5

Volcanoes & Volcanic Hazards

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:

5.1 Compare and contrast the 1980 eruption of Mount St. Helens with the most recent eruption of Kilauea, which began in 1983.

5.2 Explain why some volcanic eruptions are explosive and others are quiescent.

5.3 List and describe the three categories of materials extruded during volcanic eruptions.

5.4 Draw and label a diagram that illustrates the basic features of a typical volcanic cone.

5.5 Summarize the characteristics of shield volcanoes and provide one example of this type of volcano.

5.6 Describe the formation, size, and composition of cinder cones.

5.7 List the characteristics of composite volcanoes and describe how they form.

5.8 Describe the major geologic hazards associated with volcanoes.

5.9 List volcanic landforms other than shield, cinder cone, and composite volcanoes and describe their formation.

5.10 Explain how the global distribution of volcanic activity is related to plate tectonics.

Reventador ejecting volcanic bombs and incandescent ash at night, November 2015. This volcano, which is located in the Andes of Ecuador, has erupted more than 25 times since 1541. (Photo by Morely Read/Getty Images)

THE SIGNIFICANCE OF IGNEOUS ACTIVITY may not be obvious at first glance. However, because volcanoes extrude molten rock that formed at great depth, they provide our only means of directly observing processes that occur many kilometers below Earth's surface. Furthermore, Earth's atmosphere and oceans have evolved from gases emitted during volcanic eruptions. Either of these facts is reason enough for igneous activity to warrant our attention.

5.1 Mount St. Helens Versus Kilauea

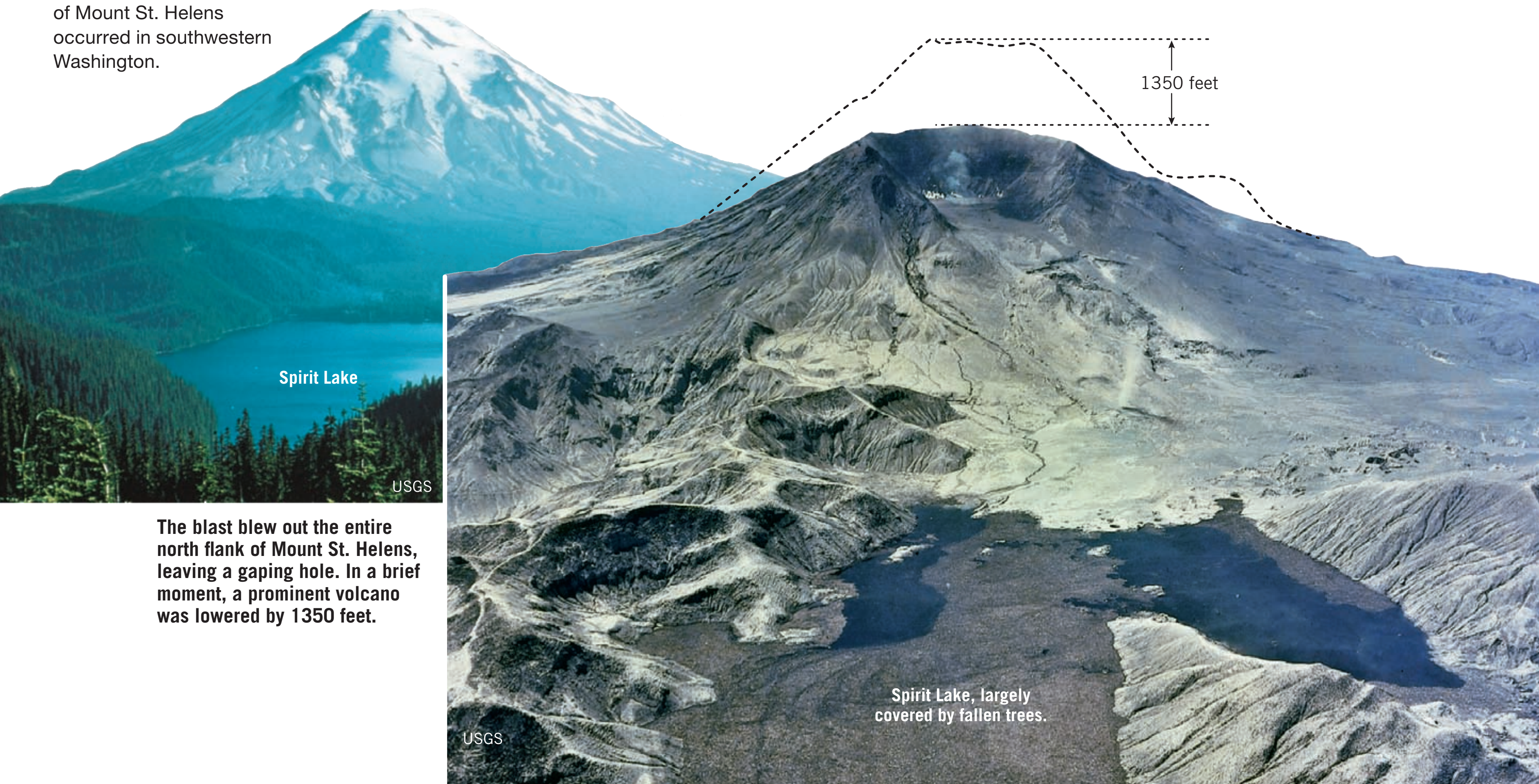
Compare and contrast the 1980 eruption of Mount St. Helens with the most recent eruption of Kilauea, which began in 1983.

On May 18, 1980, the largest volcanic eruption to occur in North America in historic times transformed a picturesque volcano into a decapitated remnant (**Figure 5.1**). On that date in southwestern Washington State, Mount St. Helens erupted with tremendous force. The blast blew out the entire north flank of the volcano, leaving a gaping hole. In one brief moment, a prominent volcano whose summit had been more than 2900 meters (9500 feet) above sea level was lowered by more than 400 meters (1350 feet).

The event devastated a wide swath of timber-rich land on the north side of the mountain (**Figure 5.2**). Trees within a 400-square-kilometer (160-square-mile) area lay intertwined and flattened, stripped of their branches and appearing from the air like toothpicks strewn about. The accompanying mudflows carried ash, trees, and water-saturated rock debris 29 kilometers (18 miles) down the Toutle River. The eruption claimed 59 lives; some died from the intense heat and the suffocating cloud of ash and gases, others from the impact of the blast, and still others from being trapped in mudflows.

The eruption ejected nearly a cubic kilometer of ash and rock debris. Following the devastating explosion, Mount St. Helens continued to emit great quantities of hot gases and ash. The force of the blast was so strong that some ash was propelled more than 18 kilometers (over 11 miles) into the stratosphere. During the next few days, this very fine-grained material was carried around Earth by strong upper-air winds. Crops were damaged in central Montana, and measurable deposits were reported

▼ **Figure 5.1 Before-and-after photographs show the transformation of Mount St. Helens** The May 18, 1980, eruption of Mount St. Helens occurred in southwestern Washington.



The blast blew out the entire north flank of Mount St. Helens, leaving a gaping hole. In a brief moment, a prominent volcano was lowered by 1350 feet.

as far away as Oklahoma and Minnesota. Meanwhile, ash fallout in the immediate vicinity exceeded 2 meters (6 feet) in depth. The air over Yakima, Washington (130 kilometers [80 miles] to the east), was so filled with ash that residents experienced midnight-like darkness at noon.

Not all volcanic eruptions are as violent as the 1980 Mount St. Helens event. Some volcanoes, such as Hawaii's Kilauea Volcano, generate relatively quiet outpourings of fluid lavas. These quiescent (non-explosive) eruptions are not without some fiery displays; occasionally fountains of incandescent lava spray hundreds of meters into the air (see Figure 5.4), but most lava pours from the vent and flows downslope. During Kilauea's most recent active phase, which began in 1983, more than 180 homes and a national park visitor center have been destroyed by flowing lava igniting material in its path.

Testimony to the quiescent nature of Kilauea's eruptions is the fact that the Hawaiian Volcanoes Observatory has operated on its summit since 1912, despite the fact that Kilauea has had more than 50 eruptive phases since record keeping began in 1823.

▲ **Figure 5.2 Douglas fir trees snapped off or uprooted by the lateral blast of Mount St. Helens** (Large photo by Lyn Topinka/AP Photo/U.S. Geological Survey; inset photo by John M. Burnley/Photo Researchers, Inc.)

CONCEPT CHECKS 5.1

1. Briefly compare the 1980 eruption of Mount St. Helens to a typical eruption of Hawaii's Kilauea Volcano.

5.2 The Nature of Volcanic Eruptions

Explain why some volcanic eruptions are explosive and others are quiescent.

Volcanic activity is commonly perceived as a process that produces a picturesque, cone-shaped structure that periodically erupts in a violent manner. However, many eruptions are not explosive, as indicated by Kilauea's activity. What determines the manner in which volcanoes erupt?

Magma: Source Material for Volcanic Eruptions

Recall that **magma**, molten rock that may contain some solid crystalline material and also contains varying amounts of dissolved gas (mainly water vapor and carbon dioxide), is the parent material of igneous rocks. Erupted magma is called **lava**.

Composition of Magma As we discussed in Chapter 4, *mafic* (basaltic) igneous rocks contain a high percentage of dark silicate minerals and calcium-rich plagioclase feldspar, and as a result, they tend to be dark in color. By contrast, *felsic* rocks (granite and its extrusive equivalent, rhyolite) contain mainly light-colored silicate minerals—quartz and potassium feldspar. *Intermediate* (andesitic) rocks have a composition between mafic and felsic rocks. Correspondingly, mafic magmas contain a much *lower* percentage of silica (SiO_2) than do felsic magmas. The compositional differences between magmas also affect several other properties, as summarized in **Figure 5.3**. As shown in Figure 5.3 mafic (basaltic) magmas have the lowest silica content and the lowest gas content, and they erupt at the highest temperatures. By contrast, felsic (granitic or rhyolitic) magmas have the highest silica content and the highest gas content, and they erupt at the lowest temperatures. Intermediate magmas have characteristics between mafic and felsic magmas.

Where Is Magma Generated? Recall that most magma is generated in Earth's upper mantle (asthenosphere) by *partial melting of solid rock*. The magmas generated by melting mantle rocks tend to have basaltic (mafic) composition. Once formed, basaltic magma, which is less dense than the surrounding rocks, slowly rises toward Earth's surface. In some settings, this hot molten rock reaches the surface, where it usually produces fluid outflows of basaltic lavas. As a result of seafloor spreading, the largest quantity of basaltic magma erupts on the

Did You Know?
The eruption of Tambora, in Indonesia, in 1815 is the largest known volcanic event in modern history. About 20 times more ash and rock were explosively ejected during this eruption than were emitted during the 1980 Mount St. Helens event. The sound of the explosion was heard an incredible 4800 km (3000 mi) away, about the distance across the conterminous United States.

Figure 5.3 **Compositional differences of magma bodies cause their properties to vary**

Properties of Magma Bodies with Differing Compositions

Composition	Silica Content (SiO_2)	Gas Content (% by weight)	Eruptive Temperature	Viscosity	Tendency to Form Pyroclastics	Volcanic Landform
Mafic (Basaltic) High in Fe, Mg, Ca, low in K, Na	**Least** (~50%)	**Least** (0.5–2%)	**Highest** 1000–1250°C	**Least**	**Least**	Shield volcanoes, basalt plateaus, cinder cones
Intermediate (Andesitic) Varying amounts of Fe, Mg, Ca, K, Na	**Intermediate** (~60%)	**Intermediate** (3–4%)	**Intermediate** 800–1050°C	**Intermediate**	**Intermediate**	Composite cones
Felsic (Granitic/Rhyolitic) High in K, Na, low in Fe, Mg, Ca	**Most** (~70%)	**Most** (5–8%)	**Lowest** 650–900°C	**Greatest**	**Greatest**	Pyroclastic flow deposits, lava domes

ocean floor along divergent plate boundaries. Extensive basaltic flows are also the product of hot-spot volcanism generated by rising hot mantle plumes (see Figure 2.26 on page 54).

In continental settings, however, overlying crustal rocks are usually less dense than the ascending basaltic magma, and as a result, the rising molten rock ponds at the crust–mantle boundary. Because the newly formed magma is much hotter than the melting temperature of crustal rocks, the rocks overlying the magma body begin to melt. This process generates a less dense, more silica-rich magma of intermediate or felsic composition, which then continues the journey toward Earth's surface.

Effusive Versus Explosive Eruptions

Volcanic eruptions exhibit a range of behavior from quiescent eruptions that produce outpourings of fluid lava to explosive eruptions. Geologists often refer to quiescent eruptions as **effusive** (meaning "pouring out") **eruptions**.

The two primary factors that determine how magma erupts are its *viscosity* and *gas content*. **Viscosity** (*viscos* = sticky) is a measure of a fluid's mobility. The more viscous a material, the greater its resistance to flow. For example, pancake syrup is more viscous, and thus more resistant to flow, than water.

Factors Affecting Viscosity Magma's viscosity depends primarily on its temperature and silica content: *The more silica in magma, the greater its viscosity*. Silicate structures begin to link together into long chains early in the crystallization process, which makes the magma more rigid and impedes its flow. Consequently, silica-rich felsic (rhyolitic) lavas are the most viscous and tend to travel at imperceptibly slow speeds to form comparatively short, thick flows. By contrast, mafic (basaltic) lavas, which contain much less silica, are relatively fluid and have been known to travel 150 kilometers (90 miles) or more before solidifying. Intermediate (andesitic) magmas have flow rates between these extremes.

Temperature affects the viscosity of magma in much the same way it affects the viscosity of pancake syrup: The hotter a magma, the more fluid (less viscous) it will be. As lava cools and begins to congeal, its viscosity increases, and the flow eventually halts.

Role of Gases The nature of volcanic eruptions also depends on the amount of dissolved gases held in the magma body by the pressure exerted by the overlying rock (the confining pressure). The most abundant gases in most magmas are water vapor and carbon dioxide. These dissolved gases tend to come out of solution when the confining pressure is reduced. This is analogous to how carbon dioxide is retained in cans and bottles of soft drinks. When the pressure is reduced on a soft drink by opening the cap, the dissolved carbon dioxide quickly separates from the solution to form bubbles that rise and escape.

The viscosity and gas content of magma are directly related to its composition, as shown in Figure 5.3. At one end of the spectrum are basaltic (mafic) magmas, which are very fluid and have a low gas content, sometimes as little as 0.5 percent by weight. At the other extreme are rhyolitic (felsic) magmas, which are highly viscous (sticky) and contain a lot of gas, as much as 8 percent by weight.

Effusive Hawaiian-Type Eruptions

All magmas contain some water vapor and other gases that are kept in solution by the immense pressure of the overlying rock. As magma rises (or the rocks confining the magma fail), the confining pressure drops, causing the dissolved gases to separate from the melt and form large numbers of tiny bubbles. When fluid basaltic magmas erupt, these pressurized gases readily escape. At temperatures that often exceed 1100°C (2000°F), these gases can quickly expand to occupy hundreds of times their original volumes. Occasionally, these expanding gases propel incandescent lava hundreds of meters into the air, producing lava fountains (**Figure 5.4**). Although spectacular, these fountains are usually harmless and generally not associated with major explosive events that cause great loss of life and property.

Eruptions that involve very fluid basaltic lavas, such as the recent eruptions of Kilauea on Hawaii's Big Island, are often triggered by the arrival of a new batch of molten rock, which accumulates in a near-surface magma chamber. Geologists can usually detect such an event because the summit of the volcano begins to inflate and rise months or even years before an eruption. The injection of a fresh supply of hot molten rock heats and remobilizes the semi-liquid magma in the chamber. In addition, swelling of the magma chamber fractures the rock above, allowing the fluid magma to move upward along the newly formed fissures, often generating effusions of fluid lava for weeks, months, or possibly years. The eruption of Kilauea that began in 1983 is ongoing.

How Explosive Eruptions Are Triggered

Recall that silica-rich rhyolitic magmas have a relatively high gas content and are quite viscous (sticky) compared to basaltic magmas. As rhyolitic magma rises, the gases remain dissolved until the confining pressure drops sufficiently, at which time tiny bubbles begin to form and increase in size. Because of the high viscosity of rhyolitic magma, gas bubbles tend to remain trapped in the magma, forming a sticky froth.

When the pressure exerted by the expanding magma exceeds the strength of the overlying rock, fracturing occurs. As the frothy magma moves up through the fractures, a further drop in confining pressure creates additional gas bubbles. This chain reaction often generates an explosive event in which magma is literally blown into fragments (ash and pumice) that are carried to great heights by the escaping hot gases. (The collapse of a volcano's flank can also greatly reduce the pressure on the magma below, causing an explosive eruption, as exemplified by the 1980 eruption of Mount St. Helens.)

▲ **Figure 5.4 Lava fountain produced by gases escaping fluid basaltic lava** Kilauea, on Hawaii's Big Island, is one of the most active volcanoes on Earth. (Photo by David Reggie/Getty Images)

▲ **SmartFigure 5.5**
Eruption column generated by viscous, silica-rich magma Steam and ash eruption column from Mount Sinabung, Indonesia, 2014. A deadly cloud of fiery ash can be seen racing down the volcano's slope in the foreground. (Photo by REUTERS/Beawiharta)

VIDEO
https://goo.gl/RH97D7

When molten rock in the uppermost portion of the magma chamber is forcefully ejected by the escaping gases, the confining pressure on the magma directly below also drops suddenly. Thus, rather than being a single "bang," an explosive eruption is really a series of violent explosions that can last for a few days.

Because highly gaseous magmas expel fragmented lava at nearly supersonic speeds, they are associated with hot, buoyant **eruption columns** consisting mainly of volcanic ash and gases (**Figure 5.5**). Eruption columns can rise perhaps 40 kilometers (25 miles) into the atmosphere. It is not uncommon for a portion of an eruption column to collapse, sending hot ash rushing down the volcanic slope at speeds exceeding 100 kilometers (60 miles) per hour. As a result, volcanoes that erupt highly viscous magmas having a high gas content are the most destructive to property and human life.

Following explosive eruptions, partially degassed lava may slowly ooze out of the vent to form thick lava flows or dome-shaped lava bodies that grow over the vent.

CONCEPT CHECKS 5.2

1. List these magmas in order, from the most silica rich to the least silica rich: mafic (basaltic) magma, felsic (rhyolitic) magma, intermediate (andesitic) magma.
2. List the two primary factors that determine the manner in which magma erupts.
3. Define *viscosity*.
4. Are volcanoes fed by highly viscous magma *more* or *less likely* to be a greater threat to life and property than volcanoes supplied with very fluid magma?

5.3 Materials Extruded During an Eruption

List and describe the three categories of materials extruded during volcanic eruptions.

Volcanoes erupt lava, large volumes of gas, and pyroclastic materials (broken rock, lava "bombs," and ash). In this section we will examine each of these materials.

Lava Flows

The vast majority of Earth's lava, more than 90 percent of the total volume, is estimated to be mafic (basaltic) in composition. Most of mafic lavas erupt on the seafloor, via a process known as *submarine volcanism*. Lavas having an intermediate (andesitic) composition account for most of the rest, while felsic (rhyolitic) flows make up as little as 1 percent of the total. Rhyolitic magmas tend to extrude mostly volcanic ash rather than lava.

On land, hot basaltic lavas, which are usually very fluid, generally flow in thin, broad sheets or streamlike ribbons. Fluid basaltic lavas have been clocked at speeds exceeding 30 kilometers (19 miles) per hour down steep slopes. However, flow rates of 10 to 300 meters (30 to 1000 feet) per hour are more common. Silica-rich rhyolitic lava, by contrast, often moves too slowly to be perceived. Furthermore, rhyolitic lavas seldom travel more than a few kilometers from their vents. As you might expect, andesitic lavas, which are intermediate in composition, exhibit flow characteristics between these extremes.

Aa & Pahoehoe Flows Fluid basaltic magmas tend to generate two types of lava flows, which are known by their Hawaiian names. The first, called **aa** (pronounced "ah-ah") **flows**, have surfaces of rough jagged blocks with dangerously sharp edges and spiny projections (Figure 5.6A). Crossing a hardened aa flow can be a trying and miserable experience. The second type, **pahoehoe** (pronounced "pah-hoy-hoy") **flows**, exhibit smooth surfaces that sometimes resemble twisted braids of ropes (Figure 5.6B).

Although both lava types can erupt from the same volcano, pahoehoe lavas are hotter and more fluid than aa flows. In addition, pahoehoe lavas can change into aa lava flows, although the reverse (aa to pahoehoe) does not occur.

Cooling that occurs as the flow moves away from the vent is one factor that facilitates the change from pahoehoe to aa. The lower temperature increases viscosity and promotes bubble formation. Escaping gas bubbles produce numerous voids (vesicles) and sharp spines in the surface of the congealing lava. As the molten interior advances, the outer crust is broken, transforming the relatively smooth surface of a pahoehoe flow into an aa flow made up of an advancing mass of rough, sharp, broken lava blocks.

Pahoehoe flows often develop cave-like tunnels called **lava tubes** that start as conduits for carrying lava from an active vent to the flow's leading edge (Figure 5.7). Lava tubes form in the interior of a lava flow, where the temperature remains high long after the exposed surface cools and hardens. Because they serve as insulated pathways that allow lava to flow great distances from its source, lava tubes are important features of fluid lava flows.

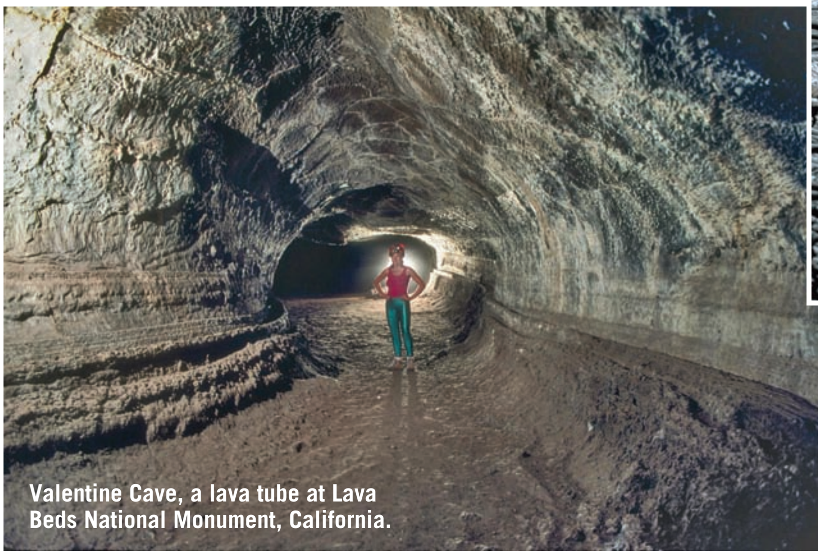
Pillow Lavas Recall that most of Earth's volcanic output occurs along oceanic ridges (divergent plate boundaries), generating new oceanic crust. When outpourings of lava occur on the ocean floor, the flow's outer skin quickly

▼ **Figure 5.6 Lava flows A.** A slow-moving, basaltic aa flow advancing over hardened pahoehoe lava. **B.** A typical fluid pahoehoe (ropy) lava. Both of these lava flows erupted from a rift on the flank of Hawaii's Kilauea Volcano. (Photos courtesy of U.S. Geological Survey)

A. Active aa flow overriding an older pahoehoe flow.

B. Pahoehoe flow displaying the characteristic ropy appearance.

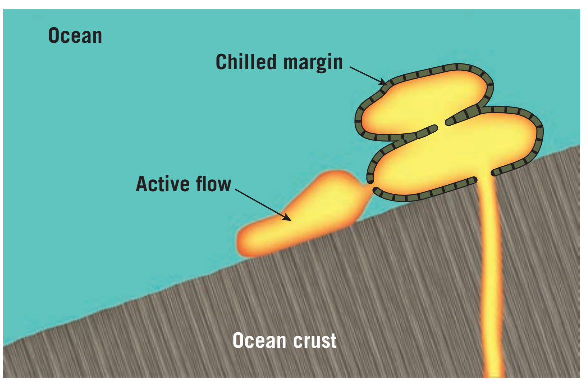
A. Lava tubes are cave-like tunnels that once served as conduits carrying lava from an active vent to the flow's leading edge.



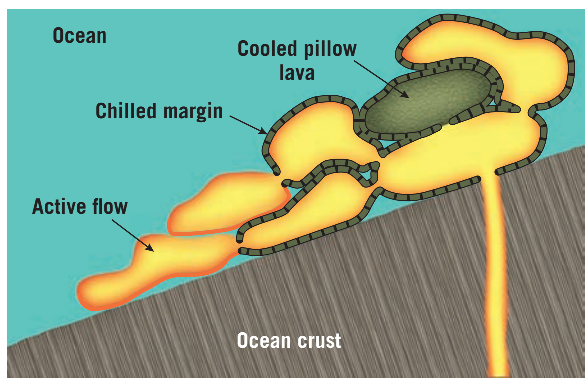
B. Skylights develop where the roofs of lava tubes collapse and reveal the hot lava flowing through the tube.

▲ **Figure 5.7 Lava tubes A.** A lava flow may develop a solid upper crust, while the molten lava below continues to advance in a conduit called a *lava tube*. Some lava tubes exhibit extraordinary dimensions. Kazumura Cave, located on the southeastern slope of Hawaii's Mauna Loa Volcano, is a lava tube extending more than 60 kilometers (40 miles). (Photo by Dave Bunell) **B.** The collapsed section of the roof of a lava tunnel results in a skylight. (Photo courtesy of U.S. Geological Survey)

freezes (solidifies) to form volcanic glass. However, the interior lava is able to move forward by breaking through the hardened surface. This process occurs over and over, as molten basalt is extruded like toothpaste from a tightly squeezed tube. The result is a lava flow composed of numerous tube-like structures called **pillow lavas**, stacked one atop the other (**Figure 5.8**). Pillow lavas are useful when reconstructing geologic history because their presence indicates that the lava flow formed below the surface of a water body.



A.



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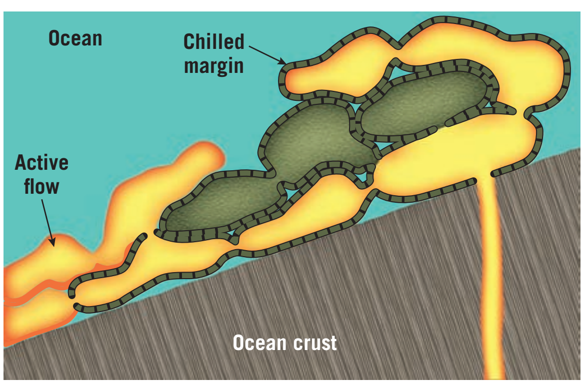


C.

D.

► **Figure 5.8 Pillow lava** These diagrams show the formation of pillow lava. The pillows tend to be elongated tube-like structures and are often variable in shape. The photo shows an undersea pillow lava flow off the coast of Hawaii. (Photo courtesy of U.S. Geological Survey)

Block Lavas In contrast to fluid basaltic magmas that can travel many kilometers, viscous andesitic and rhyolitic magmas tend to generate relatively short prominent flows—a few hundred meters to a few kilometers long. Their upper surface consists largely of massive, detached blocks—hence the name **block lava**. Although similar to aa flows, these lavas consist of blocks with slightly curved, smooth surfaces rather than the rough, sharp, spiny surfaces typical of aa flows.

Gases

Recall that magmas contain varying amounts of dissolved gases, called **volatiles**. These gases are held in the molten rock by confining pressure, just as carbon dioxide is held in cans of soft drinks. As with soft drinks, as soon as the pressure is reduced, the gases begin to escape. Obtaining gas samples from an erupting volcano is difficult and dangerous, so geologists usually must estimate the amount of gas originally contained in the magma.

The gaseous portion of most magma bodies ranges from less than 1 percent to about 8 percent of the total weight, with most of this in the form of water vapor. Although the percentage may be small, the actual quantity of emitted gas can exceed thousands of tons per day. Occasionally, eruptions emit colossal amounts of volcanic gases that rise high into the atmosphere, where they may reside for several years.

The composition of volcanic gases is important because these gases contribute significantly to our planet's atmosphere. The most abundant gas typically released into the atmosphere from volcanoes is water vapor (H_2O), followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2), with lesser amounts of hydrogen sulfide (H_2S), carbon monoxide (CO), and helium (H_2). (The relative proportion of each gas varies significantly from one volcanic region to another.) Sulfur compounds are easily recognized by their pungent odor. Volcanoes are also natural sources of air pollution; some emit large quantities of sulfur dioxide (SO_2), which readily combines with atmospheric gases to form toxic sulfuric acid and other sulfate compounds.

Pyroclastic Materials

When volcanoes erupt energetically, they eject pulverized rock and fragments of lava and glass from the vent. The particles produced, **pyroclastic materials** (*pyro* = fire, *clast* = fragment), are also called **tephra**. These fragments range in size from very fine dust and sand-sized volcanic ash (less than 2 millimeters) to pieces that weigh several tons (Figure 5.9).

Ash and *dust* particles are produced when gas-rich viscous magma erupts explosively. As magma moves up in the vent, the gases rapidly expand, generating a melt that resembles the froth that flows from a bottle of champagne. As the hot gases expand explosively, the froth is blown into very fine glassy fragments. When the hot ash falls, the glassy shards often fuse to form a rock called *welded tuff*. Sheets of this material, as well as ash deposits that later consolidate, cover vast portions of the western United States.

Somewhat larger pyroclasts that range in size from small beads to walnuts (2–64 millimeters [0.08–2.5 inches] in diameter) are known as *lapilli* ("little stones") or *cinders*. Particles larger than 64 millimeters (2.5 inches) in diameter are called *blocks* when they are made of hardened lava and *bombs* when they are ejected as incandescent lava (see Figure 5.7). Because bombs are semimolten when ejected, they often take on a streamlined

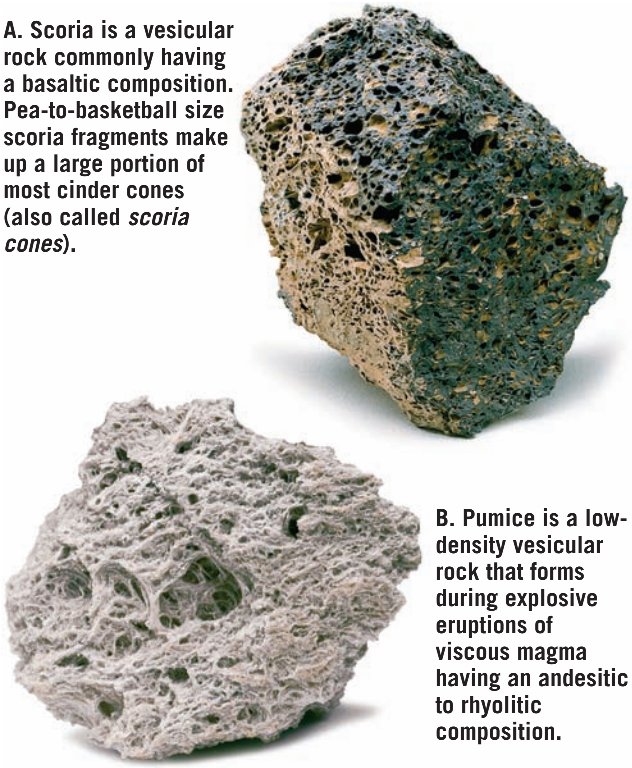
Pyroclastic Materials (Tephra)

Particle name	Particle size	Image
Volcanic ash*	Less than 2 mm (0.08 inch)	
Lapilli (Cinders)	Between 2 mm and 64 mm (0.08–2.5 inches)	
Volcanic bombs	More than 64 mm (2.5 inches)	
Volcanic blocks		

*The term volcanic dust is used for fine volcanic ash less than 0.063 mm (0.0025 inch).

▲ **Figure 5.9 Types of pyroclastic materials** Pyroclastic materials are also commonly referred to as tephra.

▶ **Figure 5.10 Common vesicular rocks** Scoria and pumice are volcanic rocks that exhibit a vesicular texture. Vesicles are small holes left by escaping gas bubbles. (Photos by E.J. Tarbuck)



A. Scoria is a vesicular rock commonly having a basaltic composition. Pea-to-basketball size scoria fragments make up a large portion of most cinder cones (also called *scoria cones*).

B. Pumice is a low-density vesicular rock that forms during explosive eruptions of viscous magma having an andesitic to rhyolitic composition.

shape as they hurl through the air. Because of their size and weight, bombs and blocks usually fall near the vent; however, they are occasionally propelled great distances. For instance, bombs 6 meters (20 feet) long and weighing about 200 tons were blown 600 meters (2000 feet) from the vent during an eruption of the Japanese volcano Asama.

Pyroclastic materials can be classified by texture and composition as well as by size. For instance, **scoria** is the term for vesicular ejecta produced most often during the eruption of basaltic magmas (Figure 5.10). These black to reddish-brown fragments are generally found in the size range of lapilli and resemble cinders and clinkers produced by furnaces used to smelt iron.

By contrast, when magmas with andesitic (intermediate) or rhyolitic (felsic) compositions erupt explosively, they emit ash and the vesicular rock **pumice** (Figure 5.10B). Pumice is usually lighter in color and less dense than scoria, and many pumice fragments have so many vesicles that they are light enough to float (see Figure 4.14, page 106).

CONCEPT CHECKS 5.3

1. Contrast pahoehoe and aa lava flows.
2. How do lava tubes form?
3. List the main gases released during a volcanic eruption.
4. How do volcanic bombs differ from blocks of pyroclastic debris?
5. What is scoria? How is scoria different from pumice?

5.4 Anatomy of a Volcano

Draw and label a diagram that illustrates the basic features of a typical volcanic cone.

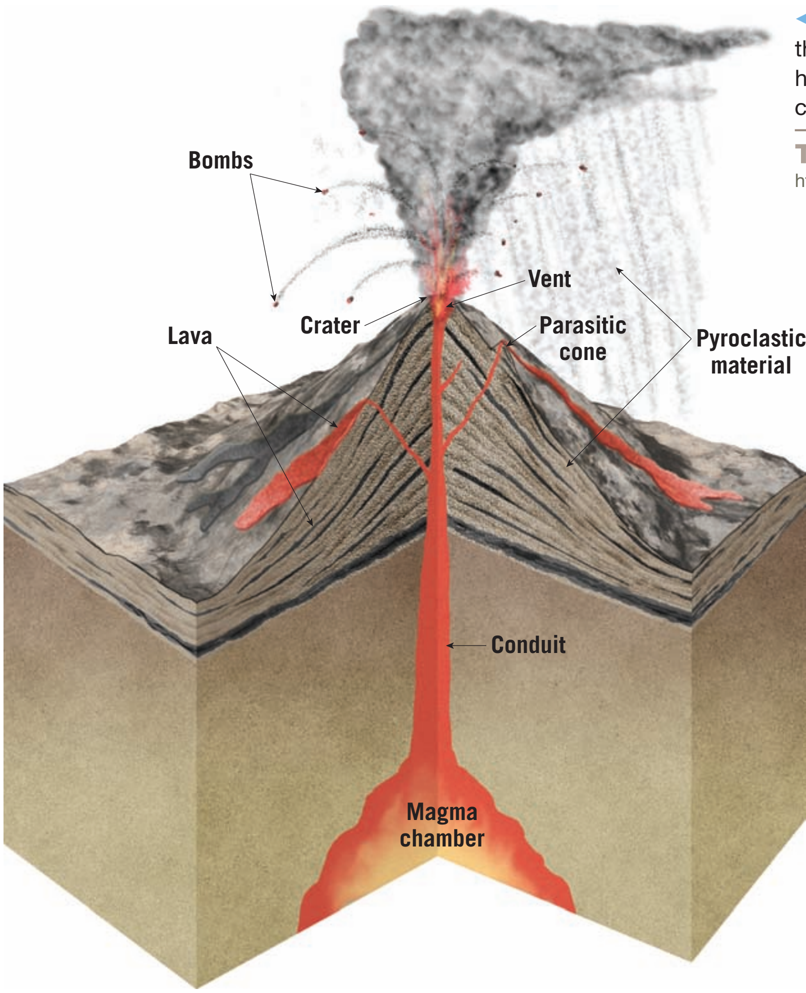
A popular image of a volcano is a solitary, graceful, snow-capped cone, such as Mount Hood in Oregon or Japan's Fujiyama. These picturesque, conical mountains are produced by volcanic activity that occurred intermittently over thousands, or even hundreds of thousands, of years. However, many volcanoes do not fit this image. Cinder cones are quite small and form during a single eruptive phase that lasts a few days to a few years. Alaska's Valley of Ten Thousand Smokes is a flat-topped ash deposit that blanketed a river valley to a depth of 200 meters (600 feet). The eruption that produced it lasted less than 60 hours yet emitted more than 20 times more volcanic material than the 1980 Mount St. Helens eruption.

Volcanic landforms come in a wide variety of shapes and sizes, and each volcano has a unique eruptive history. Nevertheless, volcanologists have been able to classify volcanic landforms and determine their eruptive patterns. In this section we will consider the general anatomy of an idealized volcanic cone. We will follow this discussion by exploring the three major types of volcanic cones—shield volcanoes, cinder cones, and composite volcanoes—as well as their associated hazards.

Volcanic activity frequently begins when a **fissure** (crack) develops in Earth's crust as magma moves forcefully toward the surface. As the gas-rich magma moves up through a fissure, its path is usually localized into a somewhat pipe-shaped **conduit** that terminates at a surface opening called a **vent** (Figure 5.11). The cone-shaped structure we call a **volcanic cone** is often created by successive eruptions of lava, pyroclastic material, or frequently a combination of both, often separated by long periods of inactivity.

Located at the summit of most volcanic cones is a somewhat funnel-shaped depression called a **crater** (*crater* = bowl). Volcanoes built primarily of pyroclastic materials typically have craters that form by gradual accumulation of volcanic debris on the surrounding rim. Other craters form during explosive eruptions, as the rapidly ejected particles erode the crater walls. Craters also form when the summit area of a volcano collapses following an eruption. Some volcanoes have very large circular depressions, called **calderas**, which have diameters that are greater than 1 kilometer (0.6 mile) and that in rare cases exceed 50 kilometers (30 miles). The formation of various

Did You Know?
Chile, Peru, and Ecuador boast the highest volcanoes in the world. Dozens of cones exceed 6000 m (20,000 ft). Two volcanoes located in Ecuador, Chimborazo and Cotopaxi, were once considered the world's highest mountains. That distinction remained until the Himalayas were surveyed in the nineteenth century.



◀ **SmartFigure 5.11 Anatomy of a volcano** Compare the structure of the "typical" composite cone shown here to that of a shield volcano (Figure 5.12) and a cinder cone (Figure 5.15).

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types of calderas will be considered later in this chapter.

During early stages of growth, most volcanic discharges come from a central summit vent. As a volcano matures, material also tends to be emitted from fissures that develop along the flanks (sides) or at the base of the volcano. Continued activity from a flank eruption may produce one or more small **parasitic cones**. Italy's Mount Etna, for example, has more than 200 secondary vents, some of which have built parasitic cones. Many of these vents, however, emit only gases and are appropriately called **fumaroles** (*fumus* = smoke).

CONCEPT CHECKS 5.4

1. Distinguish among a conduit, a vent, and a crater.
2. How is a crater different from a caldera?
3. What is a parasitic cone, and where does it form?
4. What is emitted from a fumarole?

5.5 Shield Volcanoes

Summarize the characteristics of shield volcanoes and provide one example of this type of volcano.

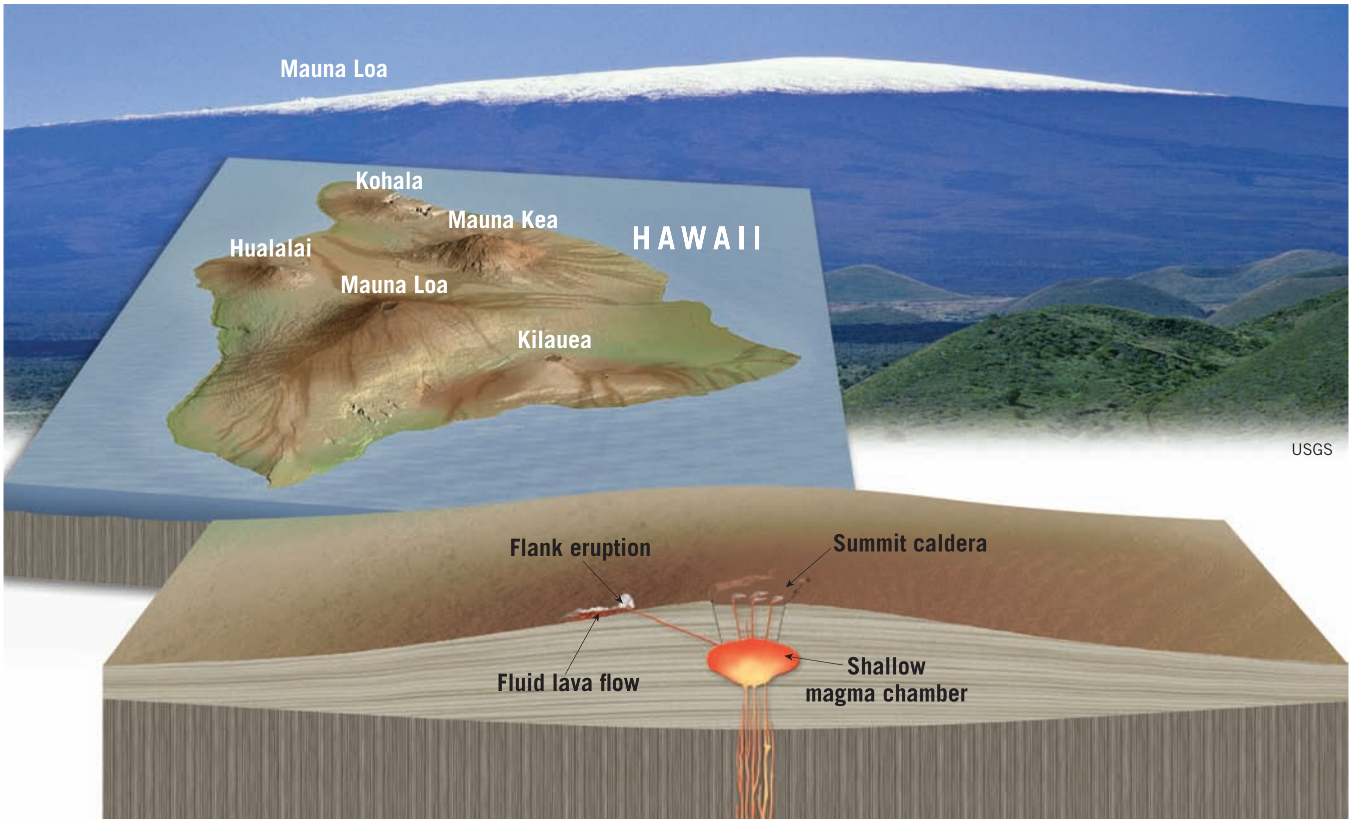
Shield volcanoes are produced by the accumulation of fluid basaltic lavas and exhibit the shape of a broad, slightly domed structure that resembles a warrior's shield (**Figure 5.12**). Most shield volcanoes begin on the ocean floor as **seamounts** (submarine volcanoes), and a few of them grow large enough to form volcanic islands. In fact, many oceanic islands are either a single shield volcano or, more often, the coalescence of two or more shields built upon massive amounts of pillow lavas. Examples include the Hawaiian Islands, the Canary Islands, Iceland, the Galápagos Islands, and Easter Island. Although less common, some shield volcanoes form on continental crust. Included in this group are Nyamuragira, Africa's most active volcano, and Newberry Volcano, Oregon.

Mauna Loa: Earth's Largest Shield Volcano

Extensive study of the Hawaiian Islands has revealed that they are constructed of a myriad of thin basaltic lava flows, each averaging a few meters thick, intermixed with relatively minor amounts of ejected pyroclastic material. Mauna Loa is the largest of five overlapping shield volcanoes that comprise the Big Island of Hawaii (see Figure 5.12). From its base on the floor of the Pacific Ocean to its summit, Mauna Loa is over 9 kilometers (6 miles) high, exceeding the height of Mount Everest above sea level. The volume of material composing Mauna Loa is roughly 200 times greater than that of the large composite cone Mount Rainier, located in Washington (**Figure 5.13**).

Like Hawaii's other shield volcanoes, Mauna Loa has flanks with gentle slopes of only a few degrees. This low angle is due to the very hot, fluid lava that traveled "fast and far" from the vent. In addition, most of the lava (perhaps 80 percent) flowed through a well-developed system of lava tubes. Another feature common to active shield volcanoes is one or more large, steep-walled calderas that occupy the summit (see Figure 5.12). Calderas on shield volcanoes usually form when the roof above the

Did You Know?
According to legend, Pele, the Hawaiian goddess of volcanoes, makes her home at the summit of Kilauea Volcano. Evidence for her existence is "Pele's hair"—thin, delicate strands of glass, which are soft and flexible and have a golden-brown color. This threadlike volcanic glass forms when blobs of hot lava are spattered and shredded by escaping gases.



▲ **Figure 5.12 Volcanoes of Hawaii** Mauna Loa, Earth's largest volcano, is one of five shield volcanoes that collectively make up the Big Island of Hawaii. Shield volcanoes are built primarily of fluid basaltic lava flows and contain only a small percentage of pyroclastic materials.

▼ **SmartFigure 5.13 Comparing scales of different volcanoes** **A.** Profile of Mauna Loa, Hawaii, the largest shield volcano in the Hawaiian chain. Note the size comparison with Mount Rainier, Washington, a large composite cone. **B.** Profile of Mount Rainier, Washington. Note how it dwarfs a typical cinder cone. **C.** Profile of Sunset Crater, Arizona, a typical steep-sided cinder cone.

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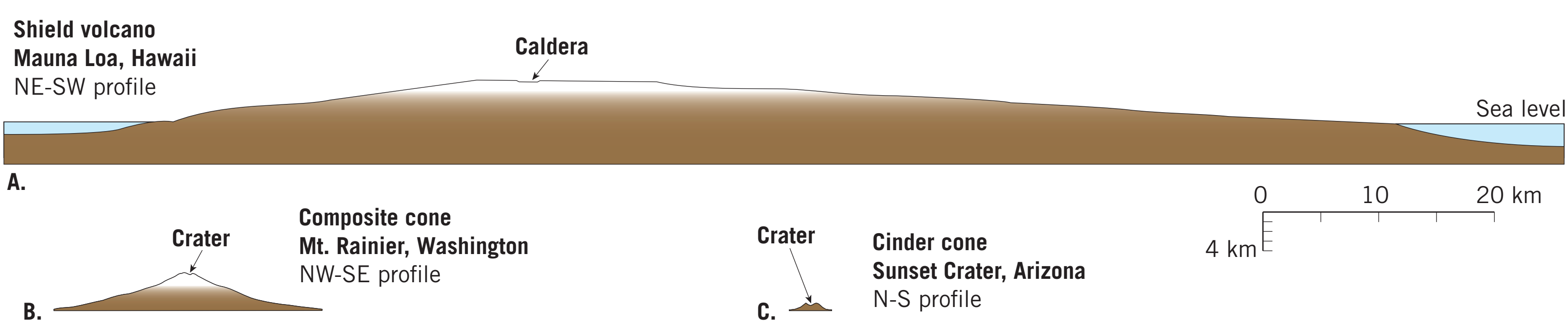
magma chamber collapses. This occurs after the magma reservoir empties, either following a large eruption or as magma migrates to the flank of a volcano to feed a fissure eruption.

In their final stage of growth, shield volcanoes erupt more sporadically, and pyroclastic ejections are more common. The lava emitted later tends to be more viscous, resulting in thicker, shorter flows. These eruptions steepen the slope of the summit area, which often becomes capped with clusters of cinder cones. This explains why Mauna Kea, a more mature volcano that has not erupted in historic times, has a steeper summit than Mauna Loa, which erupted as recently as 1984. Astronomers are so certain that Mauna Kea is "over the hill" that they built an elaborate astronomical observatory on its summit to house some of the world's most advanced and expensive telescopes.

Kilauea: Hawaii's Most Active Volcano

Volcanic activity on the Big Island of Hawaii began on what is now the northwestern flank of the island and has gradually migrated southeastward. It is currently centered on Kilauea Volcano, one of the most active and intensely studied shield volcanoes in the world. Kilauea, located in the shadow of Mauna Loa, has experienced more than 50 eruptions since record keeping began in 1823.

Several months before each eruptive phase, Kilauea inflates as magma gradually migrates upward and accumulates in a central reservoir located a few kilometers



below the summit. For up to 24 hours before an eruption, swarms of small earthquakes warn of the impending activity. Most of the recent activity on Kilauea has occurred along the flanks of the volcano, in a region called the *East Rift Zone* (**Figure 5.14**). The longest and largest rift eruption ever recorded on Kilauea began in 1983 and continues to this day, with no signs of abating.

CONCEPT CHECKS 5.5

1. Describe the composition and viscosity of the lava associated with shield volcanoes.
2. Are pyroclastic materials a significant component of shield volcanoes?
3. Where do most shield volcanoes form—on the ocean floor or on the continents?
4. Where are the best-known shield volcanoes in the United States? Name some examples in other parts of the world.

▲ **SmartFigure 5.14 Lava "curtain" extruded along the East Rift Zone, Kilauea, Hawaii** (Photo by Greg Vaughn/Alamy)

MOBILE FIELD TRIP
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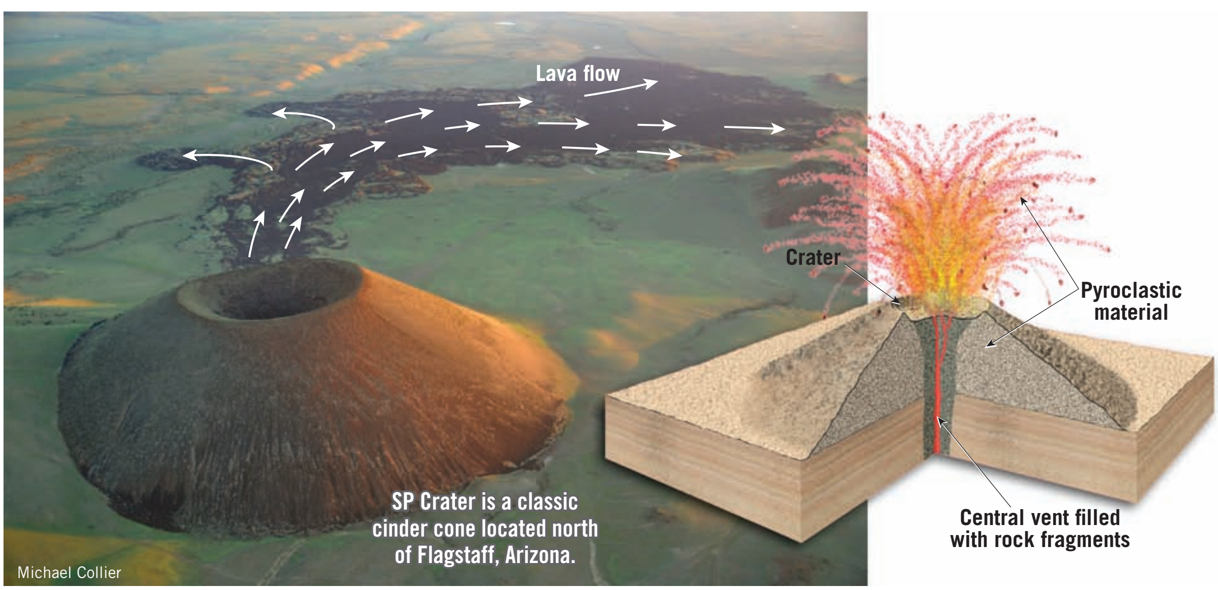
5.6 Cinder Cones

Describe the formation, size, and composition of cinder cones.

As the name suggests, **cinder cones** (also called **scoria cones**) are built from ejected lava fragments that begin to harden in flight to produce the vesicular rock *scoria* (**Figure 5.15**). These pyroclastic fragments range in size from fine ash to bombs that may exceed 1 meter (3 feet) in diameter. However, most of the volume of a cinder cone consists of pea- to walnut-sized fragments that are markedly vesicular and have a black to reddish-brown color (see Figure 5.10A). In addition, this pyroclastic material tends to have basaltic composition.

Although cinder cones are composed mostly of loose scoria fragments, some produce extensive lava fields. These lava flows generally form in the final stages of the volcano's life span, when the magma body has lost most of its gas content. Because cinder cones are composed of loose fragments rather than solid rock, the lava usually flows out from the unconsolidated base of the cone rather than from the crater.

Cinder cones have very simple, distinct shapes (see Figure 5.15). Because cinders have a high angle of repose (the steepest angle at which a pile of loose material



◄ **SmartFigure 5.15 Cinder cones** Cinder cones are built from ejected lava fragments (mostly cinders and bombs) and are relatively small—usually less than 300 meters (1000 feet) in height. (Photo by Michael Collier)

MOBILE FIELD TRIP
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remains stable), cinder cones are steep-sided, having slopes between 30 and 40 degrees. In addition, cinder cone have large, deep craters relative to the overall size of the structure. Although relatively symmetrical, some cinder cones are elongated and higher on the side that was downwind during the final eruptive phase.

Most cinder cones are produced by a single, short-lived eruptive event. One study found that half of all cinder cones examined were constructed in less than 1 month, and 95 percent of them formed in less than 1 year. Once the event ceases, the magma in the "plumbing" connecting the vent to the magma source solidifies, and the volcano usually does not erupt again. (One exception is Cerro Negro, a cinder cone in Nicaragua, which has erupted more than 20 times since it formed in 1850.) As a result of this typically short life span, cinder cones are small, usually between 30 and 300 meters (100 and 1000 feet) tall. A few rare examples exceed 700 meters (2300 feet) in height.

Cinder cones number in the thousands around the globe. Some occur in groups, such as the volcanic field near Flagstaff, Arizona, which consists of about 600 cones. Others are parasitic cones that are found on the flanks or within the calderas of larger volcanic structures.

Parícutin: Life of a Garden-Variety Cinder Cone

One of the very few volcanoes studied by geologists from its very beginning is the cinder cone called Parícutin, located about 320 kilometers (200 miles) west of Mexico City. In 1943, its eruptive phase began in a cornfield owned by Dionisio Pulido, who witnessed the event.

For 2 weeks prior to the first eruption, numerous tremors caused apprehension in the nearby village of Parícutin. Then, on February 20, sulfurous gases began billowing from a small depression that had been in the cornfield for as long as local residents could remember. During the night, hot, glowing rock fragments were ejected from the vent, producing a spectacular fireworks display. Explosive discharges continued, throwing hot fragments and ash occasionally as high as 6000 meters (20,000 feet) into the air. Larger fragments fell near the crater, some remaining incandescent as they rolled down the slope. These materials built an aesthetically pleasing cone, while finer ash fell over a much larger area, burning and eventually covering the village of Parícutin. In the first day, the cone grew to 40 meters (130 feet), and by the fifth day it was more than 100 meters (330 feet) high.

The first lava flow came from a fissure that opened just north of the cone, but after a few months flows began to emerge from the base of the cone. In June 1944, a clinkery aa flow 10 meters (30 feet) thick moved over much of the village of San Juan Parangaricutiro, leaving only remnants of the church exposed (**Figure 5.16**). After 9 years of intermittent pyroclastic explosions and nearly continuous discharge of lava from vents at its base, the activity ceased almost as quickly as it had begun. Today, Parícutin is just another one of the scores of cinder cones dotting the landscape in this region of Mexico. Like the others, it will not erupt again.

CONCEPT CHECKS 5.6

1. Describe the composition of a cinder cone.
2. How do cinder cones compare in size and steepness of their flanks with shield volcanoes?
3. Over what time span does a typical cinder cone form?

Parícutin, a cinder cone located in Mexico, erupted for 9 years.

An aa flow emanating from the base of the cone buried much of the village of San Juan Parangaricutiro, leaving only remnants of the village's church.

▶ **SmartFigure 5.16**
Parícutin, a well-known cinder cone The village of San Juan Parangaricutiro was engulfed by aa lava from Parícutin. Only portions of the church remain. (Photos by Michael Collier)

CONDOR VIDEO
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5.7 Composite Volcanoes

List the characteristics of composite volcanoes and describe how they form.

Earth's most picturesque yet potentially dangerous volcanoes are **composite volcanoes**, also known as **stratovolcanoes**. Most are located in a relatively narrow zone that rims the Pacific Ocean, appropriately called the *Ring of Fire* (see Figure 5.29, page 151). This active zone includes a chain of continental volcanoes distributed along the west coast of the Americas, including the large cones of the Andes in South America and the Cascade Range of the western United States and Canada.

Classic composite cones are large, nearly symmetrical structures consisting of alternating layers of explosively erupted cinders and ash interbedded with lava flows. A few composite cones, notably Italy's Etna and Stromboli, display very persistent eruption activity, and molten lava has been observed in their summit craters for decades. Stromboli is so well known for eruptions that eject incandescent blobs of lava that it has been called the "Lighthouse of the Mediterranean." Mount Etna has erupted, on average, once every 2 years since 1979.

Just as shield volcanoes owe their shape to fluid basaltic lavas, composite cones reflect the viscous nature of the material from which they are made. In general, composite cones are the product of silica-rich magma having an andesitic composition. However, many composite cones also emit various amounts of fluid basaltic lava and, occasionally, pyroclastic material having a felsic (rhyolitic) composition. The silica-rich magmas typical of composite cones generate thick, viscous lavas that travel less than a few kilometers. Composite cones are also noted for generating explosive eruptions that eject huge quantities of pyroclastic material.

A conical shape, with a steep summit area and gradually sloping flanks, is typical of most large composite cones. This classic profile, which adorns calendars and postcards, is partially a result of the way viscous lavas and pyroclastic ejected materials contribute to the cone's growth. Coarse fragments ejected from the summit crater tend to accumulate near their source and contribute to the steep slopes around the summit. Finer ejected materials, on the other hand, are deposited as a thin layer over a large area and hence tend to flatten the flank of the cone. In addition, during the early stages of growth, lavas tend to be more abundant and flow greater distances from the vent than they do later in the volcano's history, which contributes to the cone's broad base. As a composite volcano matures, the shorter flows that come from the central vent serve to armor and strengthen the summit area. Consequently, steep slopes exceeding 40 degrees are possible. Two of the most perfect cones—Mount Mayon in the Philippines and Fujiyama in Japan—exhibit the classic form we expect of composite cones, with steep summits and gently sloping flanks (Figure 5.17).

▼ **Figure 5.17 Fujiyama, a classic composite volcano** Japan's Fujiyama exhibits the classic form of a composite cone—a steep summit and gently sloping flanks. (Photo by Koji Nakano/Getty Images, Inc-Liaison)

Despite the symmetrical forms of many composite cones, most have complex histories. Many composite volcanoes have secondary vents on their flanks that have produced cinder cones or even much larger volcanic structures. Huge mounds of volcanic debris surrounding these structures provide evidence that large sections of these volcanoes slid downslope as massive landslides. Some develop amphitheater-shaped depressions at their summits as a result of explosive lateral eruptions—as occurred during the 1980 eruption of Mount St. Helens. Often, so much rebuilding has occurred since these eruptions that no trace of these amphitheater-shaped scars remain. Others, such as Crater Lake, have been truncated by the collapse of their summit (see Figure 5.23).

CONCEPT CHECKS 5.7

1. What name is given to the region having the greatest concentration of composite volcanoes?
2. Describe the materials that compose composite volcanoes.
3. How does the composition and viscosity of lava flows differ between composite volcanoes and shield volcanoes?

5.8 Volcanic Hazards

Describe the major geologic hazards associated with volcanoes.

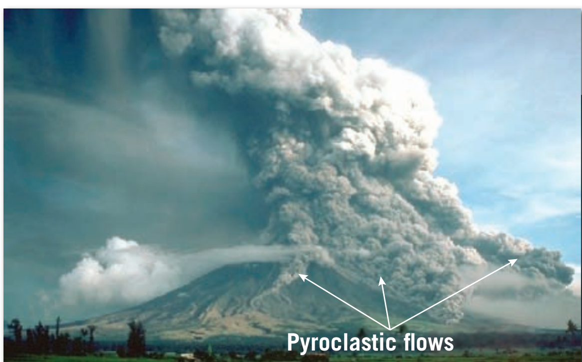
Roughly 1500 of Earth's known volcanoes have erupted at least once, and some several times, in the past 10,000 years. Based on historical records and studies of active volcanoes, 70 volcanic eruptions can be expected each year. In addition, 1 large-volume eruption can be expected every decade; these large eruptions account for the vast majority of volcano-related human fatalities.

Today, an estimated 500 million people in places such as Japan, Indonesia, Italy, and Oregon live near active volcanoes. They face a number of volcanic hazards, such as destructive pyroclastic flows, molten lava flows, mudflows called lahars, and falling ash and volcanic bombs.

Pyroclastic Flow: A Deadly Force of Nature

Some of the most destructive forces of nature are **pyroclastic flows**, which consist of hot gases infused with incandescent ash and larger lava fragments. Also referred to as **nuée ardentes** ("glowing avalanches"), these fiery flows can race down steep volcanic slopes at speeds exceeding 100 kilometers (60 miles) per hour (**Figure 5.18**). Pyroclastic flows have two components—a low-density cloud of hot expanding gases containing fine ash particles and a ground-hugging portion composed of pumice and other vesicular pyroclastic material.

Driven by Gravity Pyroclastic flows are propelled by the force of gravity and tend to move in a manner similar to snow avalanches. They are mobilized by expanding volcanic gases released from the lava fragments and by the expansion of heated air that is overtaken and trapped in the moving front. These gases reduce friction between ash and pumice fragments, which gravity propels downslope in a nearly frictionless environment. This is why some pyroclastic flow deposits are found many miles from their source.



A.

B.

▼ **Figure 5.18 Pyroclastic flows, one of the most destructive volcanic forces A.** These pyroclastic flows occurred on Mount Mayon, Philippines, during the 1984 eruption. Pyroclastic flows are composed of hot ash and pumice and/or blocky lava fragments that race down the slope of volcanoes. (Photo courtesy of USGS) **B.** Residents running away from a pyroclastic flow that reached the base of Mound Sinabung, Indonesia, 2014. (Photo by Chaideer Mahyuddin/AFP/Getty Images)

Occasionally, powerful hot blasts that carry small amounts of ash separate from the main body of a pyroclastic flow. These low-density clouds, called *surges*, can be deadly but seldom have sufficient force to destroy buildings in their paths. Nevertheless, in 2014, a hot ash cloud from Japan's Mount Ontake killed 47 hikers and injured 69 more.

Pyroclastic flows may originate in a variety of volcanic settings. Some occur when a powerful eruption blasts pyroclastic material out of the side of a volcano. More frequently, however, pyroclastic flows are generated by the collapse of tall eruption columns during an explosive event. When gravity eventually overcomes the initial upward thrust provided by the escaping gases, the ejected materials begin to fall, sending massive amounts of incandescent blocks, ash, and pumice cascading downslope.

The Destruction of St. Pierre In 1902, an infamous pyroclastic flow and associated surge from Mount Pelée, a small volcano on the Caribbean island of Martinique, destroyed the port town of St. Pierre. Although the main pyroclastic flow was largely confined to the valley of Riviere Blanche, a low-density fiery surge spread south of the river and quickly engulfed the entire city. The destruction happened in moments and was so devastating that nearly all of St. Pierre's 28,000 inhabitants were killed. Only 1 person on the outskirts of town—a prisoner protected in a dungeon—and a few people on ships in the harbor were spared (**Figure 5.19**).

Scientists who arrived on the scene within days found that although St. Pierre was mantled by only a thin layer of volcanic debris, masonry walls nearly 1 meter (3 feet) thick had been knocked over like dominoes, large trees had been uprooted, and cannons had been torn from their mounts.

The Destruction of Pompeii One well-documented event of historic proportions was the C.E. 79 eruption of the Italian volcano we now call Mount Vesuvius. For centuries prior to this eruption, Vesuvius had been dormant, with vineyards adorning its sunny slopes. Yet in less than 24 hours, the entire city of Pompeii (near Naples) and a few thousand of its residents were entombed beneath a layer of volcanic ash and pumice. The city and the victims of the eruption remained buried for nearly 17 centuries. The excavation of Pompeii gave archaeologists a superb picture of ancient Roman life (**Figure 5.20A**).

A. St. Pierre following the eruption of Mount Pelée.

B. St. Pierre before the 1902 eruption.

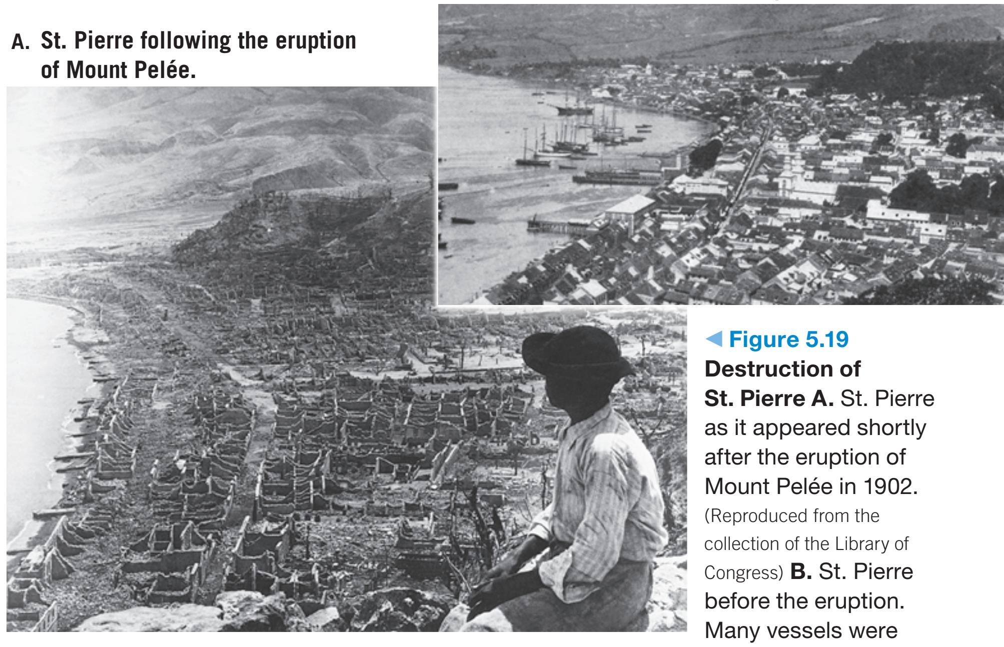
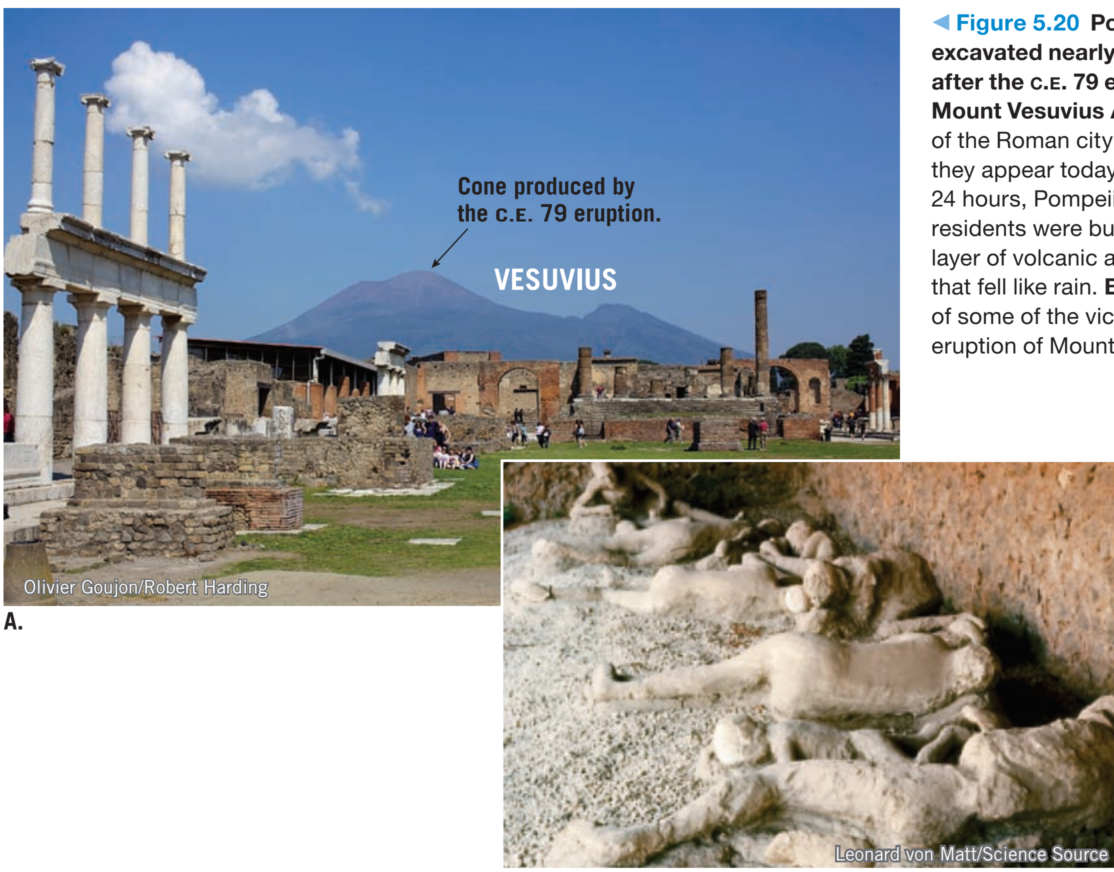


Figure 5.19 Destruction of St. Pierre A. St. Pierre as it appeared shortly after the eruption of Mount Pelée in 1902. (Reproduced from the collection of the Library of Congress) **B.** St. Pierre before the eruption. Many vessels were anchored offshore when this photo was taken, as was the case on the day of the eruption. (Photo by UPPA/Photoshot)



A.

B.

Figure 5.20 Pompeii was excavated nearly 17 centuries after the C.E. 79 eruption of Mount Vesuvius A. The ruins of the Roman city of Pompeii as they appear today. In less than 24 hours, Pompeii and all of its residents were buried under a layer of volcanic ash and pumice that fell like rain. **B.** Plaster casts of some of the victims of the eruption of Mount Vesuvius.

Did You Know?
In 1902, when Mount Pelée erupted, the U.S. Senate was preparing to vote on the location of a canal connecting the Pacific and Atlantic Oceans. The choice was between Panama and Nicaragua, a country that featured a smoking volcano on its postage stamp. Supporters of the Panamanian route used the potential threat of volcanic eruptions in Nicaragua to bolster their argument in favor of Panama. The Senate subsequently approved the construction of the Panama Canal. In 2013, Nicaragua's National Assembly approved a bill to support the construction of a second canal connecting the Pacific Ocean and the Caribbean Sea (and therefore the Atlantic) to rival the Panama Canal. However, funding for this project has not been obtained.

By reconciling historic records with detailed scientific studies of the region, volcanologists reconstructed the sequence of events. During the first day of the eruption, a rain of ash and pumice accumulated at a rate of 12 to 15 centimeters (5 to 6 inches) per hour, causing most of the roofs in Pompeii to eventually give way. Then, suddenly, a surge of searing hot ash and gas swept rapidly down the flanks of Vesuvius. This deadly pyroclastic flow killed those who had somehow managed to survive the initial ash and pumice fall. Their remains were quickly buried by falling ash, and subsequent rainfall caused the ash to harden. Over the centuries, the remains decomposed, creating cavities that were discovered by nineteenth-century excavators. Casts were then produced by pouring plaster of Paris into the voids (**Figure 5.20B**). Mount Vesuvius has had more than two dozen explosive eruptions since C.E. 79, the most recent occurring in 1944. Today, Vesuvius towers over the Naples skyline, a region occupied by roughly 3 million people. Such an image should prompt us to consider how volcanic crises might be managed in the future.

Lahars: Mudflows on Active & Inactive Cones

In addition to violent eruptions, large composite cones may generate a type of fluid mudflow, known by its Indonesian name, **lahar**. These destructive flows occur when volcanic debris becomes saturated with water and rapidly moves down steep volcanic slopes, generally following stream valleys. Some lahars are triggered when magma nears the surface of a glacially clad volcano, causing large volumes of ice and snow to melt. Others are generated when heavy rains saturate weathered volcanic deposits. Thus, lahars may occur even when a volcano is *not* erupting.

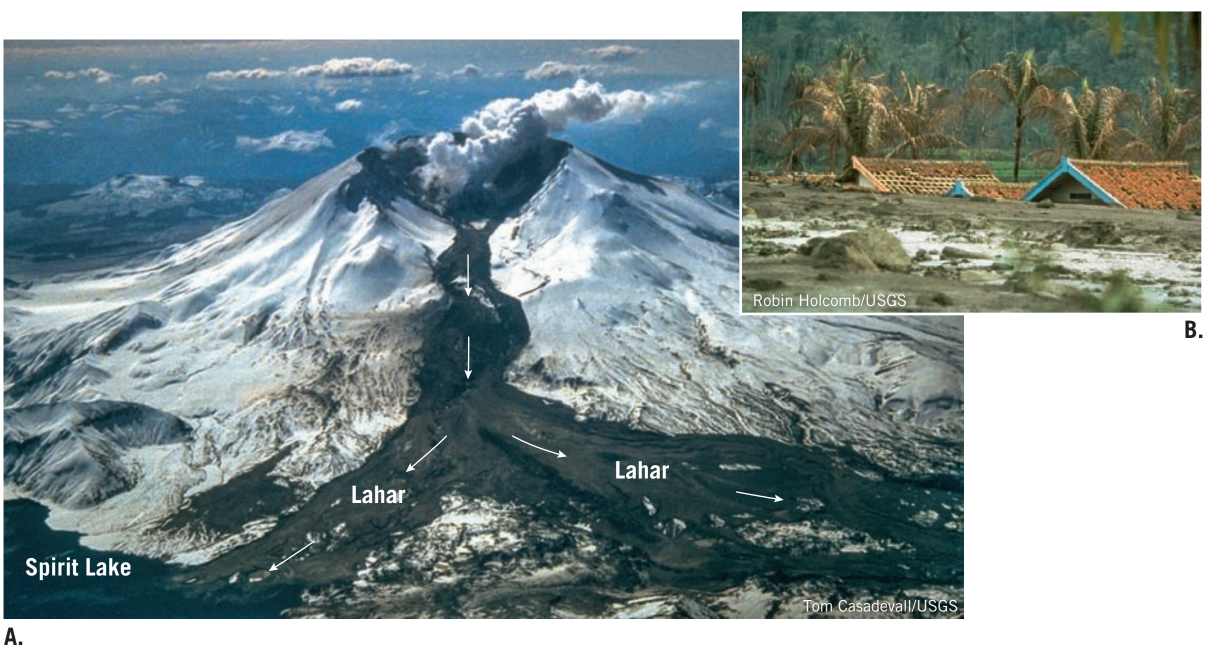
When Mount St. Helens erupted in 1980, several lahars were generated. These flows and accompanying floodwaters raced down nearby river valleys at speeds exceeding 30 kilometers (20 miles) per hour. These raging rivers of mud destroyed or severely damaged nearly all the homes and bridges along their paths (**Figure 5.21**). Fortunately, the area was not densely populated.

In 1985, deadly lahars were produced during a small eruption of Nevado del Ruiz, a 5300-meter (17,400-foot) volcano in the Andes Mountains of Colombia. Hot pyroclastic material melted ice and snow that capped the mountain (*nevado* means "snowcap" in Spanish) and sent torrents of ash and debris down three major river valleys that flank the volcano. Reaching speeds of 100 kilometers (60 miles) per hour, these mudflows tragically claimed 25,000 lives.

Many consider Mount Rainier, Washington, to be America's most dangerous volcano because, like Nevado del Ruiz, it has a thick, year-round mantle of snow and glacial ice. Adding to the risk is the fact that more than 100,000 people live in the valleys around Rainier, and many homes are built on deposits left by lahars that flowed down the volcano hundreds or thousands of years ago. A future eruption, or perhaps just a period of heavier-than-average rainfall, may produce lahars that could be similarly destructive.

Other Volcanic Hazards

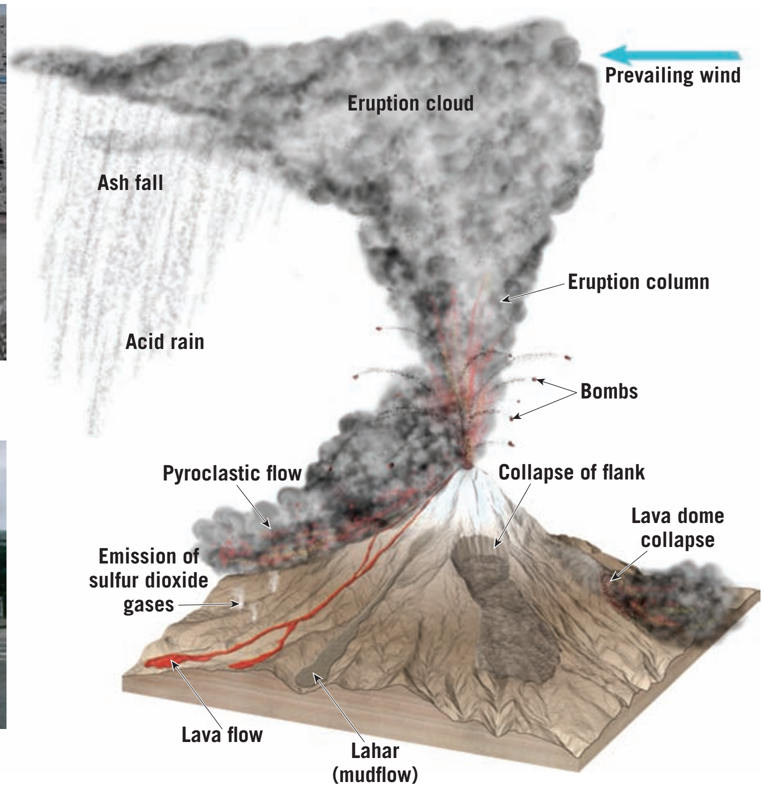
Volcanoes can be hazardous to human health and property in other ways. Ash and other pyroclastic material can collapse the roofs of buildings or may be drawn into the lungs of humans and other animals or into aircraft



▶ **Figure 5.21 Lahars, mudflows that originate on volcanic slopes** **A.** This lahar raced down the snow-covered slopes of Mount St. Helens following an explosive eruption on March 19, 1982. **B.** The aftermath of a lahar that formed following the 1982 eruption of Galunggung Volcano, Indonesia.

Ash and other pyroclastic materials can collapse roofs, or completely cover buildings.

Lava flows can destroy homes, roads, and other structures in their paths.



◀ **Figure 5.22 Volcanic hazards** In addition to generating destructive pyroclastic flows and lahars, volcanoes can be hazardous to human health and property in many other ways.

engines (**Figure 5.22**). Volcanic gases, most notably sulfur dioxide, pollute the air and, when mixed with rainwater, can destroy vegetation and reduce the quality of groundwater. Despite the known risks, millions of people live in close proximity to active volcanoes.

Volcano-Related Tsunamis Although **tsunamis** are most often associated with displacement along a fault located on the seafloor (see Chapter 9), some result from the collapse of a volcanic cone. This was dramatically demonstrated during the 1883 eruption on the Indonesian island of Krakatau, when the northern half of a volcano plunged into the Sunda Strait, creating a tsunami that exceeded 30 meters (100 ft) in height. Although Krakatau was uninhabited, an estimated 36,000 people were killed along the coastline of the islands of Java and Sumatra.

Volcanic Ash & Aviation During the past 20 years, at least 80 commercial jets have been damaged by inadvertently flying into clouds of volcanic ash. For example, in 1989, a Boeing 747 carrying more than 300 passengers encountered an ash cloud from Alaska's Redoubt Volcano; all four engines clogged with ash and stalled mid-air. Fortunately, the pilots were able to restart the engines and safely landed the aircraft in Anchorage.

More recently, the 2010 eruption of Iceland's Eyjafjallajökull Volcano sent ash high into the atmosphere. This thick plume of ash drifted over Europe, causing airlines to cancel thousands of flights and leaving hundreds of thousands of travelers stranded. Several weeks passed before air travel resumed its normal schedule.

Volcanic Gases & Respiratory Health One of the most destructive volcanic events, called the Laki eruptions, began along a large fissure in southern Iceland in 1783. An estimated 14 cubic kilometers of fluid basaltic lavas were released, along with 130 million tons of sulfur dioxide and other poisonous gases. When sulfur dioxide is inhaled, it reacts with moisture in the lungs to produce sulfuric acid, a deadly toxin. More than half of Iceland's livestock died, and the ensuing famine killed 25 percent of the island's human population.

This huge eruption also endangered people and property all across Europe. Crop failure occurred in parts of Western Europe, and thousands of residents perished from lung-related diseases. One report estimated that a similar eruption today would cause more than 140,000 cardiopulmonary fatalities in Europe alone.

Effects of Volcanic Ash & Gases on Weather & Climate Volcanic eruptions can eject dust-sized particles of volcanic ash and sulfur dioxide gas high into the atmosphere. The ash particles reflect sunlight back to space, producing temporary atmospheric cooling. The 1783 Laki eruptions in Iceland appear to have affected atmospheric circulation around the globe. Drought conditions prevailed in the Nile River valley and India, and the winter of 1784 saw the longest period of below-zero temperatures in New England's history.

Other eruptions that have produced significant effects on climate worldwide include the eruption of Indonesia's Mount Tambora in 1815, which produced the "year without a summer" (1816), and the eruption of

El Chichón in Mexico in 1982. El Chichón's eruption, although small, emitted an unusually large quantity of sulfur dioxide that reacted with water vapor in the atmosphere to produce a dense cloud of tiny sulfuric acid droplets. Such particles, called aerosols, take several years to settle out of the atmosphere. Like fine ash, these aerosols lower the mean temperature of the atmosphere by reflecting solar radiation back to space.

CONCEPT CHECKS 5.8

1. Describe pyroclastic flows and explain why they are capable of traveling great distances.
2. What is a lahar?
3. List at least three volcanic hazards besides pyroclastic flows and lahars.

5.9 Other Volcanic Landforms

List volcanic landforms other than shield, cinder cone, and composite volcanoes and describe their formation.

The most widely recognized volcanic structures are the cone-shaped edifices of composite volcanoes that dot Earth's surface. However, volcanic activity produces other distinctive and important landforms.

Calderas

Recall that *calderas* are large steep-sided depressions that have diameters exceeding 1 kilometer (0.6 miles) and have a somewhat circular form. Those that are less than 1 kilometer across are called *collapse pits*, or *craters*. Most calderas are formed by one of the following processes: (1) the collapse of the summit of a large composite volcano following an explosive eruption of silica-rich pumice and ash fragments (*Crater Lake–type calderas*); (2) the collapse of the top of a shield volcano caused by subterranean drainage from a central magma chamber (*Hawaiian-type calderas*); and (3) the collapse of a large area, caused by the discharge of colossal volumes of silica-rich pumice and ash along ring fractures (*Yellowstone-type calderas*).

Crater Lake–Type Calderas Crater Lake, Oregon, is situated in a caldera approximately 10 kilometers (6 miles) wide and 600 meters (1970 feet) deep. This caldera formed about 7000 years ago, when a composite cone named Mount Mazama violently extruded 50 to 70 cubic kilometers of pyroclastic material (Figure 5.23). With the loss of support, 1500 meters (nearly 1 mile) of the

▼ **SmartFigure 5.23**
Formation of Crater Lake–type calderas About 7000 years ago, a violent eruption partly emptied the magma chamber of former Mount Mazama, causing its summit to collapse. Precipitation and groundwater contributed to forming Crater Lake, the deepest lake in the United States—600 meters (1970 feet) deep—and the ninth-deepest in the world.

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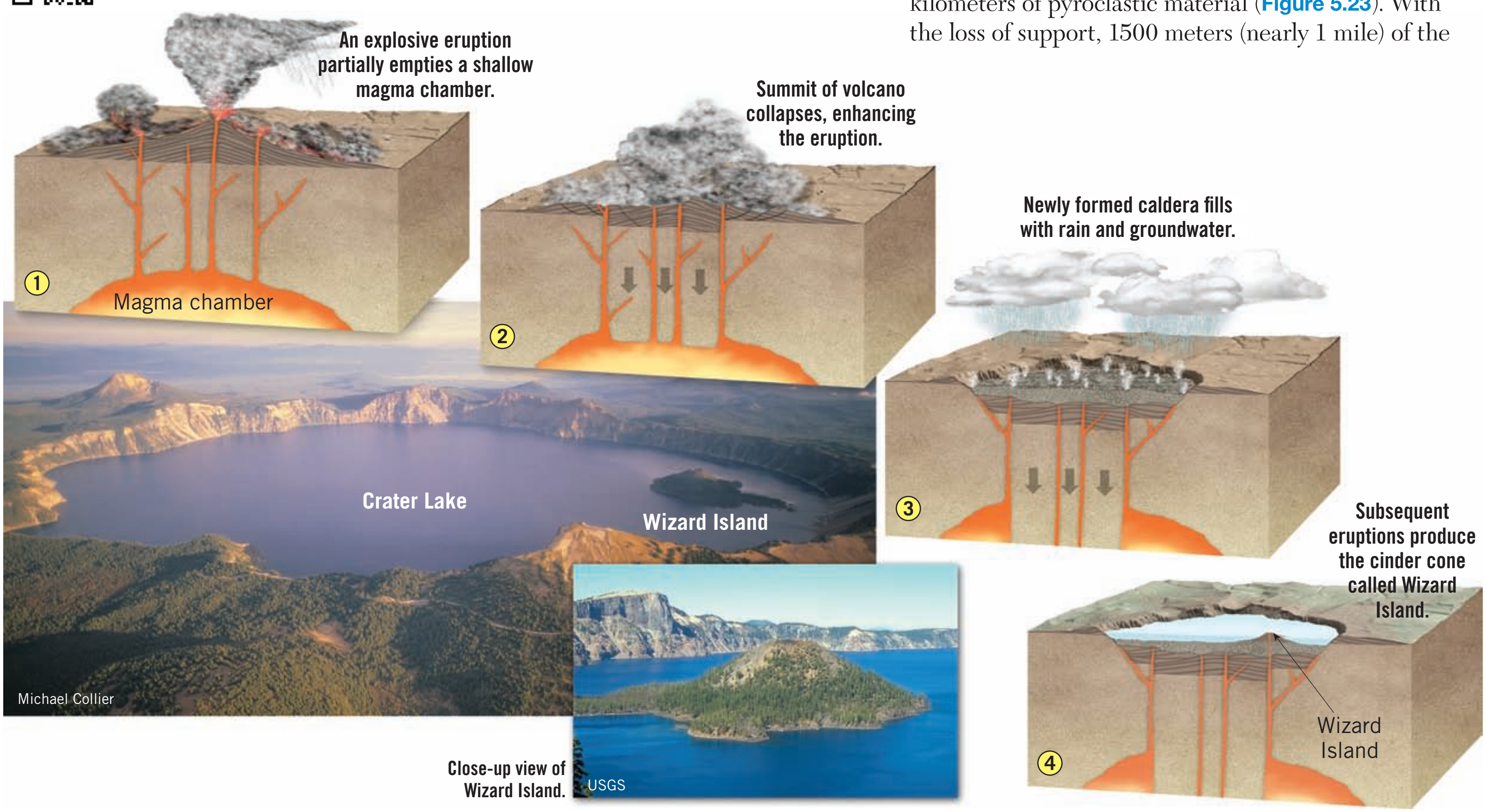


summit of this once-prominent cone collapsed, producing a caldera that eventually filled with water. Later, volcanic activity built a small cinder cone in the caldera. Today this cone, called Wizard Island, provides a mute reminder of past activity.

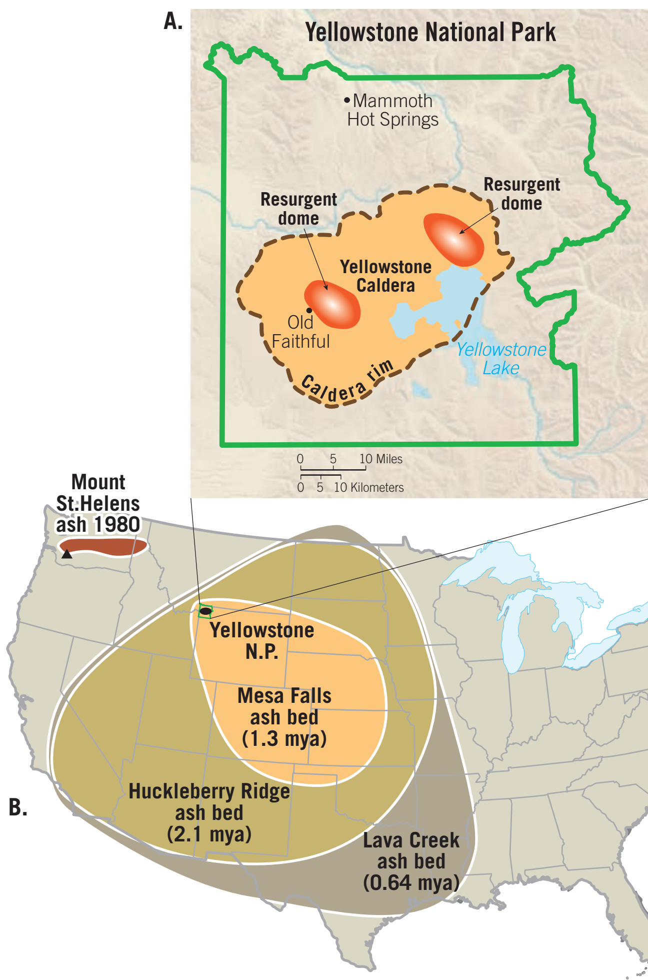
Hawaiian-Type Calderas Unlike Crater Lake–type calderas, many calderas form gradually because of the loss of lava from a shallow magma chamber underlying a volcano's summit. For example, Hawaii's active shield volcanoes, Mauna Loa and Kilauea, both have large calderas at their summits. Kilauea's measures 3.3 by 4.4 kilometers (about 2 by 3 miles) and is 150 meters (500 feet) deep. The walls are almost vertical, and as a result, the caldera looks like a vast, nearly flat-bottomed pit. Kilauea's caldera formed by gradual subsidence as magma slowly drained laterally from the underlying magma chamber, leaving the summit unsupported.

Yellowstone-Type Calderas Historic and destructive eruptions such as Mount St. Helens pale in comparison to what happened 630,000 years ago in the region now occupied by Yellowstone National Park, when approximately 1000 cubic kilometers of pyroclastic material erupted. This catastrophic eruption sent showers of ash as far as the Gulf of Mexico and formed a caldera 70 kilometers (43 miles) across (**Figure 5.24A**). Vestiges of this event are the many hot springs and geysers in the Yellowstone region.

Yellowstone-type eruptions eject huge volumes of pyroclastic materials, mainly in the form of ash and pumice fragments. Typically, these materials are ejected as *pyroclastic flows* that sweep across the landscape, destroying most living things in their paths. Upon coming to rest, the hot fragments of ash and pumice fuse together, forming a welded tuff that closely resembles a solidified lava flow. Despite the immense size of these calderas, the eruptions that produce them are brief, lasting hours to perhaps a few days.

Large calderas tend to exhibit a complex eruptive history. In the Yellowstone region, for example, three caldera-forming episodes are known to have occurred over the past 2.1 million years (**Figure 5.24B**). The most recent eruption (630,000 years ago) was followed by episodic outpourings of degassed rhyolitic and basaltic lavas. In the intervening years, a slow upheaval of the floor of the caldera has produced two elevated regions called *resurgent domes* (see Figure 5.24A). A recent study has determined that a huge magma reservoir still exists beneath Yellowstone; thus, another caldera-forming eruption is likely—but not necessarily imminent.

Unlike calderas associated with shield volcanoes or composite cones, Yellowstone-type calderas are so vast and poorly defined that many were undetected until high-quality aerial and satellite images became available. Other examples of Yellowstone-type calderas are California's Long Valley Caldera; LaGarita Caldera, located in the San Juan Mountains of southern Colorado; and the Valles Caldera, west of Los Alamos, New Mexico. These and similar calderas found around the globe are among the largest volcanic structures on Earth, hence the name *supervolcanoes*. Volcanologists compare their destructive force to that of the impact of a small asteroid. Fortunately, no Yellowstone-type eruption has occurred in historic times.



SmartFigure 5.24 Super-eruptions at Yellowstone A. This map shows Yellowstone National Park and the location and size of the Yellowstone caldera. **B.** Three huge eruptions, separated by relatively regular intervals of about 700,000 years, were responsible for the ash layers shown. The largest of these eruptions was 10,000 times greater than the 1980 eruption of Mount St. Helens.

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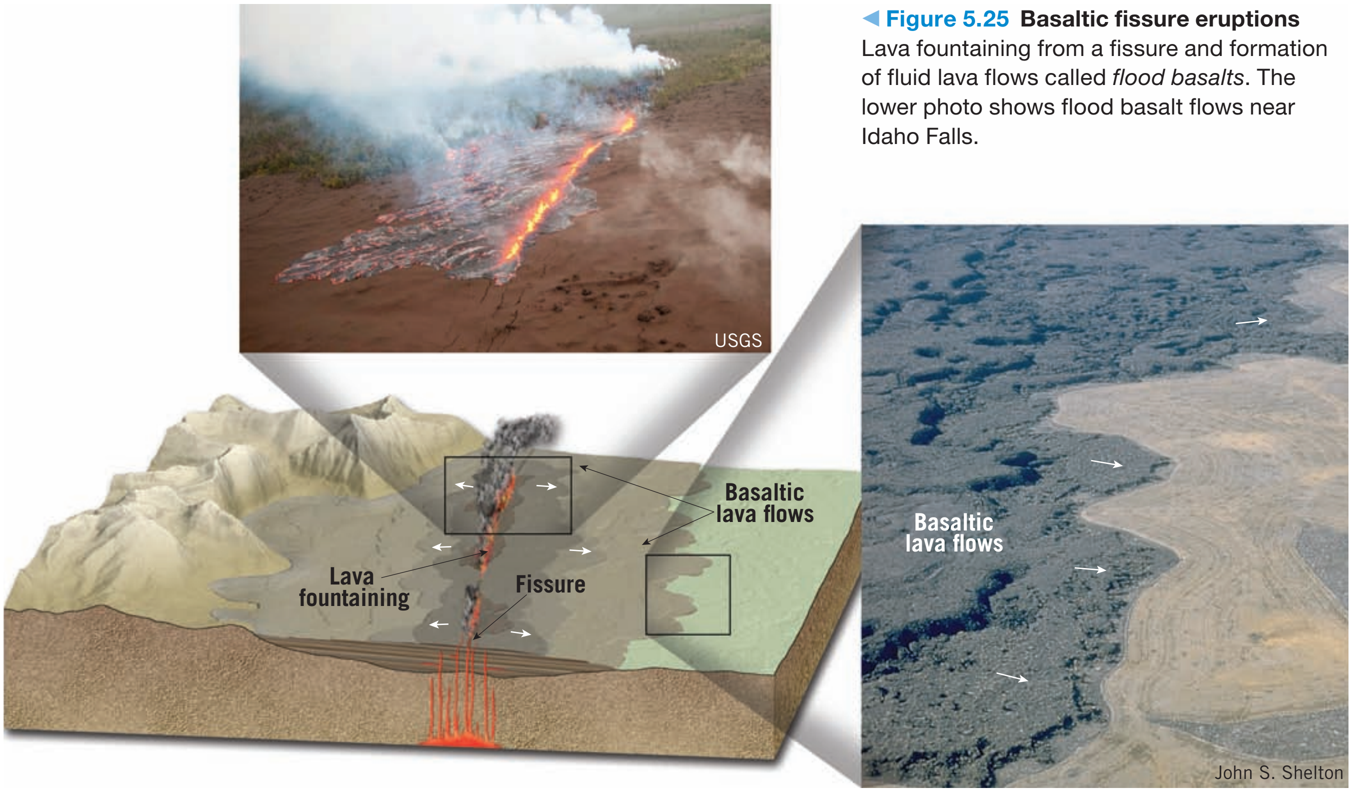
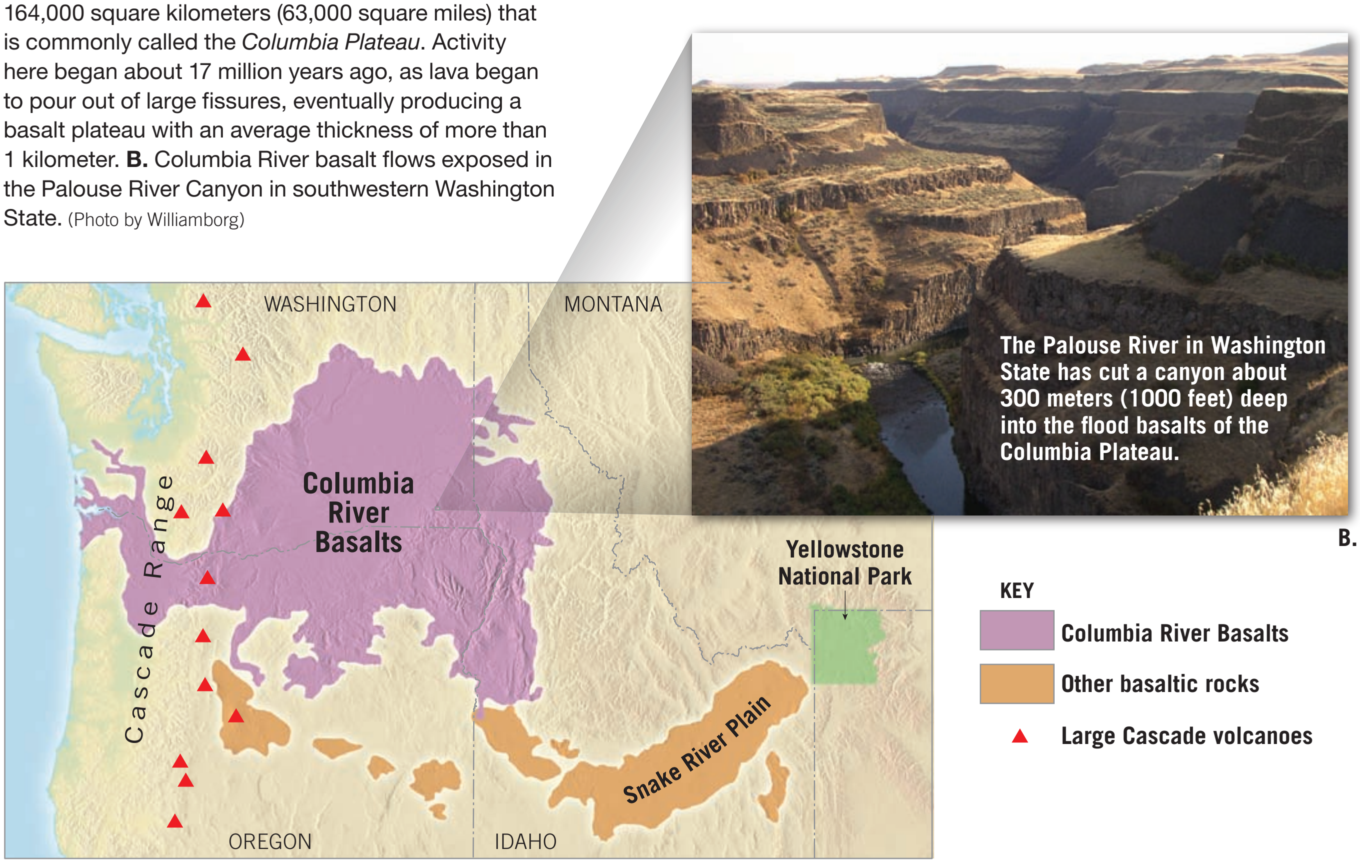
Fissure Eruptions & Basalt Plateaus

The greatest volume of volcanic material is extruded from fractures in Earth's crust, called *fissures*. Rather than building cones, **fissure eruptions** usually emit fluid basaltic lavas that blanket wide areas (**Figure 5.25**). In some locations, extraordinary amounts of lava have been extruded along fissures in a relatively short time, geologically speaking. These voluminous accumulations are commonly referred to as **basalt plateaus** because most have a basaltic composition and tend to be rather flat and broad. The Columbia Plateau in the northwestern United States, which consists of the Columbia River basalts, is a product of this type of activity (**Figure 5.26**). Numerous fissure eruptions have buried



◀ **Figure 5.25 Basaltic fissure eruptions** Lava fountaining from a fissure and formation of fluid lava flows called *flood basalts*. The lower photo shows flood basalt flows near Idaho Falls.

▼ **Figure 5.26 Columbia River basalts A.** The Columbia River basalts cover an area of nearly 164,000 square kilometers (63,000 square miles) that is commonly called the *Columbia Plateau*. Activity here began about 17 million years ago, as lava began to pour out of large fissures, eventually producing a basalt plateau with an average thickness of more than 1 kilometer. **B.** Columbia River basalt flows exposed in the Palouse River Canyon in southwestern Washington State. (Photo by Williamborg)



A.

B.

the landscape, creating a lava plateau nearly 1500 meters (1 mile) thick. Some of the lava remained molten long enough to flow 150 kilometers (90 miles) from its source. The term **flood basalts** appropriately describe these extrusions.

Massive accumulations of basaltic lava, similar to those of the Columbia Plateau, occur elsewhere in the world. One of the largest is known as the Deccan Plateau or Deccan Traps (*traps* = stairs), a thick sequence of flat-lying basalt flows covering nearly 500,000 square kilometers (195,000 square miles) of west-central India. When the Deccan Traps formed about 66 million years ago, nearly 2 million cubic kilometers of lava were extruded over a period of approximately 1 million years. Several other massive accumulations of flood basalts, including the Ontong Java Plateau, have been discovered in the deep ocean basins (see Figure 5.32, page 154).

Lava Domes

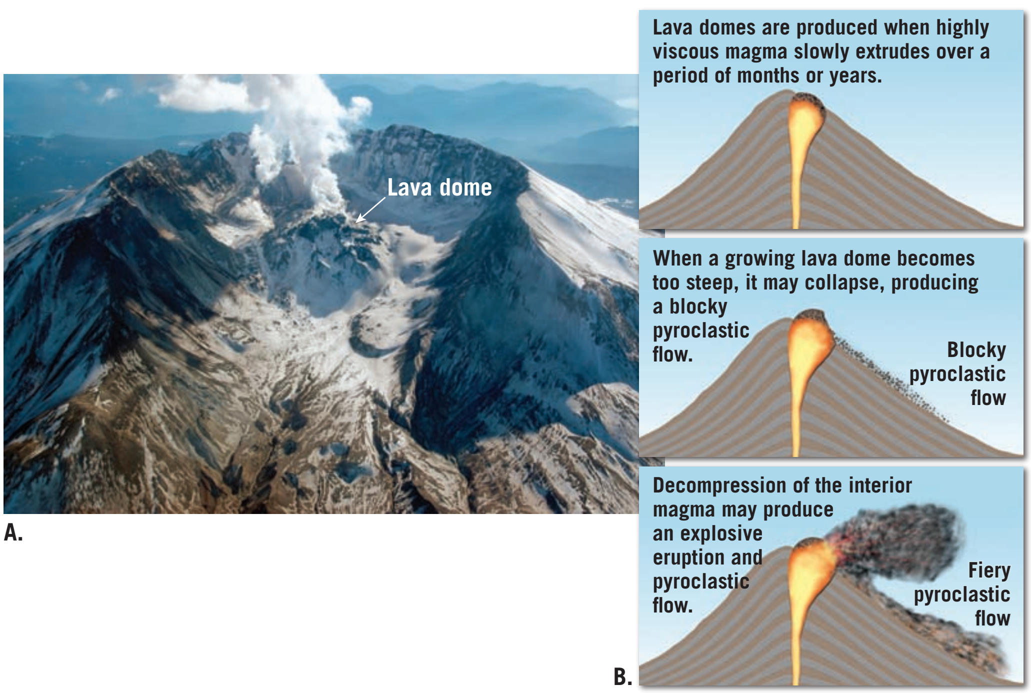
In contrast to hot basaltic lavas, cool silica-rich rhyolitic lavas are so viscous that they hardly flow at all. As the thick lava is "squeezed" out of a vent, it often produces a dome-shaped mass called a **lava dome**. Lava domes are usually only a few tens of meters high, and they come in a variety of shapes that range from pancake-like flows to steep-sided plugs that were pushed upward like pistons. Most lava domes grow over a period of several years, following an explosive eruption of silica-rich magma. A recent example is the dome that began to grow in the crater of Mount St. Helens immediately following the 1980 eruption (**Figure 5.27A**).

Collapsing lava domes, particularly those that form on the summit or along the steep flanks of composite cones, often produce powerful pyroclastic flows (**Figure 5.27B**). These flows result from highly viscous magma slowly entering the dome, causing it to expand and steepen its flanks. Over time, the cooler outer layer of the dome may start to crumble, producing relatively small pyroclastic flows consisting of dense blocks of lava. Occasionally, the rapid removal of the outer layer causes a significant decrease in pressure on the hot gaseous magma in the interior of the dome. Explosive degassing of the interior magma then triggers a fiery pyroclastic flow that races down the flanks of the volcano (see Figure 5.27B).

Since 1995, pyroclastic flows generated by the collapse of several lava domes on Soufrière Hills Volcano have rendered more than half of the Caribbean island of Montserrat uninhabitable. The capital city, Plymouth, was destroyed, and two-thirds of the population has evacuated. In 1991 a collapsed lava dome at the summit of Japan's Mount Unzen produced a pyroclastic flow that claimed 44 lives. Many of the victims were journalists and film makers who ventured too close to the volcano in order to obtain photographs and document the event.

Volcanic Necks

Most of the lava and materials erupted from a volcano travel through short conduits that connect shallow magma chambers to vents located at the surface. When a volcano becomes inactive, congealed magma is often preserved in the feeding conduit of the volcano as



◀ **Figure 5.27 Lava domes can generate pyroclastic flows A.** This lava dome began to develop in the vent of Mount St. Helens following the May 1980 eruption. **B.** The collapse of a lava dome often results in a powerful pyroclastic flow. (Photo by Lyn Topinka/U.S. Geological Survey)

▶ **SmartFigure 5.28**
Volcanic neck Shiprock, New Mexico, is a volcanic neck that stands about 520 meters (1700 feet) high. It consists of igneous rock that crystallized in the vent of a volcano that has long since been eroded.

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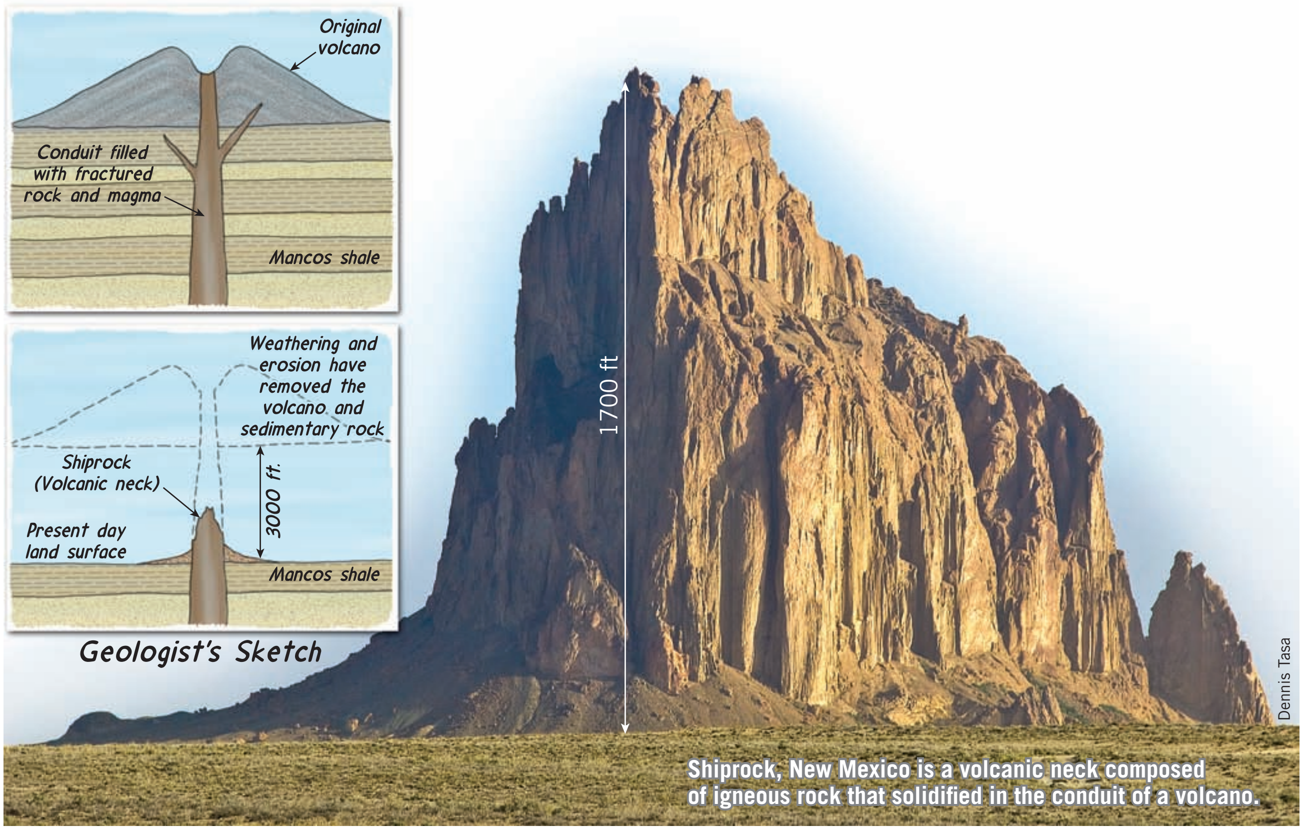


CONCEPT CHECKS 5.9

1. Describe the formation of Crater Lake. Compare it to the calderas found on shield volcanoes such as Kilauea.
2. Other than composite volcanoes, what volcanic landform can generate a pyroclastic flow?
3. How do the eruptions that created the Columbia Plateau differ from the eruptions that create large composite volcanoes?
4. What type of volcanic structure is Shiprock, New Mexico, and how did it form?

a crudely cylindrical mass. As the volcano succumbs to forces of weathering and erosion, the rock occupying the volcanic conduit, which is highly resistant to weathering, may remain standing above the surrounding terrain long after the cone has been worn away. Shiprock, New Mexico, is a widely recognized and spectacular example of these structures, which geologists call **volcanic necks** (or **plugs**) (Figure 5.28). More than 510 meters (1700 feet) high, Shiprock is taller than most skyscrapers and is one of many such landforms that protrude conspicuously from the red desert landscapes of the American Southwest.

5.10 Plate Tectonics & Volcanism

Explain how the global distribution of volcanic activity is related to plate tectonics.

Geologists have known for decades that the global distribution of most of Earth's volcanoes is not random. Most active volcanoes on land are located along the margins of the ocean basins—notably within the circum-Pacific belt known as the **Ring of Fire** (Figure 5.29), where denser oceanic lithosphere subducts under continental lithosphere. Another group of volcanoes includes the innumerable seamounts that form along the crest of the mid-ocean ridges. There are some volcanoes, however, that appear to be randomly distributed around the globe. These volcanic structures comprise most of the islands of the deep-ocean basins, including the Hawaiian Islands, the Galapagos Islands, and Easter Island.

The development of the theory of plate tectonics provided geologists with a plausible explanation

Figure 5.29 Ring of Fire Most of Earth's major volcanoes are located in a zone around the Pacific called *the Ring of Fire*. Another large group of active volcanoes lie unseen along the mid-ocean ridge system.

for the distribution of Earth's volcanoes and established the basic connection between plate tectonics and volcanism: *Plate motions provide the mechanisms by which mantle rocks undergo partial melting to generate magma.*

Volcanism at Divergent Plate Boundaries

The greatest volume of magma erupts along divergent plate boundaries associated with seafloor spreading—out of human sight (**Figure 5.30B**). Below the ridge axis where lithospheric plates are continually being pulled apart, the solid yet mobile mantle rises to fill the rift. Recall that as hot rock rises, it experiences a decrease in confining pressure and may undergo *decompression melting*. This activity continuously adds new basaltic rock to plate margins, temporarily welding them together, only to have them break again as spreading continues. Along some ridge segments, extrusions of pillow lavas build numerous volcanic structures, the largest of which is Iceland.

Although most spreading centers are located along the axis of an oceanic ridge, some are not. In particular, the East African Rift is a site where continental lithosphere is being pulled apart (see **Figure 5.30F**). Vast outpourings of fluid basaltic lavas as well as several active volcanoes are found in this region of the globe.

Volcanism at Convergent Plate Boundaries

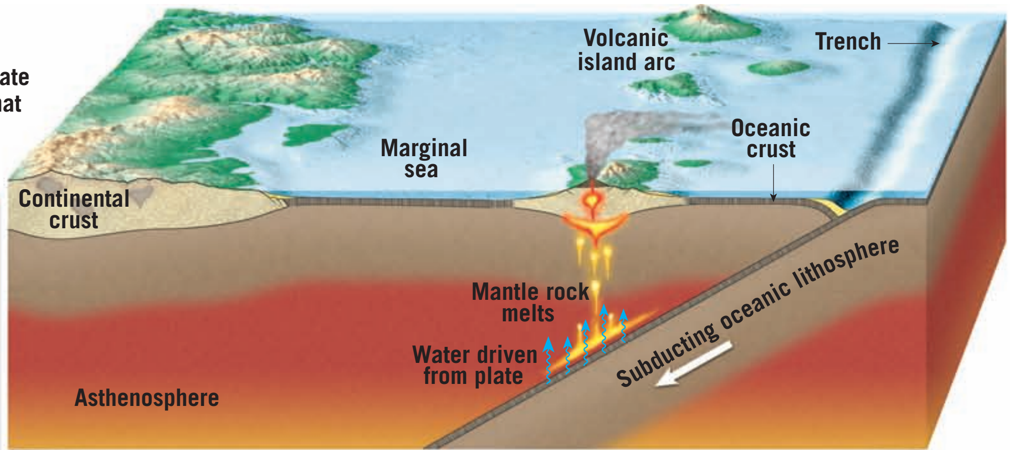
Recall that along convergent plate boundaries, two plates move toward each other, and a slab of dense oceanic lithosphere descends into the mantle. In these settings, water driven from hydrated (water-rich) minerals found in the subducting oceanic crust and overlying sediments triggers partial melting in the hot mantle above (**Figure 5.30A**).

Volcanism at a convergent plate margin results in the development of a slightly curved chain of volcanoes called a *volcanic arc*. These volcanic chains develop roughly parallel to the associated trench—at distances of 200 to 300 kilometers (100 to 200 miles). Volcanic arcs that develop within the ocean and grow large enough for their tops to rise above the surface are labeled *archipelagos* in most atlases. Geologists prefer the more descriptive term **volcanic island arcs**, or simply **island arcs** (see Figure 5.30A). Several young volcanic island arcs border the western Pacific basin, including the Aleutians, the Tongas, and the Marianas.

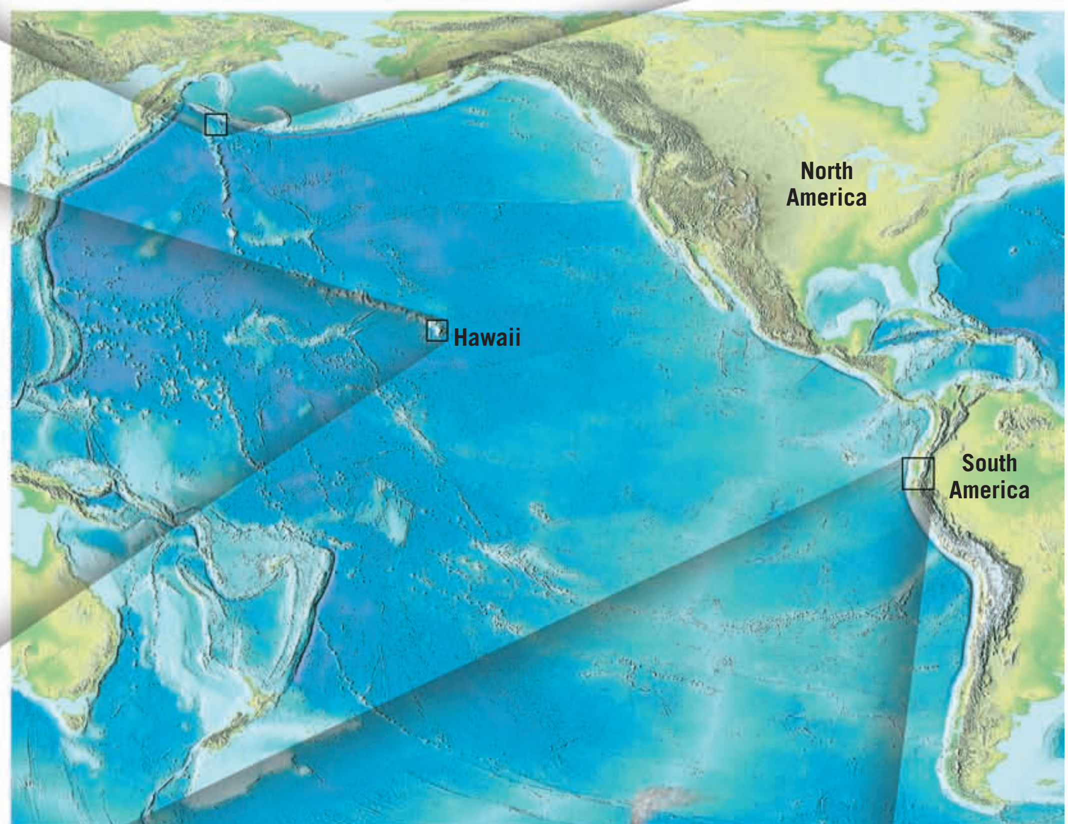
Volcanism associated with convergent plate boundaries may also take place where slabs of oceanic lithosphere are subducted under continental lithosphere to produce a **continental volcanic arc** (**Figure 5.30E**). The mechanisms that generate these mantle-derived magmas are essentially the same as those that create volcanic island arcs. The most significant difference is that continental crust is much thicker and composed of rocks having higher silica content than oceanic crust. Hence, by melting the surrounding silica-rich crustal rocks, mantle-derived magma changes composition as it rises through the crust. The volcanoes of the Cascade Range in the northwestern United States, including Mount Hood, Mount Rainier, Mount Shasta, and Mount St. Helens, are examples of volcanoes generated

Did You Know?
At 4392 m (14,411 ft) in altitude, Washington's Mount Rainier is the tallest of the 15 great volcanoes that make up the backbone of the Cascade Range. Although Mount Rainier is considered an active volcano, its summit is covered by more than 25 alpine glaciers.

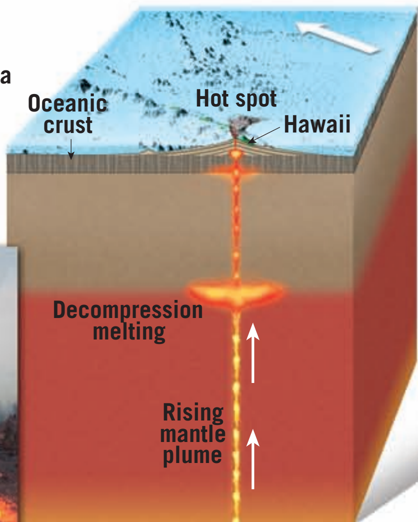
A. Convergent Plate Volcanism When an oceanic plate subducts, melting in the mantle produces magma that gives rise to a volcanic island arc on the overlying oceanic crust.



Cleveland Volcano, Aleutian Islands (USGS)

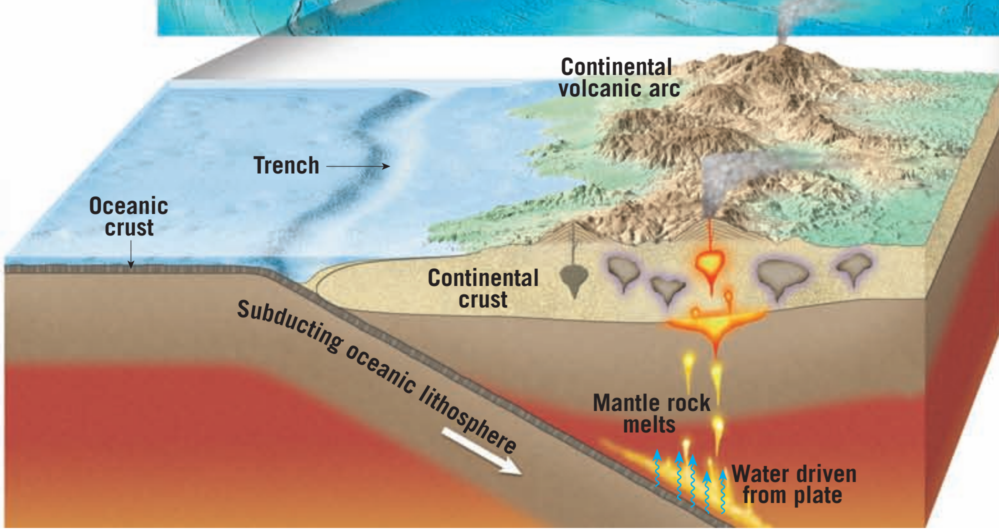


C. Intraplate Volcanism When an oceanic plate moves over a hot spot, a chain of volcanic structures such as the Hawaiian Islands is created.



Kilauea, Hawaii (USGS)

E. Convergent Plate Volcanism When oceanic lithosphere descends beneath a continent, magma generated in the mantle rises to form a continental volcanic arc.



▲ **SmartFigure 5.30**
Earth's zones of volcanism

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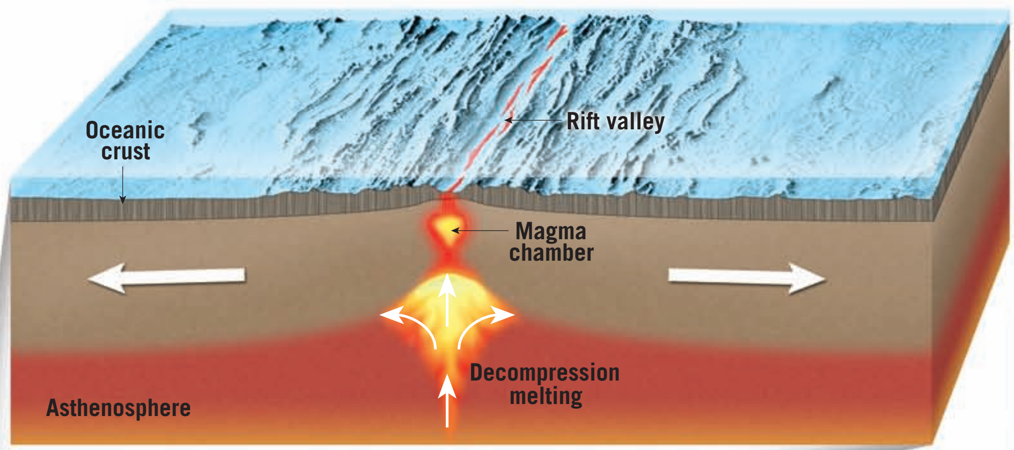
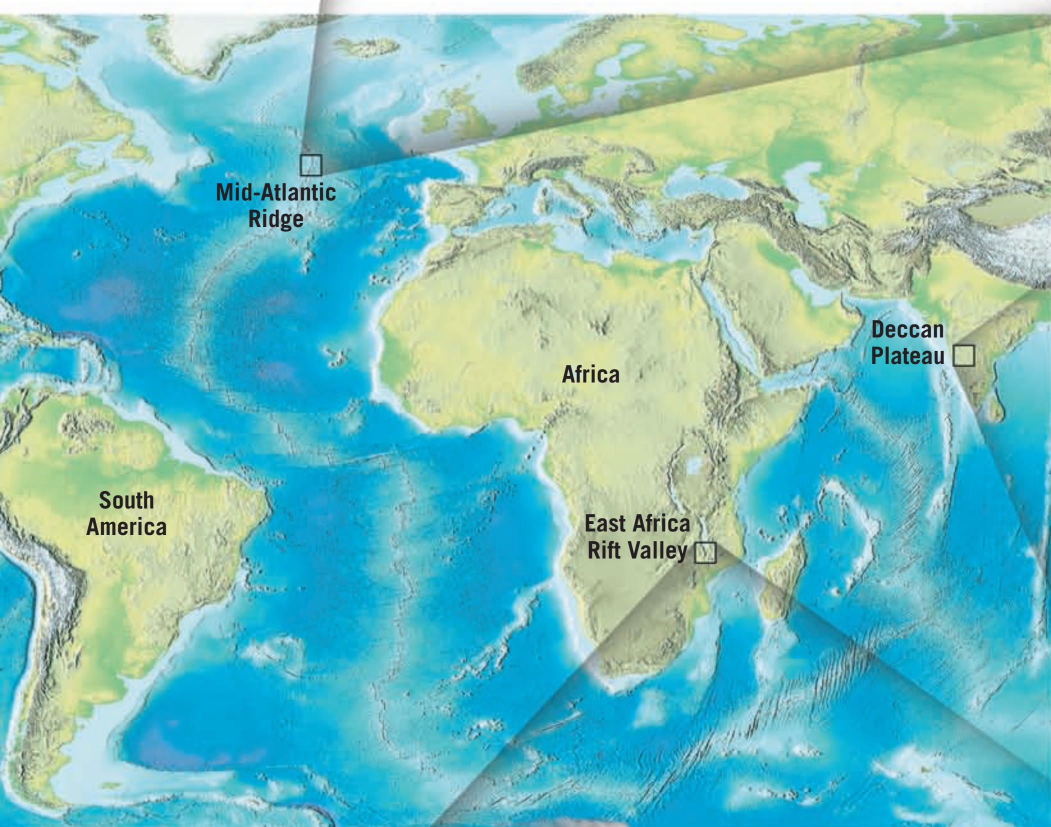
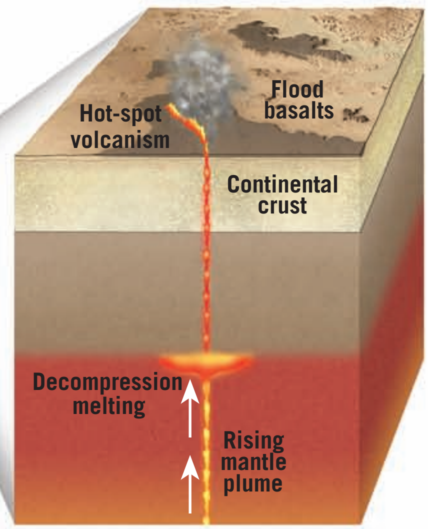
B. Divergent Plate Volcanism **Along the oceanic ridge, where two plates are being pulled apart, upwelling of hot mantle rock creates new seafloor.**



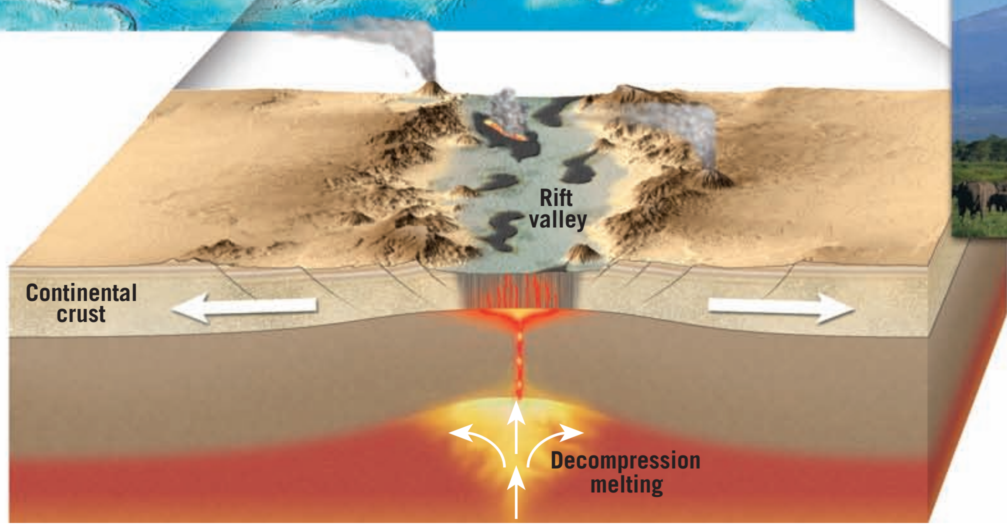
Iceland (Wedigo Ferchland)





D. Intraplate Volcanism **When a large mantle plume ascends beneath continental crust, vast outpourings of fluid basaltic lava like those that formed the Deccan Plateau may be generated.**

Mount Kilimanjaro, Africa (Corbis/Photolibrary)



F. Divergent Plate Volcanism **When plate motion pulls a continental block apart, stretching and thinning of the lithosphere causes molten rock to ascend from the mantle.**

▶ **SmartFigure 5.31**
Subduction-produced Cascade Range volcanoes Subduction of the Juan de Fuca plate along the Cascadia subduction zone produced the Cascade volcanoes.

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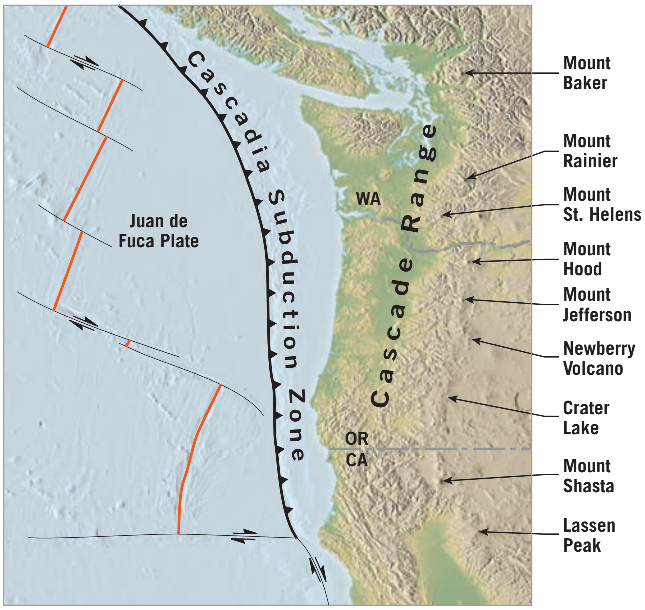


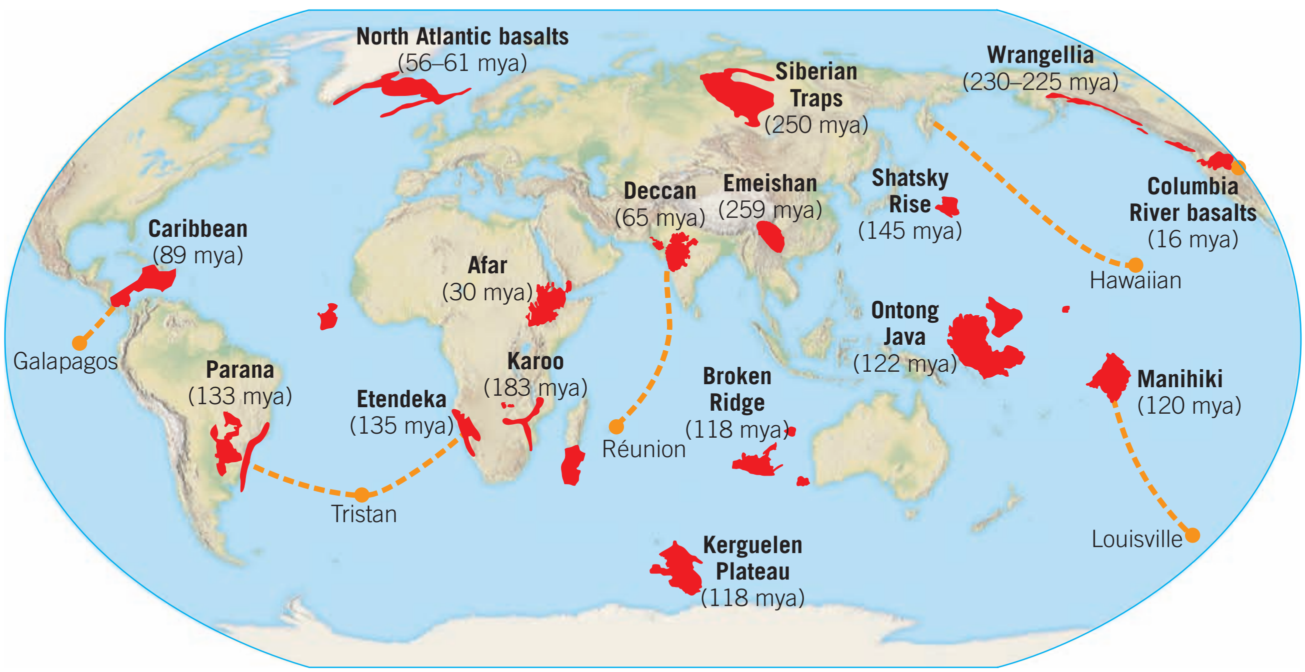
at a convergent plate boundary along a continental margin (Figure 5.31).

Intraplate Volcanism

We know why igneous activity is initiated along plate boundaries, but why do eruptions occur in the interiors of plates? Hawaii's Kilauea, considered one of the world's most active volcanoes, is situated thousands of kilometers from the nearest plate boundary, in the middle of the vast Pacific plate (Figure 5.30C). Sites of **intraplate** (meaning "within the plate") **volcanism** include the large outpourings of fluid basaltic lavas such as those that compose the Columbia Plateau, the Siberian Traps in Russia, India's Deccan Plateau, and several submerged oceanic plateaus, including the Ontong Java Plateau in the western Pacific (Figure 5.32).

Most intraplate volcanism occurs when a relatively narrow mass of hot **mantle plume** ascends toward the surface (Figure 5.33).* Although the depth at which mantle plumes originate is a topic of debate, some are thought to form deep within Earth, at the core–mantle boundary. These plumes of solid yet mobile rock rise toward the surface in a manner similar to the blobs that form within a lava lamp. Such a lamp contains two immiscible liquids in a glass container, and as the base of the lamp is heated, the denser liquid at the bottom becomes buoyant and forms blobs that rise to the top. Like the blobs in a lava lamp, a mantle plume has a bulbous head that draws out a narrow stalk beneath it as it rises. The surface manifestation of this activity is called a **hot spot**, an area of volcanism, high heat flow, and crustal uplifting a few hundred kilometers wide.

*Some geologists question the role of mantle plumes in the formation of Earth's volcanic landforms.



▲ **SmartFigure 5.32**
Global distribution of large basalt provinces. The basalt plateaus (shown in red) are thought to be the product of a burst of volcanism generated by partial melting of the bulbous head of a hot mantle plume. The orange dashed lines represent the chain of volcanic structures produced by partial melting of the plume tail. The orange dots are thought to be the current surface locations of the hot mantle plumes that generated the associated basalt plateaus.

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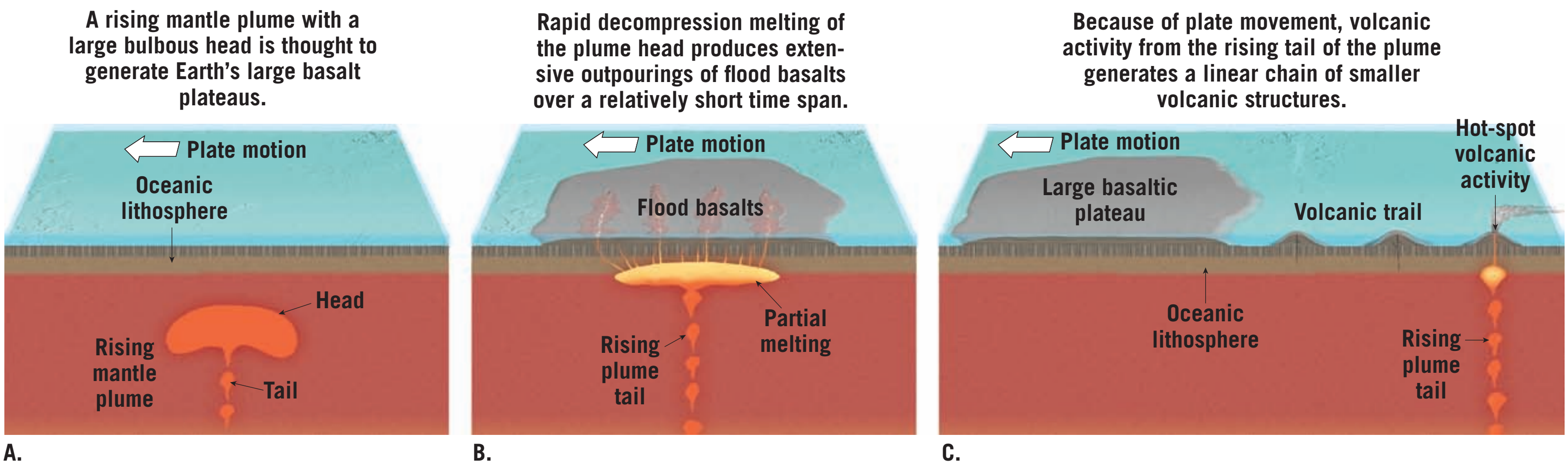


▲ **Figure 5.33 Mantle plumes and large basalt provinces** Model of hot-spot volcanism thought to explain the formation of large basalt plateaus and the chains of volcanic islands associated with these features.

Large mantle plumes, dubbed **superplumes**, are thought to be responsible for the vast outpourings of basaltic lava that created the large basalt plateaus. When the head of the plume reaches the base of the lithosphere, decompression melting progresses rapidly. This causes the burst of volcanism that emits voluminous flows of lava over a period of 1 million or so years (see Figure 5.33B). Extreme eruptions of this type would have affected Earth's climate, causing (or at least contributing to) the extinction events recorded in the fossil record.

The comparatively short initial eruptive phase is often followed by millions of years of less voluminous activity, as the plume tail slowly rises to the surface. Extending away from some large flood basalt plateaus is a chain of volcanic structures, similar to the Hawaiian chain (see Figure 5.33C).

Intraplate volcanism associated with mantle plumes is also thought to be responsible for the massive eruptions of silica-rich pyroclastic material that occurred in continental settings. Perhaps the best known of these hot-spot eruptions are the three caldera-forming eruptions that occurred in the Yellowstone region over the past 2.1 million years (see Figure 5.24).

CONCEPT CHECKS 5.10

1. Are volcanoes in the Ring of Fire generally described as effusive or explosive? Provide an example that supports your answer.
2. How is magma generated along convergent plate boundaries?
3. Volcanism at divergent plate boundaries is most often associated with which magma type? What causes rocks to melt in these settings?
4. What is thought to be the source of magma for most intraplate volcanism?
5. Which type of plate boundary generates the greatest quantity of magma?

CONCEPTS IN REVIEW
Volcanoes & Volcanic Hazards

5.1 Mount St. Helens Versus Kilauea

Compare and contrast the 1980 eruption of Mount St. Helens with the most recent eruption of Kilauea, which began in 1983.

- Volcanic eruptions cover a broad spectrum from explosive eruptions, like that of Mount St. Helens in 1980, to the quiescent eruptions of Kilauea.

5.2 The Nature of Volcanic Eruptions

Explain why some volcanic eruptions are explosive and others are quiescent.

KEY TERMS: magma, lava, effusive eruption, viscosity, eruption column

- The two primary factors determining the nature of a volcanic eruption are the viscosity (resistance to flow) of the magma and its gas content. In general, magmas that contain more silica are more viscous, while those with lower silica content are more fluid. Temperature also influences viscosity. Hot lavas are more fluid, while cool lavas are more viscous.
- Basaltic magmas, which are fluid and have low gas content, tend to generate effusive (non-explosive) eruptions. In contrast, silica-rich magmas (andesitic and rhyolitic), which are the most viscous and contain the greatest quantity of gases, are the most explosive.

? Although Kilauea mostly erupts in a gentle manner, what risks might you encounter if you chose to live nearby?


USGS

5.3 Materials Extruded During an Eruption

List and describe the three categories of materials extruded during volcanic eruptions.

KEY TERMS: aa flow, pahoehoe flow, lava tube, pillow lava, block lava, volatile, pyroclastic material, tephra, scoria, pumice

- Volcanoes erupt molten lava, gases, and solid pyroclastic materials.
- Low-viscosity basaltic lava flows can extend great distances from a volcano. On the surface, they travel as pahoehoe or aa flows. Sometimes the surface of the flow congeals, and lava continues to flow below in tunnels called lava tubes. When lava erupts underwater, the outer surface is chilled instantly to obsidian, while the inside continues to flow, producing pillow lavas.

(5.3 continued)

- The gases most commonly emitted by volcanoes are water vapor and carbon dioxide. Upon reaching the surface, these gases rapidly expand, leading to explosive eruptions that can generate a mass of lava fragments called pyroclastic materials.
- Pyroclastic materials come in several sizes. From smallest to largest, they are ash, lapilli, and blocks or bombs. Blocks exit the volcano as solid fragments, whereas bombs exit as liquid blobs.
- If bubbles of gas in lava don't pop before the lava solidifies, they are preserved as voids called vesicles. Especially frothy, silica-rich lava can cool to make lightweight pumice, while basaltic lava with lots of bubbles cools to make scoria.

? This photo shows layers of volcanic material ejected by a violent eruption and deposited roughly horizontally. What term is used to describe this type of volcanic material?


Erik Klemetti

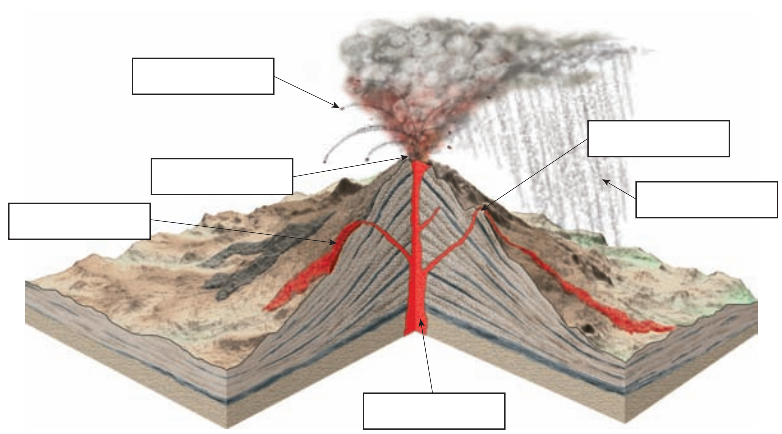
5.4 Anatomy of a Volcano

Draw and label a diagram that illustrates the basic features of a typical volcanic cone.

KEY TERMS: fissure, conduit, vent, volcanic cone, crater, caldera, parasitic cone, fumarole

- Volcanoes vary in size and form but share a few common features. Most are roughly conical piles of extruded material that collect around a central vent. The vent is usually within a summit crater or caldera. On the flanks of the volcano, there may be smaller vents marked by small parasitic cones, or there may be fumaroles, spots where gas is expelled.

? Label the diagram using the following terms: conduit, vent, lava, parasitic cone, bombs, pyroclastic material.



5.5 Shield Volcanoes

Summarize the characteristics of shield volcanoes and provide one example of this type of volcano.

KEY TERMS: shield volcano, seamount

- Shield volcanoes consist of many successive lava flows of low-viscosity basaltic lava but lack significant amounts of pyroclastic debris. Lava tubes help transport lava far from the main vent, resulting in very gentle, shield-like profiles.
- Most shield volcanoes begin as seamounts that grow from Earth's seafloor. Mauna Loa, Mauna Kea, and Kilauea in Hawaii are classic examples of the low, wide form characteristic of shield volcanoes.

5.6 Cinder Cones

Describe the formation, size, and composition of cinder cones.

KEY TERMS: cinder cone (scoria cone)

- Cinder cones are steep-sided structures composed mainly of pyroclastic debris, typically having a basaltic composition. Lava flows sometimes emerge from the base of a cinder cone but typically do not flow out of the crater.
- Cinder cones are small relative to the other major kinds of volcanoes, reflecting the fact that most form quickly, as single eruptive events. Because they are unconsolidated, cinder cones easily succumb to weathering and erosion.

5.7 Composite Volcanoes

List the characteristics of composite volcanoes and describe how they form.

KEY TERMS: composite volcano (stratovolcano)

- Composite volcanoes are called "composite" because they consist of both pyroclastic material and lava flows. They typically erupt silica-rich magmas of andesitic or rhyolitic composition. They are much larger than cinder cones and form from multiple eruptions over millions of years.
- Because andesitic and rhyolitic lavas are more viscous than basaltic lava, they accumulate at a steeper angle than does the lava from shield volcanoes. Over time, a composite volcano's combination of lava and cinders produces a towering volcano with a classic symmetrical shape.
- Mount Rainier and the other volcanoes of the Cascade Range in the northwest United States are good examples of composite volcanoes.

? If your family had to live next to a volcano, would you rather it be a shield volcano, cinder cone, or composite volcano? Explain.

5.8 Volcanic Hazards

Describe the major geologic hazards associated with volcanoes.

KEY TERMS: pyroclastic flow (nuée ardente), lahar, tsunami

- The greatest volcanic hazard to human life is the pyroclastic flow, or nuée ardente. This dense mix of hot gas and pyroclastic fragments races downhill at great speed and incinerates everything in its path. A pyroclastic flow can travel many kilometers from its source volcano. Because pyroclastic flows are hot, their deposits frequently "weld" together into a solid rock called welded tuff.
- Lahars are mudflows that form on volcanoes. These rapidly moving slurries of ash and debris suspended in water tend to follow stream valleys and can result in loss of life and/or significant damage to structures.

(5.8 continued)

- Volcanic ash in the atmosphere can be a risk to air travel when it is sucked into airplane engines. Volcanoes at sea level can generate tsunamis when they erupt or when their flanks collapse into the ocean. Those that spew large amounts of gas such as sulfur dioxide can cause respiratory problems. If volcanic gases reach the stratosphere, they screen out a portion of incoming solar radiation and can trigger short-term cooling at Earth's surface.

? What phenomenon is illustrated in the accompanying image?

(Ulet Infansasfi/Getty Images)

5.9 Other Volcanic Landforms

List volcanic landforms other than shield, cinder cone, and composite volcanoes and describe their formation.

KEY TERMS: fissure eruption, basalt plateau, flood basalt, lava dome, volcanic neck (plug)

- Calderas, which can be among the largest volcanic structures, form when the rigid, cold rock above a magma chamber cannot be supported and collapses, creating a broad, roughly circular depression. On shield volcanoes, calderas form slowly as lava drains from the magma chamber beneath the volcano. On a composite volcano, caldera collapse often follows an explosive eruption that can result in significant loss of life and destruction of property.
- Fissure eruptions occasionally produce massive floods of fluid basaltic lava from large cracks, called fissures, in the crust. Layer upon layer of these flood basalts may accumulate to significant thicknesses and blanket a wide area. The Columbia Plateau located in the northwestern United States is an example.
- Lava domes are thick masses of high-viscosity, silica-rich lava that accumulate in the summit crater or caldera of a composite volcano. When they collapse, lava domes can produce extensive pyroclastic flows.
- Shiprock, New Mexico, is an example of a volcanic neck where the lava in the "throat" of an ancient volcano crystallized to form a "plug" of solid rock that weathered more slowly than the surrounding volcanic rocks. The surrounding pyroclastic debris eroded, and the resistant neck remains as a distinctive landform.

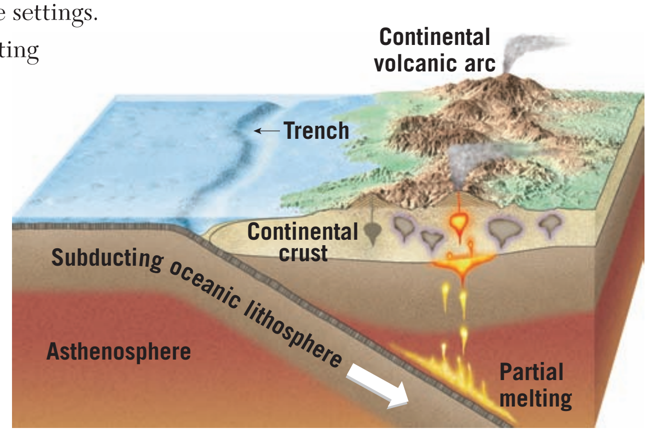
5.10 Plate Tectonics & Volcanism

Explain how the global distribution of volcanic activity is related to plate tectonics.

KEY TERMS: Ring of Fire, volcanic island arc (island arc), continental volcanic arc, intraplate volcanism, mantle plume, hot spot, superplume

- Volcanoes occur at both convergent and divergent plate boundaries, as well as in intraplate settings.
- At divergent plate boundaries, where lithosphere is being rifted apart, decompression melting is the dominant generator of magma. As warm rock rises, it can begin to melt without the addition of heat.
- Convergent plate boundaries that involve the subduction of oceanic crust are the most common site for explosive volcanoes—most prominently in the Pacific Ring of Fire. The release of water from the subducting plate triggers melting in the overlying mantle. The ascending magma interacts with the lower crust of the overlying plate and can form a volcanic arc at the surface.
- In intraplate settings, the source of magma is a mantle plume—a column of mantle rock that is warmer and more buoyant than the surrounding mantle.

? The accompanying diagram shows one of the tectonic settings where volcanism is a dominant process. Name the tectonic setting and briefly explain how magma is generated in this setting.



GIVE IT SOME THOUGHT

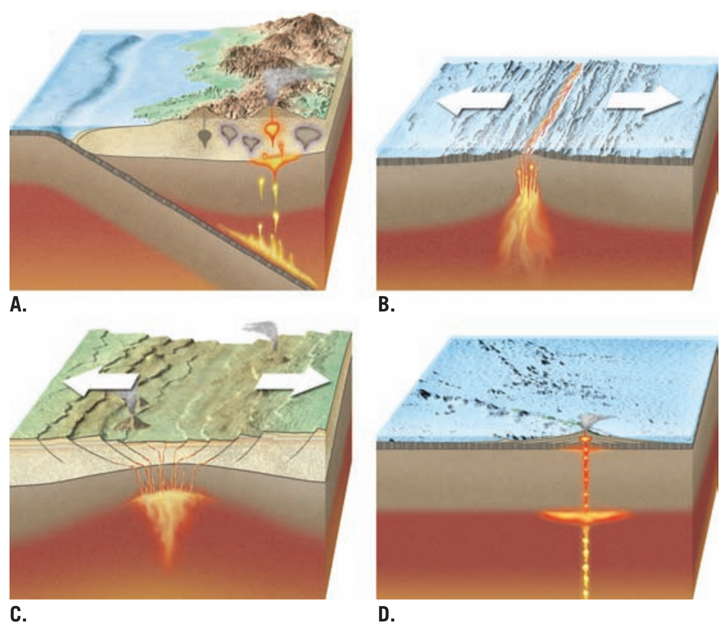
1 Examine the accompanying photo and complete the following:
  a. What type of volcano is it? What features helped you classify it as such?
  b. What is the eruptive style of such volcanoes? Describe the likely composition and viscosity of its magma.
  c. Which type of plate boundary is the likely setting for this volcano?
  d. Name a city that is vulnerable to the effects of a volcano of this type.


USGS

2 Answer the following questions about divergent boundaries, such as the Mid-Atlantic Ridge, and their associated lavas:
  a. Divergent boundaries are characterized by eruptions of what type of lava: andesitic, basaltic, or rhyolitic?
  b. What is the main source of the lavas that erupt at divergent plate boundaries?
  c. What process causes the source rocks to melt?

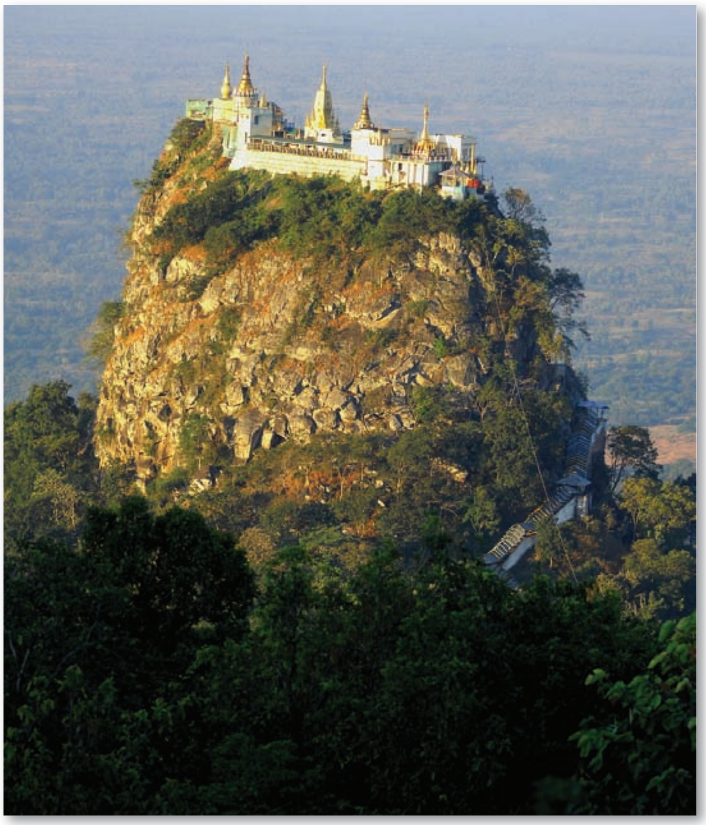
3 For each of the volcanoes or volcanic regions listed below, identify whether it is associated with a *convergent* or *divergent* plate boundary or with *intraplate volcanism*.
  a. Crater Lake
  b. Hawaii's Kilauea
  c. Mount St. Helens
  d. East African Rift
  e. Yellowstone
  f. Mount Pelée
  g. Deccan Traps
  h. Fujiyama

4 For each of the accompanying four sketches, identify the geologic setting (zone of volcanism). Which of these settings will most likely generate explosive eruptions? Which will produce outpouring of fluid basaltic lavas?



5 Explain why an eruption of Mount Rainier similar to the 1980 eruption of Mount St. Helens could be considerably more destructive.

6 This image shows the Buddhist monastery Taung Kalat, located in central Myanmar (Burma). The monastery sits high on a sheer-sided rock made mainly of magmas that solidified in the conduit of an ancient volcano. The volcano has since been worn away.
  a. Based on this information, what igneous structure do you think is shown in this photo?
  b. Would this volcanic structure most likely have been associated with a composite volcano or a cinder cone? Explain how you arrived at your answer.



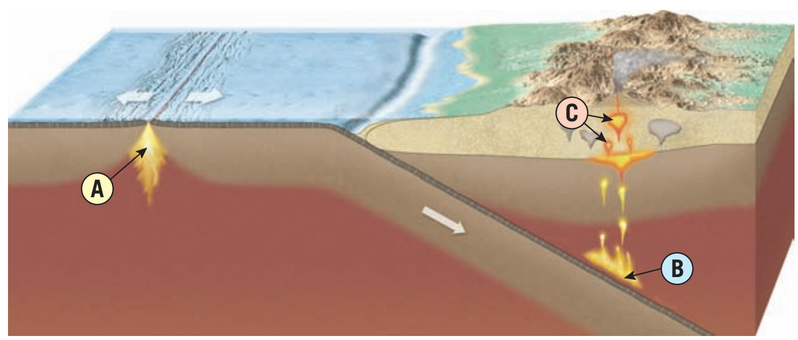
Taolmor/Dreamstime

7 The formula for the volume of a cone is $V = 1/3\pi r^2 h$ (where V = volume, $\pi = 3.14$, r = radius, and h = height). If Mauna Loa is 9 kilometers high and has a radius of roughly 85 kilometers, what is its approximate total volume?

8 The accompanying image shows a geologist at the end of an unconsolidated flow consisting of lightweight lava blocks that rapidly descended the flank of Mount St. Helens.
  a. What term best describes this type of flow: an aa flow, a pahoehoe flow, or a pyroclastic flow?
  b. What lightweight (vesicular) igneous rock type is likely the main constituent of this flow?

Donald Swanson/USGS

9 Different processes produce magma in different tectonic settings. Consider magma bodies found at locations A, B, and C in the accompanying diagram and describe the process that most likely triggered the melting that produced each.



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