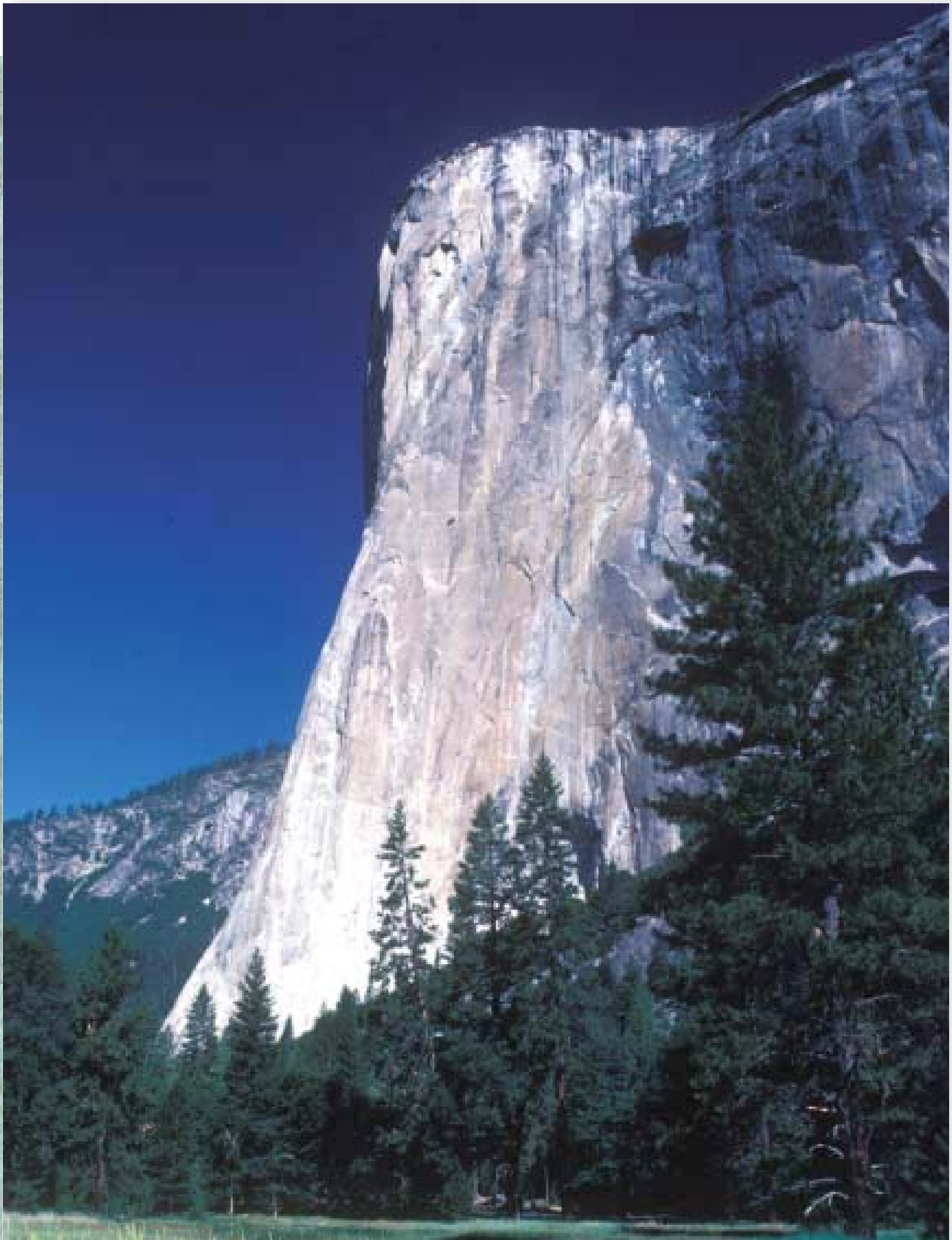
Igneous Rocks and Intrusive Igneous Activity



CHAPTER 4 OUTLINE

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OBJECTIVES

At the end of this chapter, you will have learned that:

- With few exceptions, magma is composed of silicon and oxygen with lesser amounts of several other chemical elements.
- Temperature and especially composition are the most important controls on the mobility of magma and lava.
- Most magma originates within Earth's upper mantle or lower crust at or near divergent and convergent plate boundaries.
- Several processes bring about chemical changes in magma, so magma may evolve from one kind into another.
- All igneous rocks form when magma or lava cools and crystallizes or by the consolidation of pyroclastic materials ejected during explosive eruptions.
- Geologists use texture and composition to classify igneous rocks.
- Intrusive igneous bodies called plutons form when magma cools below Earth's surface. The origin of the largest plutons is not fully understood.

This mass of granitic rock in Yosemite National Park in California is called El Capitan, meaning "The Chief." It is part of the Sierra Nevada batholith, a huge pluton mesuring 640 km long and 110 km wide. This near-vertical cliff rises more than 900 m above the valley floor, making it the highest unbroken cliff in the world.

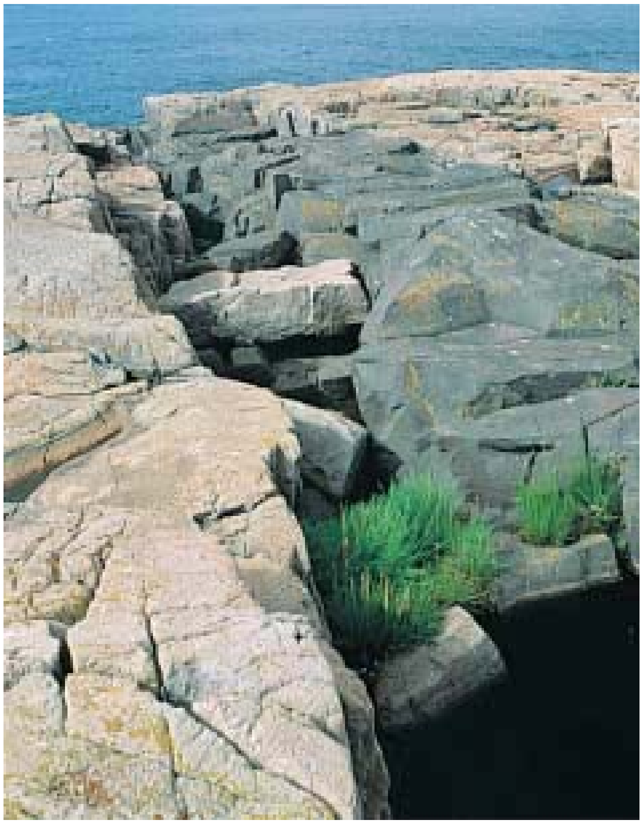
Introduction

We mentioned that the term *rock* applies to a solid aggregate of one or more minerals as well as to mineral-like matter such as natural glass and solid masses of organic matter such as coal. Furthermore, in Chapter 1 we briefly discussed the three main families of rocks: igneous, sedimentary, and metamorphic. Recall that *igneous rocks* form when molten rock material known as *magma* or *lava* cools and crystallizes to form a variety of minerals, or when particulate matter called *pyroclastic materials* become consolidated. We are most familiar with igneous rocks formed from lava flows and pyroclastic materials because they are easily observed at Earth's surface, but you should be aware that most magma never reaches the surface. Indeed, much of it cools and crystallizes far underground and thus forms *plutons,* igneous bodies of various shapes and sizes.

Granite and several similar-appearing rocks are the most common rocks in the larger plutons such as those in the Sierra Nevada of California (see the chapter opening photo) and in Acadia National Park in Maine (■ Figure 4.1a). The images of Presidents Lincoln, Roosevelt, Jefferson, and Washington at Mount Rushmore National Memorial in South Dakota (Figure 4.1b) as well as the nearby Crazy Horse Memorial (under construction) are in the 1.7-billion-year-old Harney Peak Granite, which consists of a number of plutons. These huge plutons formed far below the surface, but subsequent uplift and deep erosion exposed them in their present form.

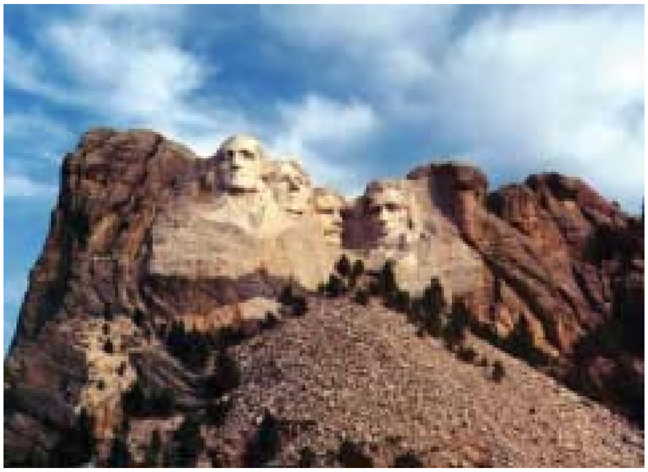
Some granite and related rocks are quite attractive, especially when sawed and polished. They are used for tombstones, mantlepieces, kitchen counters, facing stones on buildings, pedestals for statues, and statuary itself. More important, though, is the fact that fluids emanating from plutons account for many ore minerals of important metals, such as copper in adjacent rocks.

The origin of plutons, or intrusive igneous activity, and volcanism involving the eruption of lava flows, gases, and pyroclastic materials are closely related topics even though we discuss them in separate chapters. The same kinds of magmas are involved in both processes, but magma varies in its mobility, which explains why only some reaches the surface. Furthermore, plutons typically lie beneath areas of volcanism and, in fact, are the source of the overlying lava flows and pyroclastic materials. Plutons and most volcanoes are found at or near divergent and convergent plate boundaries, so the presence of igneous rocks is one criterion for recognizing ancient plate boundaries; igneous rocks also help us unravel the complexities of mountain-building episodes (see Chapter 10).



Richard Thom/Visuals Unlimited

(a)



National Park Service

(b)

■ **Figure 4.1**

(a) Light-colored granitic rocks exposed along the shoreline in Acadia National Park in Maine. The dark rock is basalt that formed when magma intruded along a fracture in the granitic rock. (b) The presidents' images at Mount Rushmore National Memorial in South Dakota are in the Harney Peak Granite.

One important reason to study igneous rocks and intrusive igneous activity is that igneous rocks are one of the three main families of rocks. In addition, igneous rocks make up large parts of all the continents and nearly all of the oceanic crust, which is formed continuously by igneous activity at divergent plate boundaries. And, as already mentioned, important mineral deposits are found adjacent to many plutons.

In this chapter, our main concerns are (1) the origin, composition, textures, and classification of igneous rocks, and (2) the origin, significance, and types of plutons. In Chapter 5, we will consider volcanism, volcanoes, and associated phenomena that result from magma reaching Earth's surface. Remember, though, that the origin of plutons and volcanism are related topics.

THE PROPERTIES AND BEHAVIOR OF MAGMA AND LAVA

In Chapter 3 we noted that one process that accounts for the origin of minerals, and thus rocks, is cooling and crystallization of magma and lava. **Magma** is molten rock below Earth's surface. Any magma is less dense than the rock from which it was derived, so it tends to move upward, but much of it cools and solidifies deep underground, thus accounting for intrusive igneous bodies known as *plutons.* However, some magma does rise to the surface where it issues forth as **lava flows,** or it is forcefully ejected into the atmosphere as particulate matter known as **pyroclastic materials** (from the Greek *pyro,* "fire," and *klastos,* "broken"). Certainly lava flows and eruptions of pyroclastic materials are the most impressive manifestations of all processes related to magma, but they result from only a small percentage of all magma that forms.

All **igneous rocks** derive from magma, but two separate processes account for them. They form when (1) magma or lava cools and crystallizes to form minerals, or (2) pyroclastic materials are consolidated to form a solid aggregate from the previously loose particles. Igneous rocks that result from the cooling of lava flows and the consolidation of pyroclastic materials are **volcanic rocks** or **extrusive igneous rocks**—that is, igneous rocks that form from materials erupted on the surface. In contrast, magma that cools below the surface forms **plutonic rocks** or **intrusive igneous rocks.**

Composition of Magma

In Chapter 3 we noted that by far the most abundant minerals in Earth's crust are silicates such as quartz, various feldspars, and several ferromagnesian silicates, all made up of silicon and oxygen, and other elements shown in Figure 3.9. As a result, melting of the crust yields mostly silica-rich magmas that also contain considerable aluminum, calcium, sodium, iron, magnesium, and potassium, and several other elements in lesser quantities. Another source of magma is Earth's upper mantle, which is composed of rocks that contain mostly ferromagnesian silicates. Thus magma from this source contains comparatively less silicon and oxygen (silica) and more iron and magnesium.

Although there are a few exceptions, the primary constituent of magma is silica, which varies enough to distinguish magmas classified as felsic, intermediate, and mafic.* **Felsic magma,** with more than 65% silica, is silica-rich and contains considerable sodium, potassium, and aluminum but little calcium, iron, and magnesium. In contrast, **mafic magma,** with less than 52% silica, is silica-poor and contains proportionately more calcium, iron, and magnesium. And as you would expect, **intermediate magma** has a composition between felsic and mafic magma (Table 4.1).

Table 4.1

The Most Common Types of Magmas and Their Characteristics

Type of Magma	Silica Content (%)	Sodium, Potassium, and Aluminum	Calcium, Iron, and Magnesium
Ultramafic	<45	↓	Increase
Mafic	45–52	↓	↑
Intermediate	53–65	↓	↑
Felsic	>65	Increase	↑

How Hot Are Magma and Lava?

Everyone knows that lava is very hot, but how hot is hot? Erupting lava generally has a temperature in the range of 1000° to 1200°C, although a temperature of 1350°C was recorded above a lava lake in Hawaii where volcanic gases reacted with the atmosphere. Magma must be even hotter than lava, but no direct

*Lava from some volcanoes in Africa cools to form carbonitite, an igneous rock with at least 50% carbonate minerals, mostly calcite and dolomite.

Figure 4.2

A geologist using a thermocouple to determine the temperature of a lava flow in Hawaii.

measurements of magma temperatures have ever been made.

Most lava temperatures are taken at volcanoes that show little or no explosive activity, so our best information comes from mafic lava flows such as those in Hawaii (Figure 4.2). In contrast, eruptions of felsic lava are not as common, and the volcanoes that these flows issue from tend to be explosive and thus cannot be approached safely. Nevertheless, the temperatures of some bulbous masses of felsic lava in lava domes have been measured at a distance with an optical pyrometer. The surfaces of these lava domes are as hot as 900°C, but their interiors must surely be even hotter.

When Mount St. Helens erupted in 1980 in Washington State, it ejected felsic magma as particulate matter in pyroclastic flows. Two weeks later, these flows had temperatures between 300° and 420°C, and a steam explosion took place more than a year later when water encountered some of the still-hot pyroclastic materials. The reason that lava and magma retain heat so well is that rock conducts heat so poorly. Accordingly, the interiors of thick lava flows and pyroclastic flow deposits may remain hot for months or years, whereas plutons, depending on their size and depth, may not cool completely for thousands to millions of years.

Viscosity—Resistance to Flow

All liquids have the property of **viscosity,** or resistance to flow. For liquids such as water, viscosity is very low so they are highly fluid and flow readily. For other liquids, though, viscosity is so high that they flow much more slowly. Good examples are cold motor oil and syrup, both of which are quite viscous and thus flow only with difficulty. But when these liquids are heated, their viscosity is much lower and they flow more easily; that is, they become more fluid with increasing temperature. Accordingly, you might suspect that temperature controls the viscosity of magma and lava, and this inference is partly correct. We can generalize and say that hot magma or lava moves more readily than cooler magma or lava, but we must qualify this statement by noting that temperature is not the only control of viscosity.

Silica content strongly controls magma and lava viscosity. With increasing silica content, numerous networks of silica tetrahedra form and retard flow because for flow to take place, the strong bonds of the networks must be ruptured. Mafic magma and lava with 45–52% silica have fewer silica tetrahedra networks and as a result are more mobile than felsic magma and lava flows. One mafic flow in 1783 in Iceland flowed about 80 km, and geologists traced ancient flows in Washington State for more than 500 km. Felsic magma, in contrast, because of its higher viscosity, does not reach the surface as commonly as mafic magma. And when felsic lava flows do occur, they tend to be slow moving and thick and to move only short distances. A thick, pasty lava flow that erupted in 1915 from Lassen Peak in California flowed only about 300 m before it ceased moving.

HOW DOES MAGMA ORIGINATE AND CHANGE?

Most of us have not witnessed a volcanic eruption, but we have nevertheless seen news reports or documentaries showing magma issuing forth as lava flows or pyroclastic materials. In any case, we are familiar with some aspects of igneous activity, but most people are unaware of how and where magma originates, how it rises from its place of origin, and how it might change. Indeed, many believe the misconception that lava comes from a continuous layer of molten rock beneath the crust or that it comes from Earth's molten outer core.

First, let us address how and where magma originates. We know that the atoms in a solid are in constant motion and that, when a solid is heated, the energy of motion exceeds the binding forces and the solid melts. We are all familiar with this phenomenon, and we are also aware that not all solids melt at the same temperature. Once magma forms, it tends to rise because it is less dense than the rock that melted, and some actually makes it to the surface.

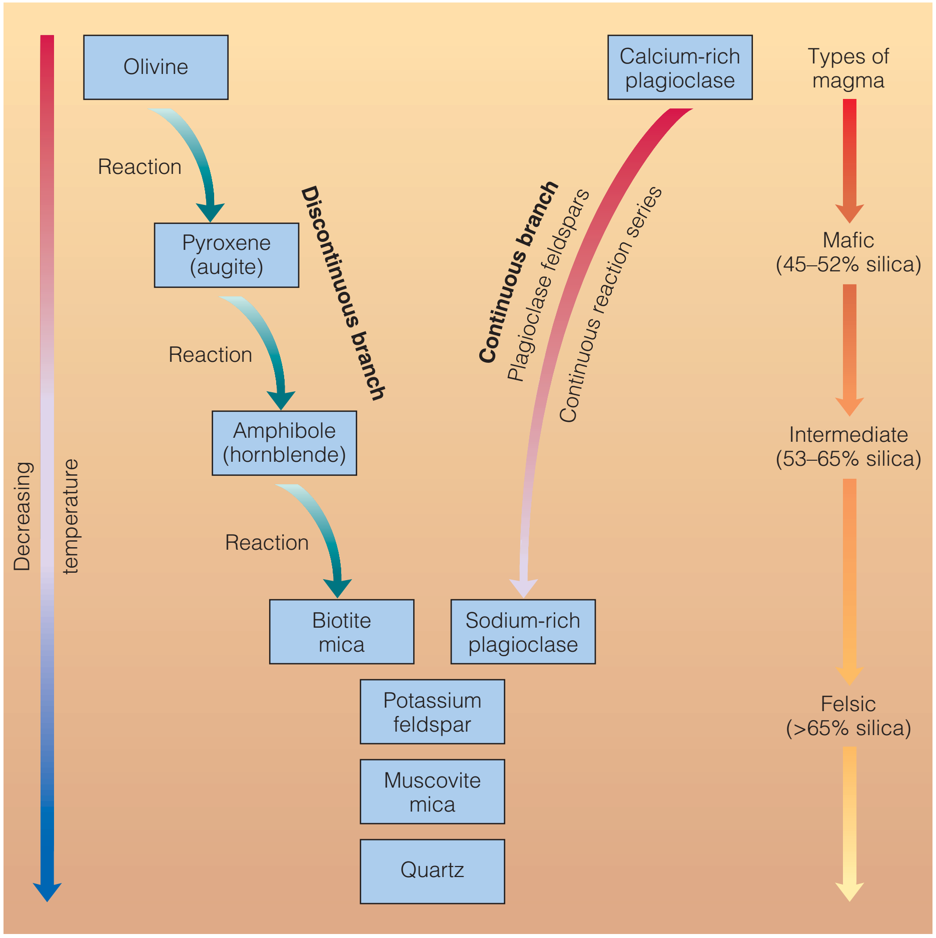
Magma may come from 100 to 300 km deep, but most forms at much shallower depths in the upper mantle or lower crust and accumulates in reservoirs known as **magma chambers.** Beneath spreading ridges, where the crust is thin, magma chambers exist at a depth of only a few kilometers, but along convergent plate boundaries, magma chambers are commonly a few tens of kilometers deep. The volume of a magma chamber ranges from a few to many hundreds of cubic kilometers of molten rock within the otherwise solid lithosphere. Some simply cools and crystallizes within Earth's crust, thus accounting for the origin of various plutons, whereas some rises to the surface and is erupted as lava flows or pyroclastic materials.

Bowen's Reaction Series

During the early part of the last century, N. L. Bowen hypothesized that mafic, intermediate, and felsic magmas could all derive from a parent mafic magma. He knew that minerals do not all crystallize simultaneously from cooling magma, but rather crystallize in a predictable sequence. Based on his observations and laboratory experiments, Bowen proposed a mechanism, now called **Bowen's reaction series,** to account for the derivation of intermediate and felsic magmas from mafic magma. Bowen's reaction series consists of two branches: a *discontinuous branch* and a *continuous branch* (■ Figure 4.3). As the temperature of magma decreases, minerals crystallize along both branches simultaneously, but for convenience we will discuss them separately.

In the discontinuous branch, which contains only ferromagnesian silicates, one mineral changes to another over specific temperature ranges (Figure 4.3). As the temperature decreases, a temperature range is reached in which a given mineral begins to crystallize. A previously formed mineral reacts with the remaining liquid magma (the melt) so that it forms the next mineral in the sequence. For instance, olivine $[(Mg,Fe)_2SiO_4]$ is the first ferromagnesian silicate to crystallize. As the magma continues to cool, it reaches the temperature range at which pyroxene is stable; a reaction occurs between the olivine and the remaining melt, and pyroxene forms.

With continued cooling, a similar reaction takes place between pyroxene and the melt, and the pyroxene structure is rearranged to form amphibole. Further cooling causes a reaction between the amphibole and the melt, and its structure is rearranged so that the sheet structure of biotite mica forms. Although the reactions just described tend to convert one mineral to the next in



■ **Figure 4.3**

Bowen's reaction series consists of a discontinuous branch along which a succession of ferromagnesian silicates crystallize as the magma's temperature decreases, and a continuous branch along which plagioclase feldspars with increasing amounts of sodium crystallize. Notice also that the composition of the initial mafic magma changes as crystallization takes place along the two branches.

What Would You Do?

You are a high school science teacher interested in developing experiments to show your students that (1) composition and temperature affect the viscosity of a lava flow, and (2) when magma or lava cools, some minerals crystallize before others. Describe the experiments you might devise to illustrate these points.

the series, the reactions are not always complete. Olivine, for example, might have a rim of pyroxene, indicating an incomplete reaction. If magma cools rapidly enough, the early-formed minerals do not have time to react with the melt, and thus all the ferromagnesian silicates in the discontinuous branch can be in one rock. In any case, by the time biotite has crystallized, essentially all the magnesium and iron present in the original magma have been used up.

Plagioclase feldspars, which are nonferromagnesian silicates, are the only minerals in the continuous branch of Bowen's reaction series (Figure 4.3). Calcium-rich plagioclase crystallizes first. As the magma continues to cool, calcium-rich plagioclase reacts with the melt, and plagioclase containing proportionately more sodium crystallizes until all of the calcium and sodium are used up. In many cases, cooling is too rapid for a complete transformation from calcium-rich to sodium-rich plagioclase to take place. Plagioclase forming under these conditions is *zoned*, meaning that it has a calcium-rich core surrounded by zones progressively richer in sodium.

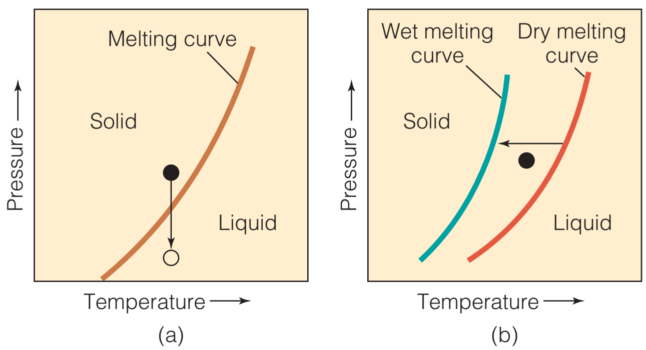
As minerals crystallize simultaneously along the two branches of Bowen's reaction series, iron and magnesium are depleted because they are used in ferromagnesian silicates, whereas calcium and sodium are used up in plagioclase feldspars. At this point, any leftover magma is enriched in potassium, aluminum, and silicon, which combine to form orthoclase ($KAlSi_3O_8$), a potassium feldspar, and if water pressure is high, the sheet silicate muscovite forms. Any remaining magma is enriched in silicon and oxygen (silica) and forms the mineral quartz (SiO_2). The crystallization of orthoclase and quartz is not a true reaction series because they form independently rather than by a reaction of orthoclase with the melt.

The Origin of Magma at Spreading Ridges

One fundamental observation regarding the origin of magma is that Earth's temperature increases with depth. Known as the *geothermal gradient*, this temperature increase averages about 25°C/km. Accordingly, rocks at depth are hot but remain solid because their melting temperature rises with increasing pressure (■ Figure 4.4a). However, beneath spreading ridges the temperature locally exceeds the melting temperature, at least in part because pressure decreases. That is, plate separation at ridges probably causes a decrease in pressure on the already hot rocks at depth, thus initiating melting (Figure 4.4a). In addition, the presence of water decreases the melting temperature beneath spreading ridges because water aids thermal energy in breaking the chemical bonds in minerals (Figure 4.4b).

Localized, cylindrical plumes of hot mantle material, called *mantle plumes*, rise beneath spreading ridges and elsewhere, and as they rise, pressure decreases and melting begins, thus yielding magma. Magma formed beneath spreading ridges is invariably mafic (45–52% silica). But the upper mantle rocks from which this magma is derived are characterized as ultramafic (<45% silica), consisting largely of ferromagnesian silicates and lesser amounts of nonferromagnesian silicates. To explain how mafic magma originates from ultramafic rock, geologists propose that the magma forms from source rock that only partially melts. This phenomenon of partial melting takes place because not all of the minerals in rocks melt at the same temperature.

Recall the sequence of minerals in Bowen's reaction series (Figure 4.3). The order in which these minerals melt is the opposite of their order of crystallization. Accordingly, rocks made up of quartz, potassium feldspar, and sodium-rich plagioclase begin melting at lower temperatures than those composed of ferromagnesian silicates and the calcic varieties of plagioclase. So when ultramafic rock starts to melt, the minerals richest in silica melt first, followed by



■ **Figure 4.4**

The effects of pressure and temperature on melting. (a) As pressure decreases, even when temperature remains constant, melting takes place. The black circle represents rock at high temperature. The same rock (open circle) melts at lower pressure. (b) If water is present, the melting curve shifts to the left because water provides an additional agent to break chemical bonds. Accordingly, rocks melt at a lower temperature (green melting curve) if water is present.

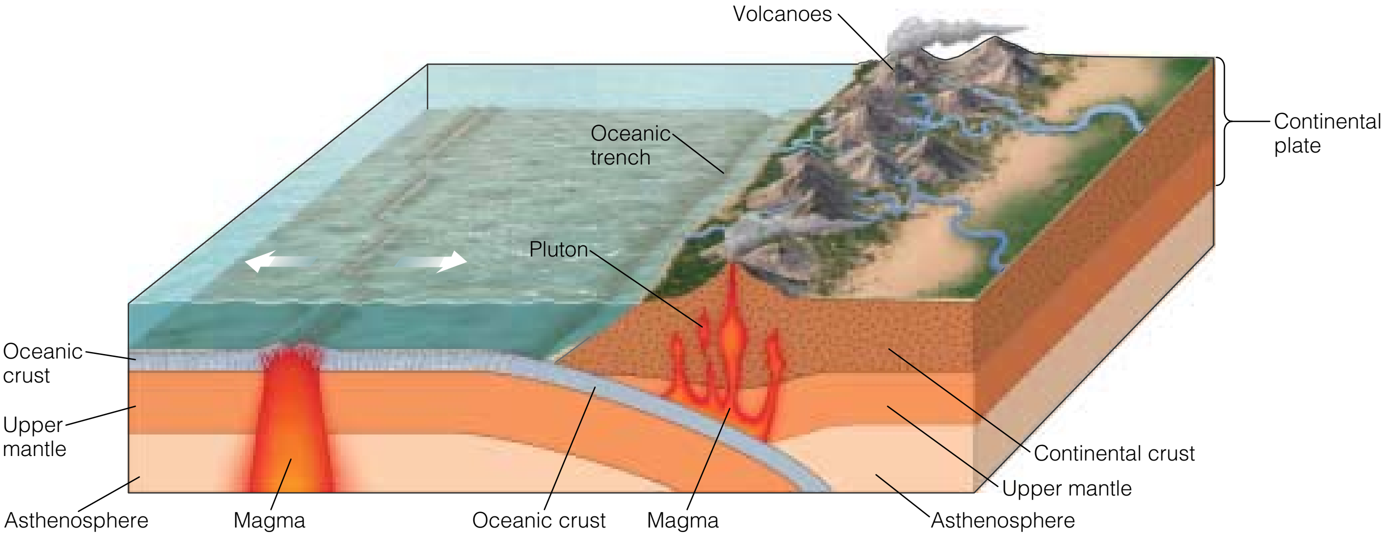


Figure 4.5

Both intrusive and extrusive igneous activity take place at divergent plate boundaries (spreading ridges) and where plates are subducted at convergent plate boundaries. Oceanic crust is composed largely of plutons and dark igneous rocks that cooled from submarine lava flows. Magma forms where an oceanic plate is subducted beneath another oceanic plate or beneath a continental plate as shown here. Much of the magma forms plutons, but some is erupted to form volcanoes (see Chapter 5).

those containing less silica. Therefore, if melting is not complete, mafic magma containing proportionately more silica than the source rock results.

Subduction Zones and the Origin of Magma

Another fundamental observation regarding magma is that, where an oceanic plate is subducted beneath either a continental plate or another oceanic plate, a belt of volcanoes and plutons is found near the leading edge of the overriding plate (■ Figure 4.5). It would seem, then, that subduction and the origin of magma must be related in some way, and indeed they are. Furthermore, magma at these convergent plate boundaries is mostly intermediate (53–65% silica) or felsic (>65% silica).

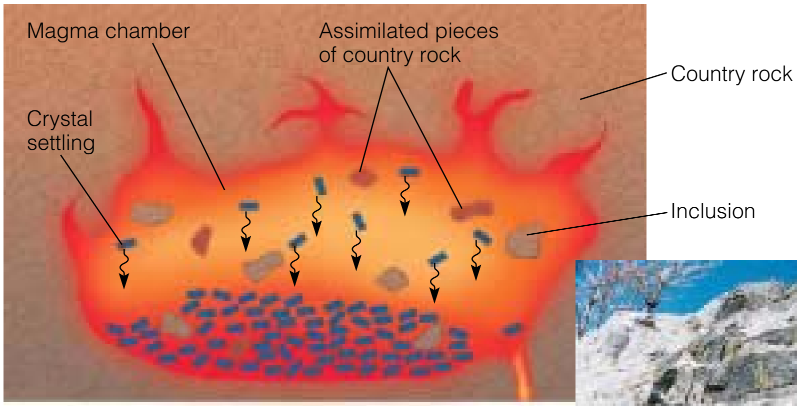
Once again, geologists invoke the phenomenon of partial melting to explain the origin and composition of magma at subduction zones. As a subducted plate descends toward the asthenosphere, it eventually reaches the depth where the temperature is high enough to initiate partial melting. In addition, the oceanic crust descends to a depth at which dewatering of hydrous minerals takes place, and as the water rises into the overlying mantle, it enhances melting and magma forms (Figure 4.4b).

Recall that partial melting of ultramafic rock at spreading ridges yields mafic magma. Similarly, partial melting of mafic rocks of the oceanic crust yields intermediate (53–65% silica) and felsic (>65% silica) magmas, both of which are richer in silica than the source rock. Moreover, some of the silica-rich sediments and sedimentary rocks of continental margins are probably carried downward with the subducted plate and contribute their silica to the magma. Also, mafic magma rising through the lower continental crust must be contaminated with silica-rich materials, which changes its composition.

Processes That Bring About Compositional Changes in Magma

Once magma forms, its composition may change by **crystal settling,** which involves the physical separation of minerals by crystallization and gravitational settling (■ Figure 4.6). Olivine, the first ferromagnesian silicate to form in the discontinuous branch of Bowen's reaction series, has a density greater than the remaining magma and tends to sink. Accordingly, the remaining magma becomes richer in silica, sodium, and potassium because much of the iron and magnesium were removed as olivine and perhaps pyroxene minerals crystallized.

Although crystal settling does take place, it does not do so on a scale that would yield very much felsic magma from mafic magma. In some thick, sheetlike plutons called *sills,* the first-formed ferromagnesian silicates are indeed concentrated in their lower parts, thus making



(a)

(b)

■ **Figure 4.6**

(a) Early-formed ferromagnesian silicates are denser than the magma and settle and accumulate in the magma chamber. Fragments of rock dislodged by upward-moving magma may melt and be incorporated into the magma, or they may remain as inclusions. (b) Dark inclusions in granitic rock.

their upper parts less mafic. But even in these plutons, crystal settling has yielded very little felsic magma.

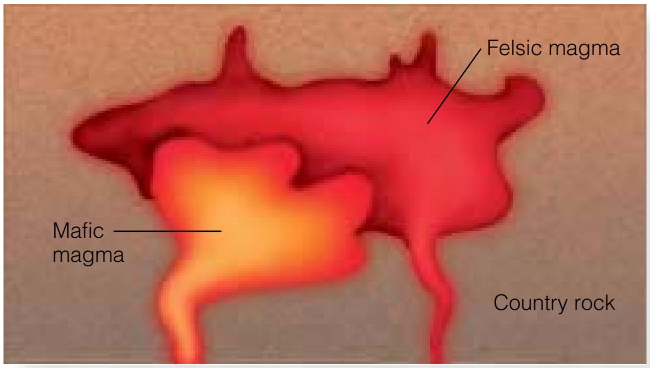
If felsic magma could be derived on a large scale from mafic magma, there should be far more mafic magma than felsic magma. To yield a particular volume of granite (a felsic igneous rock), about 10 times as much mafic magma would have to be present initially for crystal settling to yield the volume of granite in question. If this were so, then mafic intrusive igneous rocks should be much more common than felsic ones. However, just the opposite is the case, so it appears that mechanisms other than crystal settling must account for the large volume of felsic magma. Partial melting of mafic oceanic crust and silica-rich sediments of continental margins during subduction yields magma richer in silica than the source rock. Furthermore, magma rising through the continental crust absorbs some felsic materials and becomes more enriched in silica.

The composition of magma also changes by **assimilation,** a process by which magma reacts with preexisting rock, called **country rock,** with which it comes in contact (Figure 4.6). The walls of a volcanic conduit or magma chamber are, of course, heated by the adjacent magma, which may reach temperatures of 1300°C. Some of these rocks partly or completely melt, provided their melting temperature is lower than that of the magma. Because the assimilated rocks seldom have the same composition as the magma, the composition of the magma changes.

The fact that assimilation occurs is indicated by *inclusions,* incompletely melted pieces of rock that are fairly common in igneous rocks. Many inclusions were simply wedged loose from the country rock as magma forced its way into preexisting fractures (Figure 4.6). No one doubts that assimilation takes place, but its effect on the bulk composition of magma must be slight. The reason is that the heat for melting comes from the magma itself, and this has the effect of cooling the magma. Only a limited amount of rock can be assimilated by magma, and that amount is insufficient to bring about a major compositional change.

Neither crystal settling nor assimilation can produce a significant amount of felsic magma from a mafic one. But both processes, if operating concurrently, can bring about greater changes than either process acting alone. Some geologists think that this is one way that intermediate magma forms where oceanic lithosphere is subducted beneath continental lithosphere.

A single volcano can erupt lavas of different composition, indicating that magmas of differing composition are present. It seems likely that some of these magmas would come into contact and mix with one another. If this is the case, we would expect that the composition of the magma resulting from **magma mixing** would be a modified version of the parent magmas. Suppose rising mafic magma mixes with felsic magma of about the same volume (■ Figure 4.7). The resulting "new" magma would have a more intermediate composition.



■ **Figure 4.7**

Magma mixing. Two magmas mix and produce magma with a composition different from either of the parent magmas. In this case, the resulting magma would have an intermediate composition.

IGNEOUS ROCKS—THEIR CHARACTERISTICS AND CLASSIFICATION

We have already defined *plutonic* or *intrusive igneous rocks* and *volcanic* or *extrusive igneous rocks.* Here we will have considerably more to say about the texture, composition, and classification of these rocks, which constitute one of the three major rock families depicted in the rock cycle (see Figure 1.12).

Igneous Rock Textures

The term *texture* refers to the size, shape, and arrangement of the minerals that make up igneous rocks. Size is the most important because mineral crystal size is related to the cooling history of magma or lava and generally indicates whether an igneous rock is volcanic or plutonic. The atoms in magma and lava are in constant motion, but when cooling begins, some atoms bond to form small nuclei. As other atoms in the liquid chemically bond to these nuclei, they do so in an orderly geometric arrangement and the nuclei grow into crystalline *mineral grains,* the individual particles that make up igneous rocks.

During rapid cooling, as takes place in lava flows, the rate at which mineral nuclei form exceeds the rate of growth and an aggregate of many small mineral grains is formed. The result is a fine-grained or **aphanitic texture,** in which individual minerals are too small to be seen without magnification (■ Figure 4.8a, b). With slow cooling, the rate of growth exceeds the rate of nuclei formation, and relatively large mineral grains form, thus yielding a coarse-grained or **phaneritic texture,** in which minerals are clearly visible (Figure 4.8c, d). Aphanitic textures generally indicate an extrusive origin, whereas rocks with phaneritic textures are usually intrusive. However, shallow plutons might have an aphanitic texture, and the rocks that form in the interiors of thick lava flows might be phaneritic.

Another common texture in igneous rocks is one termed **porphyritic,** in which minerals of markedly different size are present in the same rock. The larger minerals are *phenocrysts* and the smaller ones collectively make up the *groundmass,* which is simply the grains between phenocrysts (Figure 4.8e, f). The groundmass can be either aphanitic or phaneritic; the only requirement for a porphyritic texture is that the phenocrysts be considerably larger than the minerals in the groundmass. Igneous rocks with porphyritic textures are designated *porphyry,* as in basalt porphyry. These rocks have more complex cooling histories than those with aphanitic or phaneritic textures that might involve, for example, magma partly cooling beneath the surface followed by its eruption and rapid cooling at the surface.

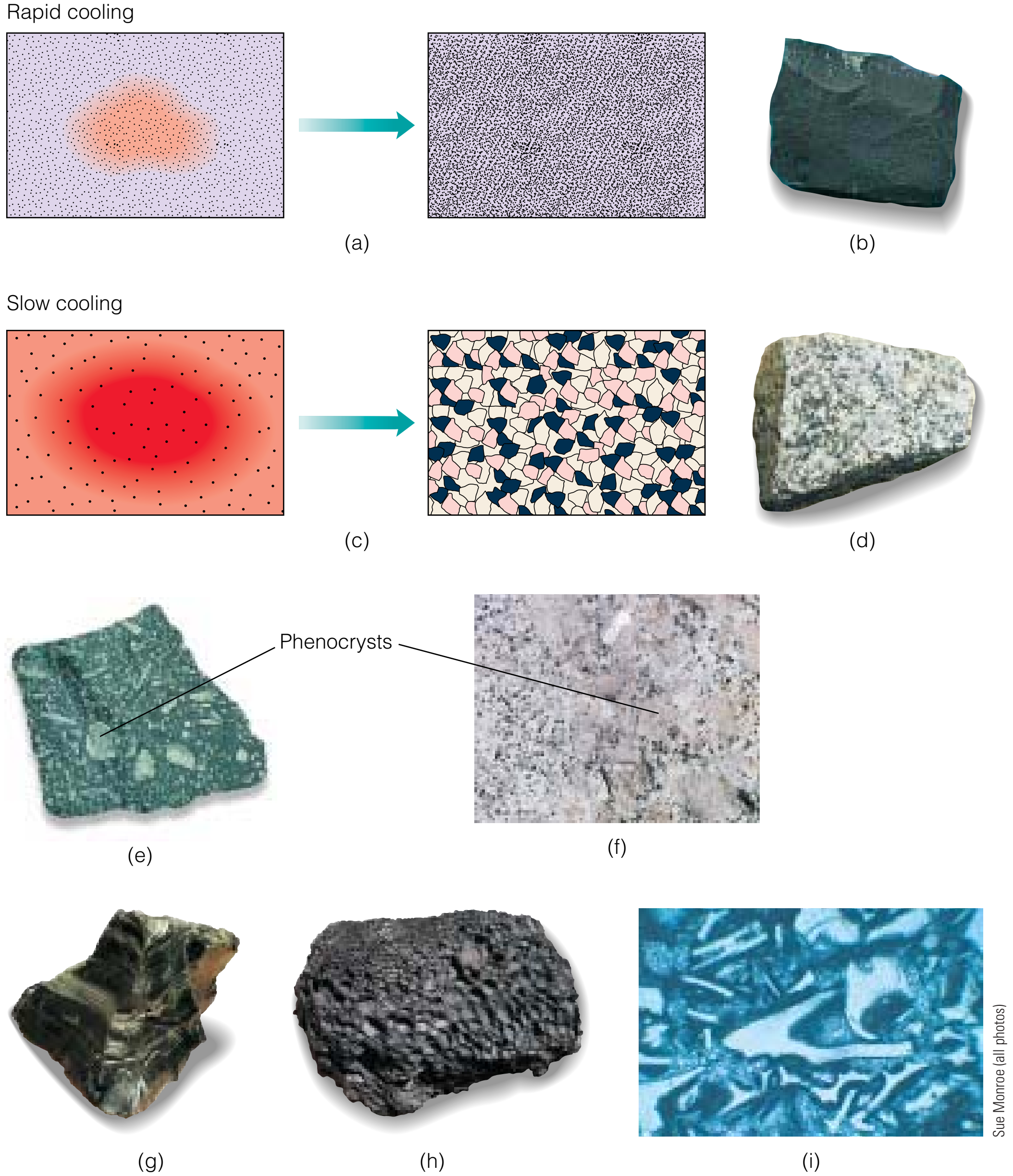
Lava may cool so rapidly that its constituent atoms do not have time to become arranged in the ordered, three-dimensional frameworks of minerals. As a consequence *natural glass* such as *obsidian* forms (Figure 4.8g). Even though obsidian with its glassy texture is not composed of minerals, geologists nevertheless classify it as an igneous rock.

Some magmas contain large amounts of water vapor and other gases. These gases may be trapped in cooling lava where they form numerous small holes or cavities known as **vesicles;** rocks with many vesicles are termed *vesicular,* as in vesicular basalt (Figure 4.8h).

A **pyroclastic** or **fragmental texture** characterizes igneous rocks formed by explosive volcanic activity (Figure 4.8i). For example, ash discharged high into the atmosphere eventually settles to the surface where it accumulates; if consolidated, it forms pyroclastic igneous rock.

Composition of Igneous Rocks

Most igneous rocks, like the magma from which they originate, are characterized as mafic (45–52% silica), intermediate (53–65% silica), or felsic (>65% silica). A few are referred to as ultramafic (<45% silica), but these are probably derived from mafic magma by a process discussed later. The parent magma plays an important role in determining the mineral composition of igneous rocks, yet it is possible for the same magma to yield a variety of igneous rocks because its composition can change as a result of the sequence in which minerals crystallize, or by crystal settling, assimilation, and magma mixing (Figures 4.3, 4.6, and 4.7).



■ **Figure 4.8**

The various textures of igneous rocks. Texture is one criterion used to classify igneous rocks. (a, b) Rapid cooling as in lava flows results in many small minerals and an aphanitic (fine-grained) texture. (c, d) Slower cooling in plutons yields a phaneritic texture. (e, f) These porphyritic textures indicate a complex cooling history. (g) Obsidian has a glassy texture because magma cooled too quickly for mineral crystals to form. (h) Gases expand in lava and yield a vesicular texture. (i) Microscopic view of an igneous rock with a fragmental texture. The colorless, angular objects are pieces of volcanic glass measuring up to 2 mm.

Classifying Igneous Rocks

Geologists use texture and composition to classify most igneous rocks. Notice in ■ Figure 4.9 that all rocks except peridotite are in pairs; the members of a pair have the same composition but different textures. Basalt and gabbro, andesite and diorite, and rhyolite and granite are compositional (mineralogical) pairs, but basalt, andesite, and rhyolite are aphanitic and most commonly extrusive (volcanic), whereas gabbro, diorite, and granite are phaneritic and mostly intrusive (plutonic). The extrusive and intrusive members of each pair can usually be distinguished by texture, but remember that rocks in some shallow plutons may be aphanitic and rocks that formed in thick lava flows may be phaneritic. In other words, all of these rocks exist in a textural continuum.

The igneous rocks in Figure 4.9 are also differentiated by composition—that is, by their mineral content. Reading across the chart from rhyolite to andesite to basalt, for example, we see that the proportions of non-

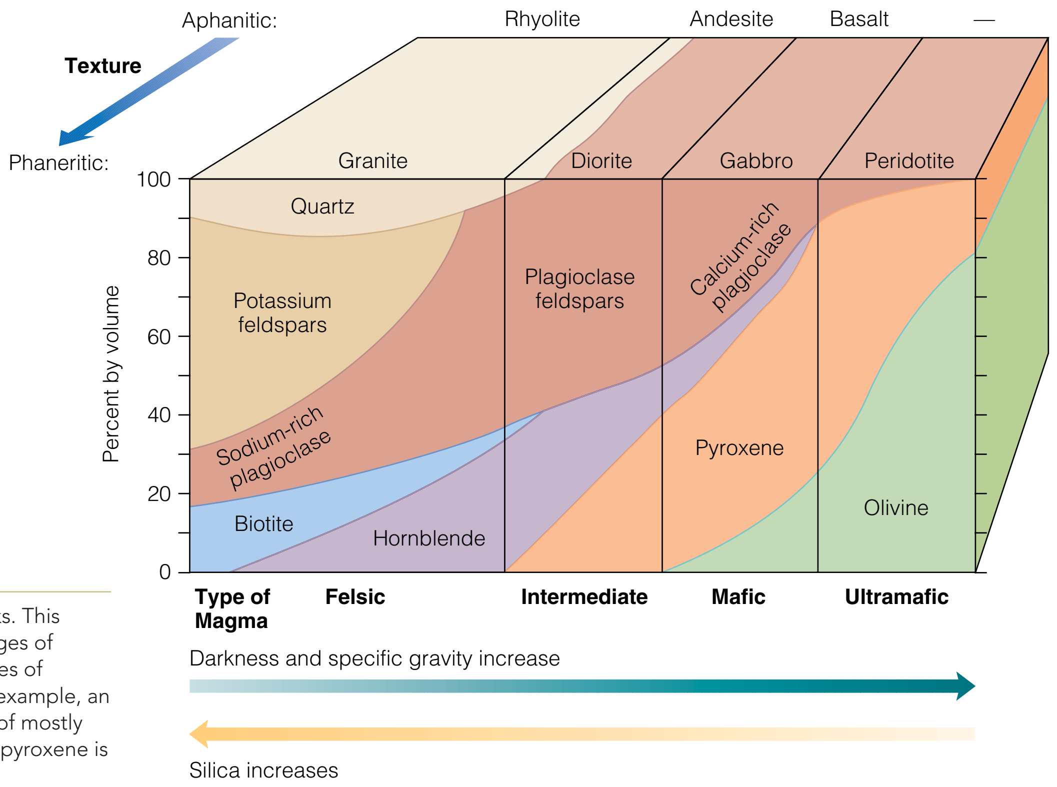


Figure 4.9

Classification of igneous rocks. This diagram shows the percentages of minerals as well as the textures of common igneous rocks. For example, an aphanitic (fine-grained) rock of mostly calcium-rich plagioclase and pyroxene is basalt.

ferromagnesian and ferromagnesian silicates change. The differences in composition, however, are gradual along a compositional continuum. In other words, there are rocks with compositions that correspond to the lines between granite and diorite, basalt and andesite, and so on.

Ultramafic Rocks Ultramafic rocks (<45% silica) are composed largely of ferromagnesian silicates. The ultramafic rock *peridotite* contains mostly olivine, lesser amounts of pyroxene, and usually a little plagioclase feldspar (Figures 4.9 and 4.10). Pyroxenite, another ultramafic rock, is composed predominately of pyroxene. Because these minerals are dark, the rocks are generally black or dark green. Peridotite is probably the rock type that makes up the upper mantle (see Chapter 9). Ultramafic rocks in Earth's crust probably originate by concentration of the early-formed ferromagnesian minerals that separated from mafic magmas.

Ultramafic lava flows are known in rocks older than 2.5 billion years, but younger ones are rare or absent. The reason is that to erupt, ultramafic lava must have a near-surface temperature of about 1600°C; the surface temperatures of present-day mafic lava flows are between 1000° and 1200°C. During early Earth history, though, more radioactive decay heated the mantle to as much as 300°C hotter than now and ultramafic lavas could erupt onto the surface. Because the amount of heat has decreased over time, Earth has cooled, and eruptions of ultramafic lava flows ceased.

Basalt-Gabbro *Basalt* and *gabbro* are the aphanitic and phaneritic rocks, respectively, that crystallize from mafic magma (45–52% silica) (Figure 4.11). Thus, both have the same composition—mostly calcium-rich plagioclase and pyroxene, with smaller amounts of olivine and amphibole (Figure 4.9). Because they contain a large proportion of ferromagnesian silicates, basalt and gabbro are dark; those that are porphyritic typically contain calcium plagioclase or olivine phenocrysts.

Extensive basalt lava flows cover vast areas in Washington, Oregon, Idaho, and northern California (see Chapter 5). Oceanic islands such as Iceland, the Galápagos, the Azores, and the Hawaiian Islands are composed mostly of basalt, and basalt makes up the upper part of the oceanic crust.

Figure 4.10

This specimen of the ultramafic rock peridotite is made up mostly of olivine. Notice in Figure 4.9 that peridotite is the only phaneritic rock that does not have an aphanitic counterpart. Peridotite is rare at Earth's surface but is very likely the rock making up the mantle. Source: Sue Monroe

(a) Basalt (b) Gabbro

■ **Figure 4.11**

Mafic igneous rocks. (a) Basalt is aphanitic, whereas (b) gabbro is phaneritic. Notice the light reflected from the crystal faces in (b). Both basalt and gabbro have the same mineral composition (see Figure 4.9).

Gabbro is much less common than basalt, at least in the continental crust or where it can be easily observed. Small intrusive bodies of gabbro are present in the continental crust, but intermediate to felsic intrusive rocks are much more common. The lower part of the oceanic crust is composed of gabbro, however.

Andesite-Diorite Intermediate composition magma (53–65% silica) crystallizes to form *andesite* and *diorite,* which are compositionally equivalent fine- and coarse-grained igneous rocks (■ Figure 4.12). Andesite and diorite are composed predominately of plagioclase feldspar, with the typical ferromagnesian component being amphibole or biotite (Figure 4.9). Andesite is generally medium to dark gray, but diorite has a salt-and-pepper appearance because of its white to light gray plagioclase and dark ferromagnesian silicates (Figure 4.12).

Andesite is a common extrusive igneous rock formed from lava erupted in volcanic chains at convergent plate boundaries. The volcanoes of the Andes Mountains of South America and the Cascade Range in western North America are composed in part of andesite. Intrusive bodies of diorite are fairly common in the continental crust.

Rhyolite-Granite *Rhyolite* and *granite* crystallize from felsic magma (>65% silica) and are therefore silica-rich rocks (■ Figure 4.13). They consist largely of potassium feldspar, sodium-rich plagioclase, and quartz, with perhaps some biotite and rarely amphibole (Figure 4.9). Because nonferromagnesian silicates predominate, rhyolite and granite are typically light colored. Rhyolite is fine grained, although most often it contains phenocrysts of potassium feldspar or quartz, and granite is coarse grained. Granite porphyry is also fairly common.

Rhyolite lava flows are much less common than andesite and basalt flows. Recall that the greatest control of magma viscosity is silica content. Thus, if felsic magma rises to the surface, it begins to cool, the pressure on it decreases, and gases are released explosively, usually yielding rhyolitic pyroclastic materials. The rhyolitic lava flows that do occur are thick and highly viscous and move only short distances.

Granite is a coarsely crystalline igneous rock with a composition corresponding to that of the field shown in Figure 4.9. Strictly speaking, not all rocks in this field are granites. For example, a rock with a composition close to the line separating granite and diorite is called *granodiorite.* To avoid the confusion that might result from introducing more rock names, we will follow the practice of referring to rocks to the left of the granite-diorite line in Figure 4.9 as *granitic.*

(a) Andesite (b) Diorite

■ **Figure 4.12**

Intermediate igneous rocks. (a) Andesite has hornblende phenocrysts, so this is andesite porphyry. (b) Diorite has a salt-and-pepper appearance because it contains light-colored nonferromagnesian silicates and dark-colored ferromagnesian silicates.

Sue Monroe

(a) Rhyolite

Sue Monroe

(b) Granite

■ **Figure 4.13**

Felsic igneous rocks. (a) Rhyolite and (b) granite are typically light colored because they contain mostly nonferromagnesian silicates. The dark spots in the granite are biotite mica. The white and pinkish minerals are feldspars, whereas the glassy minerals are quartz.

Granitic rocks are by far the most common intrusive igneous rocks, although they are restricted to the continents. Most granitic rocks were intruded at or near convergent plate margins during mountain-building episodes. When these mountainous regions are uplifted and eroded, the vast bodies of granitic rocks forming their cores are exposed. The granitic rocks of the Sierra Nevada of California form a composite body measuring about 640 km long and 110 km wide, and the granitic rocks of the Coast Ranges of British Columbia, Canada, are even more voluminous.

Pegmatite The term *pegmatite* refers to a particular texture rather than a specific composition, but most pegmatites are composed largely of quartz, potassium feldspar, and sodium-rich plagioclase, thus corresponding closely to granite. A few pegmatites are mafic or intermediate in composition and are appropriately called *gabbro* and *diorite pegmatites.* The most remarkable feature of pegmatites is the size of their minerals, which measure at least 1 cm across, and in some pegmatites they measure tens of centimeters or meters (■ Figure 4.14). Many pegmatites are associated with large granite intrusive bodies and are composed of minerals that formed from the water-rich magma that remained after most of the granite crystallized.

When magma cools and forms granite, the remaining water-rich magma has properties that differ from the magma from which it separated. It has a lower density and viscosity and commonly invades the adjacent rocks where minerals crystallize. This water-rich magma also contains a number of elements that rarely enter into the common minerals that form granite. Pegmatites that are essentially very coarsely crystalline granite are simple pegmatites, whereas those with minerals containing elements such as lithium, beryllium, cesium, boron, and several others are complex pegmatites. Some complex pegmatites contain 300 different mineral species, a few of which are important economically. In addition, several gem minerals such as emerald and aquamarine, both of which are varieties of the silicate mineral beryl, and tourmaline are found in some pegmatites. Many rare minerals of lesser value and well-formed crystals of common minerals, such as quartz, are also mined and sold to collectors and museums.

The formation and growth of mineral-crystal nuclei in pegmatites are similar to those processes in other magmas but with one critical difference: The water-rich magma from which pegmatites crystallize inhibits the formation of nuclei. However, some nuclei do form, and because the appropriate ions in the liquid can move easily and attach themselves to a growing crystal, individual minerals have the opportunity to grow very large.

Other Igneous Rocks A few igneous rocks, including tuff, volcanic breccia, obsidian, pumice, and scoria are identified primarily by their textures (■ Figure 4.15). Much of the fragmental material erupted by volcanoes is *ash,* a designation for pyroclastic materials measuring less than 2.0 mm, most of which consists of broken pieces or shards of volcanic glass (Figure 4.8i). The consolidation of ash forms the pyroclastic rock *tuff* (■ Figure 4.16a). Most tuff is silica-rich and light colored and is appropriately called *rhyolite tuff.* Some ash flows are so hot that as they come to rest, the ash particles fuse together and form a *welded tuff.* Consolidated deposits of larger pyroclastic materials, such as cinders, blocks, and bombs, are *volcanic breccia* (Figure 4.15).

Both *obsidian* and *pumice* are varieties of volcanic glass (Figure 4.16b, c). Obsidian may be black, dark gray, red, or brown, depending on the presence of iron.

Courtesy of Steve Stahl

Sue Monroel

(a) (b)

Figure 4.14

(a) The light-colored rock is pegmatite exposed in the Black Hills of South Dakota. (b) A closeup view of a pegmatite specimen with minerals measuring 2 to 3 cm across. This is a simple pegmatite that has a composition much like that of granite.

Obsidian breaks with the conchoidal (smoothly curved) fracture typical of glass. Analyses of many samples indicate that most obsidian has a high silica content and is compositionally similar to rhyolite.

Pumice is a variety of volcanic glass containing numerous vesicles that develop when gas escapes through lava and forms a froth (Figure 4.16c). If pumice falls into water, it can be carried great distances because it is so porous and light that it floats. Another vesicular rock is *scoria*. It is more crystalline and denser than pumice, but it has more vesicles than solid rock (Figure 4.16d).

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Composition		Felsic ← → Mafic	
Texture	Vesicular	Pumice	Scoria
	Glassy	Obsidian	
	Pyroclastic or fragmental	← Volcanic Breccia → Tuff/welded tuff	

Figure 4.15

Classification of igneous rocks for which texture is the main consideration. Composition is shown, but it is not essential for naming these rocks.

What Would You Do?

As the only member of your community with any geology background, you are considered the local expert on minerals and rocks. Suppose one of your friends brings you a rock specimen with the following features—composition: mostly potassium feldspar and plagioclase feldspar with about 10% quartz and minor amounts of biotite; texture: minerals average 3 mm across, but several potassium feldspars are up to 3 cm. Give the specimen a rock name and tell your friend as much as you can about the rock's history. Why are the minerals so large?

PLUTONS—THEIR CHARACTERISTICS AND ORIGINS

Unlike volcanism and the origin of volcanic rocks, we can study intrusive igneous activity only indirectly because **plutons**, intrusive igneous bodies, form when magma cools and crystallizes

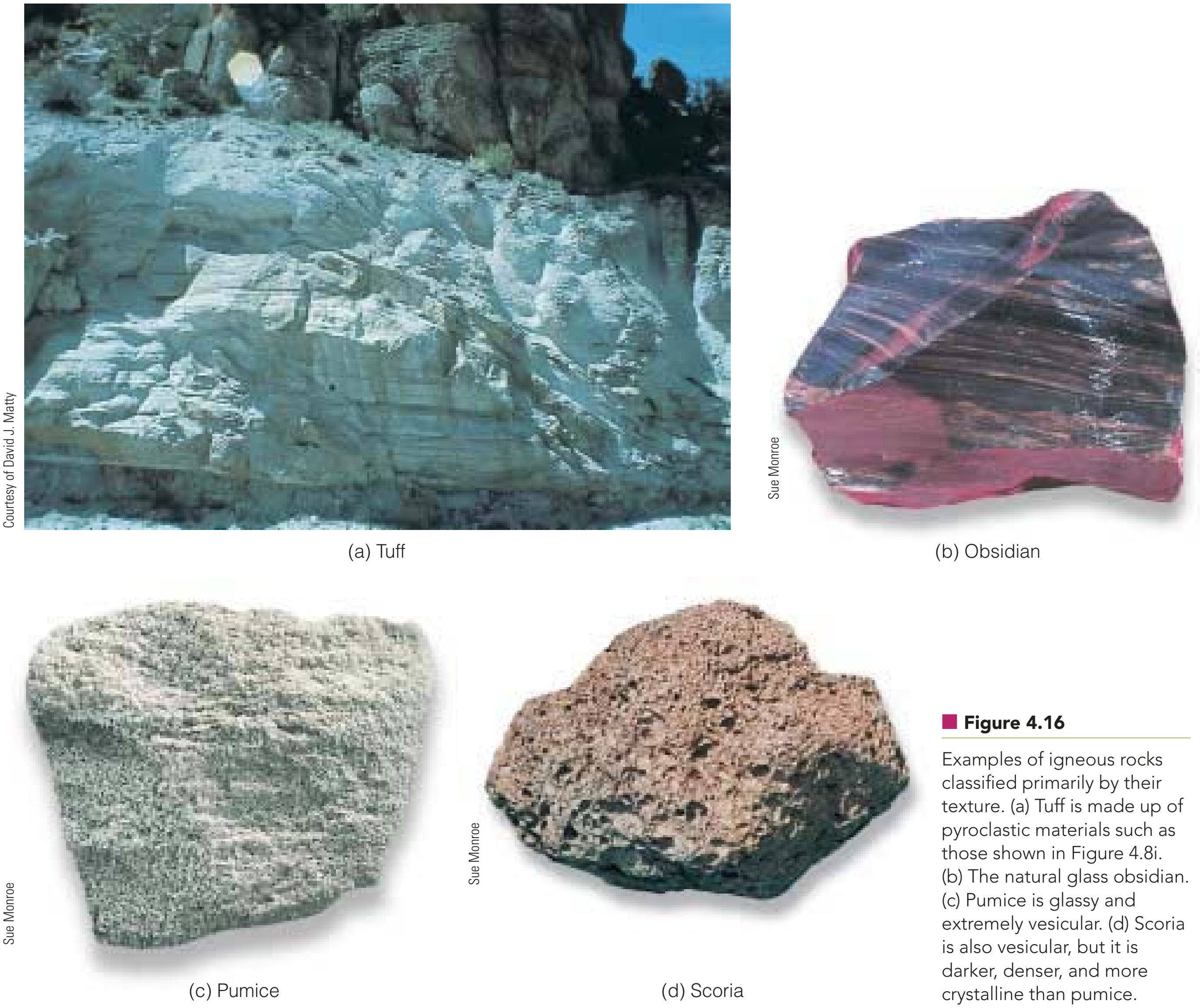


Figure 4.16

Examples of igneous rocks classified primarily by their texture. (a) Tuff is made up of pyroclastic materials such as those shown in Figure 4.8i. (b) The natural glass obsidian. (c) Pumice is glassy and extremely vesicular. (d) Scoria is also vesicular, but it is darker, denser, and more crystalline than pumice.

within Earth's crust (see "Plutons" on pages 102 and 103). We can observe them only after erosion has exposed them at the surface. Furthermore, geolgists cannot duplicate the conditions under which plutons form except in small laboratory experiments. Accordingly, geologists face a greater challenge in interpreting the mechanisms whereby plutons form. Magma that cools to form plutons is emplaced in Earth's crust mostly at convergent and divergent plate boundaries, which are also areas of volcanism.

Geologists recognize several types of plutons based on their geometry (three-dimensional shape) and relationships to the country rock. In terms of their geometry, plutons are massive (irregular), tabular, cylindrical, or mushroom-shaped. Plutons are also either **concordant,** meaning they have boundaries that parallel the layering in the country rock, or **discordant,** with boundaries that cut across the country rock's layering (see "Plutons" on pages 102 and 103).

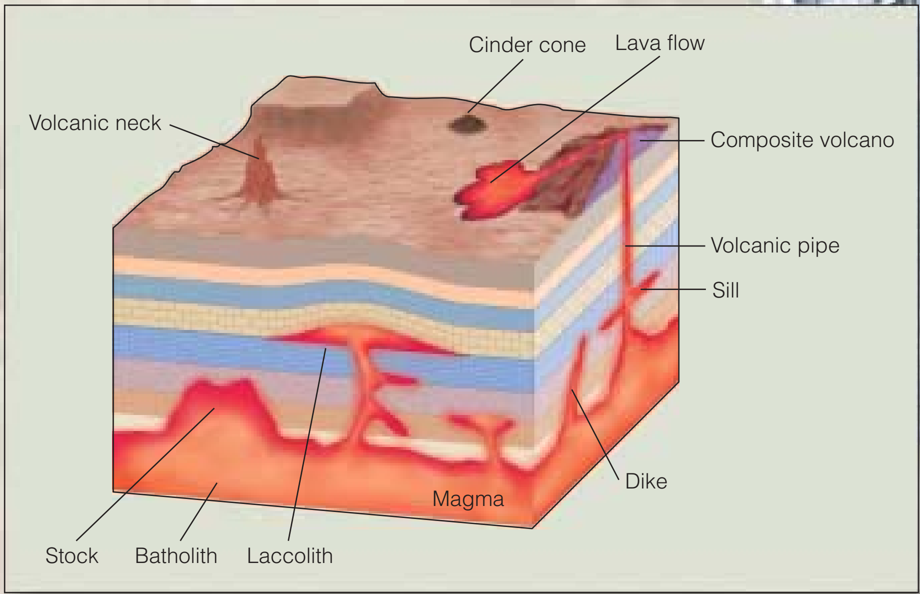
Dikes and Sills

Dikes and **sills** are tabular or sheetlike plutons, differing only in that dikes are discordant whereas sills are concordant (see "Plutons" on pages 102 and 103). Dikes are quite common; most of them are small bodies measuring 1 or 2 m across, but they range from a few centimeters to more than 100 m thick. Invariably they are emplaced within preexisting fractures or where fluid pressure is great enough for them to form their own fractures.

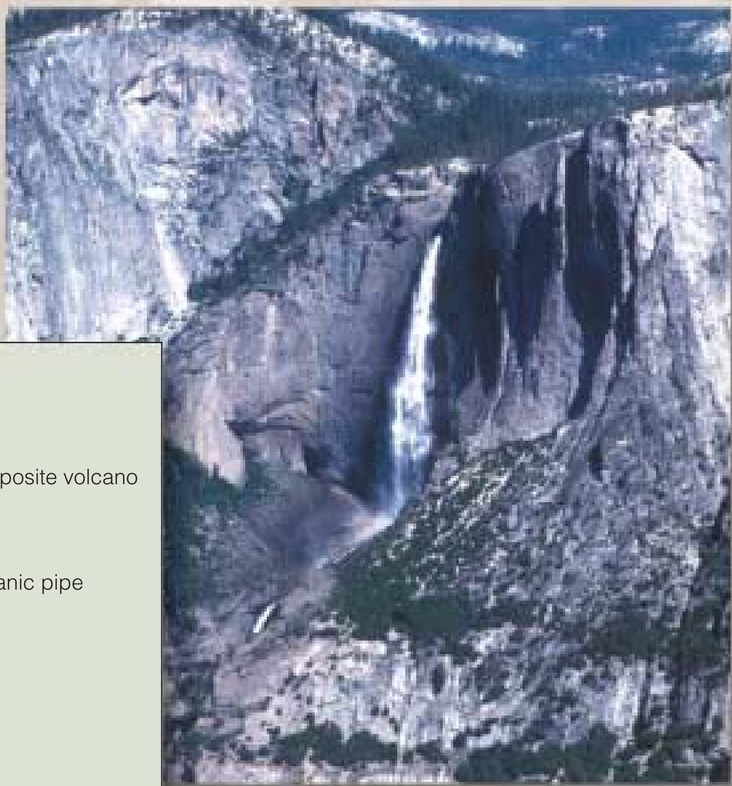
Erosion of the Hawaiian volcanoes exposes dikes in rift zones, the large fractures that cut across these volcanoes. The Columbia River basalts in Washington State (discussed in Chapter 5) issued from long fissures, and magma that cooled in the fissures formed dikes. Some of the large historic fissure eruptions are underlain by dikes; for example, dikes underlie both the Laki fissure eruption of 1783 in Iceland and the Eldgja fissure, also

Plutons

Intrusive bodies called plutons are common, but we see them at the surface only after deep erosion. Notice that they vary in geometry and their relationships to the country rock.

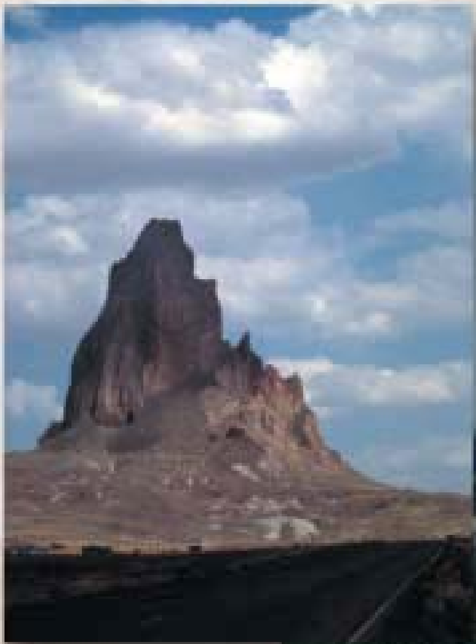


Block diagram showing various plutons. Some plutons cut across the layering in country rock and are discordant, whereas others parallel the layering and are concordant.



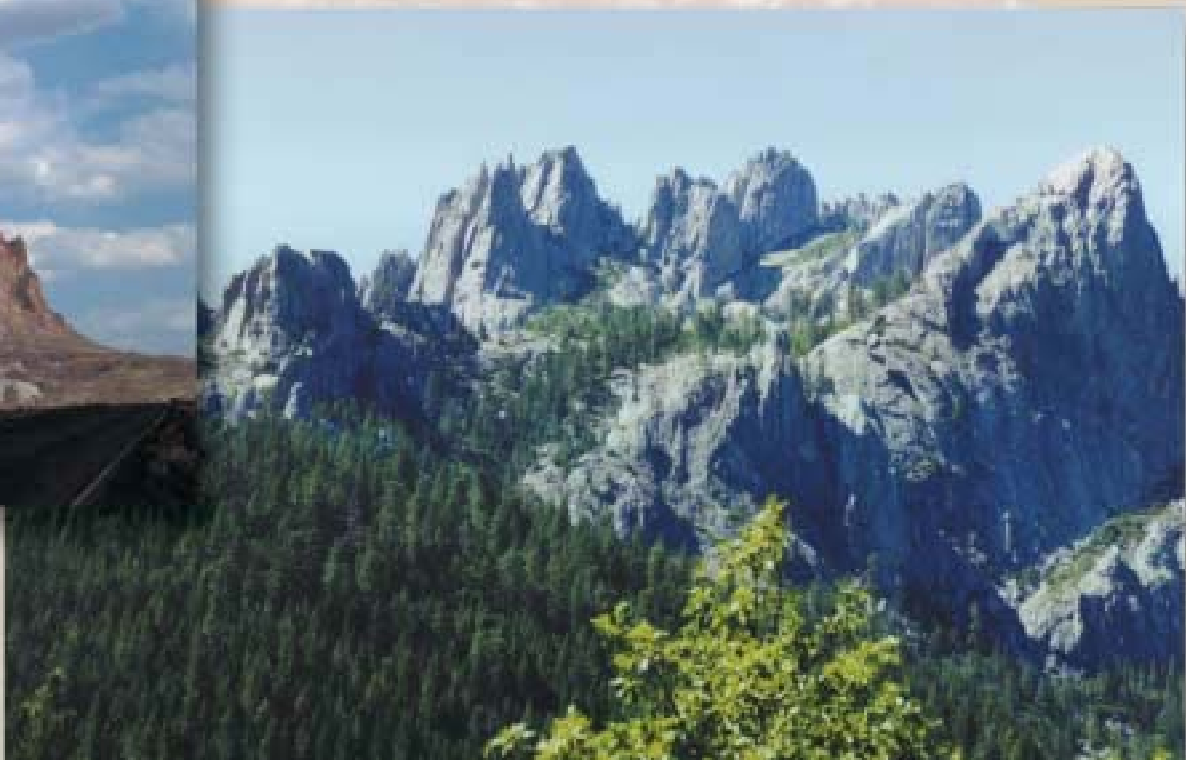
James S. Monroe

Part of the Sierra Nevada batholith in Yosemite National Park, California. The batholith, consisting of multiple intrusions of granitic rock, is more than 600 km long and up to 110 km wide. To appreciate the scale in this image, the waterfall has a descent of 435 m.



James S. Monroe

A volcanic neck in Monument Valley Tribal Park, Arizona. This landform is 457 m high. Most of the original volcano was eroded, leaving only this remnant.

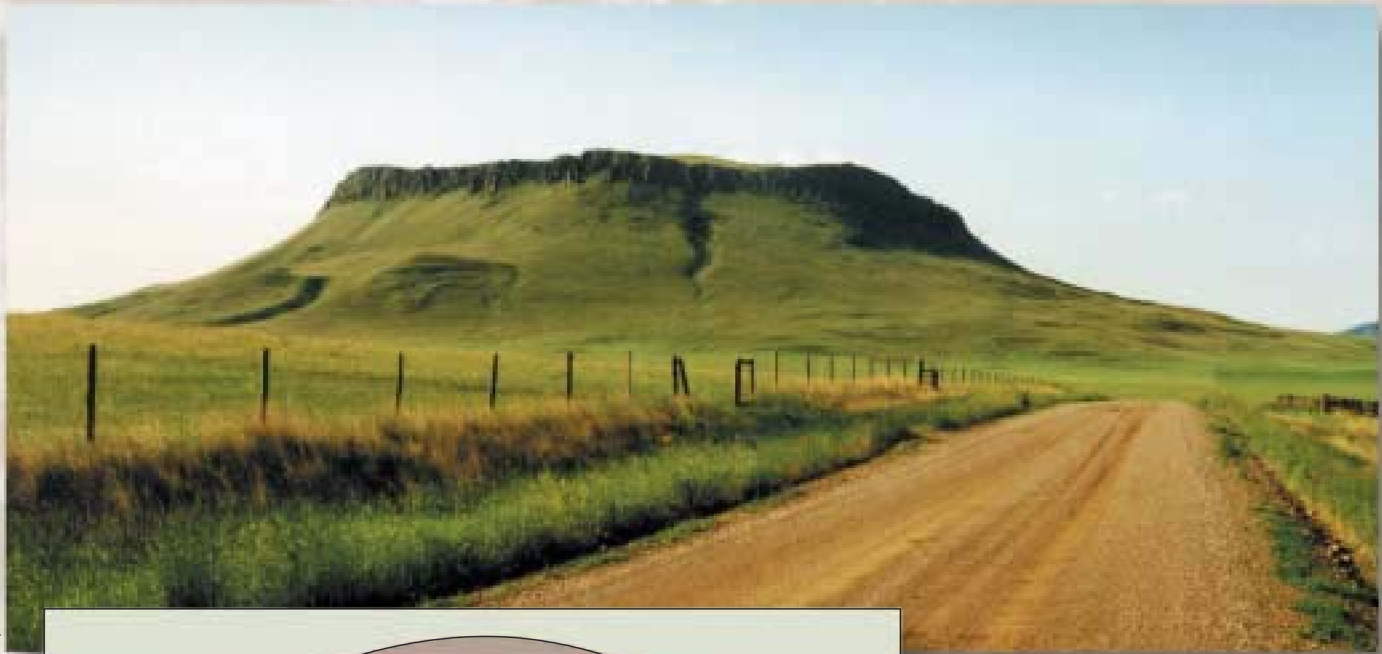


Sue Monroe

Granitic rocks of a small stock at Castle Crags State Park, California.

The dark materials in this image are igneous rocks, whereas the light layers are sedimentary. Notice that the sill parallels the layering, so it is concordant. The dike, though, clearly cuts across the layering and is discordant. Sills and dikes have sheetlike geometry, but in this view we can see them in only two dimensions.

Martin G. Miller/ Visuals Unlimited



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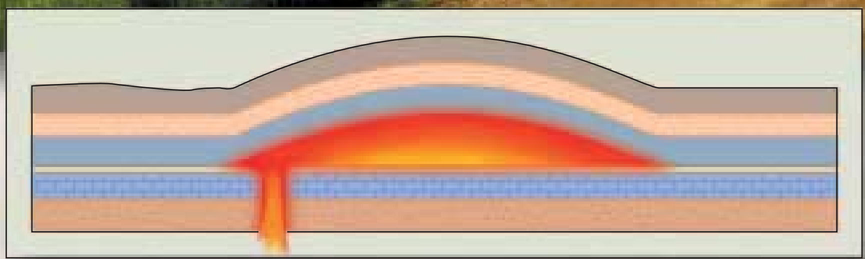
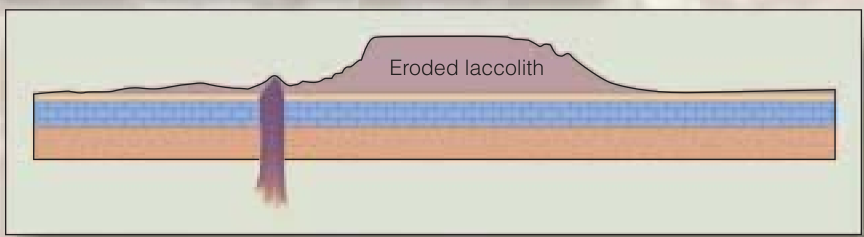


Crown Butte in Montana is an eroded laccolith standing about 300 m above the surrounding plain. The magma making up this small pluton was intruded about 50 million years ago.

Diagrams showing the evolution of an eroded laccolith.



GEOFOCUS 4.1

Some Remarkable Volcanic Necks

We mentioned that as an extinct volcano weathers and erodes, a remnant of the original mountain may persist as a volcanic neck. The origin of volcanic necks is well known, but these isolated monoliths rising above otherwise rather flat land are scenic, awe-inspiring, and the subject of legends. They are found in many areas of recently active volcanism. A small volcanic neck rising only 79 m above the surface in the town of Le Puy, France, is the site of the 11th-century chapel of Saint Michel d'Aiguilhe (■ Figure 1). It is so steep that materials and tools used in its construction had to be hauled up in baskets.

Perhaps the most famous volcanic neck in the United States is Shiprock, New Mexico, which rises nearly 550 m above the surrounding plain and is visible from 160 km away. Radiating outward from this conical structure are three vertical dikes that stand like walls above the adjacent countryside (■ Figure 2a). According to one legend, Shiprock, or *Tsae-bidahi*, meaning "winged rock," represents a giant bird that brought the Navajo people from the north. The same legend holds that the dikes are snakes that turned to stone.

An absolute age determined for one of the dikes indicates that Shiprock is about 27 million years old. When the original volcano formed, apparently during explosive eruptions, rising magma penetrated various rocks including the Mancos Shale, the rock unit now exposed at the surface adjacent to Shiprock. The rock that makes up Shiprock itself is tuff-breccia, consisting of fragmented volcanic debris as well as pieces of metamorphic, sedimentary, and igneous rocks.

Geologists agree that Devil's Tower in northeastern Wyoming cooled from a small body of magma and that erosion has exposed it in its present form (■ Figure 2b). However, opinion is divided on whether it is a volcanic neck or an eroded laccolith. In either case, the rock that makes up Devil's Tower is 45 to 50 million years old, and President Theodore Roosevelt designated this impressive landform as our first national monument in 1906. At 260 m high, Devil's Tower is visible from 48 km away and served as a landmark for early travelers in this area. It achieved further distinction in 1977 when it was featured in the film *Close Encounters of the Third Kind.*

The Cheyenne and Sioux Indians call Devil's Tower *Mateo Tepee,* meaning "Grizzly Bear Lodge." It was also called the "Bad God's Tower," and reportedly "Devil's Tower" is a translation from this phrase. The tower's most conspicuous features are the near-vertical lines that, according to Cheyenne legends, are scratch marks made by a gigantic grizzly bear. One legend holds that the bear made the scratches while pursuing a group of children. An-

in Iceland, where eruptions occurred in A.D. 950 from a fissure nearly 30 km long.

Concordant sheetlike plutons are **sills;** many sills are a meter or less thick, although some are much thicker. A well-known sill in the United States is the Palisades sill that forms the Palisades along the west side of the Hudson River in New York and New Jersey. It is exposed for 60 km along the river and is up to 300 m thick. Most sills were intruded into sedimentary rocks, but eroded volcanoes also reveal that sills are commonly injected into piles of volcanic rocks. In fact, some inflation of volcanoes preceding eruptions may be caused by the injection of sills (see Chapter 5).

In contrast to dikes, which follow zones of weakness, sills are emplaced when the fluid pressure is so great that the intruding magma actually lifts the overlying rocks. Because emplacement requires fluid pressure exceeding the force exerted by the weight of the overlying rocks, many sills are shallow intrusive bodies, but some were emplaced deep in the crust.

Laccoliths

Laccoliths are similar to sills in that they are concordant, but instead of being tabular, they have a mushroomlike geometry (see "Plutons" on pages 102 and 103). They tend to have a flat floor and are domed up in their central part. Like sills, laccoliths are rather shallow intrusive bodies that actually lift up the overlying rocks when magma is intruded. In this case, however, the rock layers other tells of six brothers and a woman also pursued by a grizzly bear. One brother carried a rock, and when he sang a song it grew into Devil's Tower, safely carrying the brothers and woman out of the bear's reach.

Although not nearly as interesting as the Cheyenne legends, the origin for the "scratch marks" is well understood. These lines actually formed at the intersections of *columnar joints*, fractures that form in response to the cooling and contraction that occur in some plutons and lava flows (see Chapter 5). The columns outlined by these fractures are up to 2.5 m across, and the pile of rubble at the tower's base is simply an accumulation of collapsed columns.

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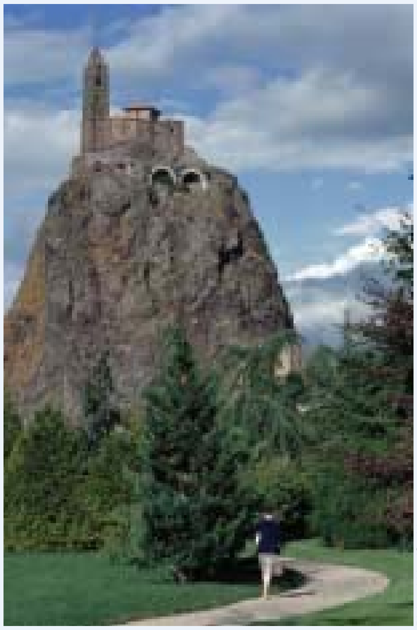

■ **Figure 1**

This volcanic neck in Le Puy, France, rises 79 m above the surrounding surface. Workers on the Chapel of Saint Michel d'Aiguilhe had to haul building materials and tools up in baskets.

(a)

(b)

■ **Figure 2**

(a) Shiprock, a volcanic neck in northwestern New Mexico, rises nearly 550 m above the surrounding plain. One of the dikes radiating from Shiprock is in the foreground. (b) Devil's Tower in northeastern Wyoming. The vertical lines result from intersections of fractures called columnar joints (see Chapter 5).

are arched up over the pluton. Most laccoliths are rather small bodies. Well-known laccoliths in the United States are in the Henry Mountains of southeastern Utah, and several buttes in Montana are eroded laccoliths.

Volcanic Pipes and Necks

A volcano has a cylindrical conduit known as a **volcanic pipe** that connects its crater with an underlying magma chamber. Through this structure magma rises to the surface. When a volcano ceases to erupt, its slopes are attacked by water, gases, and acids and it erodes, but the magma that solidified in the pipe is commonly more resistant to alteration and erosion. Consequently, much of the volcano is eroded but the pipe remains as a remnant called a **volcanic neck**. Several volcanic necks are found in the southwestern United States, especially in Arizona and New Mexico, and others are recognized elsewhere (see Geo-Focus 4.1 and "Plutons" on pages 102–103).

Batholiths and Stocks

By definition a **batholith,** the largest of all plutons, must have at least 100 km^2 of surface area, and most are far larger. A **stock,** in contrast, is similar but smaller. Some stocks are simply parts of large plutons that once exposed by erosion are batholiths (see "Plutons" on pages 102 and 103). Both batholiths and stocks are generally discordant, although locally they may be concordant, and batholiths, especially, consist of multiple intrusions. In other words, a batholith is a large composite body produced by repeated, voluminous intrusions of magma in the same region. The coastal batholith of Peru, for instance, was emplaced during a period of 60 to 70 million years and is made up of as many as 800 individual plutons.

The igneous rocks that make up batholiths are mostly granitic, although diorite may also be present. Batholiths and stocks are emplaced mostly near convergent plate boundaries during episodes of mountain building. One example is the Sierra Nevada batholith of California (see the chapter opening photo), which formed over millions of years during a mountain-building episode known as the Nevadan orogeny. Later uplift and erosion exposed this huge composite pluton at the surface. Other large batholiths in North America include the Idaho batholith, the Boulder batholith in Montana, and the Coast Range batholith in British Columbia, Canada.

Mineral resources are found in rocks of batholiths and stocks and in the adjacent country rocks. The copper deposits at Butte, Montana, are in rocks near the margins of the granitic rocks of the Boulder batholith. Near Salt Lake City, Utah, copper is mined from the mineralized rocks of the Bingham stock, a composite pluton composed of granite and granite porphyry. Granitic rocks also are the primary source of gold, which forms from mineral-rich solutions moving through cracks and fractures of the igneous body.

HOW ARE BATHOLITHS INTRUDED INTO EARTH'S CRUST?

Geologists realized long ago that the origin of batholiths posed a space problem. What happened to the rock that was once in the space now occupied by a batholith? One proposed answer was that no displacement had occurred, but rather that batholiths formed in place by alteration of the country rock through a process called *granitization*. According to this view, granite did not originate as magma but rather from hot, ion-rich solutions that simply altered the country rock and transformed it into granite. Granitization is a solid-state phenomenon, so it is essentially an extreme type of metamorphism (see Chapter 7).

Granitization is no doubt a real phenomenon, but most granitic rocks show clear evidence of an igneous origin. For one thing, if granitization had taken place, we would expect the change from country rock to granite to take place gradually over some distance. However, in almost all cases no such gradual change can be detected. In fact, most granitic rocks have what geologists refer to as sharp contacts with adjacent rocks. Another feature that indicates an igneous origin for granitic rocks is the alignment of elongate minerals parallel with their contacts, which must have occurred when magma was injected.

A few granitic rocks lack sharp contacts and gradually change in character until they resemble the adjacent country rock. These probably did originate by granitization. In the opinion of most geologists, only small quantities of granitic rock could form by this process, so it cannot account for the huge volume of granitic rocks of batholiths. Accordingly, geologists conclude that an igneous origin for almost all granite is clear, but they still must deal with the space problem.

One solution is that these large igneous bodies melted their way into the crust. In other words, they simply assimilated the country rock as they moved upward (Figure 4.6). The presence of inclusions, especially near the tops of some plutons, indicates that assimilation does occur. Nevertheless, as we noted, assimilation is a limited process because magma cools as country rock is assimilated. Calculations indicate that far too little heat is available in magma to assimilate the huge quantities of country rock necessary to make room for a batholith.

Geologists now generally agree that batholiths were emplaced by *forceful injection* as magma moved upward. Recall that granite is derived from viscous felsic magma and therefore rises slowly. It appears that the magma deforms and shoulders aside the country rock, and as it rises farther, some of the country rock fills the space beneath the magma (■ Figure 4.17a). A somewhat analogous situation was discovered in which large masses of sedimentary rock known as *rock salt* rise through the overlying rocks to form *salt domes* (Figure 4.17b–d).

Salt domes are recognized in several areas of the world, including the Gulf Coast of the United States. Layers of rock salt exist at some depth, but salt is less dense than most other types of rock materials. When under pressure, it rises toward the surface even though it remains solid, and as it moves up, it pushes aside and deforms the country rock. Natural examples of rock salt flowage are known, and it can easily be demonstrated experimentally. In the arid Middle East, for example, salt moving up in the manner described actually flows out at the surface.

Some batholiths do indeed show evidence of having been emplaced forcefully by shouldering aside and deforming the country rock. This mechanism probably occurs in the deeper parts of the crust where temperature and pressure are high and the country rocks are easily deformed in the manner described. At shallower depths, the crust is more rigid and tends to deform by fracturing. In this environment, batholiths may move upward by **stoping**, a process in which rising magma detaches and engulfs pieces of country rock (■ Figure 4.18).

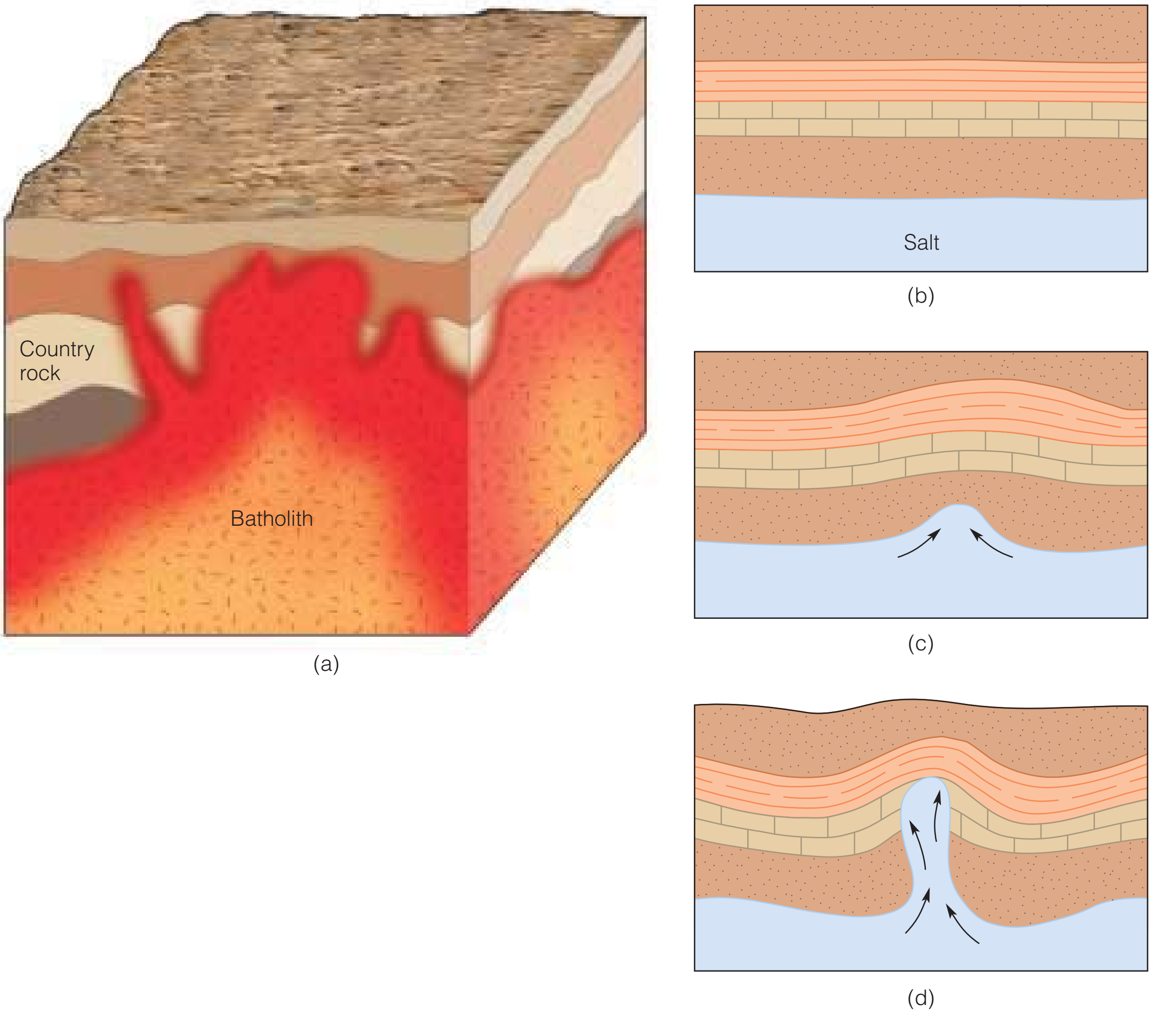

Figure 4.17

(a) Emplacement of a pluton by forceful injection. As the magma rises, it shoulders aside and deforms the country rock. (b–d) Three stages in a somewhat analogous situation when a salt dome forms by upward migration of the rock under pressure.

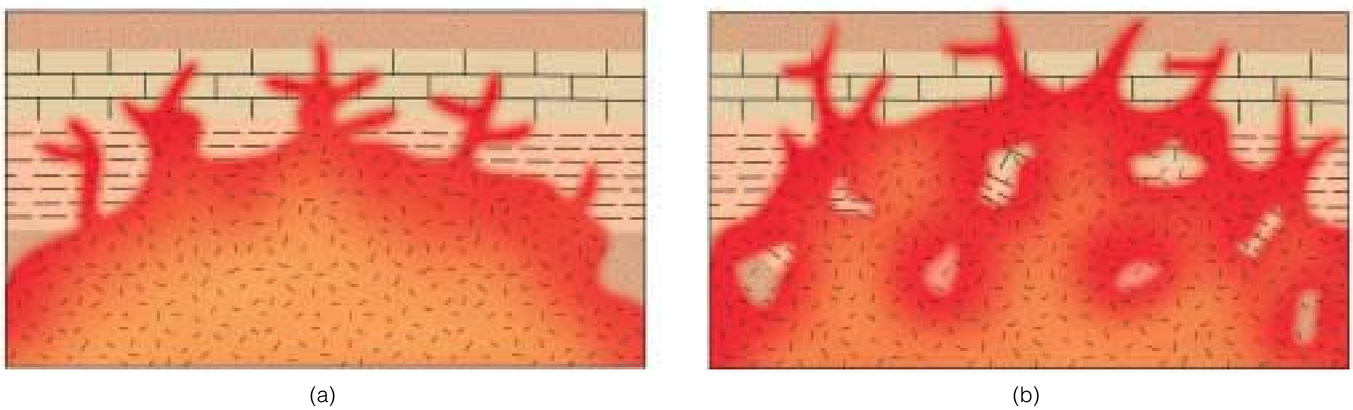

Figure 4.18

Emplacement of a batholith by stoping. (a) Magma is injected into fractures and planes between layers in the country rock. (b) Blocks of country rock are detached and engulfed in the magma, thereby making room for the magma to rise farther. Some of the engulfed blocks might be assimilated, and some may remain as inclusions (Figure 4.6).

According to this concept, magma moves up along fractures and the planes separating layers of country rock. Eventually, pieces of country rock detach and settle into the magma. No new room is created during stoping; the magma simply fills the space formerly occupied by country rock (Figure 4.18).

4 GEO RECAP

Chapter Summary

- *Magma* is the term for molten rock below Earth's surface, whereas the same material at the surface is called *lava*.
- Silica content distinguishes among mafic (45–52% silica), intermediate (53–65% silica), and felsic (>65% silica) magmas.
- Magma and lava viscosity depends on temperature and especially on composition: The more silica, the greater the viscosity.
- Minerals crystallize from magma and lava when small crystal nuclei form and grow.
- Rapid cooling accounts for the aphanitic textures of volcanic rocks, whereas comparatively slow cooling yields the phaneritic textures of plutonic rocks. Igneous rocks with markedly different sized minerals are porphyritic.
- Igneous rock composition is determined largely by the composition of the parent magma, but magma composition can change so that the same magma may yield more than one kind of igneous rock.
- According to Bowen's reaction series, cooling mafic magma yields a sequence of minerals, each of which is stable within specific temperature ranges. Only ferromagnesian silicates are found in the discontinuous branch of Bowen's reaction series. The continuous branch of the reaction series yields only plagioclase feldspars that become increasingly enriched in sodium as cooling occurs.
- A chemical change in magma may take place as early-formed ferromagnesian silicates form and, because of their density, settle in the magma.
- Compositional changes also take place in magma when it assimilates country rock or one magma mixes with another.
- Geologists recognize two broad categories of igneous rocks: volcanic or extrusive and plutonic or intrusive.
- Texture and composition are the criteria used to classify igneous rocks, although a few are defined only by texture.
- Crystallization from water-rich magma results in very large minerals in rocks known as pegmatite. Most pegmatite has an overall composition similar to granite.
- Intrusive igneous bodies known as plutons vary in their geometry and their relationships to country rock: Some are concordant, whereas others are discordant.
- The largest plutons, known as batholiths, consist of multiple intrusions of magma during long periods of time.
- Most plutons, including batholiths, are found at or near divergent and convergent plate boundaries.

Important Terms

aphanitic texture (p. 95)
assimilation (p. 94)
batholith (p. 105)
Bowen's reaction series (p. 91)
concordant pluton (p. 101)
country rock (p. 94)
crystal settling (p. 93)
dike (p. 101)
discordant pluton (p. 101)
felsic magma (p. 89)
igneous rock (p. 89)
intermediate magma (p. 89)
laccolith (p. 104)
lava flow (p. 89)
mafic magma (p. 89)
magma (p. 89)
magma chamber (p. 91)
magma mixing (p. 94)
phaneritic texture (p. 95)
pluton (p. 100)
plutonic (intrusive igneous) rock (p. 89)
porphyritic texture (p. 95)
pyroclastic (fragmental) texture (p. 95)
pyroclastic materials (p. 89)
sill (p. 104)
stock (p. 105)
stoping (p. 106)
vesicle (p. 95)
viscosity (p. 90)
volcanic neck (p. 105)
volcanic pipe (p. 105)
volcanic (extrusive igneous) rock (p. 89)

Review Questions

1. A dike is a discordant pluton, whereas a _____ is concordant.
   a._____batholith; b._____volcanic neck; c._____laccolith; d._____stock; e._____ash fall.
2. An aphanitic igneous rock composed mostly of pyroxenes and calcium-rich plagioclase is
   a._____granite; b._____obsidian; c._____rhyolite; d._____diorite; e._____basalt.
3. The size of the mineral grains that make up an igneous rock is a useful criterion for determining whether the rock is _____ or _____.
   a._____volcanic/plutonic; b._____discordant/concordant; c._____vesicular/fragmental; d._____porphyritic/felsic; e._____ultramafic/igneous.
4. Magma characterized as intermediate
   a._____flows more readily than mafic magma; b._____has between 53% and 65% silica; c._____crystallizes to form granite and rhyolite; d._____cools to form rocks that make up most of the oceanic crust; e._____is one from which ultramafic rocks are derived.
5. The phenomenon by which pieces of country rock are detached and engulfed by rising magma is known as
   a._____stoping; b._____assimilation; c._____magma mixing; d._____Bowen's reaction series; e._____crystal settling.
6. An igneous rock that has minerals large enough to see without magnification is said to have a(n) _____ texture and is probably _____.
   a._____laccolithic/pegmatite; b._____fragmental/felsic; c._____isometric/magmatic; d._____phaneritic/plutonic; e._____fragmental/obsidian.
7. Which one of the following statements about batholiths is false?
   a._____They consist of multiple voluminous intrusions; b._____They form mostly at convergent plate boundaries during mountain building; c._____They consist of a variety of volcanic rocks, but especially basalt; d._____They must have at least 100 km^2 of surface area; e._____Though locally concordant, they are mostly discordant.

8. An igneous rock characterized as a porphyry is one

   a._____that formed by crystal settling and assimilation; b._____possessing minerals of markedly different sizes; c._____made up largely of potassium feldspar and quartz; d._____that forms when pyroclastic materials are consolidated; e._____resulting from very rapid cooling.

9. Which pair of igneous rocks have the same texture?

   a._____basalt-andesite; b._____granite-rhyolite; c._____pumice-obsidian; d._____tuff-diorite; e._____scoria-lapilli.

10. One process by which magma changes composition is

    a._____crystal settling; b._____rapid cooling; c._____explosive volcanism; d._____fracturing; e._____plate convergence.

11. Two aphanitic igneous rocks have the following compositions: Specimen 1: 15% biotite; 15% sodium-rich plagioclase, 60% potassium feldspar, and 10% quartz. Specimen 2: 10% olivine, 55% pyroxene, 5% hornblende, and 30% calcium-rich plagioclase. Use Figure 4.9 to classify these rocks. Which would be the darkest and most dense?

12. How does a sill differ from a dike? (A diagram would be helpful.)

13. How do crystal settling and assimilation bring about compositional changes in magma? Also, give evidence that these processes actually take place.

14. Describe or diagram the sequence of events that lead to the origin of a volcanic neck.

15. Describe a porphyritic texture, and explain how it might originate.

16. Why are felsic lava flows so much more viscous than mafic ones?

17. How does a pegmatite form, and why are their mineral crystals so large?
18. Compare the continuous and discontinuous branches of Bowen's reaction series. Why are potassium feldspar and quartz not part of either branch?
19. You analyze the mineral composition of a thick sill and find that it has a mafic lower part but its upper part is more intermediate. Given that it all came from a single magma injected at one time, how can you account for its compositional differences?
20. What kind(s) of evidence would you look for to determine whether the granite in a batholith crystallized from magma or originated by granitization?

World Wide Web Activities

GeologyNow Assess your understanding of this chapter's topics with additional quizzing and comprehensive interactivities at

http://earthscience.brookscole.com/changingearth4e

as well as current and up-to-date weblinks, additional readings, and InfoTrac College Edition exercises.