4

Igneous Rocks & Intrusive Activity

FOCUS ON CONCEPTS

Each statement represents the primary learning objective for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

4.1 List and describe the three major components of magma.

4.2 Compare and contrast the four basic igneous compositions: felsic, intermediate, mafic, and ultramafic.

4.3 Identify and describe the six major igneous textures.

4.4 Distinguish among the common igneous rocks based on texture and mineral composition.

4.5 Summarize the major processes that generate magma from solid rock.

4.6 Describe how magmatic differentiation can generate a magma body that has a mineralogy (chemical composition) that is different from its parent magma.

4.7 Describe how partial melting of the mantle rock peridotite can generate a basaltic (mafic) magma.

4.8 Compare and contrast these intrusive igneous structures: dikes, sills, batholiths, stocks, and laccoliths.

4.9 Explain how economic deposits of gold, silver, and many other metals form.

Granite outcrops reflected in Tenaya Lake, Yosemite National Park, California. (Photo by Adan Burton/Robert Harding)

UNDERSTANDING THE STRUCTURE, composition, and internal workings of our planet requires a basic knowledge of igneous rocks. Igneous rocks and metamorphic rocks derived from igneous "parents" make up most of Earth's crust and mantle. Thus, Earth can be described as a huge mass of igneous and metamorphic rocks that is covered with a thin veneer of sedimentary rock and has a relatively small iron-rich core.

Many prominent landforms are composed of igneous rocks, including volcanoes such as Mount Rainier and the large igneous bodies that make up the Sierra Nevada, the Black Hills, and the high peaks of the Adirondacks. Igneous rocks also make excellent building stones and are widely used as decorative materials, such as for monuments and household countertops.

4.1 Magma: Parent Material of Igneous Rock

List and describe the three major components of magma.

Our discussion of the rock cycle in Chapter 1 explained that **igneous rocks** (*ignis* = fire) form as molten rock cools and solidifies. Considerable evidence supports the idea that the parent material for igneous rocks, called **magma**, is formed by partial melting that occurs at various levels within Earth's crust and upper mantle to depths of about 250 kilometers (about 150 miles). Once formed, a magma body buoyantly rises toward the surface because it is less dense than the surrounding rocks. (When rock melts, it takes up more space and, hence, it becomes less dense than the surrounding solid rock.) Occasionally, molten rock reaches Earth's surface, where it is called **lava** (Figure 4.1). Sometimes lava is emitted as fountains that are produced when escaping gases propel it from a magma chamber. On other occasions, lava is explosively ejected, producing dramatic eruptions of steam and volcanic ash. However, not all eruptions are violent; many volcanoes emit quiet outpourings of fluid lava.

▼ **Figure 4.1 Eruption of Mount Etna, July 2014, Sicily, Italy.** (Photo courtesy of AM Design/Alamy)

The Nature of Magma

Magma is rock that is completely or partly molten, and when cooled it solidifies to form igneous rocks mainly composed of silicate minerals. Most magmas consist of three materials: a *liquid* component, a *solid* component, and a *gaseous* component.

The liquid portion, called **melt**, is composed mainly of mobile ions of the eight most common elements found in Earth's crust—silicon and oxygen, along with lesser amounts of aluminum, potassium, calcium, sodium, iron, and magnesium (see Figure 3.22, page 79).

The solid components (if any) in magma are crystals of silicate minerals. As a magma body cools, the size and number of crystals increase. During the last stage of cooling, a magma body is like a "crystalline mush" (resembling a bowl of very thick oatmeal) that contains only small amounts of melt.

The gaseous components of magma, called **volatiles**, are materials that vaporize (form a gas) at surface pressures. The most common volatiles found in magma are water vapor (H_2O), carbon dioxide (CO_2), and sulfur dioxide (SO_2). When magma is deep below the surface, the immense confining pressure keeps these volatiles dissolved in the melt, the way carbon dioxide is dissolved in soda before you open the can. As the melt rises toward the surface and the confining pressure is reduced, the volatiles begin to separate from the melt—again, similar to the way carbon dioxide forms bubbles when you reduce the pressure in a soda can by opening it. As the gases build up, they may eventually propel magma from the vent. When deeply buried magma bodies crystallize, the remaining volatiles collect as hot, water-rich fluids that migrate through openings in the surrounding rocks. These hot fluids play an important role in metamorphism and will be considered in Chapter 8.

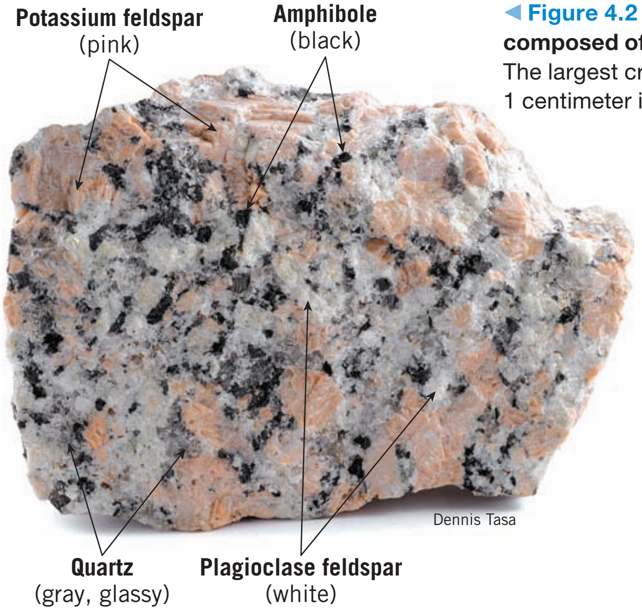
From Magma to Crystalline Rock

To better understand how magma crystallizes, let us first consider how a simple crystalline solid melts. Recall that, in any crystalline solid, the ions are arranged in a closely packed regular pattern. However, they are not without some motion; they exhibit a restricted vibration about fixed points. As the temperature rises, ions vibrate more rapidly and consequently collide with ever-increasing vigor with their neighbors. Thus, heating causes the ions to occupy more space, which in turn causes the solid to expand. When the ions are vibrating rapidly enough to overcome the force of their chemical bonds, melting occurs. At this stage, the ions are able to slide past one another, and the orderly crystalline structure disintegrates. Thus, melting converts a solid consisting of tight, uniformly packed ions into a liquid composed of unordered ions moving randomly about.

In the process called **crystallization**, cooling reverses the events of melting. As the temperature of the liquid drops, ions pack more closely together as their rate of movement slows. When they are cooled sufficiently, the forces of the chemical bonds again confine the ions to an orderly crystalline arrangement.

When a magma body cools, the silicon and oxygen atoms link together first to form silicon–oxygen tetrahedra, the basic building blocks of the silicate minerals (see Figure 3.23, page 80). As magma continues to lose heat to its surroundings, the tetrahedra join with each other and with other ions to form embryonic crystal nuclei. Each nucleus slowly grows as ions lose their mobility and join the crystalline network.

The minerals that form the earliest have space to grow and tend to have better-developed crystal faces than do the ones that form later and occupy the remaining spaces. Eventually all of the melt is transformed into a solid mass of interlocking silicate minerals that we call an *igneous rock* (**Figure 4.2**).



Dennis Tasa

◀ **Figure 4.2 Igneous rock composed of interlocking crystals** The largest crystals are about 1 centimeter in length.

Igneous Processes

Igneous rocks form in two basic settings. Molten rock may crystallize within Earth's crust over a range of depths, or it may solidify at Earth's surface (**Figure 4.3**).

▼ **SmartFigure 4.3 Intrusive versus extrusive igneous rocks**

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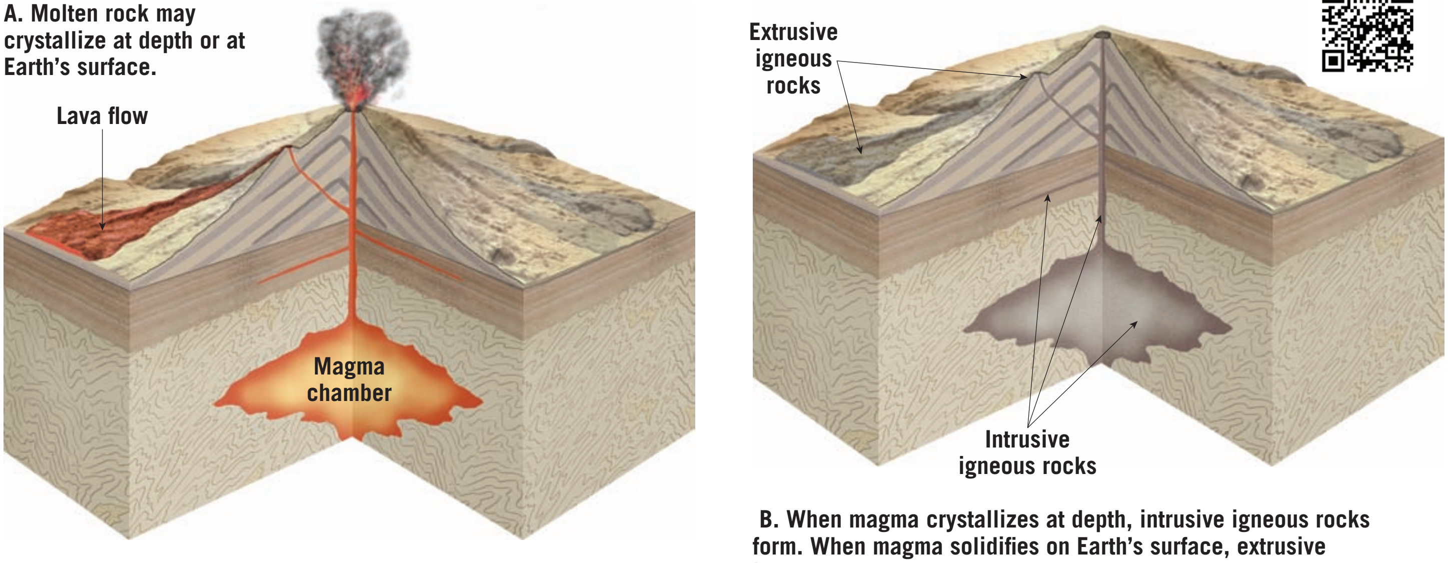


A. Molten rock may crystallize at depth or at Earth's surface.

B. When magma crystallizes at depth, intrusive igneous rocks form. When magma solidifies on Earth's surface, extrusive igneous rocks form.

▲ **Figure 4.4 Mount Rushmore National Memorial** This memorial, located in the Black Hills of South Dakota, is carved from intrusive igneous rocks. (Photo by Barbara A. Harvey/Shutterstock)

When magma crystallizes *at depth*, it forms **intrusive igneous rocks**, also known as **plutonic rocks**—after Pluto, the god of the underworld in classical mythology. These rocks can be observed at the surface in locations where uplifting and erosion have stripped away the overlying rocks. Exposures of intrusive igneous rocks occur in many places, including the White Mountains, New Hampshire; Stone Mountain, Georgia; Mount Rushmore in the Black Hills of South Dakota; and Yosemite National Park, California (**Figure 4.4**).

Igneous rocks that form when molten rock solidifies *at the surface* are classified as **extrusive igneous rocks**. They are also called **volcanic rocks**—after Vulcan, the Roman fire god. Extrusive igneous rocks form when lava solidifies or when volcanic debris falls to Earth's surface. Extrusive igneous rocks are abundant in western portions of the Americas, where they make up the volcanic peaks of the Cascade Range and the Andes Mountains. In addition, many oceanic islands, including the Hawaiian chain and Alaska's Aleutian Islands, are composed almost entirely of extrusive igneous rocks. The nature of volcanic activity will be addressed in more detail in Chapter 5.

CONCEPT CHECKS 4.1

1. What is magma? How does magma differ from lava?
2. List and describe the three components of magma.
3. Describe the process of crystallization.
4. Compare and contrast extrusive and intrusive igneous rocks.

4.2 Igneous Compositions

Compare and contrast the four basic igneous compositions: felsic, intermediate, mafic, and ultramafic.

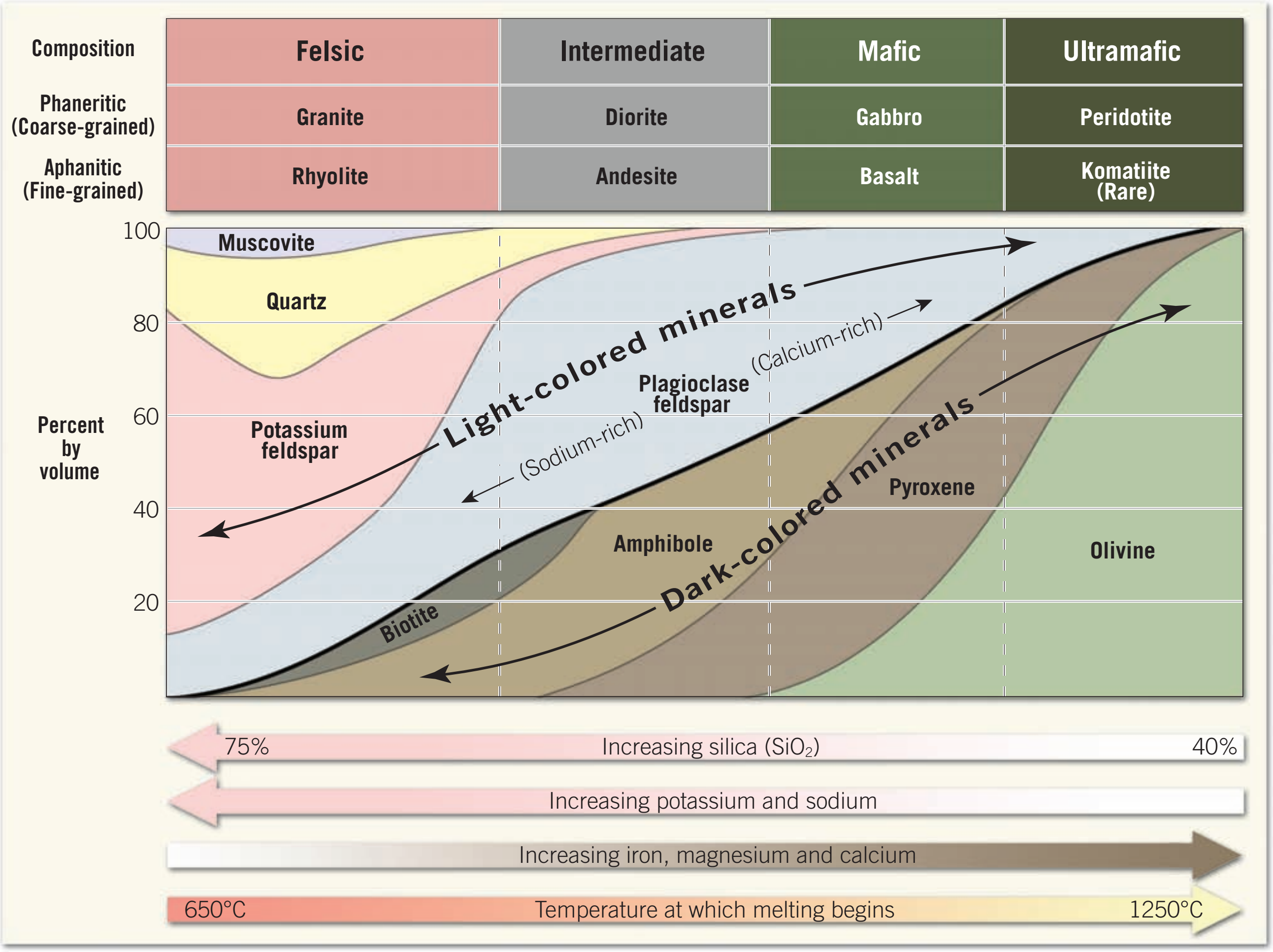
Igneous rocks are composed mainly of silicate minerals. Chemical analyses show that silicon (Si) and oxygen (O) are by far the most abundant constituents of igneous rocks. These two elements, plus ions of aluminum (Al), calcium (Ca), sodium (Na), potassium (K), magnesium (Mg), and iron (Fe), make up roughly 98 percent, by weight, of most magmas. In addition, magma contains small amounts of many other elements, including titanium and manganese, and trace amounts of rare elements, such as gold, silver, and uranium.

As magma cools and solidifies, these elements combine to form two major groups of silicate minerals. The *dark* (or *ferromagnesian*) *silicates* are rich in iron and/or magnesium and comparatively low in silica. *Olivine*, *pyroxene*, *amphibole*, and *biotite mica* are the common dark silicate minerals of Earth's crust. By contrast, the *light* (or *nonferromagnesian*) *silicates* contain greater amounts of potassium, sodium, and calcium. The light silicate minerals, including *quartz*, *muscovite mica*, and the most abundant mineral group, the *feldspars*, are richer in silica than the dark silicates.

Compositional Categories

Despite the great compositional diversity of igneous rocks, geologists classify these rocks (and the magmas from which they form) into four broad groups according to their proportions of light and dark minerals. As shown in **Figure 4.5**, these compositional groups are *felsic*, *intermediate*, *mafic*, and *ultramafic*.

Felsic Versus Mafic Near one end of the continuum are rocks composed almost entirely of light-colored silicates—quartz and potassium feldspar. The composition of igneous rocks dominated by these minerals is classified as **felsic**, a term derived from *fel*dspar and *si*lica (quartz). Because felsic magmas most commonly solidify to form *granite*, geologists also refer to this type of



◀ **SmartFigure 4.5**
Mineral makeup of common igneous rocks

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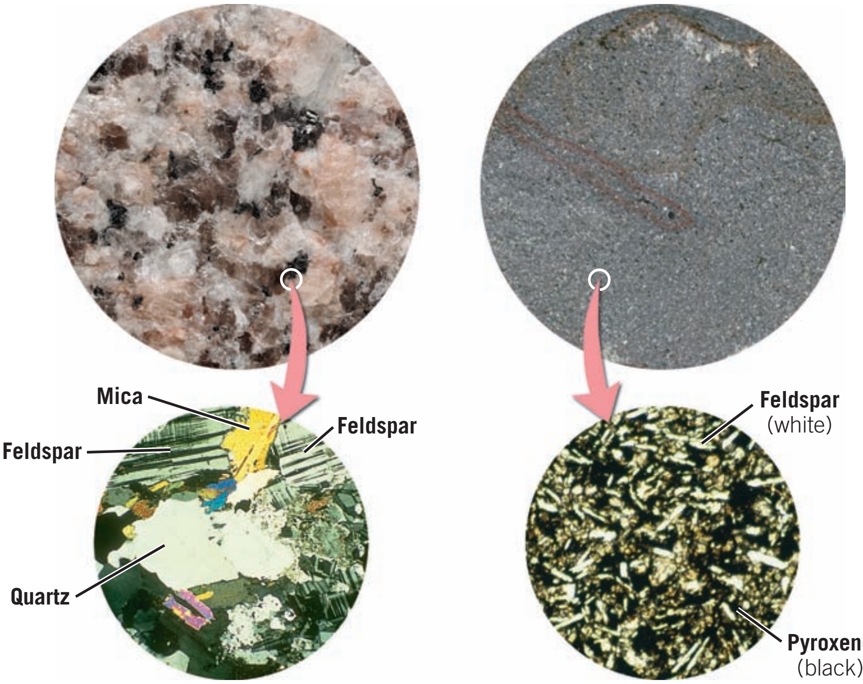
▼ **Figure 4.6 Granitic (felsic) versus basaltic (mafic) compositions** Inset images are photomicrographs that show the interlocking crystals that make up granite and basalt, respectively. (Photos provided by E. J. Tarbuck)



A. Granite is a felsic, coarse-grained igneous rock composed of light-colored silicates—quartz and potassium feldspar.

B. Basalt is a fine-grained mafic igneous rock containing substantial amounts of dark colored silicates and plagioclase feldspar.

magma as having a **granitic composition**. In addition to quartz and feldspar, most granitic rocks contain about 10 percent dark silicate minerals, usually biotite mica and amphibole (**Figure 4.6A**). Other notable characteristics of felsic rocks and the magma from which they were derived is that they are rich in silica (about 70 percent, or more) and are major constituents of the continental crust.

Rocks that contain at least 45 percent dark silicates (ferromagnesian minerals) are classified as **mafic** (from *ma*gnesium and *f*errum, the Latin name for iron). As a result of their iron content, mafic rocks are typically darker and denser than felsic rocks. Because mafic magmas most often solidify to form the igneous rock *basalt*, geologists also refer to this type of magma as having a **basaltic composition** (**Figure 4.6B**). Basaltic rocks make up the ocean floor as well as many of the volcanic islands located within the ocean basins. Basalt also forms extensive lava flows on the continents.

Other Compositional Groups As illustrated in Figure 4.5, rocks with a composition between felsic and mafic rocks are said to have an **intermediate**, or **andesitic composition**, after the common volcanic rock *andesite*.

Did You Know?

The most abundant element in Earth's crust is *oxygen*. It makes up 47 percent of Earth's crust by weight and 94 percent by volume. In fact, oxygen atoms are so much bigger than most of the other atoms in common minerals that Earth's crust is mainly oxygen atoms packed closely together, with smaller atoms such as silicon, aluminum, and potassium tucked in between.

Intermediate rocks contain at least 25 percent dark silicate minerals, mainly amphibole, pyroxene, and biotite mica, with the other dominant mineral being plagioclase feldspar. This important category of igneous rocks is often associated with volcanic activity on the seaward margins of continents and on volcanic island arcs such as the Aleutian chain.

Another important igneous rock, **peridotite**, contains mostly olivine and pyroxene and thus falls on the opposite side of the compositional spectrum from felsic rocks (see Figure 4.5). Because peridotite is composed almost entirely of ferromagnesian minerals, its chemical composition is referred to as **ultramafic**. Although ultramafic rocks are rare at Earth's surface, peridotite is the main constituent of the upper mantle.

Silica Content as an Indicator of Composition

An important aspect of the chemical composition of igneous rocks is silica (SiO_2) content. Typically, the silica content of crustal rocks ranges from as low as about 40 percent in ultramafic rocks to a high of more than 70 percent in felsic rocks (see Figure 4.5). The percentage of silica in igneous rocks varies in a systematic manner that parallels the abundance of other elements. For example, rocks that are relatively low in silica contain large amounts of iron, magnesium, and calcium. By contrast, rocks that are high in silica contain comparatively less iron, magnesium, and calcium but are enriched with sodium and potassium. Consequently, the chemical makeup of an igneous rock can be inferred directly from its silica content.

Further, the amount of silica present in magma strongly influences the magma's behavior. Felsic magma, which has a high silica content, is quite viscous ("thick") and may erupt at temperatures as low as 650°C (1200°F), whereas mafic (basaltic) magmas, which are low in silica, are generally more fluid. Mafic magmas also erupt at higher temperatures than felsic magmas—usually at temperatures between 1050° and 1250°C (1920° and 2280°F).

CONCEPT CHECKS 4.2

1. Igneous rocks are composed mainly of which group of minerals?
2. How do light-colored igneous rocks differ in composition from dark-colored igneous rocks?
3. List the four basic compositional groups of igneous rocks, in order from the group with the highest silica content to the group with the lowest silica content.
4. Name two minerals typically found in rocks with high silica content and two minerals found in rocks with relatively low silica content.

4.3 Igneous Textures: What Can They Tell Us?

Identify and describe the six major igneous textures.

The term **texture** is used to describe the overall appearance of a rock based on the size, shape, and arrangement of its mineral grains—not how it feels to touch. Texture is an important property because it reveals a great deal about the environment in which the rock formed (**Figure 4.7**). Geologists can make inferences about a rock's origin based on careful observations of grain size and other characteristics of the rock.

Three factors influence the textures of igneous rocks:

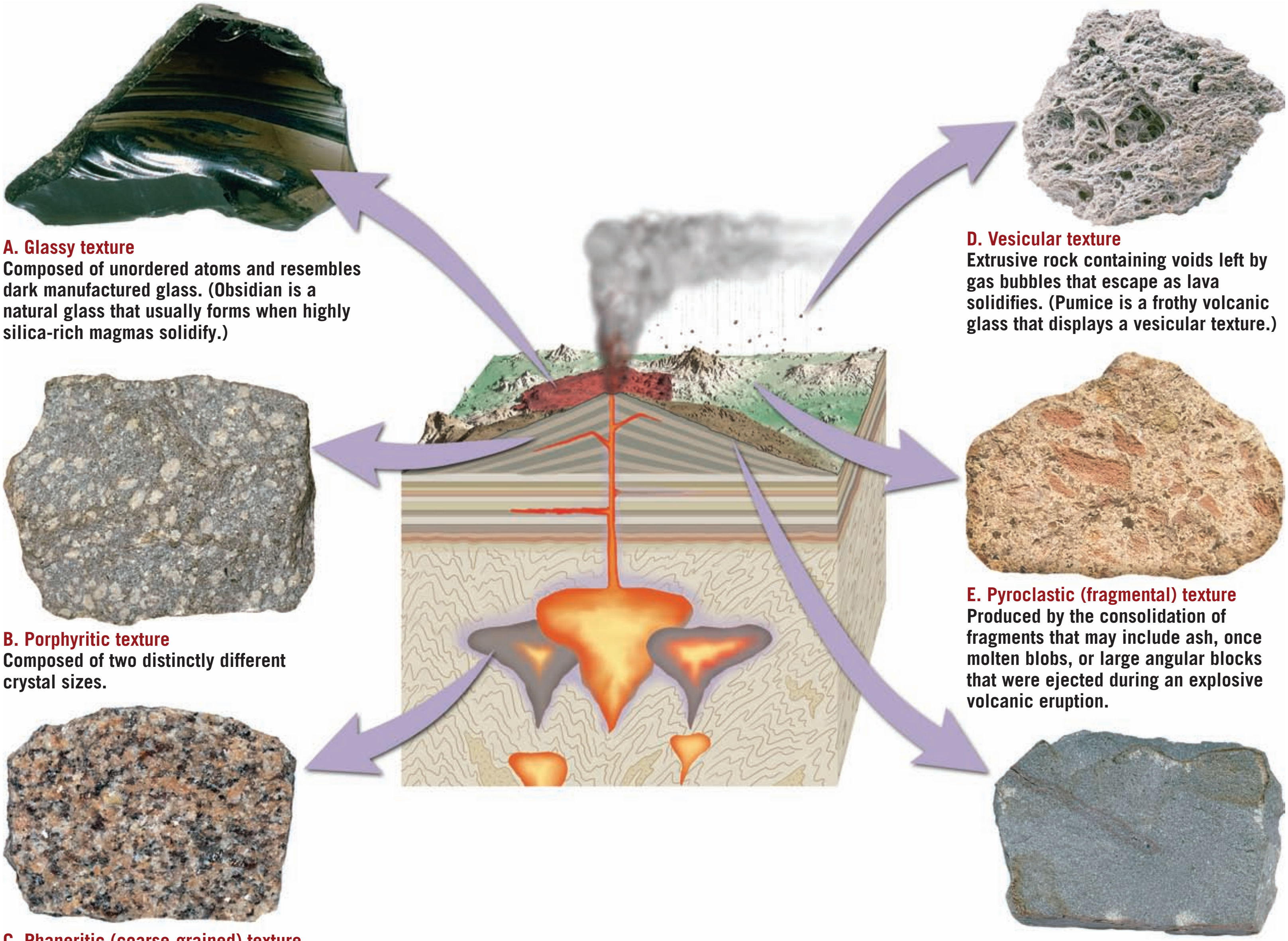
- The rate at which the molten rock cools
- The amount of silica in the magma
- The amount of dissolved gases in the magma

Among these, the rate of cooling tends to be the dominant factor. A very large magma body located many kilometers beneath Earth's surface remains insulated from lower surface temperatures by the surrounding rock and thus cools very slowly over a period of perhaps tens of thousands to millions of years. Initially, a relatively small number of crystal nuclei form. This slow cooling permits ions to migrate freely until they eventually join one of the existing crystals. Consequently, slow cooling promotes the growth of fewer but larger crystals.

On the other hand, when cooling occurs rapidly—for example, in a thin lava flow—the ions quickly lose their mobility and readily combine to form crystals. This results in the development of numerous embryonic crystal nuclei, all of which compete for the available ions. The result is a solid mass of many tiny intergrown crystals.

Types of Igneous Textures

In addition to cooling quickly or slowly, a magma body may migrate to a new location or erupt at the surface before it completely solidifies. As a result, several types of igneous textures exist, including aphanitic (fine-grained), phaneritic (coarse-grained), porphyritic, vesicular, glassy, and pyroclastic (fragmented).



A. Glassy texture
Composed of unordered atoms and resembles dark manufactured glass. (Obsidian is a natural glass that usually forms when highly silica-rich magmas solidify.)

B. Porphyritic texture
Composed of two distinctly different crystal sizes.

C. Phaneritic (coarse-grained) texture
Composed of mineral grains that are large enough to be identified without a microscope.

D. Vesicular texture
Extrusive rock containing voids left by gas bubbles that escape as lava solidifies. (Pumice is a frothy volcanic glass that displays a vesicular texture.)

E. Pyroclastic (fragmental) texture
Produced by the consolidation of fragments that may include ash, once molten blobs, or large angular blocks that were ejected during an explosive volcanic eruption.

F. Aphanitic (fine-grained) texture
Composed of crystals that are too small for the individual minerals to be identified without a microscope.

▲ **SmartFigure 4.7**
Igneous rock textures
(Photos by Dennis Tasa and E. J. Tarbuck)

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Aphanitic (Fine-Grained) Texture Igneous rocks that form at the surface or as small intrusive masses within the upper crust where cooling is relatively rapid exhibit a **fine-grained texture** termed **aphanitic** (*a* = not, *phaner* = visible). By definition, the crystals that make up aphanitic rocks are so small that individual minerals can be distinguished only with the aid of a polarizing microscope or using sophisticated techniques (see Figure 4.6B and Figure 4.7F). Therefore, we commonly characterize fine-grained rocks as being light, intermediate, or dark in color. Using this system, light-colored aphanitic rocks are those containing primarily light-colored nonferromagnesian silicate minerals.

Phaneritic (Coarse-Grained) Texture When large masses of magma slowly crystallize at great depth, they form igneous rocks that exhibit a **coarse-grained texture** described as **phaneritic** (*phaner* = visible). Coarse-grained rocks consist of a mass of intergrown crystals that are roughly equal in size and large enough for the individual minerals to be distinguished without the aid of a microscope (see Figure 4.6A and Figure 4.7C). Geologists often use a small magnifying lens to aid in identifying minerals in phaneritic rocks.

Porphyritic Texture A large mass of magma may require thousands or even millions of years to solidify. Because different minerals crystallize under different

▲ **Figure 4.8 Porphyritic texture** The large crystals in porphyritic rocks are called *phenocrysts*, and the matrix of smaller crystals is called *groundmass*. (Photo by Dennis Tasa)

environmental conditions (temperatures and pressure), it is possible for crystals of one mineral to become quite large before others even begin to form. If molten rock containing some large crystals moves to a different environment—for example, by erupting at the surface—the remaining liquid portion of the lava cools more quickly. The resulting rock, which has large crystals embedded in a matrix of smaller crystals, is said to have a **porphyritic texture** (see Figure 4.7B and Figure 4.8). The large crystals in porphyritic rocks are termed **phenocrysts** (*pheno* = show, *cryst* = crystal), whereas the matrix of smaller crystals is called **groundmass**. A rock with a *porphyritic* texture is termed a **porphyry**.

Vesicular Texture Common features of many extrusive rocks are the voids left by gas bubbles that escape as lava solidifies. These nearly spherical openings are called *vesicles*, and the rocks that contain them are said to have a **vesicular texture**. Rocks that exhibit a vesicular texture often form in the upper zone of a lava flow, where cooling occurs rapidly enough to preserve the openings produced by the expanding gas bubbles (Figure 4.9). Another common vesicular rock, called *pumice*, forms when silica-rich lava is ejected during an explosive eruption (see Figure 4.7D).

Glassy Texture During some volcanic eruptions, molten rock is ejected into the atmosphere, where it is quenched (very quickly cooled) to become a solid (see Figure 4.7A). Rapid cooling of this type may generate rocks having a **glassy texture**. Glass results when unordered ions are "frozen in place" before they are able to unite into an orderly crystalline structure.

Obsidian, a common type of natural glass, is similar in appearance to dark chunks of manufactured glass. Obsidian's excellent conchoidal fracture and ability to hold a sharp, hard edge made it a prized material from which Native Americans chipped arrowheads and cutting tools (Figure 4.10).

Obsidian flows, typically a few hundred feet thick, provide evidence that rapid cooling is not the only mechanism that produces a glassy texture. Magmas with high silica content tend to form long, chainlike structures (polymers) before crystallization is complete. These structures, in turn, slow the migration of ions, which impedes the formation of crystals. In addition. these long chainlike structures increase the magma's viscosity. (*Viscosity* is a measure of a fluid's resistance to flow.) So granitic magma, which is rich in silica, may be extruded as an extremely viscous mass that eventually solidifies to form obsidian.

By contrast, basaltic magma, which is low in silica, forms very fluid lavas that, upon cooling, usually generate fine-grained crystalline rocks. However, when a basaltic lava flow enters the ocean, its surface is quenched rapidly enough to form a thin, glassy skin.

▼ **Figure 4.9 Vesicular texture** The larger image shows a lava flow on Hawaii's Kilauea Volcano. The inset photo is a close-up showing the vesicular texture of hardened lava. Vesicles are small holes left by escaping gas bubbles. (Inset photo by E. J. Tarbuck)

USGS

▲ **Figure 4.10 Obsidian arrowhead** Native Americans made arrowheads and cutting tools from obsidian, a natural glass. (Photo by Jeffrey Scovil)

◀ **Figure 4.11 Pyroclastic rocks are the product of explosive eruptions** This eruptive column consists in part of volcanic fragments, which will fall out and may eventually consolidate to become rocks displaying a pyroclastic texture. (Photo by Richard Roscoe/Getty Images)

Pyroclastic (Fragmental) Texture Another group of igneous rocks is formed from the consolidation of individual rock fragments ejected during explosive volcanic eruptions. The ejected particles might be very fine volcanic ash, molten blobs, or large angular blocks torn from the walls of a vent during an eruption (Figure 4.11). Igneous rocks composed of these rock fragments are said to have a **pyroclastic texture**, or **fragmental texture** (see Figure 4.7E).

A common type of pyroclastic rock, called *welded tuff*, is composed of fine fragments of glass that remained hot enough to fuse together. Other pyroclastic rocks are composed of fragments that solidified before impact and became cemented together at some later time. Because pyroclastic rocks are made of individual particles or fragments rather than interlocking crystals, their textures often resemble those exhibited by sedimentary rocks rather than those associated with igneous rocks.

CONCEPT CHECKS 4.3

1. Define *texture*.
2. How does the rate of cooling influence crystal size? What other factors influence the texture of igneous rocks?
3. List the six major igneous rock textures.
4. What does a porphyritic texture indicate about the cooling history of an igneous rock?

4.4 Naming Igneous Rocks

Distinguish among the common igneous rocks based on texture and mineral composition.

Geologists classify igneous rocks on the basis of their texture and mineral composition (Figure 4.12). The various igneous textures described in the previous section result mainly from different cooling histories, whereas the mineral composition of an igneous rock depends on the chemical makeup of its parent magma. Because igneous rocks are classified on the basis of both mineral composition and texture, some rocks having similar mineral constituents but exhibiting different textures are given different names.

▶ SmartFigure 4.12 **Classification of igneous rocks** Igneous rocks are classified based on mineral composition and texture. (Photos by Dennis Tasa and E. J. Tarbuck)

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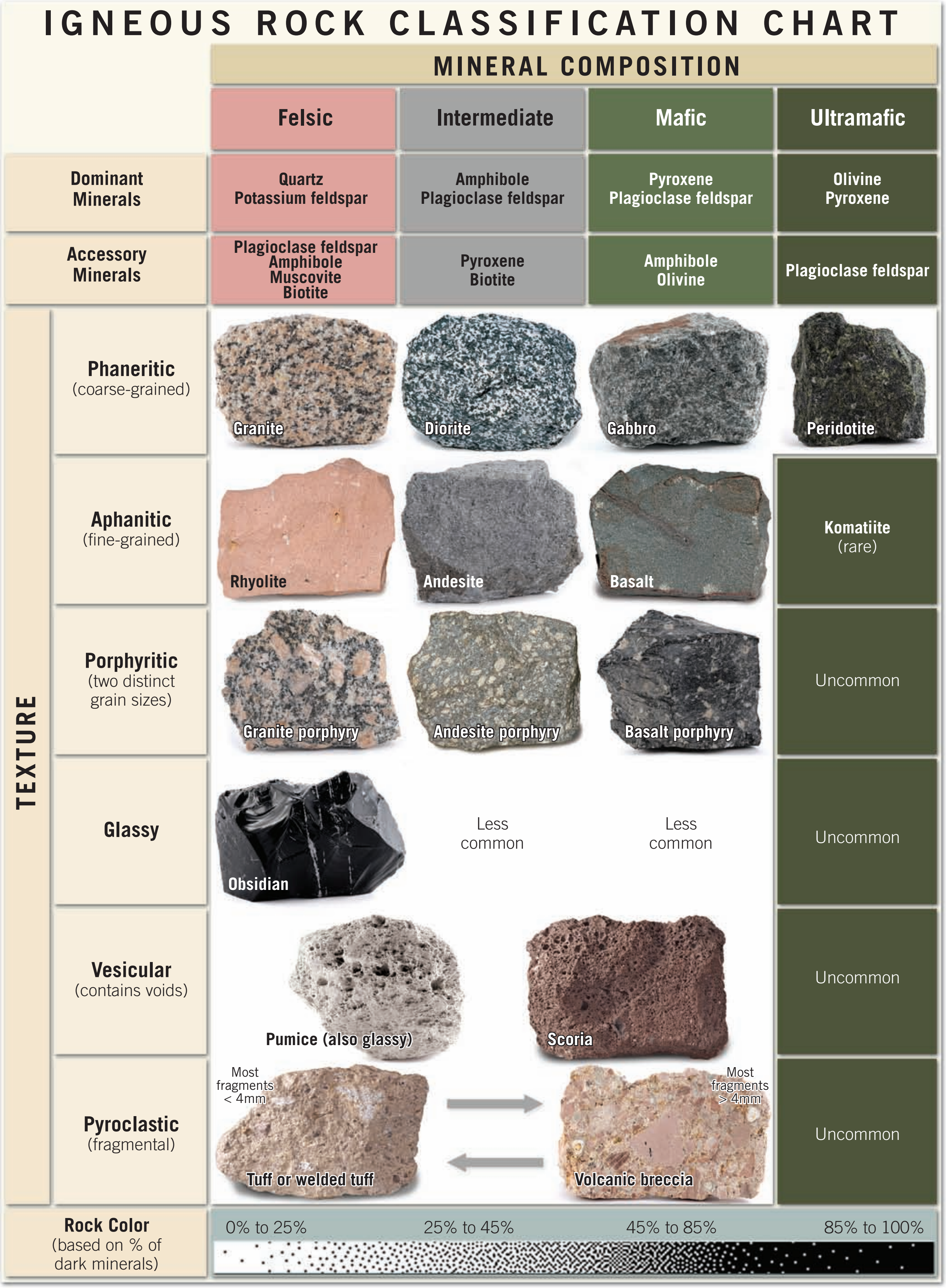


IGNEOUS ROCK CLASSIFICATION CHART

		MINERAL COMPOSITION			
		Felsic	**Intermediate**	**Mafic**	**Ultramafic**
Dominant Minerals		Quartz Potassium feldspar	Amphibole Plagioclase feldspar	Pyroxene Plagioclase feldspar	Olivine Pyroxene
Accessory Minerals		Plagioclase feldspar Amphibole Muscovite Biotite	Pyroxene Biotite	Amphibole Olivine	Plagioclase feldspar
TEXTURE	**Phaneritic** (coarse-grained)	Granite	Diorite	Gabbro	Peridotite
	Aphanitic (fine-grained)	Rhyolite	Andesite	Basalt	**Komatiite** (rare)
	Porphyritic (two distinct grain sizes)	Granite porphyry	Andesite porphyry	Basalt porphyry	Uncommon
	Glassy	Obsidian	Less common	Less common	Uncommon
	Vesicular (contains voids)	Pumice (also glassy)		Scoria	Uncommon
	Pyroclastic (fragmental)	Most fragments < 4mm Tuff or welded tuff	⇄	Most fragments > 4mm Volcanic breccia	Uncommon
Rock Color (based on % of dark minerals)		0% to 25%	25% to 45%	45% to 85%	85% to 100%

Cory Rich/Getty Images

Michael Collier

Dennis Tasa

▲ SmartFigure 4.13 **Rocks contain information about the processes that produced them** This massive granitic monolith (El Capitan) located in Yosemite National Park, California, was once a molten mass deep within Earth.

MOBILE FIELD TRIP
https://goo.gl/XvMfQ1

Felsic Igneous Rocks

Granite Of all the igneous rocks, **granite** is perhaps the best known. This is because of its natural beauty, which is enhanced when it is polished, and its abundance in the continental crust. Slabs of polished granite are commonly used for tombstones and monuments and as building stones. Well-known areas in the United States where granite is quarried include Barre, Vermont; Mount Airy, North Carolina; and St. Cloud, Minnesota.

Granite is a coarse-grained rock composed of about 10 to 20 percent quartz and roughly 50 percent feldspar. When examined close up, the quartz grains appear somewhat rounded in shape, glassy, and clear to gray in color. By contrast, feldspar crystals, which are generally white, gray, or salmon pink in color, are blocky or rectangular in shape. Other minor constituents of granite include small amounts of dark silicates, particularly biotite and amphibole, and sometimes muscovite. Although the dark components generally make up less than 10 percent of most granites, they stand out visually and give granite its speckled appearance.

From a distance, most granitic rocks appear gray in color (Figure 4.13). However, granite that is composed of dark pink feldspar grains exhibits a reddish color. In addition, granites commonly exhibit a porphyritic texture. These specimens contain elongated feldspar crystals a few centimeters in length that are scattered among smaller crystals of quartz and amphibole (see Figure 4.12).

Rhyolite **Rhyolite** is the fine-grained equivalent of granite and, like granite, is composed essentially of the light-colored silicates (see Figure 4.12). This fact accounts for its color, which is usually buff to pink or occasionally light gray. Rhyolite is fine grained and frequently contains glass fragments and voids, indicating that it cooled rapidly in a surface, or near-surface, environment. In contrast

Did You Know?
During the Stone Age, volcanic glass (obsidian) was used for making cutting tools. Today, scalpels made from obsidian are being employed for delicate plastic surgery because they leave less scarring than steel scalpels. "The steel scalpel has a rough edge, where the obsidian scalpel is smoother and sharper," explains Lee Green, MD, an associate professor at the University of Michigan Medical School.

to granite, which is widely distributed as large intrusive masses, rhyolite deposits are less common and generally less voluminous. The thick rhyolite lava flows and extensive deposits of volcanic ash in and around Yellowstone National Park are well-known exceptions to this generalization.

Obsidian **Obsidian** is a dark-colored glassy rock that usually forms when highly silica-rich lava cools quickly at Earth's surface (see Figure 4.12). In contrast to the orderly arrangement of ions characteristic of minerals, the arrangement of ions in glass is unordered. Consequently, glassy rocks such as obsidian are not composed of minerals in the same sense as most other rocks.

Although generally black or reddish-brown in color, obsidian most often has a chemical composition that is roughly equivalent to that of the light-colored igneous rock granite. Obsidian's dark color results from small amounts of metallic ions in an otherwise relatively clear, glassy substance. If you examine a thin edge, obsidian will appear nearly transparent (see Figure 4.7).

Pumice **Pumice** is a glassy volcanic rock with a vesicular texture that forms when large amounts of gas escape through silica-rich lava to generate a gray, frothy mass. In some samples the voids are quite noticeable, whereas in others the pumice resembles fine shards of intertwined glass. Because of the large percentage of voids, many samples of pumice float when placed in water (**Figure 4.14**). Oftentimes, flow lines are visible in pumice, indicating that some movement occurred before solidification was complete. Moreover, pumice and obsidian can often be found in the same rock mass, existing in alternating layers.

Intermediate Igneous Rocks

Andesite **Andesite** is a medium-gray, fine-grained rock typically of volcanic origin. Its name comes from South America's Andes Mountains, where numerous volcanoes are composed of this rock type. The volcanoes of North America's Cascade Range and many of the volcanic structures occupying the continental margins that surround the Pacific Ocean are also of andesitic composition. Andesite commonly exhibits a porphyritic texture (see Figure 4.12). When this is the case, the phenocrysts are often light, rectangular crystals of plagioclase feldspar or black, elongated amphibole crystals. Andesite may also resemble rhyolite, so its identification usually requires microscopic examination to verify mineral makeup.

Diorite **Diorite** is the intrusive equivalent of andesite. It is a coarse-grained rock that looks somewhat like gray granite but can be distinguished from granite because it contains little or no visible quartz crystals and has a higher percentage of dark silicate minerals. The mineral makeup of diorite is primarily plagioclase feldspar and amphibole. Because the light-colored feldspar grains and dark amphibole crystals appear to be roughly equal in abundance, diorite has a salt-and-pepper appearance (see Figure 4.12).

Mafic Igneous Rocks

Basalt **Basalt** is a very dark green to black, fine-grained rock composed primarily of pyroxene and calcium-rich plagioclase feldspar, with lesser amounts of olivine and amphibole (see Figure 4.12). When it is porphyritic, basalt commonly contains small light-colored feldspar phenocrysts or green, glassy-appearing olivine grains embedded in a dark groundmass.

Basalt is the most common extrusive igneous rock. Many volcanic islands, such as the Hawaiian Islands and Iceland, are composed mainly of basalt (**Figure 4.15**). Further, the upper layers of the oceanic crust consist of basalt. In the United States, large portions of central Oregon and Washington were the sites of extensive basaltic outpourings (discussed in detail in Chapter 5). At some locations, these once-fluid basaltic flows have accumulated to combined thicknesses approaching 3 kilometers (2 miles).

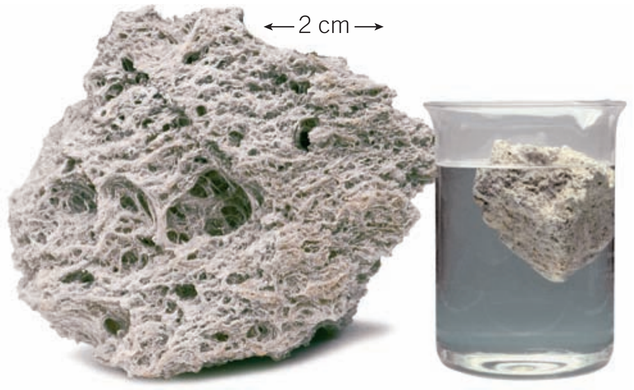
Gabbro **Gabbro** is the intrusive equivalent of basalt (see Figure 4.12). Like basalt, it tends to be dark green to black in color and composed primarily of pyroxene and calcium-rich plagioclase feldspar. Although gabbro is uncommon in the continental crust, it makes up a significant percentage of oceanic crust.

Pyroclastic Rocks

Pyroclastic rocks are composed of fragments ejected during a volcanic eruption. One of the most common pyroclastic rocks, called *tuff*, is composed mainly of tiny, ash-size fragments that were later cemented together. In situations where the ash particles remained hot enough to fuse, the rock is called *welded tuff*. Although welded tuff consists mostly of tiny glass shards, it may contain walnut-size pieces of pumice and other rock fragments.

Welded tuff deposits cover vast portions of previously volcanically active areas of the western United

Did You Know?
Although Earth's upper mantle is often depicted in diagrams as a reddish-colored layer to show its high temperature, its color is actually a dark green. But how do we know it is green? On occasion, unmelted fragments of mantle rocks are brought to Earth's surface by rapidly rising magma and are ejected from volcanoes. These mantle rocks, called *peridotite*, are composed mainly of olivine, which, as the name suggests, is olive green, and pyroxene, which is blackish green.



▶ **Figure 4.14 Pumice, a vesicular (and also glassy) igneous rock** Most samples of pumice will float in water because they contain numerous vesicles. (Inset photo by Chip Clark/Fundamental Photos)

◀ **Figure 4.15** **Basaltic lava flowing from Kilauea Volcano, Hawaii** (Photo by David Reggie/Getty Images)

States (**Figure 4.16**). Some of these tuff deposits are hundreds of feet thick and extend for more than 100 kilometers (60 miles) from their source. Most formed millions of years ago as volcanic ash spewed from large volcanic structures (calderas), sometimes spreading laterally at speeds approaching 100 kilometers (60 miles) per hour. Early investigators of these deposits incorrectly classified them as rhyolite lava flows. Today, we know that silica-rich lava is too viscous (thick) to flow more than a few miles from a vent.

Pyroclastic rocks composed mainly of particles larger than ash are called *volcanic breccia*. The particles in volcanic breccia may consist of streamlined lava blobs that solidified in air, blocks broken from the walls of the vent, volcanic ash, and glass fragments.

Unlike most igneous rock names, such as granite and basalt, the terms *tuff* and *volcanic breccia* do not imply mineral composition. Instead, they are frequently identified with a modifier; for example, *rhyolite tuff* indicates a rock composed of ash-size particles having a felsic composition.

E. J. Tarbuck

▲ **Figure 4.16** **Welded tuff, a pyroclastic igneous rock** Outcrop of welded tuff that erupted from Valles Caldera near Los Alamos, New Mexico. Tuff is composed mainly of ash-sized particles and may contain larger fragments of pumice or other volcanic rocks. (Photo by Marli Miller)

CONCEPT CHECKS 4.4

1. List the two criteria by which igneous rocks are classified.
2. How are granite and rhyolite different? In what way are they similar?
3. Classify each of the following rocks by their mineral composition (felsic, intermediate, or mafic): gabbro, obsidian, granite, and andesite.
4. Describe each of the following in terms of composition and texture: diorite, rhyolite, and basalt porphyry.
5. In what way do tuff and volcanic breccia differ from other igneous rocks such as granite and basalt?

4.5 Origin of Magma

Summarize the major processes that generate magma from solid rock.

Did You Know?
Since the 1930s carpenters, mechanics, and other people working with their hands have used *Lava Soap*, which contains powdered pumice. Because of the abrasiveness of pumice, Lava soap is particularly good at removing grease, dirt, paints, and adhesives.

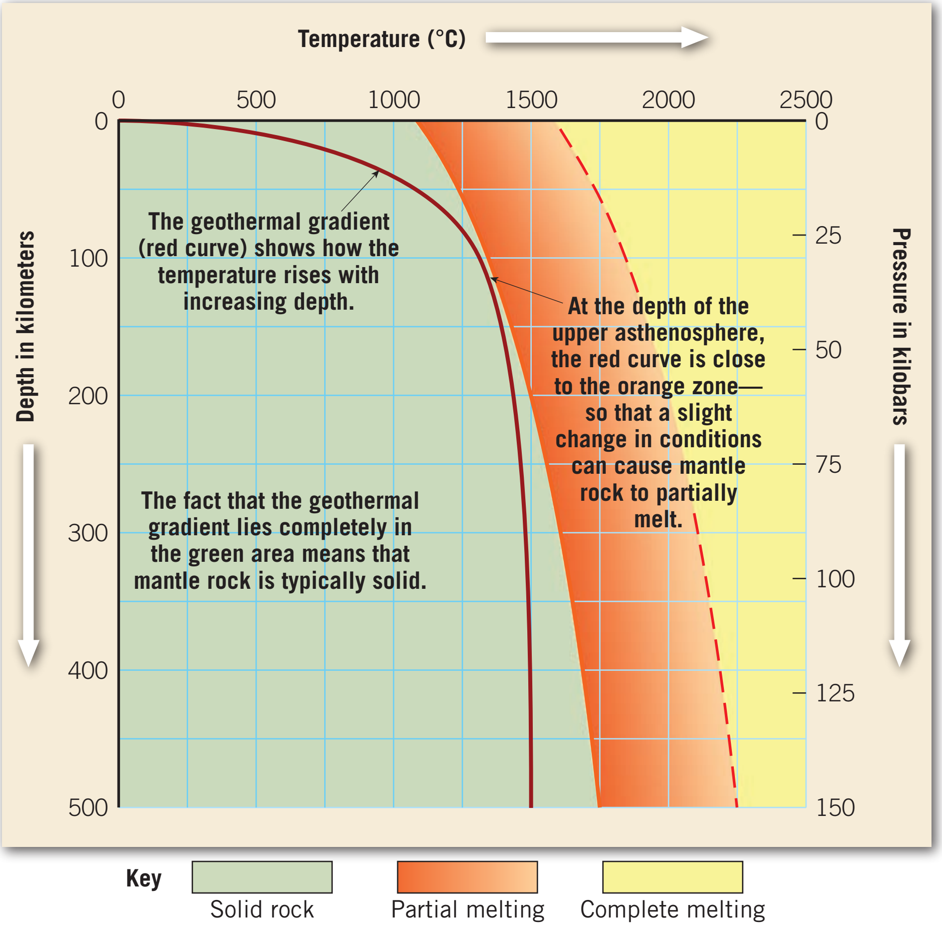
Based on evidence from the study of earthquake waves, we know that *Earth's crust and mantle are composed primarily of solid, not molten, rock*. Although the outer core is fluid, this iron-rich material is very dense and remains deep within Earth. So where does magma come from?

Most magma originates in Earth's uppermost mantle. The greatest quantities are produced at divergent plate boundaries, in association with seafloor spreading, with lesser amounts forming at subduction zones, where oceanic lithosphere descends into the mantle. Magma also can be generated when crustal rocks are heated sufficiently to melt.

Generating Magma from Solid Rock

Workers in underground mines know that temperatures increase as they descend deeper below Earth's surface. Although the rate of temperature change varies considerably from place to place, it *averages* about 25°C (75°F) per kilometer in the *upper* crust. This increase in temperature with depth is known as the **geothermal gradient**. As shown in **Figure 4.17**, when a typical geothermal gradient is compared to the melting point curve for the mantle rock peridotite, the temperature at which peridotite melts is higher than the geothermal gradient. Thus, under normal conditions, the mantle is solid. However, tectonic processes trigger melting though various means, including reducing the mantle rock's melting point (the temperature at which a material changes from solid to liquid).

▼ **Figure 4.17 Why the mantle is mainly solid** This diagram shows the geothermal gradient (the increase in temperature with depth) for the crust and upper mantle.



Decrease in Pressure: Decompression Melting

If temperature were the only factor that determined whether rock melts, our planet would be a molten ball covered with a thin, solid outer shell. This is not the case because pressure, which also increases with depth, influences the melting temperatures of rocks.

Melting, which is accompanied by an increase in volume, occurs at progressively higher temperatures with increased depth. This is the result of the steady increase in confining pressure exerted by the weight of overlying rocks. Conversely, *reducing confining pressure lowers a rock's melting temperature*. When confining pressure drops sufficiently, **decompression melting** is triggered. Decompression melting occurs wherever hot, solid mantle rock ascends, thereby moving into regions of lower pressure.

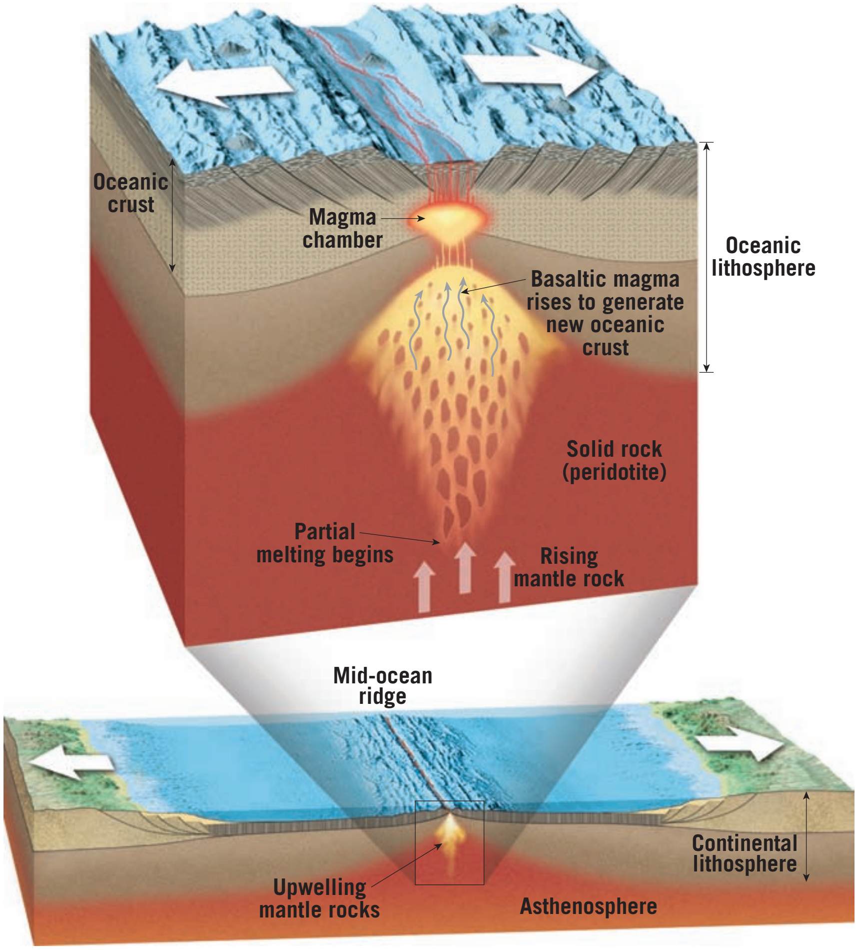
Recall from Chapter 2 that tensional forces along spreading centers promote upwelling where plates diverge. This process is responsible for generating magma along oceanic ridges (divergent plate boundaries) where plates are rifting apart (**Figure 4.18**). Below the ridge crest, hot mantle rock rises and melts, generating a magma that replaces the material that shifted horizontally away from the ridge axis.

Decompression melting also occurs when ascending mantle plumes reach the uppermost mantle. If this rising magma reaches the surface, it triggers an episode of hot-spot volcanism.

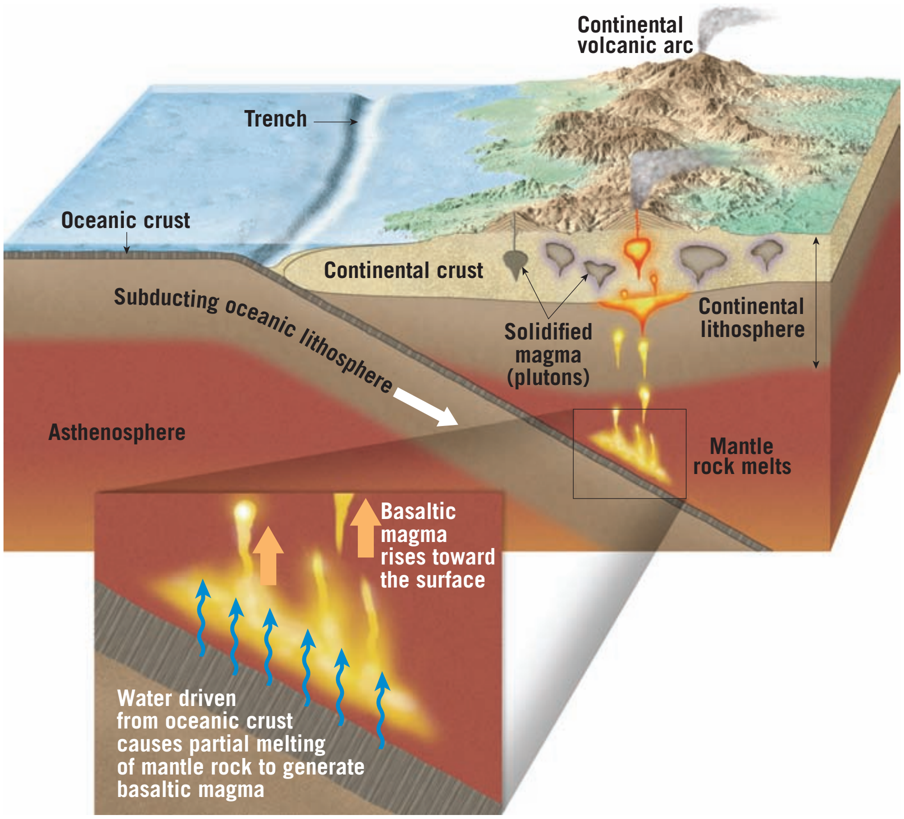
Addition of Water

Along with pressure, an important factor affecting the melting temperature of rock is its water content. Water and other volatiles, such as carbon dioxide, act in a similar way to salt melting ice. That is, water causes rock to melt at lower temperatures, just as putting rock salt on an icy sidewalk induces melting.

The introduction of water to generate magma occurs mainly at convergent plate boundaries, where cool slabs of oceanic lithosphere descend into the mantle (**Figure 4.19**). As an oceanic plate sinks, heat and pressure drive water from the subducting oceanic crust and overlying sediments. These fluids migrate into the wedge of hot mantle that lies directly above. At a depth of about 100 kilometers (60 miles), the wedge of mantle rock is sufficiently hot that the addition of water leads to some melting. Partial melting of the mantle rock peridotite generates hot basaltic magma whose temperatures may exceed 1250°C (nearly 2300°F).



▲ **Figure 4.18** **Decompression melting** As hot mantle rock ascends, it experiences continuously decreasing pressure. This drop in confining pressure usually initiates *decompression melting* in the upper mantle.



▲ **Figure 4.19** **Water lowers the melting temperature of hot mantle rock to trigger partial melting** As an oceanic plate descends into the mantle, water and other volatiles are driven from the subducting crustal rocks into the mantle above.

Temperature Increase: Melting Crustal Rocks Mantle-derived basaltic (mafic) magma tends to be less dense than the surrounding rocks, which causes the magma to buoyantly rise toward the surface. In oceanic settings, these basaltic magmas often erupt on the ocean floor, generating seamounts, which may grow to form volcanic islands, as exemplified by the Hawaiian Islands. However, in continental settings, basaltic magma often "ponds" beneath low-density crustal rocks. Because the overlying crustal rocks have lower melting temperatures than basaltic magmas, the hot basaltic magma may heat them sufficiently to generate a secondary melt of silica-rich felsic magma. If these low-density, felsic magmas reach the surface, they tend to produce explosive eruptions; such eruptions occur most often at convergent plate boundaries.

Crustal rocks can also melt during continental collisions that result in the formation of a large mountain belt (discussed in detail in Chapter 11). During these events, the crust is greatly thickened, and some crustal rocks are carried to depths where the temperatures are high enough to cause partial melting. The felsic magmas produced in this manner usually solidify before reaching the surface, so volcanism is not typically associated with these collision-type mountain belts.

In summary, magma can be generated by (1) *decompression melting*, caused by a decrease in pressure as magma rises; (2) the *introduction of water*, which lowers the melting temperature of hot mantle rock; and (3) *heating of crustal rocks* above their melting temperature.

CONCEPT CHECKS 4.5

1. What is the geothermal gradient? Describe how the geothermal gradient compares with the melting temperatures of the mantle rock peridotite at various depths.
2. Explain the process of decompression melting.
3. What roles do water and other volatiles play in the formation of magma?
4. Name two plate tectonic settings in which you would expect magma to be generated.

4.6 How Magmas Evolve

Describe how magmatic differentiation can generate a magma body that has a mineralogy (chemical composition) that is different from its parent magma.

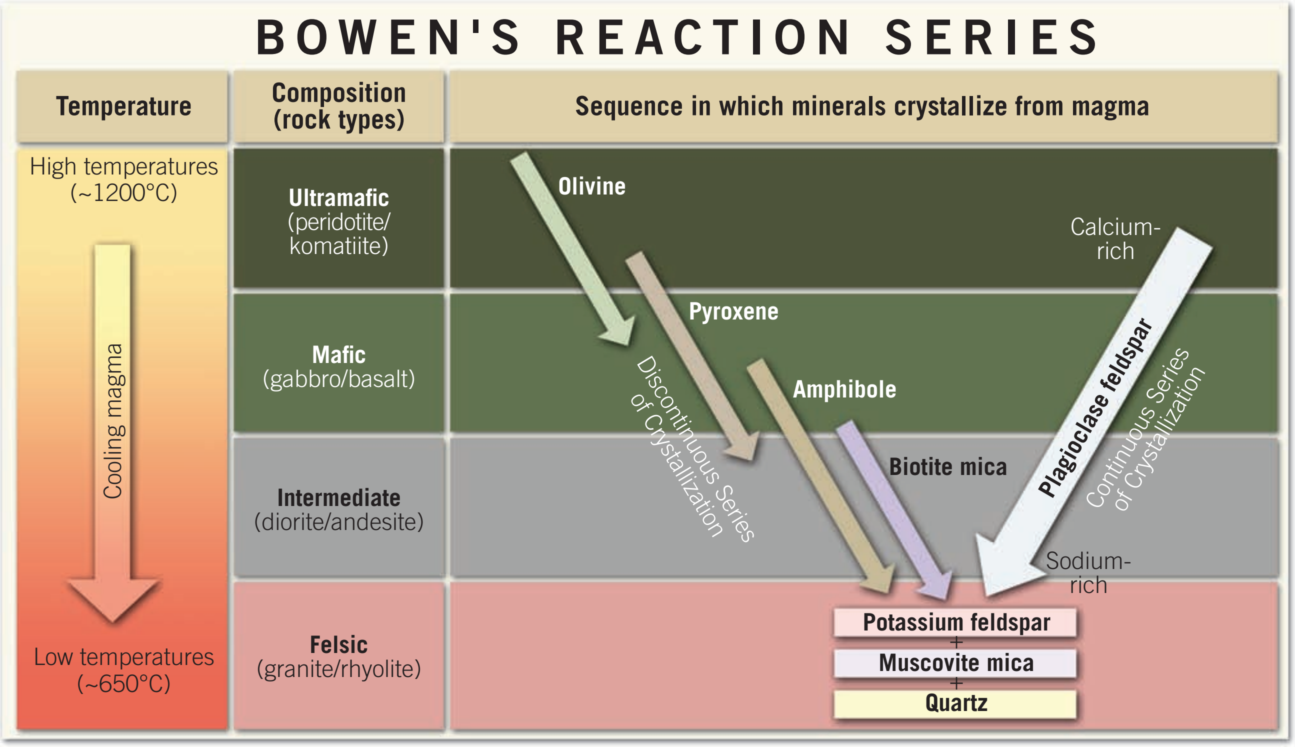
Geologists have observed that a single volcano may extrude lavas that change in composition over time. Such observations led to the idea that magma might change over time (evolve) and thus that one magma body could give rise to igneous rocks with a range of compositions. To explore this idea, N. L. Bowen carried out a pioneering investigation early in the twentieth century into the crystallization of magma.

Bowen's Reaction Series & the Composition of Igneous Rocks

Recall that ice freezes at a specific temperature, whereas basaltic magma crystallizes over a range of at least 200°C of cooling (from about 1200° to 1000°C). In a laboratory setting, Bowen and his coworkers demonstrated that as a basaltic magma cools, minerals tend to crystallize in a systematic fashion, based on their melting temperatures. As shown in Figure 4.20, the first mineral to crystallize is the ferromagnesian mineral olivine. Further cooling generates calcium-rich plagioclase feldspar as well as pyroxene, and so forth down the diagram.

During this crystallization process, the composition of the remaining liquid portion of the magma also continually changes. For example, at the stage when about one-third of the magma has solidified, the remaining molten material is nearly depleted of iron, magnesium, and calcium because these elements are major constituents of the minerals that form earliest in the process. The removal of these elements causes the melt to become enriched in sodium and potassium. Further, because the original basaltic magma contained about 50 percent silica (SiO_2), the crystallization of the earliest-formed mineral, olivine, which is only about 40 percent silica, leaves the remaining melt richer in SiO_2. Thus, the magma becomes progressively richer in silica as it evolves.

Bowen also demonstrated that when the crystals that form in a magma remain in contact with the remaining melt, then they (mainly their outer regions) continue to exchange ions with the melt (react chemically with it). As a result, the periphery of these mineral grains has a different, more evolved composition than the interiors. That is the significance of the arrows in Figure 4.20. Stated another way, minerals that remain in contact with a melt gradually change composition to become the next mineral in the series Bowen identified. This order of mineral formation became known as **Bowen's reaction series**. However, in nature, the earliest-formed minerals



▶ **Figure 4.20 Bowen's reaction series** This diagram shows the sequence in which minerals crystallize from a basaltic magma. Compare this figure to the mineral composition of the rock groups in Figure 4.12. Note that each rock group consists of minerals that crystallize in the same temperature range.

can separate from the melt, thus halting further chemical reactions.

The diagram of Bowen's reaction series in Figure 4.20 depicts the sequence in which minerals crystallize from a magma of basaltic composition under laboratory conditions. Evidence that this highly idealized crystallization model approximates what can happen in nature comes from analysis of igneous rocks. In particular, scientists know that minerals that form in the same general temperature regime depicted in Bowen's reaction series are found together in the same igneous rocks. For example, notice in Figure 4.20 that the minerals quartz, potassium feldspar, and muscovite, which are located in the same region of Bowen's diagram, are typically found together as major constituents of the intrusive igneous rock granite.

Magmatic Differentiation & Crystal Settling

Bowen demonstrated that minerals crystallize from magma in a systematic fashion. But how do Bowen's findings account for the great diversity of igneous rocks? It has been shown that, at one or more stages during the crystallization of magma, a separation of various components can occur. One mechanism that causes this to happen is called **crystal settling**. This process occurs when the earlier-formed minerals are denser (heavier) than the melt and sink toward the bottom of the magma chamber, as shown in **Figure 4.21**. When the remaining melt solidifies—either in place or at another location, if it migrates into fractures in the surrounding rocks—it will form a rock with a mineral composition that is more felsic than the parent magma. The formation of a magma body having a mineralogy or chemical composition that is different than the parent magma is called **magmatic differentiation**.

A classic example of magmatic differentiation is found in the Palisades Sill, which is a 300-meter- (1000-foot-) thick slab of dark igneous rock exposed along the west bank of the lower Hudson River across from New York City. Because of its great thickness and consequent slow rate of solidification, crystals of olivine (the first mineral to form) sank and make up about 25 percent of the lower portion of the Palisades Sill. By contrast, near the top of this igneous body, where the last melt crystallized, olivine represents only 1 percent of the rock mass.*

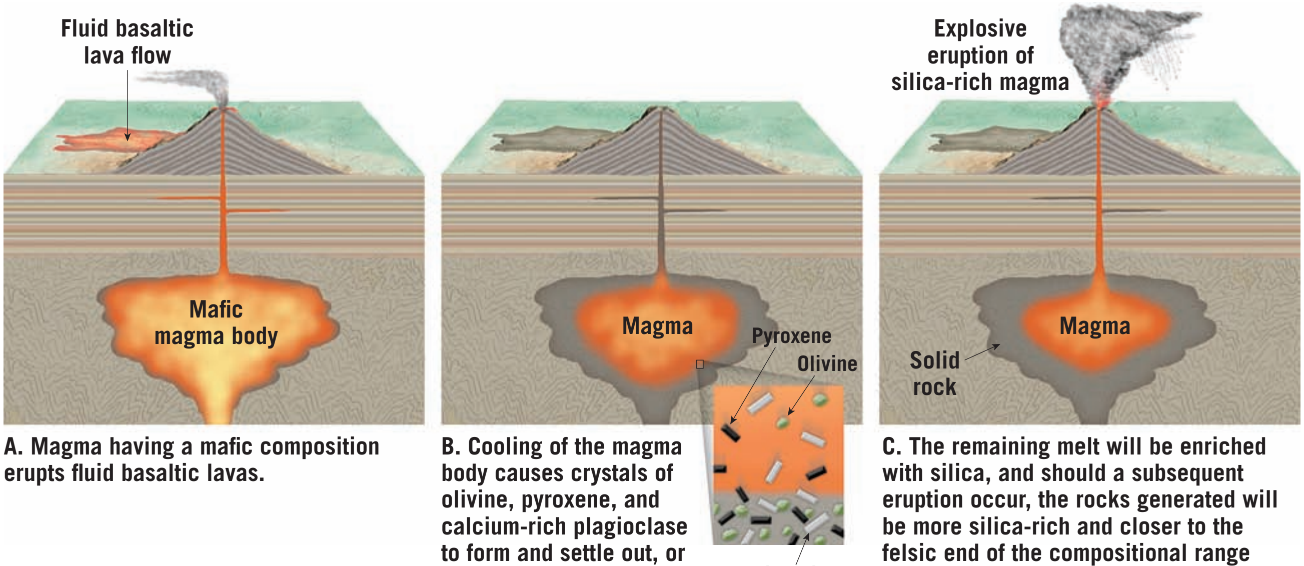
Assimilation & Magma Mixing

Bowen successfully demonstrated that through magmatic differentiation, a single parent magma can generate several mineralogically different igneous rocks. However, more recent work indicates that magmatic differentiation involving crystal settling cannot, by itself, account for the entire compositional spectrum of igneous rocks.

Once a magma body forms, the incorporation of foreign material can also change its composition. For example, in near-surface environments where rocks

Did You Know?

The formation of the most common chemical elements on Earth, such as oxygen, silicon, and iron, occurred billions of years ago inside distant massive stars. Through various processes of nuclear fusion, these stars converted the lightest elements, mostly hydrogen, into these heavier elements. In fact, most such elements found in the solar system, as well as in your body, are believed to have formed from debris scattered by stars that formed prior to the formation of the solar system.



A. Magma having a mafic composition erupts fluid basaltic lavas.

B. Cooling of the magma body causes crystals of olivine, pyroxene, and calcium-rich plagioclase to form and settle out, or crystallize along the magma body's cool margins.

C. The remaining melt will be enriched with silica, and should a subsequent eruption occur, the rocks generated will be more silica-rich and closer to the felsic end of the compositional range than the initial magma.

◀ **Figure 4.21 Crystal settling results in a change in the composition of the remaining magma** A magma evolves as the earliest-formed minerals (those richer in iron, magnesium, and calcium) crystallize and settle to the bottom of the magma chamber, leaving the remaining melt richer in sodium, potassium, and silica (SiO_2).

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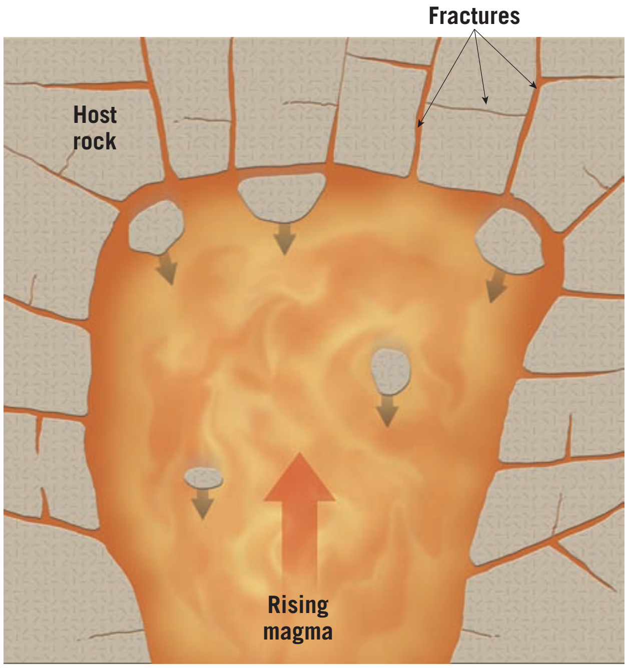
*Recent studies indicate that the Palisades Sill was produced by multiple injections of magma and does not represent a simple case of crystal settling. However, it is nonetheless an instructional example of that process.

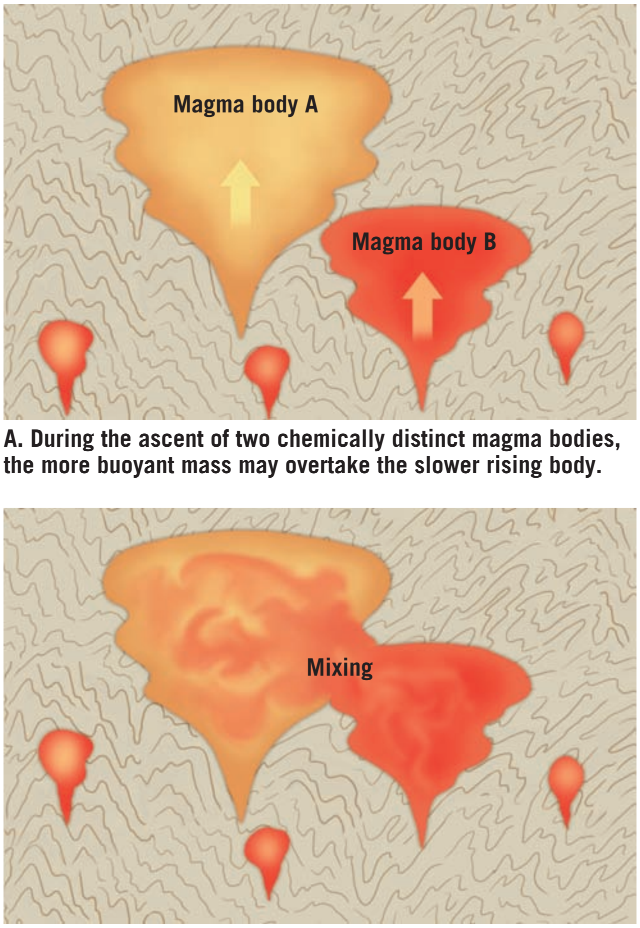
▶ **Figure 4.22** **Assimilation of the host rock by a magma body**



As magma rises through Earth's brittle upper crust, it may dislodge and incorporate the surrounding host rocks. Melting of these blocks, a process called *assimilation*, changes the overall composition of the rising magma body.

are brittle, the magma pushing upward can cause the overlying rock to fracture into numerous pieces. The force of the injected magma is often sufficient to dislodge and incorporate blocks of the surrounding host rock (Figure 4.22). Melting of these blocks, a process called **assimilation**, changes the overall chemical composition of the magma body.

Another means by which the composition of magma can be altered is called **magma mixing**. Magma mixing may occur during the ascent of two chemically distinct magma bodies as the more buoyant mass overtakes the more slowly rising body (Figure 4.23). Once they are joined, convective flow stirs the two magmas, generating a single mass that has an intermediate composition.



A. During the ascent of two chemically distinct magma bodies, the more buoyant mass may overtake the slower rising body.

B. Once joined, convective flow mixes the two magmas, generating a mass that is a blend of the two magma bodies.

▲ **Figure 4.23** **Magma mixing** This is one of the ways the composition of a magma body can change.

CONCEPT CHECKS 4.6

1. Define Bowen's reaction series.
2. How does the crystallization and settling of the earliest formed minerals affect the composition of the remaining magma?
3. Compare the processes of assimilation and magma mixing.

4.7 Partial Melting & Magma Composition

Describe how partial melting of the mantle rock peridotite can generate a basaltic (mafic) magma.

Recall that igneous rocks are composed of a mixture of minerals and, therefore, tend to melt over a temperature range of at least 200°C. As rock begins to melt, the minerals with the lowest melting temperatures are the first to melt. If melting continues, minerals with higher melting points begin to melt, and the composition of the melt steadily approaches the overall composition of the rock from which it was derived. Most often, however, melting is not complete, a process known as **partial melting**.

Recall from Bowen's reaction series that rocks with a granitic composition are composed of minerals with the lowest melting (crystallization) temperatures—namely, quartz and potassium feldspar (see Figure 4.20). Also note that as we move up Bowen's reaction series, the minerals have progressively higher melting temperatures, and that olivine, which is found at the top, has the highest melting point. When a rock undergoes partial melting, it forms a melt that is enriched in ions from minerals with the lowest melting temperatures, while the unmelted portion is composed of minerals with higher melting temperatures (**Figure 4.24**). Separation of these two fractions yields a melt with a chemical composition that is richer in silica and nearer the felsic (granitic) end of the spectrum than the rock from which it formed. In general, partial melting of *ultramafic* rocks tends to yield *mafic (basaltic) magmas*, partial melting of *mafic* rocks generally yields *intermediate (andesitic) magmas*, and partial melting of *intermediate* rocks can generate *felsic (granitic) magmas*.

Formation of Basaltic Magma

Most magma that erupts at Earth's surface is basaltic in composition and has a temperature range of 1000° to 1250°C. Experiments show that under the high-pressure conditions calculated for the upper mantle, partial melting of the ultramafic rock peridotite can generate a magma of basaltic composition. Further evidence that many basaltic magmas have a mantle source are the inclusions of peridotite, a rock that basaltic magmas often carry up to Earth's surface from the mantle.

Basaltic (mafic) magmas that originate from partial melting of mantle rocks are called *primary* or *primitive* magmas because they have not yet evolved. Recall that partial melting that produces mantle-derived magmas may be triggered by a reduction in confining pressure during the process of decompression melting. This can occur, for example, where hot mantle rock ascends as part of slow-moving convective flow at mid-ocean ridges (see Figure 4.18). Basaltic magmas are also generated at subduction zones, where water driven from the descending slab of oceanic crust promotes partial melting of the mantle rocks that lie above (see Figure 4.19).

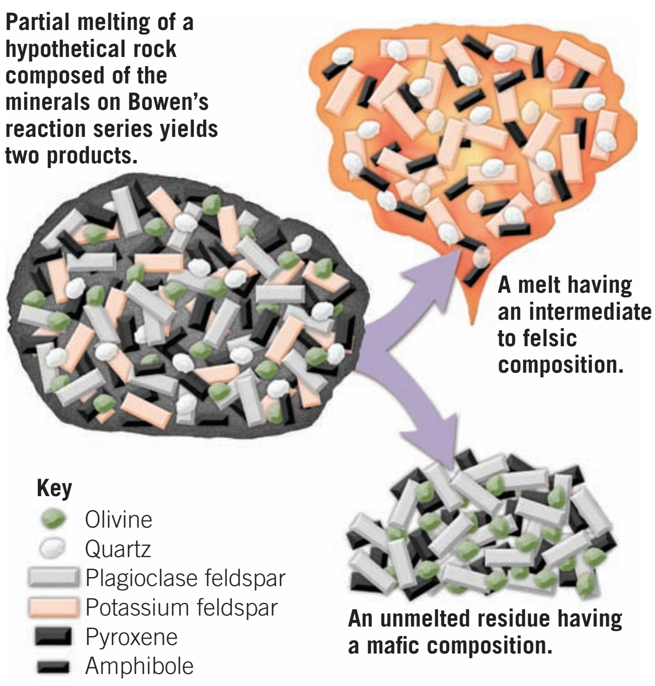
Formation of Andesitic & Granitic Magmas

If partial melting of mantle rocks generates most basaltic magmas, what is the source of the magma that crystallizes to form andesitic (intermediate) and granitic (felsic) rocks? Recall that silica-rich magmas erupt mainly along the continental margins. This is strong evidence that continental crust, which is thicker and has a lower density than oceanic crust, must play a role in generating these more highly evolved magmas.

One way andesitic magma can form is when a rising mantle-derived basaltic magma undergoes magmatic differentiation as it slowly makes its way through the continental crust. Recall from our discussion of Bowen's reaction series that as basaltic magma solidifies, the silica-poor ferromagnesian minerals crystallize first. If these iron-rich components are separated from the liquid by crystal settling, the remaining melt has an andesitic composition (see Figure 4.20).

Andesitic magmas can also form when rising basaltic magmas assimilate crustal rocks that tend to be rich in silica. Partial melting of basaltic rocks is yet another way in which at least some andesitic magmas are thought to be produced.

Although granitic magmas can be formed through magmatic differentiation of andesitic magmas, most granitic magmas probably form when hot basaltic magma ponds (becomes trapped because of its greater density) below continental crust (**Figure 4.25**). When the heat



◀ **SmartFigure 4.24**
Partial melting Partial melting generates a magma that is nearer the felsic (granitic) end of the compositional spectrum than the parent rock from which it was derived.

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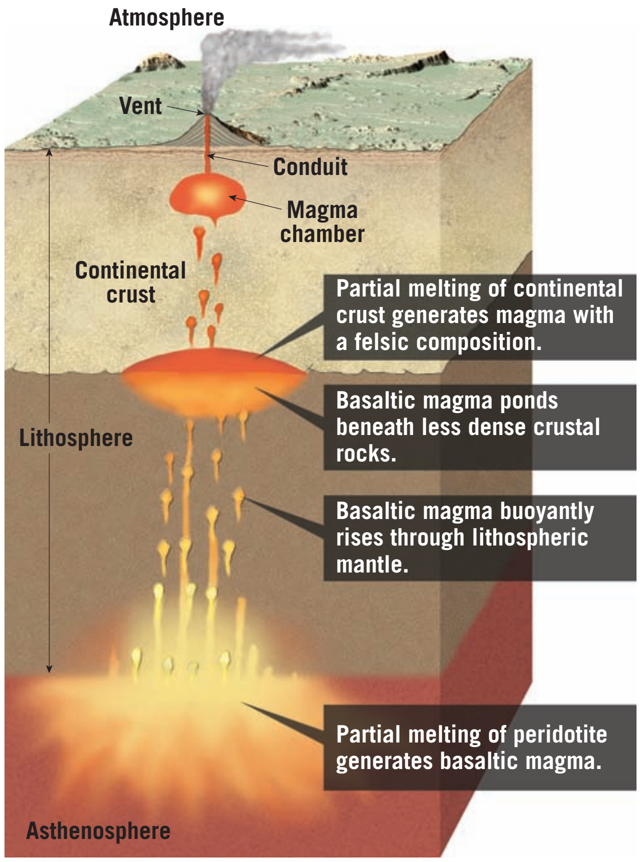

◀ **SmartFigure 4.25**
Formation of granitic magma Granitic magmas are generated by the partial melting of continental crust.

ANIMATION
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from the hot basaltic magma partially melts the overlying crustal rocks, which are silica rich and have a much lower melting temperature, the result can be the production of large quantities of granitic magmas. This process is thought to have been responsible for the volcanic activity in and around Yellowstone National Park in the distant past.

CONCEPT CHECKS 4.7

1. Briefly describe why partial melting results in a magma whose composition is different from that of the rock from which it was derived.
2. How are most basaltic magmas thought to have formed?
3. What is the process that is thought to generate most granitic magmas?

4.8 Intrusive Igneous Activity

Compare and contrast these intrusive igneous structures: dikes, sills, batholiths, stocks, and laccoliths.

Although volcanic eruptions are occasionally violent and spectacular events, most magma crystallizes at depth, without fanfare. Therefore, understanding the igneous processes that occur deep underground is as important to geologists as studying volcanic events, which are the focus of Chapter 5.

Nature of Intrusive Bodies

When magma rises through the crust, it forcefully displaces preexisting crustal rocks, termed **host rock** or **country rock**. The structures that result from the emplacement of magma into preexisting rocks are called **intrusions** or **plutons**. Because all intrusions form far below Earth's surface, they are studied primarily after uplifting and erosion (covered in later chapters) have exposed them. The challenge lies in reconstructing the events that generated these structures in vastly different conditions deep underground, millions of years ago.

Intrusions are known to occur in a great variety of sizes and shapes. Some of the most common types are illustrated in Figure 4.26. Notice that some plutons have a **tabular** (*tabula* = table) shape, whereas others are

▼ SmartFigure 4.26 **Intrusive igneous structures** (Photo: Belinda Images/SuperStock)

ANIMATION
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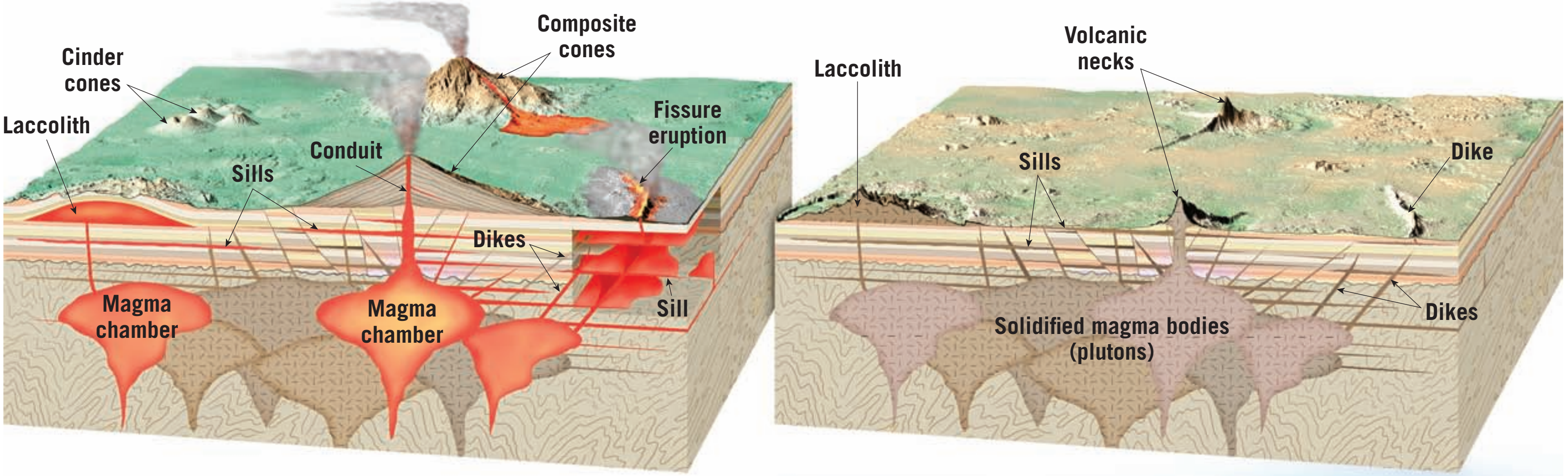
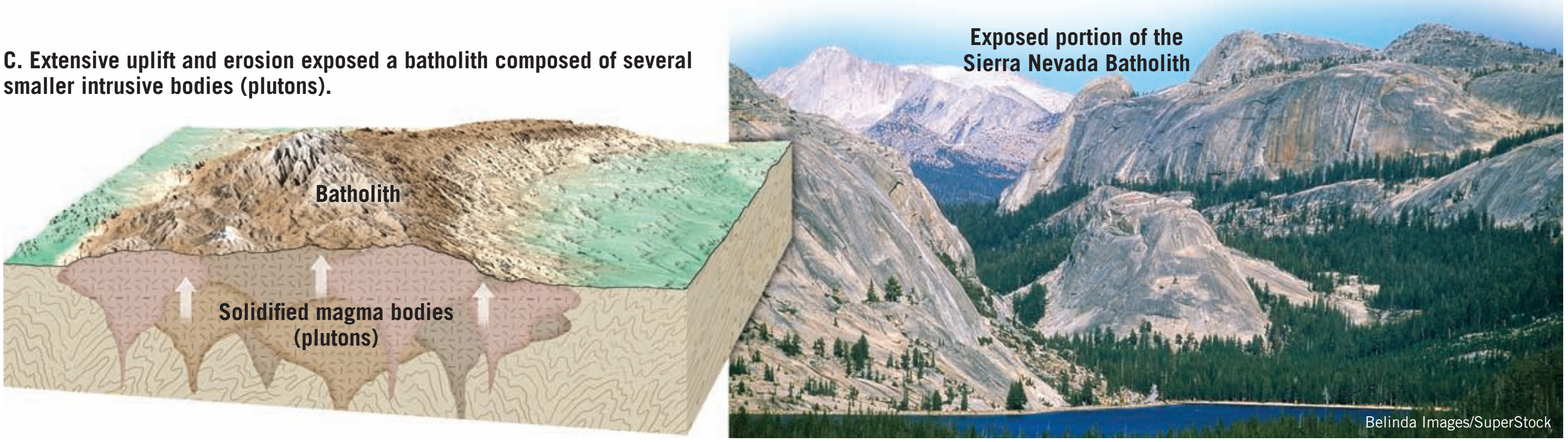
A. Relationship between volcanism and intrusive igneous activity.

B. Basic intrusive structures, some of which have been exposed by erosion.



C. Extensive uplift and erosion exposed a batholith composed of several smaller intrusive bodies (plutons).



Belinda Images/SuperStock

best described as **massive** (blob shaped). Also, observe that some of these bodies cut across existing structures, such as sedimentary strata, whereas others form when magma is injected between sedimentary layers. Because of these differences, intrusive igneous bodies are generally classified according to their shape as either tabular or massive, and by their orientation with respect to the host rock. Igneous bodies are said to be **discordant** (*discordare* = to disagree) if they cut across existing structures and **concordant** (*concordare* = to agree) if they inject parallel to features such as sedimentary strata.

Tabular Intrusive Bodies: Dikes & Sills

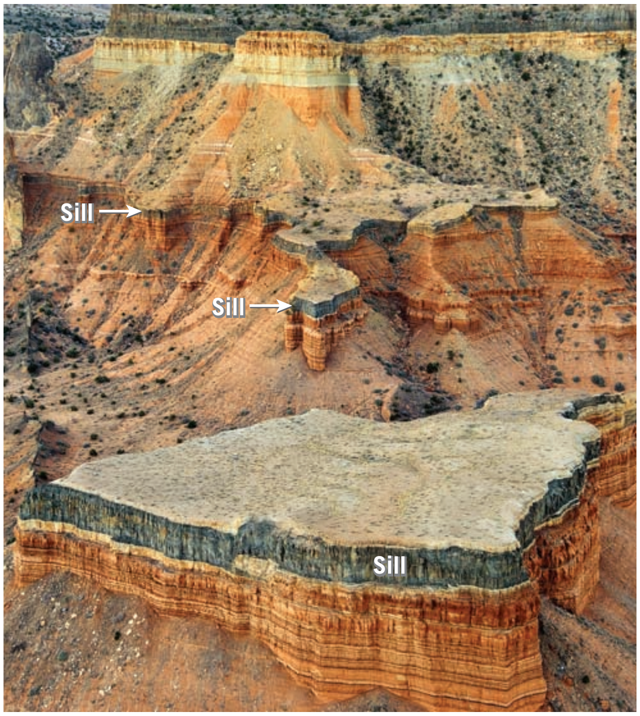
Dikes & Sills Tabular intrusive bodies are produced when magma is forcibly injected into a fracture or zone of weakness, such as a bedding surface (see Figure 4.26). **Dikes** are discordant bodies that form when magma is forcibly injected into fractures and cut across bedding surfaces and other structures in the host rock. By contrast, **sills** are nearly horizontal, concordant bodies that form when magma exploits weaknesses between sedimentary beds or other rock structures (**Figure 4.27**). In general, dikes serve as tabular conduits that transport magma upward, whereas sills tend to accumulate magma and increase in thickness.

Dikes and sills are typically shallow features, occurring where the country rocks are sufficiently brittle to fracture. They can range in thickness from less than 1 millimeter to more than 1 kilometer.

While dikes and sills can occur as solitary bodies, dikes tend to form in roughly parallel groups called *dike swarms*. These multiple structures reflect the tendency for fractures to form in sets when tensional forces pull apart brittle country rock. Dikes can also radiate from an eroded volcanic neck, like spokes on a wheel. In these situations, the active ascent of magma generated fissures in the volcanic cone, out of which lava flowed. Dikes frequently are more resistant and thus weather more slowly than the surrounding rock. Consequently, when exposed by erosion, dikes tend to have a wall-like appearance, as shown in **Figure 4.28**.

Because dikes and sills are relatively uniform in thickness and can extend for many kilometers, they are assumed to be the product of very fluid, and therefore mobile, magmas. One of the largest and most studied of all sills in the United States is the Palisades Sill. Exposed for 80 kilometers (50 miles) along the west bank of the Hudson River in southeastern New York and northeastern New Jersey, this sill is about 300 meters (1000 feet) thick. Because it is resistant to erosion, the Palisades Sill forms an imposing cliff that can be easily seen from the opposite side of the Hudson.

Columnar Jointing In many respects, sills closely resemble buried lava flows. Both are tabular and can extend over a wide area, and both may exhibit columnar jointing.



▲ **SmartFigure 4.27 Sill exposed in Sinbad County, Utah** The dark, essentially horizontal band is a sill of basaltic composition that intruded horizontal layers of sedimentary rock. (Photo by Michael Collier)

MOBILE FIELD TRIP
https://goo.gl/qC5DJE

◀ **SmartFigure 4.28 Dike exposed in the Spanish Peaks, Colorado** This wall-like dike is composed of igneous rock that is more resistant to weathering than the surrounding material. (Photo by Michael Collier)

CONDOR VIDEO
https://goo.gl/Qm3X6N

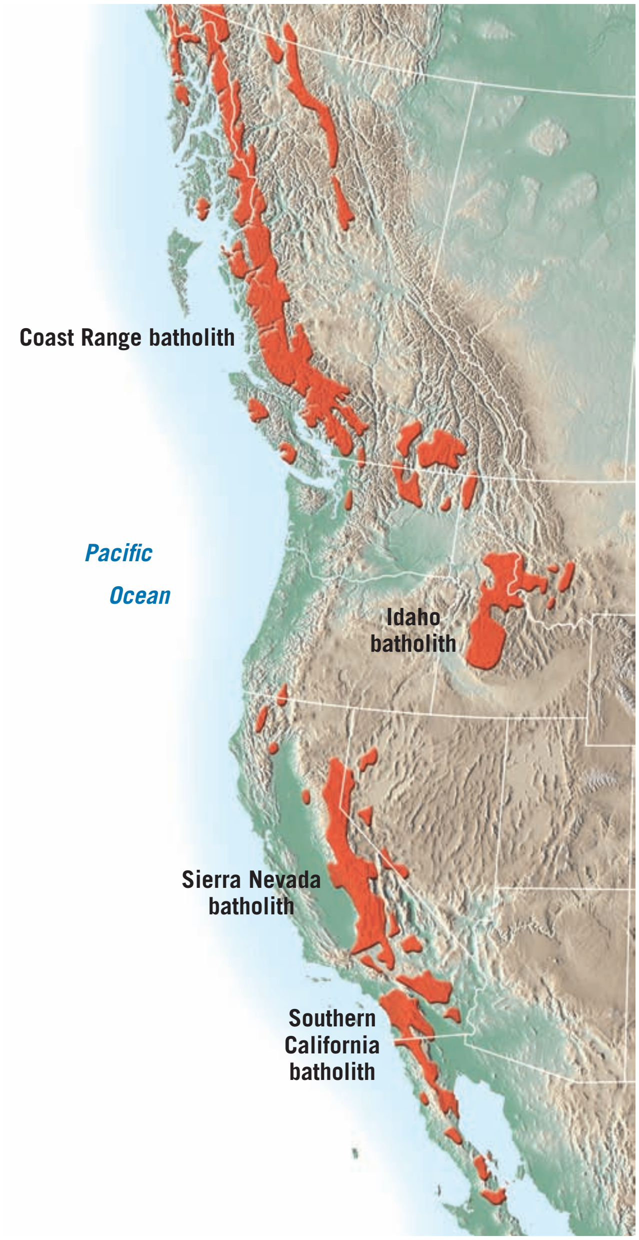
Columnar jointing occurs when igneous rocks cool and develop shrinkage fractures that produce elongated, pillar-like columns that most often have six sides (Figure 4.29). Further, because sills and dikes generally form in near-surface environments and may be only a few meters thick, the emplaced magma often cools quickly enough to generate a fine-grained texture. (Recall that most intrusive igneous bodies have a coarse-grained texture.)

Massive Intrusive Bodies: Batholiths, Stocks, & Laccoliths

Batholiths & Stocks By far the largest intrusive igneous bodies are **batholiths** (*bathos* = depth, *lithos* = stone). Batholiths occur as mammoth linear structures several hundred kilometers long and more than 100 kilometers wide (Figure 4.30). The Sierra Nevada batholith, for example, is a continuous granitic structure that forms much of the "backbone" of the Sierra Nevada in California. An even larger batholith extends for over 1800 kilometers (1100 miles) along the Coast Mountains of western Canada and into southern Alaska. Although batholiths can cover a large area, recent geophysical studies indicate that most are less than 10 kilometers (6 miles) thick. Some are even thinner; the coastal batholith of Peru, for example, is essentially a flat slab with an average thickness of only 2 to 3 kilometers (1 to 2 miles). Batholiths are typically composed of felsic (granitic) and intermediate rock types and are often called "granitic batholiths."

Early investigators thought the Sierra Nevada batholith was a huge single body of intrusive igneous rock.

▼ **Figure 4.29 Columnar jointing** Giant's Causeway in Northern Ireland is an excellent example of columnar jointing. (Photo by E. J. Tarbuck)



▲ **Figure 4.30 Granitic batholiths along the western margin of North America** These gigantic, elongated bodies consist of numerous plutons that were emplaced beginning about 150 million years ago.

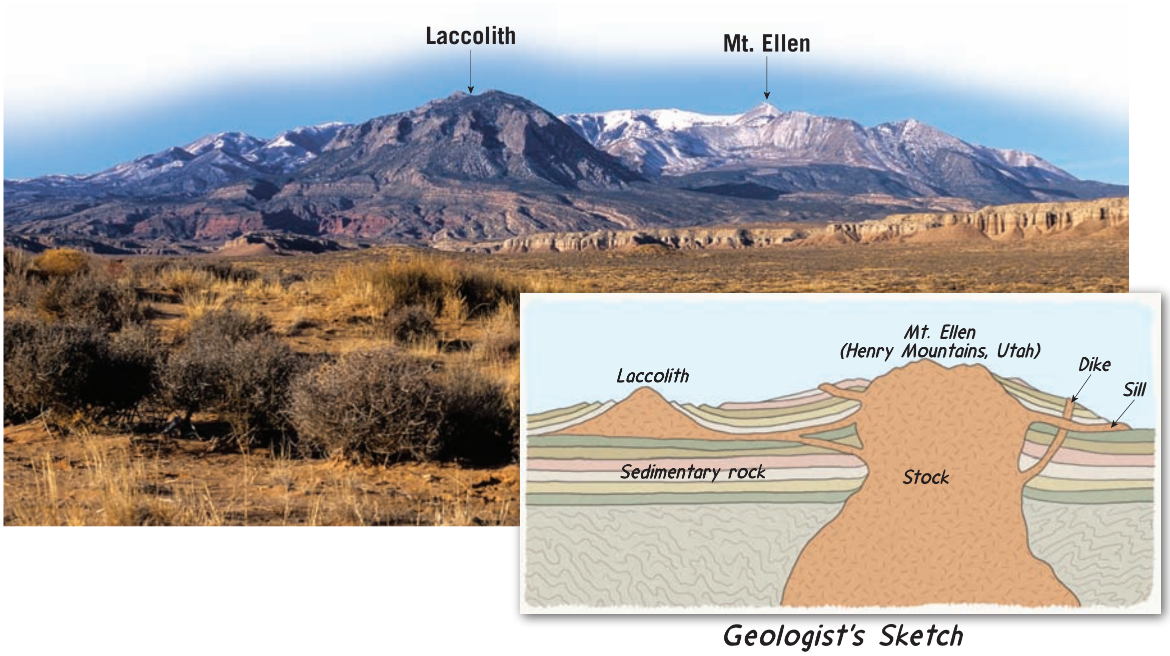


Figure 4.31
Laccoliths Mount Ellen in Utah's Henry Mountains is one of five peaks that make up this small mountain range. Although the main intrusions in the Henry Mountains are stocks, numerous laccoliths formed as offshoots of these structures. (Photo by Michael DeFreitas North America/Alamy)

Today we know that large batholiths are produced by hundreds of discrete injections of magma that form smaller intrusive bodies (plutons) that intimately crowd against or penetrate one another. These bulbous masses are emplaced over spans of millions of years. The intrusive activity that created the Sierra Nevada batholith, for example, occurred nearly continuously over a 130-million-year period that ended about 80 million years ago (see Figure 4.30).

A batholith is generally defined as a plutonic body having a surface exposure greater than 100 square kilometers (40 square miles). Smaller plutons are termed **stocks**. However, many stocks appear to be portions of much larger intrusive bodies that would be classified as batholiths if they were fully exposed.

Laccoliths A nineteenth-century study by G. K. Gilbert of the U.S. Geological Survey in the Henry Mountains of Utah produced the first clear evidence that igneous intrusions can lift the sedimentary strata they penetrate. Gilbert named the igneous intrusions he observed **laccoliths**, which he envisioned as igneous rock forcibly injected between sedimentary strata, so as to arch the beds above while leaving those below relatively flat. It is now known that the five major peaks of the Henry Mountains are not laccoliths but stocks. However, these central magma bodies are the source material for branching offshoots that are true laccoliths, as Gilbert defined them (**Figure 4.31**).

Numerous other granitic laccoliths have since been identified in Utah. The largest is a part of the Pine Valley Mountains located north of St. George, Utah. Others are found in the La Sal Mountains near Arches National Park and in the Abajo Mountains directly to the south.

CONCEPT CHECKS 4.8

1. What is meant by the term *country rock*?
2. Describe *dikes* and *sills*, using the appropriate terms from the following list: massive, discordant, tabular, and concordant.
3. Distinguish among batholiths, stocks, and laccoliths in terms of size and shape.

Did You Know?
In the eastern United States, some exposed granitic intrusions have dome-shaped, nearly treeless summits—hence the name "summit balds." Examples include Cadillac Mountain in Maine, Mount Chocorua in New Hampshire, Black Mountain in Vermont, and Stone Mountain in Georgia.

4.9 Mineral Resources & Igneous Processes

Explain how economic deposits of gold, silver, and many other metals form.

Given the growth of the middle class in countries such as China, India, and Brazil, the demand for metallic natural resources has increased exponentially in recent years. Some of the most important accumulations of metals, such as gold, silver, copper, mercury, lead, platinum, and nickel, are produced by igneous processes (**Table 4.1**). These mineral resources result from processes that concentrate desirable materials to the point where they can be profitably extracted. Therefore, knowledge of how and where these important materials are likely to be concentrated is vital to our well-being.

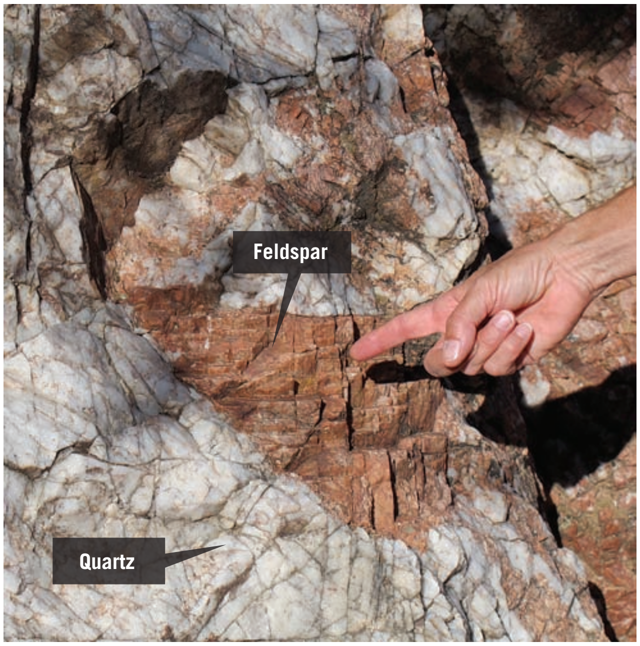
Table 4.1 Occurrences of Metallic Minerals

Metal	Principal Ores	Geologic Occurrences
Aluminum	Bauxite	Residual product of weathering
Chromium	Chromite	Magmatic differentiation
Copper	Chalcopyrite Bornite Chalcocite	Hydrothermal deposits; contact metamorphism; enrichment by weathering processes
Gold	Native gold	Hydrothermal deposits; placers
Iron	Hematite Magnetite Limonite	Banded sedimentary formations; magmatic differentiation
Lead	Galena	Hydrothermal deposits
Magnesium	Magnesite	Hydrothermal deposits
Manganese	Pyrolusite	Residual product of weathering
Mercury	Cinnabar	Hydrothermal deposits
Molybdenum	Molybdenite	Hydrothermal deposits
Nickel	Pentlandite	Magmatic differentiation
Platinum	Native platinum	Magmatic differentiation; placers
Silver	Native silver Argentite	Hydrothermal deposits; enrichment by weathering processes
Tin	Cassiterite	Hydrothermal deposits; placers
Titanium	Ilmenite	Magmatic differentiation; placers
Tungsten	Wolframite	Pegmatites; contact metamorphic deposits; placers
Uranium	Uraninite (pitchblende)	Pegmatites; sedimentary deposits
Zinc	Sphalerite	Hydrothermal deposits

Magmatic Differentiation & Ore Deposits

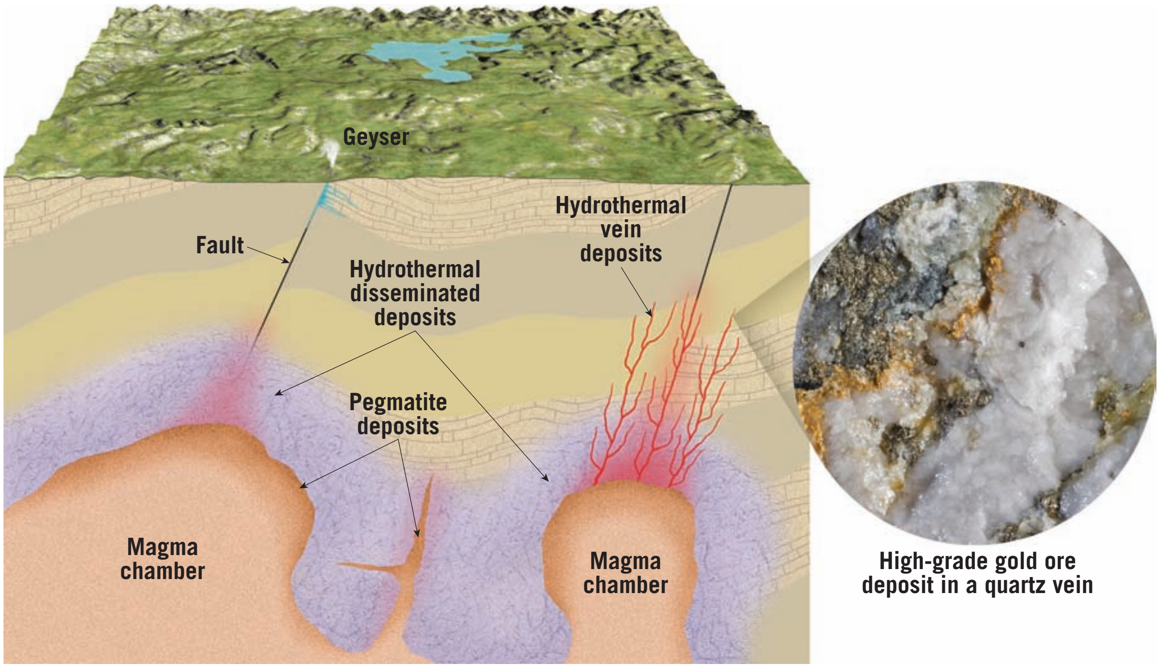
The igneous processes that generate some important metal deposits are quite straightforward. For example, as a large basaltic magma body cools, the heavy minerals that crystallize early tend to settle to the lower portion of the magma chamber. This type of magmatic differentiation serves to concentrate some metals, producing major deposits of chromite (ore of chromium), magnetite, and platinum. Layers of chromite, interbedded with other heavy minerals, are mined at Montana's Stillwater Complex, whereas the Bushveld Complex in South Africa contains over 70 percent of the world's known reserves of platinum.

Pegmatite Deposits Magmatic differentiation during the late stages of the magmatic process is important in producing ores. This is particularly true of granitic magmas, in which the residual melt can become enriched in rare elements, including some heavy metals. Further, because water and other volatile substances do not crystallize along with the bulk of the magma body, these fluids make up a high percentage of the melt during the final phase of cooling and solidification. Crystallization in a fluid-rich environment, where ion migration is enhanced, results in the formation of crystals several centimeters, or even a few meters, in length. The resulting rocks, called **pegmatites**, are composed of these unusually large crystals (Figure 4.32).



▲ **Figure 4.32 Pegmatite** This granite pegmatite, found in the inner gorge of the Grand Canyon, is composed mainly of quartz and feldspar. (Photo by Joanne Bannon/E. J. Tarbuck)

Feldspar masses the size of houses have been quarried from a pegmatite located in North Carolina. Gigantic hexagonal crystals of muscovite measuring a few



◀ **SmartFigure 4.33 Pegmatites and hydrothermal deposits** Illustration of the relationship between an igneous body and associated pegmatites and hydrothermal mineral deposits. (Photo by Greenshoots Communications/Alamy)

TUTORIAL
http://goo.gl/Olczs

meters across have been found in Ontario, Canada. In the Black Hills, spodumene crystals as thick as telephone poles have been mined. The largest of these was more than 12 meters (40 feet) long. Not all pegmatites contain such large crystals, but these examples emphasize the special conditions that must exist during their formation.

Most pegmatites are granitic in composition and consist of unusually large crystals of quartz, feldspar, and muscovite. Feldspar is used in the production of ceramics, and muscovite is used for electrical insulation and glitter. Further, pegmatites often contain some of the least abundant elements. Minerals containing the elements lithium, cesium, uranium, and the rare earths are occasionally found. Moreover, some pegmatites contain semiprecious gems such as beryl, topaz, and tourmaline. Most pegmatites are located within large igneous masses, or as dikes or veins that cut into the host rock that surrounds the magma chamber (**Figure 4.33**).

Not all late-stage magmas produce pegmatites, nor do all have a granitic composition. Some magmas instead become enriched in iron or occasionally copper. For example, at Kiruna Sweden, magma composed of over 60 percent magnetite solidified to produce one of the largest iron deposits in the world.

Hydrothermal Deposits

Among the best-known and most important ore deposits are those generated from hot, ion-rich fluids called hydrothermal (hot-water) solutions.[*] Included in this group are the gold deposits of the Homestake mine in South Dakota; the lead, zinc, and silver ores near Coeur d'Alene, Idaho; the silver deposits of the Comstock Lode in Nevada; and the copper ores of Michigan's Keweenaw Peninsula.

Hydrothermal Vein Deposits The majority of hydrothermal deposits originate from hot, metal-rich fluids that are remnants of late-stage magmatic processes. During the cooling process, liquids plus various metallic ions accumulate near the top of the magma chamber. Because of their mobility, these ion-rich solutions can migrate great distances through the surrounding rock before they are eventually deposited, usually as sulfides of various metals (see Figure 4.33). Some of these fluids move along openings such as fractures or bedding planes, where they cool and precipitate metallic ions to produce **vein deposits**. Many of the most productive deposits of gold, silver, copper, and mercury occur as hydrothermal vein deposits (**Figure 4.34**).

◀ **Figure 4.34 Native copper** This nearly pure metal from northern Michigan's Keweenaw Peninsula is an excellent example of a hydrothermal deposit. This area was once an important source of copper that is now largely depleted. (Photo by E. J. Tarbuck)

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[*] Because these hot, ion-rich fluids tend to chemically alter the host rock, this process is called hydrothermal metamorphism, and it is discussed in Chapter 8.

Did You Know? Although the United States is the largest consumer of industrial diamonds, it has no commercial source of this mineral. It does, however, manufacture large quantities of synthetic diamonds for industrial use.

Disseminated Deposits Another important type of accumulation generated by hydrothermal activity is called a **disseminated deposit**. Rather than being concentrated in narrow veins and dikes, these ores are distributed as minute masses throughout the entire rock mass. Much of the world's copper is extracted from disseminated deposits, including those at Chuquicamata, Chile, and the huge Bingham Canyon copper mine in Utah (see Figure 3.36, page 90). Because these accumulations contain only 0.4 to 0.8 percent copper, between 125 and 250 kilograms of ore must be mined for every 1 kilogram of metal recovered. The environmental impact of these large excavations is significant and includes problems related to waste disposal.

Origin of Diamonds

An economically important mineral with an igneous origin is diamond. Although best known as gems, diamonds are used extensively as abrasives. Diamonds are thought to originate at depths of nearly 200 kilometers (120 miles), where the confining pressure is great enough to generate this high-pressure form of carbon. Once crystallized, the diamonds are carried upward through pipe-shaped conduits that increase in diameter toward the surface. In diamond-bearing pipes, nearly the entire pipe contains diamond crystals that are disseminated throughout an ultramafic rock called *kimberlite*. The most productive kimberlite pipes are those in South Africa. The only equivalent source of diamonds in the United States is located near Murfreesboro, Arkansas, but several attempt at commercial diamond mining at this location failed. In 1972 the state of Arkansaa purchaced the property and developed it into Crater of Diamonds State Park. Park visitors are encourage to hunt for diamonds and can keep what they find.

CONCEPT CHECKS 4.9

1. Name and compare two types of hydrothermal deposits.
2. In what type of environment are pegmatites produced?

CONCEPTS IN REVIEW

Igneous Rocks & Intrusive Activity

4.1 Magma: Parent Material of Igneous Rock

List and describe the three major components of magma.

KEY TERMS: igneous rock magma, lava, melt, volatile, crystallization, intrusive igneous rock (plutonic rock), extrusive igneous rock (volcanic rock)

- Completely or partly molten rock is called magma if it is below Earth's surface and lava if it has erupted onto the surface. It consists of a liquid melt that may also contain solid mineral crystals and gases (volatiles), such as water vapor or carbon dioxide.
- As magma cools, silicate minerals begin to form from the "cocktail" of mobile ions in the melt. These tiny crystals grow through the addition of ions to their outer surface. As cooling proceeds, crystallization gradually transforms the magma into a solid mass of interlocking crystals—an igneous rock.
- Magmas that cool below the surface produce intrusive igneous rocks, whereas those that erupt onto Earth's surface produce extrusive igneous rocks.

4.2 Igneous Compositions

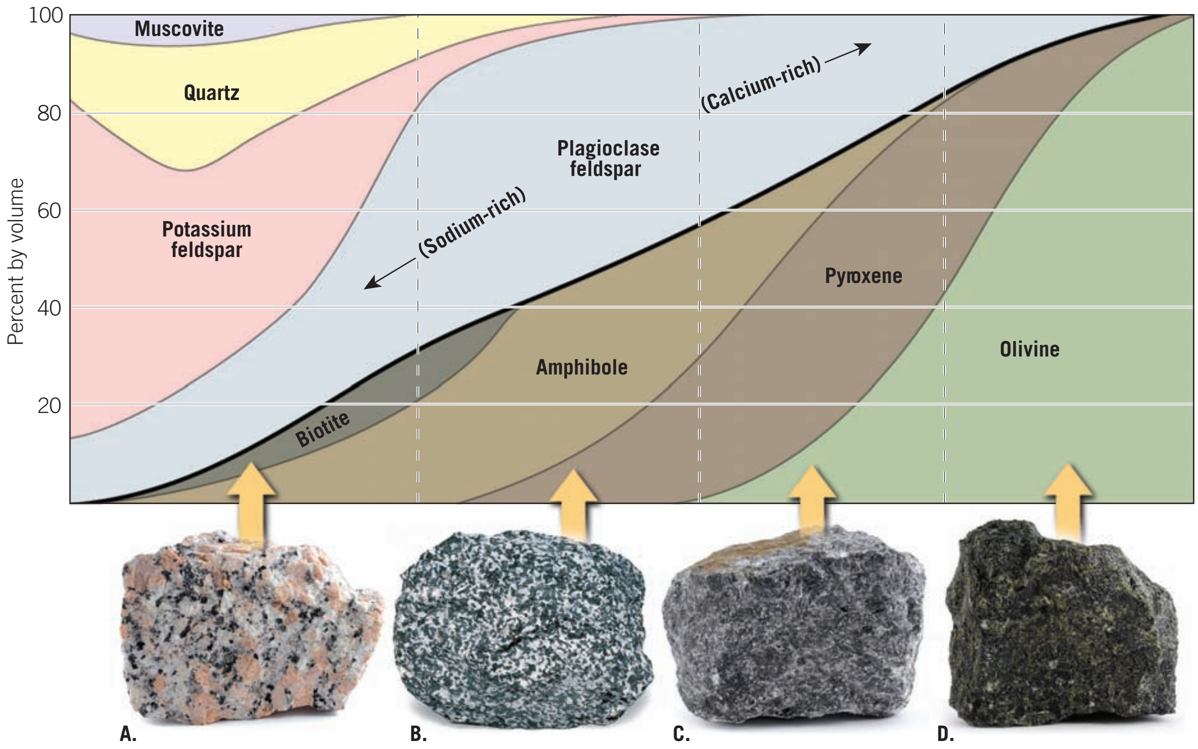
Compare and contrast the four basic igneous compositions: felsic, intermediate, mafic, and ultramafic.

KEY TERMS: felsic (granitic) composition, mafic (basaltic) composition, intermediate (andesitic) composition, peridotite, ultramafic

- Igneous rocks are composed mostly of silicate minerals. Igneous rocks that are composed mostly of light-colored silicate minerals are described as having a felsic composition. Rocks composed of greater than 45 percent ferromagnesian minerals are classified as mafic. Mafic rocks are generally darker in color and more dense than their felsic counterparts. Broadly, continental crust is felsic in composition, and oceanic crust is mafic.
- Intermediate rocks in which plagioclase feldspar predominates have a composition that is intermediate between felsic and mafic. They are typical of continental volcanic arcs. Ultramafic rocks, which are rich in the minerals olivine and pyroxene, dominate the upper mantle.
- The amount of silica (SiO_2) in an igneous rock is an indication of its overall composition. Rocks that are rich in silica (70 percent or more) are felsic, while rocks that are poor in silica (as low as 40 percent) are mafic or ultramafic. The amount of silica present in a magma determines the magma's viscosity and crystallization temperature.

? Describe igneous rocks having the compositions of samples A and D using terms such as mafic, felsic, etc. Would you ever expect to find quartz and olivine in the same rock? Why or why not?

(4.2 continued)



4.3 Igneous Textures: What Can They Tell Us?

Identify and describe the six major igneous textures.

KEY TERMS: texture, aphanitic (fine-grained texture), phaneritic (coarse-grained texture), porphyritic texture, phenocryst, groundmass, porphyry, vesicular texture, glassy texture, pyroclastic (fragmental) texture

- To geologists, "texture" is a description of the size, shape, and arrangement of mineral grains in a rock. Careful observation of the texture of igneous rocks can tell us about the conditions under which they formed. The rate at which magma or lava cools is an important factor in the rock's final texture.
- Lava cools quickly at or close to the surface, so crystallization is rapid and results in a large number of very small crystals. The result is a fine-grained texture. Magma cooling at depth loses heat more slowly. This allows sufficient time for the magma's ions to be organized into larger crystals, resulting in a rock with a coarse-grained texture. If crystals begin to form at depth and then the magma moves to a shallow depth or erupts at the surface, it will have a two-stage cooling history. The result is a rock with a porphyritic texture.
- Volcanic rocks may exhibit additional textures: vesicular if the lava had a high gas content, glassy if it was high in silica, or pyroclastic if the lava erupted explosively.

4.4 Naming Igneous Rocks

Distinguish among the common igneous rocks based on texture and mineral composition.

KEY TERMS: granite, rhyolite, obsidian, pumice, andesite, diorite, basalt, gabbro, pyroclastic rock

- Igneous rocks are classified on the basis of their textures and compositions. Figure 4.12 summarizes the naming system based on these two criteria. Two magmas with the same composition can cool at different rates, resulting in different final textures. On the other hand, two magmas that have different compositions may attain similar textures if they cool under similar circumstances.

? Is it possible for granite to be transformed into rhyolite? If so, what processes would have to be involved?

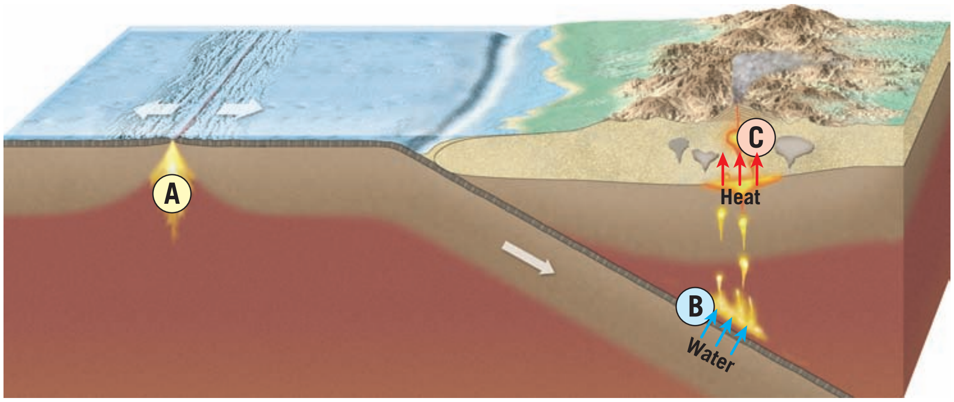
4.5 Origin of Magma

Summarize the major processes that generate magma from solid rock.

KEY TERMS: geothermal gradient, decompression melting

- Solid rock may melt under three geologic circumstances: when heat is added to the rock, raising its temperature; when already hot rock experiences lower pressures (decompression, as seen at mid-ocean ridges); and when water is added (as occurs at subduction zones).

? Different processes produce magma in various tectonic settings. Consider situations A, B, and C in the diagram and describe the processes that would be most likely to trigger melting in each.



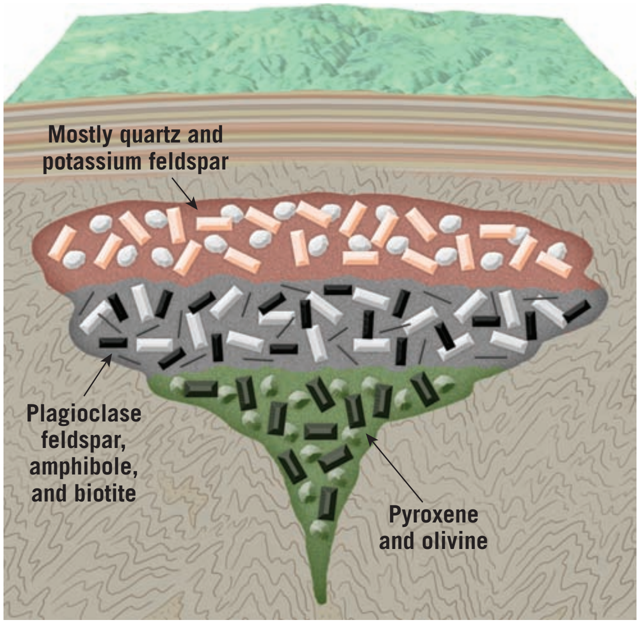
4.6 How Magmas Evolve

Describe how magmatic differentiation can generate a magma body that has a mineralogy (chemical composition) that is different from its parent magma.

KEY TERMS: Bowen's reaction series, crystal settling, magmatic differentiation, assimilation, magma mixing

- Pioneering experimentation by N. L. Bowen revealed that in a cooling magma, minerals crystallize in a specific order. Ferromagnesian silicates such as olivine crystallize first, at the highest temperatures (1250°C), and nonferromagnesian silicates such as quartz crystallize last, at the lowest temperatures (650°C). Bowen found that in between these temperatures, chemical reactions take place between the crystallized silicates and the melt, resulting in compositional changes to each and the formation of new minerals.
- Various physical processes can cause changes in the composition of magma. For instance, if crystallized silicates are denser than the remaining magma, they will sink to the bottom of the magma chamber. Because these early-formed minerals are likely to be ferromagnesian, the magma has now differentiated toward a more felsic composition.
- As they migrate, magmas may assimilate fragments of their "host" rocks or mix with other magma bodies. These processes will alter the magma's composition.

? Consider the accompanying diagram, which shows a cross-sectional view of a hypothetical magma chamber. Using your understanding of Bowen's reaction series and magma evolution, interpret the layered structure by explaining how crystallization occurred.



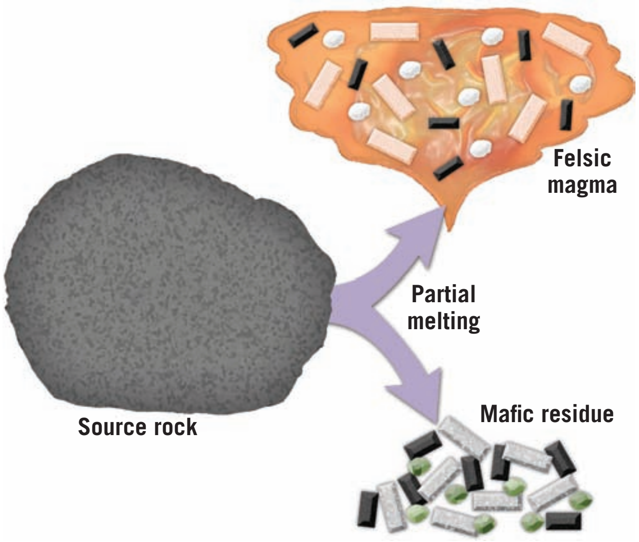
4.7 Partial Melting & Magma Composition

Describe how partial melting of the mantle rock peridotite can generate a basaltic (mafic) magma.

KEY TERMS: partial melting

- In most circumstances, when rocks melt, they do not melt completely. Different minerals have different temperatures at which they change state from solid to liquid (or liquid to solid). As rocks melt, minerals with the lowest melting temperatures melt first.
- Partial melting of the ultramafic mantle yields mafic oceanic crust. Partial melting of the lower continental crust at subduction zones produces magmas that have intermediate or felsic compositions.

? How is partial melting important for generating the different kinds of igneous rocks found on Earth?



4.8 Intrusive Igneous Activity

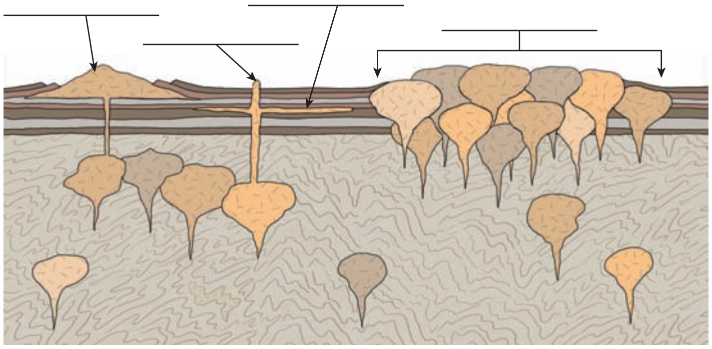
Compare and contrast these intrusive igneous structures: dikes, sills, batholiths, stocks, and laccoliths.

KEY TERMS: host (country) rock, intrusion (pluton), tabular, massive, discordant, concordant, dike, sill, columnar jointing, batholith, stock, laccolith

- When magma intrudes other rocks, it may cool and crystallize before reaching the surface to produce intrusions called plutons. Plutons come in many shapes. They may cut across the host rocks without regard for preexisting structures, or the magma may flow along weak zones in the host rock, such as between the horizontal layers of sedimentary bedding.
- Tabular intrusions may be concordant (sills) or discordant (dikes). Massive plutons may be small (stocks) or very large (batholiths). A blister-like intrusion that lifts the overlying rock layers is a laccolith. As solid igneous rock cools, its volume decreases. Contraction can produce a distinctive fracture pattern called columnar jointing.

? Label the intrusive igneous structures in the accompanying diagram, using the following terms: volcanic neck, sill, batholith, laccolith.

(4.8 continued)



4.9 Mineral Resources & Igneous Processes

Explain how economic deposits of gold, silver, and many other metals form.

KEY TERMS: pegmatite, vein deposit, disseminated deposit

- Some of the most important accumulations of metallic resources, such as gold, silver, lead, and copper, are produced by igneous processes. Magmatic differentiation can concentrate some metals, producing major deposits. Crystallization in a fluid-rich environment, where ion migration is enhanced, results in the formation of unusually large crystals. The resulting rocks, which may become enriched in rare elements and metals, such as gold and silver, are called pegmatites.
- The best-known ore deposits are generated from hydrothermal (hot-water) solutions. Many hydrothermal deposits originate from hot, metal-rich fluids that are remnants of late-stage magmatic processes. Hydrothermal solutions move along fractures or bedding planes, cool, and precipitate the metallic ions to produce vein deposits. In a disseminated deposit (e.g., much of the world's copper deposits), the ores from hydrothermal solutions are distributed as minute masses throughout the entire rock mass.

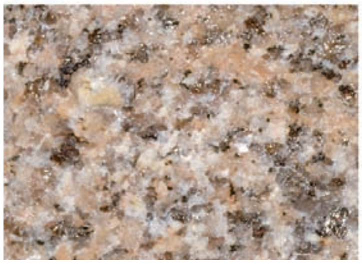
GIVE IT SOME THOUGHT

1 Would you expect all the crystals in an intrusive igneous rock to be the same size? Explain why or why not.

2 Apply your understanding of igneous rock textures to describe the cooling history of each of the igneous rocks pictured here (Photos by E. J. Tarbuck).

A.

B.



C.

D.

3 Use Figure 4.5 to classify the following igneous rocks:
- **a.** An aphanitic rock containing about 30 percent calcium-rich plagioclase feldspar, 55 percent pyroxene, and 15 percent olivine
- **b.** A phaneritic rock containing about 20 percent quartz, 40 percent potassium feldspar, 20 percent sodium-rich plagioclase feldspar, a few percent muscovite, and the remainder dark-colored silicate
- **c.** An aphanitic rock containing about 50 percent plagioclase feldspar, 35 percent amphibole, 10 percent pyroxene, and minor amounts of other light-colored silicates
- **d.** A phaneritic rock made mainly of olivine and pyroxene, with lesser amounts of calcium-rich plagioclase feldspar

4 Identify the igneous rock textures described by each of the following statements.
- **a.** Openings produced by escaping gases
- **b.** The texture of obsidian
- **c.** A matrix of fine crystals surrounding phenocrysts
- **d.** Consists of crystals that are too small to be seen without a microscope
- **e.** A texture characterized by rock fragments welded together
- **f.** Coarse grained, with crystals of roughly equal size

5 During a hike, you pick up the igneous rock shown in the accompanying photo.
- **a.** What is the mineral name of the small, rounded, glassy green crystals?
- **b.** Did the magma from which this rock formed likely originate in the mantle or in the crust? Explain.
- **c.** Was the magma likely a high-temperature magma or a low-temperature magma? Explain.
- **d.** Describe the texture of this rock.

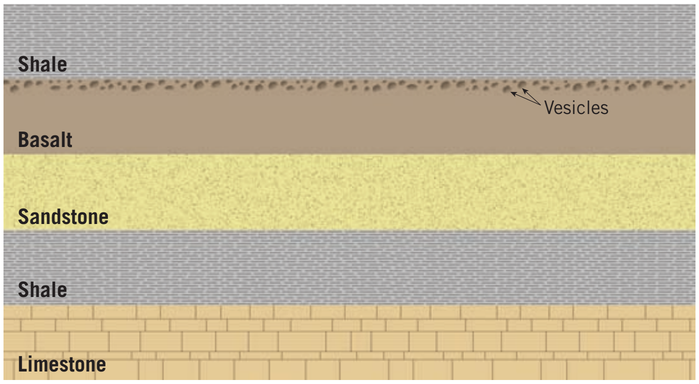
Dennis Tasa

6 A common misconception about Earth's upper mantle is that it is a thick shell of molten rock. Explain why Earth's mantle is actually solid under most conditions.

7 Describe two mechanisms by which mantle rock can melt without an increase in temperature. How do these magma-generating mechanisms relate to plate tectonics?

8 Use your understanding of Bowen's reaction series (see Figure 4.20) to explain how partial melting can generate magmas that have different compositions.

9 During a field trip with your geology class, you visit an exposure of rock layers similar to the one sketched here. A fellow student suggests that the layer of basalt is a sill, but you disagree. Why do you think the other student is incorrect? What is a more likely explanation for the basalt layer?



10 Each of the following statements describes how an intrusive feature appears when exposed at Earth's surface due to erosion. Name each feature.

a. A dome-shaped mountainous structure flanked by upturned layers of sedimentary rocks

b. A vertical wall-like feature a few meters wide and hundreds of meters long

c. A huge expanse of granitic rock forming a mountainous terrain tens of kilometers wide

d. A relatively thin layer of basalt sandwiched between horizontal layers of sedimentary rocks exposed along the walls of a river valley

11 Mount Whitney, the highest summit (4421 meters [14,505 feet]) in the contiguous United States, is located in the Sierra Nevada batholith. Based on its location, is Mount Whitney likely composed mainly of granitic, andesitic, or basaltic rocks?

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