What Are Rocks?

A geologist's primary aim is to understand the properties of rocks and to deduce their geologic origins from those properties. Such deductions further our understanding of our planet, and they also provide important information about economically important resources. For example, knowing that oil forms in certain kinds of sedimentary rocks that are rich in organic matter allows us to explore for oil reserves more intelligently. Understanding how rocks form also guides us in solving environmental problems. For example, the underground storage of radioactive and other wastes depends on analysis of the rock to be used as a repository: Will this rock be prone to earthquake-triggered landslides? How might it transmit polluted waters in the ground?

Properties of Rocks

A **rock** is a naturally occurring solid aggregate of minerals or, in some cases, nonmineral solid matter. In an *aggregate,* minerals are joined in such a way that they retain their individual identity (Figure 3.23). A few rocks are composed of nonmineral matter. These rocks include the noncrystalline, glassy volcanic rocks obsidian and pumice as well as coal, which is made up of compacted plant remains.

What determines the physical appearance of a rock? Rocks vary in color, in the sizes of their crystals or grains, and in the kinds of minerals that compose them. Along a road cut, for example, we might find a rough white and pink speckled rock composed of interlocking crystals large enough to be seen with the naked eye. Nearby, we might see a grayish rock containing many large, glittering crystals of mica and some grains of quartz and feldspar. Overlying both the white and pink rock and the gray one, we might see horizontal layers of a striped white and mauve rock that appear to be made up of sand grains cemented together. And these rocks might all be overlain by a dark, fine-grained rock with tiny white dots in it.

The identity of a rock is determined partly by its mineralogy and partly by its texture. Here, the term *mineralogy* refers to the relative proportions of a rock's constituent minerals. **Texture** describes the sizes and shapes of a rock's mineral crystals or grains and the way they are put together. If the crystals or grains, which are only a few millimeters in diameter in most rocks, are large enough to be seen with the naked eye, the rock is categorized as *coarse-grained.* If they are not large enough to be seen, the rock is categorized as *fine-grained.* The mineralogy and texture that determine a rock's appearance are themselves determined by the rock's geologic origin—where and how it formed (Figure 3.24).

The dark rock that caps the sequence of rocks in our road cut, called basalt, was formed by a volcanic eruption. Its mineralogy and texture were determined by the chemical composition of rocks that were melted deep within Earth. All rocks formed by the solidification of molten rock, such as basalt and granite, are called **igneous rocks.**

The striped white and mauve layers in the road cut are sandstone, formed as sand particles accumulated, perhaps on an ancient beach, and eventually were covered over, buried, and cemented together. All rocks formed as the burial products of layers of sediments (such as sand, mud, or the calcium carbonate shells of marine organisms), whether they were laid down on land or under the sea, are called **sedimentary rocks.**

The grayish rock of our road cut, a gneiss, contains crystals of mica, quartz, and feldspar. It formed deep in Earth's crust as high temperatures and pressures transformed the mineralogy and texture of buried sedimentary rock. All rocks formed by the transformation of preexisting solid rock under the influence of high temperatures and pressures are called **metamorphic rocks.**

The three types of rocks seen in our road cut represent the three great families of rock: igneous, sedimentary, and metamorphic. Let's take a closer look at each of these families and at the geologic processes that form them.

Igneous Rocks

Igneous rocks (from the Latin *ignis,* meaning "fire") form by crystallization from magma. When a body of magma cools slowly in Earth's interior, the minerals it contains begin to form microscopic crystals. As the magma cools below its melting point, some of these crystals have time to grow to several millimeters in diameter or larger before the whole mass crystallizes as a coarse-grained igneous rock. But when magma erupts from a volcano onto Earth's surface as lava, it cools and solidifies so rapidly that individual crystals have no time to grow gradually. In that case, many tiny crystals form simultaneously, and the result is a fine-grained igneous rock. Geologists distinguish two major types of igneous rocks—intrusive and extrusive—on the basis of the sizes of their crystals.

INTRUSIVE AND EXTRUSIVE IGNEOUS ROCKS *Intrusive igneous rocks* crystallize when magma intrudes into unmelted rock masses deep in Earth's crust. Large crystals grow as the magma slowly cools, producing coarse-grained rocks. Intrusive igneous rocks can be recognized by their large, interlocking crystals (Figure 3.25). Granite is an intrusive igneous rock.

TABLE 3-5 Some Common Minerals of Igneous, Sedimentary, and Metamorphic Rocks

Igneous Rocks	Sedimentary Rocks	Metamorphic Rocks
Quartz	Quartz	Quartz
Feldspar	Clay minerals	Feldspar
Mica	Feldspar	Mica
Pyroxene	*Calcite	Garnet
Amphibole	*Dolomite	Pyroxene
Olivine	*Gypsum	Staurolite
	*Halite	Kyanite

*Nonsilicate minerals.

Extrusive igneous rocks form from magmas that erupt at Earth's surface as lava and cool rapidly. Extrusive igneous rocks, such as basalt, are easily recognized by their glassy or fine-grained texture.

COMMON MINERALS OF IGNEOUS ROCKS Most of the minerals of igneous rocks are silicates, partly because silicon is so abundant in Earth's crust and partly because many silicate minerals melt at the high temperatures and pressures reached in deeper parts of the crust and in the mantle. The silicate minerals most commonly found in igneous rocks include quartz, feldspars, micas, pyroxenes, amphiboles, and olivines (Table 3.5).

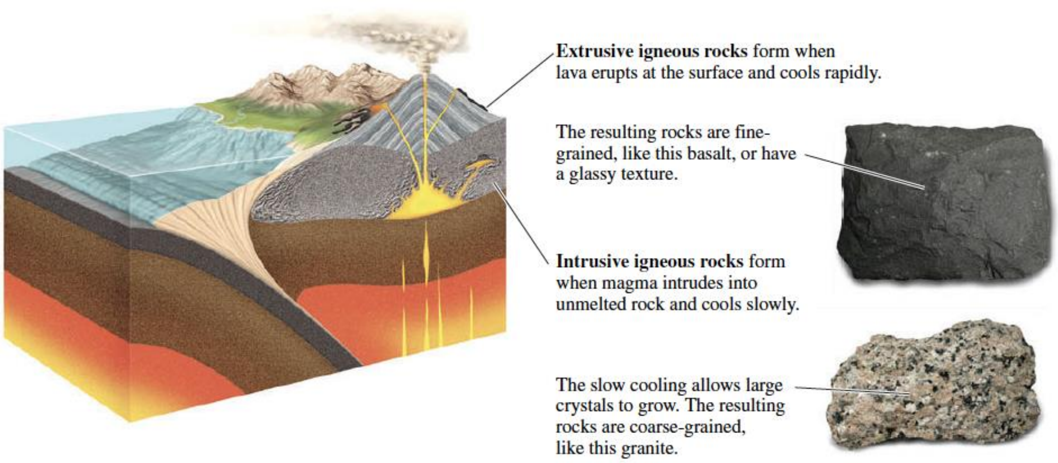

FIGURE 3.25 ■ Igneous rocks are formed by the crystallization of magma. [Photos by John Grotzinger/Ramón Rivera-Moret/Harvard Mineralogical Museum.]

Chemical and Mineral Composition

We have just seen how igneous rocks can be subdivided according to their texture. They can also be classified on the basis of their chemical and mineral composition. Volcanic glass, which is formless even under a microscope, is often classified by chemical analysis alone. One of the earliest classifications of igneous rocks was based on a simple chemical analysis of their silica content. Silica (SiO_2) is abundant in most igneous rocks, accounting for 40 to 70 percent of their total weight.

Modern classifications group igneous rocks according to their relative proportions of silicate minerals (Table 4.1; see also Appendix 4).

The silicate minerals—quartz, feldspars, muscovite and biotite micas, amphiboles and pyroxenes, and olivine—form a systematic series. *Felsic* minerals are the highest in silica; *mafic* minerals are the lowest in silica. The adjectives *felsic* (from *fel*dspar and *si*lica) and *mafic* (from *ma*gnesium and *ferric,* from the Latin *ferrum,* "iron") are applied both to minerals and to rocks containing large proportions of those minerals. Mafic minerals crystallize at higher

TABLE 4-1 Common Minerals of Igneous Rocks

Compositional Group	Mineral	Chemical Composition	Silicate Structure
FELSIC	Quartz	SiO_2	Frameworks
	Orthoclase feldspar	$KAlSi_3O_8$	
	Plagioclase feldspar	$NaAlSi_3O_8$; $CaAl_2Si_2O_8$	
	Muscovite (mica)	$KAl_3Si_3O_{10}(OH)_2$	Sheets
MAFIC	Biotite (mica)	$\left.\begin{matrix}K\\Mg\\Fe\\Al\end{matrix}\right\} Si_3O_{10}(OH)_2$	
	Amphibole group	$\left.\begin{matrix}Mg\\Fe\\Ca\\Na\end{matrix}\right\} Si_8O_{22}(OH)_2$	Double chains
	Pyroxene group	$\left.\begin{matrix}Mg\\Fe\\Ca\\Al\end{matrix}\right\} SiO_3$	Single chains
	Olivine	$(Mg,Fe)_2SiO_4$	Isolated tetrahedral

temperatures—that is, earlier in the cooling of a magma—than felsic minerals.

As the mineral and chemical compositions of igneous rocks became known, geologists soon noticed that some extrusive and intrusive rocks were identical in composition and differed only in texture. Basalt, for example, is an extrusive rock formed from lava. Gabbro has exactly the same mineral and chemical composition as basalt, but forms deep in Earth's crust (see Figure 4.3). Similarly, rhyolite and granite are identical in composition, but differ in texture. Thus, extrusive and intrusive rocks form two chemically and mineralogically parallel sets of igneous rocks. Conversely, most of the chemical and mineral compositions in the felsic-to-mafic series we have just described can appear in either extrusive or intrusive rocks. The only exceptions are very highly mafic rocks, which rarely appear as extrusive igneous rocks.

Figure 4.4 is a model that portrays these relationships. The horizontal axis plots silica content as a percentage of a given rock's weight. The percentages given—from high silica content at 70 percent to low silica content at 40 percent—cover the range found in igneous rocks. The vertical axis plots mineral content as a percentage of a given rock's volume. This model can be used to classify an unknown rock sample with a known silica content: by finding its silica content on the horizontal axis, you can determine its mineral composition and, from that, the type of rock it is.

We can use Figure 4.4 to guide our discussion of intrusive and extrusive igneous rocks. We begin with the felsic rocks at the far left of the model.

FELSIC ROCKS **Felsic rocks** are poor in iron and magnesium and rich in felsic minerals that are high in silica. Such minerals include quartz, orthoclase feldspar, and plagioclase feldspar. Orthoclase feldspars, which contain potassium, are more abundant than plagioclase feldspars. Plagioclase feldspars contain varying amounts of calcium and sodium; as Figure 4.4 indicates, they are richer in sodium near the felsic end and richer in calcium near the mafic end of the scale. Thus, just as mafic minerals crystallize at higher temperatures than felsic minerals, calcium-rich plagioclases crystallize at higher temperatures than sodium-rich plagioclases.

Felsic rocks tend to be light in color. **Granite,** one of the most abundant intrusive igneous rocks, contains about 70 percent silica. Its mineral composition includes abundant quartz and orthoclase feldspar and a smaller amount of plagioclase feldspar (see the far left of Figure 4.4). These light-colored felsic minerals give granite its pink or gray color. Granite also contains small amounts of muscovite and biotite micas and amphibole. **Rhyolite** is the extrusive equivalent of granite. This light brown to gray rock has the same felsic composition and light coloration as granite, but it is much more fine-grained. Many rhyolites are formed largely or entirely of volcanic glass.

MAFIC ROCKS **Mafic rocks** contain large proportions of pyroxenes and olivines. These minerals are relatively poor in silica but are rich in magnesium and iron, from which they get their characteristic dark colors. **Gabbro** is a coarse-grained, dark gray intrusive igneous rock. Gabbro has an abundance of mafic minerals, especially pyroxenes. It contains no quartz and only moderate amounts of calcium-rich plagioclase feldspar.

Basalt is the most abundant igneous rock of the crust, and it underlies virtually the entire seafloor. This dark gray to black rock is the fine-grained extrusive equivalent of gabbro. In some places, extensive thick sheets of basalt, called *flood basalts,* form large plateaus. The Columbia River basalts of Washington State and the remarkable formation known as the Giant's Causeway in Northern Ireland are two examples. The Deccan flood basalts of India and the Siberian flood basalts of northern Russia were formed by enormous outpourings of basalt that appear to coincide closely with two of the greatest periods of mass extinction in the fossil record.

Magmatic Differentiation

The processes we've discussed so far account for the melting of rocks to form magmas. But what accounts for the variety of igneous rocks? Are magmas of different chemical compositions made by the melting of different kinds of rock? Or do igneous processes produce a variety of rocks from an originally uniform parent material?

Again, the answers to these questions came from laboratory experiments. Geologists mixed chemical elements in proportions that simulated the compositions of natural igneous rocks, then melted those mixtures. As the melts cooled and solidified, the geologists observed and recorded the temperatures at which crystals formed, as well as the chemical compositions of those crystals. This research gave rise to the theory of **magmatic differentiation**, a process by which rocks of varying composition can arise from a uniform parent magma. Magmatic differentiation occurs because different minerals crystallize at different temperatures.

In a kind of mirror image of partial melting, the last minerals to melt are the first minerals to crystallize from a cooling magma. This initial crystallization withdraws chemical elements from the melt, changing the magma's composition. Continued cooling crystallizes the minerals that melted at the next lower temperature range. Again, the magma's chemical composition changes as various elements are withdrawn. Finally, as the magma solidifies completely, the last minerals to crystallize are the ones that melted first. Thus, the same parent magma, because of its changing chemical composition throughout the crystallization process, can give rise to different types of igneous rocks.

Igneous Processes and Plate Tectonics

Geologists have observed that the facts and theories of igneous rock formation fit nicely into a framework based on plate tectonic theory. The geometry of plate movements is the link we need to tie tectonic activity and rock composition to igneous processes (Figure 4.13). Batholiths, for example, are found in the cores of many mountain ranges formed by the convergence of two plates. This observation implies a connection between pluton formation and the mountain-building process, and between both of those processes and plate movements. Similarly, our knowledge of the temperatures and pressures at which different kinds of rock melt gives us some idea of where melting takes place. For example, we know that mixtures of sedimentary rocks, because of their composition and water content, should melt at temperatures several hundred degrees below the melting point of basalt. This information leads us to predict that basalt will start to melt near the base of the crust in tectonically active regions of the upper mantle and that sedimentary rocks will melt at shallower depths.

Magma forms most abundantly in two plate tectonic settings: mid-ocean ridges, where two plates diverge and the seafloor spreads, and subduction zones, where one plate dives beneath another. Mantle plumes, though not associated with plate boundaries, also produce large amounts of magma.

Spreading Centers as Magma Factories

Most igneous rocks are formed at mid-ocean ridges by the process of seafloor spreading. Each year, approximately 19 km^3 of basaltic magma is produced along the mid-ocean ridges in the process of seafloor spreading—a truly enormous volume. In comparison, all the active volcanoes along convergent plate boundaries (about 400) generate volcanic rock at a rate of less than 1 km^3/year. Enough magma has erupted during seafloor spreading over the past 200 million years to create all of the present-day seafloor, which covers nearly two-thirds of Earth's surface. Throughout the mid-ocean ridge network, decompression melting of mantle material that wells up along rising convection currents creates magma chambers below the ridge axis. These magmas are extruded as lavas and form new seafloor. At the same time, intrusions of gabbro are emplaced at depth.

Before the advent of plate tectonic theory, geologists were puzzled by unusual assemblages of rocks that were characteristic of the seafloor but were found on land. Known as **ophiolite suites**, these assemblages consist of deep-sea sediments, submarine basaltic lavas, and mafic igneous intrusions (Figure 4.14). Using data gathered from deep-diving submarines, dredging, deep-sea drilling, and seismic exploration, geologists now explain these rocks as fragments of oceanic lithosphere that were transported by seafloor spreading and then raised above sea level and thrust onto a continent in a later episode of plate collision. On some of the more complete ophiolite suites preserved on land, we can literally walk across rocks that used to lie along the boundary between Earth's oceanic crust and mantle.

How does seafloor spreading work? We can think of a spreading center as a huge factory that processes mantle material to produce oceanic crust. Figure 4.15 is a highly schematic and simplified representation of what may be happening, based in part on studies of ophiolite suites found on land and on information gleaned from deep-sea drilling and seismic profiling. Deep-sea drilling has penetrated to the gabbro layer of the seafloor, but not to the crust-mantle boundary below. Seismic profiling has found several small magma chambers similar to the one shown in Figure 4.15.

INPUT MATERIAL: PERIDOTITE IN THE MANTLE The raw material fed into this magma factory comes from the convecting asthenosphere, in which the dominant rock type is peridotite. The mineral composition of the average peridotite in the mantle is chiefly olivine, with smaller amounts of pyroxene and garnet. Temperatures in the asthenosphere are hot enough to melt a small fraction of this peridotite (less than 1 percent), but not hot enough to generate substantial volumes of magma.

PROCESS: DECOMPRESSION MELTING Decompression melting is the process that generates great volumes of magma from peridotite at spreading centers. Recall that a decrease in pressure generally lowers a mineral's melting temperature. As the plates pull apart, the partially molten peridotite is sucked inward and upward toward the spreading center. The decrease in pressure as the peridotite rises causes a large fraction of the rock (up to 15 percent) to melt. The buoyancy of the melt causes it to rise faster than the denser surrounding rock. This process separates the liquid rock from the remaining crystal mush to produce large volumes of magma.

Additional Reading

would have settled to the bottom more slowly (see Practicing Geology). Continued cooling would have produced pyroxene crystals, which would have reached the bottom next, followed almost immediately by calcium-rich plagioclase feldspar. The abundance of plagioclase feldspar in the upper parts of the intrusion is evidence that the magma continued to change in composition until successive layers of settled crystals were topped off by a layer of mostly sodium-rich plagioclase feldspar. In addition to crystallizing at a lower temperature, sodium-rich plagioclase feldspar is less dense than either olivine or pyroxene, so it would have settled out last.

Being able to explain the layering of the Palisades intrusion as the result of fractional crystallization was an early success in understanding magmatic differentiation. It firmly tied field observations to laboratory results and was solidly based on chemical knowledge. We now know that this intrusion actually has a more complex history that includes several injections of magma and a more complicated process of olivine settling. Nevertheless, the Palisades intrusion remains a valid example of fractional crystallization.

Granite from Basalt: Complexities of Magmatic Differentiation

Studies of volcanic lavas have shown that basaltic magmas are common—far more common than the rhyolitic magmas that correspond in composition to granites. How, then, could granites have become so abundant in Earth's crust? The answer is that the process of magmatic differentiation is much more complex than geologists first thought.

The original theory of magmatic differentiation suggested that a basaltic magma would gradually cool and differentiate into a more felsic magma by fractional crystallization. The early stages of this differentiation would produce an andesitic magma, which might erupt to form andesitic lavas or solidify by slow crystallization to form dioritic intrusions. Intermediate stages would result in magmas of granodioritic composition. If the process were carried far enough, its late stages would form rhyolitic lavas and granitic intrusions. One line of research has shown, however, that so much time would be needed for small crystals of olivine to settle through a dense, viscous magma that they might never reach the bottom of a magma chamber. Other researchers have demonstrated that many layered intrusions—similar to but much larger than the Palisades intrusion—do not show the simple progression of layers predicted by the original theory.

The greatest sticking point in the original theory, however, was the source of granite. The great volume of granite found on Earth could not have formed from basaltic magmas by magmatic differentiation, because large quantities of liquid volume are lost by crystallization during successive stages of differentiation. To produce a given amount of granite, an initial volume of basaltic magma 10 times that of the granitic intrusion would be required. Based on that observation, there should be huge quantities of basalt underlying granitic intrusions. But geologists could not find anything like that amount of basalt. Even where great volumes of basalt are found—at mid-ocean ridges—there is no wholesale conversion into granite through magmatic differentiation.

Most in question is the original idea that all granitic rocks are formed from the differentiation of a single type of magma, a basaltic melt. Instead, geologists now believe that the melting of varied rock types in the upper mantle and crust is responsible for much of the observed variation in the composition of magmas:

1. Rocks in the upper mantle undergo partial melting to produce basaltic magmas.
2. Mixtures of sedimentary rock and basaltic oceanic crust, such as those found in subduction zones, melt to form andesitic magmas.
3. Mixtures of sedimentary, igneous, and metamorphic continental crustal rocks melt to produce granitic magmas.

Thus, the mechanisms of magmatic differentiation must be much more complex than first recognized in a number of ways:

- Magmatic differentiation can begin with the partial melting of mantle and crustal rocks with a range of water contents over a range of temperatures.
- Magmas do not cool uniformly; they may exist transiently at a range of temperatures within a magma chamber. Differences in temperature within and among magma chambers may cause the chemical composition of magma to vary from one region to another.
- A few magma types are *immiscible*—they do not mix with one another, just as oil and water do not mix. When such magmas coexist in one magma chamber, each forms its own fractional crystallization series. Magmas that are *miscible*—that *do* mix—may follow a crystallization path different from that followed by any one magma type alone.

We now know more about the physical processes that interact with fractional crystallization within magma chambers (Figure 4.8). Magma at various temperatures in different parts of a magma chamber may flow turbulently, crystallizing as it circulates. Crystals may settle, then be caught up in currents again, and eventually be deposited on the chamber's walls. The margins of such a magma chamber may be a "mushy" zone of crystals and melt lying between the solid rock border of the chamber and the completely liquid magma within the heart of the chamber. And, at some mid-ocean ridges, such as the East Pacific Rise, a mushroom-shaped magma chamber may be surrounded by hot basaltic rock containing only small amounts (1 to 3 percent) of partial melt.