4 Igneous Rocks

Igneous rocks are records of the thermal history of Earth. Their origin is closely associated with the movement of tectonic plates, and they play an important role in the spreading of seafloor, the origin of mountains, and the evolution of continents. The best-known examples of igneous activity are volcanic eruptions, in which liquid rock material works its way to the surface and erupts from volcanic fissures and vents such as those shown above. Less obvious, although just as important, are the enormous volumes of liquid rock that never reach the surface but remain trapped in the crust, where they cool and solidify. Granite is the most common variety of this type of igneous rock and is typically exposed in eroded mountain belts and in the roots of ancient mountain systems now preserved in the shields.

In January 1983, Kilauea volcano began an eruption of basaltic lava that is still ongoing. The eruption has buried thousands of acres of land, destroyed homes, roads and forests. It has also added to the size of the island as lava spilled into the sea. This volcano on the south shore of the island of Hawaii is Earth's most active volcano. Volcanoes like Kilauea are dramatic proof that Earth's interior is still warm and active. In this spectacular image, you can

see igneous processes shaping the landscape as red-hot molten rock is spilled out onto the surface. This magma formed deep in the mantle when solid rock melted at depths of more than 30 km; the temperature must have exceeded 1200°C. The molten magma then rose toward the surface through a series of fractures and pipes because its density was lower than that of the surrounding solid mantle. The continuous expansion of small gas bubbles in the magma caused it to rise even higher in the throat of the volcano. Small explosions in the magma were caused by the bursting of giant bubbles of gas. The still-molten droplets accumulated as spatter around the vent to make a small cone. A weak spot in the base of the cone allowed a stream of lava to break through and feed a long lava flow that will slowly cool and crystallize to form solid rock.

In this chapter, we study the major types of igneous rocks and what they reveal about the thermal activity of Earth. We pay particular attention to the compositions and distinctive textures of igneous rocks and how we can read from the interlocking network of grains the history of how the hot liquid became part of the solid crust.

Photograph by G. Brad Lewis Photography

MAJOR CONCEPTS

1. Magma is molten rock that originates from the partial melting of the lower crust and the upper mantle, usually at depths between 10 and 200 km below the surface.
2. The texture of a rock provides important insight into the cooling history of the magma. The major textures of igneous rocks are (a) glassy, (b) aphanitic, (c) phaneritic, (d) porphyritic, and (e) pyroclastic.
3. Most magmas are part of a continuum that ranges from mafic magma to silicic magma.
4. Silicic magmas produce rocks of the granite-rhyolite family, which are composed of quartz, K-feldspar, Na-plagioclase, and minor amounts of biotite or amphibole.
5. Basaltic magmas produce rocks of the gabbro-basalt family, which are composed of Ca-plagioclase and pyroxene with lesser amounts of olivine and little or no quartz.
6. Magmas with composition intermediate between mafic and silicic compositions produce rocks of the diorite-andesite family.
7. Basalt, the most abundant type of extrusive rock, typically either erupts from fissures to produce relatively thin lava flows that cover broad areas or erupts from central vents to produce shield volcanoes and cinder cones. Volcanic features developed by intermediate to silicic magmas include viscous lava flows, ash-flow tuff, composite volcanoes, and collapse calderas. The abundance of water in silicic magma is critical to its development and eruption.
8. Masses of igneous rock formed by the cooling of magma beneath the surface are called intrusions or plutons. The most important types of intrusions are batholiths, stocks, dikes, sills, and laccoliths.
9. The wide variety of magma compositions is caused by variations in (a) the composition of the source rocks, (b) partial melting, (c) fractional crystallization, (d) mixing, and (e) assimilation of solid rock into the molten magma.
10. Most basaltic magma is generated by partial melting of the mantle at divergent plate boundaries and in rising mantle plumes. Most intermediate to silicic magma is produced at convergent plate boundaries. Partial melting of continental crust at rifts and above plumes can also produce silicic magma.

THE NATURE OF IGNEOUS ROCKS

Igneous rocks form from magma—molten rock material consisting of liquid, gas, and crystals. A wide variety of magma types exists, but important end members are (1) basaltic magma, which is typically very hot (from 900° to 1200°C) and highly fluid, and (2) silicic magma, which is cooler (less than 850°C) and highly viscous.

The term *magma* comes from the Greek word that means "kneaded mixture," like a dough or paste. In its geologic application, it refers to hot, partially molten rock material (Figure 4.1). Most **magmas** are not entirely liquid but are a combination of liquid, solid, and gas. Crystals may make up a large portion of the mass, so a magma could be thought of more accurately as a slush, a liquid melt mixed with a mass of mineral crystals. Such a mixture has a consistency similar to that of freshly mixed concrete, slushy snow, or thick oatmeal. The movement of most magmas is slow and sluggish.

Like most fluids, magma is less dense than the solid from which it forms, and because of buoyancy, it tends to migrate upward through the mantle and crust. Magma can intrude into the overlying rock by injection into fractures, it can dome the overlying rock, or it can melt and assimilate the rock it invades. Magma eventually cools

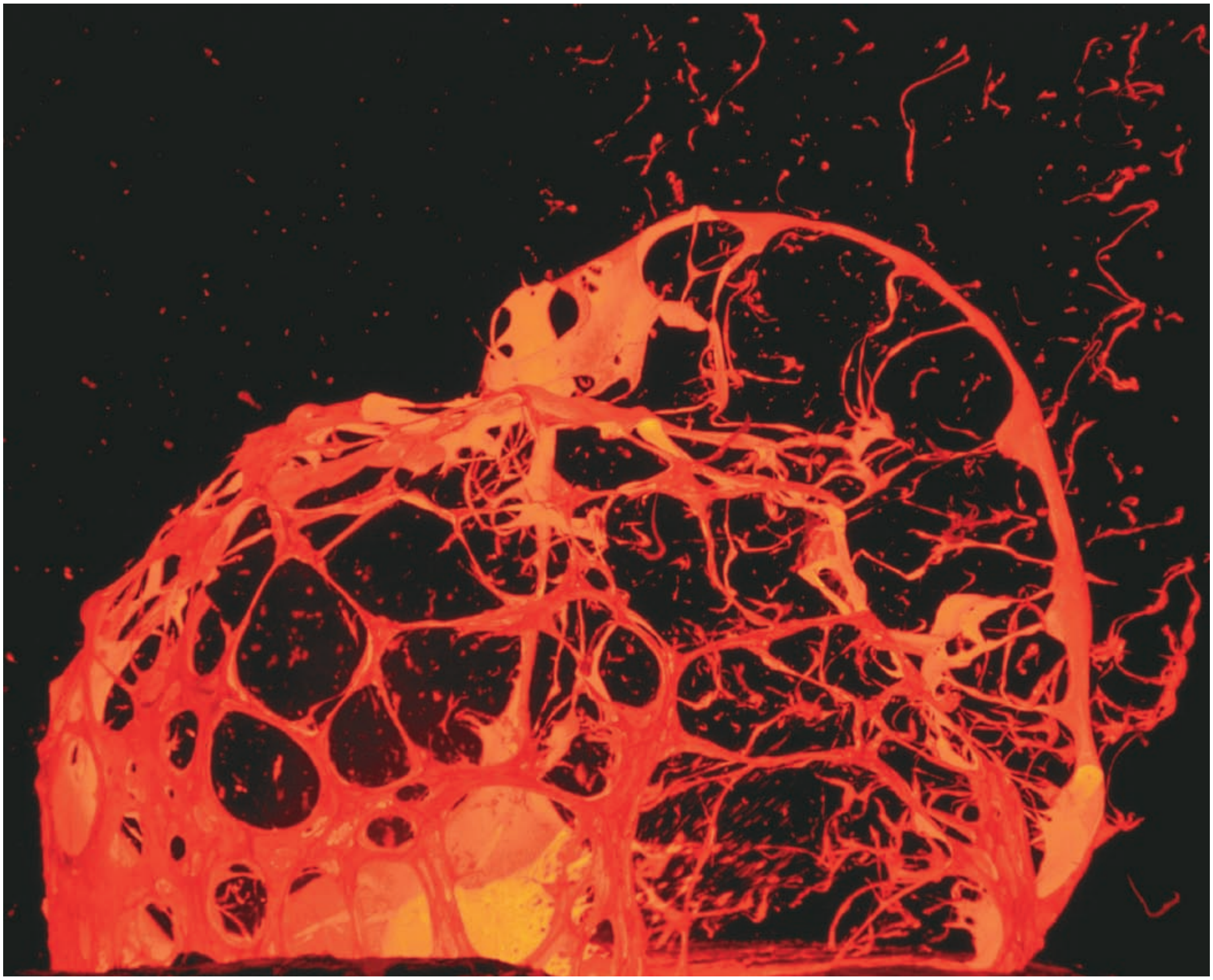


FIGURE 4.1 **Magma** is molten rock material that commonly contains gas and solids. Much of it cools deep in Earth's crust, but some of it works its way to the surface and is extruded as lava. Eruptions such as this permit us to study the nature of magma, its composition, and its physical characteristics and give us an insight into the origin of igneous rocks. *(Photograph by G. Brad Lewis Photography)*

and crystallizes to form **igneous rocks.** The rise of the magma may be halted where it comes to density equilibrium with the surrounding rocks or where the roof rocks are too strong to allow the magma to penetrate farther. Magma that solidifies below the surface forms **intrusive rock.** When magma reaches the surface without completely cooling and flows out over the landscape as **lava,** it forms **extrusive rock.**

What are the physical and chemical characteristics of molten rock?

Chemical analyses of igneous rocks have revealed a wide variety of magma types, but most terrestrial magmas consist largely of molten silicates. The principal elements in such magmas are oxygen (O), silicon (Si), aluminum (Al), calcium (Ca), sodium (Na), potassium (K), iron (Fe), and magnesium (Mg). Two constituents—silica (SiO_2) and water (H_2O)—largely control the physical properties of magma, such as its density, **viscosity** (the tendency for a material to resist flow), and the manner in which it is extruded.

Although there is great variety in magma composition, we can illustrate much about silicate magma by examining only two extreme types. *Mafic magmas* contain about 50% SiO_2 and have temperatures ranging from about 100° to 1200°C. Mafic minerals, such as olivine and pyroxene, crystallize from such magmas. *Silicic magmas* contain between 65% and 77% SiO_2 and generally have temperatures lower than 850°C. Felsic minerals, such as feldspars and quartz, are the dominant minerals that crystallize from these magmas. Basaltic magmas are characteristically fluid, whereas silicic magmas are viscous. This is because silicic magmas have lower temperatures and greater amounts of SiO_2. The viscosity of a magma is influenced by its SiO_2 content because silica tetrahedra bond or link together even before crystallization occurs, and the linkages offer resistance to flow. Temperature affects viscosity because as the temperature of a magma drops, more and more linkages—prototypes of the minerals that crystallize—are made. Therefore, the higher the silica content or the lower the temperature, the greater the magma's viscosity.

Water vapor and carbon dioxide are the principal gases dissolved in a magma. More than 90% of the gas emitted from hot magma is water (H_2O) and carbon dioxide (CO_2). Together, these **volatiles** (materials that are readily vaporized to form gases at Earth surface conditions) usually constitute from 0.1% to 5% by weight but may reach concentrations as high as 15% in some silicate magmas. These volatiles are important because they strongly influence the viscosity and melting point of a magma and the types of volcanic activity that can be produced. Dissolved water tends to decrease the viscosity of magma by breaking the Si-O bonds, which may otherwise form long, complex chains. Magmas rich in volatiles also tend to erupt more violently than volatile-poor magmas because of the explosive expansion of gas bubbles.

Where are most igneous rocks formed?

Igneous rocks are found in many parts of the globe, but they are actually formed in a few relatively restricted settings. On the continents, for example, most igneous rocks form at convergent plate margins where intrusions of magma feed overlying volcanoes. In North America (Figure 4.2), you can see ancient and recent examples. The intrusive rocks of western North America largely formed above an ancient subduction zone that no longer exists. Even older intrusive igneous rocks are exposed in the Canadian shield; they probably intruded the roots of mountain belts formed at ancient convergent plate margins. On the other hand, the young volcanic belt in the northwestern United States that extends into Alaska and the volcanic rocks of southern Mexico and Central America all erupted above still-active subduction zones. Igneous

FIGURE 4.2 Igneous rocks in North America are concentrated along recent and former convergent plate margins like those of the western (active) and eastern (inactive) mountain belts. Older, mostly intrusive, igneous rocks are found in the shields, especially that of eastern Canada. However, these igneous rocks probably formed at what were convergent plate boundaries. Igneous rocks are rare in the stable platform, but they can form above mantle plumes, like that thought to lie beneath Yellowstone Park.

rocks are not common in the stable platform, but they may form in association with a mantle plume. For example, many geologists think that the lava flows in the Columbia River Plateau and Snake River Plain may have formed above a mantle plume that lies beneath the continent. A few other volcanic rocks formed at rifts, such as the one that is forming the Gulf of California. In addition, the oceanic crust is almost entirely igneous rock formed at an oceanic rift.

TEXTURES OF IGNEOUS ROCKS

The texture of a rock refers to the size, shape, and arrangement of its constituent mineral grains. The major textures in igneous rocks are glassy, aphanitic, phaneritic, porphyritic, and pyroclastic.

The texture of a rock can be compared to the texture of a piece of cloth. In this analogy, the mineral grains in a rock are likened to the yarn or threads that compose the cloth. The cloth's texture is determined by the weave (it may be open or tight; it may be knitted, woven, or felted), by the coarseness of the yarn, or by the mix of various yarns (coarse, fine, or a mixture of thicknesses). Careful examination of a piece of cloth will reveal how the cloth was constructed and the way in which it was formed. The color and the composition of the thread (whether it is silk, wool, or cotton), however, are separate properties of the cloth. Similarly, the **texture** of a rock is the size, shape, and arrangement of its constituent minerals. It is a characteristic separate and distinct from composition. Texture is important because the mineral grains bear a record of the energy changes involved in the rock-forming process and the conditions existing when the rock originated.

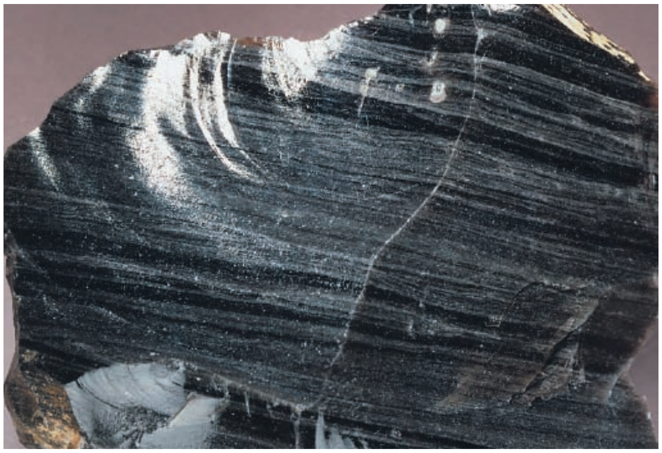
The genetic imprint left on the texture of a rock is commonly clear and easy to read. For example, rocks formed from a cooling liquid have a texture characterized by interlocking grains (see Figure 3.14).

What does the texture of a rock indicate about the cooling history of a magma?

To illustrate the importance of texture, we will consider six examples of igneous rocks that have essentially the same chemical and mineralogic composition but different textures (Figure 4.3). In each rock, a chemical analysis would disclose about 48% O, 30% Si, 7% Al, and between 1% and 4% each of Na, K, Ca, and Fe. On the basis of chemical composition alone, these rocks would be considered the same; they differ in texture *only.* It is their texture that provides the most information about how each specimen was formed.

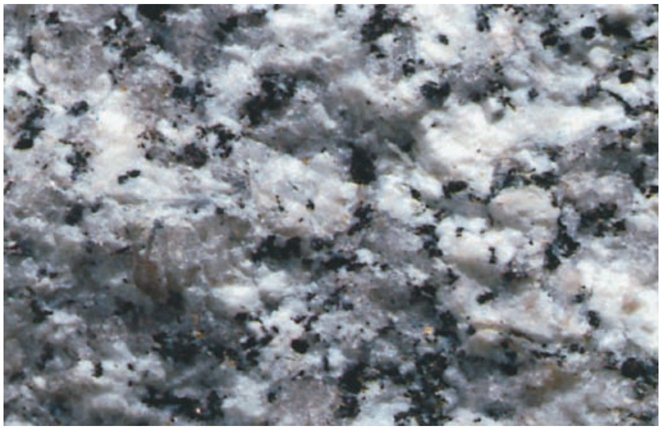
Glassy Texture. The nature of volcanic glass is illustrated in Figure 4.3A. The hand specimen displays a conchoidal fracture, with the sharp edges typical of broken glass. No distinct grains are visible, but viewed under a microscope, distinct flow layers are apparent. These result from the uneven concentration of innumerable, minute, "embryonic" crystals.

In the laboratory, melted rock or synthetic lava hardens to glass if it is quenched (or quickly cooled) from a temperature above that at which crystals would normally form. We can conclude that a **glassy texture** is produced by very rapid cooling. The randomness of the ions in a high-temperature melt is "frozen in" because the ions do not have time to migrate and organize themselves in an orderly, crystalline structure. Field observations of glassy rocks in volcanic regions support the hypothesis that rapid cooling produces glass. Small pieces of magma blown from a volcanic vent into the much cooler atmosphere harden to form glassy ash. A glassy crust forms on the surface of many lava flows, and glassy fragments form if a flow enters a body of water.

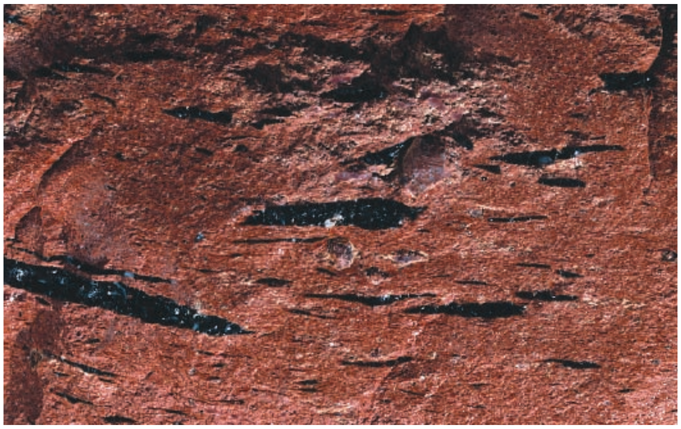


(A) A glassy texture develops when molten rock cools so rapidly that the migration of ions to form crystal grains is hampered. Glassy texture typically forms on the crust of lava flows and in viscous magma. The sample shown here is obsidian.

(B) An aphanitic texture consists of mineral grains too small to be seen without a microscope. The sample shown here is rhyolite. Only a few grains are large enough to be seen. Most are microscopic. Aphanitic texture results from rapid cooling.



(C) A phaneritic texture consists of grains large enough to be seen with the unaided eye. All grains are roughly the same size, and they interlock to form a tight mass. The large crystals suggest a relatively slow rate of cooling.



(D) A pyroclastic texture forms when crystals, fragments of rock, and glass are blown out of a volcano as hot ash. The material may accumulate as an ash fall or as an ash flow. The black lenses of glass were pumice fragments that were squashed during welding of the hot ash.

FIGURE 4.3 Textures of igneous rocks provide important information concerning rock genesis. All of the silicic rocks presented here have roughly the same chemical composition but extremely different textures. The photographs show the actual size of the specimens.

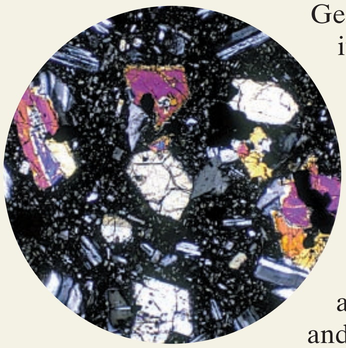
Aphanitic Texture. If crystal growth from a melt requires time for the ions to collect and organize themselves, then a crystalline rock indicates a slower rate of cooling than that of a glassy rock. The texture illustrated in Figure 4.3B is crystalline but extremely fine-grained—a texture referred to as **aphanitic** (Greek *a,* "not"; *phaneros,* "visible"). In hand specimens, few, if any, crystals can be detected in aphanitic textures. Viewed under a microscope, however, many crystals of feldspar and quartz are recognizable.

Why do volcanic rocks have aphanitic textures?

An aphanitic texture indicates relatively rapid cooling, but not nearly as rapid as the quenching that produces glass. Aphanitic textures are typical of the interiors of lava flows, in contrast to the glassy texture that forms on the surface or crust.

Many aphanitic and glassy rocks have numerous small spherical or ellipsoidal cavities, **vesicles.** These are produced by gas bubbles trapped in the solidifying rock. As hot magma rises toward Earth's surface, the confining pressure diminishes, and dissolved gas (mainly H_2O steam) separates and collects in bubbles. The process is similar to the effervescence of champagne and soda pop when the bottles are opened. Vesicular textures typically develop in the upper part of a lava

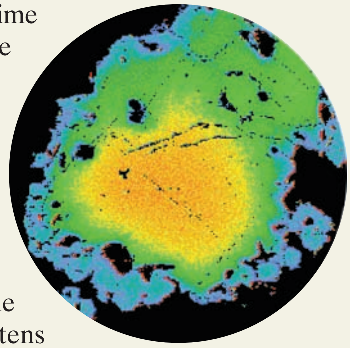
STATE OF THE ART *Microscopes Reveal Hidden Worlds of Geology*



Geologists examine Earth and its materials on a vast range of scales—from that of the entire planet down to the smallest constituent of a grain of dust. To do this, they use several sophisticated instruments. One tool used extensively to examine small features in rocks and minerals is the microscope. The last few decades have seen the development of a wide variety of microscopes, but we mention only two here: the standard optical microscope and the electron microscope.

Optical microscopes are used to examine rocks with visible wavelengths of light and can be used at magnifications as large as about 500 times. To examine a rock with a microscope, the rock is usually sliced into a thin section, glued to a glass slide, and then ground and polished until it is only 30 microns thick. Under these conditions, many minerals are transparent or translucent, although a few minerals, such as the iron oxides and pyrite, remain opaque. A series of lenses bend rays of light transmitted through the thin section to create an enlarged image. Polarizing lenses add to the discriminating power. An optical microscope can give clear pictures only of specimens that are larger than the wavelength of light used.

The photograph above shows the wealth of information that can be seen. Not only are the identities of the individual grains revealed, but the texture is also obvious, which tells us about the history of the rock. By identifying the minerals, a geologist can classify the rock as igneous, sedimentary, or metamorphic and thereby decipher some of the rock's history. The network of intergrown crystals reveals that this specimen is an igneous rock that was at one time molten. The fine-grain size shows that the molten magma cooled quickly and the rock is probably volcanic rather than plutonic.



Electron microscopes create greatly magnified images of rock surfaces or mineral grains and are capable of magnifications to several tens of thousands of times. An electron microscope accomplishes this without using optical light at all. Instead, it uses electrons, which have wave characteristics equivalent to extremely short wavelengths. A rock specimen is placed in a small vacuum chamber and bombarded by a beam of electrons stripped from a heated filament at the top of the instrument. A series of magnetic lenses bend and focus the electron beam on the specimen, which then emits a shower of secondary electrons. These secondary electrons control the intensity of another beam of electrons inside a television picture tube to construct an image that we can see with our eyes. Tiny mineral grains are thus visible for study and the details of mineral structures can be seen. Moreover, some electrons in the target atoms may be kicked into higher energy levels and when they fall back to lower energy levels X rays are given off that can be used to identify the element and its concentration in the rock. A map of the microdistribution of the elements in the mineral can be made. The colorful electron microprobe image shows the concentration of magnesium in a single crystal of garnet. The colors show that the environment changed as the garnet crystallized so that the rim is poor in magnesium (blue) and the core is high (yellow). This information can be used to infer the temperature and pressure of crystallization.

(Photograph courtesy of Nikon Inc.)

(Courtesy of Cameca Instruments, Inc.)

flow, just below the solid crust, where the upward-migrating gas bubbles are trapped. Even though vesicles change the outward appearance of the rock and indicate the presence of gas in a rapidly cooling lava, they do not change the basic aphanitic texture.

Phaneritic Texture. The specimen shown in Figure 4.3C is composed of grains large enough to be recognized without a microscope, a texture known as **phaneritic** (Greek *phaneros,* "visible"). The grains are approximately equal in size and form an interlocking mosaic. The equigranular texture suggests a uniform rate of cooling, and the large size of the crystals shows that the rate of cooling was very slow.

For cooling to take place at such a slow rate, the magma must have cooled far below the surface. Field evidence supports this conclusion, because magma crystallized after volcanic eruptions produces only aphanitic and glassy textures. Rocks with phaneritic textures are exposed only after erosion has removed thousands of meters of covering rock.

Igneous Crystallization

Some intrusive igneous rocks have especially coarse grains—as much as a meter long. These **pegmatites** probably crystallized from water-rich magmas and are typically found in association with granite.

Porphyritic Texture. Some igneous rocks have grains of two distinct sizes. The larger, well-formed crystals are referred to as **phenocrysts;** the smaller crystals constitute the **matrix,** or the **groundmass.** This texture is known as porphyritic. It occurs in either aphanitic or phaneritic rocks.

A **porphyritic texture** usually indicates two stages of cooling. An initial stage of slow cooling, during which the large grains developed, is followed by a period of more rapid cooling, during which the smaller grains formed (see Figure 4.5F). The aphanitic matrix indicates that the cooling melt had sufficient time for all of its material to crystallize. The initial stage of relatively slow cooling produced the larger grains; the later stage of rapid cooling, when the magma was extruded, produced the smaller grains. Similarly, a phaneritic matrix with phenocrysts indicates two stages of cooling (see Figure 4.5A). An initial stage of very slow cooling was followed by a second stage, when cooling was more rapid but not rapid enough to form an aphanitic matrix.

Pyroclastic Texture. The texture shown in Figure 4.3D may appear at first to be that of a porphyritic rock with phenocrysts of quartz and feldspar. Under a microscope, however, the grains are seen to be broken fragments rather than interlocking crystals. Some fragments of glass are bent and flattened. This is a **pyroclastic texture** (Greek *pyro,* "fire"; *klastos,* "broken"), produced when explosive eruptions blow crystals and bits of still molten magma into the air as a mixture of hot fragments called ash. If the fragments are still hot when they are deposited, they will be welded (fused) together by the weight of the overlying rock.

TYPES OF IGNEOUS ROCKS

Igneous rocks are classified on the basis of texture and composition. The major kinds of igneous rocks are granite, diorite, gabbro, rhyolite, andesite, and basalt.

A simple chart of the major types of igneous rocks is shown in Figure 4.4. The basis for this scheme of classification is texture and composition. Variations in composition are arranged horizontally, and variations in texture are arranged vertically. Rocks that cool below the surface are called *intrusive,* and those that cool at the surface are called *extrusive.* The rock names are printed in bold type, the

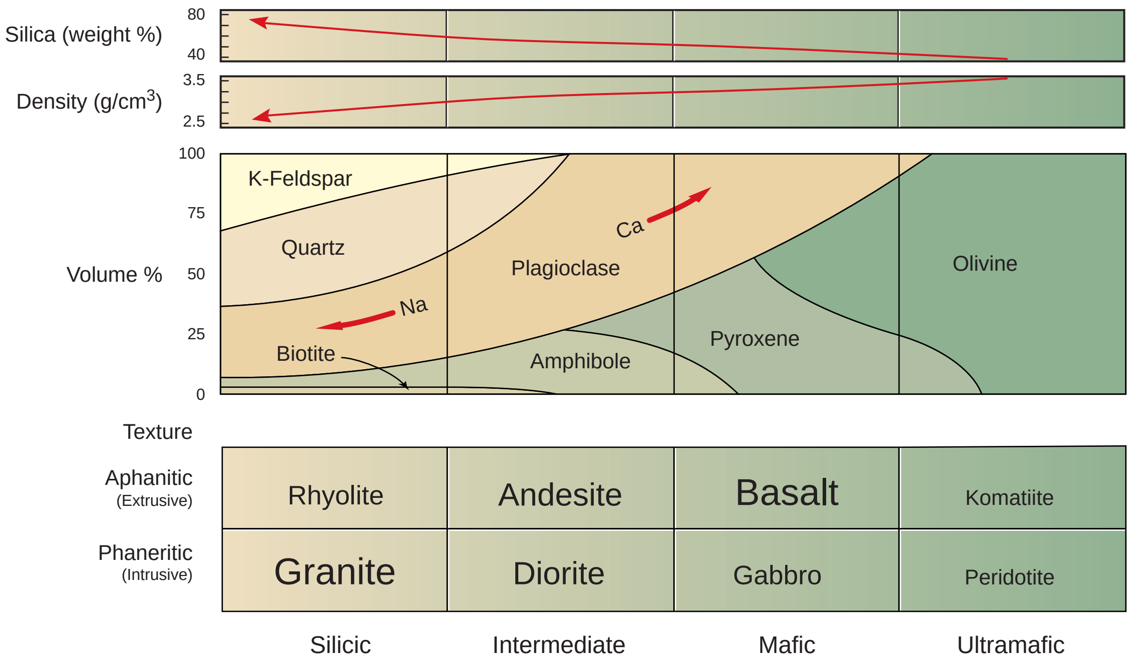


FIGURE 4.4 **The classification of common igneous rocks** is based on texture (shown vertically on the chart) and composition (shown horizontally). The size of type in which the names of the rocks are printed is roughly proportional to their abundance at Earth's surface.

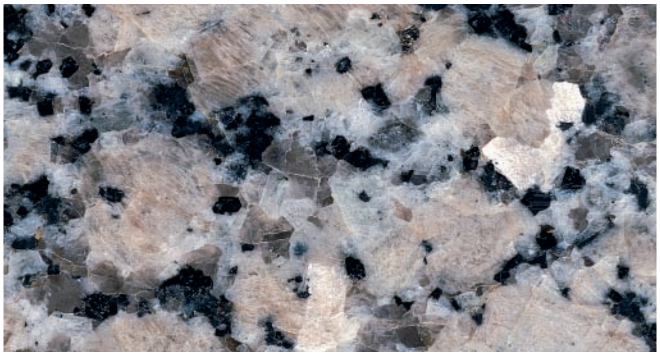
size of which is roughly proportional to the relative abundance of the rock at the surface. Rocks in the same column have the same composition but different textures. Rocks in the same horizontal row have the same texture but different compositions. The chart shows that granite, for example, has a phaneritic texture and is composed predominantly of quartz, plagioclase, and K-feldspar. The type size indicates that it is the most abundant intrusive igneous rock. Rhyolite has the same composition as granite but is aphanitic. Basalt has an aphanitic texture and is composed predominantly of Ca-plagioclase and pyroxene. It has the same composition as gabbro but is much more abundant at Earth's surface.

This classification attempts to show the natural, or genetic, relationships between the various rock types. As we saw in the preceding section, texture provides important information on the cooling history of the magma. Rocks that crystallize slowly are able to grow large crystals; those that cool rapidly have a fine-grained or glassy texture. The composition of a rock provides information about the nature and origin of the magma. Mafic magmas high in iron and magnesium and poor in silica generally originate from partial melting of the mantle; they are erupted in continental rift systems and along midoceanic ridges. Rocks richer in silica, such as andesite and rhyolite, or their intrusive equivalents, diorite and granite, typically form at convergent plate margins and in other settings, such as rifts or above hot spots, where continental crust can be partially melted by hot basalt.

What are the properties upon which igneous rocks are classified?

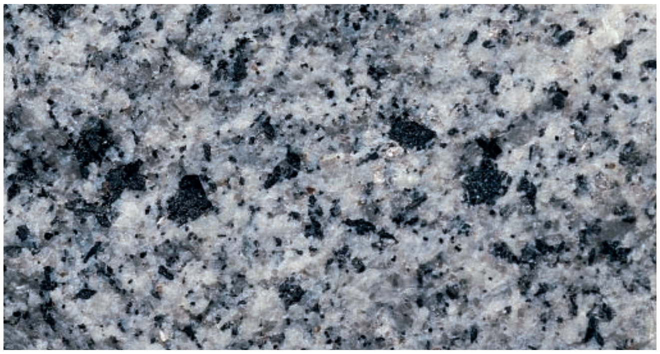
Rocks with Phaneritic Textures

Granite is a coarse-grained igneous rock composed predominantly of feldspar and quartz (Figure 4.5A). K-feldspar is the most abundant mineral, and usually it is easily recognized by its pink color. Plagioclase is present in moderate amounts, usually distinguished by its white color and its porcelain-like appearance. Mica is conspicuous as black or bronze-colored flakes, usually distributed evenly throughout the rock. A very important property of granite is its relatively low density, about 2.7 g/cm^3, in contrast to basalt and related rocks, which have a density of 3.2 g/cm^3. This fact is important in considering the nature of continents and the contrast between continental crust and oceanic crust. Granite and related rocks make up the great bulk of the continental crust.



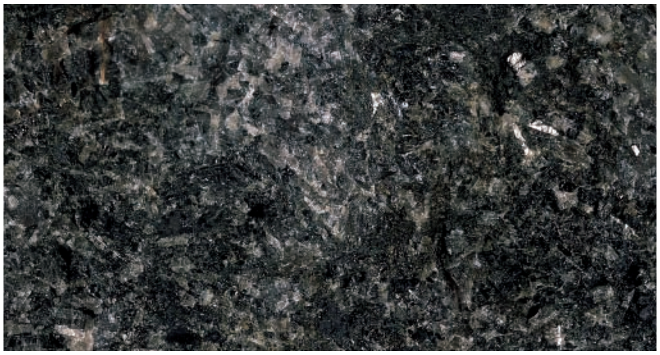
(A) Granite: K-feldspar, quartz, plagioclase, and biotite.

(B) Rhyolite: K-feldspar, plagioclase, quartz, biotite, and light-colored fine-grained groundmass..

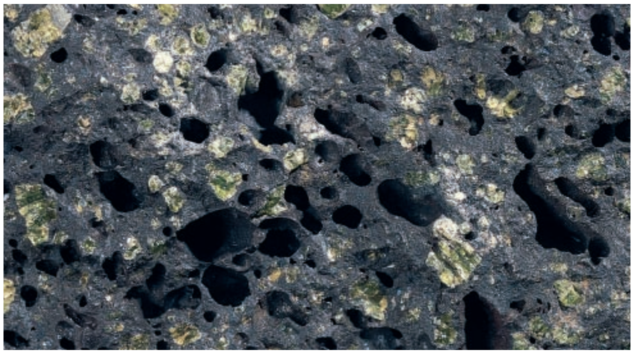


(C) Diorite: plagioclase, amphibole, quartz, and biotite.

(D) Porphyritic andesite: plagioclase, pyroxene, and amphibole along with fine-grained, gray groundmass.



(E) Gabbro: pyroxene, plagioclase, and olivine.



(F) Porphyritic basalt: pyroxene, plagioclase, and olivine along with black vesicles and gray groundmass.

(G) Peridotite: olivine and pyroxene.

(H) Komatiite: olivine and pyroxene. *(Photograph by D. A. Williams)*

FIGURE 4.5 **The major types of igneous rocks** and their mineral constituents listed from most to least abundant. Photographs are actual size.

Diorite is similar to granite in texture (Figure 4.5C), but it differs in composition. Plagioclase feldspar is the dominant mineral, and quartz and K-feldspar are minor constituents. Amphibole is an important constituent, and some pyroxene may be present. In composition, diorite is intermediate between granite and gabbro. Its extrusive equivalent is andesite.

Gabbro is not commonly exposed at Earth's surface, but this mafic rock is a major constituent of the lower part of the oceanic crust and is present in some intrusions on the continents. It has a coarse-grained texture similar to that of granite, but it is composed almost entirely of pyroxene, calcium-rich plagioclase, and olivine. Gabbro is dark green, dark gray, or almost black because of the predominance of dark-colored minerals (Figure 4.5E).

Peridotite is composed almost entirely of two minerals, olivine and pyroxene (Figure 4.5G). It is not common at Earth's surface or within the continental crust, but it is a major constituent of the mantle. Its high density, together with other physical properties, suggests that the great bulk of Earth's interior is composed of peridotite and closely related rock types. The Alps and St. Paul's Rocks (islands in the Atlantic Ocean) are two areas where peridotite from the mantle appears to have been pushed through the crust to Earth's surface. Small pieces of peridotite are also found in basaltic lava flows. These fragments were ripped out of the mantle by rapidly rising magma.

Rocks with Aphanitic Textures

Rhyolite is an aphanitic rock with the same silicic composition as granite (Figure 4.5B). It commonly contains a few phenocrysts of feldspar, quartz, and biotite. Because of their high silica contents and low temperatures, rhyolite lava flows are viscous. Instead of spreading in a linear flow, rhyolite typically piles up in large, bulbous domes (see Figure 4.13). Obsidian with the composition of rhyolite is quite common in these lava flows. Rhyolite ash-flow tuffs are also common. Rhyolite is not common along the ocean ridges or oceanic islands but is more common on the continents.

What is the difference between a rhyolite and a basalt?

Andesite is an aphanitic rock typically composed of plagioclase, pyroxene, and amphibole (Figure 4.5D). Andesite has an intermediate composition and usually contains little or no quartz and has the same composition as diorite. The texture of andesite is generally porphyritic, with phenocrysts of plagioclase feldspar and mafic minerals. The rock is named after the Andes Mountains, where volcanic eruptions have produced lavas with this composition in great abundance. Andesite is the next most abundant lava type after basalt and occurs most frequently along the convergent plate margins in island arcs and along continental margins. It is not found along oceanic ridges, and it is rare in oceanic islands or other intraplate settings related to mantle plumes.

Basalt is the most common aphanitic rock (Figure 4.5F). It is a very fine-grained, usually dark-colored rock that originates from cooling lava flows. The mineral grains are so small they can rarely be seen without a microscope. If a **thin section** (a thin, transparent slice of rock) is viewed through a microscope, the individual minerals can then be seen and studied (see Figure 3.21).

Basalt is a mafic rock composed predominantly of calcium-rich plagioclase and pyroxene, with smaller amounts of olivine. The plagioclase occurs as a mesh of elongate, lathlike crystals surrounding the more equidimensional pyroxene and olivine grains. In some cases, large crystals of olivine or pyroxene form phenocrysts, resulting in a porphyritic texture. Many basalts have some glass, especially near the tops of flows. Basalt is the most common volcanic rock on Earth, because it is so abundant on the seafloor.

Komatiite is a rare volcanic rock (Figure 4.5H) found mostly in very ancient rock sequences exposed in the continental shields. It is composed mainly of the mineral

(A) The surface of an aa flow consists of a jumbled mass of angular blocks that form when the congealed crust is broken as the flow slowly moves. Aa flows are viscous and much thicker than pahoehoe flows. This photograph shows a recent aa flow in Hawaii.

(B) The surfaces of pahoehoe flows are commonly twisted, ropy structures. Pahoehoe flows form on fluid lava and typically are very thin. The firm, hot plastic crust is wrinkled and folded by continued movement of the fluid interior. *(Photograph from U.S. Geological Survey)*

(C) Hexagonal columnar joints commonly form by contraction when a lava cools. The long axis of the column is approximately perpendicular to the cooling surface. These columns form the Giant's Causeway, Ireland. *(Photograph © Tom Till)*

(D) Lava tubes develop where the margin of the flow cools and solidifies and the interior, molten material is drained away.

(E) Pressure ridges develop in lava flows when the outer crust buckles as the flow surface folds. They commonly crack and release lava and gas from the interior of the flow.

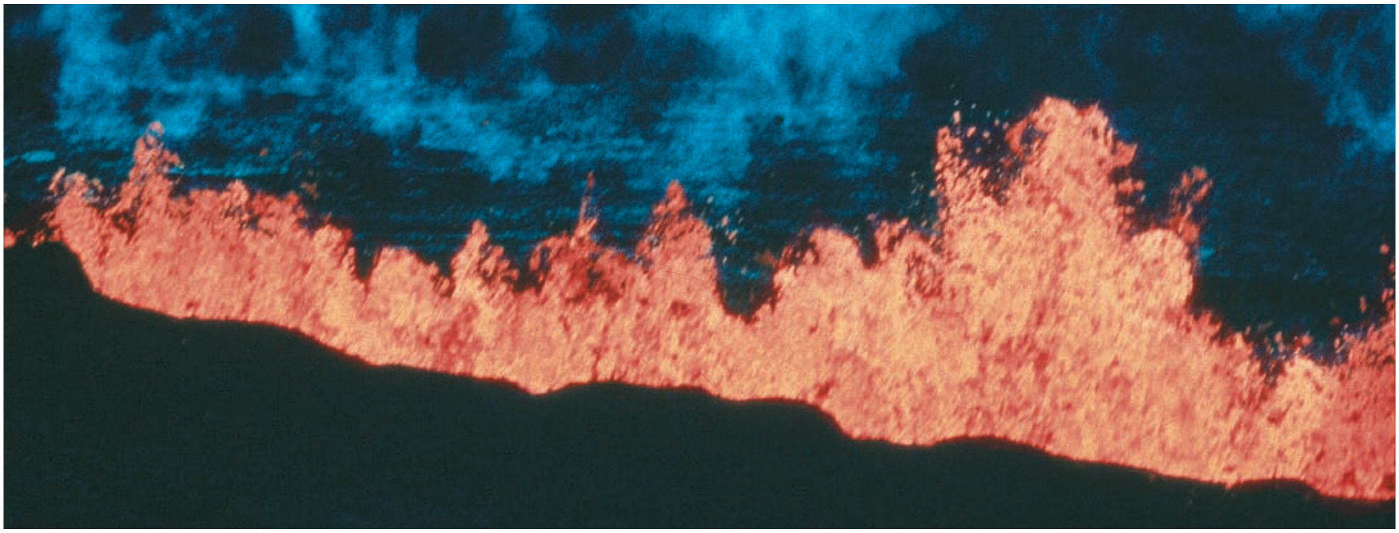
(F) Spatter cones, or ramparts, form in local areas along fissures where globs of lava accumulate near a major vent. *(Photograph from J.D. Griggs/U.S. Geological Survey)*

FIGURE 4.6 A variety of features develop on basaltic lava flows and reflect the manner of flow, rates of cooling, amount of dissolved gases, and viscosity.

(G) Pahoehoe lava flows on the island of Hawaii. The flow is moving away from the observer. The main flow forms a solid crust along its margins and upper surface. Hot liquid lava breaks through the crust, gradually cools, and forms a new crust. The process is then repeated downslope.

(H) Tephra is a general term referring to all pyroclastic material ejected from a volcano. It includes ash, dust, bombs, and rock fragments. It is commonly stratified.

(I) Volcanic bombs are fragments of lava ejected in a liquid or plastic state. As they move through the air they twist and turn and form spindle-shaped masses.



(J) Fissure eruptions are the most common type of volcanic eruption on Earth. Lava is simply extruded through cracks or fissures in the crust. This type of eruption is typical of fluid basaltic magma and is the dominant eruption style along the oceanic ridge. This photograph shows a recent fissure eruption on the island of Hawaii. *(Courtesy of Hawaii Volcano Observatory, U.S. Geological Survey)* olivine. The olivine phenocrysts may grow to exceptional lengths of as much as 50 cm, giving most komatiites a decidedly porphyritic character. The rest of the rock is made of fine crystals of pyroxene and rare plagioclase, giving it an appearance like basalt. Because of their high content of mafic minerals, these rocks have even less silica than basalt. Komatiites are important because they provide evidence for the high temperatures and other characteristics of volcanism early in Earth's history.

Rocks with Pyroclastic Textures

In what way are the products of explosive eruptions unique?

Explosive volcanic eruptions of rhyolitic and andesitic magmas commonly produce large volumes of fragmental material that are ejected high into the atmosphere. The fragments range from dust-sized pieces, or **ash,** to large blocks more than a meter in diameter. **Pumice** is a vesicular frothy glass common among the larger fragments. Some pumice fragments have densities low enough that they can float on water. **Tephra** deposits are composed of shards of volcanic glass, pumice, broken phenocrysts, and foreign rock fragments. The rock resulting from the accumulation of pyroclastic fragments is also known as **tuff.** Although of volcanic origin, tuff has many of the characteristics of sedimentary rocks because the fragments composing tuff may settle out from suspension in the air and commonly are stratified like sedimentary rocks. **Pyroclastic-fall tuff** is composed of volcanic ash that fell more or less vertically out of the atmosphere. These layers mantle the hills and valleys. In contrast, an **ash-flow tuff,** or ignimbrite, forms from particles that move laterally across the surface in a gas-charged flow in which movement resembles that of a lava flow but is much more rapid. In some ash-flow tuffs, the ash may be fused or welded together in a tight, coherent mass, and the glass fragments may be flattened and bent out of shape. This unique texture indicates that at the time of deposition, the ash fragments were hot enough to deform and fuse from the weight of the overlying ash (Figure 4.3F).

EXTRUSIVE ROCK BODIES

> Extrusive igneous rocks are those that form from magma extruded onto Earth's surface by volcanic eruptions. The rocks include lava flows and volcanic ash. Basaltic magmas are low in silica and are relatively fluid. The lava is typically extruded quietly from fissures and fractures. Silicic magmas are viscous, and their eruptions are typically explosive. The magma extrudes as thick lava flows, bulbous domes, or ash flows.

One of the most spectacular of all geologic processes is the extrusion of lava onto Earth's surface by volcanic eruptions (Figure 4.6, previous page). Throughout recorded history, more than 700 volcanoes have been known to be active, but this is only an instant in geologic time and ignores the region of the most intense volcanic activity on Earth—the region hidden beneath the oceans, where most eruptions go unnoticed. The importance of volcanic activity is that it testifies to the continuing dynamics of Earth, provides an important window on the planet's interior, and sheds light on the processes operating below the surface, in the lower crust and upper mantle.

Products of Basaltic Eruptions

Basaltic eruptions are probably the most common type of volcanic activity on Earth. The lava is generally extruded from fractures or fissures in the crust. Upon extrusion, it tends to flow freely downslope and spreads out to fill valleys and topographic depressions (Figure 4.6). This type of eruption occurs along fissures at the oceanic ridge, forming new oceanic crust where the tectonic plates move apart, and it is the major type of eruption in the volcanic plains of the continents related to hotspots and rifts. Basaltic lavas erupt with temperatures ranging between 1000° and 1200°C. A lava can flow at speeds as high as 40 km/hr down steep slopes, but rates of 20 km/hr are considered unusually rapid. For example, the flow front of the 1998 basaltic lava in the Galapagos Islands moved an average of 170 m/hr. The fronts of Hawaiian basalt flows commonly move only a few meters per hour. Rapid flows are usually found in confined flows or inside lava tubes. As a flow moves downslope, it loses gas, cools, and becomes more viscous. Movement then becomes sluggish, and the flow soon comes to rest.

There are two common types of basaltic flows, referred to by the Hawaiian terms *aa* (pronounced ah'ah') and *pahoehoe* (pronounced pa ho'e ho'e) (Figure 4.6A, B). An **aa flow** moves slowly and is typically 3 to 10 m thick. The surface of the flow cools and forms a crust while the interior remains molten. As the flow continues to move, the hardened crust is broken into a jumbled mass of angular blocks and clinkers (Figure 4.6A). Gas within the fluid interior of the flow migrates toward the top, but it may remain trapped beneath the crust. These "fossil gas bubbles," called vesicles, make the rock light and porous. **Pahoehoe flows** are more fluid than aa flows. Many are less than 1 m thick, but they can be much thicker. As a pahoehoe flow moves, it develops a thin, glassy crust, which is wrinkled into billowy folds or surfaces that can resemble coils of rope. A variety of flow features (such as those shown in Figure 4.6B, G) can develop on the surface of the flow. Commonly, the crust of the flow buckles to form a **pressure ridge,** with a central fracture through which gas and lava can escape (Figure 4.6E). Both aa and pahoehoe flows can be erupted from the same vent. Many pahoehoe flows convert to aa when the surface cools and small crystals form or where flow rates increase when the flow drops over a steep slope.

What kinds of lava flows and volcanoes form from basaltic lava flows?

The interior of a basaltic flow may be massive and nonvesicular. As a flow cools, it contracts and may develop a system of polygonal cracks, known as **columnar joints,** that are similar in many ways to mud cracks (Figure 4.6C). In some flows, the sides and top freeze solid while the interior remains fluid. The fluid interior can break through the crust and flow out, leaving a long **lava tube** (Figure 4.6D). Instead of issuing from a central vent, basaltic lava is commonly extruded from a series of fractures in the crust known as **fissures** (Figure 4.6J). The fluid lava usually spreads out over a large area rather than building an isolated cone. In some places along the fissure, the rising lava may be concentrated and erupt like a lava fountain. The splashing of lava around the fountain can build up small conical mounds called **spatter cones** (Figure 4.6F). **Flood basalts** are some of Earth's most impressive volcanic deposits; single flows can be traced for hundreds of kilometers

FIGURE 4.7 **Flood basalts** cover large areas of the Columbia Plateau. Two thick flows and several thinner ones are exposed in this valley wall. Columnar joints form fractures through much of each flow.

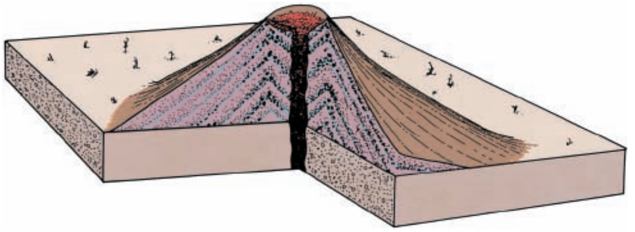


FIGURE 4.8 **A cinder cone** is a small volcano composed almost exclusively of pyroclasts blown out from a central vent, such as this one in southern Utah. The internal structure consists of layers of ash inclined away from the summit's crater. The vent, or volcanic neck, is commonly filled with solidified lava and fragmental debris.

(Figure 4.7). Individual flows can be as much as 30 m thick, and a sequence of flows may stack up to be hundreds of meters thick, as in the Columbia River Plateau of Washington. The low viscosity of basalt and high eruption rates create these plains. Studies of the Moon and planets show that this type of volcanism is the most common not only on Earth but also on all the inner planets.

Cinder Cone Eruption

Droplets and globs of lava blown out from a volcanic vent may cool by the time they fall back to the ground. This material forms **volcanic ash** and dust, collectively known as tephra (Figure 4.6H). **Volcanic bombs** are the larger fragments (Figure 4.6I). As the tephra travels through the air, it is sorted according to size. The larger particles accumulate close to the vent and form a **cinder cone** (Figures 4.8 and 4.9), and the finer, dust-sized particles are transported afar by the wind. Cinder cones, which are generally less than 200 m high and 2 km in diameter, are relatively small features compared with large shield volcanoes and stratovolcanoes.

If the extrusion of fluid basaltic lava dominates, a broad cone, or **shield volcano,** may form around a central vent or series of fissures (Figure 4.10). With each eruption, the fluid basaltic lava flows freely for some distance, spreading into a thin sheet, or tongue, before congealing. Shield volcanoes, therefore, have wide bases and gentle slopes (generally less than 10°). Their internal structure consists of innumerable thin basalt flows with comparatively little ash. The Hawaiian Islands are excellent examples of large shield volcanoes. They are enormous mounds of basaltic

FIGURE 4.10 **Shield volcanoes** are composed of innumerable thin basaltic lava flows that erupt from a central vent or fissures. This small shield, on the Snake River Plain of southern Idaho, shows the typical broad low profile. It is about 50 m high and about 5 km across. Some of the largest volcanoes, such as the Hawaiian Islands, are also shields.

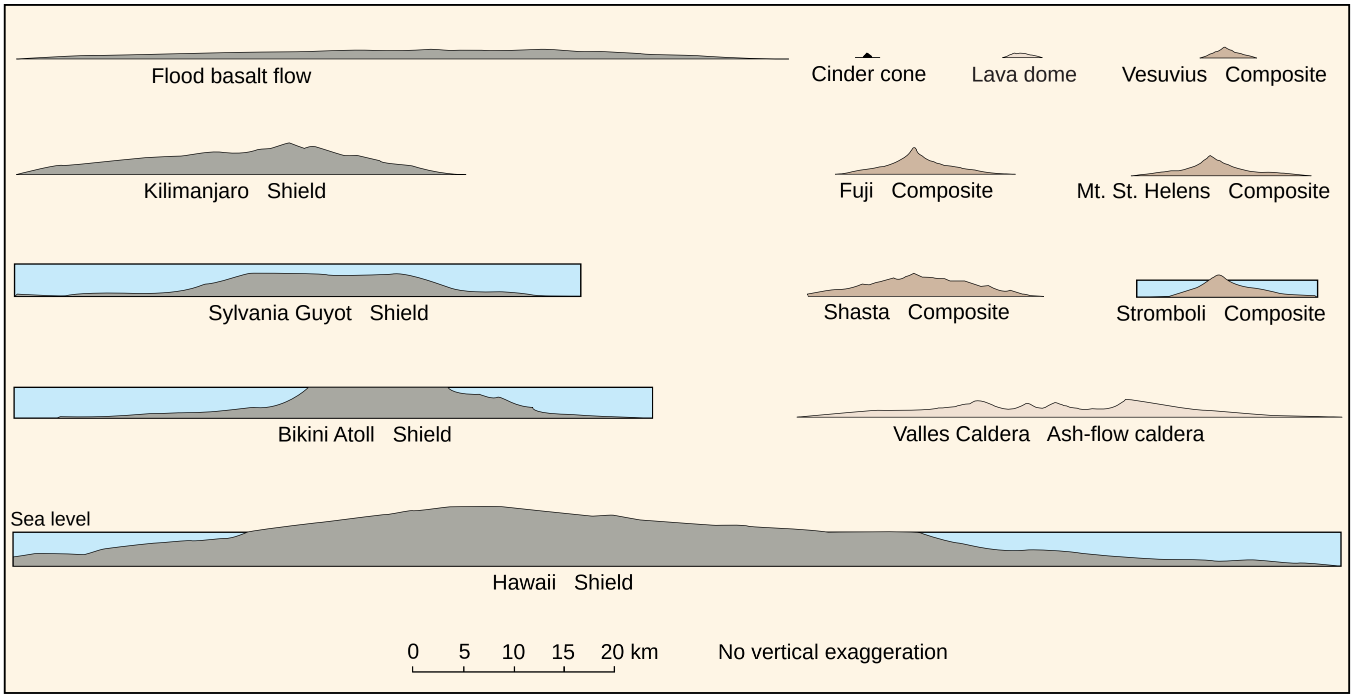


FIGURE 4.9 **Volcanoes** come in a wide variety of sizes and shapes. The smallest shown here are cinder cones and the largest are Hawaiian-type shield volcanoes. In between these extremes in size are small shield volcanoes, rhyolite lava domes, steep-sided composite volcanoes, ash-flow calderas, and vast plains covered by flood basalts.

lava, rising as high as 10,000 m above the seafloor (Figure 4.9). The younger volcanoes typically have summit craters, or **calderas,** as much as 5 km wide and several hundred meters deep, that result from subsidence following the eruption of magma from below (Figure 4.11).

The extrusion of basaltic lava into water produces a flow composed of a multitude of ellipsoidal masses referred to as **pillow lava** (Figure 4.12). The formation of pillow basalt has been observed off the coast of Hawaii, and recent undersea photographs show that it is widespread on the seafloor, anywhere volcanic activity has occurred.

Eruption of Pillow Basalt

Products of Intermediate to Silicic Eruptions

The silica-rich magmas that produce andesite and rhyolite are relatively viscous, cool (600° to 900°C), and water-rich. Consequently, their eruption and flow are quite different from basaltic lavas. Some silicic magmas are so viscous that small volumes hardly flow at all but instead form small bulbous **lava domes** over the volcanic vent (Figure 4.13).

Magmatic explosions are not driven by chemical reactions like manufactured explosives; instead, they are caused by the rapid expansion of gas bubbles at low pressure. The high viscosity of silicic magmas inhibits the escape of dissolved gas, so tremendous pressure builds up. Consequently, when eruptions occur, they are highly explosive and violent and commonly produce large quantities of tephra. Alternating layers of tephra and thick, viscous lava flows or domes typically produce a **composite volcano,** or **stratovolcano,** a high, steep-sided cone centered around the vent (Figure 4.14). This is probably the most familiar form of continental volcano, with such famous examples as Shasta, Fuji, Vesuvius, Etna, and Stromboli. A depression at the summit, the **crater,** usually marks the position of the vent. These volcanoes are long-lived and their eruptions infrequent. Although they are large structures, they are much smaller than the huge shields formed on the ocean floor (Figure 4.9).

Mt. St. Helens

Explosive eruptions of silicic volcanoes can blow out large volumes of ash and magma in a very short period. While the chamber empties, the roof becomes weak

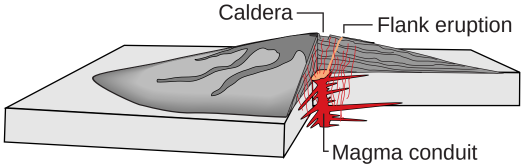


FIGURE 4.11 **Calderas** atop Mauna Loa volcano in Hawaii may have formed by subsidence when magma was withdrawn from shallow chambers within the volcano. The large caldera is about 3 km across and nearly 200 m deep. Eruption of lava onto the floor of a caldera occasionally forms a lake of lava that may spill over onto the sides of the volcano. Shield volcanoes also erupt from vents on their flanks (*Photograph by J. D. Ives)*

and unstable. As a result, the summit may collapse, forming a large caldera. Crater Lake, Oregon (Figure 4.15), for example, formed when a volcano's summit collapsed during its last major eruption and the resulting caldera filled with water. Wizard Island, a small cinder cone in the caldera, formed during subsequent minor eruptions. Other collapse calderas associated with rhyolite eruptions are as much as 50 km across. Fortunately, no eruption of the size necessary to create such a caldera has occurred during recorded history.

Crater Lake

A spectacular type of eruption associated with silicic magmas is the lateral flow of large masses of pumice and ash. This phenomenon is not a liquid lava flow or an ash fall (in which particles settle independently) but a flow consisting of fragments of hot mineral grains, ash, and pieces of rock all suspended in hot gas. It moves rapidly close to the surface like a dense dust cloud. This type of eruption is therefore known as an **ash flow** (Figure 4.16). As magma works its way to the surface, confining pressure is released and bubbles of gas coming out of solution rapidly expand. Near the surface, the magma violently explodes, ejecting pieces of lava, bits of solid rock, crystals, and gas. This material is very hot, sometimes incandescent. Initially, explosions throw this material high into the atmosphere, but being denser than the air, it eventually falls and flows across the ground surface as a thick, dense cloud of hot ash. Ash flows can reach velocities greater than 250 km/hr. There is no outrunning an ash flow. When an ash flow comes to rest, the particles of hot crystal fragments, glass, and ash may fuse to form **welded tuff** (Figures 4.17and 4.3D). As it cools, the contracting mass can develop columnar jointing. Ash-flow tuffs can be very large. Some have carried ash as much as 100 km from their vents. Some flows form layers more than 100 m thick and cover thousands of square kilometers. A few ash-flow tuffs have volumes of more than 1000 km^3. This is the equivalent of a cube 10 km on a side and probably erupted over the course of only a few weeks.

Why don't basaltic eruptions produce ash flows?

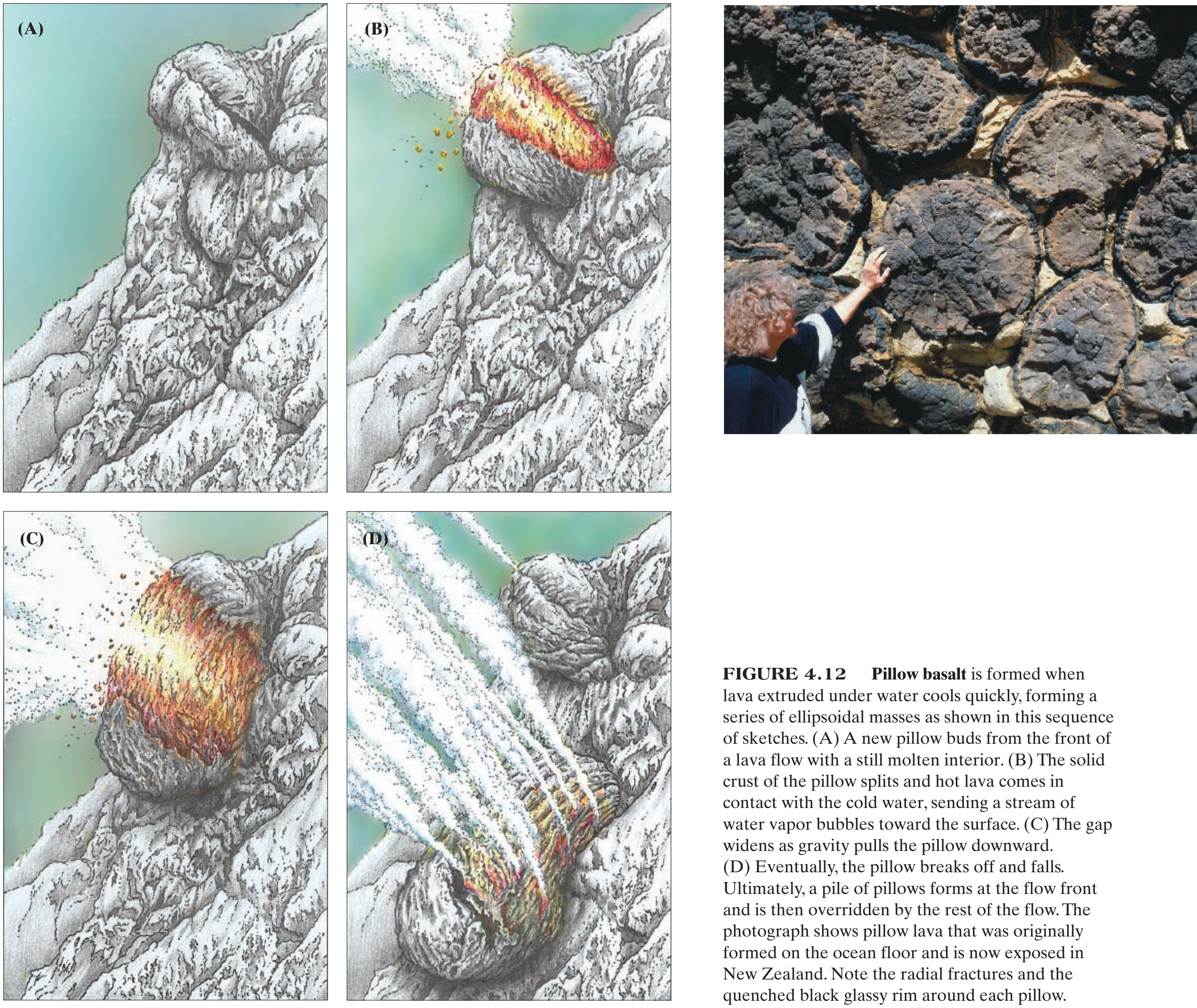


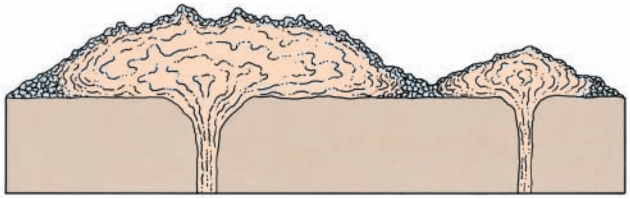
FIGURE 4.12 **Pillow basalt** is formed when lava extruded under water cools quickly, forming a series of ellipsoidal masses as shown in this sequence of sketches. (A) A new pillow buds from the front of a lava flow with a still molten interior. (B) The solid crust of the pillow splits and hot lava comes in contact with the cold water, sending a stream of water vapor bubbles toward the surface. (C) The gap widens as gravity pulls the pillow downward. (D) Eventually, the pillow breaks off and falls. Ultimately, a pile of pillows forms at the flow front and is then overridden by the rest of the flow. The photograph shows pillow lava that was originally formed on the ocean floor and is now exposed in New Zealand. Note the radial fractures and the quenched black glassy rim around each pillow.

Ash-flow calderas are the largest silicic volcanoes on Earth. Constructed of far traveled sheets of tuff, these volcanoes form very low, very broad shields dominated by the central collapse structure (Figures 4.17 and 4.9)

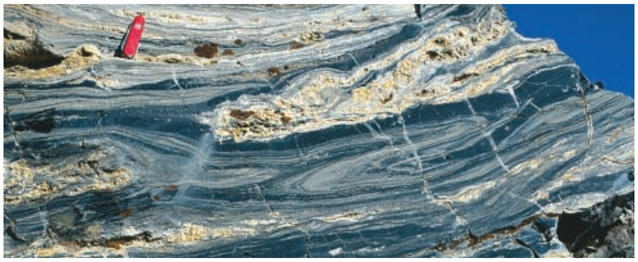
Ash-flow eruptions are catastrophic events. A few fortunate geologists have had the opportunity to witness them from afar and to make direct observations of this type of extrusion. For example, Mount Lamington, in New Guinea, was considered extinct until it erupted in 1951. It had never been examined by geologists and was not even considered to be a volcano by the local inhabitants. When it did erupt, volcanic activity began with preliminary emissions of gas and ash, accompanied by earthquakes and landslides near the crater. Sensitive seismographs were soon installed near the crater to monitor Earth's movements, and aerial photographic records were made daily. Then, on Sunday, January 21, 1951, a catastrophic explosion burst from the crater and produced an ash flow that completely devastated an area of about 200 km^2. Almost 3000 people died. The main eruption was observed and photographed at close quarters from passing aircraft, and a

(A) This small rhyolite dome, and the thick rhyolite lava flow behind it, erupted in northern California, near Mono Lake.

FIGURE 4.13 **Domes of silicic lava** form because silica-rich lava is viscous and resists flow. It therefore tends to pile up over the vent to form small bulbous domes, usually less than 1 km across.

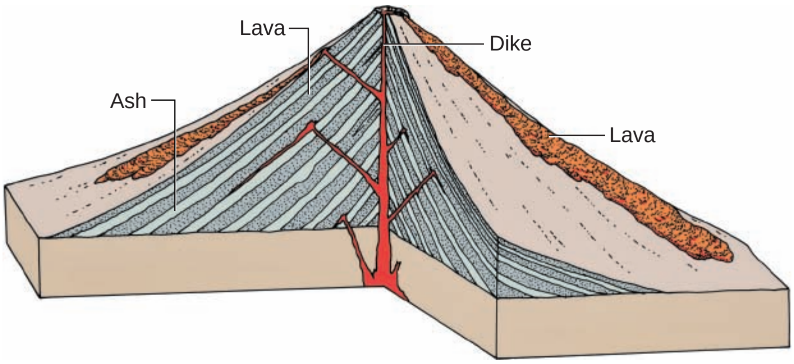


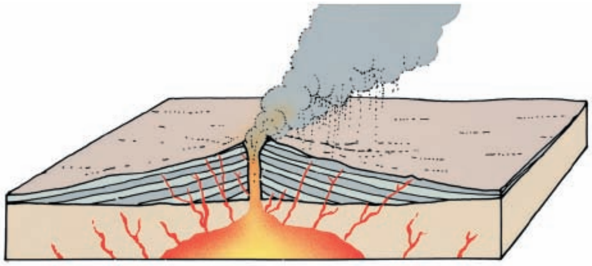
(B) Cross section showing the internal structure of a rhyolite dome. These domes inflate as magma rises from below, so the crust of the dome is continually stretched and fractured. The development is similar to that of inflating a balloon.



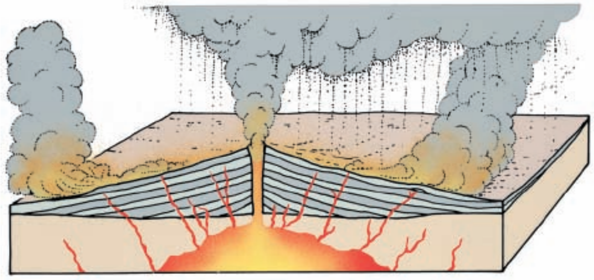
(C) Closeup photograph of glassy rhyolite flow showing contorted flow structures formed in viscous lava.

FIGURE 4.14 **Composite volcanoes** are built up of alternating layers of ash and lava flows, and intruded by lava domes. They are high, steep-sided cones such as Washington's Mt. St. Helens before its catastrophic eruption in 1980. A typical composite volcano is about 20 km across and may be 3 km high. *(Photograph by U.S. Department of Agriculture)*

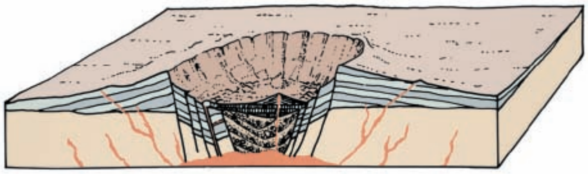




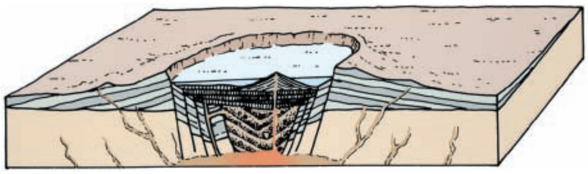
(A) Early explosive eruptions from the prehistoric volcano Mount Mazama created a high eruption column and ash fell out to form thin beds of ash.



(B) Great eruptions of ash flows emptied more of the magma chamber, causing the top of the volcano to collapse.



(C) The collapse of the summit into the partly drained magma chamber formed the caldera.



(D) A lake formed in the caldera, and subsequent minor eruptions produced small volcanic islands in the lake.

FIGURE 4.15 **The evolution of the caldera at Crater Lake, Oregon,** involved a series of great eruptions followed by the collapse of the summit into the magma chamber. *(After H. Williams, F. J. Turner, and C. M. Gilbert)*

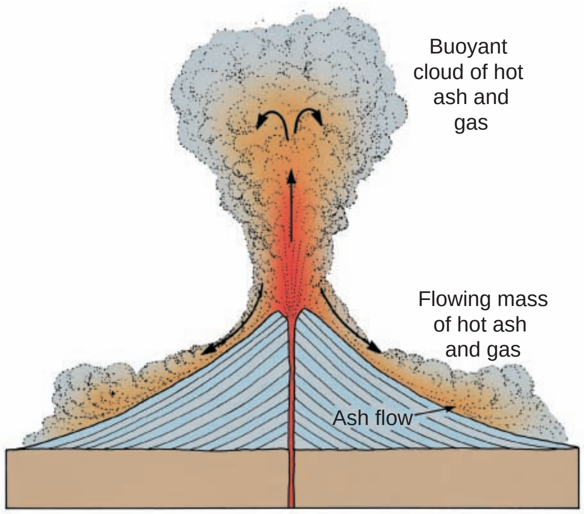


FIGURE 4.16 **An ash flow** is a hot mixture of highly mobile gas and ash that moves rapidly over the surface of the ground away from the vent. The ash rises into the air from the explosive force of the eruption but, being much denser than air, it moves en masse back to the surface and rushes down the slopes of the volcano as an ash flow. Less-dense gas and ash continue to move upward as a cloud into the atmosphere. This ash ultimately falls back to the surface as an ash fall. This photograph shows the eruption of a composite volcano on the north island of New Zealand.

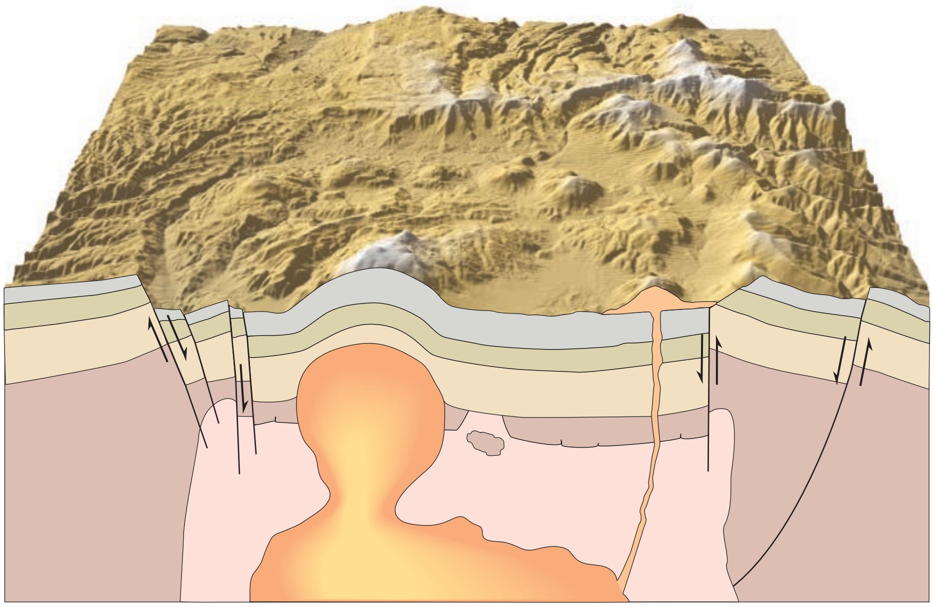


FIGURE 4.17 **Ash-flow tuffs** can form sheets tens of meters thick that extend for many kilometers away from their source calderas. These rhyolite ash-flow sheets erupted several million years ago from Valles Caldera near Los Alamos in northern New Mexico. The block diagram shows the internal structure of a caldera. The ring faults allowed the roof of the magma chamber to drop like a piston during eruption of the tuff (gray). The tuff partially filled the caldera and a thinner sheet accumulated outside. Rhyolite domes (salmon) erupted along the ring fracture. A subsequent intrusion domed the floor of the caldera.

qualified volcanologist was on the spot within 24 hours. The ash flow descended radially from the summit crater, its direction of movement controlled to some degree by the topography. As the ash flow rushed downslope, it scoured and eroded the surface. Estimated velocities of 470 km/hr were calculated from the force required to overturn certain objects. Entire buildings were ripped from their foundations, and automobiles were picked up and deposited in the tops of trees. Other examples are described in Chapter 21.

INTRUSIVE ROCK BODIES

> Igneous intrusions are masses of rock formed when magma cools beneath the surface. They are classified according to their sizes, shapes, and relationships to the older rocks that surround them. Important intrusive rock bodies are plutons, batholiths, stocks, dikes, sills, and laccoliths.

Magma is mobile, at times amazingly so. It rises because it is less dense than the surrounding rock. It can push aside surrounding rocks, force its way into cracks, and flow on the surface over distances of more than 100 km. It can move upward in the crust by melting away surrounding rocks or wedging and prying loose large blocks of rock, which it then replaces. When a magma within the crust loses its mobility, it slowly cools and solidifies, forming a mass of igneous rock called an **intrusion** (Figure 4.18). Intrusions occur in a variety of sizes and shapes and are exposed at the surface only after the overlying rock has been removed by erosion.

Plutons and Batholiths

Plutons are masses of intrusive igneous rock of any size. Ideally, each pluton represents one magma body crystallized to solid rock, but it is often hard to prove that only one batch of magma was involved.The true three-dimensional form of plutons is difficult to determine because of uncertainty about their extension deep below the surface. The bases of plutons are only rarely exposed at the surface, but evidence from gravity measurements and seismic studies, show that plutons exposed at the surface do not extend down into the mantle. They must therefore be less than 30 km thick and most are probably only a few kilometers thick.

What are the characteristics of the major types of intrusive rock bodies?

A **stock** is a small pluton with an outcrop area of less than 100 km^2. Some stocks are known to be small protrusions rising from larger underlying plutons, but the downward extent of most intrusions is unknown. Large exposures (greater than 100 km^2) of intrusive rock are called **batholiths,** but careful mapping shows that most batholiths are composite intrusions and consist of many individual plutons of different ages intruding one another. Many batholiths cover several thousand square kilometers. The Idaho batholith, for example, is a huge body of granite, exposed over an area of nearly 41,000 km^2 (Figure 4.19). The Coastal batholith of British Columbia is more than 2000 km long and 300 km wide and probably consists of several hundred separate intrusions.

Batholiths appear to be huge, slablike bodies, with horizontal extents much greater than their thicknesses. The map in Figure 4.19 gives a rough idea of the geometric form of some of the younger batholiths of western North America. The surface exposure of a granitic pluton can be elongate and elliptical or circular (Figure 4.20). It generally cuts across layering in the surrounding rock and is discordant. In some areas, however, the walls or roof of the batholith can be parallel to layering in the surrounding rocks and is said to be concordant.

Batholiths typically form in the deeper zones of mountain belts and are exposed only after considerable uplift and erosion. Some of the highest peaks of mountain ranges, such as the Sierra Nevada and the Coast Ranges of western Canada, are carved into granite batholiths (Figure 4.18E). These rocks originally cooled thousands of meters below the surface. The trend of a batholith usually parallels the axis of the mountain range, although the intrusion can cut locally across folds within the range. Extensive batholiths also are found in the shields of the continents (Figure 4.20). These exposures are considered to be the roots of ancient mountain ranges that have long since been eroded to lowlands.

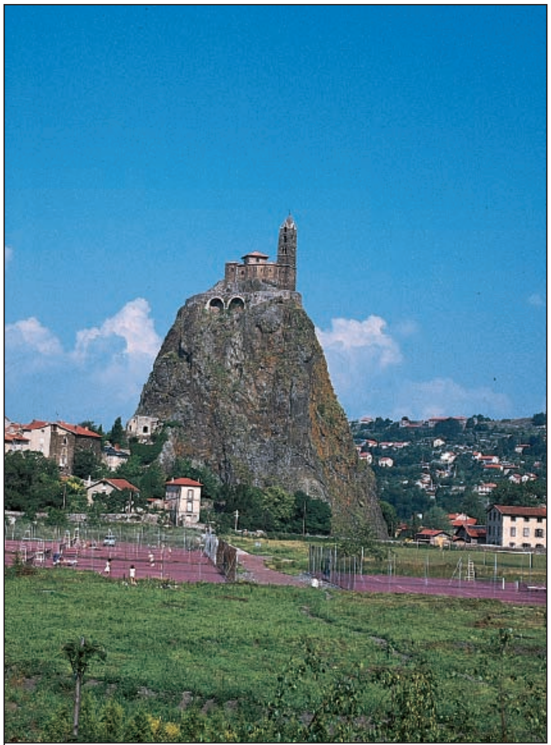
Dikes

One of the most familiar signs of ancient igneous activity is a narrow, tabular body of igneous rock known as a **dike** (Figure 4.18C). All dikes are discordant; that is, they cut across preexisting structures such as layers in metamorphic or sedimentary rocks. A dike forms when magma enters a fracture and cools. The width of a dike can range from a fraction of a centimeter to hundreds of meters. The length is always much greater than the width. The largest known example is the Great Dike of Zimbabwe, which is 600 km long and has an average width of 10 km.

How would you tell a dike from a sill?

The emplacement of dikes is controlled by fracture systems within the surrounding rock. They commonly radiate from ancient volcanic necks and thus reflect the stresses associated with volcanic activity. Sometimes, upward pressure

(A) **Laccolith** partially exposed by erosion, southern Utah. Layers of sedimentary rock were domed upward and shouldered aside by the intrusion.



(B) **Volcanic neck** exposed by erosion, central France. Necks form below volcanoes when magma solidifies in a pipe.

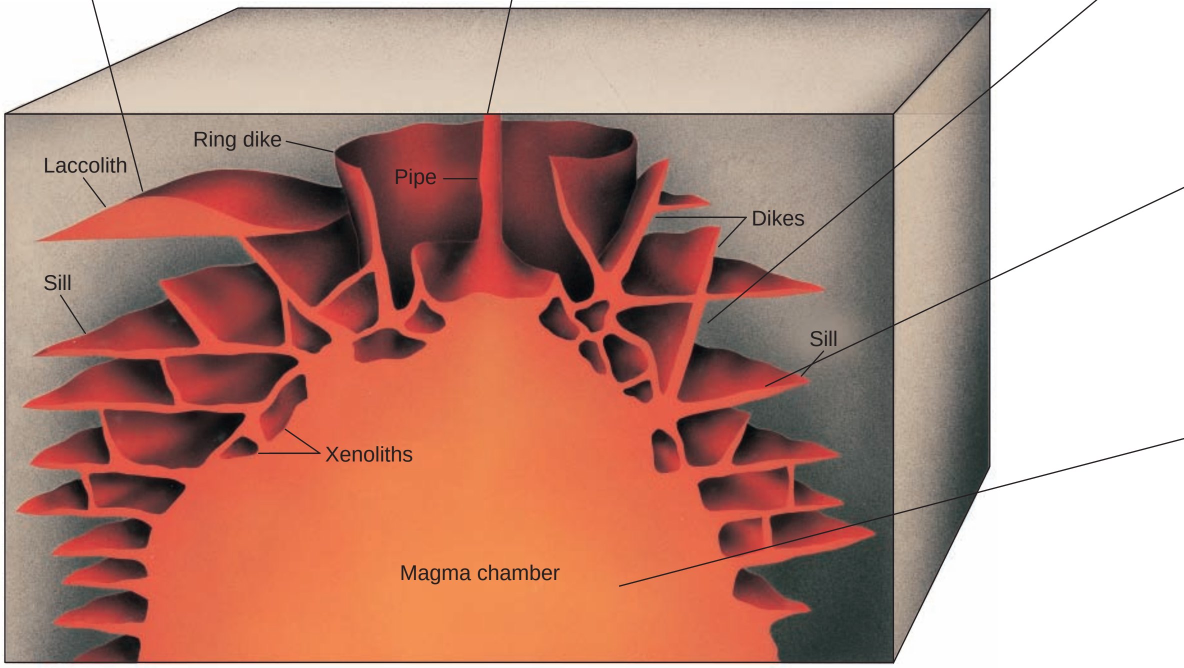
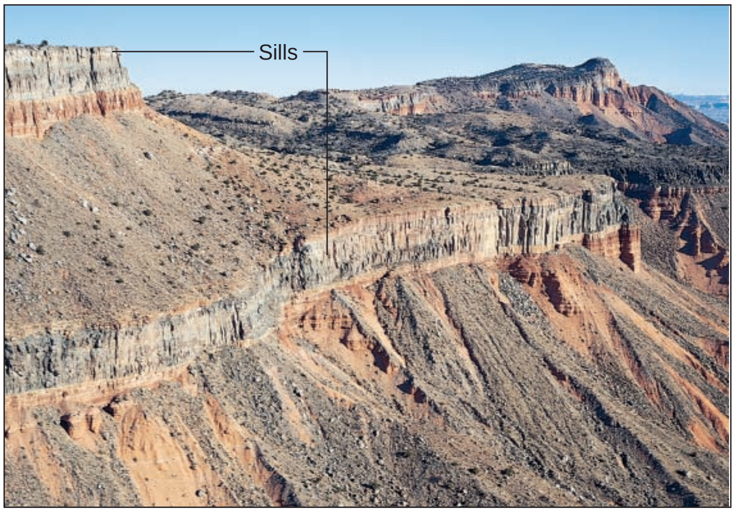


FIGURE 4.18 **Magmatic intrusions** may assume a variety of forms. Batholiths are large masses of coarsely crystalline rock that cools in the major magma chamber. Stocks are smaller masses and may be protrusions from a batholith. Dikes are discordant, tabular bodies formed as magma enters fractures and cools. Many dikes are related to conduits leading to volcanoes. Some radiate out from the volcanic neck; others form a circular pattern above a stock and are called ring dikes. Sills are layers of igneous rock squeezed in between layering. Laccoliths, dome-shaped bodies with flat floors, are formed where magma is able to arch up the overlying strata. Inclusions of the surrounding rock in the magma are called xenoliths. A pipe is a cylindrical conduit through which magma migrates upward.

(C) Dike of dark mafic rock, Bar Harbor, Maine, forms a nearly vertical sheet.



(D) Sills of mafic rock with prominent columnar joints intruded into sedimentary rocks, Capitol Reef National Park, Utah, and form nearly horizontal sheets.

(E) Sierra Nevada batholith in California. Part of the roof (dark-colored metamorphic rock) remains above the granite intrusion (tan rock low on the hillside).

from a magma chamber produces circular or elliptical fracture systems, in which injected magma forms ring dikes (Figure 4.18). Large ring dikes can be as much as 25 km in diameter and thousands of meters deep. Dikes often occur in swarms related to continental rifting that may be hundreds of kilometers across and include numerous separate dikes. After erosion, the surface expression of a dike is usually a long narrow ridge. Dikes can also erode as fast as the surrounding rock, or even faster, and they can form long narrow trenches. A **volcanic neck** forms when magma solidifies in a pipe-like conduit through which lava reaches the surface (Figure 4.18B).

FIGURE 4.19 **Batholiths** are large intrusive bodies; most are composed of many small plutons. For example, the Sierra Nevada batholith of western North America contains hundreds of mapped intrusions. It was formed by multiple intrusive events over a span of about 50 million years. The Peninsular Range batholith, the Idaho batholith, and the Coast Range batholith are similar composite bodies.

Sills

Rising magma follows the path of least resistance. If this path includes a bedding plane, which separates layers of sedimentary rock, magma may be injected between those layers to form a **sill**—a tabular intrusive body parallel to, or concordant with, the layering (Figure 4.18D). Sills range from a few centimeters to hundreds of meters thick and can extend laterally for several kilometers. A sill can resemble a buried lava flow lying within a sequence of sedimentary rock. It is an intrusion, however, squeezed between layers of older rock. The overlying rock is lifted by the intrusion. Many features evident at the contact with adjacent strata can be used to distinguish between a sill and a buried lava flow. For instance, rocks above and below a sill are commonly altered and recrystallized, and a sill shows no signs of weathering on its upper surface. Sills also commonly contain **inclusions,** blocks and pieces of the surrounding rocks. A buried lava flow, in contrast, has an eroded upper surface marked by vesicles; the younger, overlying rock commonly contains fragments of the eroded flow. Sills can form as local offshoots from dikes, or they can be connected directly to a stock or a batholith.

Laccoliths

When viscous magma is injected between layers of sedimentary rock, it may arch up the overlying strata. The resulting intrusive body, a **laccolith,** is lens-shaped, with a flat floor and an arched roof (Figure 4.18A). Laccoliths usually occur in blisterlike groups in areas of flat-lying sedimentary rocks. They can be several kilometers in diameter and thousands of meters thick. Typically, they are porphyritic.

THE ORIGIN AND DIFFERENTIATION OF MAGMA

Magma is formed by melting preexisting solid rock. The wide range of magma compositions is the result of variations in the composition of the source rocks, partial melting, fractional crystallization, assimilation, and magma mixing. Differentiation of mafic magma generally forms silicic magma.

Origin of Magma

Magma can be produced by several processes, all of which involve an attempt to reach equilibrium between solid rock and its environment. Magma is often generated by one of these processes: (1) lowering the pressure; (2) raising the temperature; or (3) by changing the composition of the rock.

Although there are many ways by which these three changes can occur, we outline three of the most common here. As the mantle convects, some portions rise from deeper zones toward the surface. As this happens, the pressure becomes lower and lower and ultimately the mantle may become partially molten. The temperature can increase if hot mafic magma is intruded into the continental crust. This may make the crust hot enough to cause it to partially melt. In the third case, magma can be generated by adding a flux, such as water, to hot but solid mantle. For ex-

FIGURE 4.20 **Plutons exposed in the shield of Egypt** are shown in this satellite image. The batholiths are large, nearly circular masses of highly fractured rock that intrude into older metamorphic rock. The largest plutons are about 30 km across. *(Courtesy of Earth Satellite Corporation/Science Photo Library/Photo Researchers, Inc.)*

ample, experiments show that the addition of only 0.1% water to dry mantle peridotite lowers its temperature of first melting by more than 100°C.

Differentiation of Magma

By now it is probably obvious to you that there are many different kinds of magmas—magmas that have different mineral constituents, magmas that have different element compositions, and magmas that have different temperatures. Moreover, many plutons, lava flows, and ash-flow tuffs reveal that the composition of magma in almost all magma chambers changes as time passes. We call the processes that cause these differences **magmatic differentiation.**

Why is there such great variability in the composition of magma?

One of the major causes of variability in magmas is the variability in composition of the **source rocks** from which the magma formed (Figure 4.21). Obviously, a magma derived from the mantle will be very different (mafic) from a magma formed by melting of the continental crust (silicic). The molten fraction must be in equilibrium with the solid part; consequently, the melt is a reflection of the source from which it is derived. For example, granites derived from melting of sedimentary rocks are distinctive from those produced from other sources.

A second important cause of variation is **partial melting** of magma source rocks (Figure 4.21). Bear in mind that most rocks are composed of more than one mineral (Figure 4.4). Unlike water ice, which melts completely when heated above 0°C, a typical rock does not have a single melting temperature at which it becomes completely molten. Most natural rocks melt over a span of several hundred degrees, with the proportion of melting increasing with temperature. The liquid is different in composition than the solid source. The partial melt is enriched in components of the minerals that melt at low temperatures and depleted in elements that remain in the still-solid minerals. Because of this simple process of partial melting, the liq-

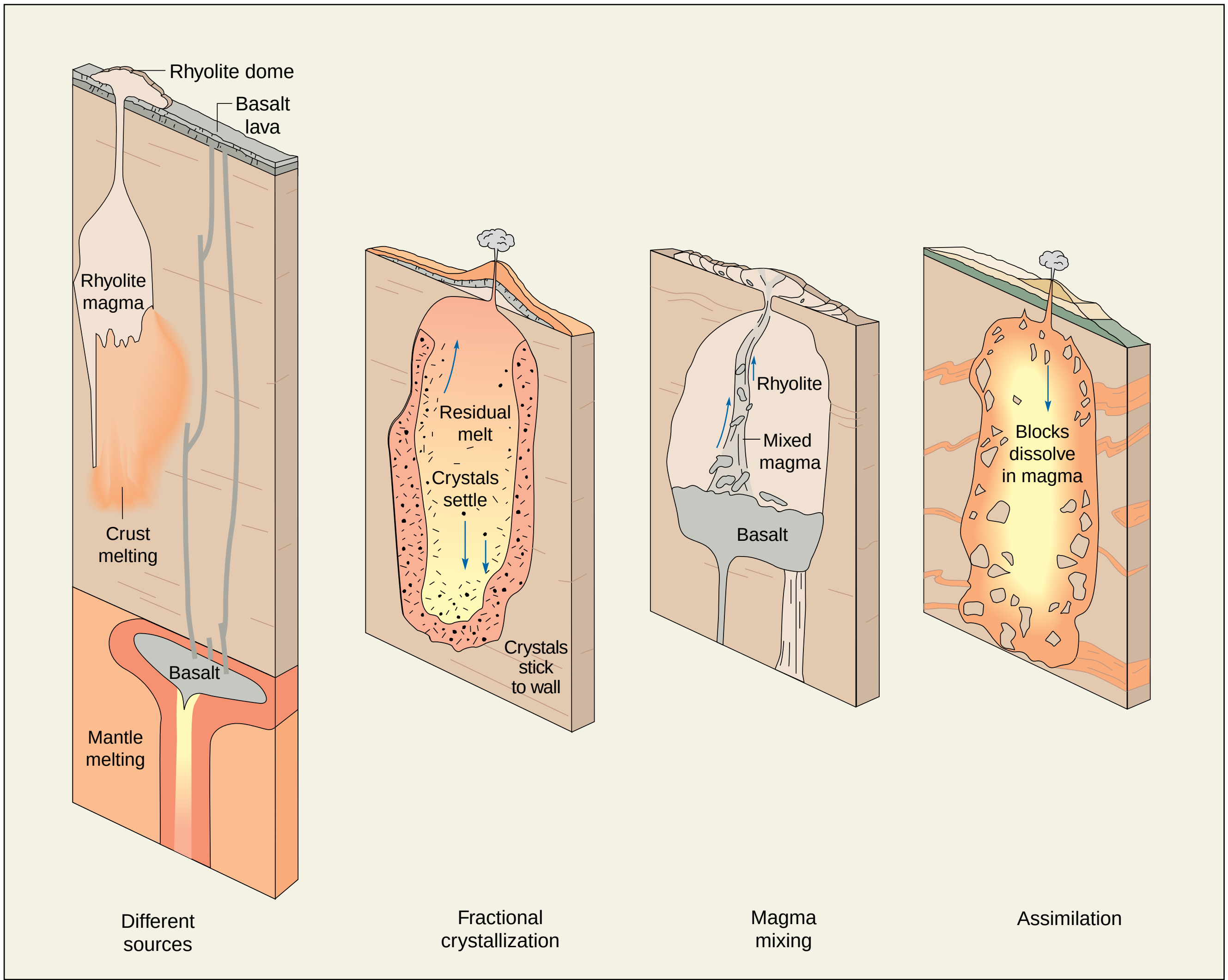


FIGURE 4.21 **Magmatic differentiation** is caused by several processes, including variations in the composition of the source rocks, fractional crystallization, magma mixing, and assimilation of wall rocks. Each of these is in turn controlled by the tectonic setting .

uid is, in nearly all cases, richer in SiO_2 and less dense than the original solid rock. Thus, although the magma is a reflection of its source, it is not a perfect reflection that preserves the exact composition of the source. Consider an extreme but familiar example. A snowball mixed with sand consists of two fundamentally different kinds of minerals with different melting points—water ice and quartz sand. On a cold day, the ice and the quartz coexist as solids. If you place the iceball in a sieve and raise the temperature slightly, the ice melts and pure liquid water flows away from the silicate minerals. As a result of the *partial* melting, the molten water does not have the same composition as the original solid mixture of snow and sand.

When magma cools and equilibrates with its environment, different minerals begin to crystallize at different temperatures and in a sequence that depends on the pressure and composition of the melt. Just as a rock does not melt at a single temperature, a magma does not crystallize completely at one temperature. The general order of crystallization of minerals from common magmas is summarized in Figure 4.22. When partial crystallization occurs, the crystal fraction can be separated from the remaining liquid, leaving a residual melt quite different from the parent magma. This process, **fractional crystallization,** usually makes daughter melts that are richer in SiO_2 than the parent melt. By this process, andesite and rhyolite can be sequentially derived from some basaltic magmas. Crystals can be

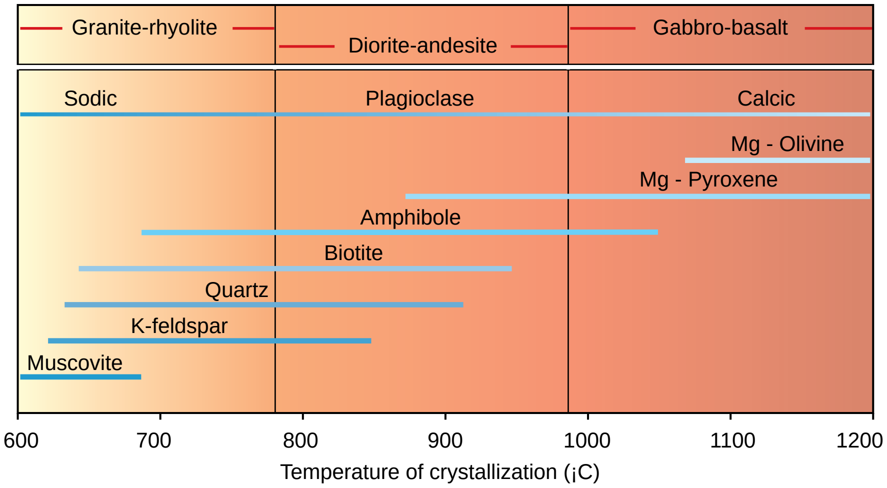


FIGURE 4.22 The temperature of crystallization of common minerals provides a key to the history of a magma. Olivine, pyroxene, and calcium-rich plagioclase crystallize at high temperatures in mafic magmas. Amphibole, plagioclase, and biotite crystallize at intermediate temperatures. Quartz, K-feldspar, sodium-rich plagioclase, and muscovite crystallize at low temperatures in silicic magmas. This sequence of crystallization is sometimes called *Bowen's reaction series* after the geologist whose experiments showed the temperature sequence. Of course, not every magma crystallizes all of these minerals.

removed from a magma by simple gravitational settling or by adhering to the walls of the magma chamber. In either case, the liquid is generally less dense and can flow away from the solids and accumulate in the upper part of the magma chamber (Figure 4.21). Thus, even in a closed magmatic system the composition of the residual melt can become quite different from the original. The elements in some important gems and ores are concentrated by this progressive enrichment process.

The magmatic differentiation processes described above can occur in closed systems, but you can probably imagine ways in which an open magmatic system can become differentiated as well. One obvious mechanism involves the mixing of two different magmas. **Magma mixing** can involve magmas as diverse as basalt and rhyolite (Figure 4.21). Sometimes, the mixing is complete enough to form a homogeneous intermediate, such as andesite. But just as often, the mixing process is evident in the form of blebs of mafic rock incompletely mixed with silicic rock to make a magmatic marble cake. Mixing of magmas is probably a universal process that occurs at all levels of the crust, from initial melting to final eruption.

Another open-system process that differentiates magmas is **assimilation** of the wall rock through which the magma passes (Figure 4.21). Chunks of rock surrounding a magma body may fall into the chamber and become dissolved in the magma. The composition of the magma is changed by the incorporation of these foreign materials.

IGNEOUS ROCKS AND PLATE TECTONICS

At divergent plate margins, basaltic magma is formed as mantle peridotite rises and partially melts. Along convergent plate boundaries, distinctive magmas are generated in the mantle as a result of dehydration of the slab. These magmas may differentiate to form andesite and other silicic magmas. In mantle plumes, basaltic magma is produced when hot solids rise from the deep mantle and the pressure drops. The addition of hot basaltic magma to the continental crust can create rhyolitic magma in many different tectonic settings.

Generation of Magma at Divergent Plate Boundaries

As lithospheric plates move apart at divergent plate boundaries, solid mantle peridotite wells upward to fill the void. As it does, the pressure becomes lower and lower, and conditions appropriate for partial melting are reached at depths of 10 to 30 km (Figure 4.23). The first minerals to melt yield basaltic magma. Laboratory

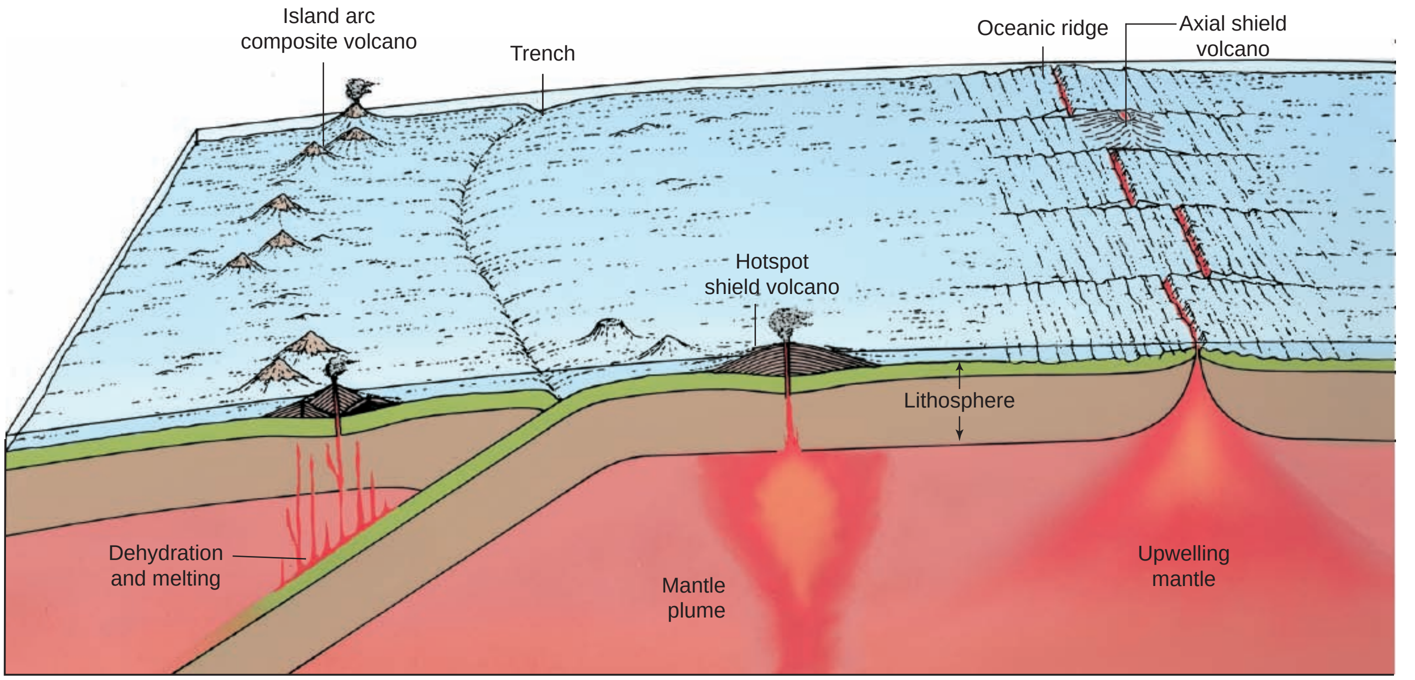


FIGURE 4.23 Magmas form in distinctive tectonic settings, generally related to plate boundaries. Basaltic magma originates by partial melting of the upper mantle at diverging plate margins. As mantle material moves upward in a convection cell, the peridotite (major rock in the mantle) begins to melt because of a decrease in pressure. The material that melts first produces a

experiments on melting peridotite at these pressures show that basaltic magma is produced by 10% to 30% melting. The basaltic magma, being less dense than the still-solid portion of the peridotite, rises beneath the oceanic ridge and creates new oceanic crust by filling a small magma chamber just below the rift floor. Fractional crystallization to form silicic magma is inhibited by repeated injection of new batches of basaltic magma from below. Some magma is extruded to form small shield volcanoes, fissure-fed flows, and pillow basalts. The rest of the magma cools to form intrusive gabbro.

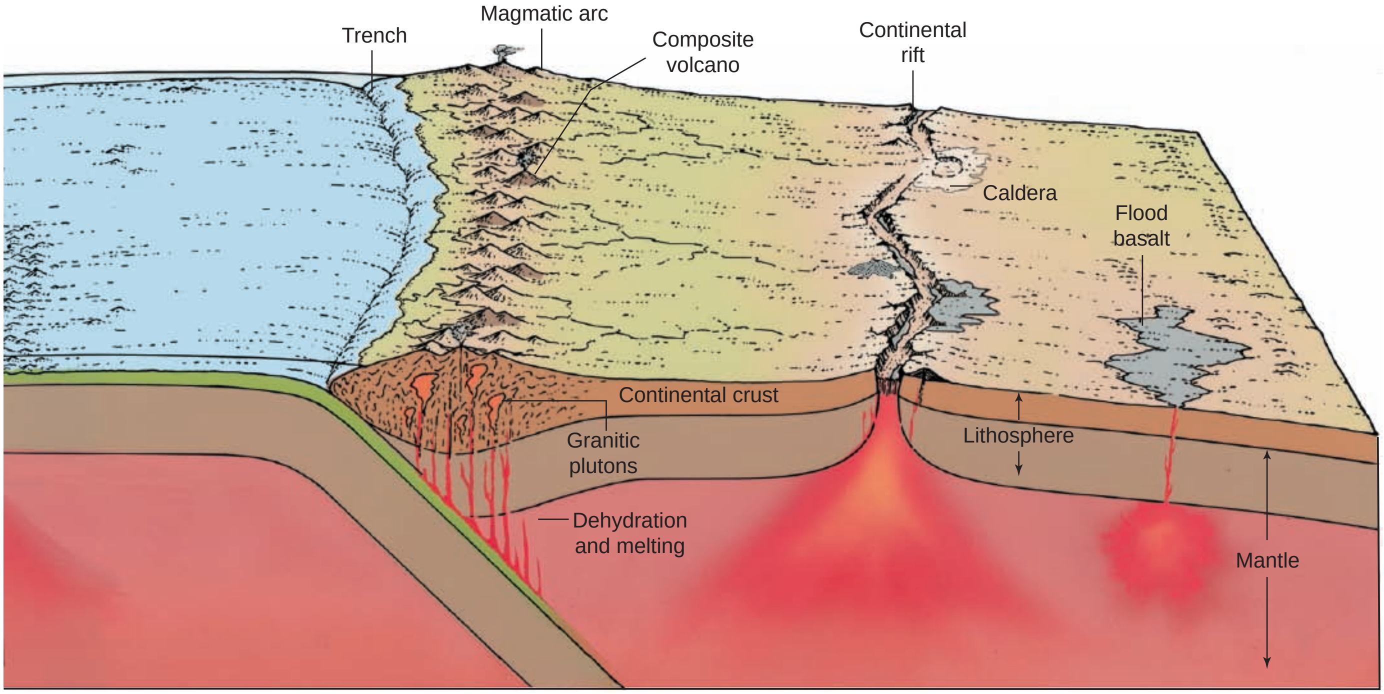
How would a magma derived from the mantle differ from one that formed by partial melting of the continental crust?

If rifting occurs in a slab of continental crust, the hot, dense basaltic magma from the mantle may lodge at or near the base of the crust and cause a second episode of partial melting. Experiments show that such crustal melts are rhyolitic. The low-density rhyolite may rise to the surface and erupt to form small lava domes, or it may accumulate in huge, shallow magma reservoirs that catastrophically erupt to form calderas. Magma intermediate between basalt and rhyolite is rare in continental rift settings.

Generation of Magma at Convergent Plate Boundaries

At convergent plate boundaries, oceanic crust, composed of cold, wet basalt, and a veneer of marine sediment, descends deep into the mantle and is heated (Figure 4.23). At a depth of about 100 km, the temperature becomes high enough so that either the oceanic crust partially melts or the water in its minerals is driven out by dehydration. This low-density fluid rises into the overlying wedge of mantle peridotite and causes it to partially melt. The water acts as a flux to lower the mantle's melting point. Moreover, the resulting magma is rich in water and oxygen derived from the oceanic crust. Fractional crystallization of this magma leads to andesite and rhyolite. In addition, if the magma also interacts with the continental crust, it may become even more silicic as SiO_2-rich crust is assimilated into the magma. Much of this magma stalls in the crust to form plutons that may coalesce into a huge

Why are different types of magma produced at different types of plate boundaries?



magma of basaltic composition. Granitic magma is generated at subduction zones by partial melting and fractional crystallization. As the oceanic crust (containing basalt, oceanic sediments, and water) descends into the mantle, it is heated and dehydrates. The resulting fluid is lighter than the surrounding rock and rises to cause melting in the overlying mantle.

composite batholith, like those unroofed by erosion at ancient convergent plate boundaries. The granites and diorites of California's Sierra Nevada batholith are good examples. Some magma makes its way to the surface to form andesitic composite volcanoes, characteristic of convergent plate boundaries; however, a wide variety of magmas, ranging from basalt to rhyolite, are erupted along with the andesite. Where continents collide, silica-rich magmas like granite develop from the partial melting of continental crust.

What kind of magma is most characteristic of a convergent margin?

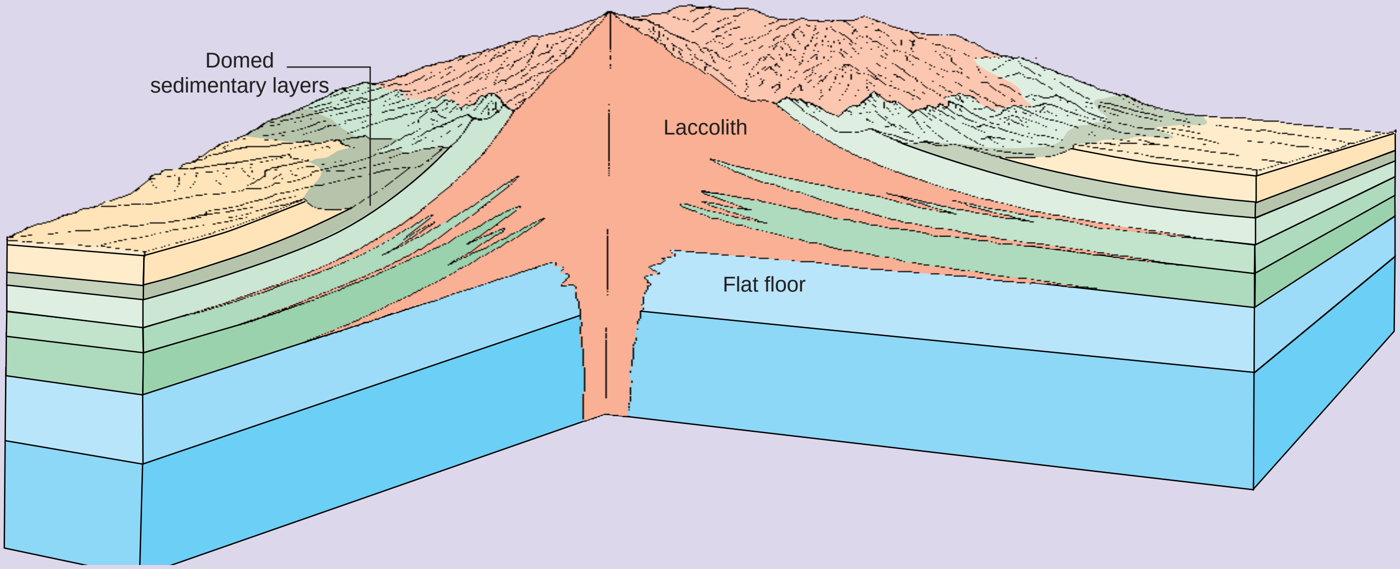
Generation of Magma in Mantle Plumes

The origin of magma in ocean islands found in the middle of the plates far from plate boundaries has long been a mystery. A distinctive type of basalt is found in oceanic islands and seamounts. The details of the composition of these basaltic lavas suggest to many geologists that they are generated by partial melting of rising plumes of solid mantle (Figure 4.23). Presumably, they rise because they are more buoyant and warmer than the rest of the mantle. As the material in the plume nears the surface, the plume partially melts to produce basalt that rises to the surface. The basaltic magma may erupt to form chains of shield volcanoes, like the Hawaiian Islands, or to form large provinces covered by flood basalts. Thus, the magma-generating process is very similar to that at oceanic ridges, but the composition and the shape of the zone of magma generation and eruption are significantly different.

Do all igneous rocks form at some kind of plate boundary?

If hot basaltic magma from a mantle plume impinges on the continental crust, rhyolite may be produced by the melting of continental materials. These rhyolites or intrusive granites are similar to those found in rifts at divergent boundaries. For example, the basaltic lavas of the Snake River Plain and the huge rhyolitic calderas that created the spectacular scenery of Yellowstone National Park may have been powered by heat derived from a mantle plume.

GeoLogic Laccoliths of the Henry Mountains



Several large dome-shaped hills rise above the horizontal sedimentary strata of Utah's Colorado Plateau. They look like huge blisters. How did these distinctive mountains form? How did these mountains appear before erosion? What is the structure of the rocks below the surface? The surface exposures of these rocks provide a clear picture of what lies below each mountain and tell us how they formed.

Observations

1. Each mountain has a core of the coarse-grained igneous rock called diorite.
2. The sedimentary rocks form a nearly circular ring around the diorite.
3. The sedimentary beds are horizontal in the adjacent areas but are upturned to form domes around the diorite masses.
4. Locally, horizontal sedimentary rocks also form a floor below the intrusion.

Interpretations

The diorite was once molten magma. This interpretation is based on the rock's composition, its high temperature minerals, and its texture. Coarse grains indicate the magma cooled slowly below the surface. The magma intruded into and between the layers of sedimentary rock, pushing them upward to form a dome. Originally, the sedimentary rocks completely covered the igneous rocks but erosion has removed much of the sedimentary cover and exposed the core of igneous rocks.

The geologic interpretation of these facts is summarized in the diagram below. Do you see the domal structure in the photograph? Can you infer the extent of the sedimentary rocks before erosion? Is the interpretation logical? Are there other logical interpretations?

KEY TERMS

aa flow (p. 95)
andesite (p. 91)
aphanitic texture (p. 86)
ash (p. 94)
ash flow (p. 98)
ash-flow tuff (p. 94)
ash-flow caldera (p. 99)
assimilation (p. 109)
basalt (p. 91)
batholith (p. 103)
caldera (p. 97)
cinder cone (p. 96)
columnar joint (p. 95)
composite volcano (p. 97)
crater (p. 97)
dike (p. 103)
diorite (p. 91)
extrusive rock (p. 83)
fissure (p. 95)
flood basalts (p. 95)
fractional crystallization (p. 108)
gabbro (p. 91)
glass (p. 85)
glassy texture (p. 85)
granite (p. 89)
groundmass (p. 88)
igneous rock (p. 83)
ignimbrite (p. 94)
inclusion (p. 106)
intrusion (p. 103)
intrusive rock (p. 83)
komatiite (p. 91)
laccolith (p. 106)
lava (p. 83)
lava dome (p. 97)
lava tube (p. 95)
magma (p. 82)
magma mixing (p. 109)
magmatic differentiation (p. 107)
matrix (p. 88)
pahoehoe flow (p. 95)
partial melting (p. 107)
pegmatite (p. 88)
peridotite (p. 91)
phaneritic texture (p. 88)
phenocryst (p. 88)
pillow lava (p. 97)
pluton (p. 103)
porphyritic texture (p. 88)
pressure ridge (p. 95)
pumice (p. 94)
pyroclastic-fall tuff (p. 94)
pyroclastic texture (p. 88)
rhyolite (p. 91)
shield volcano (p. 96)
sill (p. 106)
source rock (p. 107)
spatter cone (p. 95)
stock (p. 103)
stratovolcano (p. 97)
tephra (p. 94)
texture (p. 85)
thin section (p. 91)
tuff (p. 94)
vesicle (p. 86)
viscosity (p. 83)
volatile (p. 84)
volcanic ash (p. 96)
volcanic bomb (p. 96)
volcanic neck (p. 106)
welded tuff (p. 98)

REVIEW QUESTIONS

1. Define the term *magma.*
2. Name the principal gases (volatiles) in magma.
3. Name two principal types of magma.
4. List the major types of igneous rock textures. Why is texture important in the study of rocks?
5. List the major types of igneous rocks, and briefly describe their texture and composition.
6. Describe some common surface features of basaltic flows.
7. Why does magma tend to rise upward toward Earth's surface?
8. Draw a series of diagrams showing the form and internal structure of (a) a cinder cone, (b) a composite volcano, and (c) a shield volcano.
9. Describe the events that are typically involved in the formation of a caldera.
10. Describe the extrusion of an ash flow.
11. Describe and illustrate the major types of igneous intrusions. What is the textural difference between intrusive rocks and extrusive rocks?
12. Explain how an igneous rock can be produced from magma that does not have the same composition as the rock from which it melts.
13. What is fractional crystallization?
14. Draw a simple diagram and explain how basaltic magma originates from the partial melting of the mantle at divergent plate boundaries or at a mantle plume.
15. Draw a simple diagram, and explain how granitic and andesitic magma originate in a subduction zone.
16. Why can't a basalt be produced by partial melting of a granite?

ADDITIONAL READINGS

Best, M. G., and E. H. Christiansen. 2000. *Igneous Petrology.* Boston: Blackwell.
Blatt, H., and R. J. Tracy. 1996. *Petrology: Igneous, Sedimentary, and Metamorphic.* New York: Freeman.
Decker, R., and B. Decker. 1998. *Volcanoes*. New York: Freeman.
MacKenzie, W. S., C. H. Donaldson, and C. Guilford. 1982. *Atlas of Igneous Rocks and Their Textures.* New York: Halstead Press.
Winter, J. D. 2002. *An Introduction to Igneous and Metamorphic Petrology*. Upper Saddle River, NJ: Prentice Hall.

MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of crystallization of liquids
- Video clips of volcanic eruptions
- Slide shows with examples of igneous rocks
- A direct link to the Companion Website