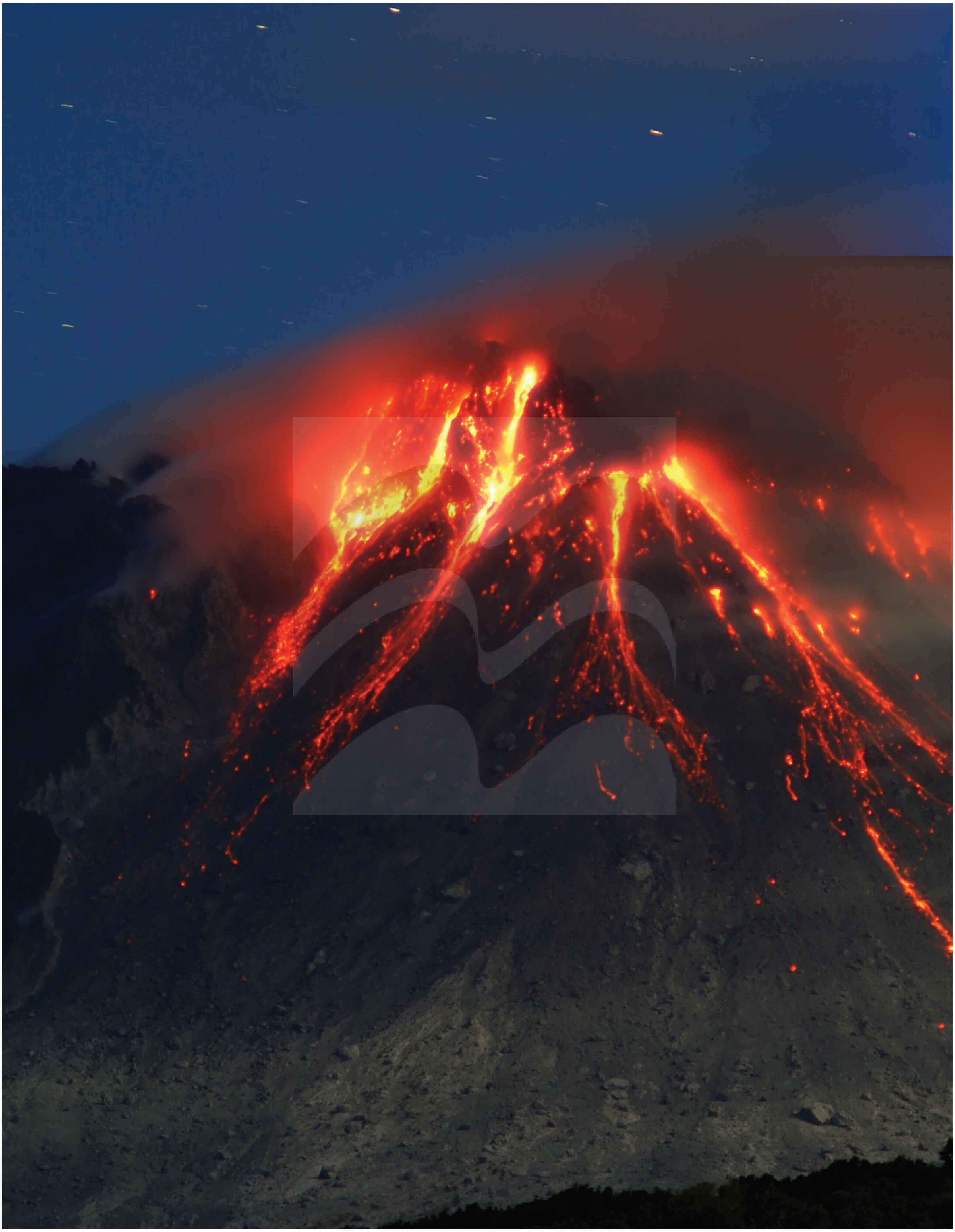


Volcanoes 5

Learning Objectives

After you have studied this chapter, you should be able to:

5.1 Describe how volcanoes transport magma from the Earth's interior to its surface.

5.2 Differentiate between the major types of volcanic deposits and explain how the textures of volcanic rocks can reflect the conditions under which they solidified.

5.3 Summarize how volcanic landforms are shaped.

5.4 Discuss how volcanic gases can affect the hydrosphere and atmosphere.

5.5 Explain how the global pattern of volcanism is related to plate tectonics.

5.6 Illustrate the hazards and beneficial effects of volcanism.

Soufriere Hills is a stratovolcano composed of alternating layers of hardened lava, solidified ash, and rocks ejected by previous eruptions. The eruption of Soufriere Hills, Montserrat, Caribbean, began on Friday, January 8th, 2010. Residents said it was one of the largest eruptions they have witnessed at the volcano since its reawakening in 1995. Scientists don't believe there was a major collapse of the dome, but a significant amount of material was lost. After the seventeenth century, the volcano experienced no recorded eruptions until 1995, when a series of major eruptions eventually forced the evacuation of Montserrat's former capital, Plymouth. [Marco Fulle/Barcroft Media.]

The northwestern corner of Wyoming is a geologic wonderland of geysers, hot springs, and steam vents—the visible signs of a vast active volcano that stretches across the wilderness of Yellowstone National Park. Every day, this volcano expels more energy in the form of heat than is consumed as electric power in the three surrounding states of Wyoming, Idaho, and Montana combined. This energy is not released steadily; some of it builds up in hot magma chambers until the volcano blows its top. A cataclysmic eruption of the Yellowstone volcano 630,000 years ago ejected 1000 km^3 of rock into the air, covering regions as far away as Texas and California with a layer of volcanic ash.

The geologic record shows that volcanic explosions nearly this big, or even bigger, have occurred in the western United States at least six times during the last 2 million years, so we can be fairly certain that such an eruption will happen again. We can only imagine what it might do to human civilization. Hot ash would snuff out all life within 100 km or more, and cooler but choking ash would blanket the ground more than 1000 km away. Ash thrown high into the stratosphere would dim the Sun for several years, dropping temperatures and plunging the Northern Hemisphere into an extended volcanic winter.

The hazards volcanoes pose to human society, as well as the mineral resources and energy they provide, are certainly good enough reasons to study them. In addition, volcanoes are fascinating because they are windows through which we can look into Earth's deep interior to understand the igneous and plate tectonic processes that have generated its oceanic and continental crust.

In this chapter, we will examine how magma rises through Earth's crust, emerges onto its surface as lava, and cools into solid volcanic rock. We will see how plate tectonic processes and mantle convection explain volcanism at plate boundaries and at "hot spots" within plates. We will see how volcanoes interact with other components of the Earth system, particularly the hydrosphere and the atmosphere. Finally, we will consider their destructive power as well as the potential benefits they can provide for human society.

Volcanoes as Geosystems

The geologic processes that give rise to volcanoes and volcanic rocks are known collectively as *volcanism.* We had a glimpse of some of these processes when we examined the formation of igneous rocks in Chapter 4, but we will take a more detailed look at them here.

Ancient philosophers were awed by volcanoes and their fearsome eruptions of molten rock. In their efforts to explain volcanoes, they spun myths about a hot, hellish underworld below Earth's surface. Basically, they had the right idea. Modern researchers also see evidence of Earth's internal heat in volcanoes. Temperature readings of rocks as far down as humans have drilled (about 10 km) show that Earth does indeed get hotter with depth. We now believe that temperatures at depths of 100 km and more—within the asthenosphere—reach at least 1300°C, high enough for the rocks there to begin to melt. For this reason, we identify the asthenosphere as a main source of *magma,* the molten rock that we call *lava* after it rises to the surface and erupts. Portions of the solid lithosphere that ride above the asthenosphere may also melt to form magma.

Because magma is liquid, it is less dense than the rocks that produce it. Therefore, as magma accumulates, it begins to float upward through the lithosphere. In some places, the magma may find a path to the surface by fracturing the lithosphere along zones of weakness. In other places, the rising magma melts its way toward the surface. Most of the magma freezes at depth, but some fraction, probably only 10 to 30 percent, eventually reaches the surface and erupts as lava. A **volcano** is a hill or mountain constructed from the accumulation of lava and other erupted materials.

Taken together, the rocks, magmas, and processes needed to describe the entire sequence of events from melting to eruption constitute a **volcanic geosystem.** This type of geosystem can be viewed as a chemical factory that processes the input material (magmas from the asthenosphere) and transports the end product (lava) to the surface through an internal plumbing system.

Figure 5.1 is a simplified diagram of a volcano, showing the plumbing system through which magma travels to the surface. Magmas rising buoyantly through the lithosphere pool together in a magma chamber, usually at shallow depths in the crust. This chamber periodically empties through a pipelike feeder channel to a central vent on the surface in repeated cycles of *central eruptions.* Lava can also erupt from vertical cracks and other vents on the flanks of a volcano.

As we saw in Chapter 4, only a small fraction of the asthenosphere melts in the first place. The resulting magma gains chemical components as it melts the surrounding rocks while rising through the lithosphere. It loses other components as crystals settle out during transport or in shallow magma chambers. And its gaseous constituents escape to the atmosphere or ocean as it erupts at the surface. By accounting for these changes, we can extract clues to the chemical composition and physical state of the upper mantle where the lavas originated. We can also learn about eruptions that occurred millions or even billions of years ago by using isotopic dating (see Chapter 8) to determine the ages of lavas.

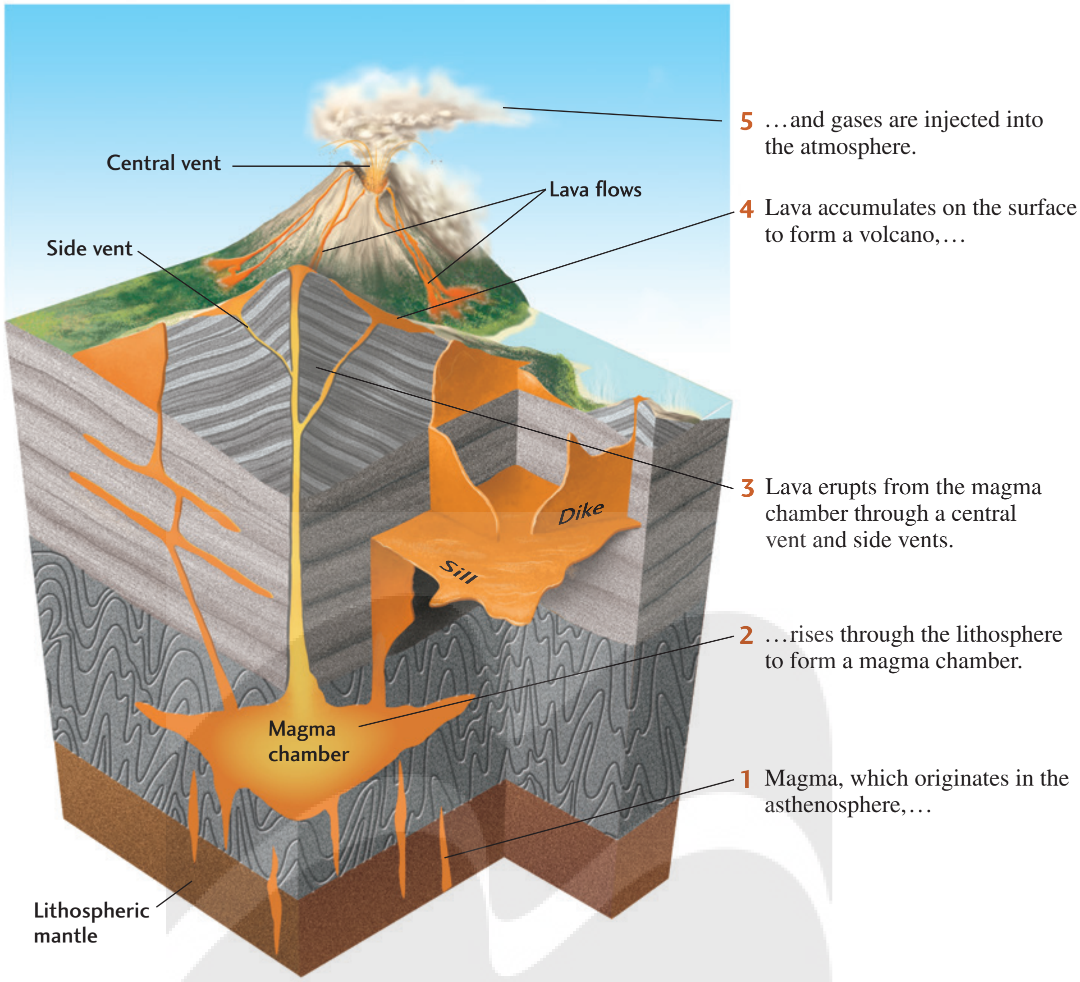


FIGURE 5.1 Volcanoes transport magma from Earth's interior to its surface, where rocks are formed and gases are injected into the atmosphere (or hydrosphere, in the case of an underwater eruption).

Lavas and Other Volcanic Deposits

Lavas of different types produce different landforms. The differences depend on the chemical composition, gas content, and temperature of the lavas. The higher the silica content and the lower the temperature, for example, the more viscous the lava is, and the more slowly it moves. The more gas a lava contains, the more violent its eruption is likely to be.

Types of Lava

Erupted lavas, the end products of volcanic geosystems, usually solidify into one of three major types of igneous rock (see Chapter 4): basalt, andesite, or rhyolite.

Basaltic Lavas Basalt is an extrusive igneous rock of mafic composition (high in magnesium, iron, and calcium) and has the lowest silica content of the three igneous rock types; its intrusive equivalent is gabbro. Basaltic magma, the product of mantle melting, is the most common magma type. It is produced along mid-ocean ridges and at hot spots within plates, as well as in continental rift valleys and other zones of extension. The volcanic island of Hawaii, which is made up primarily of basaltic lava, lies above a hot spot.

Basaltic lavas erupt when hot, fluid magmas fill up a volcano's plumbing system and overflow (Figure 5.2). Basaltic eruptions are rarely explosive. On land, a basaltic eruption sends lava down the flanks of the volcano in great streams that can engulf everything in their path (Figure 5.3). When cool, these lavas are black or dark gray, but at their high eruption temperatures (1000°C to 1200°C), they glow in reds and yellows. Because their temperatures are high and their silica content low, they are extremely fluid and can flow downhill fast and far. Lava streams flowing as fast as 100 km/hour have been observed, although velocities of a few kilometers per hour are more common. In 1938, two daring Russian volcanologists measured temperatures and collected gas samples while floating down a river of molten basalt on a raft of colder solidified lava. The surface

FIGURE 5.2 A central vent eruption from Kilauea, a shield volcano on the island of Hawaii, produces a river of hot, fast-flowing basaltic lava. [J. D. Griggs/USGS.]

temperature of the raft was 300°C, and the river temperature was 870°C. Lava streams have been observed to travel more than 50 km from their sources.

Basaltic lava flows take on different forms depending on how they cool. On land, they solidify as pahoehoe (pronounced pa-hoh-ee-hoh-ee) or aa (ah-ah) (**Figure 5.4**). *Pahoehoe* (the word is Hawaiian for "ropy") forms when a highly fluid lava spreads in sheets and a thin, glassy, elastic skin congeals on its surface as it cools. As the molten liquid continues to flow below the surface, the skin is dragged and twisted into coiled folds that resemble rope.

"*Aa*" is what the unwary exclaim after venturing barefoot onto lava that looks like clumps of moist, freshly plowed earth. Aa forms when lava loses its gases and consequently flows more slowly than pahoehoe, allowing a thick skin to form. As the flow continues to move, the thick skin breaks into rough, jagged blocks. The blocks pile up in a steep front of angular boulders that advances like a tractor tread. Aa is truly treacherous to cross. A good pair of boots may last about a week on it, and the traveler can count on cut knees and elbows.

A single downhill basaltic flow commonly has the features of pahoehoe near its source, where the lava is still fluid and hot, and of aa farther downstream, where the

FIGURE 5.3 A partly buried school bus in Kalapana, Hawaii. The village was buried by a basaltic lava flow from Kilauea. [J. D. Griggs/USGS.]

FIGURE 5.4 The two forms of basaltic lava are shown here: The jagged aa lava flow is moving over a pahoehoe lava flow on the island of Hawaii. [InterNetwork Media/Getty Images.]

FIGURE 5.5 These bulbous pillow lavas, which were recently extruded on the Mid-Atlantic Ridge, were photographed from the deep-sea submersible *Alvin*. [OAR/National Undersea Research Program (NURP)/NOAA.]

flow's surface—having been exposed to cool air longer—has developed a thicker outer skin.

Basaltic lava that cools under water forms *pillow lavas:* piles of ellipsoidal, pillowlike blocks of basalt about a meter wide (**Figure 5.5**). Pillow lavas are an important indicator that a region on dry land was once under water. Scuba-diving geologists have actually observed pillow lavas forming on the ocean floor off Hawaii. Tongues of molten basaltic lava develop a tough, plastic skin on contact with the cold ocean water. Because the lava inside the skin cools more slowly, the pillow's interior develops a crystalline texture, whereas the quickly chilled skin solidifies to a crystal-less glass.

Andesitic Lavas Andesite is an extrusive igneous rock with an intermediate silica content; its intrusive equivalent is diorite. Andesitic magmas are produced mainly in the volcanic mountain belts above subduction zones. The name comes from a prime example: the Andes of South America.

The temperatures of **andesitic lavas** are lower than those of basalts, and because their silica content is higher, they flow more slowly and lump up in sticky masses. If one of these sticky masses plugs the central vent of a volcano, gases can build up beneath the plug and eventually blow off the top of the volcano. The explosive eruption of Mount St. Helens in 1980 (**Figure 5.6**) is a famous example.

(a)

(b)

(c)

FIGURE 5.6 Mount St. Helens, an andesitic volcano in southwestern Washington State, before, during, and after its cataclysmic eruption in May 1980, which ejected about 1 km^3 of pyroclastic material. The collapsed northern flank can be seen in the bottom photo. [(a) U.S. Forest Service/USGS; (b) USGS; (c) Lyn Topinka/USGS.]

FIGURE 5.7 A phreatic eruption of an island-arc volcano spews out plumes of steam into the atmosphere. The volcano, about 6 miles off the Tongan island of Tongatau, is one of about 36 in the area. [Dana Stephenson/Getty Images.]

Some of the most destructive volcanic eruptions in history have been *phreatic,* or steam, explosions, which occur when hot, gas-charged magma encounters groundwater or seawater, generating vast quantities of superheated steam (**Figure 5.7**). In 1883, the island of Krakatau, an andesitic volcano in Indonesia, was destroyed by a phreatic explosion. This legendary eruption was heard thousands of kilometers away, and it generated a tsunami that killed more than 40,000 people.

Rhyolitic Lavas Rhyolite is an extrusive igneous rock of felsic composition (high in sodium and potassium) with a silica content greater than 68 percent; its intrusive equivalent is granite. It is light in color, often a pretty pink. Rhyolitic magmas are produced in zones where heat from the mantle has melted large volumes of continental crust. Today, the Yellowstone volcano is producing huge amounts of rhyolitic magma that are building up in shallow chambers.

Rhyolite has a lower melting point than andesite, becoming liquid at temperatures of only 600°C to 800°C. Because **rhyolitic lavas** are richer in silica than any other lava type, they are the most viscous. A rhyolitic flow typically moves about 10 times more slowly than a basaltic flow, and it tends to pile up in thick, bulbous deposits (**Figure 5.8**). Gases are

FIGURE 5.8 Aerial view of a rhyolite dome that erupted about 1300 years ago in Newberry Caldera, Oregon. The light-colored rhyolite flow stands out against the trees with Paulina Peak in the background. Its dome shape indicates that the lava was very viscous. [William Scott/USGS.]

easily trapped beneath rhyolitic lavas, and large rhyolitic volcanoes such as Yellowstone produce the most explosive of all volcanic eruptions.

Textures of Volcanic Rocks

The textures of volcanic rocks, like the surfaces of solidified lava flows, reflect the conditions under which they solidified. Coarse-grained textures with visible crystals can result if lavas cool slowly. Lavas that cool quickly tend to have fine-grained textures. If they are silica-rich, rapidly cooled lavas can form *obsidian,* a volcanic glass.

Volcanic rock often contains little bubbles, created as gases are released during an eruption. As we have seen, magma is typically charged with gas, like soda in an unopened bottle. When magma rises toward Earth's surface, the pressure on it decreases, just as the pressure on the soda drops when the bottle cap is removed. And just as the carbon dioxide in the soda forms bubbles when the pressure is released, the water vapor and other dissolved gases escaping from lava as it erupts create gas cavities, or *vesicles* (**Figure 5.9**). *Pumice* is an extremely vesicular volcanic rock, usually rhyolitic in composition. Some pumice has so many vesicles that it is light enough to float on water.

FIGURE 5.9 A sample of vesicular basalt. [Courtesy John Grotzinger.]

Pyroclastic Deposits

Water and gases in magma can have even more dramatic effects than bubble formation. Before magma erupts, the confining pressure of the overlying rock keeps these volatiles from escaping. When the magma rises close to the surface and the pressure drops, the volatiles may be released with explosive force, shattering the lava and any overlying solidified rock and sending fragments of various sizes, shapes, and textures into the air (**Figure 5.10**). These fragments, known as *pyroclasts,* are classified according to their size.

Volcanic Ejecta

The finest pyroclasts are fragments less than 2 mm in diameter, which are classified as *volcanic ash.* Volcanic eruptions can spray ash high into the atmosphere, where ash that is fine enough to stay aloft can be carried great distances. Within two weeks of the 1991 eruption of Mount Pinatubo in the Philippines, for example, its ash was traced all the way around the world by Earth-orbiting satellites.

Fragments ejected as blobs of lava that cool in flight and become rounded, or as chunks torn loose from previously solidified volcanic rock, can be much larger. These

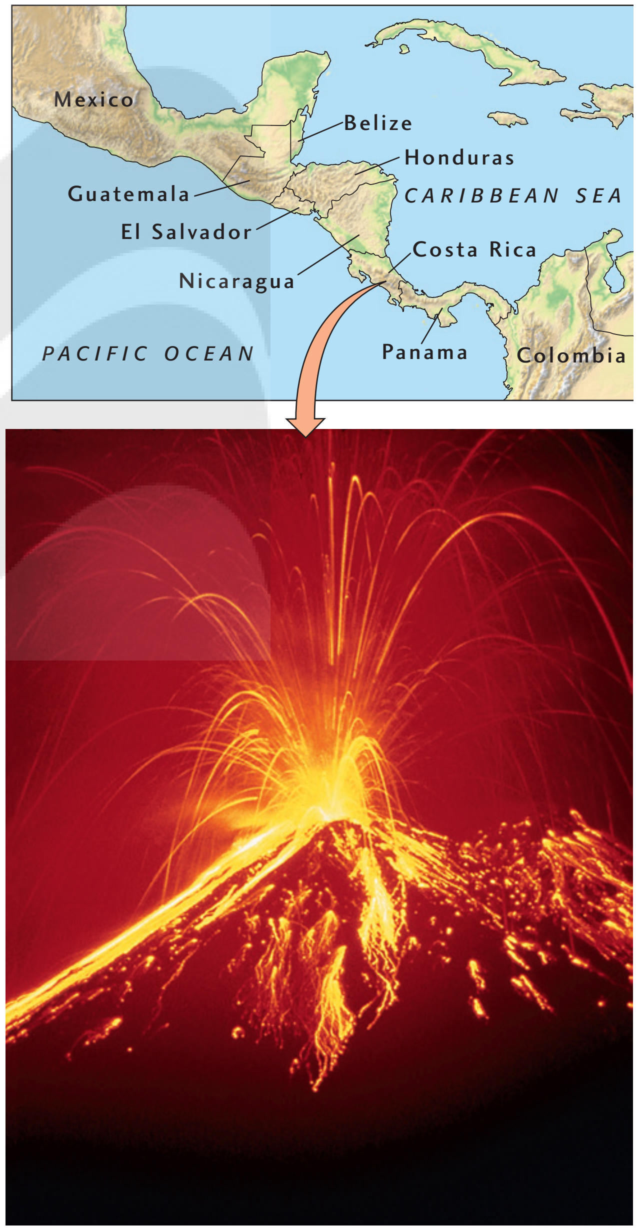


FIGURE 5.10 An explosive eruption at Arenal volcano, Costa Rica, hurls pyroclasts into the air. [Gregory G. Dimijian/Science Source.]

FIGURE 5.11 Volcanic bombs within a stratified pyroclastic deposit at Hawaii Volcanoes National Park. These explosive eruptions eject volcanic materials up into the atmosphere, which then fall down and accumulate as poorly sorted deposits in pyroclastic flows. [Courtesy John Grotzinger.]

fragments are called *volcanic bombs* (Figure 5.11). Volcanic bombs as large as houses have been thrown more than 10 km by explosive eruptions.

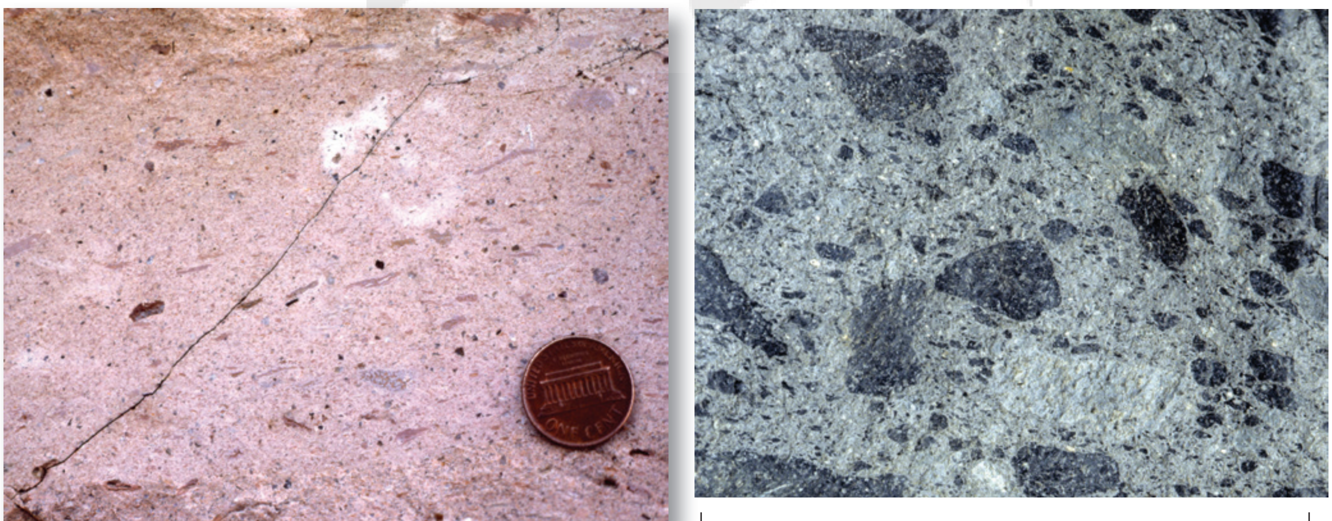
Sooner or later, these pyroclasts fall to Earth, building the largest deposits near their source. As they cool, the hot, sticky fragments become welded together (lithified). Rocks created from smaller fragments are called **tuffs;** those formed from larger fragments are called **breccias** (Figure 5.12).

Pyroclastic Flows **Pyroclastic flows,** which are particularly spectacular and often deadly, occur when a volcano ejects hot ash and gases in a glowing cloud that rolls downhill at high speeds. The solid particles are buoyed up by the hot gases, so there is little frictional resistance to their movement.

In 1902, with very little warning, a pyroclastic flow with an internal temperature of 800°C exploded from the side of Mont Pelée, on the Caribbean island of Martinique. The avalanche of choking hot gas and glowing volcanic ash plunged down the slopes at a hurricane speed of 160 km/hour. In one minute and with hardly a sound, the searing emulsion of gas and ash enveloped the town of St. Pierre and killed 29,000 people. It is sobering to recall the statement of one Professor Landes, issued the day before the cataclysm: "The Montagne Pelée presents no more danger to the inhabitants of St. Pierre than does Vesuvius to those of Naples." Professor Landes perished with the others. In 1991, Mount Pinatubo erupted and created a major pyroclastic flow that was captured on camera in this impressive image (Figure 5.13).

Eruptive Styles and Landforms

The surface features produced by a volcano as it ejects material vary with the properties of the magma, especially its chemical composition and gas content, the type of material (lava versus pyroclasts) erupted, and the environmental conditions under which it erupts—on land or under the sea.



(a) (b)

FIGURE 5.12 Welded tuff is a volcanic igneous rock that forms when still warm ash-flow deposits weld together under the weight of overlying deposits. [(a) Courtesy John Grotzinger; (b) W. K. Fletcher/Science Source.]

FIGURE 5.13 Pyroclastic flow emanating from Mount Pinatubo, Philippines. After being dormant for 611 years, Mount Pinatubo erupted with massive violence, destroying everything in its path and killing 847 people. The Mount Pinatubo eruption is considered the world's most violent and destructive volcanic eruption of the 20th century. [Alberto Garcia/Redux.]

Volcanic landforms also depend on the rate at which lava is produced and the plumbing system that gets it to the surface (Figure 5.14).

Central Eruptions

Central eruptions discharge lava or pyroclasts from a *central vent,* an opening atop a pipelike feeder channel rising from the magma chamber. The magma ascends through this channel to erupt at Earth's surface. Central eruptions create the most familiar of all volcanic features: the volcanic mountain, shaped like a cone.

Shield Volcanoes A *lava cone* is built by successive flows of lava from a central vent. If the lava is basaltic, it flows easily and spreads widely. If flows are copious and frequent, they create a broad, shield-shaped volcano two or more kilometers high and many tens of kilometers in circumference, with relatively gentle slopes. Mauna Loa, on the island of Hawaii, is the classic example of such a **shield volcano** (Figure 5.14a). Although it rises only 4 km above sea level, it is actually the world's tallest mountain: Measured from its base on the seafloor, Mauna Loa is 10 km high, taller than Mount Everest! It grew to this enormous size by the accumulation of thousands of lava flows, each only a few meters thick, over a period of about a million years. The island of Hawaii actually consists of the overlapping tops of several active shield volcanoes emerging from the ocean.

Volcanic Domes In contrast to basaltic lavas, andesitic and rhyolitic lavas are so viscous they can barely flow. They often produce a *volcanic dome,* a bulbous, steep-sided mass of rock (see Figure 5.8). Domes look as though the lava has been squeezed out of a vent like toothpaste, with very little lateral spreading. Domes often plug vents, trapping gases beneath them (Figure 5.14b). Pressure can increase until an explosion occurs, blasting the dome into fragments.

Cinder Cones When volcanic vents discharge pyroclasts, these solid fragments can build up to create *cinder cones.* The profile of a cinder cone is determined by the *angle of repose* of the fragments: the maximum angle at which the fragments will remain stable rather than sliding downhill. The larger fragments, which fall near the vent, form very steep but stable slopes. Finer particles are carried farther from the vent and form gentler slopes at the base of the cone. The classic concave-shaped volcanic cone with its central vent at the summit develops in this way (Figure 5.14c).

Stratovolcanoes When a volcano emits lava as well as pyroclasts, alternating lava flows and beds of pyroclasts build a concave-shaped composite volcano, or **stratovolcano** (Figure 5.14d). Lava that solidifies in the central feeder channel and in radiating dikes strengthen the cone structure. Stratovolcanoes are common above subduction zones. Famous examples are Mount Fuji in Japan, Mount Vesuvius and Mount Etna in Italy, and Mount Rainier in Washington State. Mount St. Helens had a near-perfect stratovolcano shape until its eruption in 1980 destroyed its northern flank (see Figure 5.6c).

Craters A bowl-shaped pit, or **crater,** is found at the summit of most volcanic mountains, surrounding the central vent. During an eruption, the upwelling lava overflows

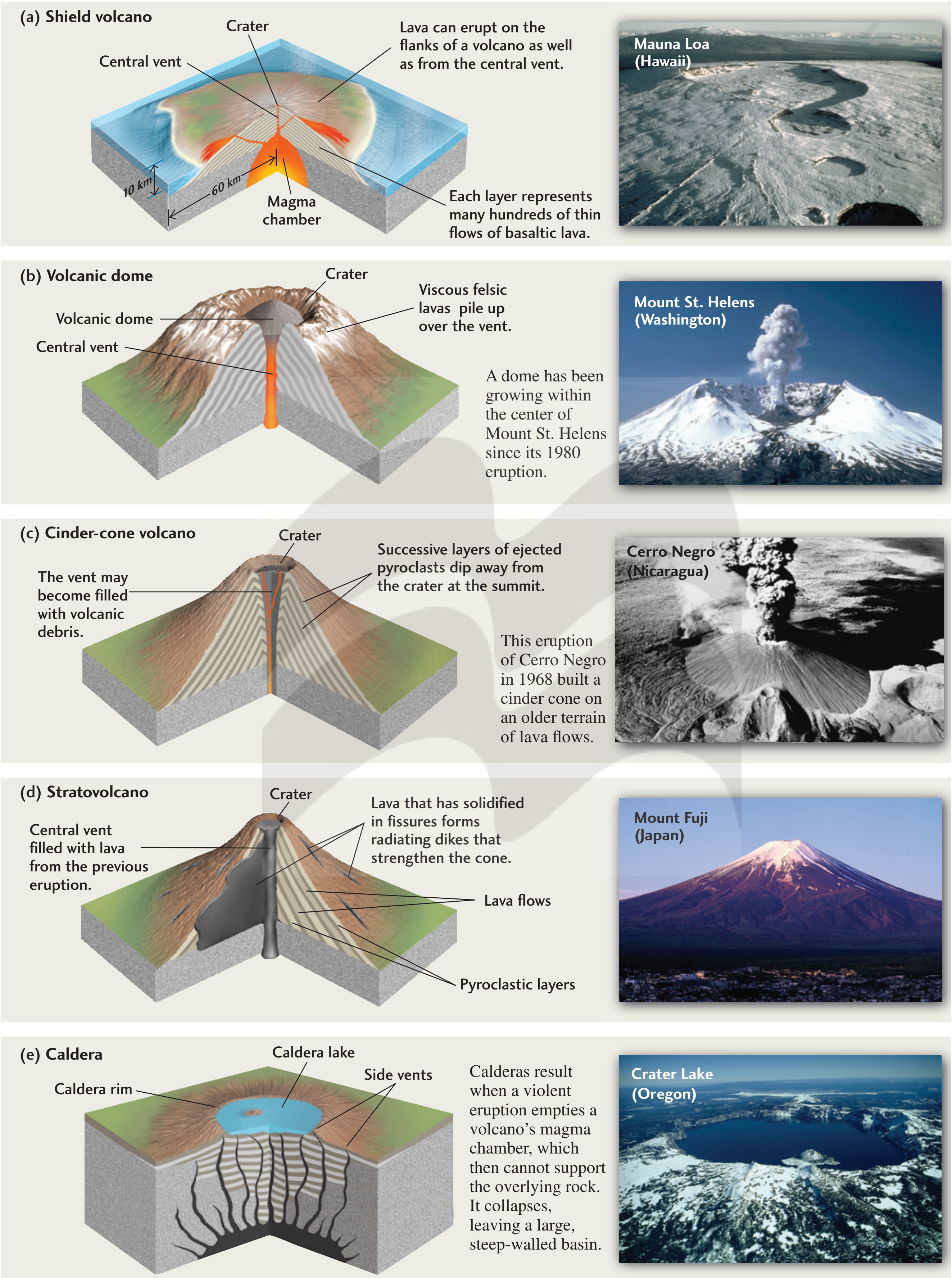


FIGURE 5.14 The eruptive styles of volcanoes and the landforms they create are determined principally by the composition of magma. [(a) USGS; (b) Lyn Topinka/USGS Cascades Volcano Observatory; (c) Smithsonian; (d) Corbis; (e) Bates Littlehales/Getty Images.]

the crater walls. When the eruption ceases, the lava that remains in the crater often sinks back into the vent and solidifies, and the crater may become partly filled by rock fragments that fall back into it. When the next eruption occurs, that material may be blasted out of the crater. Because a crater's walls are steep, they may cave in or become eroded over time. In this way, a crater can grow to several times the diameter of the vent and hundreds of meters deep. The crater of Mount Etna in Sicily, for example, is currently 300 m in diameter.

Calderas When great volumes of magma are discharged rapidly from a large magma chamber, the chamber can no longer support its roof. In such cases, the overlying volcanic structure can collapse catastrophically, leaving a large, steep-walled, basin-shaped depression much larger than a crater, called a **caldera** (Figure 5.14e). The development of the caldera that forms Crater Lake in Oregon is shown in **Figure 5.15**. Calderas can be impressive features, ranging in diameter from a few kilometers to 50 km or more. Owing to their size and high-volume eruptions, large caldera systems are sometimes called "supervolcanoes." The Yellowstone supervolcano, which is the largest active volcano in the United States, has a caldera with an area greater than Rhode Island.

After some hundreds of thousands of years, enough fresh magma may reenter the collapsed magma chamber to reinflate it, forcing the caldera floor to dome upward again to create a *resurgent caldera*. The cycle of eruption, collapse, and resurgence may occur repeatedly over geologic time. Three times over the last 2 million years, the Yellowstone supervolcano has erupted catastrophically, in each instance ejecting hundreds or thousands of times more material than the 1980 Mount St. Helens eruption and depositing ash over much of what is now the western United States. Other resurgent calderas are Valles Caldera in New Mexico and Long Valley Caldera in California, which last erupted about 1.2 million and 760,000 years ago, respectively.

Diatremes When magma from Earth's deep interior escapes explosively, the vent and the feeder channel below it are often left filled with volcanic breccia as the eruption wanes. The resulting structure is called a **diatreme.** Shiprock, a formation that towers over the surrounding plain in New Mexico, is a diatreme exposed by erosion of the sedimentary rocks through which it erupted. To transcontinental air travelers, Shiprock looks like a gigantic black skyscraper in the red desert (**Figure 5.16**).

The eruptive mechanism that produces diatremes has been pieced together from the geologic record. The kinds of minerals and rocks found in some diatremes could have formed only at great depths—100 km or so, well within the

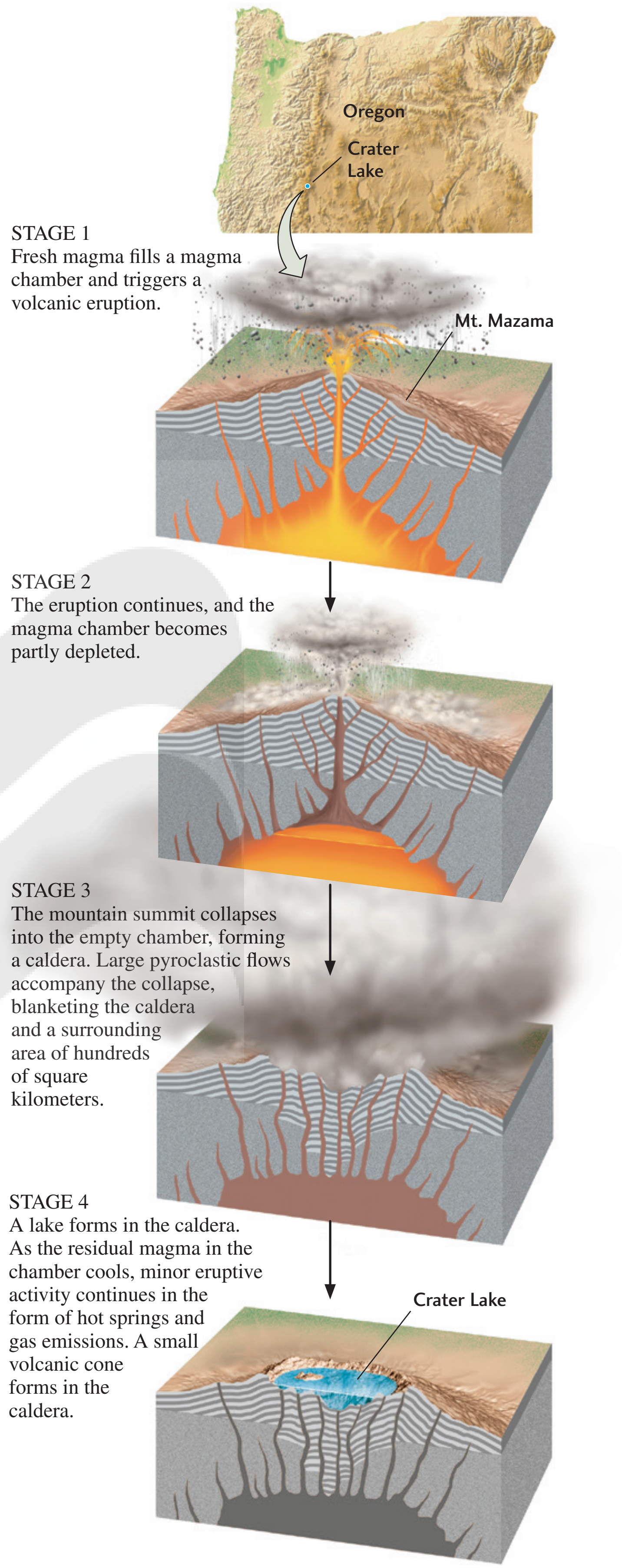


FIGURE 5.15 Stages in the formation of the Crater Lake caldera. The Stage 3 collapse occurred about 7700 years ago.

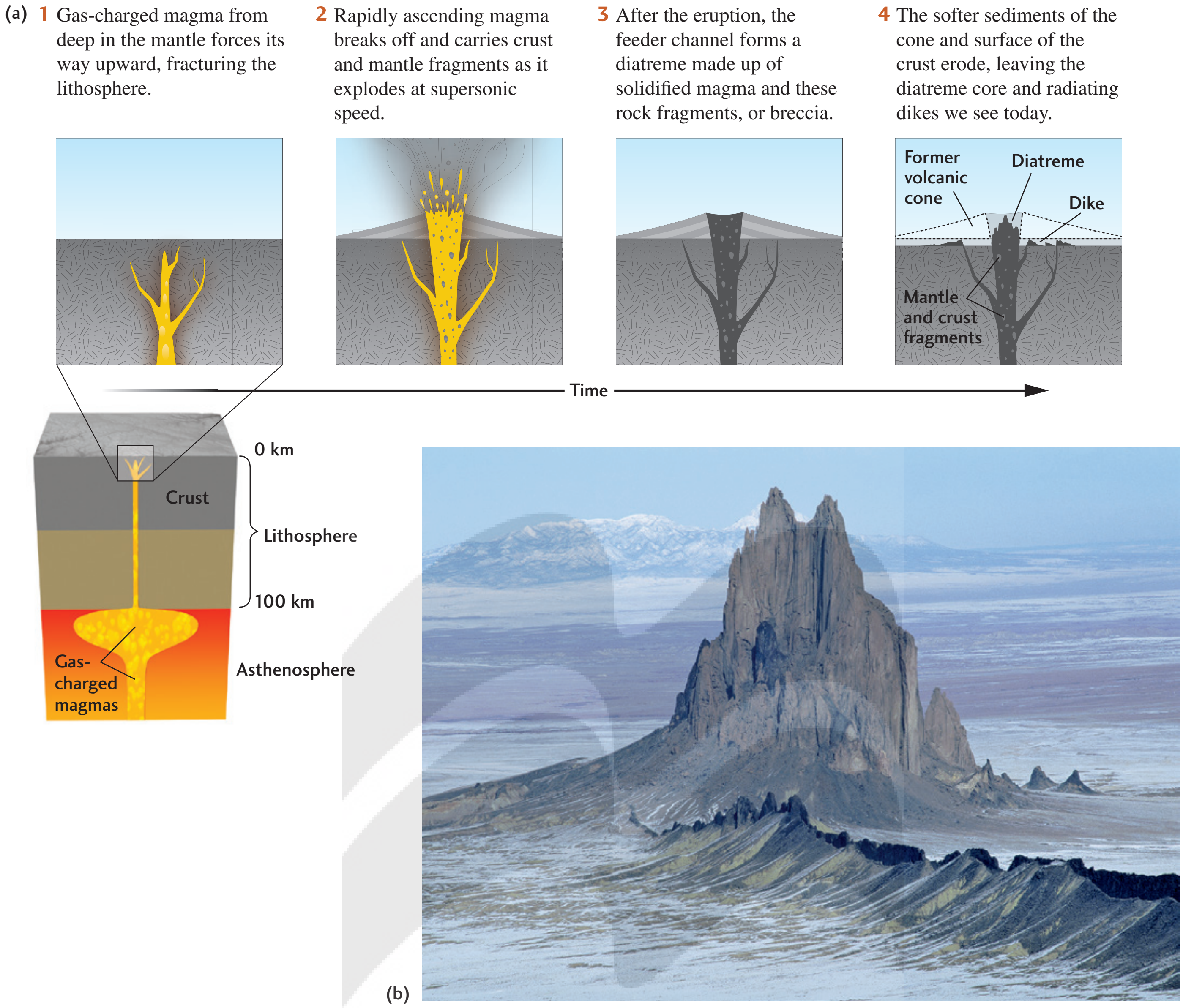


FIGURE 5.16 (a) The formation of a diatreme. (b) Shiprock, towering 515 m above the surrounding flat-lying sediments of New Mexico, is a diatreme that has been exposed by erosion of the softer sedimentary rocks that once enclosed it. Note the vertical dike, one of six radiating from the central vent. [Airphoto—Jim Wark.]

upper mantle. Gas-charged magmas force their way upward from these depths by fracturing the lithosphere and exploding into the atmosphere, ejecting gases and solid fragments torn from the deep crust and mantle, sometimes at supersonic speed. Such an eruption would probably look like the exhaust jet of a giant rocket upside down in the ground blowing rocks and gases into the air.

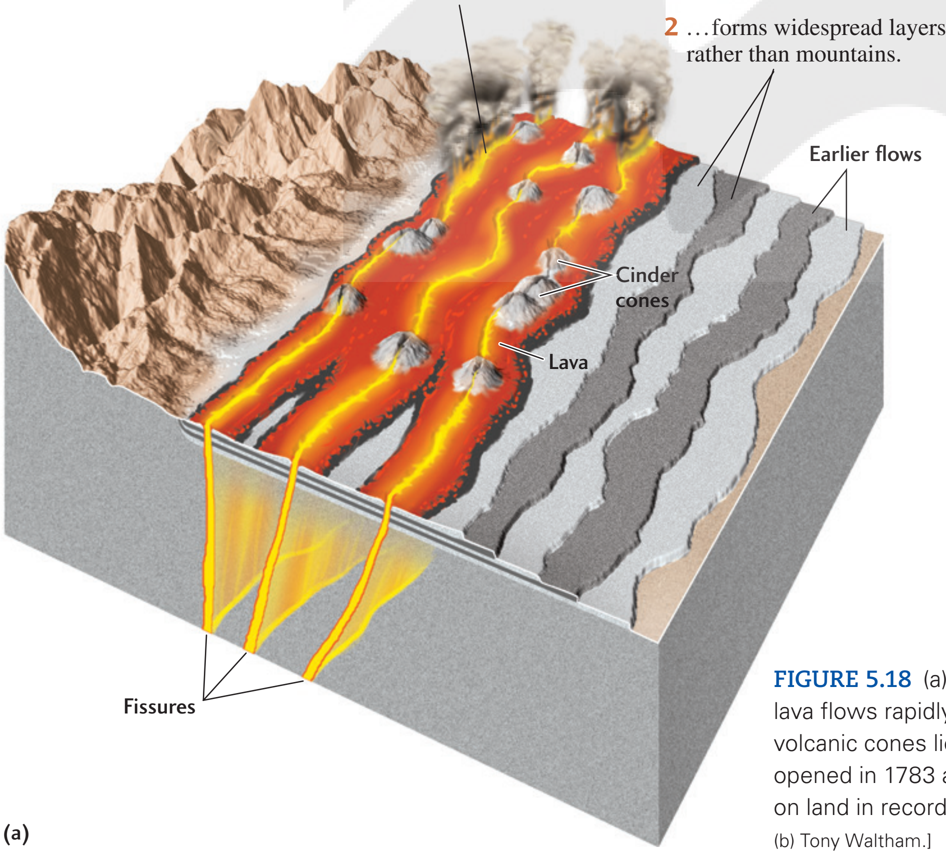
Perhaps the most exotic diatremes are *kimberlite pipes,* named after the fabled Kimberley diamond mines of South Africa. Kimberlite is a volcanic type of peridotite—an ultramafic rock composed primarily of olivine. Kimberlite pipes also contain a variety of mantle fragments, including diamonds that were pulled into the magma as it exploded toward the surface (see Figure 21.25). The extremely high pressures needed to squeeze carbon into the mineral diamond are reached only at depths greater than 150 km. From careful studies of diamonds and other mantle fragments found in kimberlite pipes, geologists have been able to reconstruct sections of the mantle as if they had had been able to drill down to 200 km or more. These studies provide strong support for the theory that the upper mantle is made primarily of peridotite.

Fissure Eruptions

The largest volcanic eruptions do not come from a central vent, but through large, nearly vertical cracks in Earth's

FIGURE 5.17 A fissure eruption generates a "curtain of fire" on Kilauea, Hawaii, in 1992. [USGS.]

surface, sometimes tens of kilometers long (Figure 5.17). Such **fissure eruptions** are the main style of volcanism along mid-ocean ridges, where new oceanic crust is formed. A moderate-sized fissure eruption occurred in 1783 on a segment of the Mid-Atlantic Ridge that comes ashore in Iceland (Figure 5.18). A fissure 32 km long opened and, in six months, spewed out 12 km^3 of basalt, enough to cover Manhattan to a height about halfway up the Empire State Building. The eruption also released more than 100 megatons of sulfur dioxide, creating a poisonous blue haze that



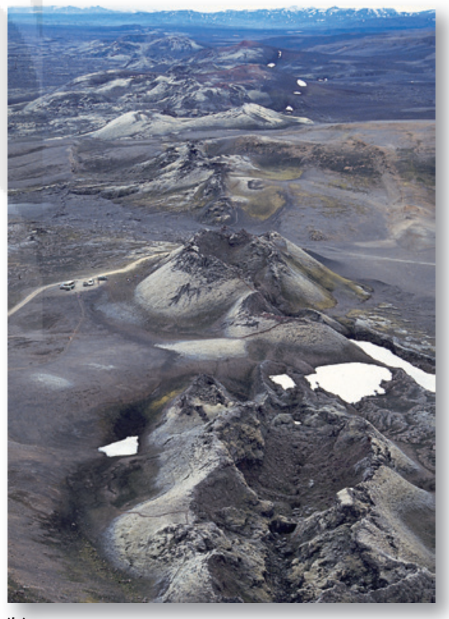


FIGURE 5.18 (a) In a fissure eruption, highly fluid basaltic lava flows rapidly away from the fissures. (b) These volcanic cones lie along the Laki fissure in Iceland, which opened in 1783 and erupted the largest flow of lava on land in recorded history. [(a) Data from R. S. Fiske/USGS; (b) Tony Waltham.]

hung over Iceland for more than a year. The resulting crop failures caused three-quarters of the island's livestock and one-fifth of its human population to die of starvation. Sulphuric aerosols from the Laki eruption were transported by the prevailing winds across Europe, causing crop damage and respiratory illnesses in many countries.

Flood Basalts Highly fluid basaltic lavas erupting from fissures on continents can spread out in sheets over flat terrain. Successive flows often pile up into immense basalt plateaus, called **flood basalts,** rather than forming a shield volcano as they do when the eruption is confined to a central vent. In North America, a huge eruption of flood basalts about 16 million years ago buried 160,000 km^2 of preexisting topography in what is now Washington, Oregon, and Idaho to form the Columbia Plateau (Figure 5.19). Individual flows were more than 100 m thick and some were so fluid that they traveled more than 500 km from their source. An entirely new landscape with new river valleys has since developed atop the lava that buried the old surface. Plateaus formed by flood basalts are found on every continent as well as on the seafloor.

Ash-Flow Deposits Eruptions of pyroclasts on continents have produced extensive sheets of hard volcanic tuffs called **ash-flow deposits.** A succession of forests in Yellowstone National Park has been buried under such ash flows. Some of the largest pyroclastic deposits on the planet are the ash flows that erupted in the mid-Cenozoic era, 45 million to 30 million years ago, through fissures in what is now the Basin and Range province of the western United States. The amount of material released during this pyroclastic flare-up was a staggering 500,000 km^3—enough to cover the entire state of Nevada with a layer of rock nearly 2 km thick! Humans have never witnessed one of these spectacular events.

Interactions of Volcanoes with Other Geosystems

Volcanoes are chemical factories that produce gases as well as solid materials. Courageous volcanologists have collected volcanic gases during eruptions and analyzed them to determine their composition. Water vapor is the main constituent of volcanic gases (70 to 95 percent), followed by carbon dioxide, sulfur dioxide, and traces of nitrogen, hydrogen, carbon monoxide, sulfur, and chlorine. Volcanic eruptions can release enormous amounts of these gases. Some volcanic gases may come from deep within Earth, making their way to the surface for the first time. Some may be recycled groundwater and ocean water, recycled atmospheric gases, or gases that were trapped in earlier generations of rocks.

As we have seen, volcanic gases released at Earth's surface have a number of effects on other geosystems.

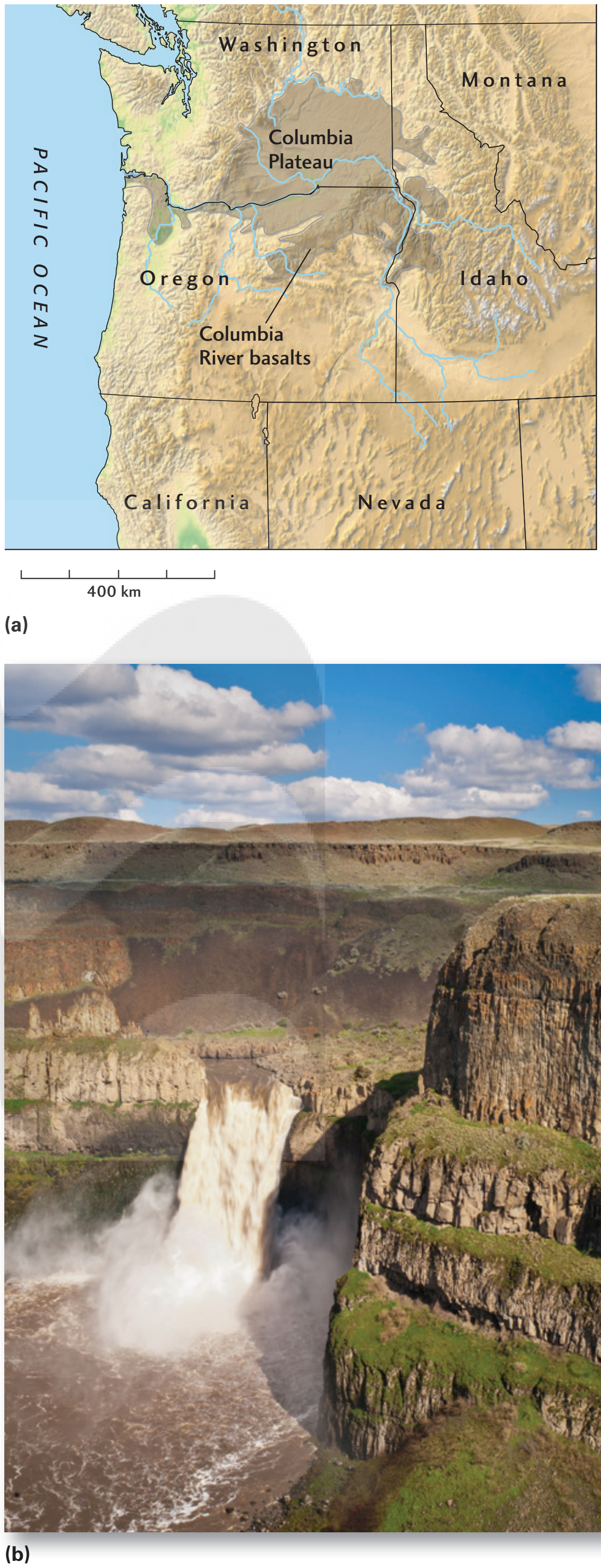


FIGURE 5.19 (a) The Columbia Plateau covers 160,000 km^2 in Washington, Oregon, and Idaho. (b) Successive flows of flood basalts piled up to build this immense plateau, here cut by the Palouse River. [© Charles Bolin/Alamy.]

The emission of volcanic gases during Earth's early history is thought to have created the oceans and the atmosphere, and volcanic gas emissions continue to influence those components of the Earth system today. Periods of intense volcanic activity have affected Earth's climate repeatedly, and they may have been responsible for some of the mass extinctions documented in the geologic record.

Volcanism and the Hydrosphere

Volcanic activity does not stop when lava or pyroclastic materials cease to flow. For decades, or even centuries after a major eruption, volcanoes continue to emit steam and other gases through small vents called *fumaroles* (**Figure 5.20**). These emanations contain dissolved materials that precipitate onto surrounding surfaces as the water evaporates or cools, forming various encrusting deposits. Some of these precipitates contain valuable minerals.

Fumaroles are a surface manifestation of **hydrothermal activity:** the circulation of water through hot volcanic rocks and magmas. Circulating groundwater that comes into contact with buried magma (which may remain hot for hundreds of thousands of years) is heated and returned to the surface as hot springs and geysers. A *geyser* is a hot-water fountain that spouts intermittently with great force, frequently accompanied by a thunderous roar. The best-known geyser in the United States is Old Faithful in Yellowstone National Park, which erupts about every 65 or 90 minutes, sending a jet of hot water as high as 60 m into the air (**Figure 5.21**). We'll take a closer look at the mechanisms that drive hot springs and geysers in Chapter 17.

Hydrothermal activity is especially intense in the spreading centers at mid-ocean ridges, where huge volumes of water and magma come into contact. Fissures created by tensional forces allow seawater to circulate throughout the newly formed oceanic crust. Heat from the hot volcanic rocks and deeper magmas drives a vigorous convection current that pulls cold seawater into the crust, heats it, and expels the hot water back into the overlying ocean through vents on the rift valley floor (**Figure 5.22**).

FIGURE 5.21 Old Faithful geyser, in Yellowstone National Park, erupts regularly about every 65 or 90 minutes. [SPL/Science Source.]

FIGURE 5.20 A fumarole encrusted with sulfur deposits on the Merapi volcano in Indonesia. [R. L. Christiansen/USGS.]

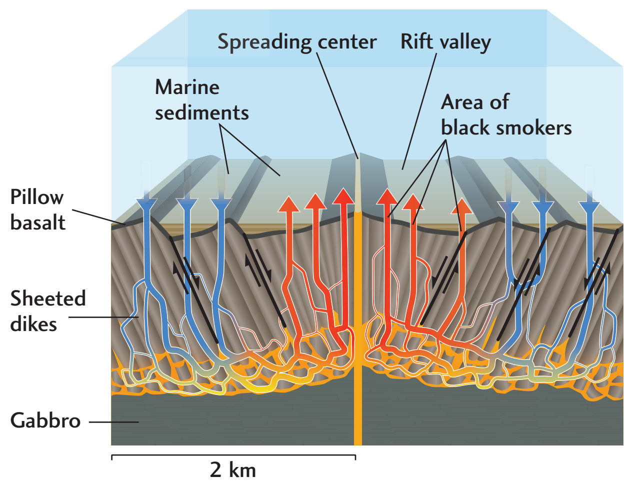


FIGURE 5.22 Near spreading centers, seawater circulates through the oceanic crust, is heated by magma, and is reinjected into the ocean, forming black smokers and depositing minerals on the seafloor.

Given the common occurrence of hot springs and geysers in volcanic geosystems on land, the evidence for pervasive hydrothermal activity at spreading centers immersed in deep water should come as no surprise. Nevertheless, geologists were amazed once they recognized the intensity of the convection and discovered some of its chemical and biological consequences. The most spectacular manifestations of this process were first found in the eastern Pacific Ocean in 1977. Plumes of hot, mineral-laden water with temperatures as high as 350°C were seen spouting through hydrothermal vents at the crest of the East Pacific Rise (see Chapter 22). The rates of fluid flow turned out to be very high. Marine geologists have estimated that the entire volume of the ocean's water is circulated through the cracks and vents of Earth's spreading centers in only 10 million years.

Scientists have come to realize that the interactions between the lithosphere and the hydrosphere at spreading centers profoundly affect the geology, chemistry, and biology of the oceans in a number of ways:

- The creation of new lithosphere accounts for almost 60 percent of the energy flowing out of Earth's interior. Circulating seawater cools the new lithosphere very efficiently and therefore plays a major role in the outward transport of Earth's internal heat.
- Hydrothermal activity leaches metals and other elements from the new crust, injecting them into the oceans. These elements contribute as much to seawater chemistry as the mineral components dumped into the oceans by all the world's rivers.
- Metal-rich minerals precipitate out of the circulating seawater and form ores of zinc, copper, and iron in shallow parts of the oceanic crust. These ores form when seawater sinks through porous volcanic rocks, is heated, and leaches these elements from the new crust. When the heated seawater, enriched with dissolved minerals, rises and reenters the cold ocean, the ore-forming minerals precipitate.

The energy and nutrients at hydrothermal vents feed unusual colonies of strange organisms whose energy comes from Earth's interior rather than from sunlight. Chemoautotrophic hyperthermophiles, similar to those that populate hot springs on land, form the base of complex ecosystems, providing food for giant clams and tube worms up to several meters long. Some scientists have speculated that life on Earth may have begun in the energetic, chemically rich environments of hydrothermal vents (see Chapter 22).

Volcanism and the Atmosphere

Volcanism in the lithosphere affects weather and climate by changing the composition and properties of the atmosphere. Large eruptions can inject sulfurous gases into the atmosphere tens of kilometers above Earth (Figure 5.23). Through various chemical reactions, these gases form an aerosol (a fine airborne mist) containing tens of millions of

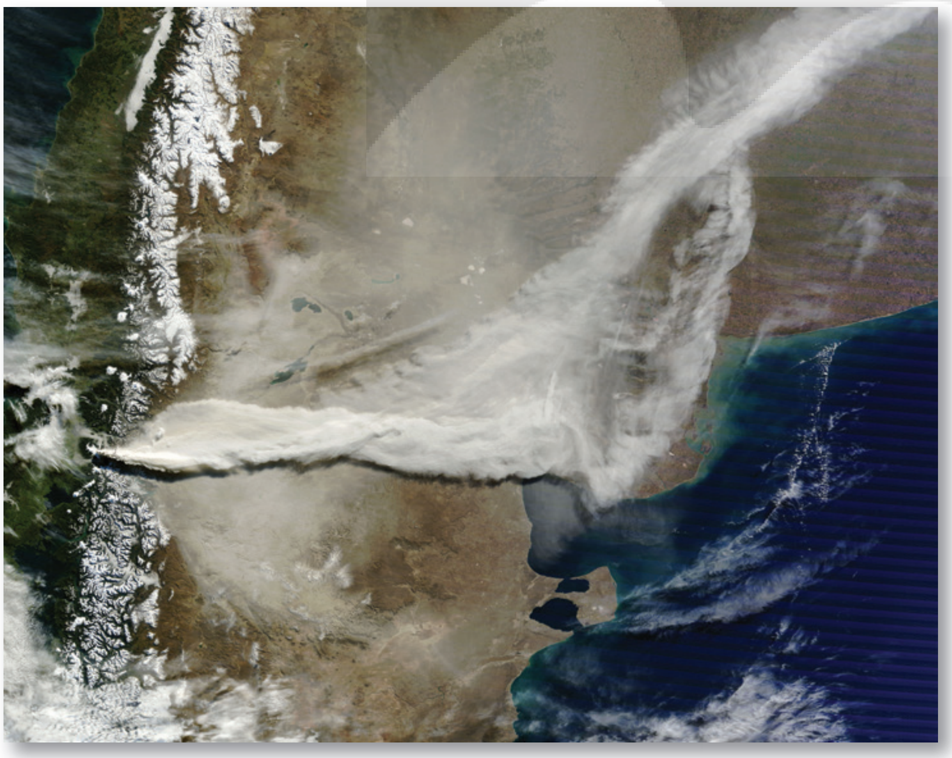


FIGURE 5.23 Satellite image of the huge ash cloud spewing from the erupting Cordón Caulle volcano in central Chile on June 13, 2011. The ash plume extends 800 km from the snow-covered Andes mountains (on left side of photo) to the Argentine city of Buenos Aires (center right of photo). This ash cloud encircled the planet, closing airports in Australia and New Zealand. [NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC.]

metric tons of sulfuric acid. Such aerosols may block enough of the Sun's radiation from reaching Earth's surface to lower global temperatures for a year or two. The eruption of Mount Pinatubo, one of the largest explosive eruptions of the twentieth century, led to a global cooling of at least 0.5°C in 1992. (Chlorine emissions from Mount Pinatubo also hastened the loss of ozone in the atmosphere, nature's shield that protects the biosphere from the Sun's ultraviolet radiation.)

The debris lofted into the atmosphere during the 1815 eruption of Mount Tambora in Indonesia resulted in even greater cooling. The next year, the Northern Hemisphere suffered a very cold summer; according to a diarist in Vermont, "no month passed without a frost, nor one without a snow." The drop in temperature and the ash fall caused widespread crop failures. More than 90,000 people perished in that "year without a summer," which inspired Lord Byron's gloomy poem, "Darkness":

I had a dream, which was not all a dream.
The bright sun was extinguish'd, and the stars
Did wander darkling in the eternal space,
Rayless, and pathless, and the icy earth
Swung blind and blackening in the moonless air;
Morn came and went—and came, and brought no day.
And men forgot their passions in the dread
Of this their desolation; and all hearts
Were chill'd into a selfish prayer for light.

The Global Pattern of Volcanism

Before the advent of plate tectonic theory, geologists noted a concentration of volcanoes around the rim of the Pacific Ocean and nicknamed it the Ring of Fire (see Figure 2.6). The explanation of the Ring of Fire in terms of subduction zones was one of the great successes of the new theory. As we will see in this section, plate tectonics can explain essentially all major features in the global pattern of volcanism (**Figure 5.24**).

Figure 5.25 shows the locations of the world's active volcanoes that occur on land or above the ocean surface. About 80 percent are found at convergent plate boundaries, 15 percent at divergent plate boundaries, and the remaining few within plate interiors. There are many more active volcanoes than shown on this map, however. Most of the lava erupted on Earth's surface comes from vents beneath the oceans, located at spreading centers on mid-ocean ridges.

Volcanism at Spreading Centers

As we have seen, enormous volumes of basaltic lava erupt continually along the global network of mid-ocean ridges—enough to have created all of the present-day seafloor. This "crustal factory" lies beneath a rift valley a few kilometers

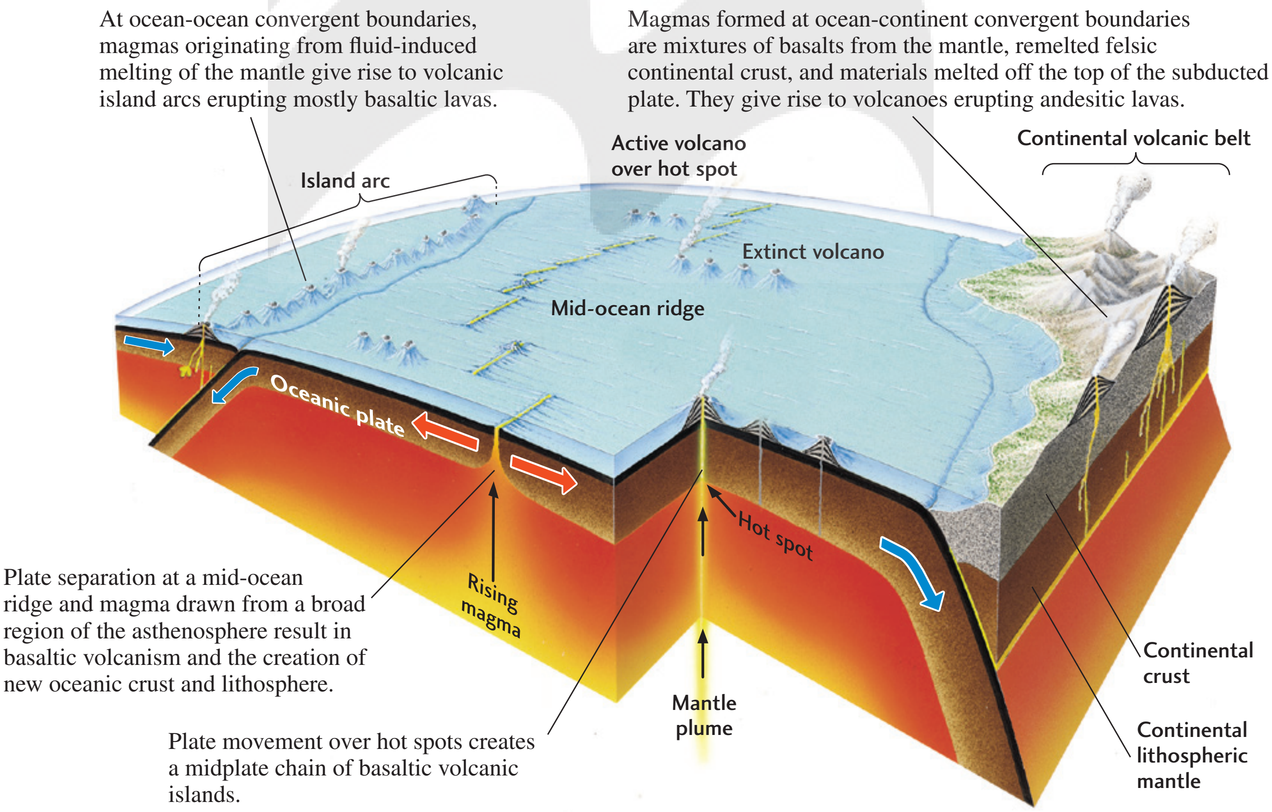


FIGURE 5.24 Plate tectonic processes explain the global pattern of volcanism.

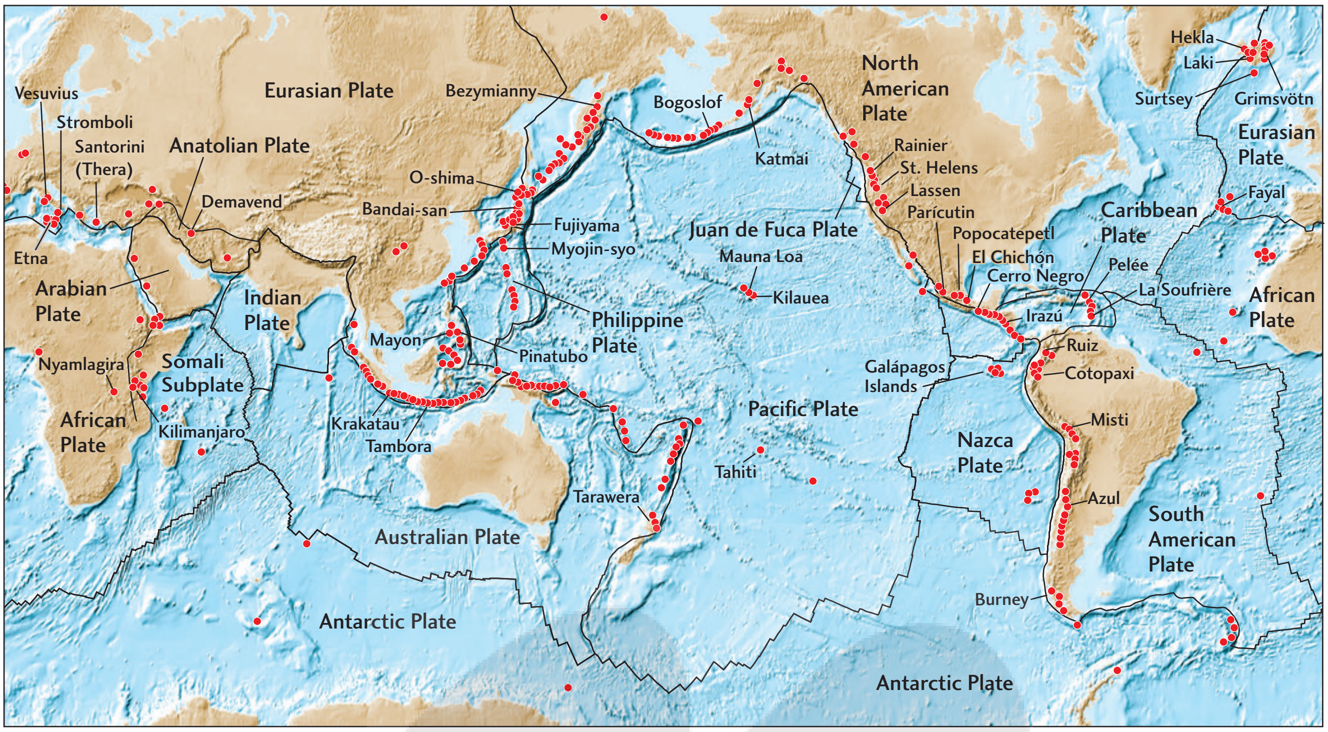


FIGURE 5.25 The active volcanoes of the world with vents on land or above the ocean surface are represented on this map by red dots. Black lines represent plate boundaries. Not shown on this map are the numerous vents of the mid-ocean ridge system below the ocean surface.

wide, and it extends along the thousands of kilometers of mid-ocean ridges (see Figure 5.24). The erupted magma is formed by decompression melting of mantle peridotite, as described in Chapter 4.

Divergent boundaries comprise segments of a mid-ocean ridge offset in a zigzag pattern by transform faults (see Figure 2.7). Detailed geologic mapping of the seafloor has revealed that the ridge segments can themselves be quite complex. They are often composed of shorter, parallel spreading centers that are offset by a few kilometers and may partly overlap. Each of these spreading centers is an "axial volcano" that erupts basaltic lava at variable rates along its length. Basalts from nearby axial volcanoes often show slight geochemical differences, indicating that the axial volcanoes have separate plumbing systems.

In Iceland, the Mid-Atlantic Ridge rises above the ocean and large basaltic eruptions are common. The most recent major eruption, from a volcano beneath the Eyjafjallajökull ice cap on the southern coast of Iceland in 2010, ejected massive amounts of very fine-grained ash high into the atmosphere, which disrupted air traffic across western Europe for many weeks (see Earth Issues 5.1).

Volcanism in Subduction Zones

One of the most striking features of a subduction zone is the chain of volcanic mountains that parallels the convergent boundary above the sinking slab of oceanic lithosphere, regardless of whether the overriding lithosphere is oceanic or continental (see Figure 5.24). The magmas that feed subduction-zone volcanoes are produced by fluid-induced melting (see Chapter 4) and are more varied in their chemical composition than the basaltic magmas produced at mid-ocean ridges. They range from mafic to felsic—that is, from basaltic to rhyolitic—although intermediate (andesitic) compositions are the most common observed on land.

Where the overriding lithosphere is oceanic, subduction-zone volcanoes form volcanic island arcs, such as the Aleutian Islands of Alaska and the Mariana Islands of the western Pacific. Where oceanic lithosphere is subducted beneath a continent, the volcanoes and volcanic rocks coalesce to form a volcanic mountain belt on land, such as the Andes, which mark the subduction of the oceanic Nazca Plate beneath continental South America.

Recently, Indonesia's Mount Sinabung volcano has been very active, with major eruptions in 2010, 2013, and 2018. A phase of continuous eruption started in 2013 and has extended all the way through to 2018, culminating in the largest explosion to date in February 2018. Curiously, that largest explosion occurred during a period of time when eruption frequency was declining (Figure 5.26), yet it was the most powerful and actually blew the top off the volcano.

The terrain of Japan is a prime example of the complex of intrusive and extrusive igneous rock that may evolve over many millions of years at a subduction zone. Everywhere in this small country are all kinds of extrusive igneous rocks of various ages, mixed in with mafic and intermediate intrusives,

Earth Issues 5.1 Volcanic Ash Clouds over Europe

On April 14, 2010, the Eyjafjallajökull volcano in Iceland began a series of eruptions that shut down air travel over western and northern Europe for a period of six days. [According to the joke, "Eyjafjallajökull" is Icelandic for "name that no one can pronounce." Actually, it's pronounced: aye-ya-fyah-dla-jow-kudl and means "island-mountain glacier."] These eruptions led to the closure of most of Europe's larger airports and caused the cancellation of many flights to and from Europe, resulting in the highest level of air traffic disruption since World War II. Many people were stranded for days with little comfort as flights were sequentially canceled, leaving people to struggle to find alternative means of transportation or accommodations. In the week following the eruption, it is estimated that 250,000 British, French, and Irish citizens were stranded abroad, the European economy may have lost almost 2 billion dollars, and the aviation industry lost up to 250 million dollars per day.

The eruptions were predicted well in advance. Seismic activity in and around Eyjafjallajökull began in late 2009 and increased in intensity and frequency until March 20, 2010, when a small eruption occurred. A second, much larger eruption occurred on April 14th, ejecting 250 million cubic meters of volcanic ash. The ash cloud rose to elevations of 9000 meters and, though not as large as the 1980 Mount St. Helens eruption in Oregon, it was high enough to enter the jet stream, which flowed directly over Iceland at the time. The eastward flow of the jet stream transported the ash to Europe, where it spread out over a large part of the continent.

Much of this volcanic ash was produced by the interaction of hot magma with glacial ice and water,

In this April 16, 2010, photo, the Eyjafjallajökull volcano in southern Iceland sends ash into the air just prior to sunset. [AP Photo/Brynjar Gauti.]

which made it very fine-grained, less than 2 mm in size. When ash of this size gets caught up in jet engines, the high temperatures of the jet (up to 2000°C) can remelt it, re-creating a sticky lava that can cause engine failure. In extreme cases, planes have had to literally glide their way out of the ash cloud before engines can be restarted.

The Eyjafjallajökull eruptions lasted for only one month; by June 2010, very little ash was being ejected. But future eruptions in Iceland are inevitable, and the agricultural and environmental consequences for Europe are potentially dire. Right now, geologists are carefully monitoring the nearby Katla volcano, whose historical eruptions have often followed those of Eyjafjallajökull.

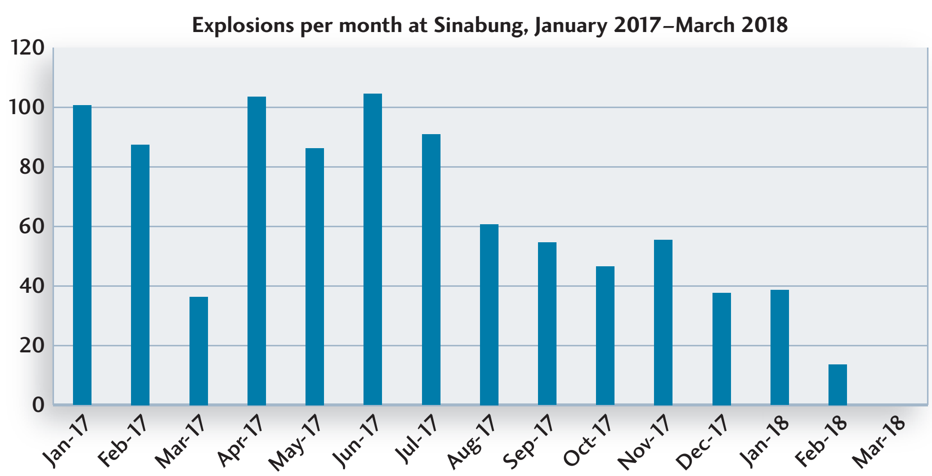


FIGURE 5.26 This graph shows the number of explosions per month at Sinabung reported from January 2017 to March 2018. Only partial data was reported for January 18 to 31 and no explosions were reported during March 2018. [Data from the Center for Volcanology and Geological Disaster Mitigation (PVMBG).]

metamorphosed volcanic rocks, and sedimentary rocks derived from erosion of the igneous rocks. The erosion of these various rocks has contributed to the distinctive landscapes portrayed in so many classic and modern Japanese paintings.

Intraplate Volcanism: The Mantle Plume Hypothesis

Decompression melting explains volcanism at spreading centers, and fluid-induced melting can account for the volcanism above subduction zones, but how can plate tectonic theory explain *intraplate volcanism*—that is, volcanoes far from plate boundaries? Geologists have found a clue in the ages of such volcanoes.

Hot Spots and Mantle Plumes Consider the Hawaiian Islands, which stretch across the middle of the Pacific Plate. This island chain begins with the active volcanoes on the island of Hawaii and continues to the northwest as a string of progressively older, extinct, eroded, and submerged volcanic mountains and ridges. In contrast to the seismically active mid-ocean ridges, the Hawaiian island chain is not marked by frequent large earthquakes (except near the active volcanoes). It is essentially aseismic (without earthquakes), and is therefore called an *aseismic ridge.* Active volcanoes at the beginnings of progressively older aseismic ridges can be found elsewhere in the Pacific and in other large ocean basins. Two examples are the active volcanoes of Tahiti, at the southeastern end of the Society

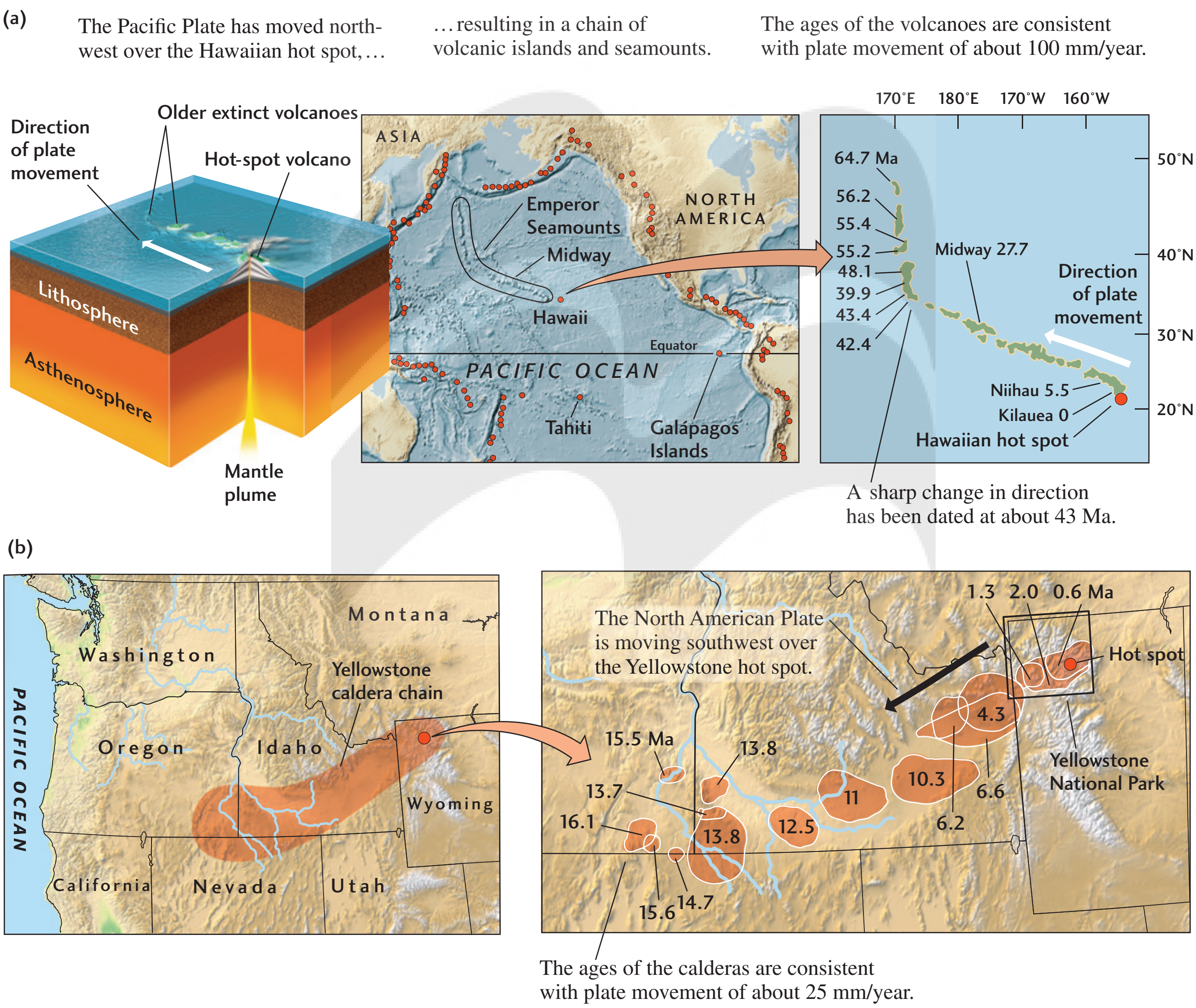


FIGURE 5.27 The movement of a plate over a hot spot generates a trail of progressively older volcanoes. (a) The volcanoes of the Hawaiian island chain and its extension into the northwestern Pacific (the Emperor seamounts) show a northwestward trend toward progressively older ages. (b) A chain of progressively older calderas marks the movement of the North American Plate over a continental hot spot during the past 16 million years. (Ma, million years ago.) [Data from Wheeling Jesuit University/NASA Classroom of the Future.]

Islands, and the Galápagos Islands, at the western end of the aseismic Nazca Ridge (see Figure 5.25).

Once the general pattern of plate movements had been worked out, geologists were able to show that these aseismic ridges approximated the paths that the plates would take over a set of volcanically active **hot spots** that were fixed relative to one another, as if they were blowtorches anchored in Earth's mantle (**Figure 5.27**). Based on this evidence, they hypothesized that hot spots were caused by hot, solid material rising in narrow, cylindrical jets from deep within the mantle (perhaps as deep as the core-mantle boundary), called **mantle plumes.** According to the mantle plume hypothesis, when peridotites transported upward in a mantle plume reach lower pressures at shallower depths, they begin to melt, producing basaltic magma. The magma penetrates the lithosphere and erupts at the surface. The current position of a plate over the hot spot is marked by an active volcano, which becomes inactive as plate movement carries it away from the hot spot. The movement of the plate thus generates a trail of extinct, progressively older volcanoes. As shown in Figure 5.27a, the Hawaiian Islands fit this pattern well. Dating of the volcanoes yields a rate of movement of the Pacific Plate over the Hawaiian hot spot of about 100 mm/year.

Some aspects of intraplate volcanism within continents can also been explained by the mantle plume hypothesis. The modern Yellowstone Caldera, only 630,000 years old, is still volcanically active, as evidenced by the geysers, hot springs, uplift, and earthquakes observed in the area. It is the youngest member of a chain of sequentially older and now-extinct calderas that supposedly mark the movement of the North American Plate over the Yellowstone hot spot (Figure 5.27b). The oldest member of the chain, a volcanic area in Oregon, erupted about 16 million years ago, producing some of the flood basalts of the Columbia Plateau. The North American Plate has moved over the Yellowstone hot spot to the southwest at a rate of about 25 mm/year during the past 16 million years. Accounting for the relative movement of the Pacific and North American plates, this rate and direction are consistent with the plate movements inferred from the Hawaiian Islands.

2018 Eruption of Kilauea Volcano, Hawaii

The 2018 eruption of the Kilauea volcano, on the island of Hawaii, is a reminder of the ongoing and nearly constant impact of mid-plate volcanism. The current phase of eruption began on May 3, 2018, and has continued through at least August of 2018 (**Figure 5.28**). Lava has been pouring through fissures associated with the volcano's East Rift Zone in Puna (**Figure 5.29**). The eruption closely coincided with a magnitude 6.9 earthquake and opening of dozens of fissures through which lava poured, causing the evacuation of approximately 2000 residents. By August of 2018, almost 15 square miles have been covered by fresh lava, destroying over 700 homes and a major geothermal energy facility that created about 25 percent of the island's electricity. This eruption is the most destructive in the United States since the eruption of Mount St. Helens in 1980.

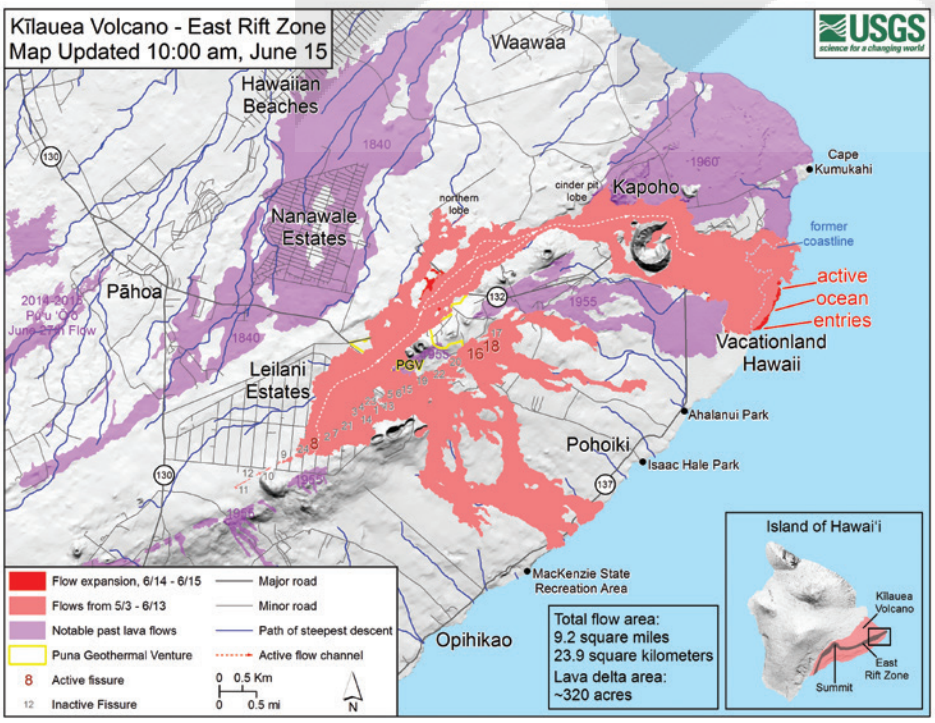


FIGURE 5.28 The 2018 eruption of the Kilauea volcano, on the island of Hawaii, is an example of mid-plate volcanism. The current phase of eruption began on May 3, 2018, and has continued through at least August of 2018. [USGS.]

FIGURE 5.29 Lava. This photo taken on March 6, 2011, shows lava pouring through fissures associated with the Kilauea volcano's East Rift Zone in Puna. [USGS.]

Measuring Plate Movements Using Hot-Spot Tracks Assuming that hot spots are anchored by plumes rising from the deep mantle, geologists can use the worldwide distribution of their volcanic tracks to compute how the global system of plates is moving with respect to the deep mantle. The results are sometimes called "absolute plate movements" to distinguish them from the movements of plates relative to each other. The absolute plate movements calculated from hot-spot tracks have helped geologists understand the forces driving the plates. Plates that are being subducted along large fractions of their boundaries—such as the Pacific, Nazca, Cocos, Indian, and Australian plates—are moving rapidly with respect to the hot spots, whereas plates without much subducting slab—such as the Eurasian and African plates—are moving slowly. This observation supports the hypothesis that the gravitational pull of the dense sinking slabs is an important force driving plate movements (see Chapter 2).

The use of hot-spot tracks to reconstruct absolute plate movements works fairly well for recent plate movements. Over longer periods, however, a number of problems arise. For instance, according to the fixed-hot-spot hypothesis, the sharp bend in the Hawaiian aseismic ridge (where it becomes the north-trending Emperor seamount chain; see Figure 5.27a), dated at about 43 million years ago, should coincide with an abrupt shift in the direction of the Pacific Plate. However, no sign of such a shift is evident in magnetic isochron maps, leading some geologists to question the fixed-hot-spot hypothesis. Others have pointed out that, in a convecting mantle, plumes would not necessarily remain fixed relative to one another, but might be moved about by shifting convection currents.

Large Igneous Provinces The origin of fissure eruptions on continents—such as those that formed the Columbia Plateau and even larger basalt plateaus in Brazil and Paraguay, India, and Siberia—is a major puzzle. The geologic record shows that these eruptions can release immense amounts of lava—up to several million cubic kilometers—in a period as short as a million years.

Flood basalts are not limited to continents; they also create large oceanic plateaus, such as the Ontong Java Plateau on the northern side of the island of New Guinea and major parts of the Kerguelen Plateau in the southern Indian Ocean. These features are all examples of what geologists call **large igneous provinces** (LIPs) (Figure 5.30). LIPs are large volumes of predominantly mafic extrusive and intrusive igneous rock whose origins lie in processes other than normal seafloor spreading. LIPs include continental flood basalts and associated intrusive rocks, oceanic basalt plateaus, and the aseismic ridges produced by hot spots.

The fissure eruption that covered much of Siberia with basaltic lava is of special interest to geobiologists because it happened at the same time as the greatest mass extinction in the geologic record, which occurred at the end of the Permian period, about 251 million years ago (see Chapter 22). Some geologists think that the eruption caused the mass extinction, perhaps by polluting the atmosphere with volcanic gases that triggered major climate changes (see the Practicing Geology Exercise).

Many geologists believe that almost all LIPs were created at hot spots by mantle plumes. However, the amount of lava erupting from the most active hot spot on Earth

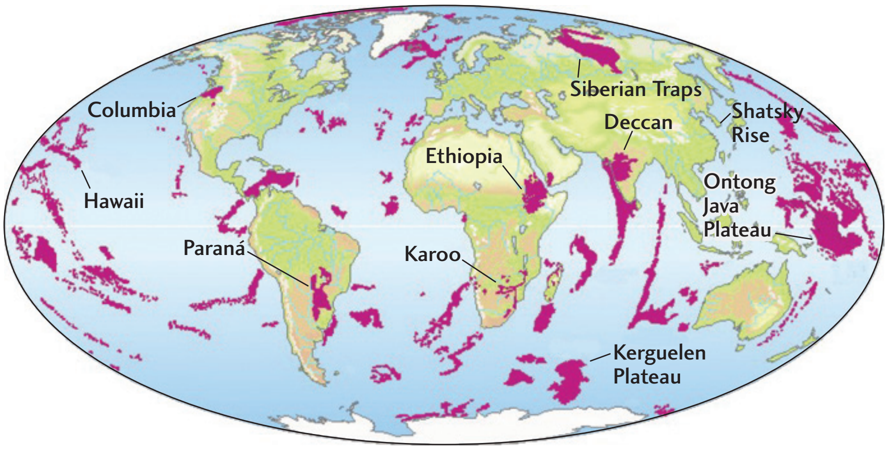


FIGURE 5.30 The global distribution of large igneous provinces on continents and in ocean basins. These provinces are marked by unusually large deposits of basaltic magma. [Data from M. Coffin and O. Eldholm, *Reviews of Geophysics, 32* (1994): 1–36, Figure 1.]

today, Hawaii, is paltry compared with the enormous outpourings of fissure eruptions. What explains these unusual bursts of basaltic magma from the mantle? Some geologists speculate that they result when a new plume rises from the core-mantle boundary. According to this hypothesis, a large, turbulent blob of hot material—a "plume head"—leads the way. When this plume head reaches the top of the mantle, it generates a huge quantity of magma by decompression melting, which erupts in massive flood basalts (Figure 5.31). Others dispute this hypothesis, pointing out that continental flood basalts often seem to be associated with preexisting zones of weakness in the continental crust and suggesting that the magmas are generated by convective processes localized in the upper mantle. Sorting out the origins of LIPs is one of the most exciting areas of current geologic research.

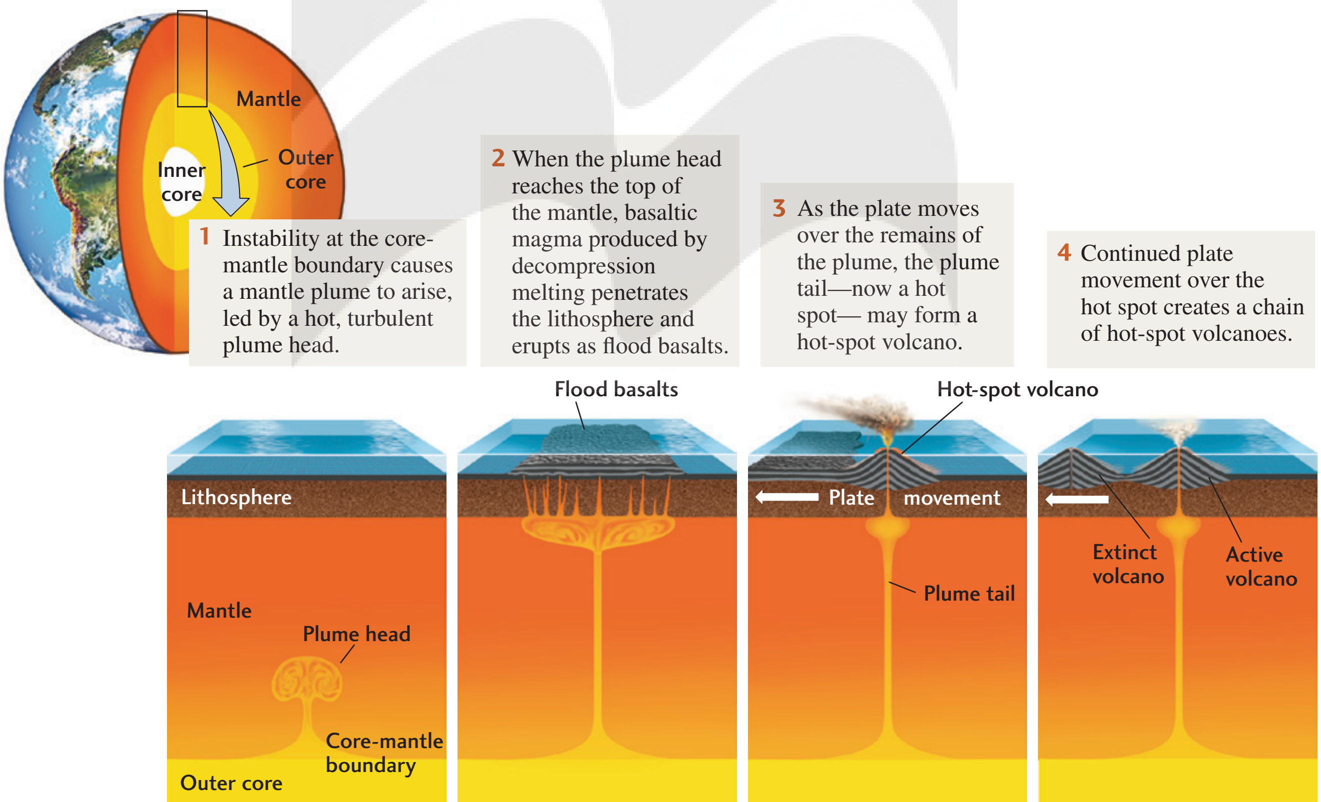
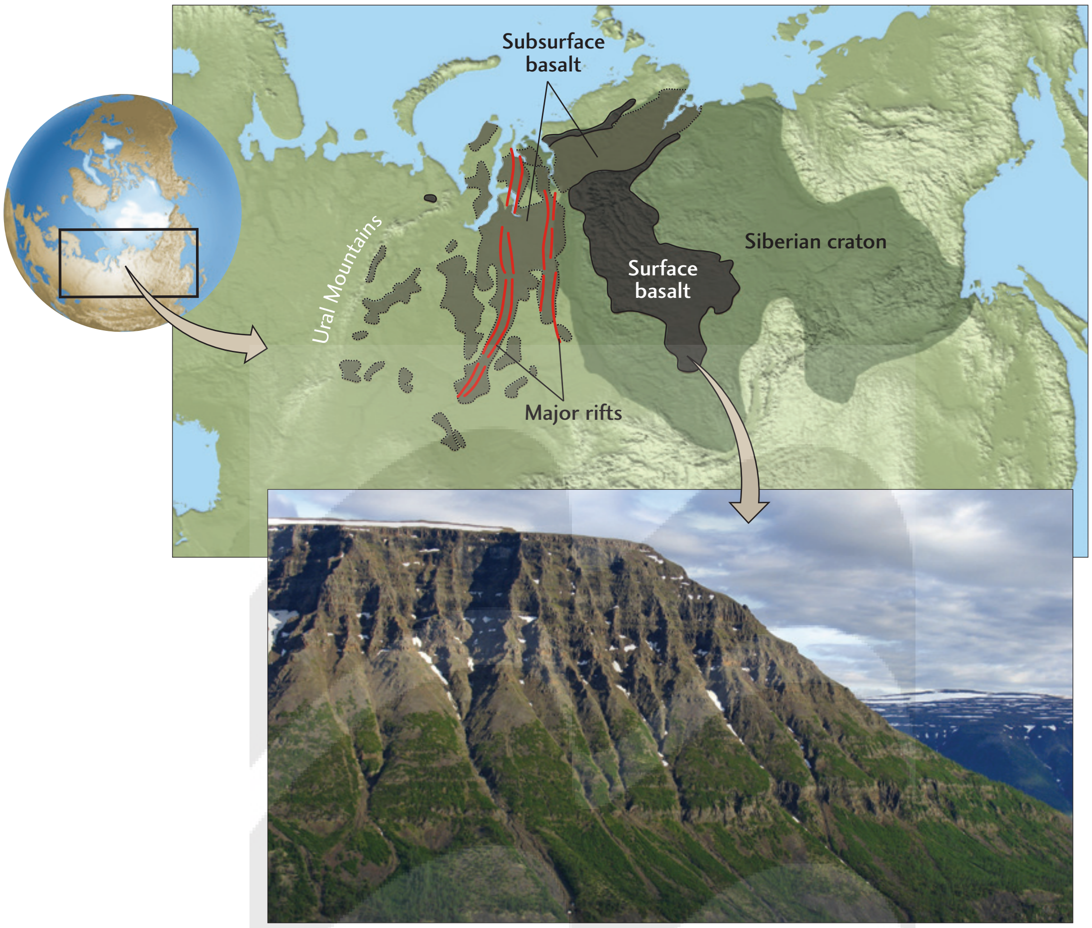


FIGURE 5.31 A speculative model for the formation of flood basalts and other large igneous provinces. A new mantle plume rises from the core-mantle boundary, led by a hot, turbulent plume head. When the plume head reaches the top of the mantle, it flattens, generating a huge volume of basaltic magma, which erupts as flood basalts.

PRACTICING GEOLOGY EXERCISE

Are the Siberian Traps a Smoking Gun of Mass Extinction?



The Siberian Traps are flood basalts that cover an area almost twice the size of Alaska. The basalts exposed on the Siberian craton reach thicknesses of more than 6 km and have been heavily eroded since their eruption 251 million years ago. A vast area of these flood basalts is now buried beneath the sediments of the Siberian platform. [Sergey Anatolievich Pristyazhnyuk/123RF.com.]

The mass extinction at the end of the Permian period, dated at 251 million years ago, marks the transition from the Paleozoic era to the Mesozoic era (see Chapter 9). The flood basalts of Siberia—the product of the largest continental volcanic eruption in the Phanerozoic eon—have also been dated at 251 million years ago. Is this

Volcanism and Human Affairs

Large volcanic eruptions are not just of academic interest to geologists. More than 600 million people live close enough to active volcanoes to be directly affected by eruptions. A repeat of the largest eruptions observed in the geologic record could disrupt or even destroy civilization itself. We must understand volcanic hazards to reduce the risks they pose. But in a world of growing human consumption, we also need to understand and appreciate the benefits volcanism provides to society in the form of mineral resources, fertile soils, and thermal energy.

just a coincidence, or was the eruption of the flood basalts responsible for the end-Permian mass extinction?

Let's first consider the size and rate of the Siberian eruption. Geologic mapping of these flood basalts, called the Siberian Traps, shows that they once extended across much of the Siberian platform and craton, covering an area exceeding 4 million square kilometers. Although much has been eroded away or buried beneath younger sediments, the total volume of the basalts must have originally exceeded 2 million cubic kilometers and may have been as much as 4 million cubic kilometers. Isotopic dating indicates that the basalts were extruded over a period of about 1 million years, implying an average eruption rate of 2 to 4 km^3/year.

To appreciate how large this rate really is, we can compare it with the volcanism at rapidly diverging plate boundaries. Enough basalt is extruded along mid-ocean ridges to form the entire oceanic crust, so the production rate of seafloor spreading is given by the formula

$$\text{production rate} = \text{spreading rate} \times \text{crustal thickness} \times \text{ridge length}$$

The fastest spreading we see today is along the East Pacific Rise near the equator, where the Pacific Plate is separating from the Nazca Plate at an average rate of about 140 mm/year, or 1.4×10^{-4} km/year (see Figure 2.7), creating a basaltic crust with an average thickness of 7 km. The length of the Pacific-Nazca Plate boundary is about 3600 km, so the production rate along this spreading center is

$$1.4 \times 10^{-4}\ \text{km/year} \times 7\ \text{km} \times 3600\ \text{km} = 3.5\ \text{km}^3/\text{year}$$

From this calculation, we see that the Siberian eruption produced basalt at a rate comparable to that of the entire Pacific-Nazca Plate boundary, the largest magma factory on Earth today!

You can sail on the tropical sea surface over the Pacific-Nazca Plate boundary and be completely unaware of the magmatic activity deep beneath you. Most of the magma generated by seafloor spreading solidifies as igneous intrusions to form the basaltic dikes and massive gabbros of the oceanic crust (see Figure 4.15). The basalts that are extruded onto the seafloor are quickly quenched by seawater to produce pillow lavas, and the gases that are emitted dissolve into the ocean.

But if you were visiting Siberia about 251 million years ago, you would probably not be so comfortable. The Siberian basalts were erupted directly onto the land surface through fissures in the continental crust, flooding millions of square kilometers. This exceptionally rapid extrusion of lavas would have generated huge pyroclastic deposits—much more than typical flood basalt eruptions, such as those of the Columbia Plateau—and it would also have discharged massive amounts of ash and gases, including carbon dioxide and methane, into the atmosphere. Such an eruption could have triggered changes in Earth's climate of a magnitude that might have led to the end-Permian mass extinction, in which 95 percent of the species living at the time were completely wiped out (see Chapter 9).

Some geologists have argued for years that the end-Permian mass extinction was the result of this intense Siberian volcanism, possibly caused by the sudden arrival of a "plume head" at Earth's surface (see Figure 5.31). Others have preferred alternative hypotheses, such as a meteorite impact or a sudden release of gases from the ocean. However, recent isotopic dating with improved techniques has shown that the Siberian volcanism occurred immediately before or during the end-Permian mass extinction. The finding that these extreme events so precisely coincide has convinced many more geologists that the Siberian Traps are the "smoking gun" behind the largest killing of species in Earth history.

PROBLEM: The Big Island of Hawaii, which has a total rock volume of about 100,000 km^3, has been formed by a series of basaltic eruptions over the last 1 million years. Calculate the production rate of the Hawaiian basalts and compare it with that of the Siberian Traps. What length of the Nazca-Pacific Plate boundary produces basalt at a rate equivalent to the Hawaiian hot spot?

Volcanic Hazards

Volcanic eruptions have a prominent place in human history and mythology. The myth of the lost continent of Atlantis may have its source in the explosion of Thera, a volcanic island in the Aegean Sea (also known as Santorini). The eruption, which has been dated at 1623 B.C., formed a caldera 7 km by 10 km in diameter, visible today as a lagoon up to 500 m deep with two small active volcanoes in the center. The eruption and the tsunami that followed it destroyed dozens of coastal settlements over a large part of the eastern Mediterranean. Some scientists have attributed the mysterious demise of the Minoan civilization to this ancient catastrophe.

Of the 500 to 600 active volcanoes that rise above sea level (see Figure 5.25), at least one in six is known to have claimed human lives. So far in this century, only about 600 people have died in volcanic eruptions, more than half of them in the 2010 eruptions of Mount Merapi in Indonesia. But history teaches us that this luck will not hold over the longer term. In the past 500 years alone, more than 250,000 people have been killed by volcanic eruptions (**Figure 5.32a**). Volcanoes can kill people and damage property in many ways, some of which are listed in Figure 5.32b and depicted in **Figure 5.33**. We have already mentioned some of these hazards, including pyroclastic flows and tsunamis. Several additional volcanic hazards are of special concern.

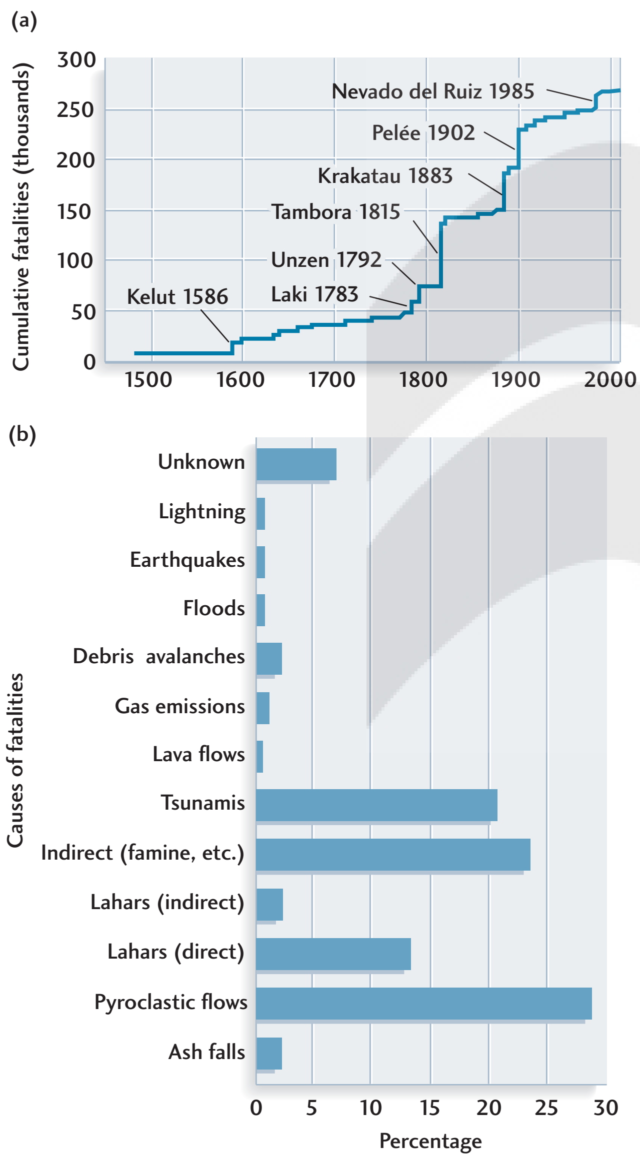


FIGURE 5.32 (a) The eight eruptions that dominate the fatality record, each of which claimed 10,000 or more victims. These eruptions account for two-thirds of the total deaths caused by volcanic eruptions. (b) Specific causes of volcano fatalities since A.D. 1500.

Lahars Among the most dangerous volcanic events are the torrential flows of wet volcanic debris called **lahars**. They can occur when a pyroclastic flow meets a river or a snowbank; when the wall of a water-filled crater breaks; when a lava flow melts glacial ice; or when heavy rainfall transforms new ash deposits into mud. One extensive layer of volcanic debris in the Sierra Nevada of California contains 8000 km^3 of material of lahar origin, enough to cover all of Delaware with a deposit more than a kilometer thick. Lahars have been known to carry huge boulders for tens of kilometers. When Nevado del Ruiz in the Colombian Andes erupted in 1985, lahars triggered by the melting of glacial ice near the summit plunged down the slopes and buried the town of Armero 50 km away, killing more than 25,000 people. In volcanic terrains beneath icecaps, a common danger is the torrential release of floodwater when magma melts large volumes of glacial ice; this very fluidized type of lahar is called a *jökulhlaup* (you-kyl-loop) in Icelandic.

Following the 1997 eruption of the Soufriere Hills volcano on Montserrat, a lahar was generated that blanketed part of the island, resulting in 19 deaths (**Figure 5.34**). Montserrat's tourist industry collapsed and it took 15 years to begin to recover.

Flank Collapse A volcanic mountain is constructed from thousands of deposits of lava or pyroclasts or both—not the best way to build a stable structure. The volcano's sides may become too steep and break or slip off. In recent years, volcanologists have discovered many prehistoric examples of catastrophic structural failures in which a big piece of a volcano broke off, perhaps because of an earthquake, and slid downhill in a massive, destructive landslide. On a worldwide basis, such *flank collapses* occur at an average rate of about four times per century. The collapse of one side of Mount St. Helens was the most damaging part of its 1980 eruption (see Figure 5.6).

Surveys of the seafloor off the Hawaiian Islands have revealed many giant landslides on the underwater flanks of the Hawaiian Ridge. When they occurred, these massive earth movements probably triggered huge tsunamis. In fact, coral-bearing marine sediments have been found some 300 m above sea level on one of the Hawaiian Islands. These sediments were probably deposited by a giant tsunami caused by a prehistoric flank collapse.

The southern flank of Kilauea, on the island of Hawaii, is advancing toward the ocean at a rate of 100 mm/year, which is relatively fast, geologically speaking. This advance became even more worrisome when it suddenly accelerated by a factor of several hundred on November 8, 2000. A network of motion sensors detected an ominous surge in velocity of about 50 mm/day. The surge lasted for 36 hours, after which the normal motion was reestablished. Since then, similar surge events, though variable in size, have been observed every two to three years. Someday—maybe thousands of years from now, but perhaps sooner—the southern flank of the volcano is likely to break off and slide into the ocean. This catastrophic event would trigger a tsunami

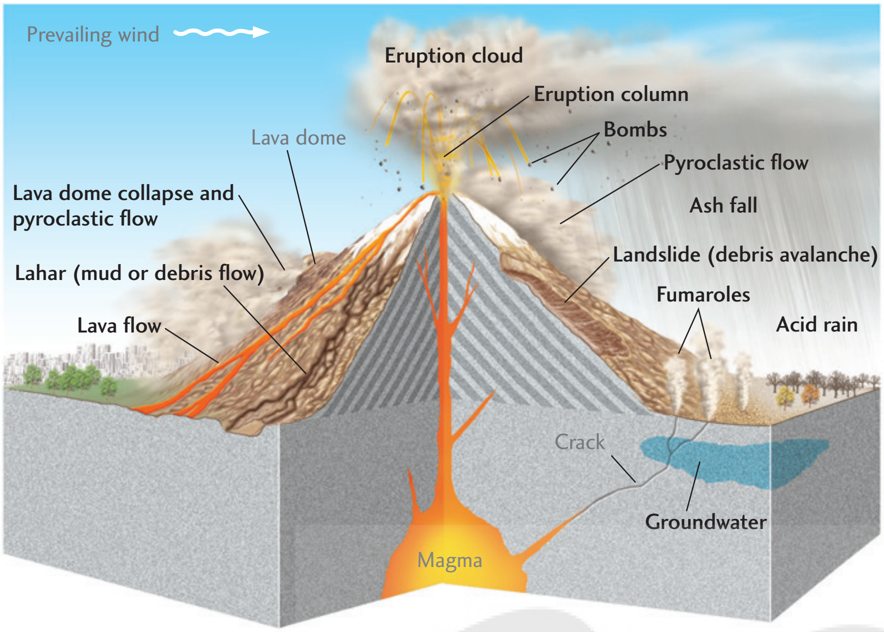


FIGURE 5.33 Some of the volcanic hazards that can kill people and destroy property.

that could prove disastrous for Hawaii, California, and other Pacific coastal areas.

Caldera Collapse Although infrequent, collapses of large calderas are some of the most destructive natural phenomena on Earth. Monitoring the activity of calderas is very important because of their long-term potential for widespread destruction. Fortunately, no catastrophic collapses have occurred in North America during recorded history, but geologists are concerned about an increase in small earthquakes in the Yellowstone and Long Valley calderas as well as other indications of activity in their underlying magma chambers. For example, carbon dioxide leaking into the soil from magma in the crust has been killing trees since 1992 on Mammoth Mountain, a volcano on the boundary of Long Valley Caldera. Regions of the Yellowstone Caldera have been rising at rates as high as 7 cm/year since 2004, and a swarm of more than a thousand small earthquakes occurred near the center of the caldera in a two-week period from December 2008 to January 2009. As in the case of the

FIGURE 5.34 Montserrat in the Caribbean was flooded by lahars after an eruption of the Soufriere Hills volcano in 1997. [Prisma Bildagentur AG/Alamy.]

Long Valley Caldera, these observations are consistent with the injection of magma at mid-crustal depths.

Eruption Clouds A less deadly but still costly hazard comes from the eruption of ash clouds that can damage the jet engines of airplanes that fly through them. More than 60 commercial jet passenger planes have been damaged by such clouds. One Boeing 747 temporarily lost all four engines when ash from an erupting volcano in Alaska was sucked into the engines and caused them to flame out. Fortunately, the pilot was able to make an emergency landing. Warnings of eruption clouds near air traffic lanes are now being issued by several countries. The eruptions of the Eyjafjallajökull, Iceland, volcano in April and May of 2010 disrupted air traffic across the North Atlantic, resulting in over a billion dollars of losses to commercial airlines (see Earth Issues 5.1).

Reducing the Risks of Volcanic Hazards

There are about 100 high-risk volcanoes in the world today, and some 50 volcanic eruptions occur each year. These volcanic eruptions cannot be prevented, but their catastrophic effects can be greatly reduced by a combination of science and enlightened public policy. Volcanology has progressed to the point that we can identify the world's dangerous volcanoes and characterize their potential hazards by studying deposits laid down in earlier eruptions. Some potentially dangerous volcanoes in the United States and Canada are identified in Figure 5.35. Assessments of their hazards can be used to guide zoning regulations to restrict land use—the most effective measure to reduce property losses and casualties.

Such studies indicate that Mount Rainier, because of its proximity to the heavily populated cities of Seattle and Tacoma, probably poses the greatest volcanic risk in the United States (Figure 5.36). At least 80,000 people and their homes are at risk in Mount Rainier's lahar-hazard zones. An eruption could kill thousands of people and cripple the economy of the Pacific Northwest.

Predicting Eruptions Can volcanic eruptions be predicted? In many cases, the answer is yes, as long as it's close to the actual time of eruption. The "grumblings" (seismic tremors) of volcanoes tend to increase just shortly before they erupt. Instrumented monitoring can detect signals such as earthquakes, magnetic pulses, changes in gravity, swelling of the volcano, and gas emissions that warn of impending eruptions. High-resolution GPS measurements can detect movements in the magma chamber beneath the surface of the volcano. People at risk can be evacuated if the authorities are organized and prepared. Scientists monitoring Mount St. Helens were able to warn people before its eruption in 1980 (see Earth Issues 5.2). Government infrastructure was in place to evaluate the warnings and to enforce evacuation orders, so very few people were killed.

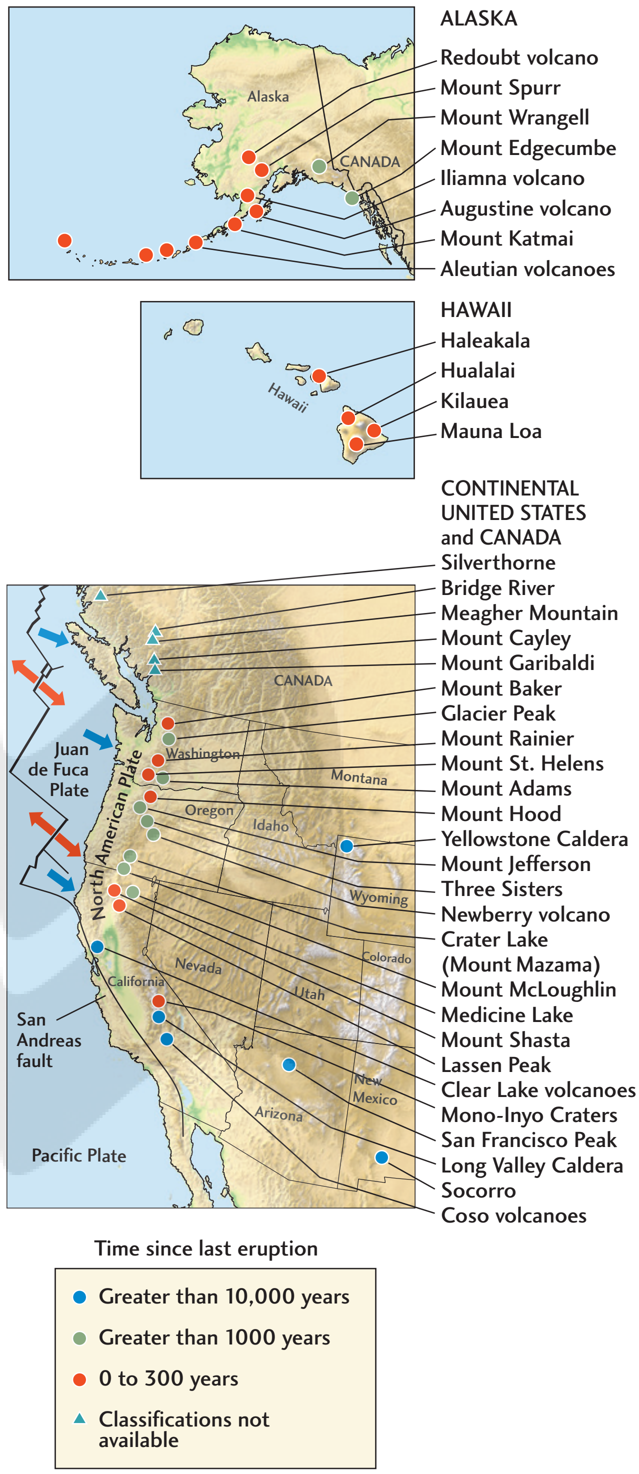


FIGURE 5.35 Locations of potentially hazardous volcanoes in the United States and Canada. Volcanoes within each U.S. group are color-coded by time since their last eruption; those that have erupted most recently are thought to present the greatest cause for concern. (These classifications are subject to revision as studies progress and are not available for Canadian volcanoes.) Note the relationship between the volcanoes extending from northern California to British Columbia and the convergent boundary between the North American Plate and the Juan de Fuca Plate. [Data from R. A. Bailey, P. R. Beauchemin, F. P. Kapinos, and D. W. Klick/USGS.]

FIGURE 5.36 Mount Rainier, seen from Tacoma, Washington. [Patrick Lynch/Alamy.]

Another successful warning was issued a few days before the cataclysmic eruption of Mount Pinatubo in the Philippines on June 15, 1991. A quarter of a million people were evacuated, including some 16,000 residents of the nearby U.S. Clark Air Force Base (which was heavily damaged by the eruption and has since been permanently abandoned). Tens of thousands of lives were saved from the lahars that destroyed everything in their paths. Casualties were limited to the few who disregarded the evacuation order. And in 1994, 30,000 residents of Rabaul, Papua New Guinea, were successfully evacuated by land and sea hours before the two volcanoes on either side of the town erupted, destroying or damaging most of it. Many owe their lives to the government, which conducted evacuation drills, and to scientists at the local volcano observatory, who issued a warning when their seismographs recorded the ground tremors that signaled magma moving toward the surface.

Over the long term, prediction of eruptions is much more difficult because they must be based on the history of volcanic eruptions, so-called "eruption recurrence intervals." These are notoriously unreliable for two reasons: 1) Few volcanoes are sufficiently well studied to provide an accurate eruptive history over the many hundreds, or tens of thousands, of years necessary to establish a reliable recurrence interval; and 2) Few volcanoes maintain the same behavior for long. More often than not, as soon as a repetitive pattern becomes apparent, the volcano changes behavior.

Controlling Eruptions Can we go further by actually controlling volcanic eruptions? Not likely, because large volcanoes release energy on a scale that dwarfs our capabilities for control. Under special circumstances and on a small scale, however, the damage can be reduced. Perhaps the most successful attempt to manage volcanic activity was made on the Icelandic island of Heimaey in January 1973. By spraying advancing lava with seawater, residents cooled and slowed the flow, preventing the lava from blocking the entrance to their harbor and saving some homes from destruction. The best focus for our efforts, however, will be the establishment of more warning and evacuation systems and more rigorous restriction of settlements in potentially dangerous locations.

Natural Resources from Volcanoes

In this chapter, we have seen something of the beauty of volcanoes and something of their destructiveness. But it should be kept in mind that volcanoes contribute to our well-being in many, though often indirect, ways. Soils derived from volcanic materials are exceptionally fertile because of the mineral nutrients they contain. Volcanic rock, gases, and steam are also sources of important industrial materials and chemicals, such as pumice, boric acid, ammonia, sulfur, carbon dioxide, and some metals. Hydrothermal activity is responsible for the deposition of unusual minerals that concentrate relatively rare elements, particularly metals, into ore deposits of great economic value. Seawater circulating through mid-ocean ridges is a major factor in the formation of such ores and in the maintenance of the chemical balance of the oceans.

In some regions where geothermal gradients are steep, Earth's internal heat can be tapped to heat homes and drive electric generators. **Geothermal energy** depends on the heating of water as it passes through a region of hot rock (a *heat reservoir*) that may be hundreds or thousands of meters beneath Earth's surface. Hot water or steam can be brought to the surface through boreholes drilled for the purpose. Usually, the water is naturally occurring groundwater that seeps downward along fractures in rock. Less typically, the water is artificially introduced by pumping from the surface.

By far the most abundant source of geothermal energy is naturally occurring groundwater that has been heated to temperatures of 80°C to 180°C. Water at these relatively low temperatures is used for residential, commercial, and industrial heating. Warm groundwater drawn from a heat reservoir in the Paris sedimentary basin now heats more

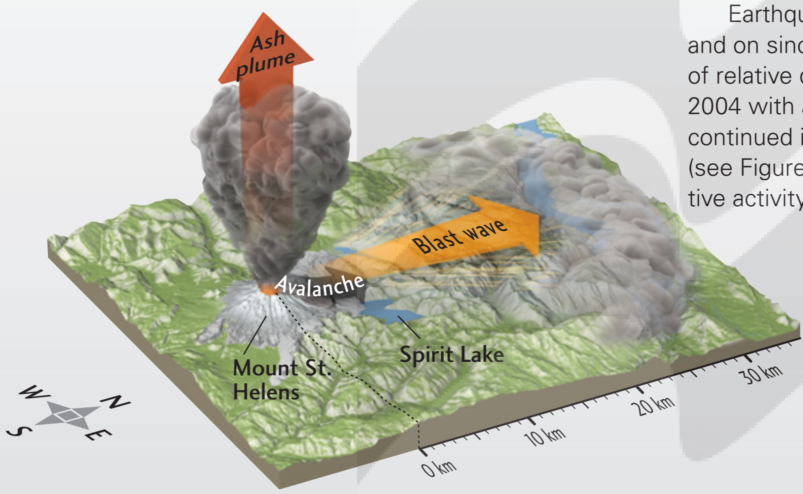
Earth Issues 5.2 Mount St. Helens: Dangerous but Predictable

Mount St. Helens, in the Cascade Range of the Pacific Northwest, is the most active and explosive volcano in the contiguous United States (see Figure 5.6). It has a documented 4500-year history of destructive lava flows, pyroclastic flows, lahars, and distant ash falls. Beginning on March 20, 1980, a series of small to moderate earthquakes under the volcano signaled the start of a new eruptive phase after 123 years of dormancy, motivating the U.S. Geological Survey to issue a formal hazard alert. The first outburst of ash and steam erupted from a newly opened crater on the summit one week later.

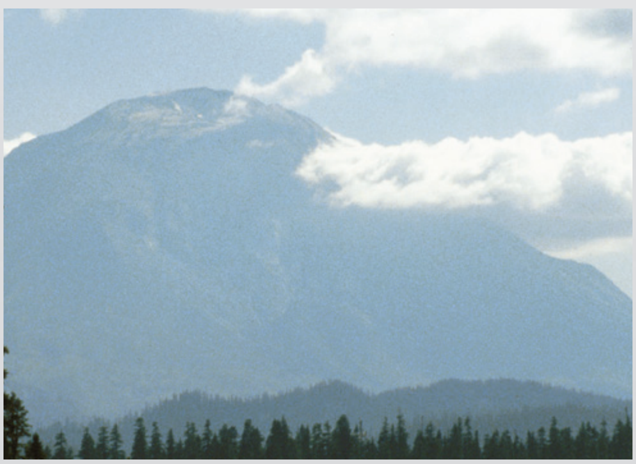
Throughout April, the seismic tremors increased, indicating that magma was moving beneath the summit, and instruments detected an ominous swelling of the northeastern flank of the mountain. The USGS issued a more serious warning and people were ordered out of the vicinity. On May 18, the main eruption began abruptly. A large earthquake apparently triggered the collapse of the north side of the mountain, loosening a massive landslide, the largest ever recorded anywhere. As this huge debris avalanche plummeted down the mountain, gas and steam under high pressure were released in a tremendous lateral blast that blew out the northern flank of the mountain.

USGS geologist David A. Johnston was monitoring the volcano from his observation post 8 km to the north. He must have seen the advancing blast wave before he radioed his last message: "Vancouver, Vancouver, this is it!" A northward-directed jet of superheated (500°C) ash, gas, and steam roared out of the breach with hurricane force, devastating a zone 20 km outward from the volcano and 30 km wide. A vertical eruption column sent an ash plume 25 km into the sky, twice as high as a commercial jet flies. The ash plume drifted to the east and northeast with the prevailing winds, bringing darkness at noon to an area 250 km to the east and depositing a layer of ash as deep as 10 cm over much of Washington, northern Idaho, and western Montana. The energy of the blast was equivalent to about 25 million tons of TNT. The volcano's summit was destroyed, its elevation was reduced by 400 m, and its northern flank disappeared. In effect, the mountain was hollowed out.

Earthquakes and magmatic activity have continued off and on since the 1980 eruption. After more than a decade of relative quiescence, the volcano reawoke in September 2004 with a series of minor steam and ash eruptions that continued into 2005. Growth of the central volcanic dome (see Figure 5.14b) suggests that the current phase of eruptive activity may persist for some time into the future.



The eruption of Mount St. Helens on May 18, 1980, sent an ash plume into the stratosphere and an avalanche and blast wave toward the north.



(May 17, 3 P.M.) View of Mount St. Helens the day before its eruption. The north side of the volcano has bulged outward from magma intruded at shallow levels during the previous two months. [Keith Ronnholm.]

(May 18, 8:33 A.M.) An earthquake and massive landslide "uncork" the volcano, releasing an ash plume and a powerful lateral blast wave. [Keith Ronnholm.]

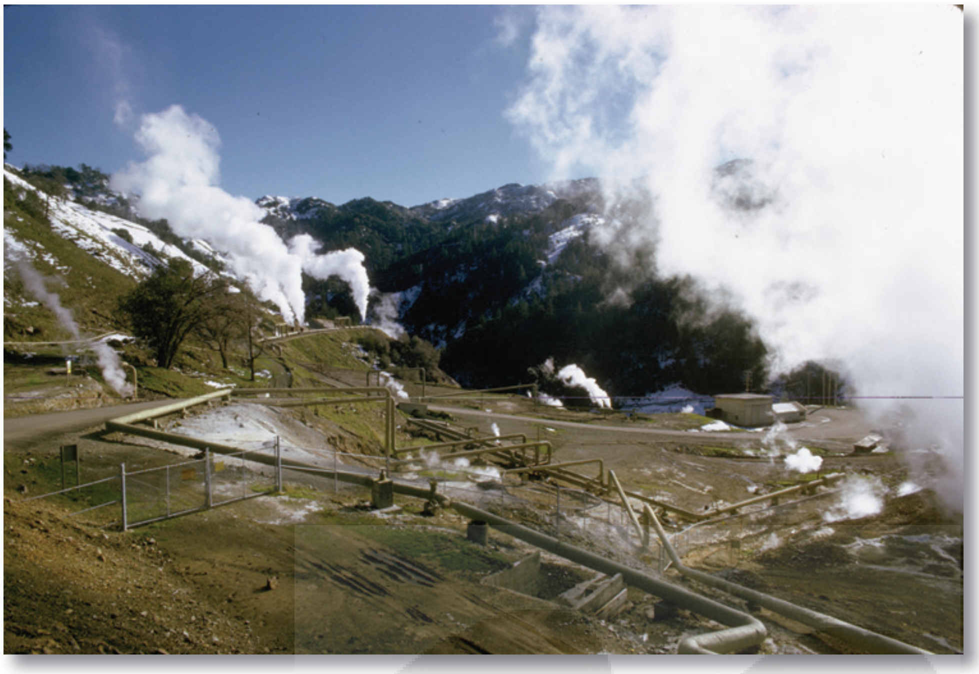


FIGURE 5.37 The Geysers, one of the world's largest supplies of natural steam. The geothermal energy is converted into electricity for San Francisco, 120 km to the south. [Charles Rotkin/Getty Images.]

than 20,000 apartments in France. Reykjavik, the capital of Iceland, which sits atop the Mid-Atlantic Ridge, is almost entirely heated by geothermal energy.

Heat reservoirs with temperatures above 180°C are useful for generating electricity. They are present primarily in regions of recent volcanism as hot, dry rock, natural hot water, or natural steam. Naturally occurring water heated above the boiling point and naturally occurring steam are highly prized resources. The world's largest facility for producing electricity from natural steam, located at The Geysers, 120 km north of San Francisco, generates more than 600 megawatts of electricity (**Figure 5.37**). Some 70 geothermal electricity-generating plants operate in California, Utah, Nevada, and Hawaii, producing 2800 megawatts of power—enough to supply about a million people.

KEY TERMS AND CONCEPTS

andesitic lava (p. 121)
ash-flow deposit (p. 130)
basaltic lava (p. 119)
breccia (p. 124)
caldera (p. 127)
crater (p. 125)
diatreme (p. 127)
fissure eruption (p. 129)
flood basalt (p. 130)
geothermal energy (p. 145)
hot spot (p. 136)
hydrothermal activity (p. 131)
lahar (p. 142)
large igneous province (p. 138)
mantle plume (p. 137)
pyroclastic flow (p. 124)
rhyolitic lava (p. 122)
shield volcano (p. 125)
stratovolcano (p. 125)
tuff (p. 124)
volcanic geosystem (p. 118)
volcano (p. 118)

REVIEW OF LEARNING OBJECTIVES

5.1 Describe how volcanoes transport magma from the Earth's interior to its surface.

Temperatures within the asthenosphere can reach at least 1300°C, high enough to begin to melt rocks. The asthenosphere is the main source of magma, and once that molten rock reaches the surface and erupts it is called lava. Because magma is liquid, it is less dense than the rocks that produce it, and will begin to float upward through the lithosphere. In some places, the magma may fracture the lithosphere along zones of weakness. The rocks, magmas, and processes needed to describe the entire sequence of events from melting to eruption constitute a volcanic geosystem.

Study Assignment: Figure 5.1

Exercise: What is the difference between magma and lava? Describe a geologic situation in which a magma does not form a lava.

Thought Question: Give a few examples of what geologists have learned about Earth's interior by studying volcanoes and volcanic rocks.

5.2 Differentiate between the major types of volcanic deposits and explain how the textures of volcanic rocks can reflect the conditions under which they solidified.

Lavas of different types produce different landforms. These differences depend on chemical composition, gas content, and temperature of the lavas. The textures of volcanic rocks reflect the conditions under which they solidified. Erupted lavas usually solidify into one of three major types of rock: basaltic (mafic), andesitic (intermediate), or rhyolitic (felsic), which are classified on the basis of their content of silica and other minerals. Basaltic lavas are relatively fluid and flow freely; andesitic and rhyolitic lavas are more viscous. Lavas differ from pyroclasts, which are formed by explosive eruptions and vary in size from fine ash particles to house-sized bombs.

Study Assignment: Figures 5.4, 5.6, 5.8

Exercise: What are the three major types of volcanic rocks and their intrusive counterparts? Is kimberlite one of these three types?

Thought Question: While on a field trip, you come across a volcanic formation that resembles a field of sandbags. The individual ellipsoidal forms have a smooth, glassy surface texture. What type of lava is this, and what information does this give you about its history?

5.3 Summarize how volcanic landforms are shaped.

The chemical composition and gas content of magma are important factors in a volcano's eruptive style and in the shape of the landforms it creates. Volcanic landforms are also dependent on the rate at which lava is produced and the plumbing system that gets it to the surface. A shield volcano grows from repeated eruptions of basaltic lava from a central vent. Andesitic and rhyolitic lavas tend to erupt explosively. The erupted pyroclasts may pile up into a cinder cone. A stratovolcano is built of alternating layers of lava flows and pyroclastic deposits. The rapid ejection of magma from a large magma chamber, followed by collapse of the chamber's roof, results in a large depression, or caldera. Basaltic lavas can erupt from fissures along mid-ocean ridges as well as on continents, where they flow over the landscape in sheets to form flood basalts. Pyroclastic eruptions from fissures can cover an extensive area with ash-flow deposits.

Study Assignment: Figure 5.14

Exercise: What type of volcano is the Arenal volcano, shown in Figure 5.10?

Thought Question: Why are eruptions of stratovolcanoes generally more explosive than those of shield volcanoes?

5.4 Discuss how volcanic gases can affect the hydrosphere and atmosphere.

Volcanoes produce gases as well as solid materials. These gases may come from deep within the Earth, making their way to the surface for the first time. These gases have a number of effects on other geosystems, including the hydrosphere and atmosphere. Even when lavas and pyroclastics cease to flow, volcanoes continue to emit steam and gases for many years. Hydrothermal activity is the circulation of water through hot volcanic rocks and magmas, which is heated and returned to the surface as hot springs and geysers. Hydrothermal activity is especially intense at spreading centers and mid-ocean ridges, where large volumes of water and magma come into contact. Volcanism can also affect the water and climate by changing the composition and properties of the atmosphere. Large eruptions can inject sulfurous gases into the atmosphere, blocking the Sun's radiation and lowering global temperatures.

Study Assignment: Figure 5.22

Exercise: Describe how interactions between the lithosphere and hydrosphere at spreading centers affect the geology, chemistry, and biology of the oceans.

Thought Question: How could periods of intense volcanic activity be responsible for some of the mass extinctions documented in the geologic record?

5.5 Explain how the global pattern of volcanism is related to plate tectonics.

Of the world's active volcanoes that occur on land or above the ocean surface, 80 percent are found at convergent plate boundaries, 15 percent at divergent plate boundaries, and 5 percent within plate interiors. The huge volumes of basaltic magma that form oceanic crust are produced by decompression melting and erupted at spreading centers on mid-ocean ridges. Interactions between the lithosphere and hydrosphere at spreading centers affect the geology, chemistry, and biology of the oceans. Andesitic lavas are the most common lava type in the volcanic mountain belts of ocean-continent subduction zones. Rhyolitic lavas are produced by the melting of felsic continental crust. Within plates, basaltic volcanism occurs above hot spots, which are manifestations of rising plumes of hot mantle material.

Study Assignment: Figure 5.24

Exercise: On Earth's surface as a whole, what process generates the greater volume of volcanic rock, decompression melting or fluid-induced melting? Which of these processes creates the more dangerous volcanoes?

Thought Question: Why are the volcanoes on the northwestern side of the island of Hawaii dormant whereas those on the southeastern side are more active?

5.6 Illustrate the hazards and beneficial effects of volcanism.

Volcanic hazards that can kill people and damage property include pyroclastic flows, tsunamis, lahars, flank collapses, caldera collapses, eruption clouds, and ash falls. Volcanic eruptions have killed about 250,000 people in the past 500 years. On the positive side, volcanic materials produce nutrient-rich soils, and hydrothermal processes are important in the formation of many economically valuable mineral ores. Seawater circulating through mid-ocean ridges is a major factor in the formation of such ores and in the maintenance of the chemical balance of the oceans. Geothermal heat drawn from areas of hydrothermal activity is a useful source of energy in some regions.

Study Assignment: Figure 5.33

Exercise: How do scientists predict volcanic eruptions?

Thought Question: What might be the effects on civilization of a Yellowstone-type caldera eruption, such as the one described at the opening of this chapter?

VISUAL LITERACY EXERCISE

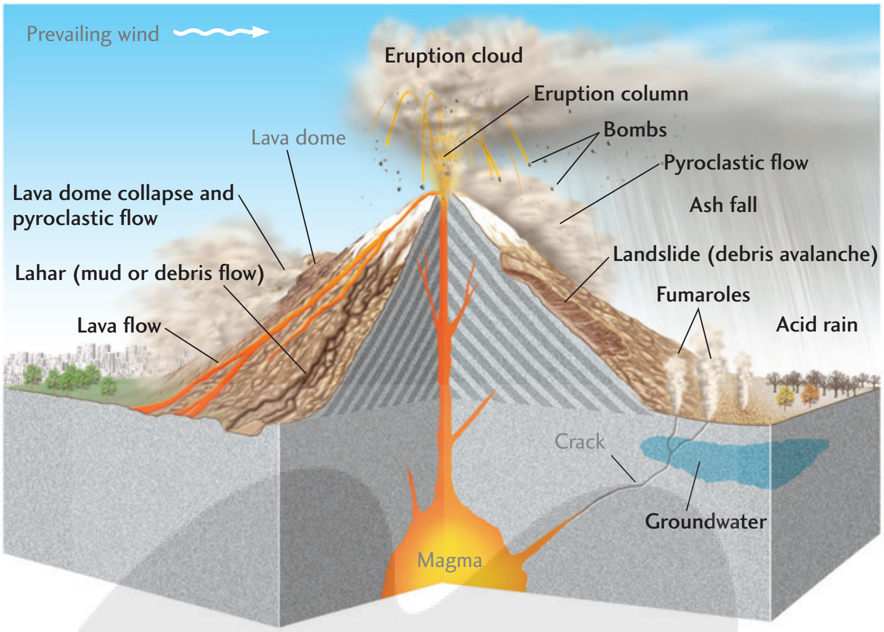


FIGURE 5.33 Some of the volcanic hazards that can kill people and destroy property.

1. **What causes a pyroclastic flow?**
   - **a.** Lava dome collapse
   - **b.** Acid rain
   - **c.** Erupting groundwater
   - **d.** Entrainment by prevailing winds

2. **When do volcanic bombs move?**
   - **a.** During a landslide
   - **b.** In flowing lava
   - **c.** During a volcanic eruption
   - **d.** During formation of fumaroles

3. **How is water heated that feeds fumaroles?**
   - **a.** When groundwater comes in contact with rocks heated by magma
   - **b.** During rainfall
   - **c.** By friction generated in debris flows
   - **d.** When lava flows down the sides of volcanoes

4. **Which is correct?**
   - **a.** A pyroclastic flow is generated by a volcanic eruption.
   - **b.** Volcanic ash fall from an eruption cloud.
   - **c.** Prevailing winds push an eruption cloud in the direction of that wind.
   - **d.** Ash can travel further than bombs.

5. **What are lahars composed of?**
   - **a.** Acid rain
   - **b.** Groundwater
   - **c.** Bombs
   - **d.** Mud