, as shown by the arrows that cut across the diagram. Igneous rocks form by the cooling and crystallizing of molten lava or magma. Igneous rocks can be remelted and recrystallized to form new igneous rocks; can be changed into metamorphic rocks by heat and/or pressure; or can be weathered into fragments that are eroded, transported, and deposited to form sedimentary rocks. Sedimentary rocks consist of particles and deposits derived from any of the three basic rock types. Metamorphic rocks can be created by means of heat and pressure applied to igneous or sedimentary rock or through further metamorphism into a new rock type. In addition, metamorphic rocks can be heated sufficiently to melt into magma and cool to form igneous rocks.