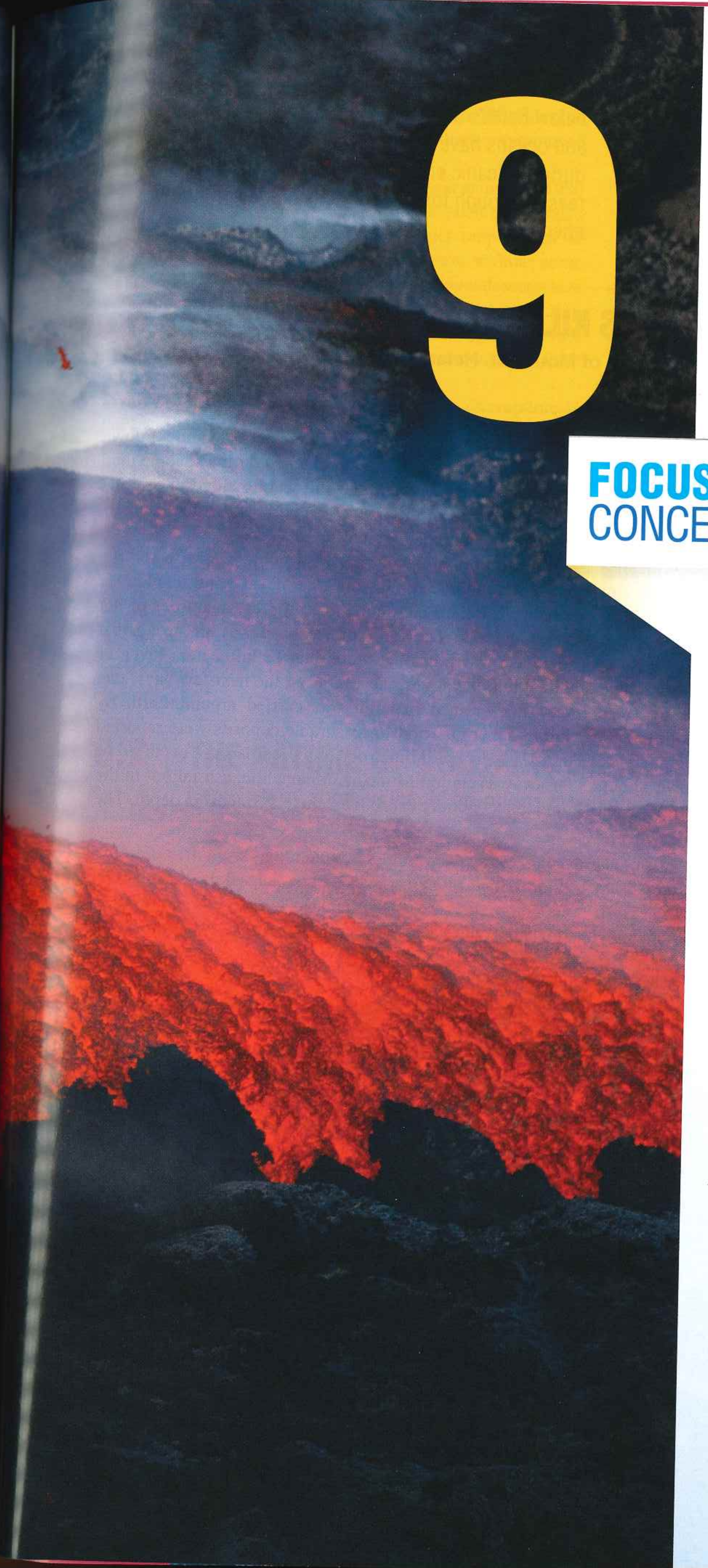


9

Volcanoes and Other Igneous Activity

FOCUS ON CONCEPTS

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

9.1 Compare and contrast the 1980 eruption of Mount St. Helens with the eruption of Kilauea, which began in 1983 and continues today.

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

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

9.4 Label a diagram that illustrates the basic features of a typical volcanic cone.

9.5 Summarize the characteristics of shield volcanoes and provide one example.

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

9.7 Explain the formation, distribution, and characteristics of composite volcanoes.

9.8 Discuss the major geologic hazards associated with volcanoes.

9.9 List and describe volcanic landforms other than volcanic cones.

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

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

9.12 Relate the distribution of volcanic activity to plate tectonics.

Fluid basaltic lava erupting from Mount Etna, Italy. (Photo by Westend61 GmbH/Alamy)

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, the 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.

9.1 MOUNT ST. HELENS VERSUS KILAUEA

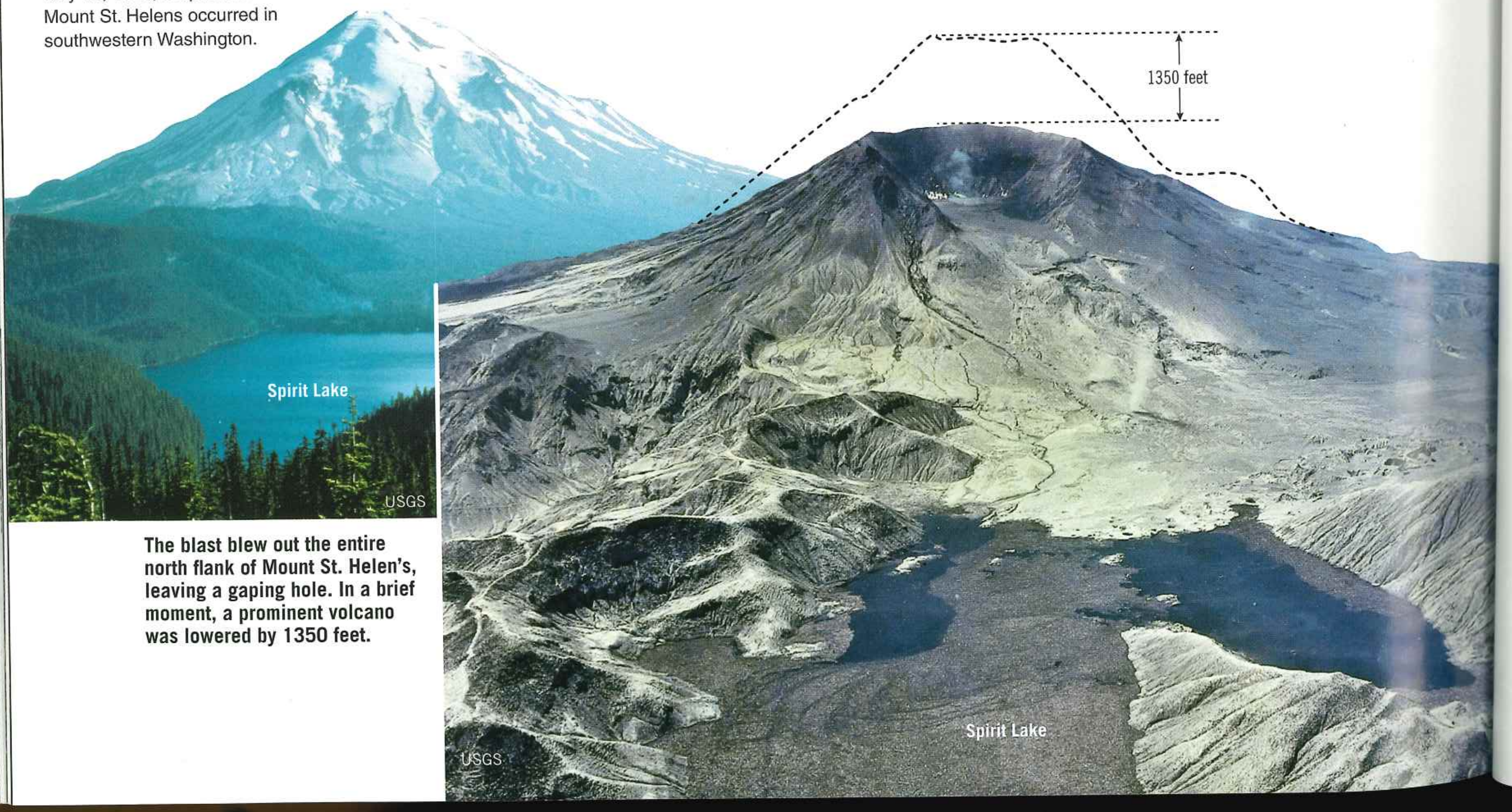
Compare and contrast the 1980 eruption of Mount St. Helens with the eruption of Kilauea, which began in 1983 and continues today.

On Sunday, May 18, 1980, the largest volcanic eruption to occur in North America in historic times transformed a picturesque volcano into a decapitated remnant (**FIGURE 9.1**). 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 9.2**). 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 entrapped in mudflows.

The eruption ejected nearly 1 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. Measurable deposits were reported in Oklahoma and Minnesota, and crop damage occurred as far away as central Montana. Meanwhile, ash fallout in the immediate vicinity exceeded 2 meters (6 feet) in depth. The

FIGURE 9.1 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. Helen's, leaving a gaping hole. In a brief moment, a prominent volcano was lowered by 1350 feet.

air over Yakima, Washington (130 kilometers [80 miles] to the east), was so filled with ash that residents experienced midnight-like darkness at noon.

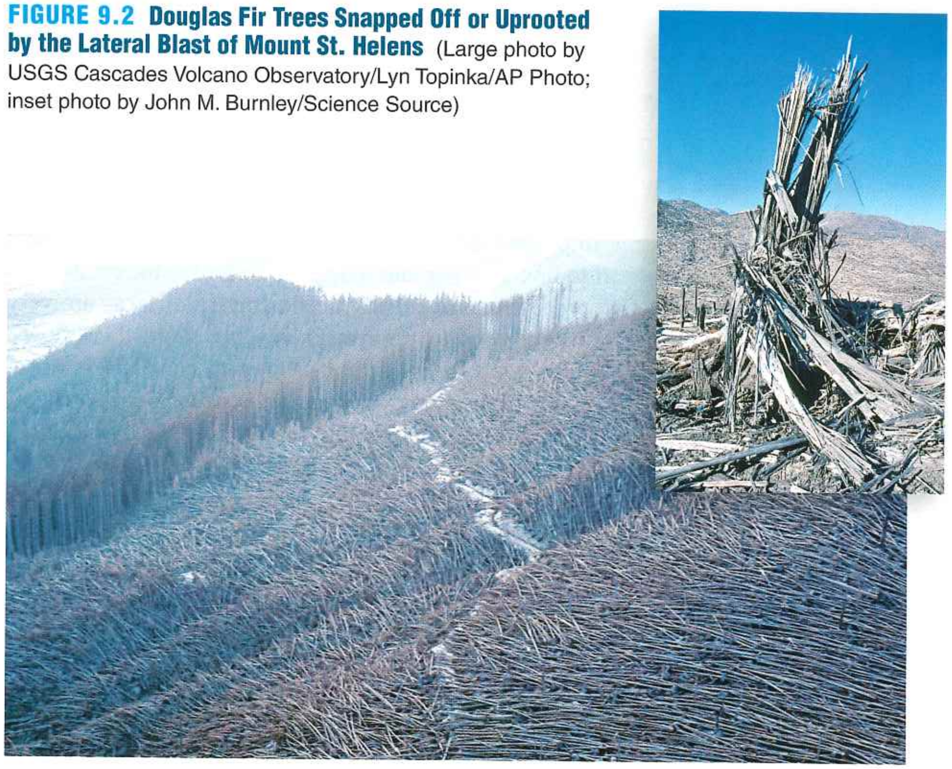
Not all volcanic eruptions are as violent as the 1980 Mount St. Helens event. Some volcanoes, such as Hawaii's Kilauea volcano, generate relatively quiet outpourings of fluid lavas. These "gentle" eruptions are not without some fiery displays; occasionally fountains of incandescent lava spray hundreds of meters into the air. Nevertheless, during Kilauea's most recent active phase, which began in 1983, more than 180 homes and a national park visitor center have been destroyed.

Testimony to the "quiet 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.

9.1 CONCEPT CHECKS

1 Briefly compare the May 18, 1980, eruption of Mount St. Helens to a typical eruption of Hawaii's Kilauea volcano.

FIGURE 9.2 Douglas Fir Trees Snapped Off or Uprooted by the Lateral Blast of Mount St. Helens (Large photo by USGS Cascades Volcano Observatory/Lyn Topinka/AP Photo; inset photo by John M. Burnley/Science Source)



9.2 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. What determines the manner in which volcanoes erupt?

Factors Affecting Viscosity

The source material for volcanic eruptions is **magma**, molten rock that usually contains some crystals and varying amounts of dissolved gas. Erupted magma is called **lava**. The primary factors that affect the behavior of magma and lava are its *temperature* and *composition* and, to a lesser extent, the amount of *dissolved gases* it contains. To varying degrees, these factors determine a magma's mobility, or **viscosity** (*viscos* = sticky). The more viscous the material, the greater its resistance to flow. For example, syrup is more viscous and, thus, more resistant to flow, than water.

Temperature The effect of temperature on viscosity is easily seen. Just as heating syrup makes it more fluid (less viscous), temperature also strongly influences the mobility of lava. As lava cools and begins to congeal, its viscosity increases, and eventually the flow halts.

Composition Another significant factor influencing volcanic behavior is the chemical composition of the magma. Recall that a major difference among various igneous rocks is their silica (SiO_2) content (**TABLE 9.1**). Magmas

TABLE 9.1 Different Compositions of Magmas Cause Properties to Vary

Composition	Silica Content	Gas Content	Eruptive Temperatures	Viscosity	Tendency to Form Pyroclastics	Volcanic Landform
Basaltic (mafic)	Least (~50%)	Least (1–2%)	1000–1250°C	Least	Least	Shield volcanoes, basalt plateaus, cinder cones
Andesitic (intermediate)	Intermediate (~60%)	Intermediate (3–4%)	800–1050°C	Intermediate	Intermediate	Composite cones
Rhyolitic (felsic)	Most (~70%)	Most (4–6%)	650–900°C	Greatest	Greatest	Pyroclastic flows, lava domes

that produce mafic rocks such as basalt contain about 50 percent silica, whereas magmas that produce felsic rocks (granite and its extrusive equivalent, rhyolite) contain more than 70 percent silica. Intermediate rock types—andesite and diorite—contain about 60 percent silica.

A magma's viscosity is directly related to its silica content: *The more silica in magma, the greater its viscosity*. Silica impedes the flow of magma because silicate structures start to link together into long chains early in the crystallization process. Consequently, felsic (rhyolitic) lavas are very viscous and tend to form comparatively short, thick flows. By contrast, mafic (basaltic) lavas, which contain less silica, are relatively fluid and have been known to travel 150 kilometers (90 miles) or more before solidifying.

Dissolved Gases

The gaseous components in magma (mainly dissolved water and carbon dioxide), called **volatiles**, also affect the mobility of magma. Other factors being equal, water dissolved in magma tends to increase fluidity because it reduces formation of long silicate chains by breaking silicon–oxygen bonds. It follows, therefore, that the loss of gases renders magma (lava) more viscous. Gases also give magmas their explosive character.

Quiescent Versus Explosive Eruptions

Most magma is generated by partial melting of the rock in the upper mantle and has a basaltic composition, a topic we will consider later in the chapter. The newly formed magma, which is less dense than the surrounding rock, slowly rises toward the surface. In some settings, high-temperature basaltic magmas reach Earth's surface, where they produce highly fluid lavas. This most commonly occurs on the ocean floor, in association with seafloor spreading. In continental settings, however, the density of crustal rocks is less than that of the ascending material, causing the magma to pond at the crust–mantle boundary. Heat from the hot magma is often sufficient to partially melt the overlying crustal rocks, generating a less dense, silica-rich magma, which continues the journey toward Earth's surface.

FIGURE 9.3 Lava Fountain Produced by Gases Escaping Fluid Basaltic Lava Lava erupting from Mount Etna, Italy. (Photo by D. Szczepanski terras/AGE Fotostock)

Gases readily escape hot fluid basaltic flows, producing lava fountains. Although often spectacular, these features generally do not cause great loss of life or property.

Quiescent Hawaiian-Type Eruptions

Eruptions that involve very fluid basaltic lavas, such as the eruptions of Kilauea on Hawaii's Big Island, are often triggered by the arrival of a new batch of molten rock into a near-surface magma chamber. Such an event can usually be detected 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 chamber. In addition, swelling of the magma chamber fractures the rock above, allowing the fluid magma to move upward along the newly formed openings, often generating outpourings of lava for weeks, months, or possibly years. The eruption of Kilauea that began in 1983 has been ongoing for more than 30 years.

Triggering Explosive 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 pressure reduces, and the dissolved gases begin to separate from the melt, forming tiny bubbles. This is analogous to opening a can of soda and allowing the carbon dioxide bubbles to escape.

When fluid basaltic magmas erupt, the 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 9.3**). Although spectacular, these fountains are usually harmless and generally not associated with major explosive events that cause great loss of life and property.

At the other extreme, highly viscous magmas expel particles of fragmented lava and gases at nearly supersonic speeds, creating buoyant plumes called **eruption columns**. Eruption columns can rise perhaps 40 kilometers (25 miles) into the atmosphere (**FIGURE 9.4**). Because silica-rich magmas are sticky (viscous), a significant portion of the gaseous material remains dissolved until the magma nears Earth's surface, at which time tiny bubbles begin to form and grow. When the pressure of the expanding magma body exceeds the strength of the overlying rock, fracturing occurs. As magma moves up the fractures, a further drop in confining pressure causes more gas bubbles to form and grow. This chain reaction may generate an explosive event in which magma is literally blown into fragments (ash and pumice) that are carried to great heights by the hot gases. (As exemplified by the 1980 eruption of Mount St. Helens, the collapse of a volcano's flank can result in a reduction in the pressure on the magma below, triggering an explosive eruption.)

When magma in the uppermost portion of the magma chamber is forcefully ejected by the escaping gases, the confining pressure on the molten rock directly below drops suddenly. Thus, rather than a single "bang," volcanic eruptions are really a series of explosions. Following explosive eruptions, degassed lava may slowly ooze out of the vent to form short rhyolitic flows or dome-shaped lava bodies that grow over the vent.

9.2 CONCEPT CHECKS

1. Define *viscosity* and list three factors that influence the viscosity of magma.
2. Explain how the viscosity of magma influences the explosiveness of a volcano.
3. List these three magmas in order from *most* silica rich to *least* silica rich, based on their compositions: mafic (basaltic), felsic (rhyolitic), intermediate (andesitic).
4. The eruption of what type of magma may produce an eruption column?
5. Why is a volcano that is fed by highly viscous magma likely to be a greater threat to life and property than a volcano supplied with very fluid magma?

FIGURE 9.4 Eruption Column Generated by Viscous, Silica-Rich Magma Steam and ash eruption column from Mount Augustine, Cook Inlet, Alaska. (Photo by Steve Kaufman/Getty Images)

Eruptions of highly viscous lavas may produce explosive clouds of hot ash and gases called eruption columns.

9.3 MATERIALS EXTRUDED DURING AN ERUPTION

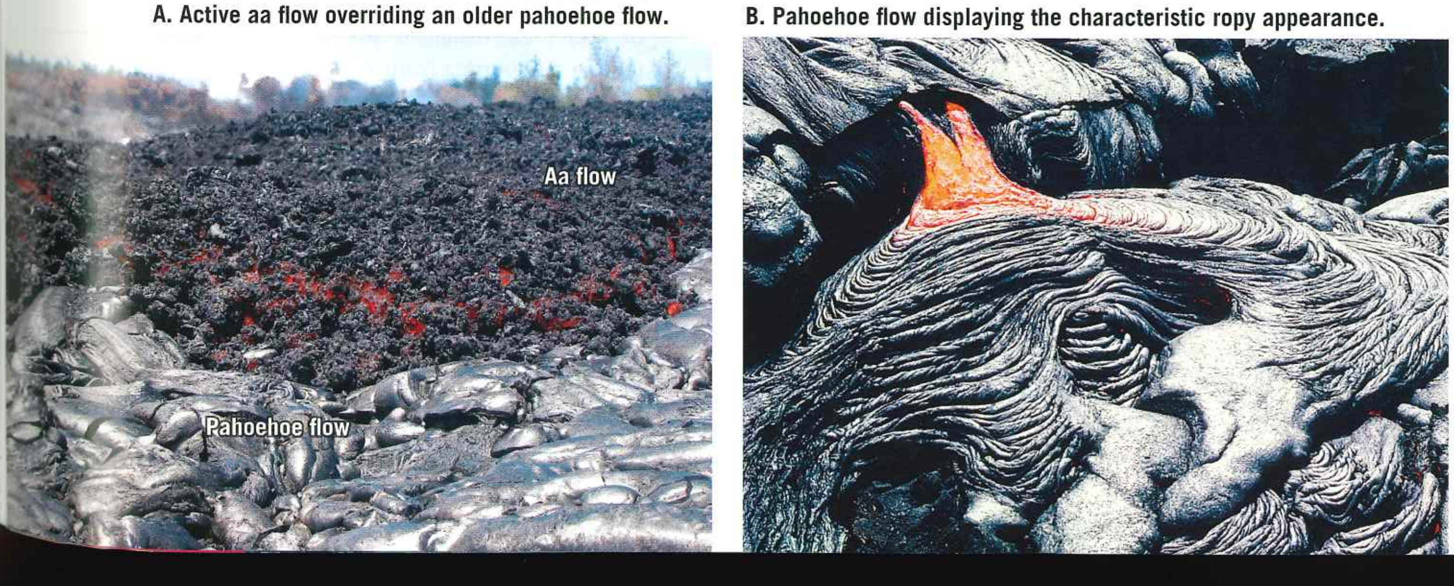
List and describe the three categories of materials extruded during volcanic eruptions.

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

Lava Flows

The vast majority of lava on Earth—more than 90 percent of the total volume—is estimated to be basaltic in composition. Andesites and other lavas of intermediate composition account for most of the rest, while rhyolitic (felsic) flows make up as little as 1 percent of the total.

Hot basaltic lavas, which are usually very fluid, generally flow in thin, broad sheets or streamlike ribbons. On the Big Island of Hawaii, these lavas have been clocked at 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. By contrast, the movement of silica-rich, rhyolitic lava may be too slow to perceive. Furthermore, most



A. Active aa flow overriding an older pahoehoe flow.

B. Pahoehoe flow displaying the characteristic ropy appearance.

FIGURE 9.5 Lava Flows **A.** A typical slow-moving, basaltic, aa flow. **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 USGS)

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 9.6 Lava Tubes 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. One such structure, Kazumura Cave, located on the southeastern slope of Hawaii's Mauna Loa Volcano, extends more than 60 kilometers (40 miles). (Photo A. by Dave Bunnell and Photo B. Courtesy of USGS)

rhyolitic lavas seldom travel more than a few kilometers from their vents. As you might expect, andesitic lavas, which are intermediate in composition, exhibit characteristics that are between the extremes.

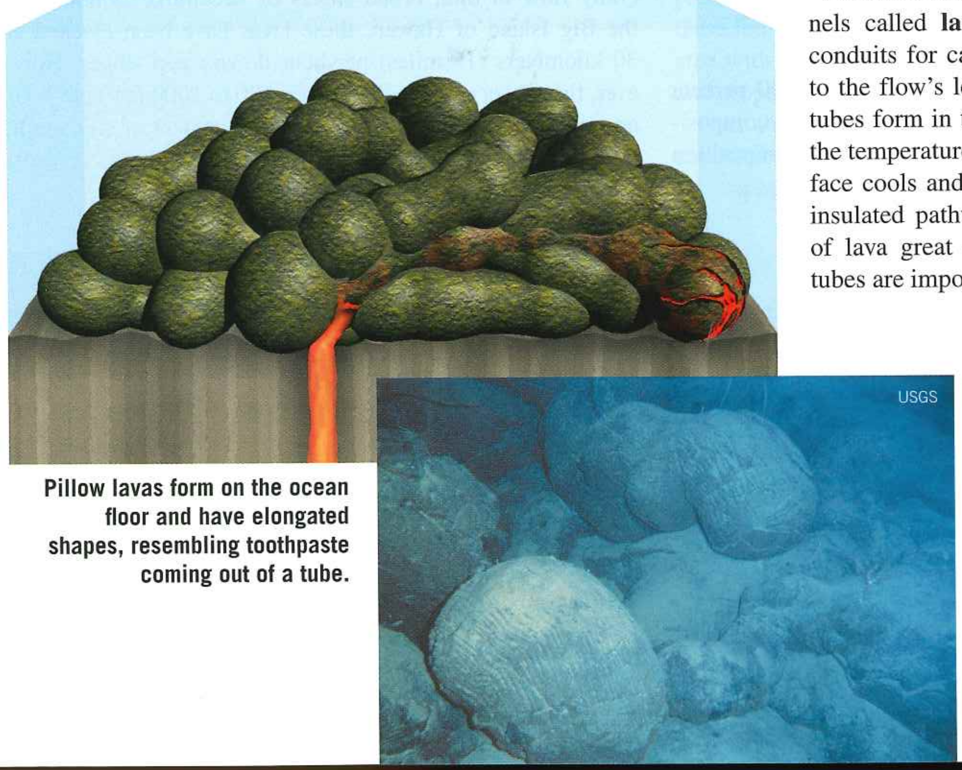
Aa and Pahoehoe Flows Fluid basaltic magmas tend to generate two types of lava flows known by Hawaiian names. One of these, called **aa** (pronounced "ah-ah") **flows**, have surfaces of rough, jagged blocks with dangerously sharp edges and spiny projections (**FIGURE 9.5A**). Crossing a hardened aa 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 9.5B**). Pahoehoe means "on which one can walk."

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 reduction in 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 a 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 were previously conduits for carrying lava from an active vent to the flow's leading edge (**FIGURE 9.6**). Lava tubes form in the interior of a lava flow where the temperature remains high long after the surface cools and hardens. Because they serve as insulated pathways that facilitate the advance of lava great distances from its source, lava tubes are important features of fluid lava flows.

FIGURE 9.7 Pillow Lava This image shows pillow lava that formed off the coast of Hawaii.



Pillow lavas form on the ocean floor and have elongated shapes, resembling toothpaste coming out of a tube.

Pillow Lavas Recall that much of Earth's volcanic output occurs along oceanic ridges (divergent plate boundaries). When outpourings of lava occur on the ocean floor, the flow's outer skin quickly freezes to form obsidian. 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 9.7**). Pillow lavas are useful in the reconstruction of geologic history because their presence indicates that the lava flow formed below the surface of a water body.

Gases

Magmas contain varying amounts of dissolved gases (*volatiles*) held in the molten rock by confining pressure, just as carbon dioxide is held in cans and bottles 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 magmas makes up 1 to 6 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. Some of these eruptions may have an impact on Earth's climate, a topic we consider later in this chapter.

The composition of volcanic gases is important because these gases contribute significantly to our planet's atmosphere. Analyses of samples taken during Hawaiian eruptions indicate that the gas component is about 70 percent water vapor, 15 percent carbon dioxide, 5 percent nitrogen, and 5 percent sulfur dioxide, with lesser amounts of chlorine, hydrogen, and argon. (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, which readily combines with atmospheric gases to form sulfuric acid and other sulfate compounds.

Pyroclastic Materials

When volcanoes erupt energetically, they eject pulverized rock, lava, and glass fragments from the vent. The particles produced are called **pyroclastic materials** (*pyro* = fire, *clast* = fragment) and are also referred to as *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 9.8**).

Pyroclastic Materials (Tephra)

Particle name	Particle size	Image
Volcanic Ash*	Less than 2mm (0.08 inch)	
Lapilli (Cinders)	Between 2mm 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 9.8 Types of Pyroclastic Materials Pyroclastic materials are also commonly referred to as tephra.

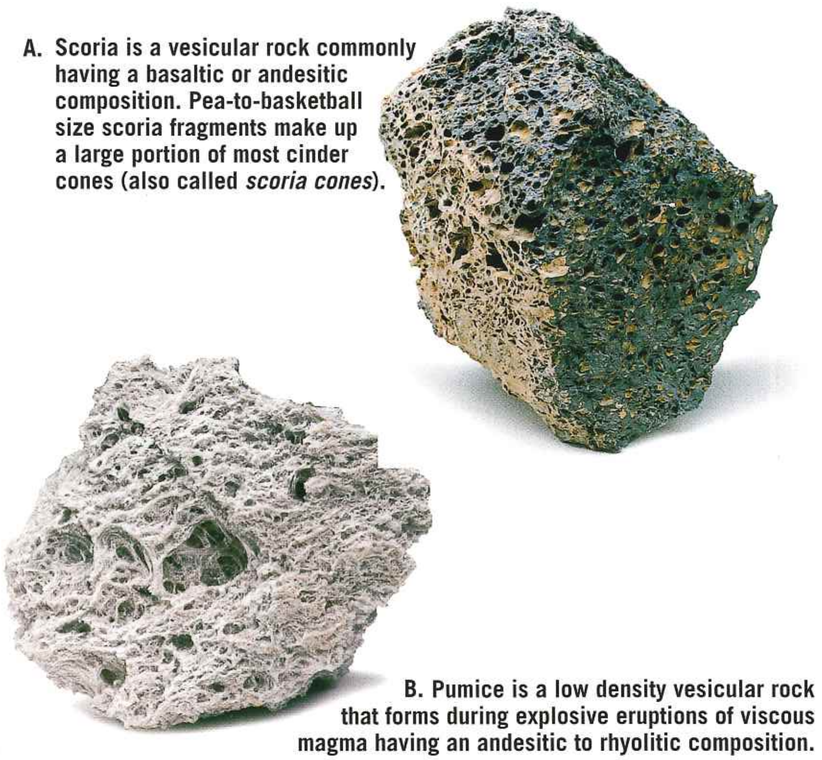


FIGURE 9.9 Common Vesicular Rocks Scoria and pumice are volcanic rocks that exhibit a vesicular texture. Vesicles are small holes left by escaping gas bubbles. (Photos by E. J. Tarbuck)

Ash and *dust* particles are produced when gas-rich viscous magma erupts explosively (see Figure 9.7). 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 are known as *lapilli* ("little stones"). These ejecta are commonly called *cinders* (2–64 millimeters). 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 9.8). Because bombs are semimolten upon ejection, they often take on a streamlined shape as they hurtle through the air. Because of their size, 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.

So far we have distinguished various pyroclastic materials based largely on the sizes of the fragments. Some materials are also identified by their texture and composition. In particular, **scoria** is the name applied to vesicular ejecta that is a product of basaltic magma (**FIGURE 9.9A**). 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. When magmas with intermediate (andesitic) or felsic (rhyolitic) compositions erupt explosively, they emit ash and the vesicular rock **pumice** (**FIGURE 9.9B**). 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.

9.3 CONCEPT CHECKS

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

9.4 ANATOMY OF A VOLCANO

Label a diagram that illustrates the basic features of a typical volcanic cone.

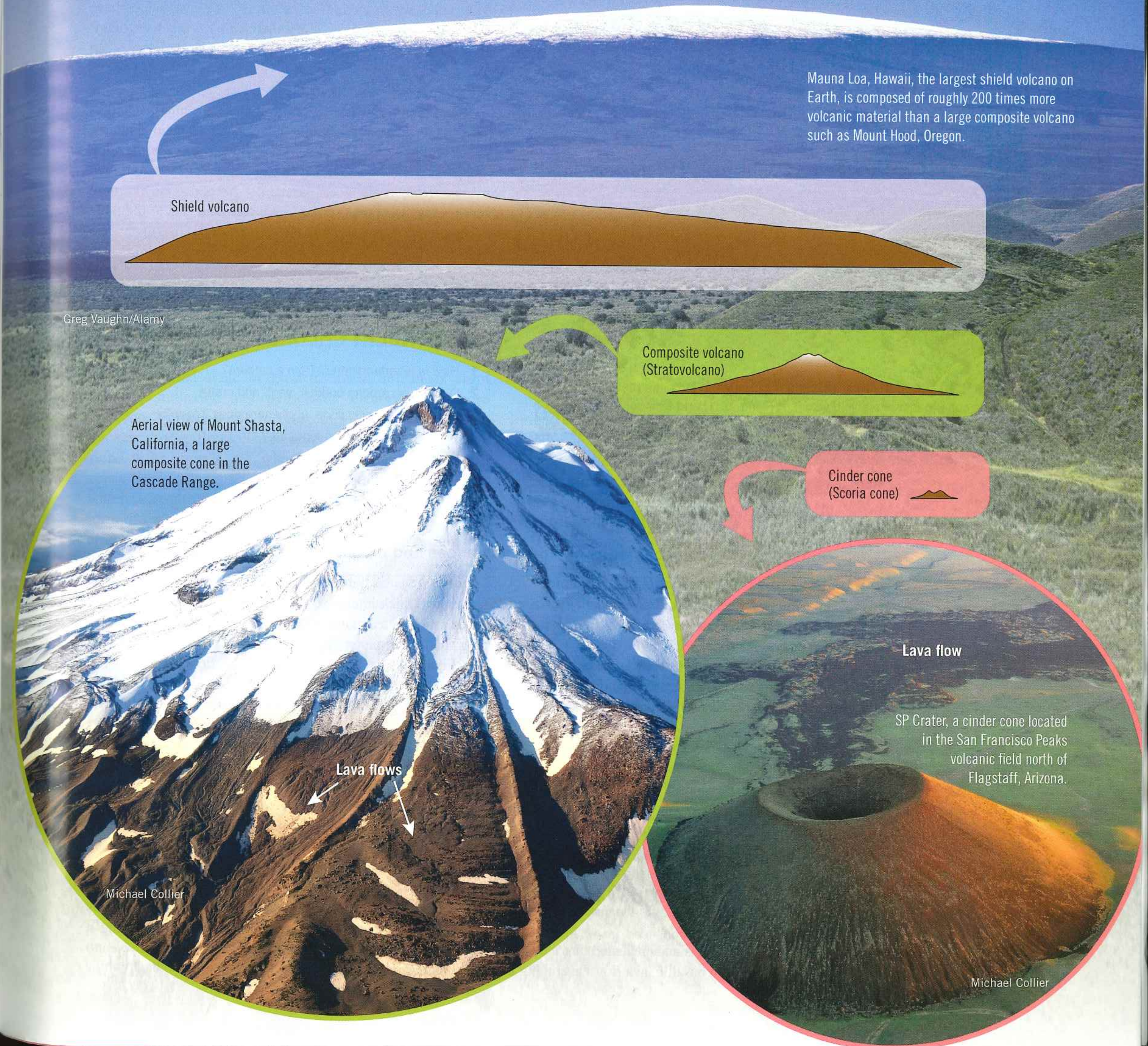
A popular image of a volcano is a solitary, graceful, snow-capped cone, such as Mount Hood in Oregon or Japan's Fujiyama. These picturesque conical mountains are produced by volcanic activity that occurred intermittently over thousands, or even hundreds of thousands, of years. However, many volcanoes 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 deposit consisting of 15 cubic kilometers (more than 3.5 cubic miles) of ash, more than 20 times the volume of the 1980 Mount St. Helens eruption. It formed in less than 60 hours and blanketed a river valley to a depth of 200 meters (600 feet).

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 circular **conduit** that terminates at a surface opening called a **vent** (**FIGURE 9.10**). The cone-shaped structure we call a **volcanic cone** is often created by successive eruptions of lava,

Comparison of Three Types of Volcanic Cones

These images and drawings compare the relative sizes and shapes of three different volcanoes. Note the size comparison between a large shield volcano and a large composite volcano.



Mauna Loa, Hawaii, the largest shield volcano on Earth, is composed of roughly 200 times more volcanic material than a large composite volcano such as Mount Hood, Oregon.

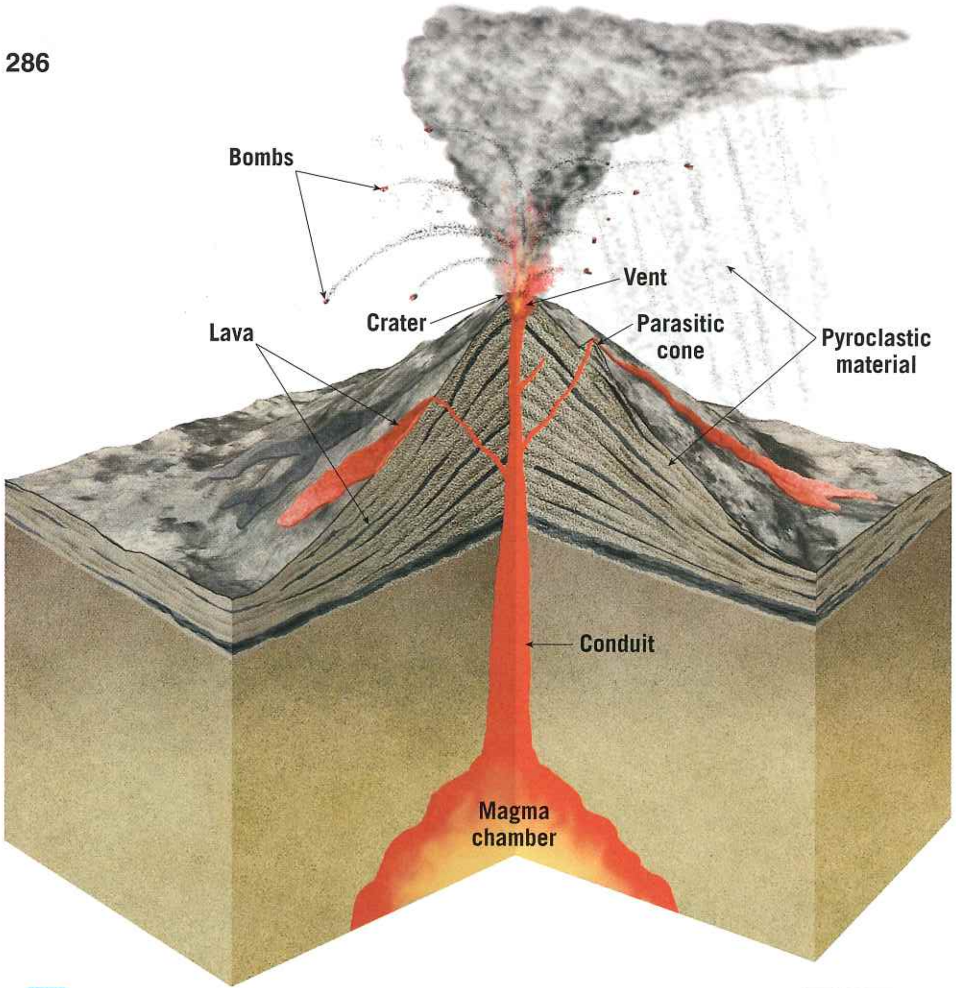
Greg Vaughn/Alamy

Aerial view of Mount Shasta, California, a large composite cone in the Cascade Range.

Michael Collier

SP Crater, a cinder cone located in the San Francisco Peaks volcanic field north of Flagstaff, Arizona.

Michael Collier



SmartFigure 9.10 Anatomy of a Volcano Compare the structure of a "typical" composite cone to that of a shield volcano (Figure 9.11) and a cinder cone (Figure 9.12).

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* that have diameters greater than 1 kilometer (0.6 mile) and in some cases can exceed 50 kilometers (30 miles). We consider the formation of various types of calderas 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 or at the base of the volcano. Continued activity from a flank eruption may produce one or more small **parasitic cones** (*parasitus* = one who eats at the table of another). 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).

9.4 CONCEPT CHECKS

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

9.5 SHIELD VOLCANOES

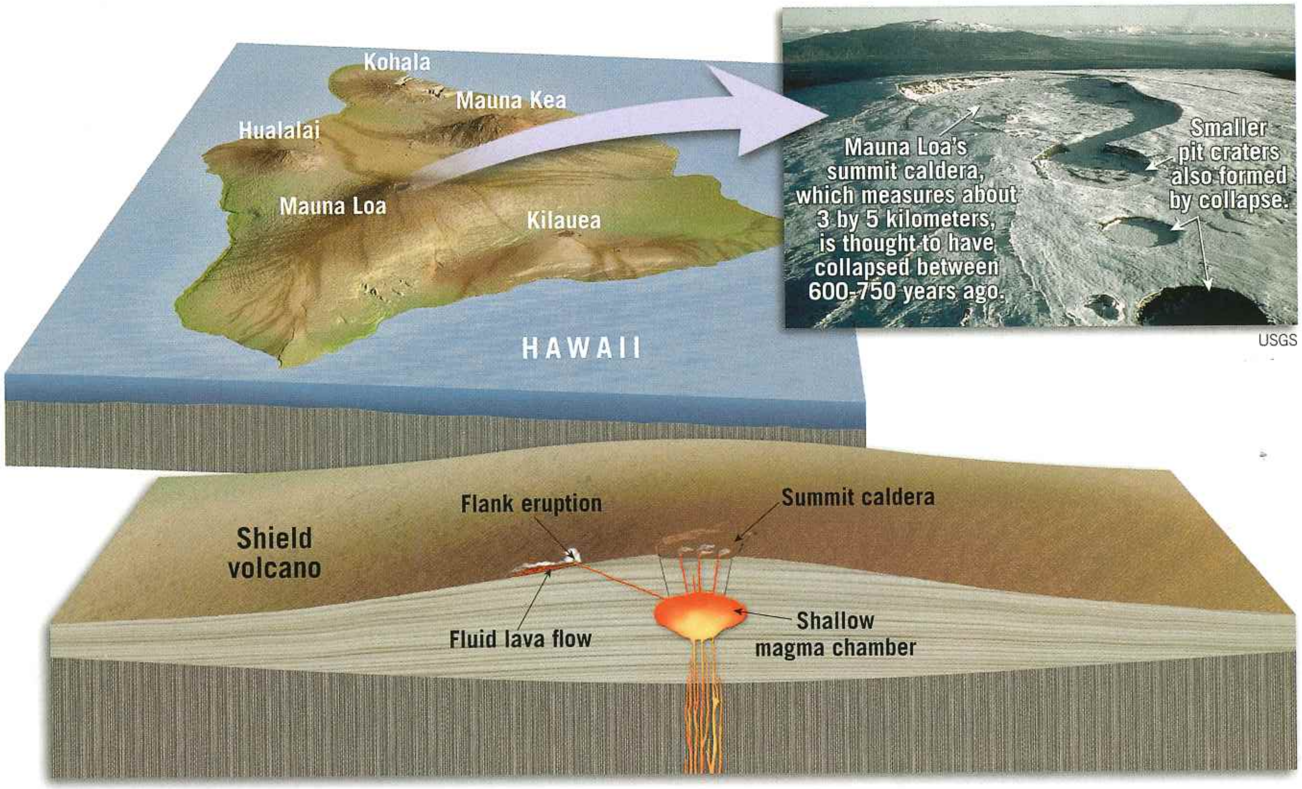
Summarize the characteristics of shield volcanoes and provide one example.

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 9.11**). Most shield volcanoes begin on the ocean floor as seamounts, a few of which grow large enough to form volcanic islands. In fact, with the exception of the volcanic islands that form above subduction zones, most other small oceanic islands are either a single shield volcano or, more often, the coalescence of two or more shields built on massive amounts of pillow lavas. Examples include the Canary islands, the Hawaiian islands, the Galapagos, and Easter Island. In addition, some shield volcanoes form on continental crust. Included in this group are Nyamuragira, Africa's most active volcano, and Newberry volcano, located in Oregon.

Mauna Loa: Earth's Largest Shield Volcano

Extensive study of the Hawaiian islands revealed that they are constructed of a myriad of thin basaltic lava flows averaging a few meters thick intermixed with relatively minor amounts of pyroclastic ejected material. Mauna Loa is one of five overlapping shield volcanoes that comprise the Big Island of Hawaii (see Figure 9.11). From its base on the floor of the Pacific Ocean to its summit, Mauna Loa is over 9 kilometers (6 miles) high, exceeding the elevation of Mount Everest. The volume of material composing Mauna Loa is roughly 200 times greater than that of a large composite cone such as Mount Rainier.

The flanks of Mauna Loa have gentle slopes of only a few degrees. This low angle results because very hot, fluid lava travelled "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 many active shield volcanoes is a large, steep-walled caldera that occupies the summit (see Figure 9.11). A caldera usually forms when the roof of solid rock above a magma chamber collapses. This usually occurs as the magma reservoir empties following a large eruption, or as magma migrates to the flank of a volcano to feed a fissure eruption.



USGS

FIGURE 9.11 Mauna Loa: Earth's Largest Volcano Mauna Loa 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.

In the final stage of growth, shield volcanoes erupt more sporadically, and pyroclastic ejections are more common. Further, lavas increase in viscosity, resulting in thicker, shorter flows. These eruptions tend to steepen the slope of the summit area, which often becomes capped with clusters of cinder cones. This may explain why Mauna Kea, which is 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, housing some of the most advanced and expensive telescopes.

Kilauea, Hawaii: Eruption of a Shield Volcano

Kilauea, the most active and intensely studied shield volcano in the world, is located on the island of Hawaii, in the shadow of Mauna Loa. More than 50 eruptions have been witnessed here 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. The longest and largest rift eruption ever recorded on Kilauea began in 1983 and continues to this day, with no signs of abating (see the GEOgraphics on pages 288–289). The first discharge began along a 6-kilometer (4-mile) fissure where a 100-meter- (300-foot-) high "curtain of fire" formed as red-hot lava was ejected skyward. When the activity became localized, a cinder and spatter cone, given the Hawaiian name *Puu Oo*, was built. Over the next 3 years, the general eruptive pattern consisted of short periods (hours to days) when fountains of gas-rich lava sprayed skyward. Each event was followed by nearly a month of inactivity.

By the summer of 1986, a new vent opened 3 kilometers (nearly 2 miles) downrift. Here smooth-surfaced pahoehoe lava formed a lava lake. Occasionally the lake overflowed, but more often lava escaped through tunnels to feed flows that moved down the southeastern flank of the volcano toward the sea. These flows destroyed nearly 180 rural homes, covered a major roadway, and eventually reached the sea. Lava has been intermittently pouring into the ocean ever since, adding new land to the island of Hawaii.

9.5 CONCEPT CHECKS

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. Relate lava tubes to the extent of lava flows associated with shield volcanoes.
5. Where are the best-known shield volcanoes in the United States? Name some examples in other parts of the world.

Kilauea's East Rift Zone Eruption

Kilauea, one of the most active volcanoes in the world, is located on the island of Hawaii in the shadow of Mauna Loa. Most of the recent activity on Kilauea has occurred along the flanks of the volcano in a region called the East Rift Zone. The longest and largest eruption ever recorded on Kilauea began in 1983, and continues with no signs of abating.

Greg Vaughn/Alamy

1 Kilauea's most recent eruptive phase began along a 6-kilometer (4 mile) fissure where a 100-meter (300-foot) high "curtain of fire" formed as red-hot basaltic lava was ejected skyward.

David Reggie/ Getty Images

2 The activity became localized at a single vent and a series of 44 short-lived episodes of lava fountaining built a cinder and spatter cone—given the Hawaiian name *Puu Oo.*

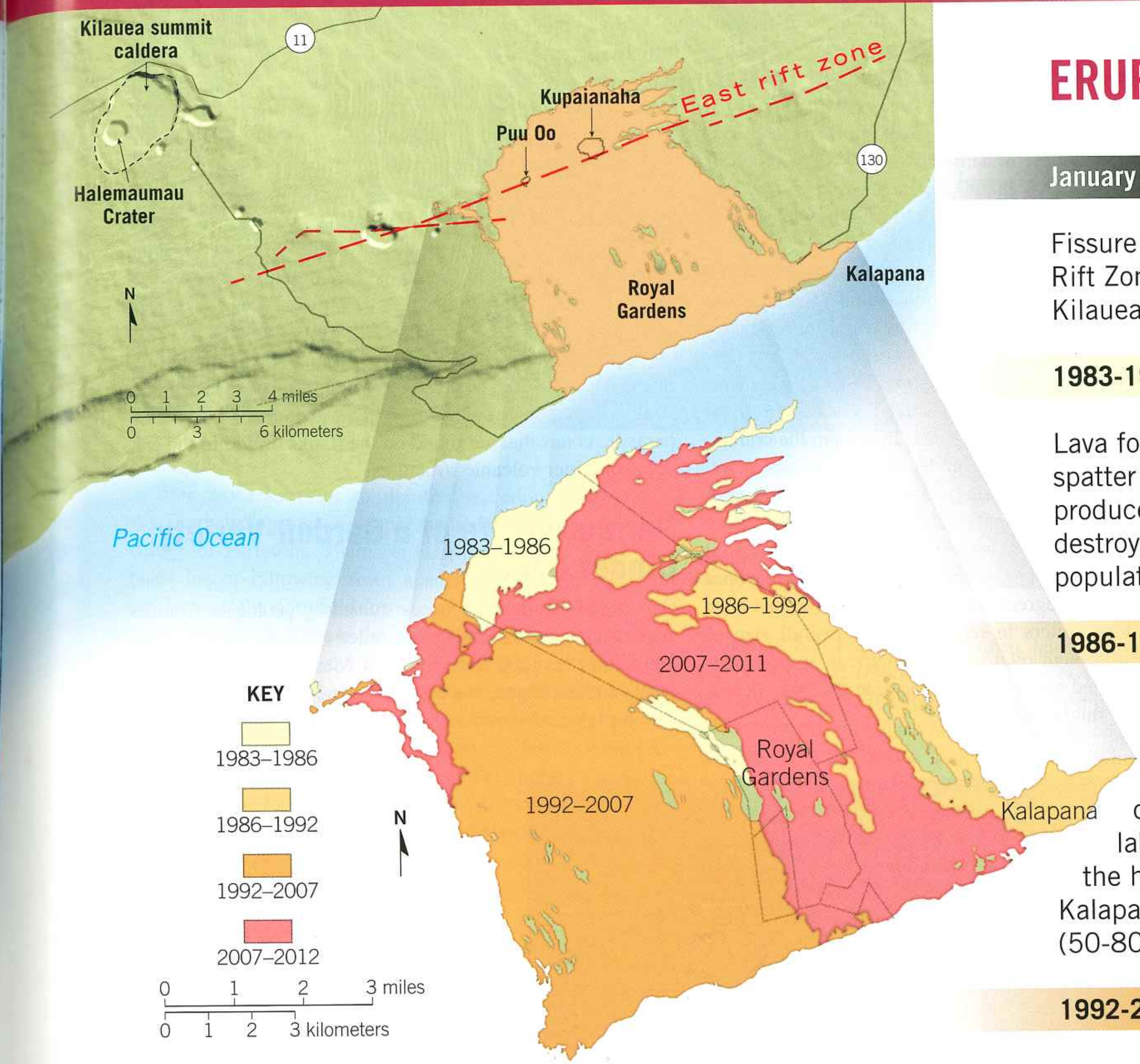
Michael Collier

3 One of many fluid pahoehoe flows that have moved down the flanks of Kilauea since 1983.

USGS

4 By the summer of 1986 a new vent opened along the rift. Pahoehoe lava flowing from this vent cut off the coastal highway and destroyed more than 180 structures including the National Park Visitor Center.

1983 to Present



ERUPTION SUMMARY

January 3, 1983

Fissure eruption began along East Rift Zone in an area southeast of Kilauea's summit caldera.

1983-1986

Lava fountains built a cinder-and-spatter cone called Puu Oo and produced mainly aa flows that destroyed 16 homes in the sparsely populated Royal Gardens subdivision.

1986-1992

Eruption moved eastward and built a small shield volcano called Kupaianaha which contained an extensive lava lake. Lava flows buried most of the homes in the village of Kalapana under 15-25 meters (50-80 feet) of lava.

1992-2007

Activity returned to the flanks of Puu Oo. Lava tubes carried lava nearly continuously to the ocean.

2007-2012

Several new vents open, including a small vent within Kilauea's summit caldera.

Other vents have since opened around Puu Oo and lava continues to flow toward the sea. 5

USGS

9.6 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 9.12**). 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. 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 determined by the slope that loose pyroclastic material maintains as it comes to rest (see Figure 9.12). Cinder cones have a high angle of repose (the steepest angle at which material remains stable) and are therefore steep-sided, with slopes between 30 and 40 degrees. In addition, cinder cones have quite large, deep craters in relation 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.

Mobile Field Trip 9.12 Cinder Cone

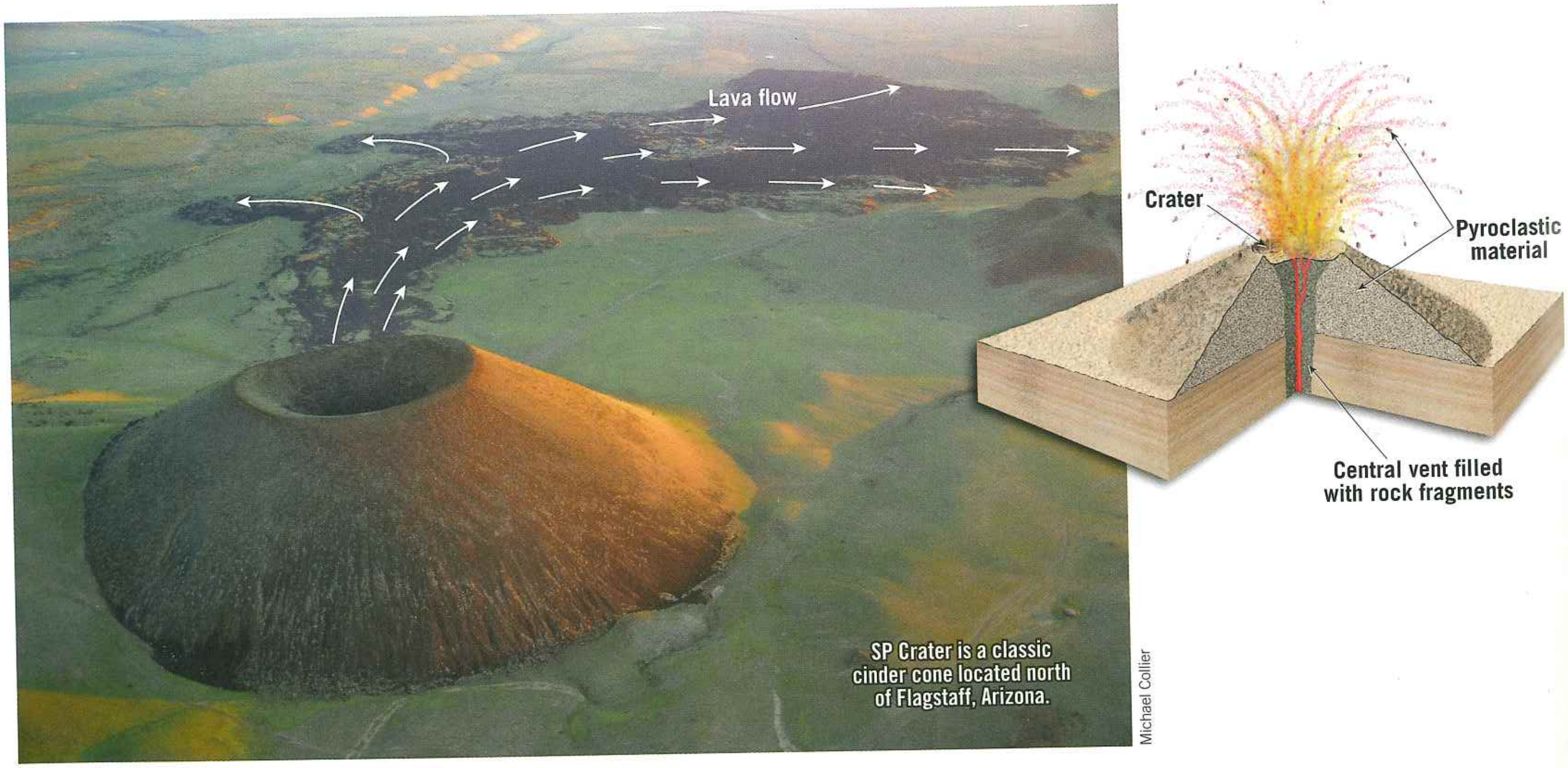
Cinder cones are built from ejected lava fragments (mostly cinders and bombs) and are relatively small—usually less than 300 meters (1000 feet) in height.

Most cinder cones are produced by a single, short-lived eruptive event. In one study, half of all cinder cones examined were constructed in less than 1 month, and 95 percent were 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 consequence of this typically short life span, cinder cones are small, usually between 30 meters (100 feet) and 300 meters (1000 feet). A few rare examples exceed 700 meters (2100 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 as he prepared the field for planting.



SP Crater is a classic cinder cone located north of Flagstaff, Arizona.

Michael Collier

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.

Photos by Michael Collier

FIGURE 9.13 Parícutin, a Well-Known Cinder Cone The village of San Juan Parangaricutiro was engulfed by aa lava from Parícutin. Only the church towers remain.

For 2 weeks prior to the first eruption, numerous Earth 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 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 the church steeple exposed (**FIGURE 9.13**). 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 one of the scores of cinder cones dotting the landscape in this region of Mexico. Like the others, it will not erupt again.

9.6 CONCEPT CHECKS

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

9.7 COMPOSITE VOLCANOES

Explain the formation, distribution, and characteristics of composite volcanoes.

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 9.32). This active zone consists in part of a chain of continental volcanoes that are 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 referred to as the "Lighthouse of the Mediterranean."

GEOGRAPHICS

Eruption of Mount Vesuvius, AD 79

One well-documented volcanic eruption of historic proportions was the AD 79 eruption of the Italian volcano we now call Mount Vesuvius. For centuries prior to this eruption, Vesuvius had been relatively quiescent and its slopes were adorned with vineyards. However, the tranquility abruptly ended, and in less than 24 hours the entire city of Pompeii and a few thousand of its residents were entombed beneath a layer of volcanic ash and pumice that fell like rain.

Mount Vesuvius has had more than two dozen explosive eruptions since AD 79, the most recent occurring in 1944. Today, roughly 3 million people inhabit the area around Mount Vesuvius, making it potentially one of the most dangerous volcanoes in the world.

© Google Earth

Olivier Goujon/Robert Harding

Ruins of Pompeii Nearly 17 centuries after the eruption, excavation of Pompeii gave archeologists a superb picture of Roman life. Most of the roofs in Pompeii collapsed under the weight of volcanic debris that fell at the rate of 5 to 6 inches per hour. Herculaneum, located closer to the modern city of Naples, was buried under 75 feet of ash and pumice.

Leonard von Matt/Photo Researchers, Inc.

Victims of the AD 79 eruption of Mount Vesuvius The remains of human victims were quickly buried by falling ash and subsequent rainfall caused the ash to harden. Over the centuries, the remains decomposed which created cavities discovered by nineteenth-century excavators. Casts were then produced by pouring plaster into the voids.

José Fuste Raga/Corbis/Glow Images

Mount Vesuvius today This image of Naples, Italy, with Vesuvius in the background, should prompt us to consider how volcanic crises might be managed in the future.

FIGURE 9.14 Fujiyama, a Classic Composite Volcano Japan's Fujiyama exhibits the classic form of a composite cone—steep summit and gently sloping flanks. (Photo by Koji Nakano/Sebun Photo/Getty Images)

Mount Etna, on the other hand, has erupted, on average, once every 2 years since 1979 (see the chapter-opening photo).

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 felsic (rhyolitic) composition. The silica-rich magmas typical of composite cones generate thick, viscous lavas that travel less than a few kilometers. In addition, composite cones are 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 consequence of the way viscous lavas and pyroclastic ejected material contribute to the growth of the cone. Coarse fragments ejected from the summit crater tend to accumulate near their source and contribute to the steep slopes of the summit area. Finer ejected materials, on the other hand, are deposited as a thin layer over a large area that acts 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 later in the volcano's history; this contributes to the cone's broad base. As the 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 9.14**).

Despite the symmetrical forms of many composite cones, most have complex histories. Many composite volcanoes have secondary vents that have produced cinder cones or even much larger volcanic structures on their flanks. 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 the amphitheater-shaped scars remain. Others, such as Crater Lake, have been truncated by the collapse of their summit (see Figure 9.20).

9.7 CONCEPT CHECKS

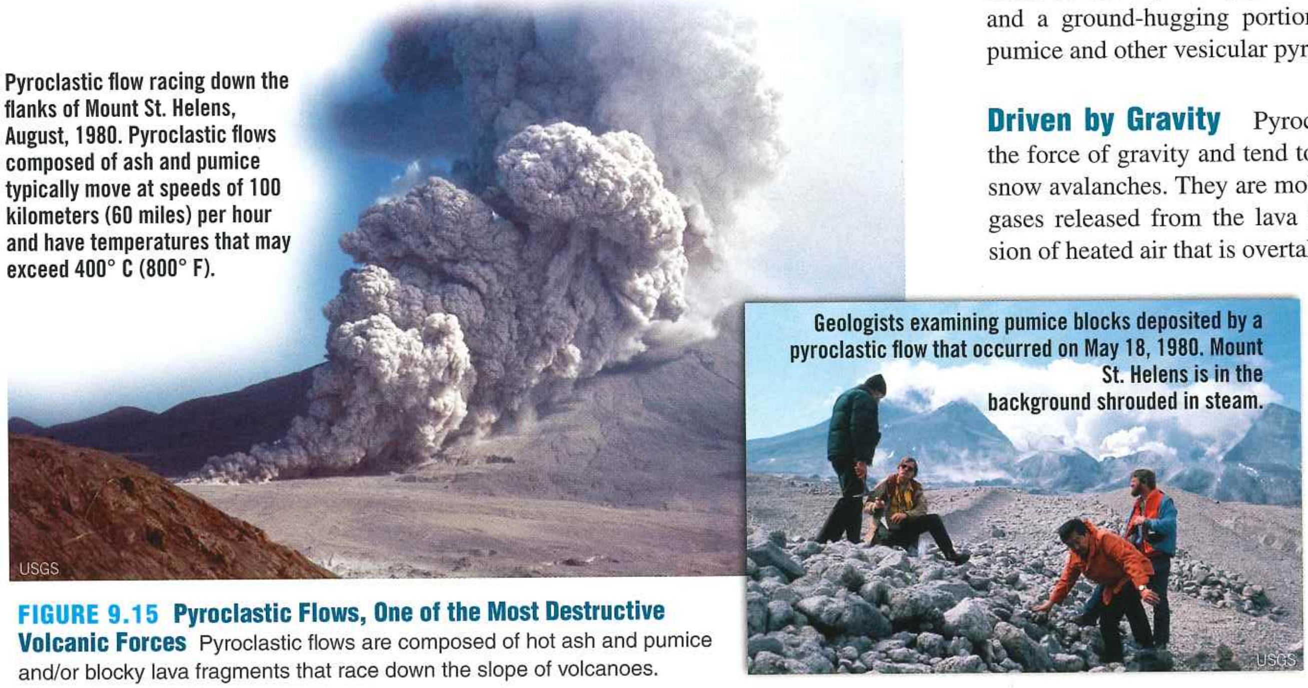
1. What zone on Earth has the greatest concentration of composite volcanoes?
2. Describe the materials that compose composite volcanoes.
3. How does the composition and viscosity of lava flows differ between composite volcanoes and shield volcanoes?

9.8 VOLCANIC HAZARDS

Discuss 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 and 1 large-volume eruption every decade. These large-volume eruptions account for the vast majority of human fatalities. For example, the 1902 eruption of Mount Pelée killed 28,000 people, wiping out the entire population of the nearby city of St. Pierre.

Today, an estimated 500 million people from Japan and Indonesia to Italy and Oregon live near active volcanoes. They face a number of volcanic hazards, such as pyroclastic flows, lahars, lava flows, falling volcanic ash, and volcanic gases.



Pyroclastic flow racing down the flanks of Mount St. Helens, August, 1980. Pyroclastic flows composed of ash and pumice typically move at speeds of 100 kilometers (60 miles) per hour and have temperatures that may exceed 400° C (800° F).

Geologists examining pumice blocks deposited by a pyroclastic flow that occurred on May 18, 1980. Mount St. Helens is in the background shrouded in steam.

FIGURE 9.15 Pyroclastic Flows, One of the Most Destructive Volcanic Forces Pyroclastic flows are composed of hot ash and pumice and/or blocky lava fragments that race down the slope of volcanoes.

Pyroclastic Flow: A Deadly Force of Nature

One of the most destructive forces of nature is **pyroclastic flows**, which consist of hot gases infused with incandescent ash and large lava fragments. Also referred to as **nuée ardentes** (*glowing avalanches*), these fiery flows are capable of racing down steep volcanic slopes at speeds that can exceed 100 kilometers (60 miles) per hour (**FIGURE 9.15**). Pyroclastic flows are composed of two parts: a low-density cloud of hot expanding gases containing fine ash particles and a ground-hugging portion that is often 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 the reason some pyroclastic flow deposits are found many miles from their source.

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 1991, a hot ash cloud from Japan's Unzen volcano engulfed and burned hundreds of homes and moved cars as much as 80 meters (250 feet).

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 9.16**).

Within days of this calamitous eruption, scientists arrived on the scene. Although St. Pierre was mantled by only a thin layer of volcanic debris, the scientists discovered that masonry walls nearly 1 meter (3 feet) thick had been knocked over like

St. Pierre before the 1902 eruption.

St. Pierre following the eruption of Mount Pelée.

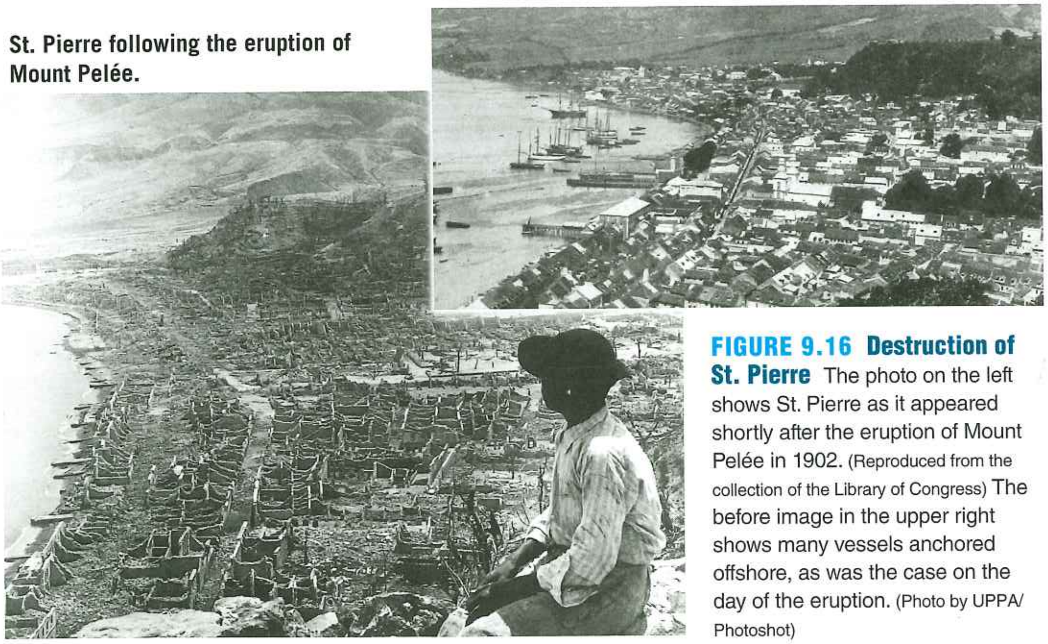


FIGURE 9.16 Destruction of St. Pierre The photo on the left shows St. Pierre as it appeared shortly after the eruption of Mount Pelée in 1902. (Reproduced from the collection of the Library of Congress) The before image in the upper right shows many vessels anchored offshore, as was the case on the day of the eruption. (Photo by UPPA/Photoshot)

dominoes, large trees had been uprooted, and cannons had been torn from their mounts.

Lahars: Mudflows on Active and Inactive Cones

In addition to violent eruptions, large composite cones may generate a type of fluid mudflow referred to by its Indonesian name, **lahar**. These destructive flows occur when volcanic ash and 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 glacial 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 9.17**). 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 "snow" 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 various ways. Ash and other pyroclastic material can collapse the roofs of buildings or can be drawn into the lungs of humans and other animals or into aircraft engines (**FIGURE 9.18**). Volcanoes also emit gases, most notably sulfur dioxide, which affects air quality and, when mixed with rainwater, may destroy vegetation and reduce the quality of groundwater. Despite the known risks, millions of people live in close proximity to active volcanoes.

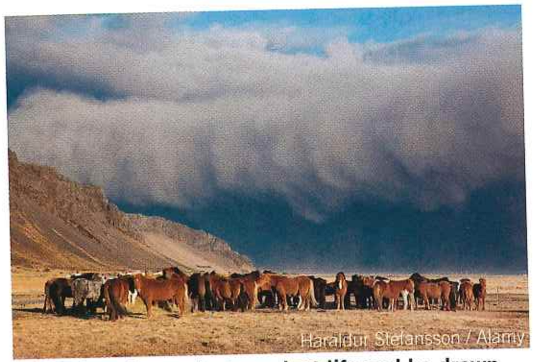
Volcano-Related Tsunami One hazard associated with volcanoes is their ability to generate tsunami. Although they are usually caused by strong earthquakes, these destructive sea waves sometimes result from powerful volcanic explosions or the sudden collapse of flanks of volcanoes into the ocean. In 1883, a volcanic eruption on the Indonesian island Krakatoa literally tore the island apart and generated a tsunami that claimed an estimated 36,000 lives.

FIGURE 9.17 Lahars, Mudflows That Originate on Volcanic Slopes This lahar raced down the Muddy River, located southeast of Mount St. Helens, following the May 18, 1980, eruption. Notice the former height of this fluid mudflow, as recorded by the mudflow line on the tree trunks. Note the person (circled) for scale. (Photo by Lyn Topinka/USGS)

Volcanic Ash and Aviation During the past 15 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 of the engines stalled when they became clogged with ash. Fortunately, the pilots were able to restart the engines and safely land the aircraft in Anchorage.

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

Volcanic Gases and 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 (3.4 cubic miles) of fluid basaltic lavas, in addition to 130 million tons of sulfur dioxide and other poisonous gases, were released. When sulfur dioxide is inhaled, it reacts with moisture in the lungs to produce sulfuric acid. This eruption's sulfur dioxide release caused the death of more than 50 percent of Iceland's livestock. The ensuing famine killed 25 percent of the island's human population. In addition, this huge eruption endangered people and property across Europe. Crop failure occurred in parts of Western Europe, and thousands of residents perished from lung-related diseases. A recent report estimates that a similar eruption today would cause more than 140,000 cardiopulmonary fatalities in Europe alone.



Volcanic ash can destroy plant life and be drawn into the lungs of humans and other animals.

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

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

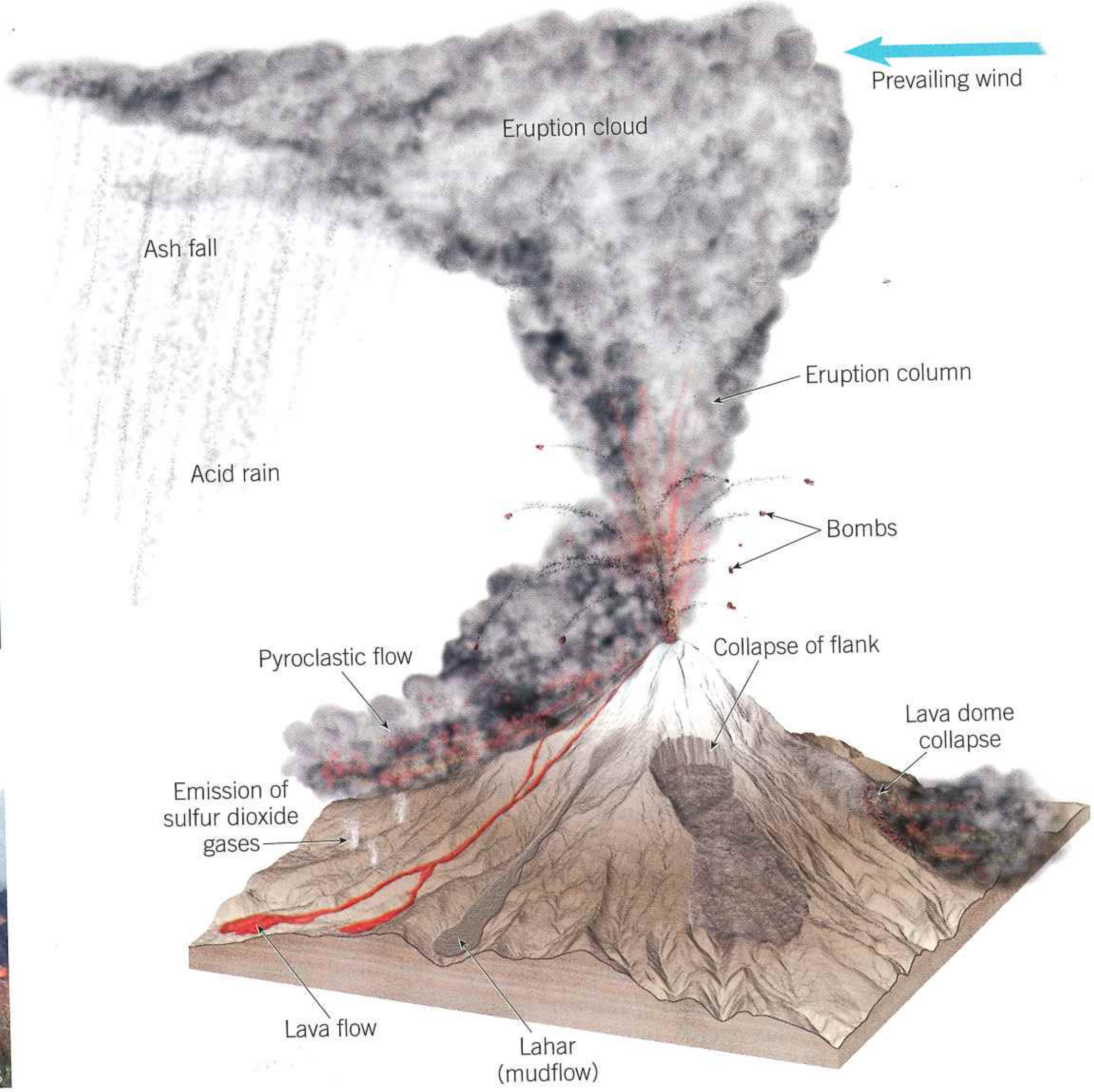


FIGURE 9.18 Volcanic Hazards In addition to generating pyroclastic flows and lahars, volcanoes can be hazardous to human health and property in many other ways.

Effects of Volcanic Ash and Gases on Weather and Climate Volcanic eruptions can eject dust-sized particles of volcanic ash and sulfur dioxide gas high into the atmosphere. The ash particles reflect solar energy back toward space, producing temporary atmospheric cooling. In the case of the 1783 eruption in Iceland, the atmospheric circulation around the globe appears to have been affected. Drought conditions prevailed in the Nile River valley and in India, while the winter of 1784 brought 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. The eruption of El Chichón, 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. These particles, called **aerosols**, take several years to settle out. Like fine ash, these aerosols lower the mean temperature of the atmosphere by reflecting solar radiation back to space.

9.8 CONCEPT CHECKS

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 other than pyroclastic flows and lahars.

9.9 OTHER VOLCANIC LANDFORMS

List and describe volcanic landforms other than volcanic cones.

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

Calderas

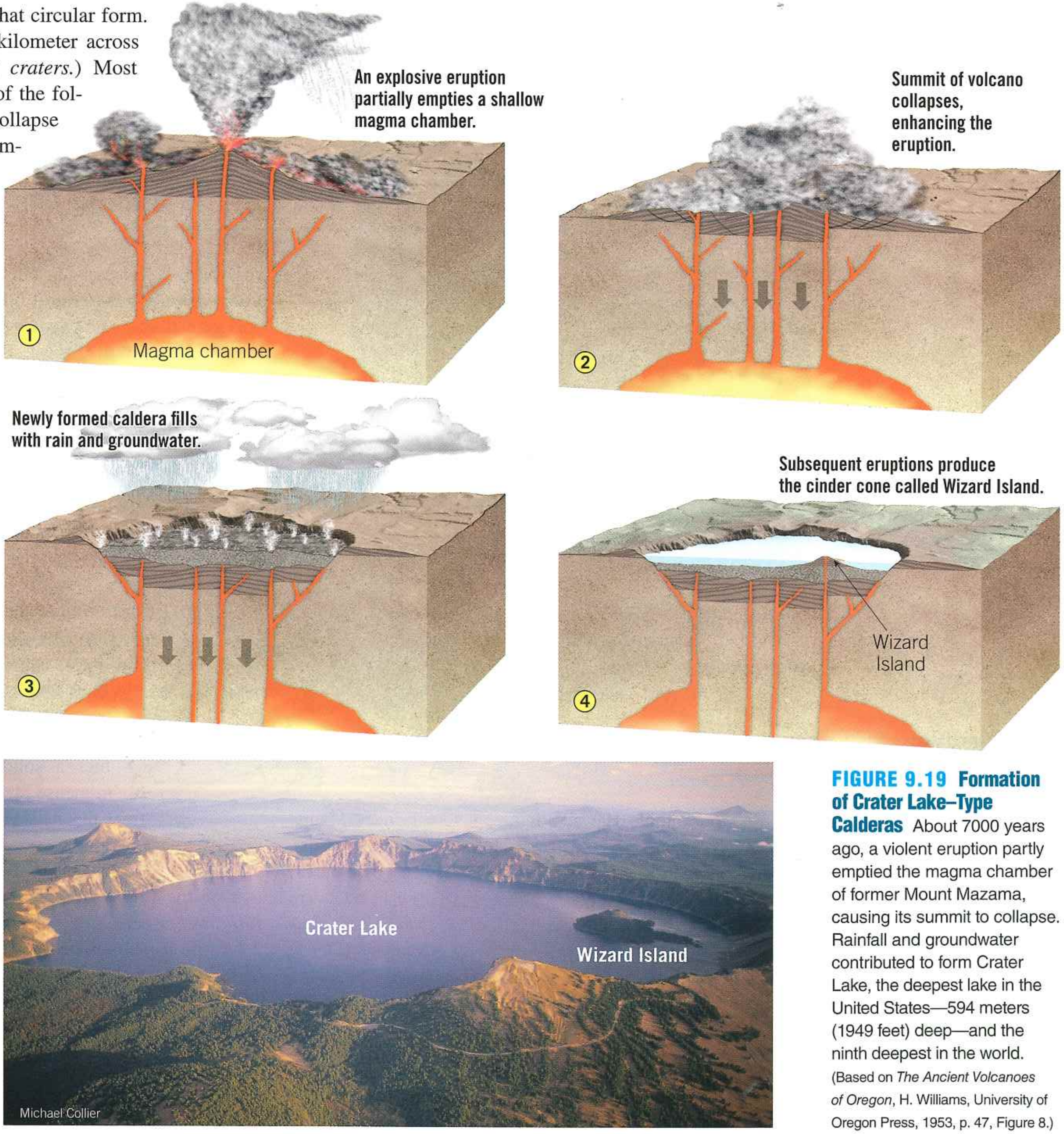
Calderas (*caldaria* = cooking pot) are large steep-sided depressions with diameters that exceed 1 kilometer (0.6 mile) and have a somewhat circular form. (Those that are less than 1 kilometer across are called *collapse pits*, or *craters.*) Most calderas are formed by one of the following processes: (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 1175 meters (more than 3800 feet) deep. This caldera formed about 7000 years ago, when a composite cone, named Mount Mazama, violently extruded 50 to 70 cubic kilometers (12 to 17 cubic miles) of pyroclastic material (**FIGURE 9.19**). With the loss of support, 1500 meters (nearly 1 mile) of the summit of this once-prominent cone collapsed, producing a caldera that eventually filled with rainwater. Later, volcanic activity built a small cinder cone in the caldera. Today this cone, called Wizard Island, provides a mute reminder of past activity (see Figure 9.19).

Hawaiian-Type Calderas

Unlike Crater Lake–type calderas, many calderas form gradually because of the loss of lava from a shallow magma chamber underlying the volcano's



An explosive eruption partially empties a shallow magma chamber.

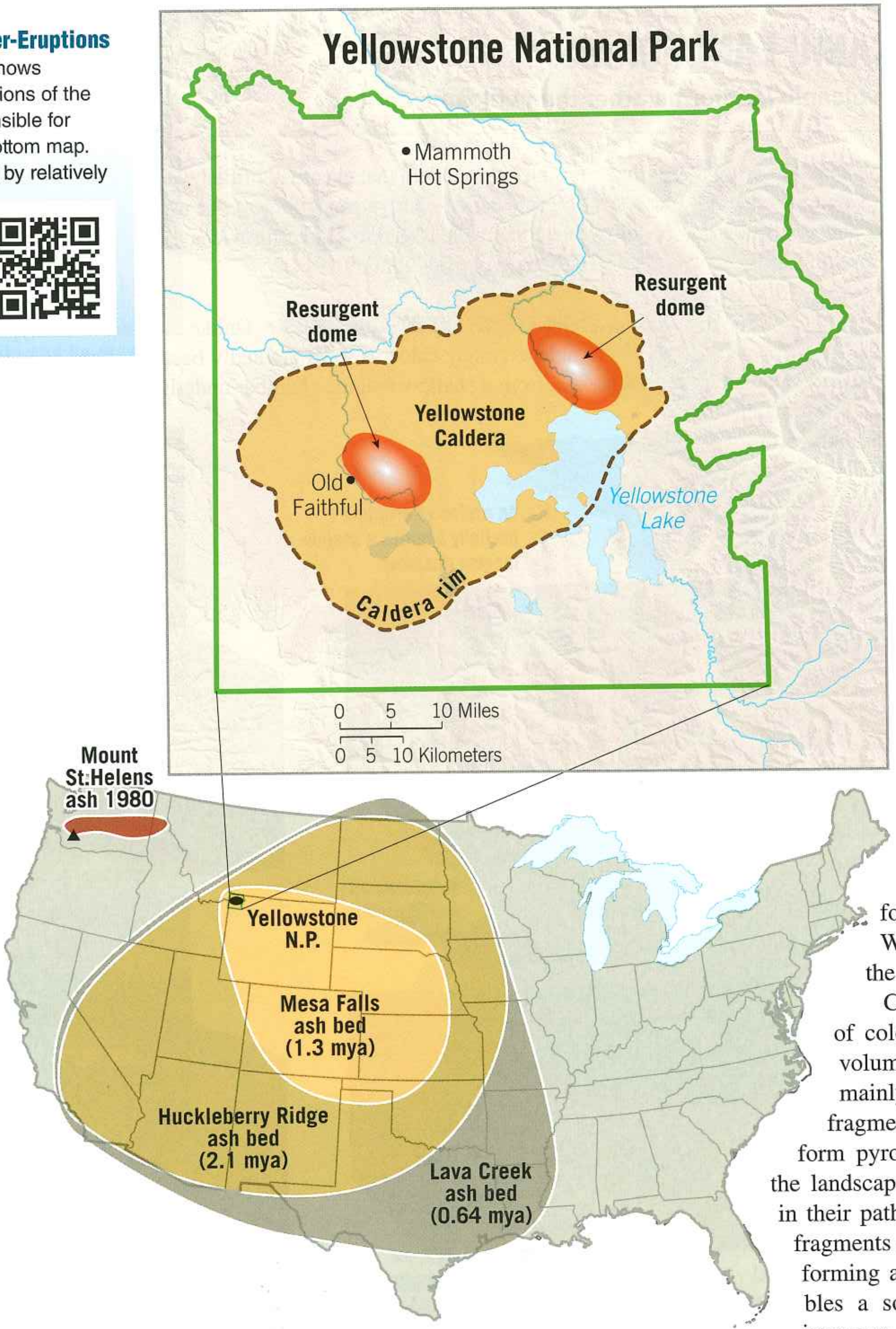
Summit of volcano collapses, enhancing the eruption.

Newly formed caldera fills with rain and groundwater.

Subsequent eruptions produce the cinder cone called Wizard Island.

Michael Collier

FIGURE 9.19 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. Rainfall and groundwater contributed to form Crater Lake, the deepest lake in the United States—594 meters (1949 feet) deep—and the ninth deepest in the world. (Based on *The Ancient Volcanoes of Oregon*, H. Williams, University of Oregon Press, 1953, p. 47, Figure 8.)



SmartFigure 9.20 Super-Eruptions at Yellowstone The top map shows Yellowstone National Park. Eruptions of the Yellowstone caldera were responsible for the layers of ash shown in the bottom map. These eruptions were separated by relatively regular intervals of about 700,000 years. The largest of these eruptions was 10,000 times larger the 1980 eruption of Mount St. Helens.

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 of this caldera are almost vertical, and as a result, it 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 and Vesuvius pale in comparison to what happened 630,000 years ago in the region now occupied by Yellowstone National Park, when approximately 1000 cubic kilometers (240 cubic miles) of pyroclastic material erupted. This catastrophic eruption sent showers of ash as far as the Gulf of Mexico and resulted in the formation of a caldera 70 kilometers (43 miles) across (**FIGURE 9.20**). Vestiges of this event are the many hot springs and geysers in the Yellowstone region.

Based on the extraordinary volume of erupted material, researchers have determined that the magma chambers associated with Yellowstone-type calderas must be similarly monstrous. As more and more magma accumulates, the pressure within the magma chamber begins to exceed the pressure exerted by the weight of the overlying rocks. An eruption occurs when the gas-rich magma raises the overlying crust enough to create vertical fractures that extend to the surface. Magma surges upward along these cracks, forming a ring-shaped eruption. With a loss of support, the roof of the magma chamber collapses.

Caldera-forming eruptions are of colossal proportions, ejecting huge volumes of pyroclastic materials, mainly in the form of ash and pumice fragments. Typically, these materials form 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 cause 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. The most recent event (630,000 years ago) was followed by episodic outpourings of degassed rhyolitic and basaltic lavas. Geologic evidence suggests that a magma reservoir still exists beneath Yellowstone; thus, another caldera-forming eruption is likely but not necessarily imminent.

A distinctive characteristic of large caldera-forming eruptions is a slow upheaval of the floor of the caldera that produces a central elevated region called a *resurgent dome* (see Figure 9.20). Unlike calderas associated with shield volcanoes or composite cones, Yellowstone-type depressions are so large and poorly defined that many remained undetected until high-quality aerial and satellite images became available. Other examples of large calderas located in the United States 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 elsewhere around the globe are among the largest volcanic structures on Earth, hence the name "supervolcanoes." Volcanologists have compared their destructive force with that of the impact of a small asteroid. Fortunately, no caldera-forming eruption has occurred in historic times.

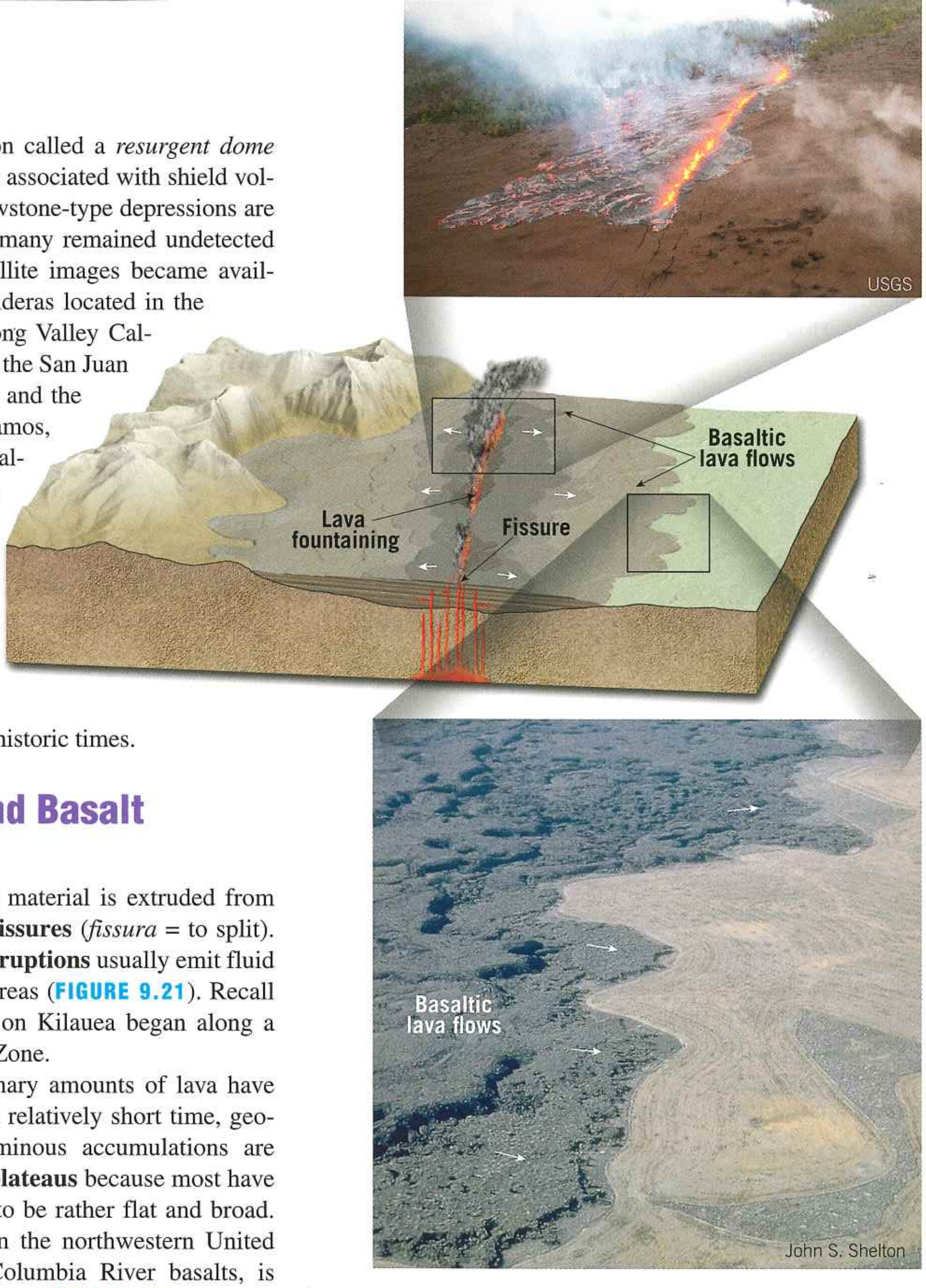


FIGURE 9.21 Basaltic Fissure Eruptions Lava fountaining from a fissure and formation of fluid lava flows called *flood basalts.* The lower photo shows flood basalt flows near Idaho Falls.

Fissure Eruptions and Basalt Plateaus

The greatest volume of volcanic material is extruded from fractures in Earth's crust called **fissures** (*fissura* = to split). Rather than build cones, **fissure eruptions** usually emit fluid basaltic lavas that blanket wide areas (**FIGURE 9.21**). Recall that the recent volcanic activity on Kilauea began along a series of fissures in the East Rift Zone.

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 located in the northwestern United States, which consists of the Columbia River basalts, is the product of this type of activity (**FIGURE 9.22**). Numerous fissure eruptions have buried 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.

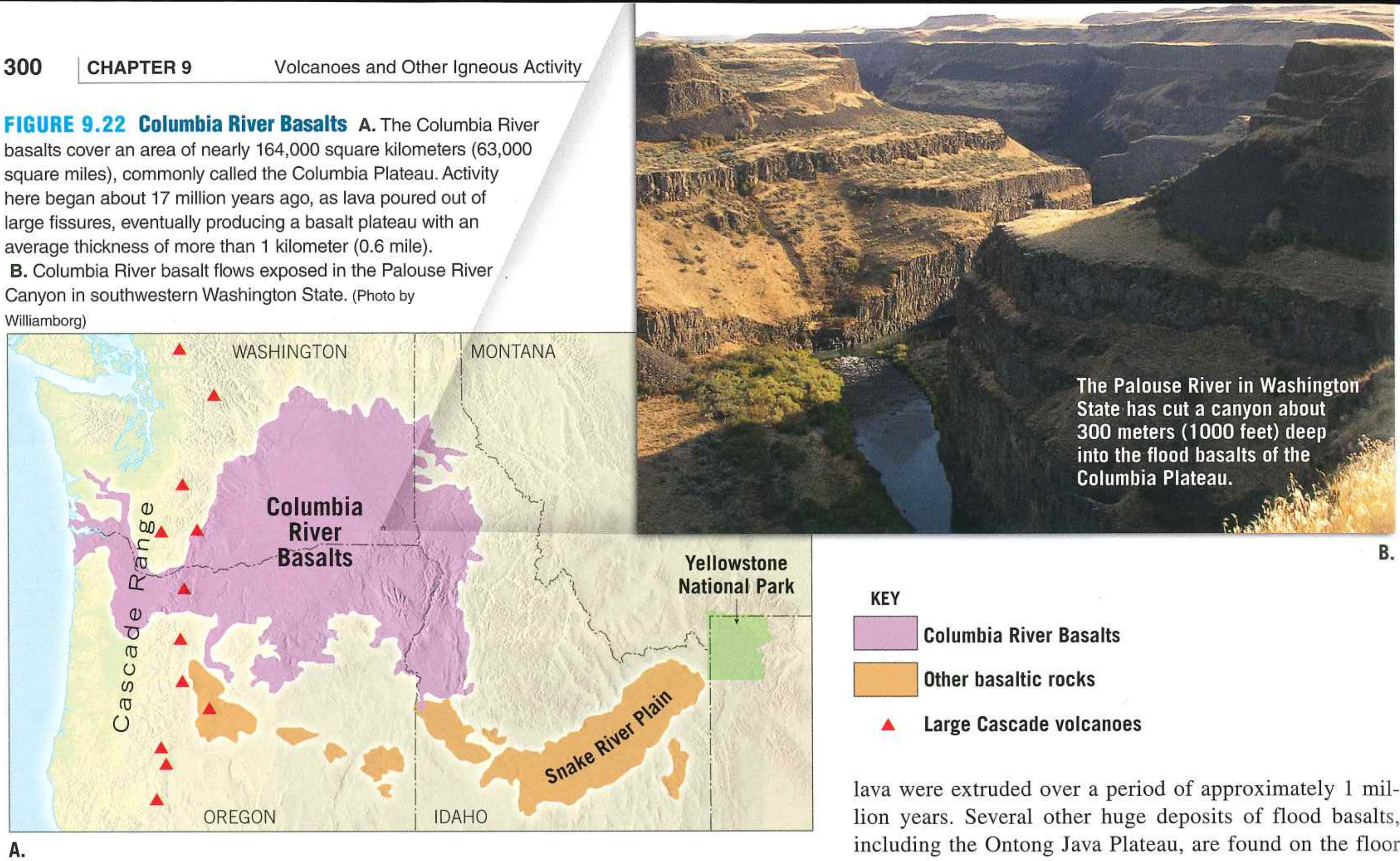
EYE ON EARTH

This image was obtained during the 1991 eruption of Mount Pinatubo in the Philippines. This was the largest eruption to affect a densely populated area in recent times. Timely forecasts of the event by scientists were credited with saving at least 5000 lives. (Alberto Garcia/CORBIS)

QUESTION 1 *What name is given to the ash- and pumice-laden cloud that is racing toward the photographer?*

QUESTION 2 *At what speeds can these fiery clouds move down steep mountain slopes?*

FIGURE 9.22 Columbia River Basalts **A.** The Columbia River basalts cover an area of nearly 164,000 square kilometers (63,000 square miles), commonly called the Columbia Plateau. Activity here began about 17 million years ago, as lava poured out of large fissures, eventually producing a basalt plateau with an average thickness of more than 1 kilometer (0.6 mile). **B.** Columbia River basalt flows exposed in the Palouse River Canyon in southwestern Washington State. (Photo by Williamborg)



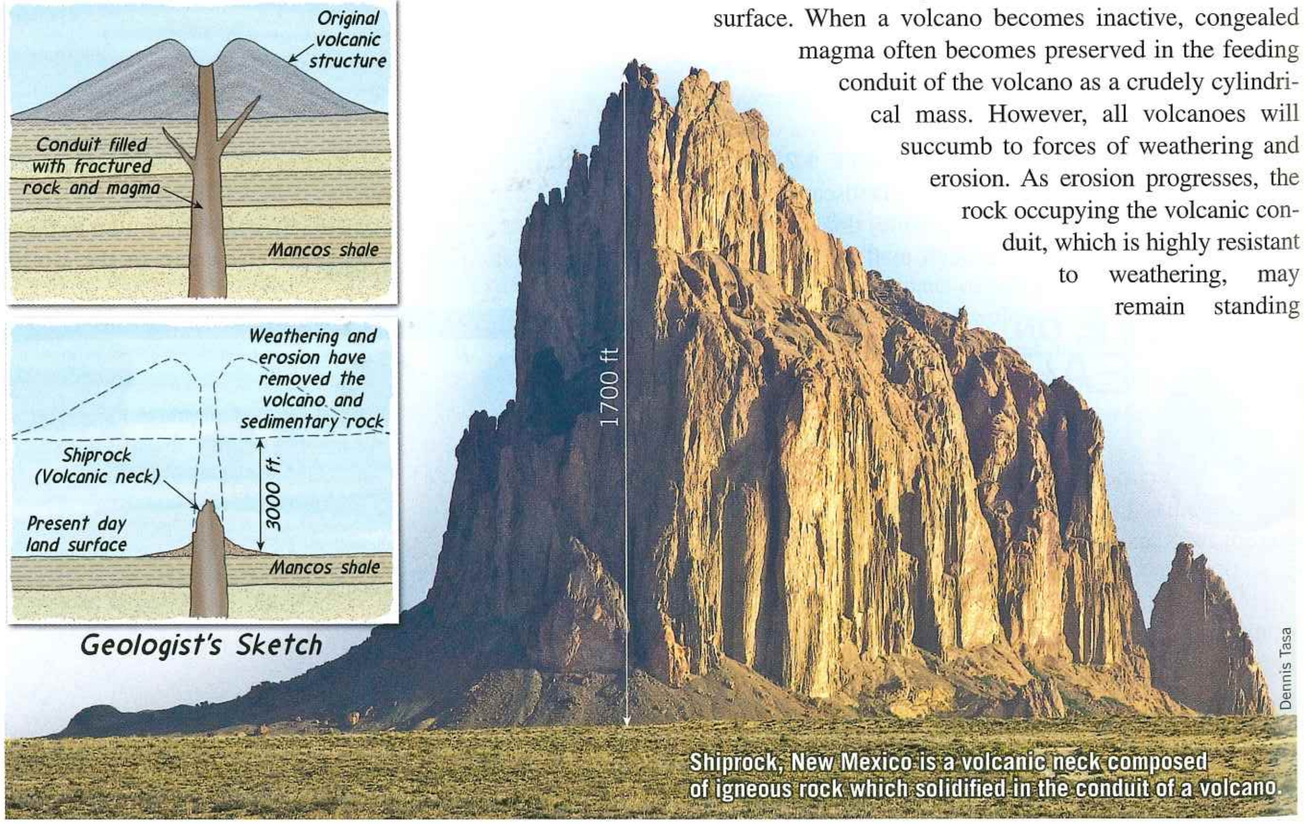
The Palouse River in Washington State has cut a canyon about 300 meters (1000 feet) deep into the flood basalts of the Columbia Plateau.

One of the largest is the Deccan Traps, 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 (480,000 cubic miles) of lava were extruded over a period of approximately 1 million years. Several other huge deposits of flood basalts, including the Ontong Java Plateau, are found on the floor of the ocean.

Volcanic Necks and Pipes

Most volcanic eruptions are fed lava through short conduits that connect shallow magma chambers to vents located at the surface. When a volcano becomes inactive, congealed magma often becomes preserved in the feeding conduit of the volcano as a crudely cylindrical mass. However, all volcanoes will succumb to forces of weathering and erosion. As erosion progresses, the rock occupying the volcanic conduit, which is highly resistant to weathering, may remain standing

FIGURE 9.23 Volcanic Neck Shiprock, New Mexico, is a volcanic neck that stands over 420 meters (1380 feet) high. It consists of igneous rock that crystallized in the vent of a volcano that has long since been eroded.



Shiprock, New Mexico is a volcanic neck composed of igneous rock which solidified in the conduit of a volcano.

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 geologists call **volcanic necks** (or **plugs**) (**FIGURE 9.23**). More than 510 meters (1700 feet) high, Shiprock is higher than most skyscrapers and one of many such landforms that protrude conspicuously from the red desert landscapes of the American Southwest.

One rare type of conduit, called a **pipe**, carries magma that originated in the mantle at depths that may exceed 150 kilometers (93 miles). The gas-laden magmas that migrate through pipes travel rapidly enough to undergo minimal alteration during their ascent.

The best-known volcanic pipes are the diamond-bearing kimberlite pipes of South Africa. The rocks filling these pipes originated at great depths, where pressure is sufficiently high to generate diamonds and other high-pressure minerals. The process of transporting essentially unaltered magma (along with diamond inclusions) through 150 kilometers (93 miles) of solid rock is exceptional—and accounts for the scarcity of natural diamonds. Geologists consider pipes to be "windows" into Earth that allow us to view rocks that normally form only at great depths.

9.9 CONCEPT CHECKS

1. Describe the formation of Crater Lake. Compare it to the calderas found on shield volcanoes such as Kilauea.
2. Pyroclastic flows are associated with what volcanic structure that is not a cinder cone?
3. How do the eruptions that created the Columbia Plateau differ from eruptions that create large composite volcanoes?
4. Contrast the composition of a typical lava dome and a typical fissure eruption.
5. What type of volcanic structure is Shiprock, New Mexico, and how did it form?

9.10 INTRUSIVE IGNEOUS ACTIVITY

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

Although volcanic eruptions can be violent and spectacular events, most magma is emplaced and crystallizes at depth, without fanfare. Therefore, understanding the igneous processes that occur deep underground is as important to geologists as the study of volcanic events.

Nature of Intrusive Bodies

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

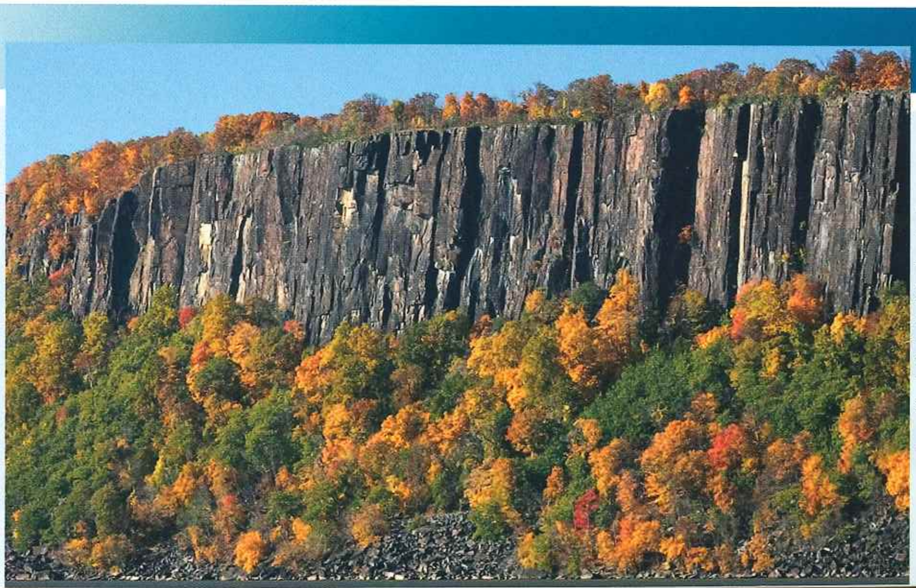
Intrusions are known to occur in a great variety of sizes and shapes. Some of the most common types are illustrated in **FIGURE 9.24**. Notice that some plutons have a tabular (tablet) shape, whereas others are best described as massive (blob shaped). Also, observe that some of these bodies cut across existing structures, such as sedimentary strata, whereas others form when magma is injected between sedimentary layers. Because of these differences, intrusive igneous bodies are generally classified according to their shape as either **tabular** (*like a tablet*) or **massive** and by their orientation with respect to the host rock. Igneous bodies are said to be **discordant** (*discordare* = to disagree) if they cut across existing structures and **concordant** (*concordare* = to agree) if they inject parallel to features such as sedimentary strata.

EYE ON EARTH

The Palisades form impressive cliffs along the western side of the Hudson River for more than 80 kilometers (50 miles). This igneous feature, which is visible from Manhattan, formed when magma was injected between layers of sandstone and shale.

QUESTION 1 *What type of igneous feature constitutes the Palisades?*

QUESTION 2 *Is this feature tabular or massive?*



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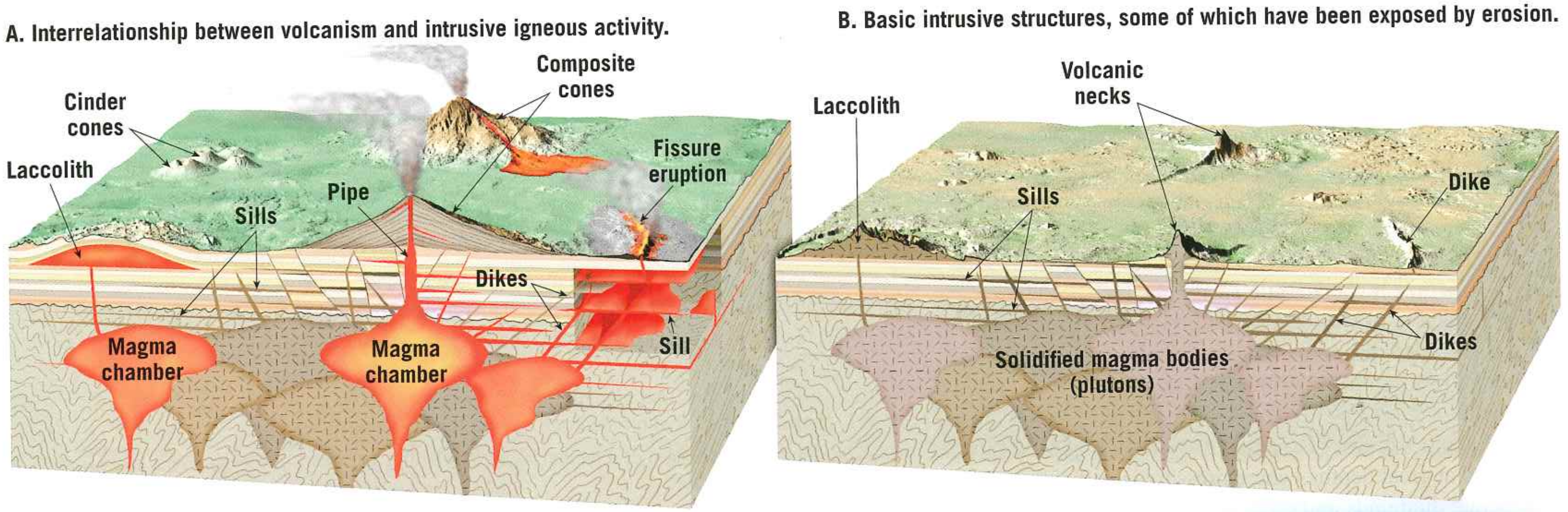
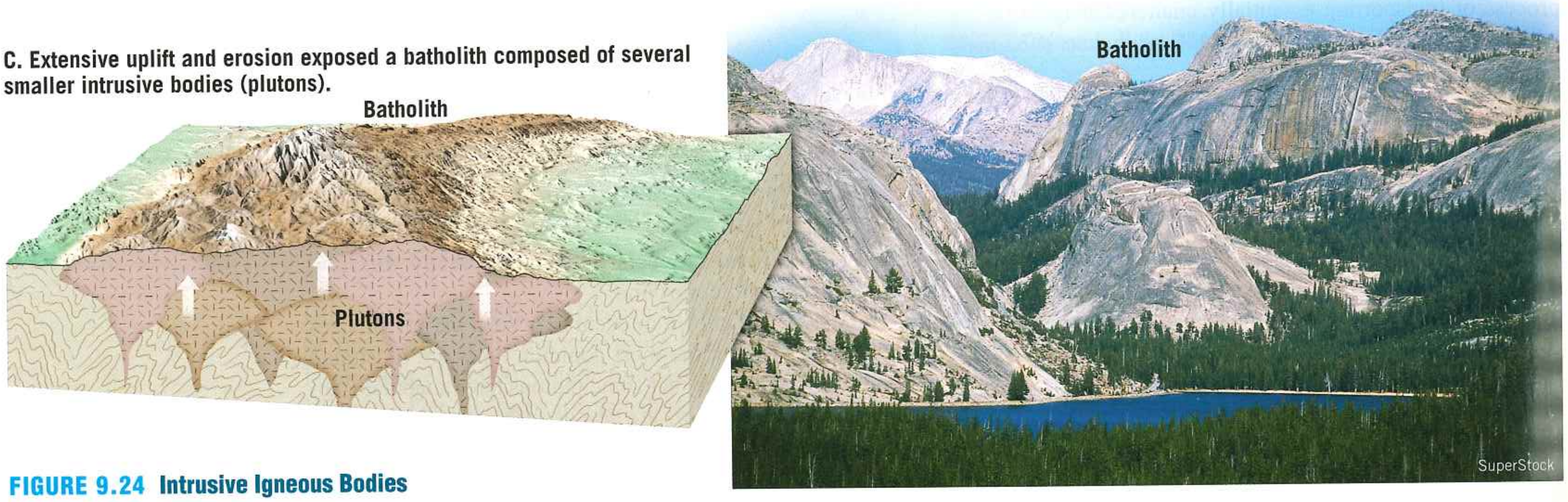


A. Interrelationship between volcanism and intrusive igneous activity.

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

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



SuperStock

FIGURE 9.24 Intrusive Igneous Bodies

Mobile Field Trip 9.25 Sill Exposed in Utah's Sinbad Country The dark, essentially horizontal bands are sills of basaltic composition that intruded horizontal layers of sedimentary rock. (Photo by Michael Collier)

Tabular Intrusive Bodies: Dikes and Sills

Tabular intrusive bodies are produced when magma is forcibly injected into a fracture or zone of weakness, such as a bedding surface (see Figure 9.24). **Dikes** are discordant bodies that cut across bedding surfaces or other structures in the country rock. By contrast, **sills** are nearly horizontal, concordant bodies that form when magma exploits weaknesses between sedimentary beds or other structures (**FIGURE 9.25**). In general, dikes serve as tabular conduits that transport magma, whereas sills tend to accumulate magma and increase in thickness.

Dikes and sills are typically shallow features, occurring where the country rocks are sufficiently brittle to fracture. They can range in thickness from less than 1 millimeter to more than 1 kilometer (0.6 mile).

While dikes and sills can occur as solitary bodies, dikes tend to form in roughly parallel groups called *dike swarms*. These multiple structures reflect the tendency for fractures to form in sets when tensional forces stretch brittle country rock. Dikes can also occur radiating from an eroded volcanic neck, like spokes on a wheel. In these situations, the active

FIGURE 9.26 Dike Exposed in the Spanish Peaks, Colorado This elongated dike is composed of igneous rock that is more resistant to weathering than the surrounding material.

ascent of magma generated fissures in the volcanic cone out of which lava flowed. Dikes frequently weather more slowly than the surrounding rock. Consequently, when exposed by erosion, dikes tend to have a wall-like appearance, as shown in **FIGURE 9.26**.

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

In many respects, sills closely resemble buried lava flows. Both are tabular and can have a wide aerial extent, and both may exhibit columnar jointing. **Columnar jointing** occurs when igneous rocks cool and develop shrinkage fractures that produce elongated, pillar-like columns that most often have six sides (**FIGURE 9.27**). Further, because sills generally form in near-surface environments and may be only a few meters thick, the emplaced magma often cools quickly enough to generate a fine-grained texture. (Recall that most intrusive igneous bodies have a coarse-grained texture.)

Massive Intrusive Bodies: Batholiths, Stocks, and Laccoliths

By far the largest intrusive igneous bodies are **batholiths** (*bathos* = depth, *lithos* = stone). Batholiths occur as mammoth linear structures several hundreds of kilometers long and up to 100 kilometers wide (see Figure 9.24C). The Sierra Nevada batholith, for example, is a continuous granitic structure that forms much of the Sierra Nevada, in California. An even larger batholith extends for over 1800 kilometers (1100 miles) along the Coast Mountains of western Canada and into southern Alaska. Although batholiths can cover a large area, recent gravitational studies indicate that most are less than 10 kilometers (6 miles) thick. Some are even thinner; the Coastal batholith of Peru, for example, is essentially a flat slab with an average thickness of only 2 to 3 kilometers (1 to 2 miles).

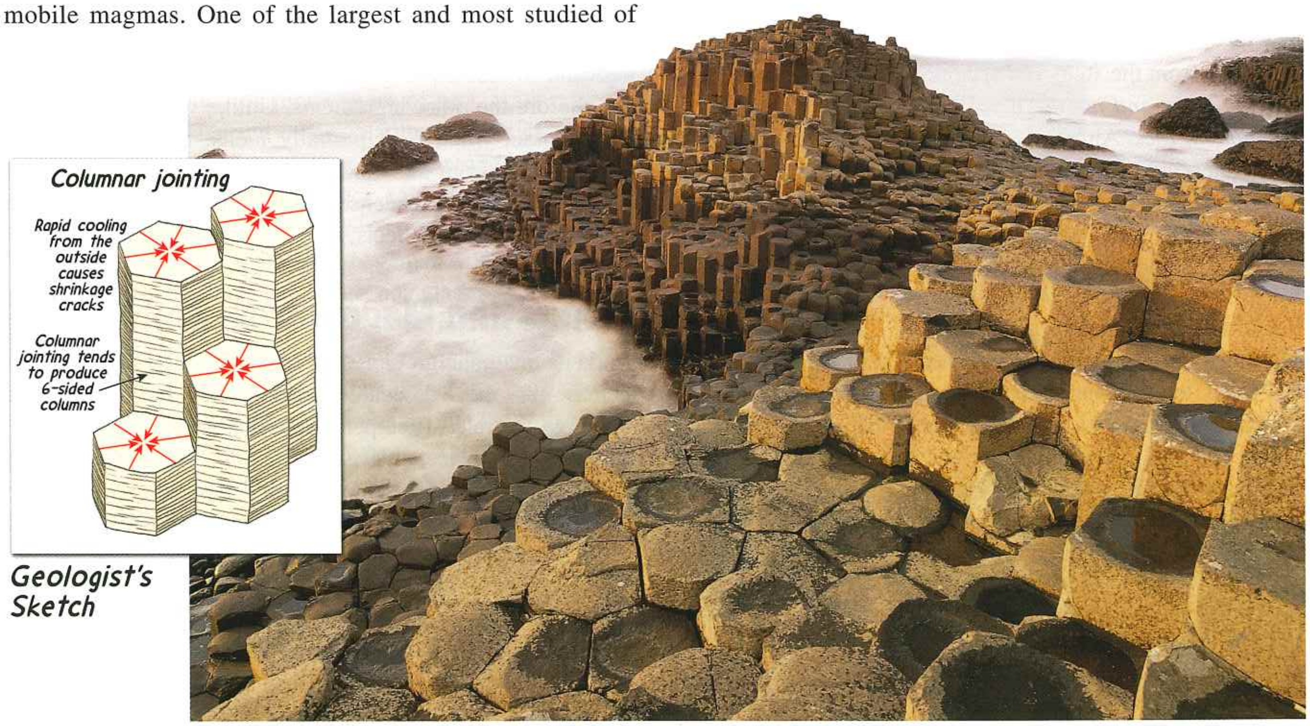


FIGURE 9.27 Columnar Jointing Giant's Causeway in Northern Ireland is an excellent example of columnar jointing. (Photo by John Lawrence/Getty Images)

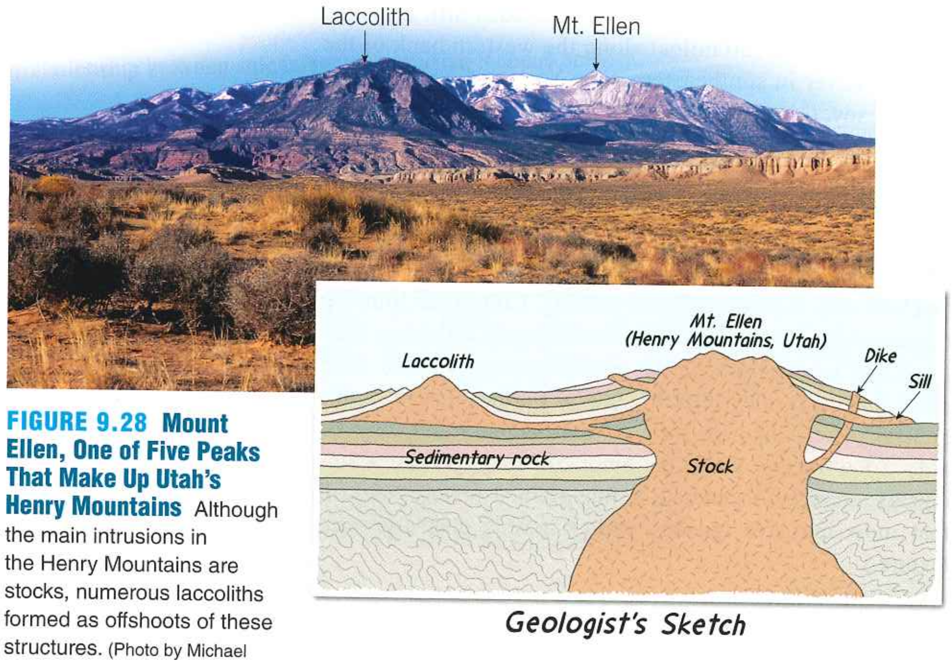


FIGURE 9.28 Mount Ellen, One of Five Peaks That Make Up Utah's Henry Mountains Although the main intrusions in the Henry Mountains are stocks, numerous laccoliths formed as offshoots of these structures. (Photo by Michael DeFreitas North America/Alamy)

Batholiths are typically composed of felsic and intermediate rock types and are often referred to as "granite batholiths." Large granite batholiths consist of hundreds of plutons that intimately crowd against or penetrate one another. These bulbous masses were emplaced over spans of millions of years. The intrusive activity that created the Sierra Nevada batholith, for example, occurred nearly continuously over a 130-million-year period that ended about 80 million years ago.

By definition, a plutonic body must have a surface exposure greater than 100 square kilometers (40 square miles) in order to be considered a batholith. Smaller plutons are termed **stocks**. However, many stocks appear to be portions of much larger intrusive bodies that would be classified as batholiths if they were fully exposed.

Laccoliths A nineteenth-century study by G. K. Gilbert of the U.S. Geological Survey in the Henry Mountains of Utah produced the first clear evidence that igneous intrusions can lift the sedimentary strata they penetrate. Gilbert gave the name **laccoliths** to the igneous intrusions he observed, which he envisioned as igneous rock forcibly injected between sedimentary strata so as to arch the beds above while leaving those below relatively flat. It is now known that the five major peaks of the Henry Mountains are not laccoliths but stocks. However, these central magma bodies are the source material for branching offshoots that are true laccoliths, as Gilbert defined them (**FIGURE 9.28**).

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

9.10 CONCEPT CHECKS

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

9.11 PARTIAL MELTING AND THE ORIGIN OF MAGMA

Summarize the major processes that generate magma from solid rock.

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

Partial Melting

Recall that igneous rocks are composed of a mixture of minerals. Since these minerals have different melting points, igneous rocks tend to melt over a temperature range of at least 200°C (360°F). As rock begins to melt, the minerals with the lowest melting temperatures are the first to melt. If melting continues, minerals with higher melting points begin to melt, and the composition of the melt steadily approaches the overall composition of the rock from which it was derived.

Most often, however, melting is not complete. The incomplete melting of rocks is known as **partial melting**, a process that produces most magma. Partial melting can be likened to a chocolate chip cookie containing nuts that is left out in the Sun. The chocolate chips represent the minerals with the lowest melting points because they will begin to melt before the other ingredients. Unlike with the chocolate chip cookie, when rock partially melts, the molten material separates from the solid components. Also, because the molten material is less dense that the remaining solids, when enough of the melt collects, it rises toward Earth's surface.

Generating Magma from Solid Rock

Workers in underground mines know that temperatures increase as they descend deeper below Earth's surface. Although the rate of temperature change varies considerably from place to place, it *averages* about 25°C per kilometer in the *upper* crust. This increase in temperature with depth is known as the **geothermal gradient**. As shown in **FIGURE 9.29**, when a typical geothermal gradient is compared to the melting point curve for the mantle rock peridotite, the temperature at which peridotite melts is higher than the geothermal gradient. Thus, under normal conditions, the mantle is solid. However, tectonic processes exist that trigger melting by reducing the melting point (temperature) of mantle rock.

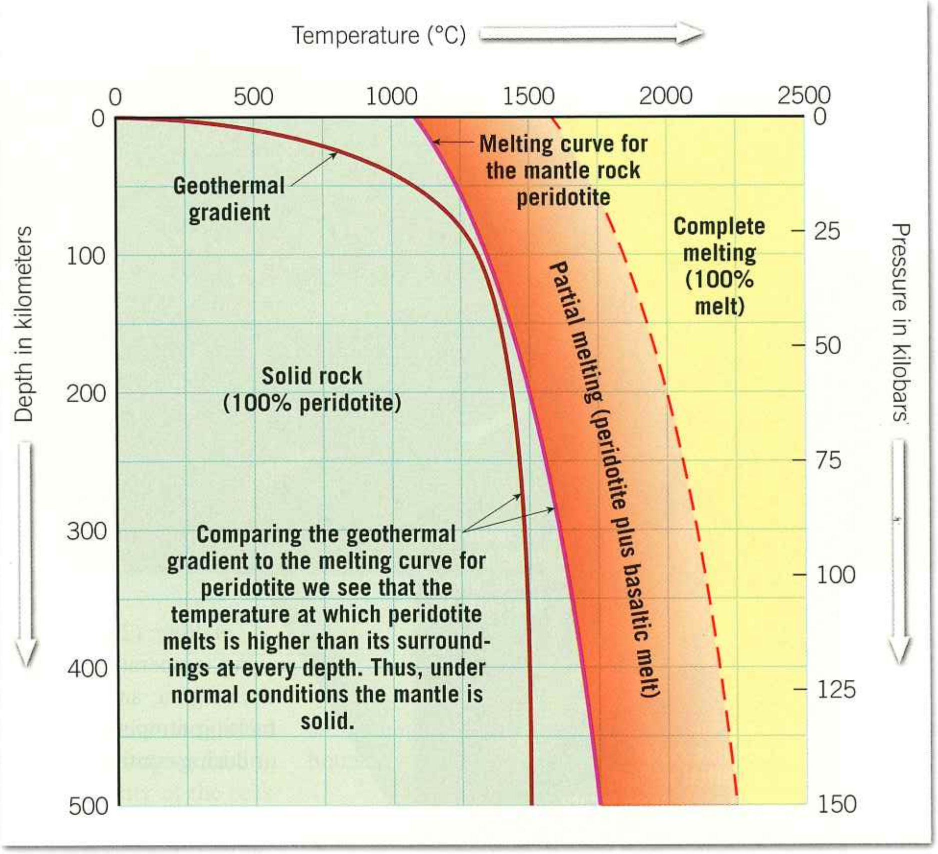


FIGURE 9.29 Diagram Illustrating Why the Mantle Is Mainly Solid This diagram shows the geothermal gradient (increase in temperature with depth) for the crust and upper mantle. Also plotted is the melting point curve for the mantle rock peridotite. When we compare the change in temperature with depth (geothermal gradient) to the melting point of peridotite, the temperature at which peridotite melts is higher than the geothermal gradient at every depth. Thus, under normal conditions, the mantle is solid.

Decrease in Pressure: Decompression Melting

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

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

Decompression melting occurs where hot, solid mantle rock ascends in zones of convective upwelling, thereby moving into regions of lower pressure. This process is responsible for generating magma along divergent plate boundaries (oceanic ridges) where plates are rifting apart (**FIGURE 9.30**). Below the ridge crest, hot mantle rock rises and melts, replacing the material that shifted horizontally away from the ridge axis. Decompression melting also occurs when ascending mantle plumes reach the uppermost mantle.

Addition of Water

Another important factor affecting the melting temperature of rock is its water content. Water and other volatiles act as salt does to melt ice. Water causes rock to melt at lower temperatures, just as putting rock salt on an icy sidewalk induces melting.

The introduction of water to generate magma occurs mainly at convergent plate boundaries where cool slabs of oceanic lithosphere descend into the mantle (**FIGURE 9.31**). As an oceanic plate sinks, heat and pressure drive water from the subducting oceanic crust and overlying sediments. These fluids migrate into the wedge of hot mantle that lies directly above. At a depth of about 100 kilometers (60 miles), the addition of water lowers the melting temperature of mantle rock sufficiently to trigger partial melting. Partial melting of the mantle rock peridotite generates hot basaltic magmas with temperatures that may exceed 1250°C (2300°F).

Temperature Increase: Melting Crustal Rocks

When enough mantle-derived basaltic magma forms, it buoyantly rises toward the surface. In continental settings, basaltic magma often "ponds" beneath crustal rocks, which have a lower density and are already near their melting temperature.

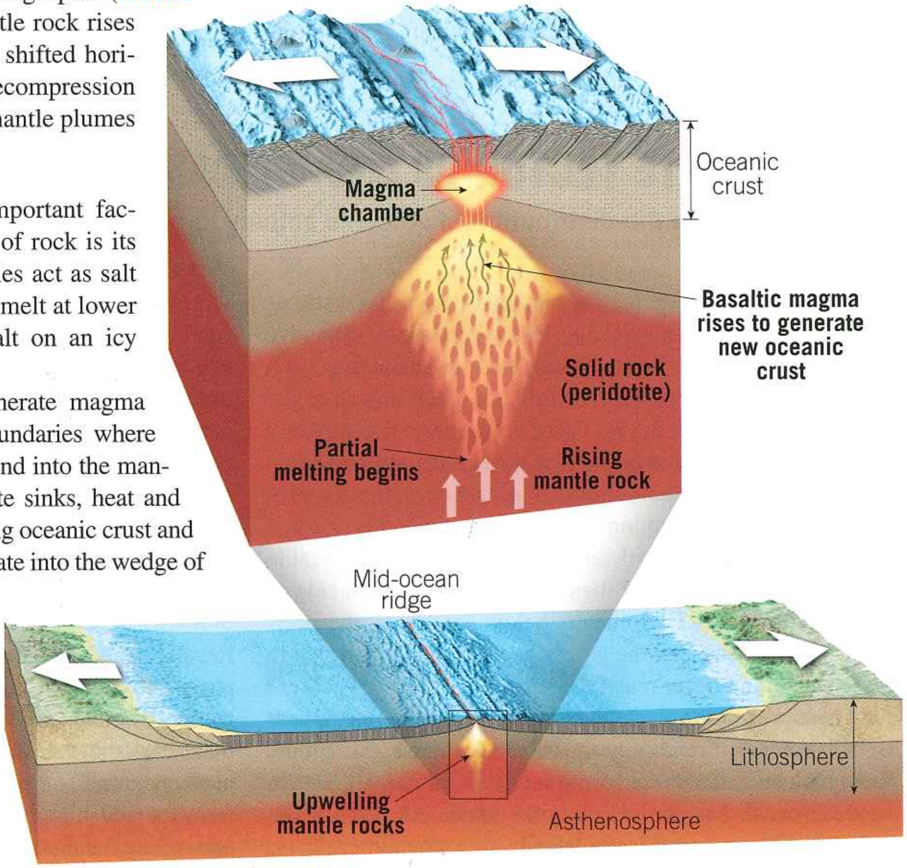
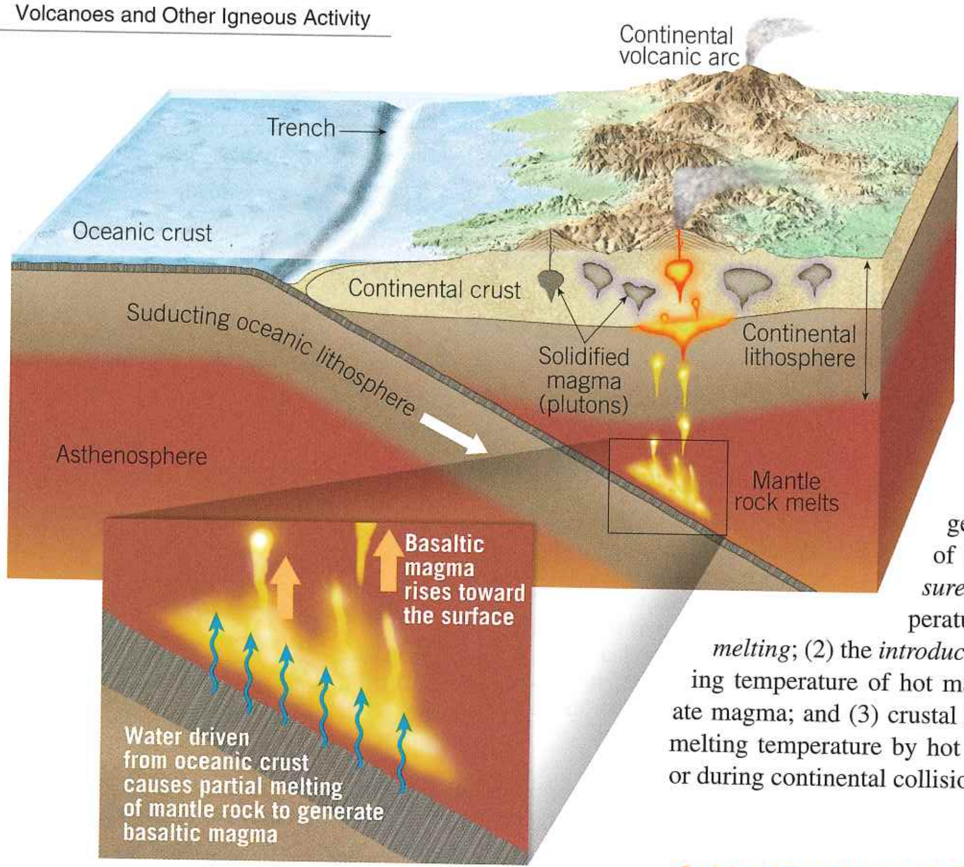


FIGURE 9.30 Decompression Melting As hot mantle rock ascends, it continually moves into zones of lower and lower pressure. This drop in confining pressure initiates *decompression melting* in the upper mantle. Decompression melting occurs without an outside source of energy (heat).

FIGURE 9.31 The Introduction of Water Can Lower the Melting Temperature of Hot Mantle Rock to Trigger Melting As an oceanic plate descends into the mantle, water and other volatiles are driven from the subducting crustal rocks into the wedge of mantle above. At a depth of about 100 kilometers (60 miles), mantle rock is hot enough that the addition of water can cause melting.



The hot basaltic magma may heat the overlying crustal rocks sufficiently to generate a secondary, silica-rich magma. If these low-density silica-rich magmas reach the surface, they tend to produce explosive eruptions that we associate with convergent plate boundaries.

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

In summary, magma can be generated three ways: (1) in zones of upwelling, *a decrease in pressure* (without an increase in temperature) can result in *decompression melting*; (2) the *introduction of water* can lower the melting temperature of hot mantle rock sufficiently to generate magma; and (3) crustal rocks can be heated above their melting temperature by hot mantle-derived basaltic magma or during continental collisions.

9.11 CONCEPT CHECKS

1. What is the geothermal gradient? Describe how the geothermal gradient compares with the melting temperatures of the mantle rock peridotite at various depths.
2. Describe the process of decompression melting.
3. What role do water and other volatiles play in the formation of magma?

9.12 PLATE TECTONICS AND VOLCANIC ACTIVITY

Relate the distribution of volcanic activity 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 9.32**). These volcanoes consist mainly of composite cones that emit volatile-rich magma having an andesitic (intermediate) composition and occasionally produce awe-inspiring eruptions.

Another group of volcanoes includes the innumerable seamounts that form along the crest of the mid-ocean ridges. At these depths (1–3 kilometers below sea level), the pressures are so intense that the gases emitted quickly dissolve in the seawater and never reach the surface.

There are some volcanic structures, however, that appear to be somewhat 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.

Prior to the development of the theory of plate tectonics, geologists did not have an acceptable explanation for the distribution of Earth's volcanoes. Recall that most magma originates in rocks from Earth's upper mantle that is essentially solid, *not molten*. The basic connection between plate tectonics and volcanism is that *plate motions provide the mechanisms by which mantle rocks undergo partial melting to generate magma.*

Volcanism at Convergent Plate Boundaries

Recall that along certain convergent plate boundaries, two plates move toward each other, and a slab of oceanic lithosphere descends into the mantle, generating a deep-ocean trench. As the slab sinks deeper into the mantle, the increase in temperature and pressure drives water and carbon dioxide from the oceanic crust. These mobile fluids migrate upward and reduce the melting point of hot mantle rock sufficiently to

FIGURE 9.32 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 sits mainly undiscovered along the mid-ocean ridge system.

trigger some melting (**FIGURE 9.33A**). Recall that the partial melting of mantle rock (peridotite) generates magma having a basaltic composition. After a sufficient quantity of the rock has melted, blobs of buoyant magma slowly migrate upward.

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 can be constructed on oceanic as well as continental lithosphere. Those 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 9.33A). 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 develop where slabs of oceanic lithosphere are subducted under continental lithosphere to produce a **continental volcanic arc** (**FIGURE 9.33E**). 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 is composed of rocks having higher silica content than oceanic crust. Hence, a mantle-derived magma changes chemically as it rises by assimilating silica-rich crustal rocks. At the same time, extensive magmatic differentiation occurs. (Recall that magmatic differentiation is the formation of secondary magmas from parent magma.) Stated another way, the magma generated in the mantle may change from a fluid basaltic magma to a silica-rich andesitic or rhyolitic magma as it moves up through the continental crust.

The Ring of Fire, a belt of explosive volcanoes, surrounds the Pacific basin. The Ring of Fire exists because oceanic lithosphere is being subducted beneath most of the landmasses that surround the Pacific Ocean. The volcanoes of the Cascade Range in the northwestern United States, including Mount Hood, Mount Rainier, and Mount Shasta, are examples of volcanoes generated at a convergent plate boundary (**FIGURE 9.34**).

Volcanism at Divergent Plate Boundaries

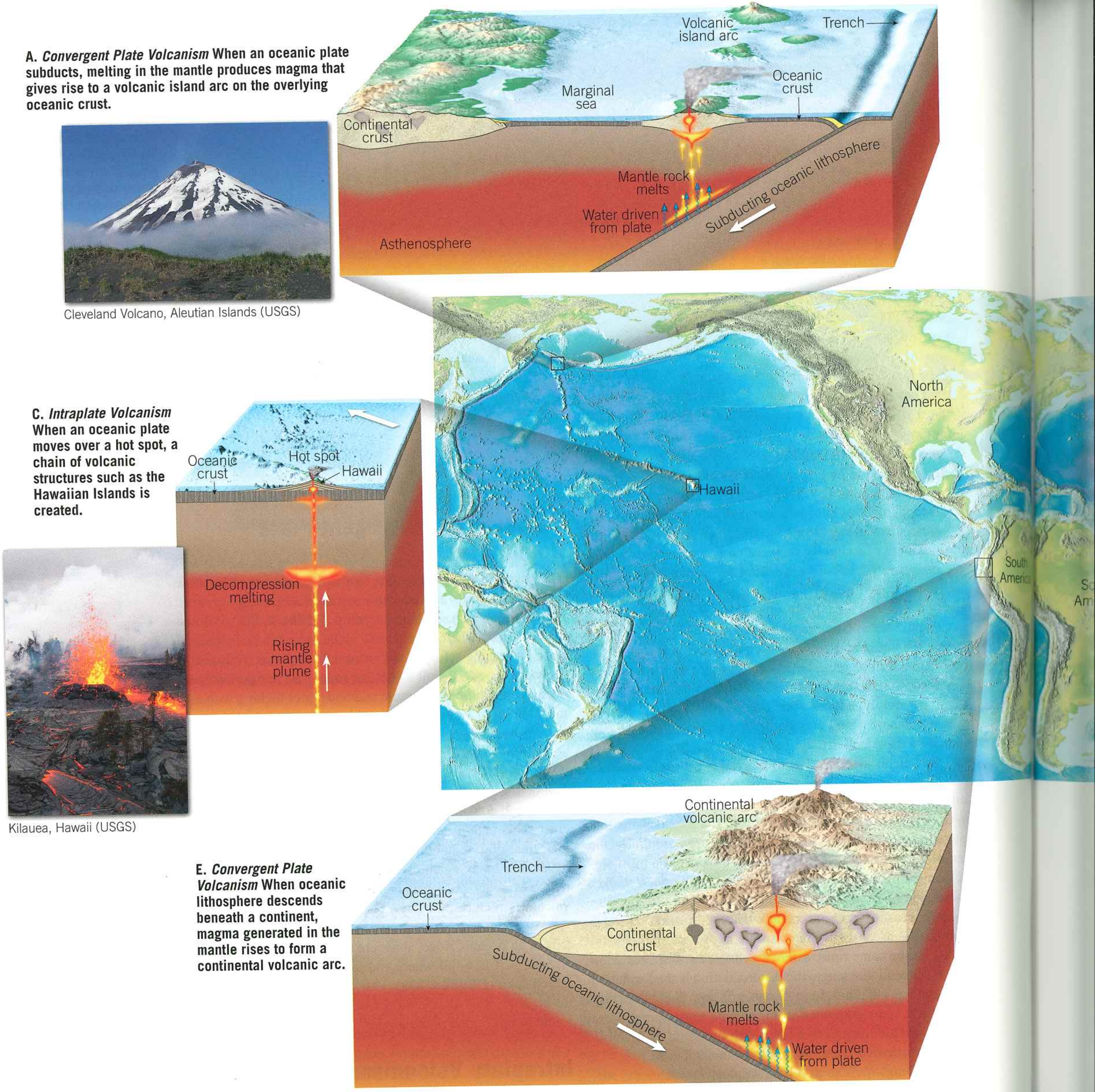
The greatest volume of magma (perhaps 60 percent of Earth's total yearly output) is produced along the oceanic ridge system in association with seafloor spreading (**FIGURE 9.33B**). Below the ridge axis where lithospheric plates are continually being pulled apart, the solid yet mobile mantle responds by ascending to fill the rift. Recall that as hot rock rises, it experiences a decrease in confining pressure and undergoes melting without the addition of heat. Recall that this process is called *decompression melting*.

Partial melting of mantle rock at spreading centers produces basaltic magma. Because this newly formed magma is less dense than the mantle rock from which it was derived, it rises and collects in reservoirs located just below the ridge crest. 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, outpourings 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 (**FIGURE 9.33F**). Vast outpourings of fluid basaltic lavas as well as several active composite volcanoes are found in this region of the globe.

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, 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



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.**

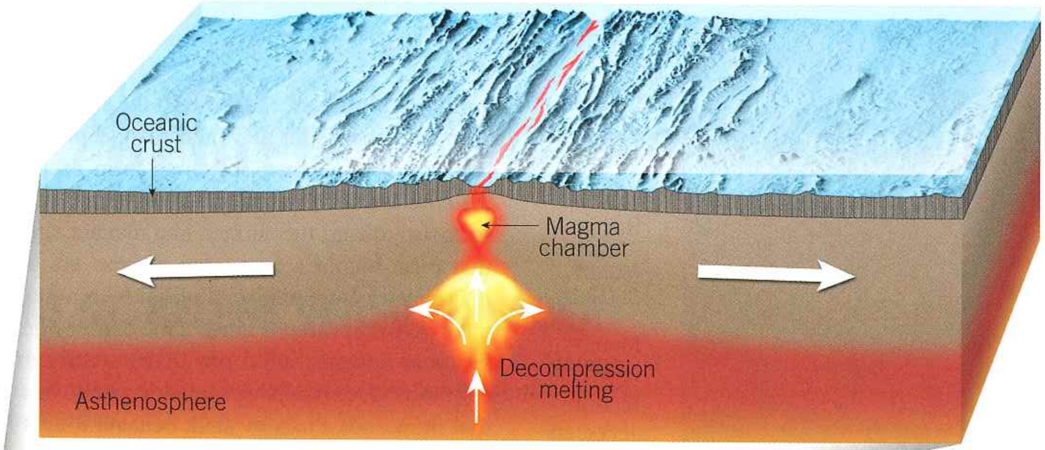
Cleveland Volcano, Aleutian Islands (USGS)

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

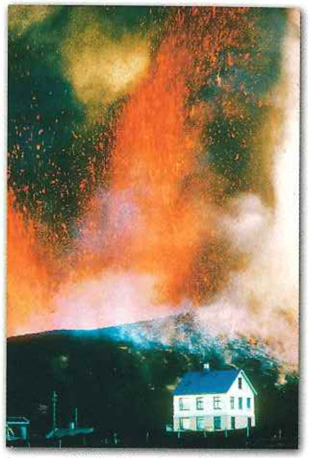
Kilauea, Hawaii (USGS)

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

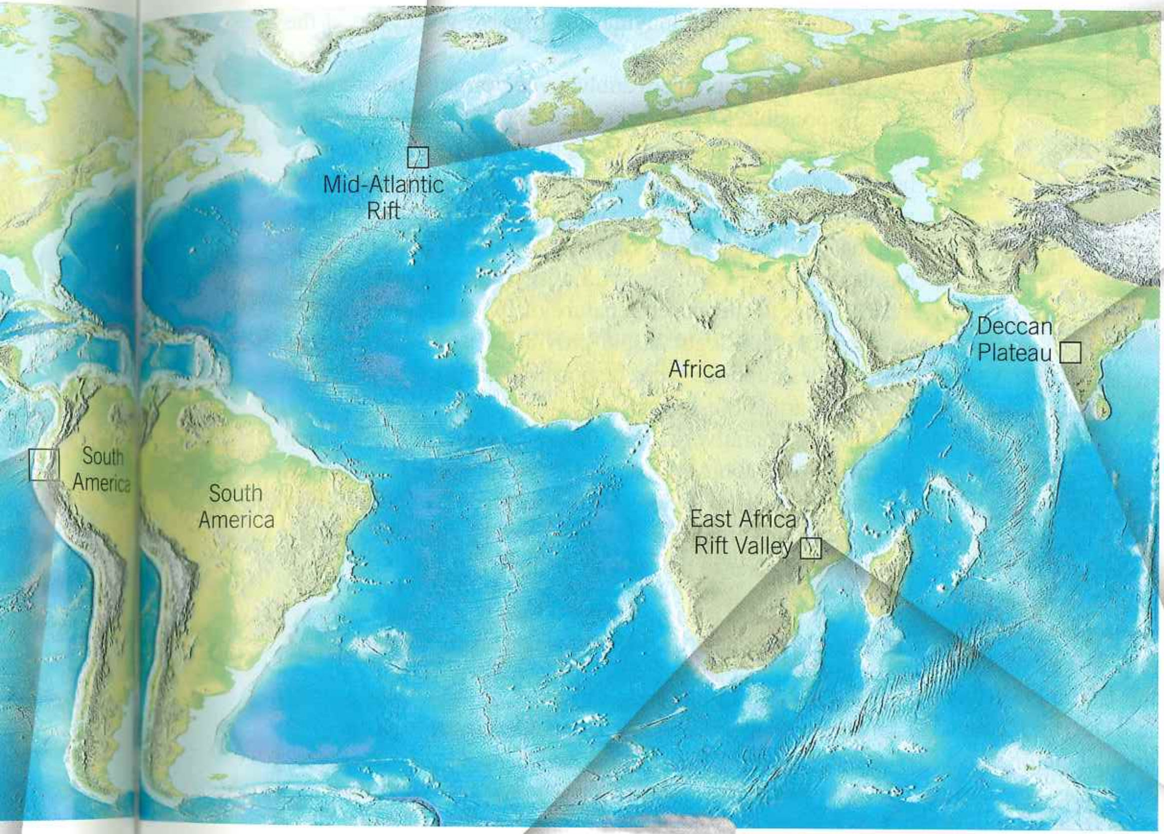
SmartFigure 9.33 Earth's Zones of Volcanism

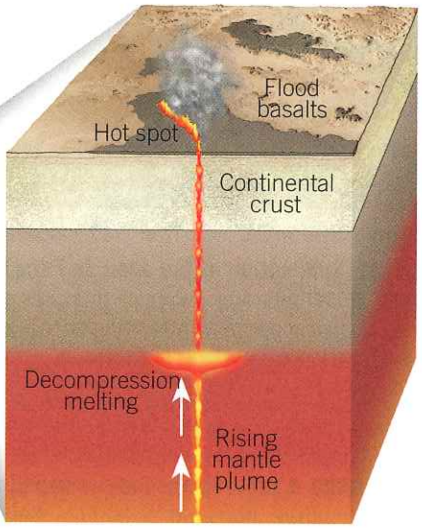


B. ***Divergent Plate Volcanism*** **Along the oceanic ridge, where two plates are being pulled apart, upwelling of hot mantle rock creates new seafloor.**

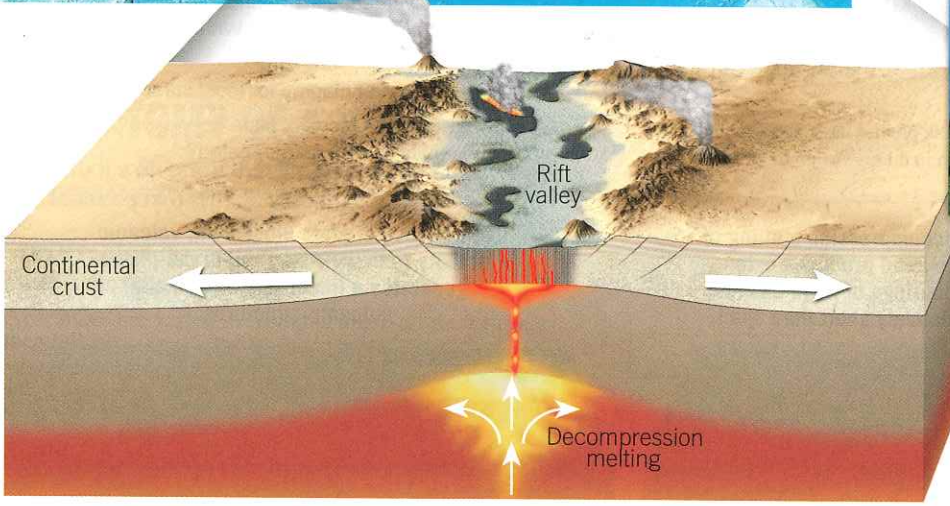


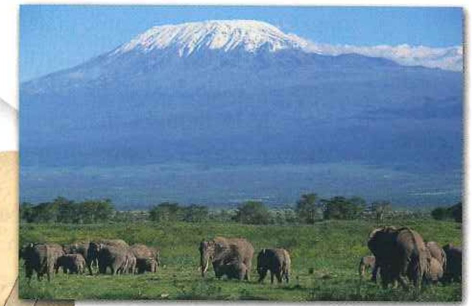
Iceland (Wedigo Ferchland/Photoshot)





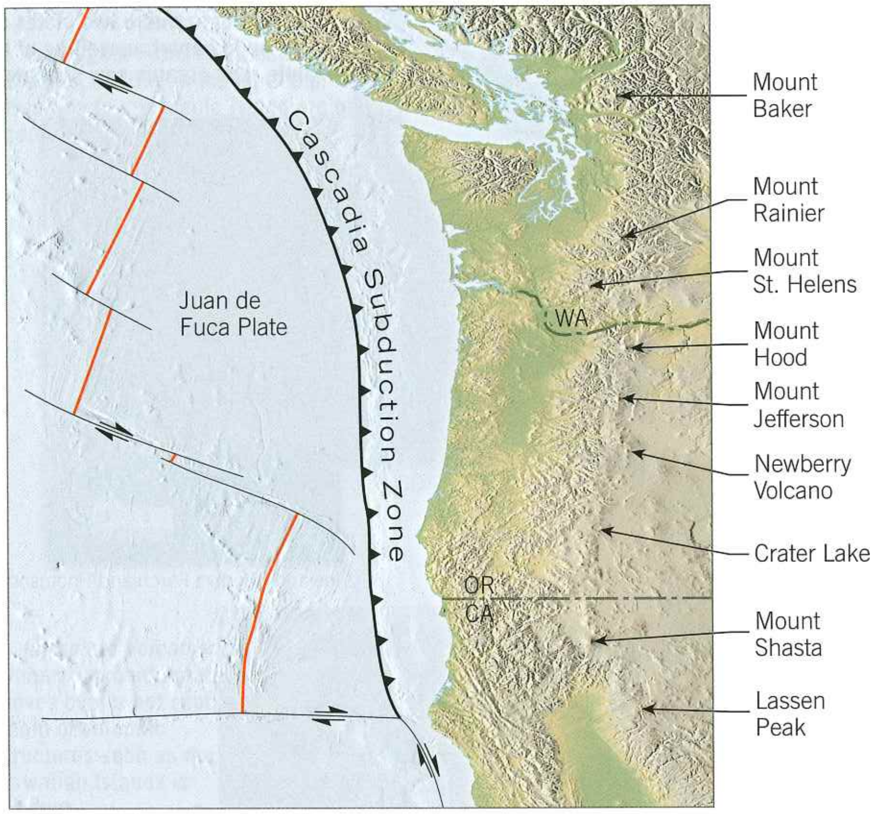
D. ***Intraplate Volcanism*** **When a large mantle plume ascends beneath continental crust, vast outpourings of fluid basaltic lava like those that formed the Deccan Plateau may be generated.**





Mount Kilimanjaro, Africa (Corbis)

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 9.34 Subduction of the Juan de Fuca Plate Produced the Cascade Volcanoes Major volcanic structures of the Cascade Range formed along a convergent plate boundary (Cascadia subduction zone) off the Pacific coast of North America.

(**FIGURE 9.33C**). Other sites of **intraplate volcanism** (meaning "within the plate") include large outpourings of fluid basaltic lavas like those that compose the Columbia River basalts, the Siberian Traps in Russia, India's Deccan Plateau, and several large oceanic plateaus, including the Ontong Java Plateau located in the western Pacific. These massive structures are estimated to be 10 to 40 kilometers (6 to 25 miles) thick. It is thought that most intraplate volcanism occurs where a mass of hotter-than-normal mantle material called a **mantle plume** ascends toward the surface (**FIGURE 9.35A**).* Although the depth at which mantle plumes originate is a topic of debate, some appear 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. (These are the trendy lamps that contain two immiscible liquids in a glass container. 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. Once the plume head nears the top of the mantle, decompression melting generates basaltic magma that triggers volcanism at the surface.

Large mantle plumes, dubbed *superplumes*, are thought to be responsible for the vast outpourings of basaltic lava that created the large basalt provinces (**FIGURE 9.35A**). When the head of a superplume reaches the base of the lithosphere, melting progresses rapidly. This causes the burst of volcanism that emits voluminous outpourings of lava to form a huge basalt province in a matter of a million or so years (**FIGURE 9.35B**). Due to the extreme nature of the eruptions required to produce the large basalt provinces, some researchers believe the eruptions were responsible for the extinction of many of Earth's life-forms.

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 provinces is a chain of volcanic structures, similar to the Hawaiian chain (**FIGURE 9.35C**).

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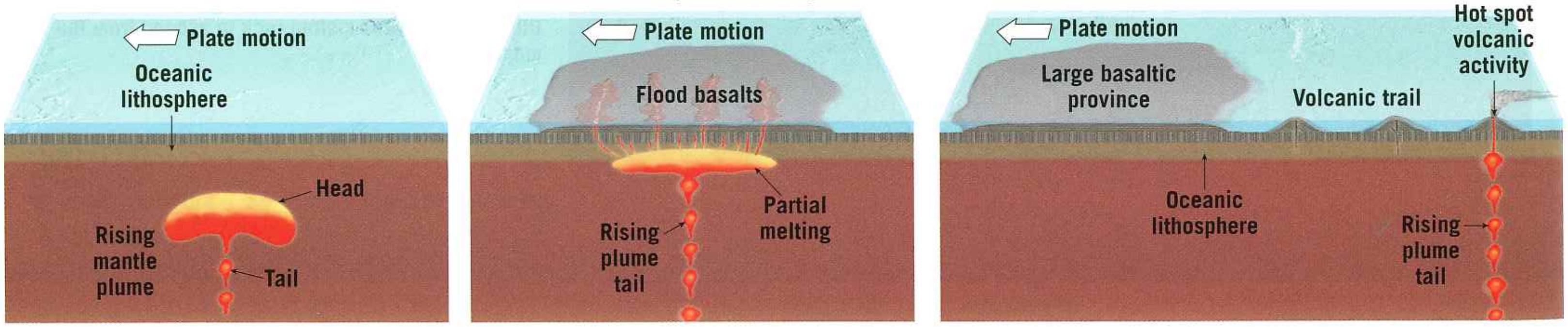
*Recent research on the nature of mantle plumes has caused some geologists to question their role, if any, in the formation of at least some large basalt provinces.

9.12 CONCEPT CHECKS

1. Are volcanoes in the Ring of Fire generally described as quiescent or explosive? Name 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 rock type? What causes rocks to melt in these settings?
4. What is the source of magma for most intraplate volcanism?
5. At which of the three types of plate boundaries is the greatest quantity of magma generated?

FIGURE 9.35 Hot Spots and Mantle Plumes This model of hot-spot volcanism explains the formation of oceanic plateaus, large basalt provinces on land, and chains of volcanic islands such as the Hawaiian chain.


A. A rising mantle plume with a large bulbous head is thought to generate Earth's large basalt provinces.

B. Rapid decompression melting of the plume head produces extensive outpourings of flood basalts over a relatively short time span.

C. Because of plate movement, volcanic activity from the rising tail of the plume generates a linear chain of smaller volcanic structures.

9 CONCEPTS IN REVIEW

Volcanoes and Other Igneous Activity

9.1 MOUNT ST. HELENS VERSUS KILAUEA

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

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

Q Although Kilauea usually erupts in a gentle manner, what risks might you encounter if you lived nearby?

USGS

9.2 THE NATURE OF VOLCANIC ERUPTIONS

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

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

- One important characteristic that differentiates various lavas is their viscosity (resistance to flow). In general, the higher silica content of a lava, the more viscous it is. The lower the silica content, the runnier the lava. Another factor that influences viscosity is temperature. Hot lavas are more fluid, while cool lavas are more viscous.
- High-silica, low-temperature lavas are the most viscous and allow the greatest amount of pressure to build up before they "let go" in an eruption. In contrast, lavas that are hot and low in silica are the most fluid. Because basaltic lavas are less viscous, they produce relatively gentle eruptions, while volcanoes that erupt felsic lavas (rhyolite and andesite) tend to be more explosive.

9.3 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, pyroclastic materials, scoria, pumice

- Volcanoes bring hot molten lava, gases, and solid rocky chunks to Earth's surface.
- Because of their low viscosity, basaltic lava flows can extend great distances from a volcano, where they travel over the surface as pahoehoe or aa flows. Sometimes the surface of the flow congeals, but lava continues to flow below in tunnels called lava tubes.
- The gases most commonly emitted by volcanoes are water vapor and carbon dioxide. Upon reaching the surface, these gases rapidly expand, resulting in explosive eruptions that generate an eruptive column and produce 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, depending on whether the material left the volcano as solid fragments or 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 pumice, which may float in water. Basaltic (mafic) lava with lots of bubbles cools to make scoria.

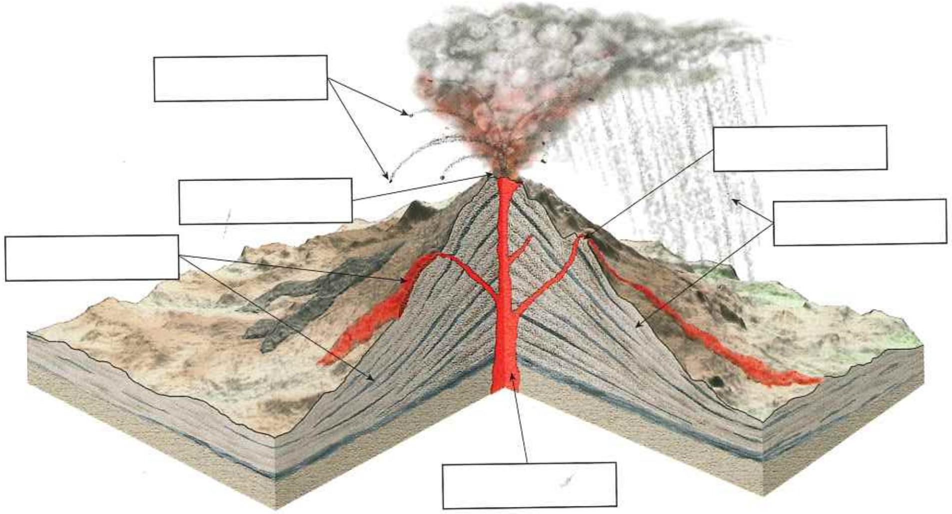
9.4 ANATOMY OF A VOLCANO

Label a diagram that illustrates the basic features of a typical volcanic cone.

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

- Volcanoes are varied in 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 fumaroles, spots where gas is expelled.

Q Label the diagram with the following terms: conduit, vent, bombs, lava, parasitic cone, pyroclastic material



9.5 SHIELD VOLCANOES

Summarize the characteristics of shield volcanoes and provide one example.

KEY TERM: shield volcano

- Shield volcanoes consist of many successive layers of low-viscosity basaltic lava and lack significant amounts of pyroclastic debris. Lava tubes help transport lava far from the main vent, resulting in very gentle, shield-like profiles.
- Most large shield volcanoes are associated with hot-spot volcanism. The volcanoes Kilauea, Mauna Loa, and Mauna Kea in Hawaii are classic examples of the low, wide form.

9.6 CINDER CONES

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

KEY TERM: 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 they form quickly, in single eruptive events. Because they are unconsolidated, cinder cones easily succumb to weathering and erosion.

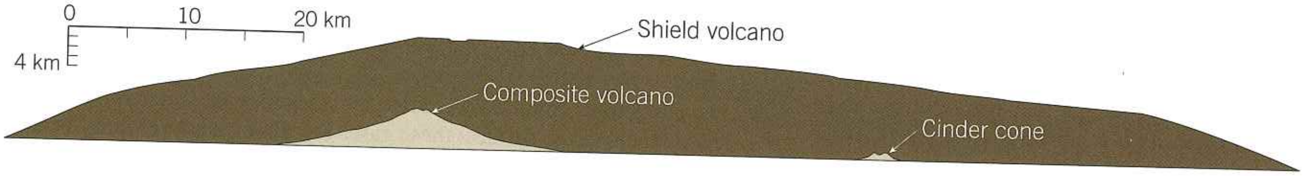
9.7 COMPOSITE VOLCANOES

Explain the formation, distribution, and characteristics of composite volcanoes.

KEY TERM: composite volcano (stratovolcano)

- Composite volcanoes are called "composite" because they consist of both pyroclastic material and lava flows. They typically erupt silica-rich lavas that cool to produce andesite or rhyolite. They are much larger than cinder cones and form from multiple eruptions over a million years or longer.
- Because the andesitic or rhyolitic lava erupted from composite volcanoes is more viscous than basaltic lava, it accumulates at a steeper angle than does the lava from shield volcanoes. Over time, a composite volcano's combination of lava and cinders produces towering volcanoes with a classic symmetrical shape.
- Mount Rainier and the other volcanoes of the Cascade Range in the northwestern United States are good examples of composite volcanoes, as are the other volcanoes of the Pacific Ocean's Ring of Fire.

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



9.8 VOLCANIC HAZARDS

Discuss the major geologic hazards associated with volcanoes.

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

- The greatest volcanic hazard to human life is 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 miles from its source volcano. Because pyroclastic flows are hot, their deposits frequently "weld" together into a solid rock called welded tuff.
- Lahars are volcanic mudflows. These rapidly moving slurries of ash and debris suspended in water can occur even when a volcano isn't actively erupting. They tend to follow stream valleys and can result in loss of life and/or significant damage to structures in their path.
- 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 tsunami when they erupt or their flanks collapse into the ocean. In addition, volcanoes that spew large amounts of gas such as sulfur dioxide can cause human 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.

Q What do lahars and pyroclastic flows have in common? What is the best strategy for avoiding their worst effects?

9.9 OTHER VOLCANIC LANDFORMS

List and describe volcanic landforms other than volcanic cones.

KEY TERMS: caldera, fissure, fissure eruption, basalt plateau, flood basalt, volcanic neck (plug), pipe

- Calderas are among the largest volcanic structures. They form when the stiff, cold rock above a magma chamber cannot be supported and collapses to create a broad, bowl-like depression. On shield volcanoes, calderas form slowly as lava is drained from the magma chamber beneath the volcano. On composite volcanoes, a caldera collapse often follows an explosive eruption that can result in significant loss of life and destruction of property.
- Fissure eruptions produce massive floods of low-viscosity, silica-poor lava from large cracks in the crust. Layer upon layer of these flood basalts may build up to significant thicknesses, as in the Columbia Plateau or the Deccan Traps. The defining feature of a flood basalt is the broad area it covers.
- An example of a volcanic neck is preserved at Shiprock, New Mexico. The lava in the "throat" of this ancient volcano crystallized to form a "plug" of solid rock, and it weathers more slowly than the conical volcano in which it formed. Now, after the mound of pyroclastic debris has been eroded away, the resistant neck is a distinctive landform.

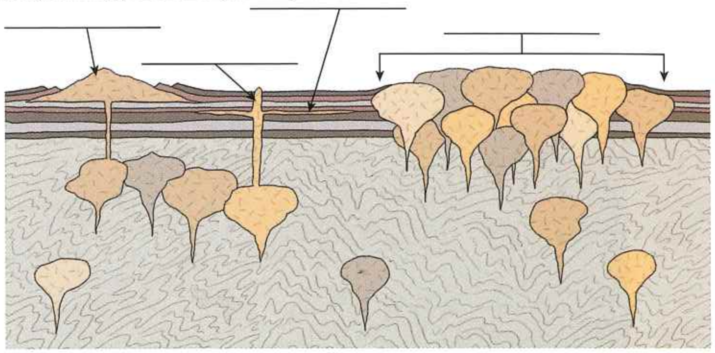
9.10 INTRUSIVE IGNEOUS ACTIVITY

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

KEY TERMS: intrusion, pluton, tabular, massive, discordant, concordant, dike, sill, columnar jointing, batholith, stock, laccolith

- When magma intrudes other rocks, it may cool and crystallize before reaching the surface, producing intrusions called plutons. Plutons come in many shapes. They may cut across the host rocks without regard for preexisting structures, or the magma may flow along weak zones in the host rock, such as between the horizontal layers of sedimentary bedding.
- Tabular intrusions may be concordant (sills) or discordant (dikes). Massive plutons may be small (stocks) or very large (batholiths). Blister-like intrusions also exist (laccoliths). As solid igneous rock cools, its volume decreases. Contraction can produce columnar jointing, a distinctive pattern consisting mainly of six-sided fractures.

Q Label the accompanying diagram using the following terms: batholith, laccolith, sill, and dike.



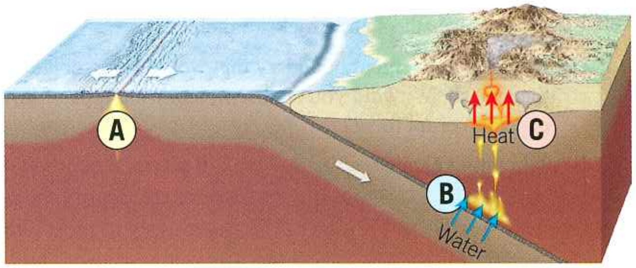
9.11 PARTIAL MELTING AND THE ORIGIN OF MAGMA

Summarize the major processes that generate magma from solid rock.

KEY TERMS: partial melting, geothermal gradient, decompression melting

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

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



9.12 PLATE TECTONICS AND VOLCANIC ACTIVITY

Relate the distribution of volcanic activity to plate tectonics.

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

- Volcanoes occur at both convergent and divergent plate boundaries, as well as in intraplate settings.
- Convergent plate boundaries that involve the subduction of oceanic crust are the sites where the explosive volcanoes of the Pacific "Ring of Fire" are most prevalent. Here, release of water from the subducted plate triggers melting in the overlying mantle. The resulting magma interacts with the lower crust of the overlying plate during its ascent and results in the formation of a volcanic arc at the surface.
- At divergent boundaries, decompression melting is the dominant generator of magma. As warm rock rises, it can begin to melt without the addition of heat. The result will be a rift valley if the overlying crust is continental or a mid-ocean ridge if it is oceanic.
- In an intraplate setting, the source of magma is a mantle plume: a column of warm, rising solid mantle rock that begins to melt in the uppermost mantle.

GIVE IT SOME **THOUGHT**

1. Match each of these volcanic regions with one of the three zones of volcanism (convergent plate boundaries, divergent plate boundaries, or intraplate volcanism):
   - **a.** Crater Lake
   - **b.** Hawaii's Kilauea
   - **c.** Mount St. Helens
   - **d.** East African Rift
   - **e.** Yellowstone
   - **f.** Vesuvius
   - **g.** Deccan Plateau
   - **h.** Mount Etna
2. Examine the accompanying photo and complete the following:
   - **a.** What type of volcano is this? What features helped you make a decision?