An ash plume rising 9.5 km into the atmosphere … caused the shutdown of airspace above northern Europe

5



APPLYING the 5 fundamental concepts Eyjafjallajökull 2010 Eruption

1

Science helps us predict hazards.

By understanding the relationship between seismic activity and volcanic activity, scientists were able to forecast the 2010 eruption of Eyjafjallajökull volcano.

2

Knowing hazard risks can help people make decisions.

Although volcanoes are present on all continents, in the oceans, and on islands like Iceland, their locations are not random but are expected in particular geologic settings. If you live in a volcanically active setting, a certain probability of experiencing an eruption exists depending on the frequency with which the volcanoes erupt.

Volcanoes

Eyjafjallajökull 2010 Eruption

Located in the middle of the Atlantic Ocean, Iceland—an island one-quarter the size of California—is home to more than 30 active volcanoes. Even though volcanic eruptions light up the Icelandic skies every three to four years,[1] the effects of the eruptions are usually limited to those living on the island. In April 2010, however, an ash plume rising 9.5 km (~6 mi.) into the atmosphere above the erupting Eyjafjallajökull volcano caused the shutdown of airspace above northern Europe, the United Kingdom, Ireland, Sweden, and Norway, which lie more than 1000 km (~620 mi.) to the southeast (Figure 5.1). This volcanic activity caused the largest aerial closure in Europe since World War II—about 95,000 flights were canceled, stranding hundreds of thousands of travelers and costing the airline industry more than a billion dollars during a one-week period.[2]

Increased seismic activity around Eyjafjallajökull in December 2009 signaled the awakening of the volcano, which had not erupted since 1821. Although the 2010 eruption was not completely unexpected, the height of the plume of ash ejected from the volcano was surprising since all previous eruptions in the past 1,500 years had been comparatively small.[1] Such large volcanic ash plumes are unusual for Icelandic volcanic eruptions, with the last occurring nearly 100 years ago, long before airplanes filled the skies like today.

< 2010 ICELANDIC VOLCANIC ERUPTION

Ash, steam, and glowing molten rock erupt skyward from beneath the ice-covered Eyjafjallajokull volcano, in southern Iceland. *(Orvar Porgiersson / Barcroft Media / Getty Images)*

LEARNING Objectives

Of the approximately 1,500 active volcanoes on Earth, nearly 400 have erupted in the past century. In fact, while you are reading this paragraph, at least 20 volcanoes are erupting on our planet. Volcanoes occur on all seven continents as well as in the middle of the ocean. When human beings live in the path of an active volcano, the results can be devastating.

After reading this chapter, you should be able to:

LO:1 Explain the relationship of volcanoes to plate tectonics.

LO:2 Identify the different types of volcanoes and their associated features.

LO:3 Locate on a map the geographic regions at risk from volcanoes.

LO:4 Describe the effects of volcanoes and how they are linked to other natural hazards.

LO:5 List the potential benefits of volcanic eruptions.

LO:6 Discuss how humans can minimize the volcanic hazard.

LO:7 Recommend adjustments we can make to avoid death and damage from volcanoes.

3

Linkages exist between natural hazards.

The confluence of "fire and ice" on the island of Iceland is an exceptional example of how hazards can be linked to one another, and often it is the linked hazards that are the most damaging.

4

Humans can turn disastrous events into catastrophes.

As the 2010 airline shutdowns showed, in our highly connected modern world, a perceived local natural hazard can have global impacts.

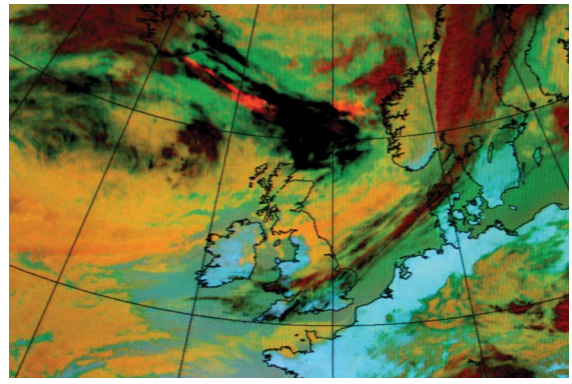
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Consequences of hazards can be minimized.

Volcanic and hydrologic monitoring around Eyjafjallajökull's volcano enabled early warnings to be issued and successful evacuation of the Icelanders living in harm's way.



(a)



(b)

FIGURE 5.1 Volcanic Ash Shuts Down Air Travel
(a) Volcanic ash plume rising from Eyjafjallajökull volcano reaches an elevation of about 9.5 km (~6 mi.). *(Lee Frost/Robert Harding World Imagery/Alamy)* (b) Enhanced color satellite image highlighting a volcanic ash plume (black colour) moving from Iceland toward the United Kingdom on April 15, 2010; all flights in and out of Britain's airports were grounded. *(Matt Cardy/Getty Images News/Getty Images)*



FIGURE 5.2 Fire and Ice
A massive volume of water cascades down the mountain, flooding the valleys below, as the Icelandic ice cap partially melts due to the erupting volcano. Such volcanically induced floods are known by the Icelandic name, jökulhlaup. *(UPPA/ZUMAPRESS/Newscom)*

Many of Iceland's large volcanoes lie beneath thick glacial ice caps. In fact, Eyjafjallajökull means "island mountain glacier," and it is this glacial ice cap from which the volcano takes its name. During volcanic eruptions, escaping heat from Earth's interior can rapidly melt large volumes of ice and trigger massive flooding, which is one of the most significant natural hazards on Iceland (Figure 5.2). Because such glacial floods are common in Iceland, scientists often use the Icelandic word *jökulhlaups* for these megafloods. To mitigate the effects of jökulhlaups, a network of hydrological stations monitors water flow downstream of glacially capped volcanoes; when flooding occurs, Icelanders living in hazardous regions are immediately notified.

Although the 2010 eruption was relatively small—about one-tenth the size of the 1980 Mount St. Helens eruption in Washington state (see Case Study 5.3: Mount St. Helens)—the effects were felt globally as well as locally. For many Icelanders living around Eyjafjallajökull, the eruption was a small taste of what might lie ahead if the volcano's more explosive neighbor Katla were to erupt. Since 2010, Katla has shown signs of unrest, and Iceland's president has issued this warning: "The time for Katla to erupt is coming close ... we have prepared ... it is high time for European governments and airline authorities all over Europe and the world to start planning."[3]

5.1 Introduction to Volcanism

Volcanic activity, or volcanism, is typically related to plate tectonics, with most volcanoes being located near active plate boundaries. Approximately two-thirds of all active volcanoes above sea level on Earth are located within the Pacific "Ring of Fire" (Figure 5.3).[4] This relationship exists because spreading or sinking plates at plate boundaries interact with other earth materials to produce molten rock, called **magma** within Earth, or **lava** when it erupts onto the surface. Volcanoes are constructed around an opening, called a **volcanic vent**, through which lava and other volcanic materials are extruded onto the surface. Vents may be roughly circular, or they may be elongated cracks called *fissures*.



FIGURE 5.3 The "Ring of Fire"
The thick orange line outlines the Ring of Fire surrounding the Pacific plate. Although no fire is present, the Ring of Fire contains most of the world's explosive volcanoes. *(From E. J. Tarbuck and L. K. Lutgens,* Earth*, 11e.*
© 2014 Pearson Education, Inc.)

Because the processes that result in volcano formation are different for different tectonic settings, volcanoes are not all the same. By understanding the various ways that magma forms and the plate tectonic settings of volcanically active regions, you will be able to understand the different types, shapes, and eruption behavior of volcanoes around the world.

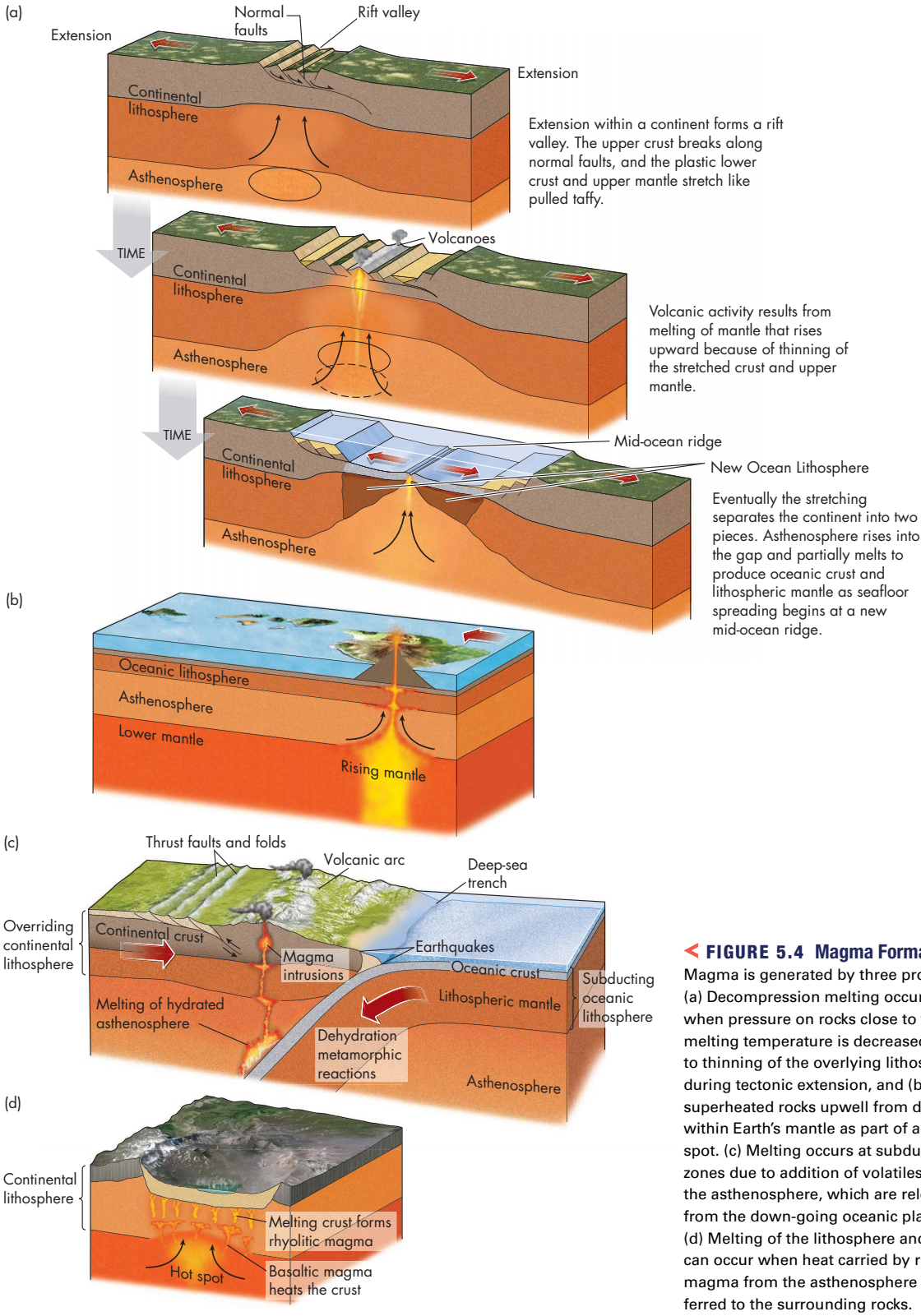
HOW AND WHERE MAGMA FORMS

It is a common misconception that the plates move around on an ocean of molten rock. This is not true. With the exception of the outer core, deep within Earth's interior, the planet is composed of solid rock (see Section 2.2). So then, where does the magma that forms Earth's volcanoes come from?

Most magma comes from the asthenosphere—the weak layer within the mantle that allows the overlying rigid lithospheric plates to move around the globe (see Section 2.1). The asthenosphere is weak and able to flow because it is close to its melting temperature. This means that the asthenosphere is more prone to melting than the lithosphere above or lower mantle below.[5] Figure 5.4 illustrates the different geologic settings where melting occurs and the three principal processes that generate magma—decompression melting, addition of volatiles, and addition of heat.

1. *Decompression melting* occurs when the overlying pressure exerted on hot rock within the asthenosphere is decreased. The melting temperature for mantle rocks at Earth's surface is approximately 1200°C (~2200°F). Although this temperature is exceeded within the upper 50 km (~30 mi.) of Earth's surface in most tectonic settings, the mantle is a solid.[5] Like temperature, pressure also increases with depth. This great pressure, generated by the weight of overlying rock, keeps Earth's mantle in a solid state far above the surface melting temperature of the rock. In other words, for a given increase in depth, an additional amount of heat is required to melt the rock. Conversely, if rocks are close to their melting temperature and the pressure from above is decreased, **decompression melting** occurs and magma will begin to form even though the temperature stays the same.

   Decompression melting predominates at locations where Earth's lithosphere is being stretched and thinned. About three-quarters of all



< FIGURE 5.4 Magma Formation
Magma is generated by three processes. (a) Decompression melting occurs when pressure on rocks close to their melting temperature is decreased due to thinning of the overlying lithosphere during tectonic extension, and (b) when superheated rocks upwell from deep within Earth's mantle as part of a hot spot. (c) Melting occurs at subduction zones due to addition of volatiles to the asthenosphere, which are released from the down-going oceanic plate. (d) Melting of the lithosphere and crust can occur when heat carried by rising magma from the asthenosphere is transferred to the surrounding rocks.

lava erupted on Earth is extruded from undersea mid-ocean ridges, which are divergent plate boundaries.[6] Recall from Chapter 2 that a mid-ocean ridge forms when a continent is pulled apart and a rift valley develops due to extension and normal faulting. Continued stretching causes thinning of the entire lithosphere and the asthenosphere must upwell toward the surface to fill the space (Figure 5.4a). Now nearer to Earth's surface, the asthenosphere is under less pressure than before and decompression melting occurs. Some of the magma at this point may rise rapidly to the surface and erupt onto the continent to produce a volcano. If the stretching is great enough and continues for long enough (tens to hundreds of million years), the region will subside below sea level and a mid-ocean ridge will develop (Figure 5.4a). Cooling of the voluminous amounts of magma generated by decompression melting at mid-ocean ridges has created all of Earth's oceanic lithosphere over the course of the past 200 million years.

Decompression melting also occurs at "hot spots," where a plume of superheated rock rises from deep within the mantle toward the surface (Figure 5.4b). Compared to magma formation at mid-ocean ridges, hot spots are responsible for a relatively small amount of decompression melting on Earth. However, melting at any one hot spot can be extensive due to the great depth from which the mantle upwells.

2. *Addition of volatiles* lowers the melting temperature of rocks by helping to break chemical bonds within minerals. **Volatiles** are chemical compounds, such as water (H_2O), carbon dioxide (CO_2), and sulfur dioxide (SO_2), that evaporate easily and exist in a gaseous state at Earth's surface. However, volatiles are present deep in Earth as solid compounds that are incorporated into minerals. When volatiles, such as water, are added as a fluid to rocks that are close to their melting temperature, the rocks will begin to melt. For example, at a depth of 100 km (~62 mi.) the mantle has a dry (volatile-free) melting temperature of about 1500°C (~2700°F), but in the presence of a small percentage of water, the mantle melting temperature is about 800°C (~1500°F).[7] This process is analogous to using salt on sidewalks in cold climates to melt ice—salt lowers the melting temperature of water from 0°C (~32°F) to –8°C (~17°F); therefore, salted ice will melt even though it is below freezing outside.

Magma formation due to the addition of volatiles occurs at subduction zones and is responsible for the "Ring of Fire" that surrounds the Pacific Ocean, which represents more than half of Earth's active volcanoes above sea level (see Figure 5.3).[8] This ring has formed above the subduction zones where the Pacific, Nazca, Cocos, Philippine, and Juan de Fuca plates are sinking below adjacent plates. Volatiles trapped within the sediments on the seafloor and in minerals that compose the oceanic lithosphere are released as the subducting oceanic plate is forced downward into the hotter mantle (Figure 5.4c). The volatiles are then free to rise upward into the formerly dry (volatile-free) asthenosphere causing magma to form due to a lowering of the mantle melting temperature. The volatiles become dissolved into the rising magma and play an important role in the eruptive behavior of the volcano.

3. *Addition of heat* to rocks will induce melting if the temperature exceeds the melting temperature of the rocks at that depth. The best way to move heat rapidly from areas of higher temperature to areas of lower temperature is within large bodies of magma. As the magma rises within the mantle and ultimately through the crust, heat from deep within Earth is carried toward the surface and along the way is transferred to the surrounding rocks. This heat may cause the cooler, shallower rocks to melt and this newly formed magma may become mixed with the rising magma. The degree to which this mixing occurs depends on whether the surrounding rocks are already close to their melting temperature and the amount and temperature of the rising magma.

Magma formation due to the addition of heat is likely widespread wherever magma rises and comes into contact with cooler rocks, but it is more difficult to quantify. However, where hot spots occur beneath continents, pooling of basaltic magma near the base of Earth's crust can cause extremely large magma chambers to develop (Figure 5.4d). Perhaps more important than the volume of magma at continental hot spots is the effect of crustal melting and magma mixing—*crustal assimilation*—on the chemical composition of the magma at these locations. As you will see in the next section, magma composition has a strong effect on the type of volcano and the eruptive behavior of the different volcano types, which is why continental hot spot volcanoes are some of the largest and most dangerous on Earth.

MAGMA PROPERTIES

Magma is composed of melted silicate rocks and dissolved gases. Silica (SiO_2), the most abundant chemical compound in silicate minerals, is the primary

constituent of magma. The three major types of magma—*basaltic*, *andesitic*, and *rhyolitic*—vary in their silica content (Figure 5.5). All magmas that form by melting of the asthenosphere are basaltic. Because most magmas form by melting the asthenosphere, as you learned in the previous section, basaltic magma is the most common magma type. Basaltic magmas have a relatively low silica content (45–55 percent) and are referred to as *mafic* in composition. Rhyolitic magma contains more than 65 percent silica and is referred to as *felsic*, whereas andesitic magma is *intermediate* in composition (55–65 percent silica). When these magmas erupt onto Earth's surface, each lava type solidifies to produce a different volcanic rock—*basalt*, *andesite*, and *rhyolite* (Figure 5.5).

Magma is less dense than the surrounding rock; therefore, it rises buoyantly toward the surface and sometimes accumulates near Earth's surface in large pools, known as **magma chambers**. While pooled in a magma chamber or along its path toward the surface, chemical changes due to cooling and crustal assimilation change the composition of the melt and it becomes more felsic (increasing silica content) over time. The change in magma composition from primitive mafic basalt toward felsic magma as it ascends toward the surface is known as *magma evolution*. The degree of magma evolution depends on how fast the magma rises through the lithosphere and the amount of volatiles dissolved into the melt—greater volatile content increases the rate of magma evolution. When the magma reaches the surface, the type of volcano formed and its eruptive behavior are controlled not only by the composition but also by the viscosity and volatile content of the melt.

Viscosity Greater amounts of silica make it more difficult for magma to flow. Resistance to flow in fluids is called *viscosity*. Fluids that do not flow easily, such as molasses or refrigerated honey, are like silica-rich felsic magma—they have a high viscosity. Other fluids that flow readily, such as water, warm honey, and low-silica mafic magma, have a low viscosity. As the example of honey suggests, viscosity is typically influenced by temperature as well as composition (see Figure 5.5). For example, a low-silica content, basaltic lava flow may have a low viscosity when it erupts onto Earth's surface, but as it flows down the flank of the volcano and cools, its viscosity will increase, causing the flow to move more slowly and change in form (see Section 5.4).

The variability in magma viscosity strongly influences both the mobility of the magma under the surface and the velocity and form it takes if it reaches the surface as a lava flow. Rhyolitic lava flows have high viscosity, move slowly, may be a hundred feet thick, are generally restricted to the vent region, and form steep-sided domes. In contrast, basaltic lava flows can move rapidly, are often thin (< 3 m or 10 ft.), and may travel tens of kilometers from the vent. These differences in flow characteristics affect the shape of the volcano formed by different lava types. More

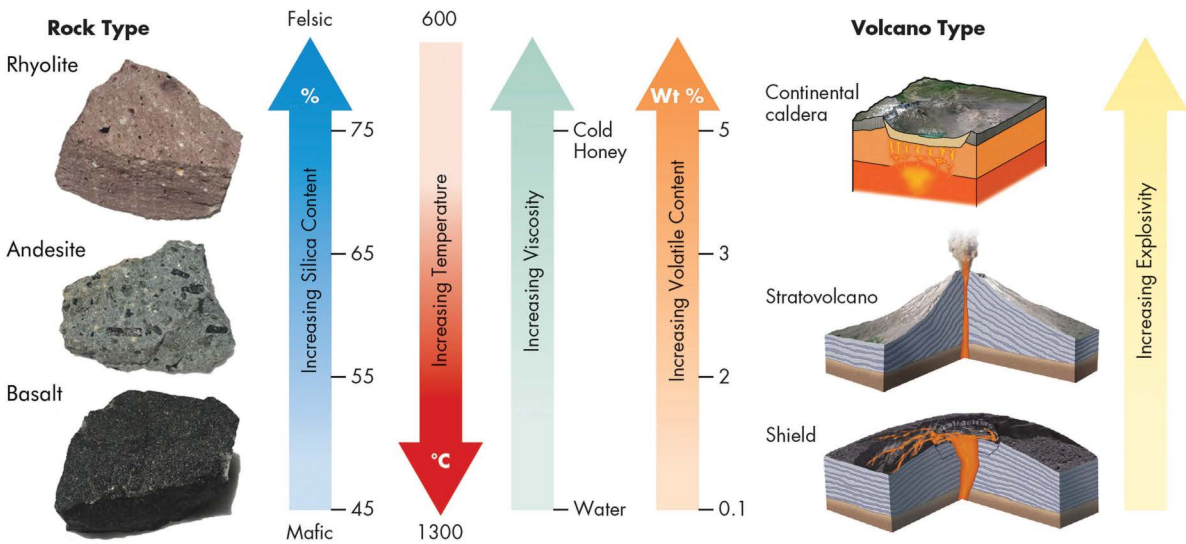


FIGURE 5.5 Volcano Characteristics
The eruptive character, shape, and type of volcano that forms are directly related to the silica content of the magma, which defines the rock type and also affects the viscosity and volatile content of the melt.

importantly, the viscosity is often correlated to the volatile content of the magma, which is responsible for whether or not volcanic eruptions are peaceful or explosive (Figure 5.5).

Volatile Content Uncorking a bottle of champagne and opening a shaken carbonated beverage are good analogies to explain why volcanoes erupt explosively. When the champagne is depressurized by uncorking, the dissolved volatiles (CO_2) come out of solution from the liquid, forming bubbles. The rapid expansion of the bubbles causes the liquid to vigorously squirt from the bottle. Similarly, a high concentration of dissolved volatiles within the magma will cause an explosive eruption when the magma chamber is decompressed. In fact, the characteristic semicircular depression at the top of many volcanoes, called a volcanic **crater**, is caused by explosive extrusion of volcanic material during an eruption.

In general, volatile content increases with increasing silica content (Figure 5.5). Andesitic-to-rhyolitic magma has more dissolved gas (2–5 weight percent) than basaltic magma (< 1 wt. percent). Thus, volcanoes with andesitic-to-rhyolitic magma are more prone to explosive eruptions than volcanoes with basaltic lava flows. Eruption of volatile-poor basaltic magma results in **effusive eruptions**, which are typified by passive outpouring of low-viscosity lava onto Earth's surface (Figure 5.6a). By contrast, the rapid formation and expansion of bubbles within volatile-rich, high-viscosity magma causes explosive eruptions, in which the molten material fragments into fine-grained particles that are propelled high into the atmosphere (Figure 5.6b). Volcanic materials, such as ash, that are explosively ejected from a volcano are collectively called **pyroclastic debris** (see Section 5.4).

5.1 CHECK your understanding

1. What is magma and where does it come from?
2. Describe the physical and chemical changes that cause rocks to melt.
3. What is the relationship between plate tectonics and the location of volcanoes?
4. What is viscosity and what determines magma viscosity?
5. Explain the relationship between magma composition, viscosity, and gas content.



(a)



(b)

▲ FIGURE 5.6 Effusive vs. Explosive Eruptions
The degree to which the direct effects of a volcanic eruption are hazardous is related to the viscosity of the magma. (a) Low-viscosity lava shoots 30 m (~100 ft.) from Pu'u 'Ō'ō' crater on Hawaii in 1983, creating a spectacular fire fountain display, and then flows from the vent downhill like a river. *(J. D. Griggs/USGS)* (b) Rapid expansion of volatiles trapped in high-viscosity magma explosively propels ash more than 8 km (~5 mi.) into the atmosphere during the 2008 eruption of Chaitén volcano in Chile. *(Oliver Wien/epa European Pressphoto Agency creative account/Alamy)*

5.2 Volcano Types, Formation, and Eruptive Behavior

Volcanoes are landforms that vary greatly in size, shape, composition, and eruptive behavior (Table 5.1). Some volcano types form during a single eruption, while others may be the results of hundreds or thousands of eruptions over millions of years. The type of volcano that forms is the result of how and where the magma formed, the amount of magma evolution (silica enrichment) that occurred on the way to the surface, and the volatile content of the melt. Although every volcanic eruption is unique, and even eruptions from the same volcano differ, volatile content and viscosity are the primary controls on whether a volcano erupts effusively or explosively. The eruptive behavior of specific volcano types can be broadly generalized and predicted. A somewhat more quantitative means of evaluating a volcano's eruption is the **volcanic explosivity index (VEI)**. The VEI is a relative scale by which different eruptions can be compared based on quantitative and qualitative observations of explosivity. Explosivity is based on the height of the eruption plume and the volume of ejected material, as well as the overall violence of the eruption (Table 5.2). With the exception of VEI 0 through VEI 2, the scale is logarithmic, with each interval representing a tenfold increase in the volume of ejected material.

Stratovolcanoes Known for their beautiful conical shapes (Figure 5.7), Mount Fuji in Japan and Mount St. Helens, Mount Rainer, and Mount Shasta in the United States are examples of **stratovolcanoes**. Over time, stratovolcanoes will erupt a variety of different lava compositions from basalt to rhyolite, but intermediate to felsic compositions dominate (see Table 5.1). Because of their high viscosity, these lavas do not travel far from the vent and therefore pile up, giving stratovolcanoes their steep sides. Stratovolcanoes have high water content because they form above subduction zones where magma formation is caused by addition of volatiles (see Section 5.1). The high-volatile content of these volcanoes means that eruptions can be extremely explosive. In fact, stratovolcanoes are a composite of a series of layered pyroclastic debris that rains down after an explosive eruption and effusive lava flows (Figure 5.8a). As a result, these volcanoes are also called *composite cones*.

Stratovolcanoes are common within the Ring of Fire, where subduction is the dominant tectonic process, such as the Cascadia subduction zone in the Pacific Northwest and southwestern Canada (see Figure 5.3). As the volatile-rich basaltic melt rises upward from the asthenosphere through the overriding plate, the magma evolves, becoming more felsic. The volcanoes formed by these magmas are commonly andesitic to rhyolitic in composition and their silica content lies somewhere between basaltic oceanic crust and more silica-rich

TABLE 5.1 Volcano Characteristics

Volcano Type	Composition	Volatile Content	Shape	Eruption Type	Volcano Examples
Stratovolcano, or composite cone	Andesite	High	Cone shaped with steep sides; built of lava flows and pyroclastic deposits	Combination of lava flows and pyroclastic activity	Mount Shasta, California (Figure 5.7); Mount St. Helens, Washington (Figure 5.34); Eyjafjallajökull, Iceland (chapter-opener photograph)
Lava dome	Andesite to rhyolite	Low to moderate	Dome shaped; steep sided	Mostly effusive with lavas piling up near the vent, but can be explosive.	Mount Lassen, California; Mt. Unzen dome, Japan (Figure 5.9)
Shield volcano	Basalt	Low	Gentle arch or shield shape, with shallow slopes; built up of many lava flows	Far-traveling lava flows	Mauna Loa, Hawaii (Figure 5.10); Kīlauea, Hawaii
Cinder cone	Basalt	Low to moderate	Cone shaped with steep sides and summit crater	Mostly tephra ejection (nut to fist sized) lava flows	SP Crater, Arizona (Figure 5.14); Parícutin, Mexico (Figure 5.15); Eldfell, Iceland (Figure 5.44)
Continental calderas	Rhyolite	High	Broad uplift with large summit depression	Tephra	Yellowstone caldera; Mount Mazama (Figure 5.17)

Source: Data partially derived from Ollier, C., *Volcanoes.* Cambridge, MA: MIT Press, 1969.

continental crust. The higher silica content and higher volatile content make these volcanoes explosively unpredictable (Table 5.2). Stratovolcanoes are responsible for more than 80 percent of the volcanic eruptions in historic times and for most of the death and destruction caused by volcanoes throughout history.[9]

Explosive eruptions of stratovolcanoes are known as *Plinian-type eruptions*—named after the 17-year-old Roman boy Pliny the Younger, who first described this type of eruption at Mount Vesuvius in Italy in A.D. 79. During a Plinian-type eruption, such as Chaitén, a Chilean volcano shown in Figure 5.6b, tens of cubic kilometers of rock and pyroclastic debris may be ejected (Table 5.2). The pyroclastic material is propelled skyward by decompressed hot volatilies, forming a plume that may climb to more than 30 km (~18.6 mi.) into the atmosphere (Figure 5.8a). Although much of the pyroclastic debris will fall near the volcano, as discussed in the next section, fallout from an eruption plume is one of the effects of volcanoes that can have global impacts.

Lava Domes Similar to stratovolcanoes, **lava domes** are characterized by highly viscous felsic magma and are common along the Ring of Fire. Unlike stratovolcanoes, however, lava domes are relatively small and have low to moderate volatile content. Nevertheless, the high viscosity of the magma means that these volcanoes can explode and, therefore, present a serious hazard to anyone living in the area.

Lava domes often form in the vent of a stratovolcano days to years after an explosive eruption. Having exhausted much of the volatile content of the magma during the preceding eruption, the degassed high-viscosity lava slowly oozes out and cools, forming a steep-sided plug in the vent that may be only a few hundred meters high and a kilometer across (Figure 5.8b and Figure 5.9). A lava dome may grow in a single event immediately following an eruption or may grow episodically over decades, as did the Mount St. Helens dome following the 1980 eruption (see Case Study 5.3: Mount St. Helens). Once the vent is plugged, volatile content begins to build again

TABLE 5.2 Volcanic Explosivity Index (VEI)

VEI	Eruption Type	Typical Volcano Type	Eruption Behavior	Plume Height	Ejecta Volume	Frequency	Eruption Examples
0	Hawaiian	Shield	Effusive, not explosive	<100 m	<10,000 m^3	Constant	Kilauea (1983–present)
1	Hawaiian/ Strombolian	Shield, Cinder cone	Effusive, mildly explosive	100–1000 m	<10,000 m^3	Daily	Stromboli, Eldfell (1973)
2	Strombolian/ Vulcanian	Cinder cone, Stratovolcano	Mild	1–5 km	>1,000,000 m^3	Weekly	Galeras (1993), Mount Sinabung (2010)
3	Vulcanian/ Peléan	Stratovolcano, Lava dome	Severe	3–15 km	>10,000,000 m^3	Few months	Mount Unzen (1995), Nevado del Ruiz (1985), Soufriere Hills (1995)
4	Peléan/Plinian	Stratovolcano	Cataclysmic	10–25 km	>0.1 km^3	≥1 yr	Mount Pelée (1902), Eyjafjallajökull (2010)
5	Plinian	Stratovolcano	Cataclysmic	20–35 km	>1 km^3	≥10 yrs	Mount Vesuvius (A.D. 79), Mount St. Helens (1980), Chaitén (2008; Figure 5.6)
6	Plinian/Ultra-Plinian	Stratovolcano, Continental caldera	Colossal	> 30 km	>10 km^3	≥100 yrs	Krakatoa (1883), Mount Pinatubo (1991)
7	Ultra-Plinian	Continental caldera	Supercolossal	> 40 km	>100 km^3	≥1,000 yrs	Mazama (5600 B.C.), Tambora (1815)
8	Supervolcanic	Continental caldera	Megacolossal	> 50 km	>1,000 km^3	≥10,000 yrs	Yellowstone (640,000 B.C.), Toba (74,000 B.C.)

Source: Based on "Volcanic Explosivity Index," Wikipedia, http://en.wikipedia.org/wiki/Volcanic_Explosivity_Index.



FIGURE 5.7 Stratovolcano
Mount Shasta, in northern California, is the most voluminous volcano in the Cascade Range (85 cubic miles) and reaches an elevation of 4,322 m (~14,179 ft.). *(Duane E. DeVecchio)*

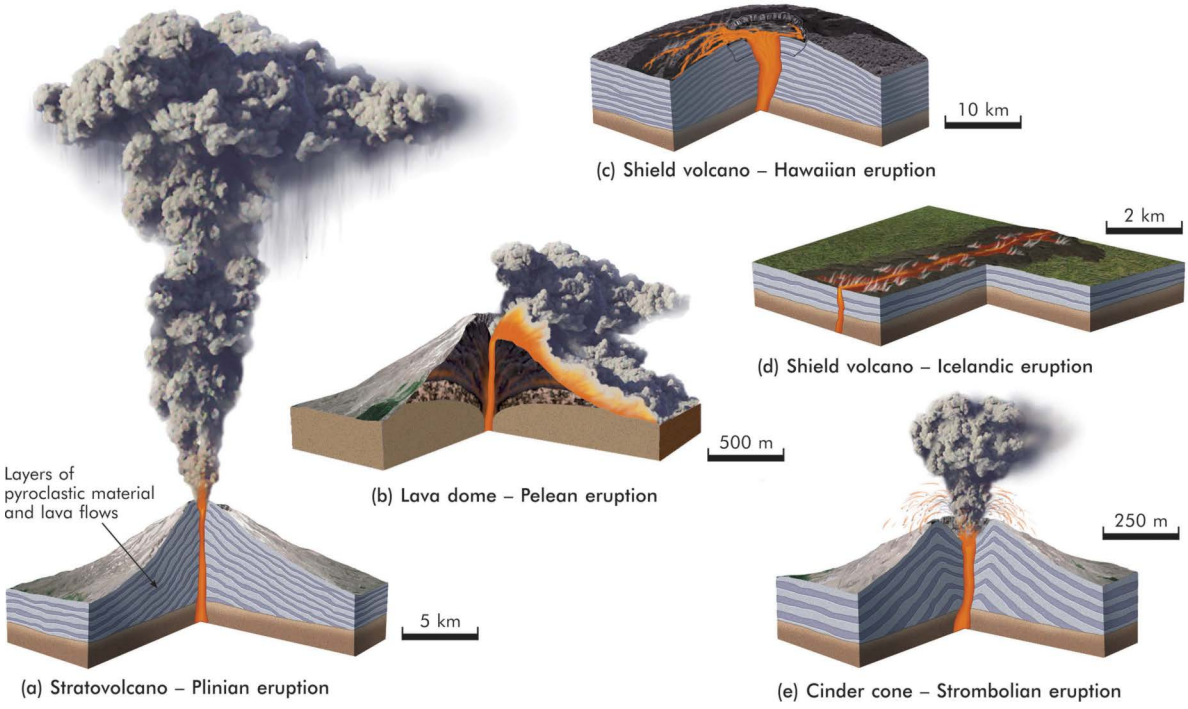


FIGURE 5.8 Volcanoes and Eruption Types
Most volcanoes will erupt numerous times over their lifetime, and although the eruption type is not unique to volcano type (see Table 5.2), characteristic eruption types for each of the different volcanoes is provided here. *(Based on "Icelandic eruption: types of volcanic eruption,"* Britannica Kids, *http://kids.britannica.com/comptons/art-156012/The-six-major-types-of-volcanic-eruptions-differin-their_Britannica)*



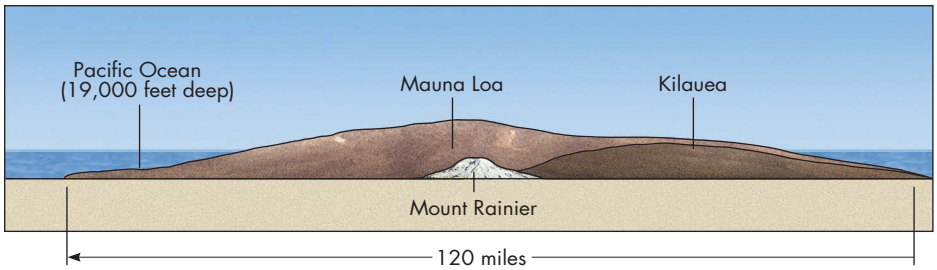
< FIGURE 5.9 Lava Dome
Glowing high-viscosity lava builds up in the vent of Japan's Mount Unzen. The large blocks of cooled magma periodically collapse, releasing trapped volatiles and causing a Peléan eruption. *(Stocktrek Images/SuperStock)*



< FIGURE 5.10 Shield Volcano
Peering above the clouds view, Mauna Loa, the largest shield volcano on Earth is located on the big island Hawaii. Notice the gently sloping profile of the volcano, similar to that of a warrior's shield lying on the ground. Dark patches are less vegetated regions that mark the locations where more recent low-viscosity basaltic lavas have flowed down the flank of the mountain. Note reddish basaltic cinder cones in the foreground. *(Duane E. DeVecchio)*

and periodic eruptions may occur during lava dome growth and collapse (Figure 5.8b). Collapse of a growing lava dome can cause explosive release of trapped volatiles and large destructive volcanic avalanches, such as those during eruptions of Mount Unzen in Japan between 1991 and 1995 (see Case Study 5.1: Mount Unzen). Mount Lassen in California similarly experienced a series of eruptions from 1914 to 1917, which included a tremendous horizontal (lateral) blast that affected a large area. These eruptions are known as *Peléan-type*, and have VEIs of 3 to 4 (see Table 5.2).

Shield Volcanoes The largest volcanoes in the world are **shield volcanoes**. They are common in the Hawaiian Islands, Iceland, and in the East African Rift (see Figure 5.3). Shield volcanoes are constructed from basaltic lavas and in profile appear as broad arc with gentle slopes (Figure 5.10). Because of the low viscosity of the lava, when a shield volcano erupts the lava can flow great distances away from the vent down the flanks of the volcano. An accumulation of thousands of thin basaltic lava flows over a large region gives these volcanoes their gentle slopes (Figure 5.10). Although shield volcanoes are much wider than they are tall, they are



< FIGURE 5.11
Volcano Dimensions
Comparison between the shape and size of a shield volcano (Mauna Loa and Kilauea) and a strato-volcano (Mount Rainier, one of the largest in the Cascade Range).

still among the tallest mountains on Earth when measured from their bases, which are often located on the ocean floor. By contrast, a stratovolcano constructed of viscous lava, such as Mount Rainier in Washington State, has a height more similar to its width (Figure 5.11).

Shield volcanoes are most common at hot spots in the oceanic lithosphere and at divergent plate boundaries and continental rifts, where decompression melting occurs (see Figure 5.4a). Because the lithosphere is thin in these environments, basaltic magma is able to rise rapidly to Earth's surface with little time to chemically evolve. The low-silica content and the absence of volatiles during magma formation mean these volcanoes erupt effusively rather than explosively. Consequently, rather than having an explosive crater near the vent, shield volcanoes develop a **caldera**, which forms by the inward collapse of the volcano top due to removal of magma from the subsurface (Figure 5.8c).

Effusive eruptions such as the ones that build shield volcanoes are known as *Hawaiian-type* eruptions, after the island of Hawaii, which is the most active and largest shield volcano on Earth (see Figure 5.10). Although these eruptions are not explosive, during the initial phase of a Hawaiian-type eruption, lava may shoot up more than 300 m (~1000 ft.), forming a "fire fountain" like the one that formed at Pu'u 'Ō'ō' crater on Hawaii in 1983 (see Figure 5.6a). The passive behavior of these types of eruptions encourages large groups of geotourists to flock to Hawaii or Iceland with the hope of seeing lava flowing across the surface. By contrast, when a stratovolcano like Mount St. Helens or Pinatubo in the Philippines erupts, large areas must be evacuated (see Figure 5.6b).

Another type of effusive eruption, known as an *Icelandic-type* eruption, occurs when basaltic lava erupts from an elongate fissure rather than from a central vent, producing what is called a "curtain of fire." The absence of a central vent means that shield volcanoes constructed from Icelandic-type eruptions are typically smaller and characterized by a broad and flat upland surface (Figure 5.8d). Fissure eruptions, similar to Icelandic-type eruptions, also occur on the flanks of shield volcanoes, such as the 2011 Kamoamoa eruption on Kilauea shield volcano in Hawaii (Figure 5.12).



< FIGURE 5.12 Fissure Eruption
Lava fountaining from the 2.3 km (~1.4 mi.) long fissure during the 2011 Kamoamoa eruption on Kilauea, a shield volcano. *(Jay Robinson/NPS)*

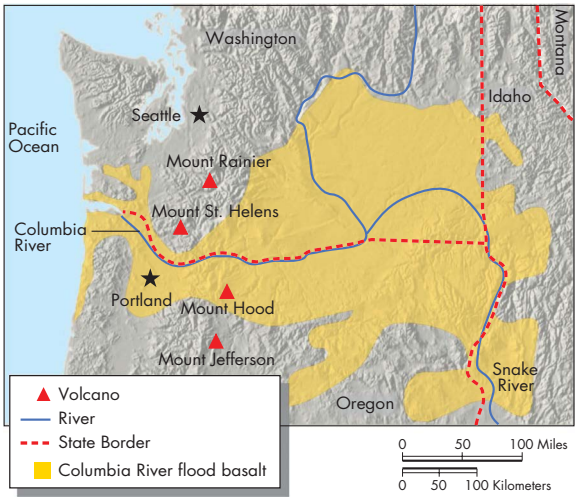


FIGURE 5.13 Columbia River Flood Basalts
From approximately 17 to 15.5 million years ago, thousands of basalt flows poured out onto the surface of the Pacific Northwest, blanketing the states of Washington, Oregon, and Idaho in volcanic rock that locally reaches a thickness of 3500 m (~11,000 ft).

Although the preceding paragraphs have emphasized that eruptions of low-volatile content basaltic magma are typically nonexplosive with VEIs of 0 to 1 (Table 5.2), don't be tricked into believing that there is no hazard associated with basaltic eruptions. Some of the largest and most catastrophic eruptions in Earth's history have been Icelandic-type eruptions of basaltic magma. Many of these massive outpourings of lava, called *flood basalts*, are correlated to sudden loss of large numbers of plant and animal species on Earth (see Chapter 14). The best-known accumulation of flood basalts in the United States is the Columbia Plateau in Washington, Oregon, and the Snake River Plain in Idaho (Figure 5.13). These flood basalts cover about 130,000 km^2 (~50,000 $mi.^2$), an area slightly larger than the state of Mississippi.

Basaltic eruptions can also be explosive when magma comes into contact with groundwater, snow, or ice, which can cause large steam blasts creating pyroclastic debris that may rise 10 km (~6.2 mi.) into the atmosphere (see Applying the 5 Fundamental Concepts: Eyjafjallajökull 2010 Eruption). These types of eruptions are known as *phreatomagmatic* or *Vulcanian-type* eruptions and can have a VEI as high as 3.

Cinder Cones Built up by the accumulation of volcanic rock near a volcanic vent, **cinder cones** are relatively small and composed of nut- to fist-sized pieces of vesicular red or black lava (Figure 5.14).[10] Scoria, the name for vesicular mafic volcanic rock, forms when basaltic magma with intermediate amounts of volatile

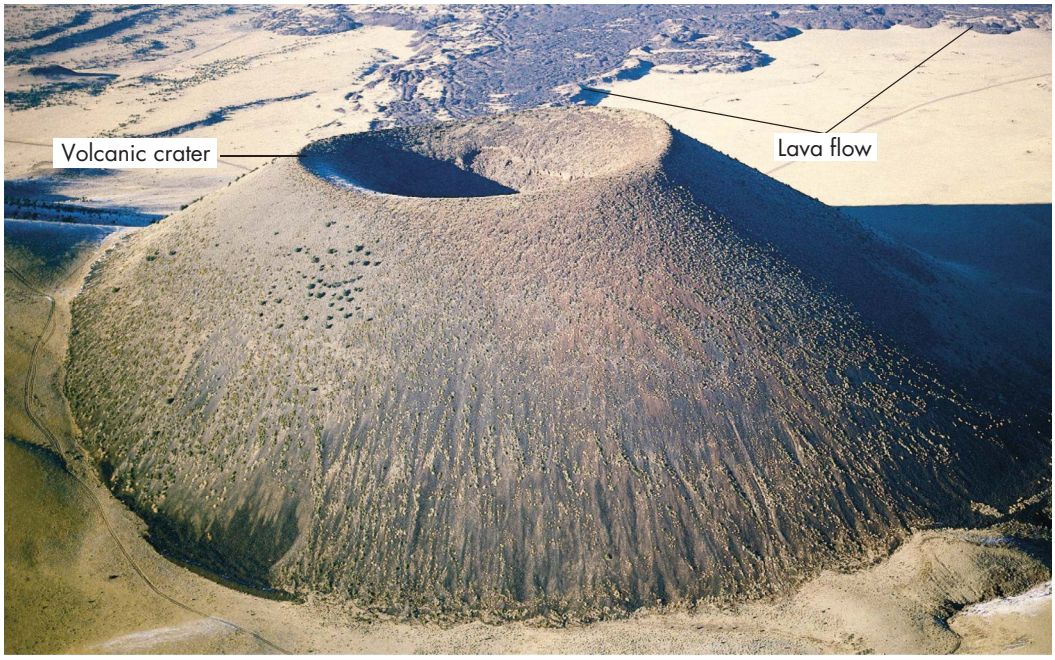


FIGURE 5.14 Cinder Cone
SP Crater, a cinder cone with a small crater at the top in the San Francisco Peaks volcanic field near Gray Mountain, Arizona. The lava flow in the upper part of the photograph originated from the base of the cinder cone and extends about 6 km (~4 mi.). *(Michael Collier)*

content is explosively ejected, cools, and falls to the ground (Figure 5.8e). The conical shape of the volcano comes from the accumulation of loose scoria around the vent; therefore, these volcanoes are also called *scoria cones*. Scoria formed at cinder cones is the "lava rock" used widely in commercial landscaping, and the vesicles, which are small holes formed by bubbles in the magma, indicate that this mafic lava had intermediate volatile contents.

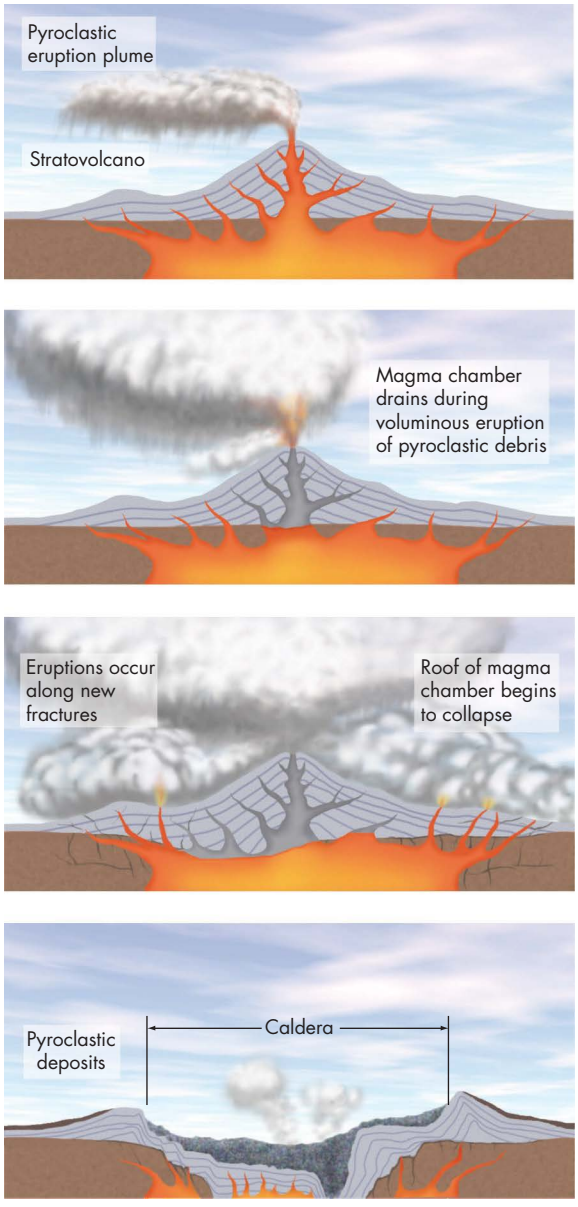
Basaltic eruptions with intermediate explosivity are known as *Strombolian-type* eruptions—named for the volcano Stromboli offshore southwestern Italy. Strombolian-type eruptions are more explosive than Hawaiian-type eruptions due to a higher volatile content (Table 5.2) but are similarly associated with lava flows. Because basaltic magma is the most common type of magma formed in most tectonic settings, it is common for small amounts to reach the surface forming a small cinder cone. As such, cinder cones are common on the flanks of larger volcanoes, along normal faults, and along cracks or fissures.

The Parícutin cinder cone in the Itzicuaro Valley of central Mexico, about 320 km (~200 mi.) west of Mexico City, offered a rare opportunity to observe the birth and rapid growth of a volcano at a location where none had existed before (Figure 5.15). On February 20, 1943, following several weeks of earthquakes and sounds like thunder coming from beneath Earth's surface, an astounding event occurred. As Dionisio Pulido was preparing his cornfield for planting, he noticed that a hole he had been trying to fill for years had opened in the ground at the base of a knoll. As Señor Pulido watched, the surrounding ground swelled, rising more than 2 meters (more than 6 ft.), while sulfurous gases and ash began billowing from the hole. By that night, the hole was ejecting glowing-red rock fragments high into the air. By the next day, the cinder cone had grown to 10 m (~33 ft.) high as rocks and ash continued to be blown into the sky by the eruption. After only five days, the cinder cone had grown to more than 100 m (~330 ft.) high. In June 1944, a fissure opened in the base of the cone that was now 400 m (~1300 ft.) high. The fissure produced a basaltic lava flow that overran the nearby village of San Juan Parangaricutiro, leaving little but the church steeple exposed. No one was killed in these eruptions, and within a decade, Parícutin cinder cone became a dormant volcano. Nevertheless, over nine years more than a billion cubic meters (~1.3 billion cubic yards) of ash and 700 million m^3 (~900 billion $yd.^3$) of lava were erupted from Señor Pulido's cornfield. Crops failed, especially when buried by ash faster than they could grow, and livestock sickened and died. Although several villages were relocated to other areas, some residents moved back to the vicinity of Parícutin. Locating property boundaries has been difficult because markers are generally covered by ash and lava, resulting in many land ownership disputes.[10]



▲ FIGURE 5.15 Rapid Growth of a Volcano
In this 1943 photograph, Parícutin cinder cone in central Mexico is erupting a cloud of volcanic ash and gases (background). A basaltic lava flow has nearly buried the village of San Juan Parangaricutiro, leaving only the church steeple exposed. *(© Getty Images/Evans/Stringer)*

Continental Caldera The largest and most violent eruptions occur when calderas form due to collapse of the land surface or volcanic edifice following partial emptying of the magma chamber (Figure 5.16). Unlike the passive formation of a caldera on a shield volcano, this inward collapse causes an explosive release of the magma and the volatiles that still remain in the magma chamber. Fortunately, these eruptions are rare and none have occurred in the United States in the past few thousand years. However, at least 10 such eruptions have occurred in the past million years, three of which were in North America. Large caldera-forming eruptions, known as *ultra-Plinian* type, may explosively extrude more than 100 km^3 (~62 $mi.^3$) of pyroclastic debris consisting mostly of ash (see Table 5.2). A quantity this large would cover the island of Manhattan to a height of about 1.6 km (~1 mi.)—four times the height of the Empire State Building. This volume is approximately 1,000 times the amount of ash ejected by the 1980 eruption of Mount St. Helens! Ash deposits from such an eruption could be 100 m (~300 ft.) thick near the crater's



▲ FIGURE 5.16 Large Calderas Form by Explosion and Collapse

Large calderas, such as the one illustrated here, generally form by explosion and subsequent collapse of the magma chamber below a composite volcano. The resulting depression may be 20 km (~12 mi.) or more in diameter. This process may occur once, like Crater Lake in Oregon, or multiple times, like the formation of resurgent calderas in Yellowstone National Park, Wyoming. *(Based on Smith, G. A., and Pun, A. How does Earth Work? Physical Geology and the Process of Science. © 2006 Upper Saddle River, NJ: Pearson Prentice Hall)*

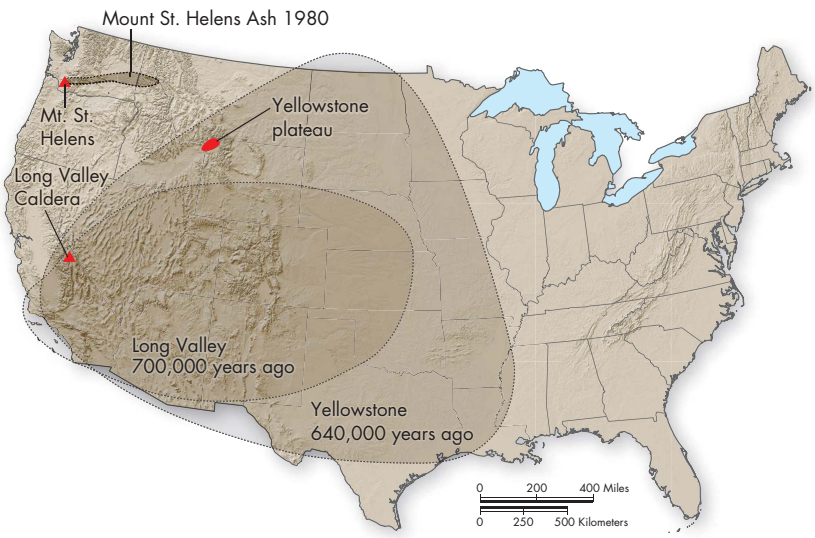
rim and a meter (~3 ft.) or so thick 100 km (~60 mi.) away from the source.[11] Crater Lake in Oregon fills the caldera that formed following the 5677 B.C. eruption of Mount Mazama (Figure 5.17). Other notable historic ultra-Plinian eruptions include the 1815 Tambora and 1883 Krakatau explosions in Indonesia.

The largest caldera eruptions are known as the *supervolcanic*-type (see Table 5.2). These eruptions are associated with rhyolitic magmas having very high volatile content. The high silica and volatile content suggests that significant amounts of continental crust have been melted and mixed with the magma. This mixing occurs in areas where large volumes of magma are generated and must rise through thick felsic crust, such as when a hot spot is located beneath continental lithosphere (see Figure 5.4d). The most recent incident occurred 27,000 years ago in New Zealand. Today this caldera is the site of Lake Taupo, a famous trout fishery on North Island. The eruption ejected between 1000 and 2000 km^3 (~240–480 $mi.^3$) of volcanic ash and created a caldera that has an area of 616 km^2 (~238 $mi.^2$). The best-known caldera-forming eruptions in North America occurred about 640,000 years ago at Yellowstone National Park in Wyoming and 780,000 years ago in Long Valley, California. These eruptions that blanketed large parts of North America in ash (Figure 5.18) would devastate the U.S. economy and food production capabilities, not to mention the negative impacts on global climate change, if they happened today. Although the most recent volcanic eruptions at Long Valley occurred about 400 years ago, potential hazards from a future volcanic eruption do still exist. In the early 1980s, measurable uplift of the land accompanied by swarms of earthquakes up to **M** 6 suggested that magma was moving upward at Long Valley. This prompted the U.S. Geological Survey (USGS) to issue a potential volcanic hazard warning that was subsequently lifted. Although activity at Long Valley has subsided, the future remains uncertain.

The main events in a caldera-producing eruption can occur quickly—in a few days to a few weeks—but intermittent, lesser-magnitude volcanic activity can linger on for a million years. Caldera-producing eruptions at Yellowstone have left us hot springs and geysers, including Old Faithful, whereas the Long Valley eruption has left us a potential volcanic hazard. In fact, both sites are still capable of producing volcanic activity because magma is present at shallow depths beneath the caldera floors. Both are considered *resurgent calderas* because their floors have slowly domed upward since the explosive eruptions that formed them.



< FIGURE 5.17 Crater Lake Caldera
Aerial view of Crater Lake, Oregon, which was produced by an explosive eruption of Mount Mazama around 7,700 years ago. Crater Lake is 8 by 10 km (~5 by 6 mi.) across and almost 600 m (~2000 ft.) deep, making it the second deepest lake in North America. Originally a stratovolcano around 1200 m (~4000 ft.) higher than it is today, the explosion and subsequent collapse of the caldera took place in an eruption that was 42 times greater than the 1980 eruption of Mount St. Helens. Each year close to 500,000 people visit Crater Lake National Park. *(USGS)*



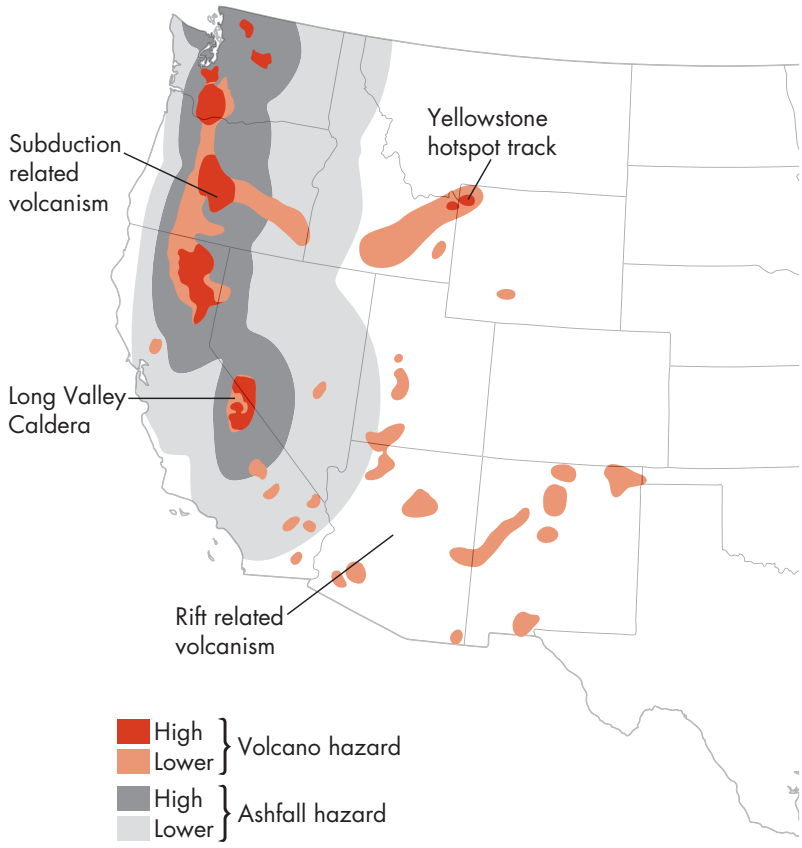
< FIGURE 5.18 Ash Fall Hazard
Caldera-forming eruptions, like the most recent eruptions at Yellowstone and Long Valley, can affect a very large area. Distribution of heavy ash fallout from the 1980 Plinian eruption of Mount St. Helens is shown for comparison.

5.2 CHECK your understanding

1. How is a volcanic crater different from a caldera?
2. Describe the major types of volcanoes and their composition.
3. What characteristic of a volcano controls its shape, and how?
4. How are Icelandic-type and Hawaiian-type eruptions different and the same?
5. Both stratovolcanoes and lava domes form in the same tectonic setting and have similar composition, but why do they have different explosive behavior?
6. Explain how large caldera eruptions occur and why they are so dangerous.

5.3 Geographic Regions at Risk from Volcanoes

Like earthquakes, volcanoes are intimately related to plate tectonics and most occur along the Ring of Fire surrounding the Pacific Ocean basin (see Figure 5.3). Areas outside the Ring of Fire can also experience volcanoes because of hot spot activity (Yellowstone) or because they are located on a portion of the mid-ocean ridge (Iceland). East Africa has volcanism related to the rifting, or pulling away from one another, of three tectonic plates. Also large, infrequent eruptions at Long Valley and those centered in Yellowstone National Park in North America indicate that these areas may be at risk in the future. The area at highest risk of local volcanic activity in the contiguous United States and Canada



< FIGURE 5.19 United States Volcanic Hazards
Volcanic hazards for the contiguous United States based on activity during the past 15,000 years. Red colors show high and lower risk of local volcanic activity, whereas gray colors show regions at risk of receiving 5 cm (~2 in.) or more of ash fall from large explosive eruptions. The hazard belt in Washington State continues north into southern British Columbia. *(U.S. Geological Survey)*

is in the mountainous regions of the Pacific Coast and at Yellowstone (Figure 5.19). Other isolated areas of the U.S. Southwest are at risk, whereas the eastern two-thirds of the United States and Canada is risk free of local volcanic activity. However, the effects of a large caldera explosion in the western United States or Canada would likely be felt far from the source in the form of ash fall and ash clouds in the atmosphere.

5.3 CHECK your understanding

1. What part of the United States has the greatest volcanic hazard, and why?
2. Why is there no volcanic hazard on the East Coast of the United States and Canada?

5.4 Effects of Volcanoes

Worldwide, 50 to 60 volcanoes erupt each year.[12] With the exception of the Kilauea volcano on the big island of Hawaii, which has been erupting continuously since 1983, eruptions in the United States occur two or three times per year, mostly in Alaska. Eruptions are often in sparsely populated areas of the state, causing little, if any, loss of life or economic damage. However, when an eruption takes place near a densely populated area, the effects can be catastrophic (Table 5.3).[13] Approximately 500 million people on Earth live close to volcanoes, and as the human population grows, more and more people are living on the flanks, or sides, of active or potentially active volcanoes. In the past 100 years, nearly 100,000 people have been killed by volcanic eruptions—approximately 28,500 lives were lost in the decade of the 1980s alone.[12,13] Densely populated countries with many active volcanoes, such as Japan, Mexico (especially near Mexico City), the Philippines, and Indonesia, are particularly vulnerable.[14] Several active or potentially active volcanoes in the western United States are near cities, such as Seattle, with populations of more than 720,000 people (Figure 5.20).

Volcanic hazards include the *primary effects* of volcanic activity, which are the direct results of an eruption, and the *secondary effects*, which may be caused by the primary effects. Lava flows, pyroclastic activity such as ash fall, pyroclastic flows and lateral blasts, and release of volcanic gases are primary effects. Secondary effects include debris flows, mudflows, landslides or debris

TABLE 5.3 Selected Historic Volcanic Events

Volcano or City	Year	Effect
Mount Vesuvius, Italy	A.D. 79	Destroyed Pompeii and killed 16,000 people. City was buried by volcanic activity and rediscovered in 1595.
Skaptar Jokull, Iceland	1783	Killed 10,000 people (many died from famine) and most of the island's livestock. Also killed some crops as far away as Scotland.
Tambora, Indonesia	1815	Global cooling; killed 10,000 people and 80,000 starved; produced "year without a summer."
Krakatau, Indonesia	1883	Tremendous explosion; more than 36,000 deaths from tsunami.
Mount Pelée, Martinique	1902	Ash flow killed 30,000 people in a matter of minutes.
La Soufrière, St. Vincent	1902	Killed 2,000 people and caused the extinction of the Carib Indians.
Mount Lamington, Papua New Guinea	1951	Killed 6,000 people.
Villarica, Chile	1963–64	Forced 30,000 people to evacuate their homes.
Mount Helgafell, Heimaey Island, Iceland	1973	Forced 5,200 people to evacuate their homes.
Mount St. Helens, Washington, United States	1980	Debris avalanche, lateral blast, and mudflows; killed 57 people, destroyed more than 100 homes.
Nevado del Ruiz, Colombia	1985	Eruption generated mudflows that killed at least 22,000 people.
Mount Unzen, Japan	1991	Ash flows and other activity killed 41 people and burned more than 125 homes. More than 10,000 people evacuated.
Mount Pinatubo, Philippines	1991	Tremendous explosions, ash flows, and mudflows combined with a typhoon killed more than 740 people; several thousand people evacuated.
Montserrat, Caribbean	1995	Explosive eruptions and pyroclastic flows; south side of island evacuated, including capital city of Plymouth; several hundred homes destroyed.
Chaitén, Chile	2008	Explosive eruptions and pyroclastic flows: 5,000 people evacuated and disrupted aviation in South America for weeks.
Mount Merapi, Indonesia	2010	Multiple explosions and dome collapses; 320,000 people displaced, and more than 300 killed in Indonesia.
Eyjafjallajökull, Iceland	2010	Large ash emission: disrupted air travel in the United Kingdom and northern Europe for several weeks.

Source: Based on USGS Volcanic Activity Alert-Notification System and U.S. Geological Survey Fact Sheet 2006–3139.

avalanches, floods, fires, and tsunamis (discussed in Chapter 4). At the planetary level, global cooling of the atmosphere for a year or so is a secondary effect of a large eruption.[11]

LAVA FLOWS

A **lava flow** is one of the most familiar products of volcanic activity. Lava flows result when magma reaches the surface and overflows the central crater or erupts from a volcanic vent along the flank of the volcano. The three major types of lava take their names from the volcanic rocks they form: basaltic—by far the most abundant of the three—andesitic, and rhyolitic.

Lava flows can be quite fluid and move rapidly or be relatively viscous and move slowly. Basaltic lavas, which have lower viscosity and higher eruptive temperatures, are the fastest and can move 15–35 km (~10–20 mi.) per hour near the vent. Called *pahoehoe* (pronounced pa-hoy-hoy), these lavas have a smooth, sometimes ropey surface texture when they harden (Figure 5.21a). As the lava cools, it becomes more viscous and may move only a few meters (around 6 to 10 ft.) per day. Called *aa* (pronounced ah-ah), these flows have a blocky surface texture after cooling and hardening (Figure 5.21b). With the exception of some flows on steep slopes or near to the vent, most lava flows are slow enough for people to easily move out of the way as they approach.[15]

In addition to flowing down the sides of a volcano, lava can move away from its source in other ways. Magma can move for many kilometers just below the surface in *lava tubes* (Figure 5.22a). The rock walls of these tubes insulate the magma, keeping it hot and fluid for great distances. When an eruption ends the lava will



▲ FIGURE 5.20 Locations of Volcanoes in the United States
Index maps show locations of active and potentially active volcanoes and nearby population centers (not all labeled) of the United States. There are at least 11 active and potentially active volcanoes in British Columbia and the Yukon Territory. *(From Wright, T. L., and Pierson, T. C., U.S. Geological Survey Circular 1073, 1992)*

drain from the tube, leaving behind a sinuous cavern system (Figure 5.22b). These form natural pipes for movement of groundwater and may cause engineering problems when encountered during construction projects.

Lava flows from rift eruptions on the flank of Kilauea in Hawaii began in 1983 with the eruption of Pu'u 'Ō'ō' crater (see Figure 5.6a), which has become the longest and largest eruption of Kilauea in history.[4] Most of the time, tubes carry the lava for more than 9.5 km (~6 mi.) from the crater to the coast where it enters the sea, but periodic eruptions from the tubes and overland flow have caused significant damage. By 2005, more than 50 structures in the village of Kalapana were destroyed by lava flows, including the National Park Visitors Center. Lava flowed across part of the famous Kaimu Black Sand Beach and into the ocean. The village of Kalapana has virtually disappeared, and it will be many decades before much of the land is productive again. On the other hand, the eruptions, in concert with beach processes, have produced new black sand beaches. Black sand is produced when the molten lava enters the relatively cold ocean water and shatters into sand-sized particles.



(a)



(b)

FIGURE 5.21 Lava Flows

(a) Pahoehoe Lava Flow. The basaltic lava flow surrounding and destroying this home at Kalapana, Hawaii, in 1990 has the characteristic smooth surface texture of most pahoehoe. Such flows destroyed more than 100 structures, including the National Park Service Visitors Center. Some pahoehoe flows are referred to as ropey lava because the surface texture can look like a piece of rope lying on its side as if it were coiled. *(Bettmann/Corbis).* (b) Aa Lava Flow. This active aa lava flow is moving over an earlier flow of solidified pahoehoe lava. Both aa and pahoehoe are common types of basaltic lava; aa has a blocky surface that develops from cooler, thicker, slower-moving, and less fluid lava. *(Corbis)*



(a)



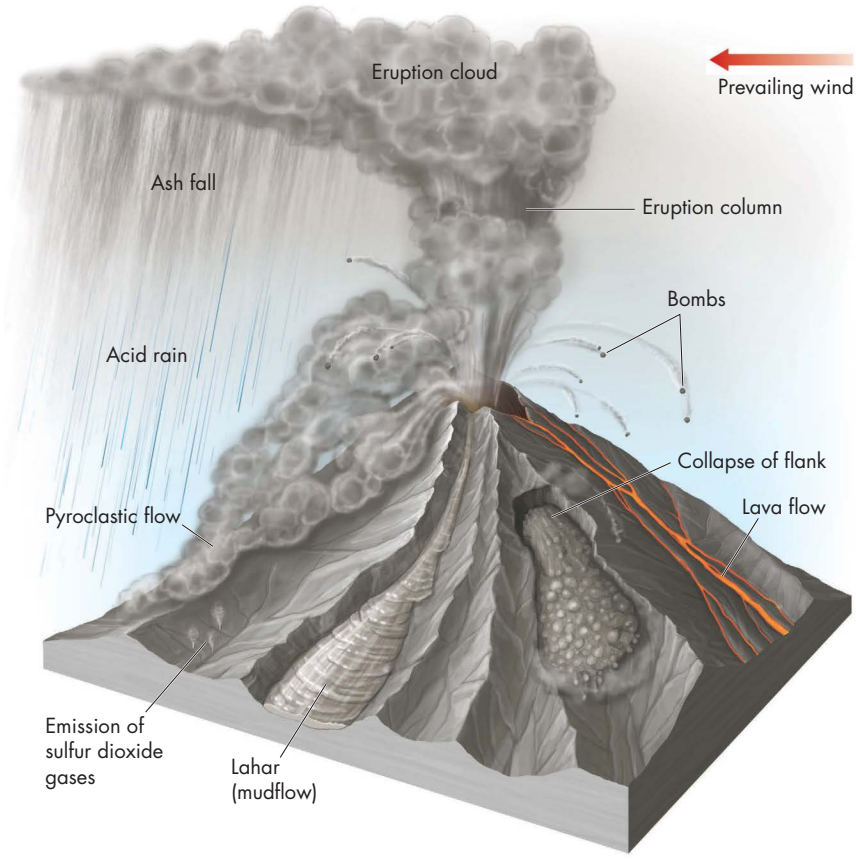
(b)

FIGURE 5.22 Lava Tubes

Magma can move many kilometers below ground in tunnels called lava tubes that form below cooled crusts of basaltic lava. Both active and drained tubes can be hazards when roofs collapse. (a) Holes, called skylights, develop in the roof of some active tubes such as this one on the Kilauea volcano in Hawaii. *(Jeffrey B. Judd/USGS)* (b) Older drained tubes, such as the Thurston (Nahuku) lava tube shown here near the summit of Kilauea, are attractions for tourists. *(Simone Genoese/Alamy Stock Photo)*

PYROCLASTIC ACTIVITY

Pyroclastic activity refers to explosive volcanism in which magma and the rocks that compose the volcano are physically blasted from a volcanic vent into the atmosphere forming *pyroclastic debris* (Greek *pyro*, "fire," and *klastos*, "broken"). Pyroclastic debris is known as **tephra** and can range from fine dust to sand-sized ash less than 2 mm (~0.1 in.), to small gravel-sized *lapilli* 2 to 64 mm (~0.1 to 2.5 in.), to large angular *blocks* and smooth-surfaced *bombs* greater than 64 mm (~2.5 in.). Tephra entrained in the hot, low-density, rising gases will form an *eruption column* that is carried skyward until it cannot rise any longer or is blown by prevailing winds, forming an eruption cloud (Figure 5.23). Like the old saying, "What goes up must come down," tephra may come down cool and lightly like falling snow, or hot, fast, and heavy like a freight train. Accumulation of tephra forms a **pyroclastic deposit** that when deposited hot can be fused to form a *pyroclastic rock*.



< FIGURE 5.23 Pyroclastic Activity
Tephra ejected from an erupting volcano is responsible for numerous hazards related to volcanic eruptions.

Fall Volcanic ash develops due to explosive fragmentation of magma during an eruption. This ash can cover hundreds or even thousands of square kilometers and if it reaches high enough it can encircle the globe making it the farthest reaching volcanic hazard. **Ash fall** occurs downwind of the volcano as the fine particles carried aloft cool and fall back toward Earth's surface (Figure 5.23). Towns and agricultural lands upwind of the volcano will likely be unaffected by ash fall during the eruption. The thickness of the ash fall in any one location will be controlled by the amount and duration of ash ejection, local and regional wind patterns, and distance from the volcano—decreasing thickness with increasing distance. Ash fallout creates several direct hazards:

- Vegetation, including crops and trees, may be destroyed.
- Surface water may be contaminated by sediment and toxic compounds. The very fine particles clog the gills of fish and kill other aquatic life. Chemical coatings on the ash can cause a temporary increase in the acidity of the water, which may last for several hours after an eruption ceases.
- Structural damage to buildings may occur as ash piles up on roofs (Figure 5.24). As little as 1 centimeter (~0.4 inch) of ash can place an extra 2.5 tons of weight on an average house with a 140 m^3 (~1500 $ft.^3$) roof.
- Health hazards, such as irritation of the respiratory system and eyes, are caused by contact with volcanic ash and associated caustic fumes.[13]
- Engines of jet aircraft may "flame out" as melted silica-rich ash forms a thin coating of volcanic glass in the engines. In 1989, a KLM 747 jet on the way to Japan flew though a cloud of volcanic ash from Redoubt volcano in Alaska. Power to all four of its jet engines was lost and the plane began a silent, 4270 m (~14,000 ft.) fall before the engines could be restarted.[16] Since this event, Federal Aviation Administration (FAA) guidelines limit air traffic near volcanic ash clouds (see Applying 5 Fundamental Concepts: Eyjafjallajökull 2010 Eruption).

Pyroclastic Flows One of the most lethal aspects of volcanic eruptions is **pyroclastic flow** (Figure 5.23). Unlike ash fallout, these flows of pyroclastic



FIGURE 5.24 Volcanic Tephra on Buildings
Fall out of ash and cinders may completely bury houses and increase the load on walls and roofs causing structural collapse. *(PhotoAlto sas/Alamy)*

debris are hot and race down the side of the volcano, attaining speeds in excess of 400 km/hr (~250 mph).[12] The gases within the flow can reach temperatures of 1000°C (~1830°F), which is hot enough to incinerate any organic matter in its path. Pyroclastic flows are also known as ash flows, hot avalanches, or *nuée ardentes* (French for "glowing clouds"). As the pyroclastic flows move down the side of the mountain, hot expanding gases carry low-density ash upward, forming a billowing gray cloud that rises above the higher-density base of the flow. In addition to ash, the base of the flow contains larger debris such as pumice, rock fragments, and whatever else the flow sweeps up off the surface on its way down the mountain. Pyroclastic flows are associated with Peléan-, Plinian-, Ultra-Plinian- and supervolcanic-type eruptions (see Table 5.2). Overall, these flows have killed more people than any other volcanic hazard in the past 2,000 years.[17]

Pyroclastic flows can be catastrophic if a populated area is in their path. A tragic example occurred in 1902 on the Caribbean island of Martinique. On the morning of May 8, a flow of hot, glowing ash, steam, and other gases roared down Mount Peleé and through the town of St. Pierre, killing an estimated 30,000 people. A jailed prisoner was one of only two survivors, and he was severely burned and horribly scarred. Reportedly, he spent the rest of his life touring circus sideshows as the "Prisoner of St. Pierre." The second survivor was a shoemaker who ran inside a building. Although he was burned, he escaped being suffocated by the ash that killed nearly everyone else. Flows like these have occurred on volcanoes of the Pacific Northwest, Alaska, and Japan in the past and also can be expected to occur in the future.

Pyroclastic flows form by three different volcanic processes:

1. During large ash-generating eruptions (VEI > 3), the eruption column is loaded with pyroclastic debris. Although this debris is denser than the surrounding atmosphere, it is carried upward by the hot expanding gases erupting from the volcanic crater. However, an increase in the density of the pyroclastic debris aloft or a decrease in the upward thrust of the gases can cause parts of the eruption column to collapse, forming a flow of hot pyroclastic material down the eruption column and the flank of the volcano (Figures 5.23 and 5.25). Multiple collapses of the eruption column during the A.D. 79 eruption of Mount Vesuvius killed more than 16,000 people living in the Roman towns of Pompeii and Herculaneum. Buried beneath as much as 20 m (~65 ft.) of pyroclastic debris, the remains of the towns and many of the residents who died there lay undisturbed for about 1,500 years before being unearthed (Figure 5.26).
2. Pyroclastic flows known as **lateral blasts** form when an explosion destroys part of the volcano, ejecting hot gases and pyroclastic debris horizontally from the side of the mountain rather than vertically. These are the fastest-moving pyroclastic flows that can mow down entire forests in their path (see Case Study 5.3: Mount St. Helens).
3. Lava dome collapse is the most common volcanic process that causes pyroclastic flows. Recall that lava domes are made of extremely viscous

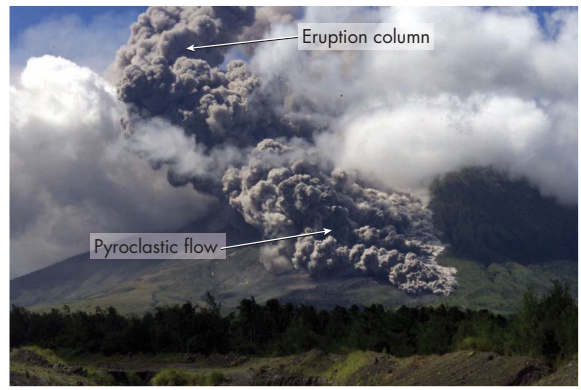


FIGURE 5.25 Pyroclastic Flow
A dense flow of superheated ash, pumice, and rock fragments cascade down the slopes of Mayon Volcano in the Philippines during the 2006 eruption. The pyroclastic flow was caused by partial collapse of the eruption column. *(AP Photo/Bullit Marquez)*



FIGURE 5.26 Plaster Casts of Volcano Victims
In A.D. 79, pyroclastic flows from Mount Vesuvius destroyed the Roman towns of Pompeii and Herculaneum, killing more than 16,000 people. Archaeologists have excaveted the remains of some 2,000 people asphyxiated in the eruption. Plaster casts of molds of the victims reveal adults, children, and dogs in their death positions. Pompeii was buried by up to 3 m (~10 ft.) of ash and pumice, and Herculaneum was excavated from beneath 20 m (~65 ft.) of volcanic debris. *(Jim Zuckerman/Alamy Stock Photo)*

magma that often forms a plug in a volcanic vent, causing volatiles to build within the magma (see Figure 5.9). Over years to centuries, periodic growth of the lava dome may cause the steep flanks of the dome to collapse, decompressing the volatiles that lie beneath. The avalanche of volatile-rich boulders and fresh magma continues to explosively decompress forming the characteristic gray billowing ash cloud as the hot material makes its way down the mountain, as happened at Mount Unzen in 1991 (see Case Study 5.1: Mount Unzen).

5.1 CASE study

Mount Unzen

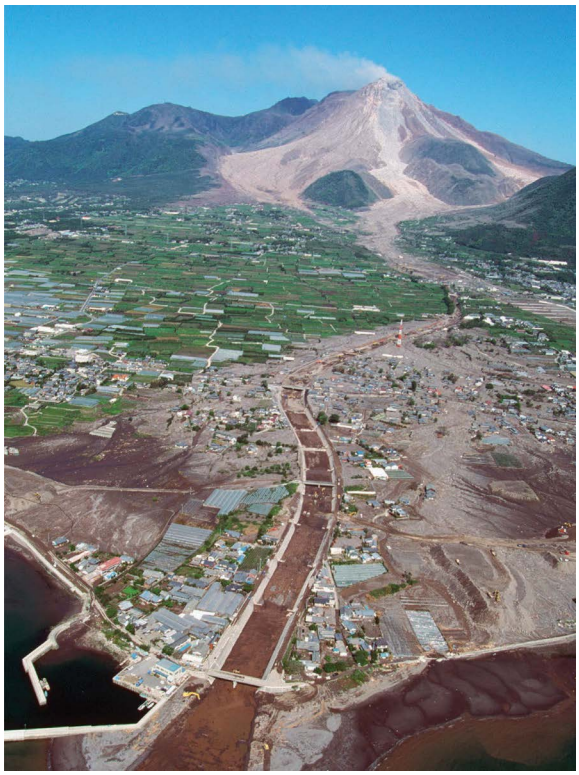
Just over 220 years ago, Mount Unzen in southwestern Japan erupted, triggering both a volcanic avalanche that devastated the center of Shimabara City on its way to the sea and a tsunami that killed an estimated 15,000 people. The volcano then lay dormant until November 1989 when a swarm of earthquakes was detected 20 km (~12 mi.) beneath the volcano, signaling an awakening of the mountain. Over the next 12 months earthquake foci became shallower and migrated toward the summit of the mountain, indicating movement of molten rock toward the summit. Explosive eruptions began in November 1990 and continued episodically for the next five years. During this period, Mount Unzen produced more than 9,000 pyroclastic flows due to lava dome growth and collapse.[18] The great number and regularity of pyroclastic flows produced at Unzen attracted numerous volcanologists interested in studying these flows to Japan (Figure 5.27).[12,14] The numerous pyroclastic flows also resulted in large accumulations of volcanic debris on the flanks of the volcano, which could spell disaster during the rainy season. Given Shimabara's



FIGURE 5.27 Pyroclastic Flow from Mount Unzen
The gray cloud on the forested slope of Mount Unzen at the top of the photo is moving rapidly downslope toward a village in the June 1991 eruption. The cloud is a pyroclastic flow of extremely hot gases, volcanic ash, and large rocks. Both the firefighters in the truck and the individual are running for their lives. Fortunately, the flow stopped before reaching both the firefighters and the village. *(© Getty Images/Mike Lyvers)*

history with Mount Unzen, specially designed debris flow channels were constructed through the center of town to divert volcanic mudflows. Unfortunately, frequent debris flows caused overtopping of the levees and destroyed more than 1,700 buildings (Figure 5.28).

In May 1991, monitoring of the volcano indicated the potential for increased pyroclastic activity so more than 12,000 people were evacuated from the area. But before evacuation was complete, on June 3, 1991, a landslide triggered by an earthquake caused a devastating pyroclastic flow that killed 43 people, including three volcanologists. By the end of 1993, Mount Unzen had produced about 0.2 km^3 (~0.05 $mi.^3$) of lava.



▲ FIGURE 5.28 Mount Unzen
The large mountain in the top center is Mount Unzen, one of Japan's 19 active volcanoes. Dormant for more than two centuries until 1991, the volcano threatens parts of Fukae Town and Shimabara City in the foreground. In the 1991 eruption, searing hot pyroclastic flows killed 43 people and burned a school and more than 600 homes. This 1993 aerial photograph shows a channel constructed to divert volcanic mudflows to the sea. *(Michael S. Yamashita/Corbis)*

VOLCANIC GASES

A number of gases, including water vapor (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S), are emitted during volcanic activity. Water and carbon dioxide make up more than 90 percent of all emitted gases. Toxic concentrations of hazardous volcanic gases rarely reach populated areas. A notable tragic exception occurred at Lake Nyos, a deep crater lake on a dormant volcano in the Cameroon highlands of West Africa. Over a period of time, carbon dioxide escaping from the crater floor accumulated in the sediment and the bottom waters of the lake. On an August night in 1986, with little warning other than a loud rumbling, Lake Nyos released a misty cloud of dense, mainly carbon dioxide gas. Nearly odorless, the gas cloud flowed from the volcano into valleys below, displacing the air. As the cloud lost its water droplets, it became invisible, spreading silently through five villages. The cloud traveled 23 km (~14 mi.) from Lake Nyos, suffocating 1,742 people, an estimated 3,000 cattle, and numerous other animals (Figure 5.29a and Figure 5.29b).[19]

Since 1986, Lake Nyos has continued to accumulate carbon dioxide in the bottom of the lake, and another release could occur at any time.[19] Although the lake area was to remain closed to all but scientists studying the hazard, thousands of people are returning to farm the land. Scientists have installed an alarm system at the lake that will sound if carbon dioxide levels become high. They have also installed a pipe from the lake bottom to a degassing fountain on the surface of the lake that allows the carbon dioxide gas to escape slowly into the atmosphere (Figure 5.29c). The hazard is being slowly reduced as the single degassing fountain is now releasing a little more carbon dioxide gas than is naturally seeping into the lake. Additional pipes with degassing fountains will be necessary to adequately reduce the hazard.

Sulfur dioxide, a gas that smells like gunpowder, is often released from volcanoes. It can be a direct hazard to people, and evacuations or area closures are ordered if large amounts are released. For example, in 2007 part of Crater Rim Drive at the Kilauea volcano in Hawaii was closed because of high levels of the gas. Sulfur dioxide can also react in the atmosphere to produce *acid rain* downwind of an eruption. Toxic concentrations of some chemicals emitted as gases may be adsorbed by volcanic ash that falls onto the land. In some cases, these chemicals have contaminated the soil and have been absorbed by plants that are eaten by people and livestock. For example, in 1783 a "dry fog" of sulfur dioxide gas from the eruption of the Skaptar Jokull volcano in Iceland blanketed much of Europe. The cloud



(a)



(b)



(c)

FIGURE 5.29 Poisonous Gas from Dormant Volcano

(a) Water in Lake Nyos, a crater lake in Cameroon, Africa, accumulated and then released immense volumes of carbon dioxide in 1986. A landslide into the lake triggered the carbon dioxide eruption and is responsible for the muddy water in this photograph. *(Thierry Orban/Sygma/Corbis)* (b) Aerial view of some of the 3,000 cattle that died by asphyxiation from the carbon dioxide. *(Peter Turnley/Corbis)* (c) Gas is being released from the bottom waters of Lake Nyos with a degassing fountain in 2001. *(Louise Gubb/Corbis)*

contained fluorine in the form of fine droplets of acidic hydrogen fluoride. These droplets contaminated pastures with fluorine and caused the death of grazing cattle in as little as two days.[20]

In Japan, volcanoes are monitored to detect the release of poisonous gases such as hydrogen sulfide. When releases are detected, sirens are sounded to advise people to evacuate to high ground to escape the gas.

Volcanoes can also create air pollution over larger areas. This pollution can take the form of volcanic smog, known as *vog* (volcanic material, "v," and fog, "og"), or a haze from steam plumes created by lava flowing into the ocean. For example, the eruptions of Kilauea in Hawaii since 1983 have at times produced vog mixed with acid rain downwind of the volcano. This combination has covered the southeastern part of the Big Island with a thick, blue acidic haze that far exceeds air quality standards for sulfur dioxide. Public health warnings have been issued because small, acidic aerosol particulates and sulfur dioxide concentrations can induce asthma attacks and cause other respiratory problems. Residents and visitors have reported breathing difficulties, headaches, sore throats, watery eyes, and flulike symptoms when exposed to vog. In addition, acid rain has made the water in some shallow wells and household rainwater-collection systems undrinkable. The acidic rainwater has dissolved lead from metal roofing and water pipes and may have caused elevated lead levels in the blood of some residents.[21] These eruptions have also produced nearly continuous lava flows into the ocean, resulting in steam explosions (Figure 5.30). Haze from the steam explosions contains corrosive hydrogen chloride gas from the vaporized seawater and tiny glass fragments that can irritate and sometimes damage eyes.[22]



FIGURE 5.30 Lava Creates Corrosive Steam Cloud
Volcanoes produce a wide range of hazards including toxic gases and corrosive clouds of steam. In this picture, lava from Hawaii's Kilauea volcano vaporizes seawater at temperatures of more than 1000°C (~1800°F). Flowing from the end of a lava tube, the molten rock creates a cloud of steam mixed with corrosive hydrogen chloride gas before it cools in the Pacific Ocean. *(Brocken Inaglory/Wikimeda)*



FIGURE 5.31 Volcanic Mudflow Catastrophe
Armero, Columbia was almost completely buried by a volcanic mudflow when pyroclastic fallout caused rapid melting of mountain snowpack during the 1985 eruption of Nevado del Ruiz stratovolcano. *(STf/AFP/Getty Images)*

DEBRIS FLOWS, MUDFLOWS, AND VOLCANIC LANDSLIDES

The most serious secondary effects of volcanic activity are **debris flows** and **mudflows**, known collectively by their Indonesian name, *lahar*. Lahars are produced when large amounts of loose volcanic ash and other tephra are saturated with water, become unstable, and suddenly move downslope. Debris flows differ from mudflows in that they are coarser; more than half of their particles are larger than sand grains. Unlike pyroclastic flows, lahars can occur without an eruption and are generally low-temperature flows.

Debris Flows Even relatively small eruptions of hot volcanic material may quickly melt large volumes of snow and ice on a volcano. This rapid melting produces a flood of meltwater that erodes the slope of the volcano to create a debris flow. Volcanic debris flows are fast-moving mixtures of fine sediment and large rocks that have a consistency similar to wet concrete. Debris flows can travel many tens of kilometers down valleys on the flanks of the volcano where they formed, which makes them particularly hazardous, like the one that destroyed Armero, Colombia, in 1985.

Nevado del Ruiz in northwestern Colombia is a stratovolcano that developed above the Andean subduction zone, which runs the length of the western coast of South America (see Figure 5.3). In November 1985 the volcano erupted, sending a Plinian-type eruption column about 30 km (~19 mi.) into the atmosphere. Successive collapse of the eruption column triggered pyroclastic flows that melted summit glaciers and unleashed a torrent of water. Floodwaters mixed with pyroclastic debris, forming a dense slurry that moved down the river valleys at 100 km (~60 mi.) per hour, sweeping up everything along the way. By the time the debris flows reached the mouth of the valley, 45 km (~28 mi.) downslope from where Armero was located, the volume of the flows had increased fourfold and had attained a maximum width of 50 m (~200 ft.). Armero was almost completely wiped out, killing three-quarters of the population, or about 21,000 people (Figure 5.31).

Mudflows Gigantic mudflows have originated on the flanks of volcanoes in the Pacific Northwest in both historic and prehistoric times. Two of these, the Osceola mudflow and the Electron mudflow, started on Mount Rainier (Figure 5.32). Approximately 5,000 years ago, the Osceola mudflow moved 1.9 km^3 (~0.5 $mi.^3$) of sediment a distance of more than 80 km (~50 mi.) from the volcano. This volume would fill the Mall between the U.S. Capitol and the Washington Monument with a pile of debris more than a mile high (10.5 times the height of the Washington Monument). Deposits of the younger, 500-year-old Electron mudflow extended about 56 km (~35 mi.) from the volcano.

Hundreds of thousands of people now live on the area covered by these old flows with no guarantee that similar flows will not occur again. Many areas southeast of Puget Sound are at potential risk for debris,

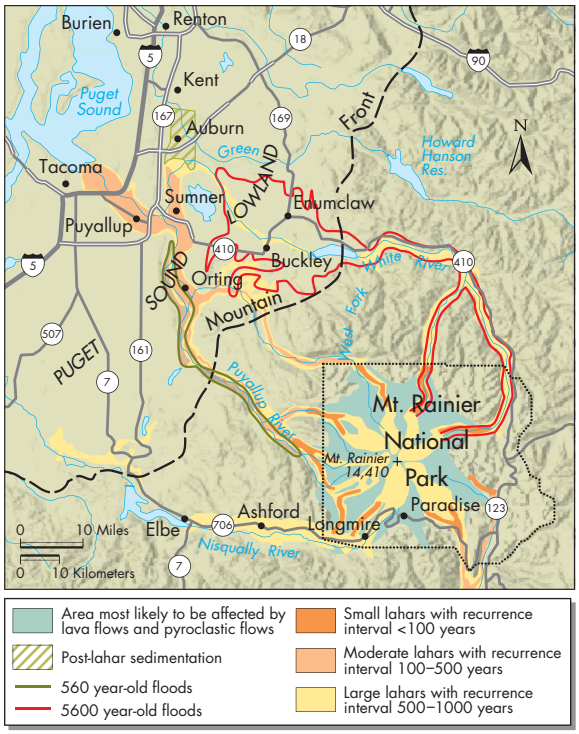


FIGURE 5.32 Mount Rainier Volcanic Hazard Map
Map of Mount Rainier and vicinity showing the extent of the 5,600-year-old Osceola mudflow in the White River Valley and the 560-year-old Electron mudflow in the Puyallup River Valley. Shaded areas show the modern potential hazards from lahars, lava flows, and pyroclastic flows. The Seattle/Tacoma suburbs of Puyallup, Sumner, Orting, and Auburn are all in potential hazard areas. *(Based on Crandell, D. R., and Mullineaux, D. R., U.S. Geological Survey Bulletin 1238, and Hoblitt and others, 1998, USGS Open-File Report 98–428)*

mud, lava, or pyroclastic flows from Mount Rainier (Figure 5.32). An observer in the valley would see a debris or mudflow as a wall of mud the height of a ranch house moving toward them at close to 30 km (~20 mi.) per hour. With the flow moving at 8.3 m (nearly 30 ft.) per second, the observer would need a car headed in the right direction toward high ground to escape being buried alive.[15]

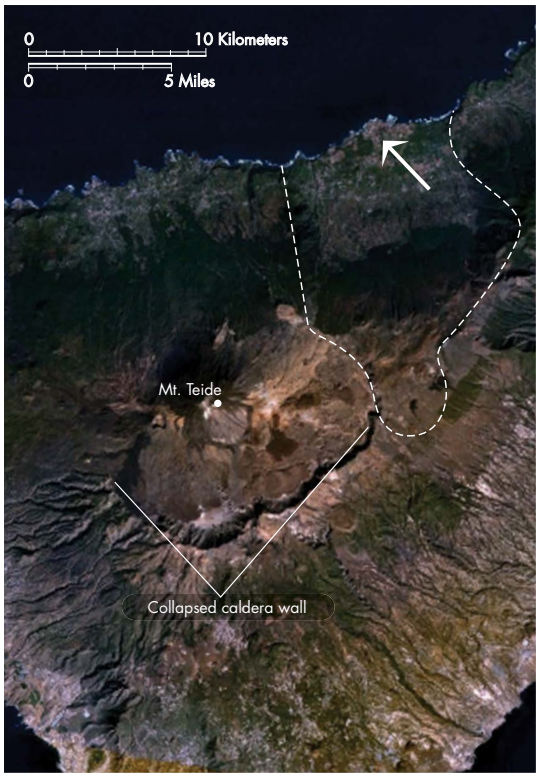
The USGS has recently developed an automated, solar-powered lahar detection system for several volcanoes in the United States (e.g., Mount Rainier), Indonesia, the Philippines, Mexico, and Japan. These systems have acoustic-flow monitors that sense ground vibrations from a moving lahar and can warn people that a flow is moving down the valley. This system replaces visual sightings and cameras that are unreliable in bad weather or at night and require continual maintenance. Dangerous lahars can occur quickly and with little warning, so people in their path must be alerted immediately. Alarms from these USGS lahar detection systems should give people sufficient time to evacuate to the safety of higher ground.[23]

Landslides Volcanic landslides are another secondary effect of volcanic activity. Like lahars, they may be triggered by events other than an eruption. Large volcanic landslides may affect areas far from their source. For example, massive landslide deposits on the seafloor off the coasts of Hawaii and the Canary Islands are likely to have generated huge tsunamis (see Case Study 5.2: Volcanic Landslides and Tsunamis).[24] These large waves would cause catastrophic damage far from the islands where they originated (see Chapter 4).

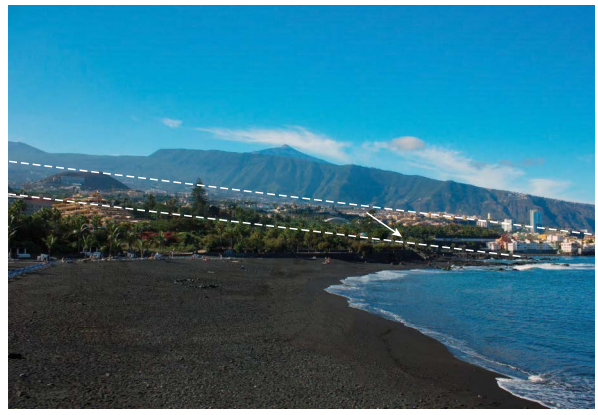
5.2 CASE study Volcanic Landslides and Tsunamis

What may be the largest active landslides on Earth are located on Hawaii. They are up to 100 km (~60 mi.) wide, 10 km (~6 mi.) thick, and 20 km (~12 mi.) long and extend from a volcanic rift zone on land to an endpoint beneath the sea. Currently these landslides creep along at around 10 cm (~4 in.) per year and contain blocks of rock the size of Manhattan Island. The fear is that they might again become a giant, fast-moving submarine debris avalanche. This avalanche would generate a huge tsunami capable of lifting marine debris hundreds of meters above sea level onto nearby islands, causing catastrophic damage around the Pacific Basin. Fortunately, such high-magnitude events are rare; the average recurrence interval seems to be about 100,000 years or so.[4]

Other huge volcano-related landslides or debris avalanches have been documented in the Canary Islands, located in the Atlantic Ocean off the western coast of Africa. On Tenerife, the largest island, six huge landslides have occurred during the past several million years (Figure 5.33), the most recent of which took place less than 150,000 years ago. The seafloor just north of Tenerife is covered by 5500 km^2 (~2150 $mi.^2$) of landslide deposits, an area nearly as large as the state of Delaware and more than twice the land surface of the island.[24]



(a)



(b)

▲ FIGURE 5.33 Giant Landslide on Volcano
(a) Aerial view of part of the island of Tenerife, the largest island of the Canary Islands in the Atlantic Ocean. Labeled are the collapsed La Cañadas caldera and the Mount Teide volcano (elevation 3.7 km [~12,100 ft.]). The white dashed line outlines the extent of the Orotova landslide, one of many large landslides on the island. The white arrow in both photographs (a) and (b) points to the seaward end of this landslide. *(NASA)*
(b) Seaward end of the Orotova landslide is outlined by the white dashed line. Snow-capped Mount Teide is in the distance. *(Neirfy/shutterstock)*

5.3 CASE study

Mount St. Helens 1980–2010: From Lateral Blasts to Lava Flows

The eruption of Mount St. Helens on May 18, 1980, in the southwestern corner of Washington State exemplifies the many types of volcanic events expected from a Cascade volcano (Figure 5.34). The eruption, like many other natural events, was unique and complex, making generalizations somewhat difficult. Nevertheless, we have learned a great deal from Mount St. Helens, and the story is not yet complete.

Mount St. Helens awoke in March 1980, after 120 years of dormancy, with seismic activity and small explosions created by the boiling of groundwater as it came in contact with hot rock. By May 1, a prominent bulge on the northern flank of the mountain could clearly be observed, and it grew at a rate of about 1.5 m (~5 ft.) per day (Figure 5.35a). Only a few weeks later, at 8:32 A.M. on May 18, 1980, a magnitude 5.1 earthquake centered below the volcano triggered a large landslide/debris avalanche of approximately 2.3 km^3 (~0.6 $mi.^3$) of earth material.[25] The avalanche, which involved the entire bulge area (Figure 5.35b), shot down the north flank of the mountain, displacing water in nearby Spirit Lake. It then struck and overrode a ridge 8 km (~5 mi.) to the north and made an abrupt turn, moving 18 km (~11 mi.) down the North Fork of the Toutle River (Figure 5.36a).

Seconds after the failure of the bulge, Mount St. Helens erupted with a lateral blast directly from the area that the bulge had occupied (Figure 5.35c). The blast moved at speeds of more than 480 km (~300 mi.) per hour—greater than the velocity of the fastest bullet train. Effects of the blast were felt nearly 30 km (~19 mi.) from its source and devastated about 600 km^2 (~230 $mi.^2$).[26] Debris-avalanche deposits, blasted-down timber, scorched timber, pyroclastic flows, and mudflows from the eruption covered large areas north of the volcano (Figure 5.36a).

The first of several mudflows consisting of water, volcanic ash, rock, and organic debris such as logs



(a) (b)

FIGURE 5.34 Mount St. Helens, Before and After

(a) Mount St. Helens before the May 18, 1980, eruption. *(Dennis Hallinan/Alamy)* (b) Mount St. Helens after the 1980 eruption. During the eruption, much of the northern side of the composite volcano was blown away, and the altitude of the summit was reduced by approximately 400 m (~1314 ft.). The lateral blast originated in the amphitheater-like area in the top center of the photograph and knocked down 600 km^2 (~230 $mi.^2$) of trees, some of which can be seen in the foreground. *(Danita Delimont/Alamy)*

occurred minutes after the start of the eruption. These flows and accompanying floods raced down the valleys of both forks of the Toutle River at estimated speeds of 29 to 55 km (~18 to 34 mi.) per hour, threatening the lives of people camped along the river.

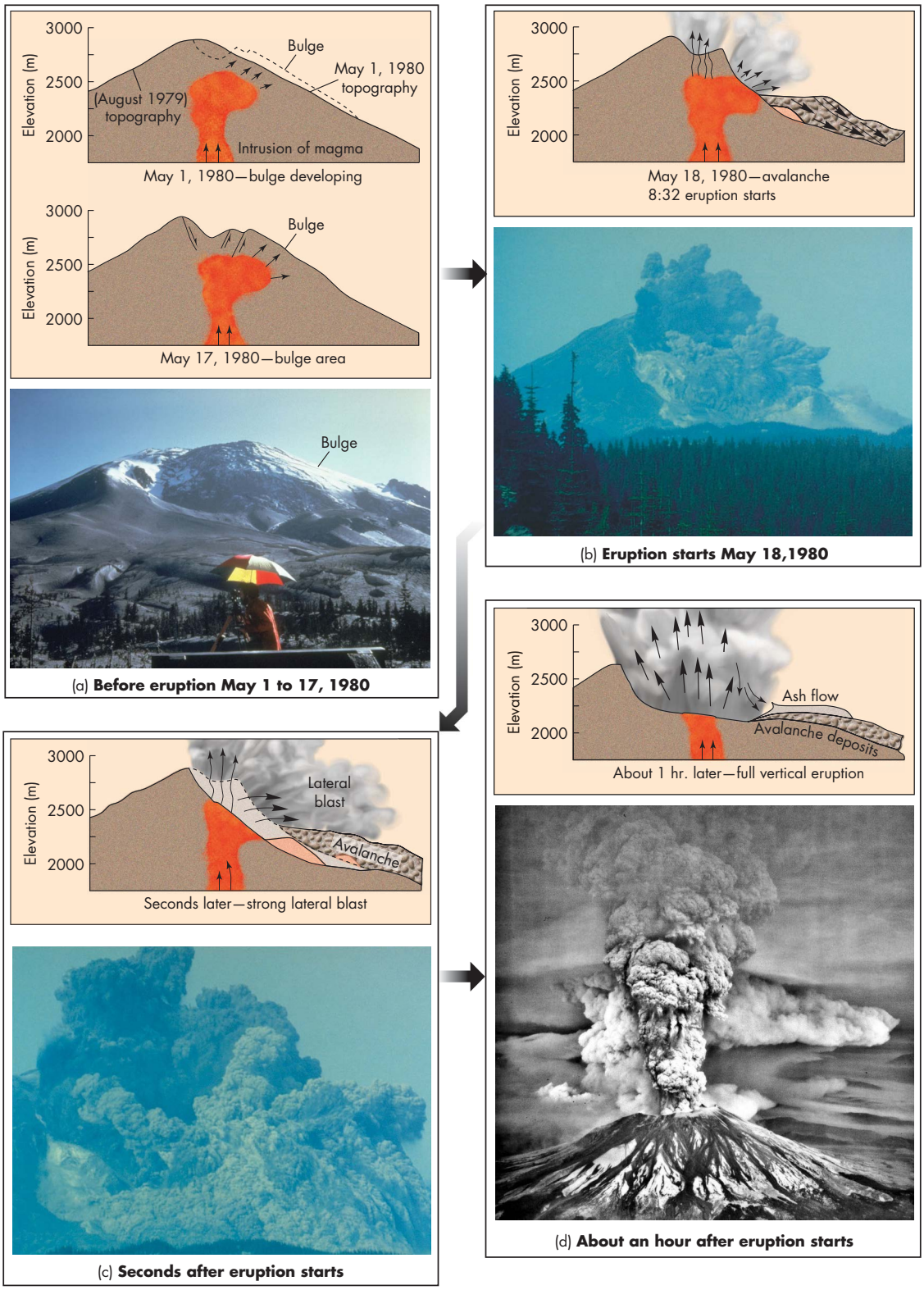
Two young people on a fishing trip on the North Fork of the Toutle River about 36 km (~22 mi.) downstream from Spirit Lake were awakened that morning by a loud rumbling noise from the river, which was covered by felled trees. The campers attempted to run to their car, but water from the rising river poured over the road, preventing their escape. A mass of mud then crashed through the forest toward their car, and the couple climbed on its roof to escape the mud. They were safe only momentarily, however, as the mud pushed the vehicle over the bank and into the river. Leaping off the roof, they fell into the river, which was by now a rolling mass of mud, logs, collapsed train trestles, and other debris. They disappeared several times beneath the surface of the flow but were lucky enough to emerge again. The two were carried downstream for approximately 1.5 km (~0.9 mi.) before another family of campers spotted and rescued them.

Within an hour after the lateral blast, a large vertical cloud had quickly risen to an altitude of approximately 19 km (~12 mi.), extending more than 4 km (~2.5 mi.) into the stratosphere (Figure 5.35d). Eruption of the vertical column continued for more than nine hours, and large volumes of volcanic ash fell on a wide area of Washington, northern Idaho, and western and central Montana. During the nine-hour eruption, a number of pyroclastic flows swept down the northern slope of the volcano (Figure 5.36a). The total amount of volcanic ash ejected was about 1 km^3 (~0.26 $mi.^3$), and a large cloud of ash moved over the United States, reaching as far east as New England (Figure 5.36b). In less than three weeks, the ash cloud had circled the Earth.

The entire northern slope of the volcano, which is the upper part of the North Fork of the Toutle River watershed, was devastated. Forested slopes were transformed into a gray landscape of mounded volcanic ash, rocks, blocks of melting glacial ice, narrow gullies, and hot steaming pits (Figure 5.37).[25]

When the volcano could be viewed again following the eruption, the top of the mountain had been reduced by about 400 m (~1314 ft.). What was originally a symmetrical volcano was now a huge, steep-walled amphitheater facing northward, and what was originally Spirit Lake (Figure 5.34a) was now filled with sediment (Figure 5.34b). The debris avalanche, horizontal blast, pyroclastic flows, and mudflows devastated an area larger than Chicago, Illinois. The eruption killed 57 people and associated flooding destroyed more than 100 homes. Approximately 800 million board feet of timber were flattened by the blast—enough wood to build 50,000 homes. Total damage from the eruption exceeded $1 billion.

Both volcanic and seismic activity has continued since the deadly 1980 eruption. During the first six years



▲ FIGURE 5.35 Mount St. Helens Erupts

Diagrams and photographs showing the sequence of events for the May 18, 1980, eruption of Mount St. Helens. *(A-Pf/Alamy)* Photographs (b) and (c) of the lateral blast were taken less than 10 seconds apart. *(Keith Ronnholm) (d) (R.M. Krimme/USGS)*

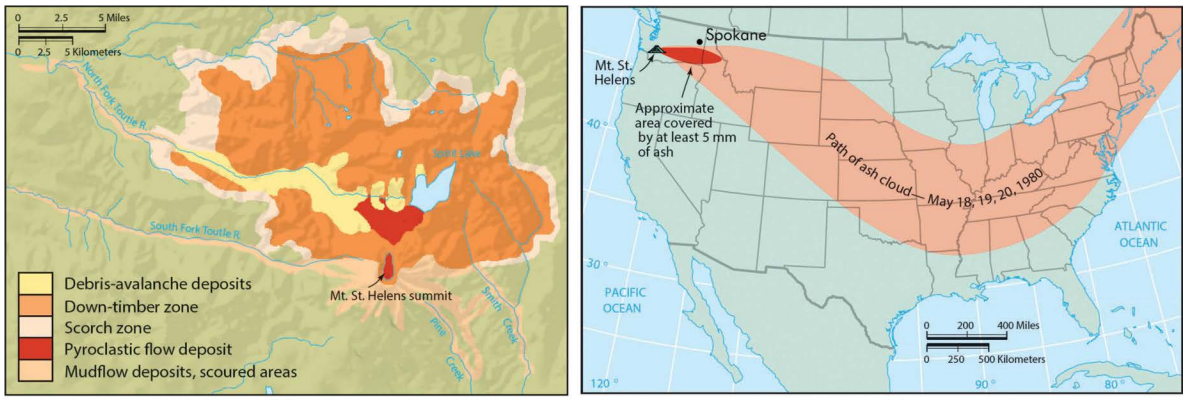


FIGURE 5.36 Debris Avalanche and Ash Cloud

(a) Debris-avalanche deposits, zones of trees blown down or scorched, mudflows, and pyroclastic flow deposits associated with the May 18, 1980, eruption of Mount St. Helens. *(Based on information from the USGS)* (b) Path of the ash cloud (orange) from the 1980 eruption. Area covered by at least 5 mm (~0.2 in.) is shown in red in the upper-left corner. *(Data from various U.S. Geological Survey publications)*

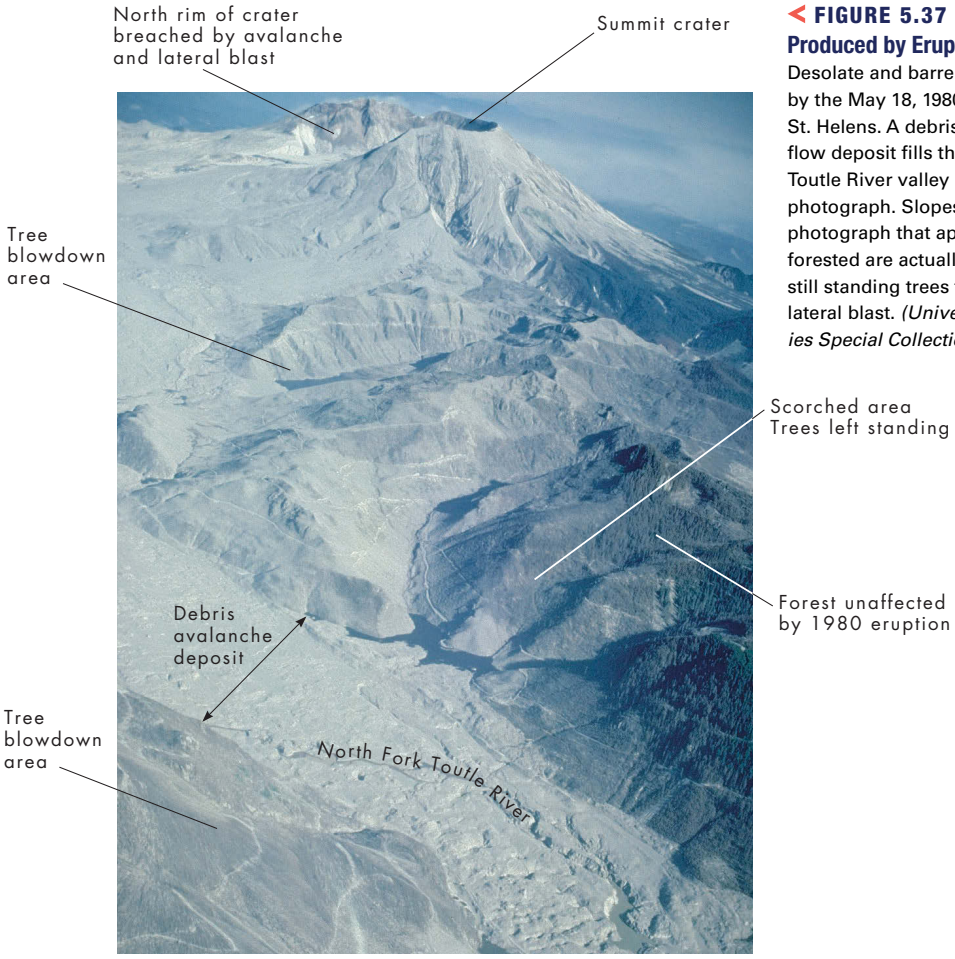


FIGURE 5.37 Barren Landscape Produced by Eruption

Desolate and barren landscape produced by the May 18, 1980, eruption of Mount St. Helens. A debris-avalanche and debris-flow deposit fills the North Fork of the Toutle River valley in the lower half of the photograph. Slopes in the right half of the photograph that appear to be sparsely forested are actually areas with scorched but still standing trees that were seared by the lateral blast. *(University of Washington Libraries Special Collections KCZ3–22)*



< FIGURE 5.38 Continued Growth of Dome in Crater
Steam and volcanic gases rise from cooling lava being added to a dome in Mount St. Helens's crater. Growth of this dome occurred from 1980 to 1986 and resumed in 2004. Heat from the new growth on the dome melts snowfall. The opening in the crater wall on the lower right is where the avalanche and lateral blast occurred in 1980 (Figure 5.35c). *(USGS)*

following the eruption, 19 smaller eruptions occurred. Lava flows from these eruptions began building a lava dome above the 1980 crater floor (Figure 5.38). Between 1989 and 2004, earthquake activity increased, and the quakes were sometimes accompanied by small explosions, ash flows, and mudflows.

On September 23, 2004, Mount St. Helens came back to life when magma began moving up toward the crater floor. Construction of the lava dome resumed and continued until January 2008. An estimated 0.5 m^3 (~0.6 $yd.^3$) of lava, about the volume of a five-drawer file cabinet, was being added to the dome every second.[26] The lava dome now rises 350 m (~1155 ft.) above the crater floor, close to the height of the Empire State Building.[27,28]

Scientists at the USGS Cascade Volcano Observatory in Vancouver, Washington, monitor Mount St. Helens at all times. This monitoring includes a network of automated seismographs and global positioning system (GPS) satellite receivers to detect earthquakes and ground deformation, aerial gas sampling, acoustic monitors for mudflows, and surveillance with webcams.[26]

By 1998, 18 years following the main eruption, life had returned to the mountain and its surrounding area, making many places green once more. However, the mounds of landslide deposits are still prominent, a reminder of the catastrophic event of 1980. Mount St. Helens National Monument now has two visitor centers and has attracted more than 3 million visitors since 1983, who have come to the enjoy the beauty and power of the volcano.

5.4 CHECK your understanding

1. Describe the primary and secondary effects of volcanic eruptions.
2. Compare and contrast ash falls and pyroclastic flows.
3. What are the major gases emitted in a volcanic eruption? How can they be hazardous?
4. Explain how volcanoes can produce gigantic debris flows or mudflows.

5.5 Linkages between Volcanoes and Other Natural Hazards

Volcanoes are intimately linked to their physical environment as well as to several other natural hazards. We have stressed the relationship between volcanoes and plate tectonics, the connection between plate tectonic setting and the type of magma, and the influence that magma type has on the nature of volcanic eruptions. Volcanoes are also directly related to other natural hazards such as fire, earthquakes, landslides, and climate change.

Although volcanoes are not a major cause of fires, it isn't difficult to imagine that a linkage between these hazards exists. As molten lava pours down the sides of a volcano, or pyroclastic debris is ejected, plants and



FIGURE 5.39 Lava Ignites Fires in Africa
A lava flow erupting from the Nyiragongo volcano in the Democratic Republic of Congo ignited this fire in January 2002. More than 400,000 people were displaced by fires and lava flows in the city of Goma. *(PEDRO UGARTE/AFP/Getty Images)*

manufactured structures commonly catch fire. In fact, the Hawaiian Volcano Observatory on the Big Island of Hawaii warns tourists of the fires caused by Kilauea's active lava flows. These fires can start from explosions of methane gas that form as vegetation is intensely heated by the lava. In January 2002, Africa's most destructive volcanic eruption in 25 years sent residents of the Democratic Republic of Congo fleeing raging fires ignited by lava flows (Figure 5.39). Sadly, the lava also sparked an explosion, killing 60 people.

Earthquakes commonly accompany or precede volcanic eruptions as magma rises through Earth's crust. For example, weeks of earthquakes preceded the appearance of the Parícutin volcano 320 km (~200 mi.) west of Mexico City. Some earthquakes may be large enough to do damage independent of the volcano. Similar examples are also discussed in the Mount Unzen and Eyjafjallajökull case studies.

Landslides are possibly the most common side effect of volcanic activity. These mass movements can be part of the slope or flank of the volcano (see Case Study 5.2: Volcanic Landslides and Tsunamis) or lahars, the volcanic debris flows and mudflows discussed earlier. Both types of mass wasting have the potential to do great damage and take many lives.



FIGURE 5.40 Volcano Temporarily Cools Global Climate
An eruption of Mount Pinatubo in 1991, shown here, ejected vast amounts of volcanic ash and sulfur dioxide up to about 30 km (~19 mi.) into the atmosphere. Extremely fine particles, called aerosols, from the eruption remained in the upper atmosphere and circled Earth for more than a year. This aerosol cloud temporarily lowered the average global temperature. The Mount Pinatubo eruption was the second largest in the twentieth century. *(D. Harlow/USGS)*

Finally, volcanic eruptions may affect our global climate. The best-known example of climate change from a volcanic eruption occurred following the great eruption of the Tambora volcano in Indonesia in 1815. The eruption created a global cloud of sulfuric acid droplets, referred to as aerosols, in the stratosphere, which were later detected in glacial ice formed that year in both Greenland and Antarctica.[29,30] This cloud caused regional cooling of up to 1°C (~2°F) and resulted in 1816 being called the "year without a summer" in New England. Climate change from the eruption caused major hardships in both North America and Europe, including crop failures, famine, and disease.[29] A smaller but still significant climatic cooling occurred after the 1991 eruptions of Mount Pinatubo in the Philippines. The cloud of ash and sulfuric acid aerosol from the Pinatubo eruption remained in the atmosphere for more than a year (Figure 5.40). Ash particles and aerosol droplets scattered incoming sunlight and slightly cooled the global climate for two years following the eruptions.[31]

5.5 CHECK your understanding

1. How can volcanic eruptions affect the global climate?
2. Why are volcanoes commonly linked with earthquake activity?

5.6 Natural Service Functions of Volcanoes

Although volcanoes pose a serious threat to those who live in their paths, like most other hazards, they also provide important natural service functions. Perhaps their greatest gift to us occurred billions of years ago when gases and water vapor released from volcanoes contributed to our atmospheric and hydrologic systems, allowing life, as we know it, to evolve. Additionally, volcanoes provide us with fertile soils, a source of power, mineral resources, and recreational opportunities, as well as the creation of new land.

VOLCANIC SOILS

From an agricultural perspective, volcanic eruptions are quite valuable, providing an excellent growth medium for plants. The nutrients produced by the weathering of volcanic rocks allow crops such as coffee, maize, pineapple, sugarcane, and grapes to thrive in volcanic soils. However, rich, fertile soils produced by volcanoes encourage people to live in hazardous areas. So although volcanic soils provide an important resource, nearby volcanic activity can make it difficult to use that resource safely.

GEOTHERMAL POWER

Another benefit provided by volcanoes is their potential for geothermal power. The internal heat associated with volcanoes may be used to create power for nearby urban areas. In fact, volcanic energy is being harnessed as geothermal power in Kilauea, Hawaii; Santa Rosa, California; and Long Valley, California. An important benefit of geothermal energy is that it can be a renewable resource. Unlike fossil fuels, it can be used at a rate that doesn't outpace its replenishment. However, care must be taken so that the heat and/or steam driving the system is not removed faster than it can be restored naturally or it will become depleted, at least temporarily. In addition to using hot geothermal water to make electricity, the heat can be used for heating and industrial processes. The hot water can be pumped directly through a building or utilized with a recirculating heat-exchange system. Reykjavik, Iceland; Paris, France; and Klamath Falls, Oregon, are just a few of the many locations that use geothermal water for heating.[32]

MINERAL RESOURCES

Volcanism is the source and volcanic rocks are the host for many mineral resources. These include economic concentrations of metals, such as gold, silver, platinum, copper, nickel, lead, and zinc, and nonmetallic resources, such as pumice, tuff, perlite, scoria, basalt, and volcanic clays. Although these mineral deposits form today in volcanic belts around the world, including underwater at mid-ocean ridges, most of those that we use formed in the geologic past. In the case of metallic mineral resources, most are found in much older Precambrian rocks. These older deposits formed at a time when the composition of some magma differed from today's volcanoes. Examples include gold accumulations in Precambrian volcanic rocks in Western Australia and Ontario, Canada. In addition to metals, volcanic rocks are used in a wide range of commercial products, including soap, building stone, aggregate for roads and railroads, oil and gas drilling mud, landscaping gravel, ceiling tile, cement, plaster, and cat litter.[33]

RECREATION

Besides being an energy source, the heat associated with volcanoes provides recreational opportunities. Many health spas and hot springs are developed in volcanic areas. Volcanoes also provide opportunities for hiking, snow sports, and education. More than 1 million tourists visit the Kilauea volcano each year, many of whom come to observe the volcano during eruption (Figure 5.41).

CREATION OF NEW LAND

In our discussion of the benefits of volcanoes, we should not forget to mention that they are responsible for creating much of the land we inhabit. For the past several decades, the residents of Hawaii are reminded of this fact as lava flows from Kilauea build deltas of land into the Pacific Ocean (see Figure 5.30 and



FIGURE 5.41 Erupting Volcanoes as Tourist Attractions
Tourists on the cliff to the right view a lava flow from Kilauea volcano on the coast of Hawaii. *(Paul A. Souders/CORBIS)*

Figure 5.41). Not only are volcanic processes the major force that builds continents, but also oceanic islands such as Hawaii and Iceland would not exist without volcanoes!

5.6 CHECK your understanding

1. What contribution to human and animal food supply do volcanoes provide?
2. What is geothermal energy and what is it's primary advantage over fossil fuels?

5.7 Human Interactions with Volcanoes

Unlike earthquakes, volcanoes do not lend themselves to human tinkering. That is to say, there is little we can do to affect the timing and severity of volcanic eruptions. Whereas deep-well disposal may increase the number of earthquakes in an area, and clearing the land for agriculture may contribute to flooding, there does not appear to be any human activity that affects volcanoes. They truly are a hazard that is beyond our control, and the best we can do is to attempt to minimize the loss of life and property associated with eruptions.

5.8 Minimizing the Volcanic Hazard

Forecasting volcanic eruptions is a major component of the goal to reduce volcanic hazards. A "forecast" for a volcanic eruption is a probabilistic statement describing the time, place, and character of an eruption. It is analogous to forecasting the weather and is not as precise a statement as a prediction.[4]

FORECASTING

It is unlikely that we will be able to accurately forecast the majority of volcanic activity in the near future, but valuable information is being gathered about phenomena that occur prior to eruptions. One problem is that most forecasting techniques require experience with actual eruptions before the mechanism is understood. Thus, we are better able to predict eruptions in the Hawaiian Islands because we have had so much experience there.

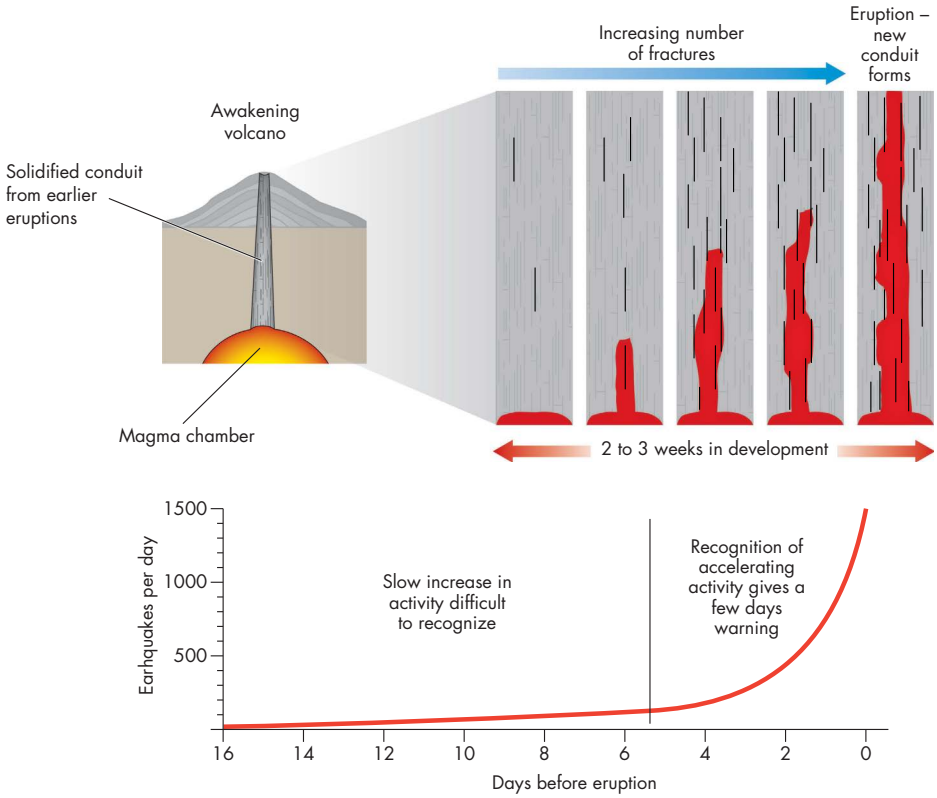
Forecasting volcanic eruptions uses information gained by

- monitoring seismic activity
- monitoring thermal, magnetic, and hydrologic conditions
- monitoring the land surface to detect tilting or swelling of the volcano
- monitoring volcanic gas emissions
- studying the geologic history of a particular volcano or volcanic center.[13,30]

Seismic Activity Monitoring Our experience with volcanoes, such as Mount St. Helens and those on the Big Island of Hawaii, suggests that earthquakes may provide the earliest warning of an impending volcanic eruption. Shallow earthquakes and tremors are produced below a volcano as upward-moving magma fractures the surrounding rock and gas bubbles in the magma form and burst. In the case of Mount St. Helens, earthquake activity started in mid-March before the eruption in May. Activity in March began suddenly with nearly continuous, shallow swarms of earthquakes. Unfortunately, there was no additional increase in earthquakes immediately preceding the catastrophic eruption on May 18. In Hawaii, earthquakes have been used to monitor the movement of magma as it approaches the surface.

Several months prior to the 1991 Mount Pinatubo eruptions, small steam explosions and earthquakes began.[4] Unlike Mount St. Helens, Pinatubo was an eroded ridge that did not have the classic shape of a volcano. Furthermore, it hadn't erupted in 500 years, so the majority of people living near it did not even know it was a volcano! After the initial steam explosions, scientists began monitoring earthquakes on the volcano and studying past volcanic activity, which was determined to have been explosive. Earthquakes increased in number and magnitude prior to the catastrophic eruption, and foci migrated from deep beneath the volcano to shallow depths beneath the summit.[4]

Recently, geophysicists have proposed a generalized model for seismic activity that may help in predicting eruptions.[34] This model is used for explosive stratovolcanoes, such as those in the Cascade Mountains, which may awaken after an extended period of inactivity (Figure 5.42). In a reawakening volcano, the magma must fracture and break previously solidified igneous rock above the magma chamber to work its way to the surface. Several weeks before reawakening, increasing pressure creates numerous fractures in the plugged volcanic conduit above the chamber. At first, the increase in seismic events will be gradual and a seismologist may need 10 days or so to confidently recognize an accelerating trend



< FIGURE 5.42 A Volcano Reawakens Increased seismic activity is a good indicator of a forthcoming volcanic eruption. As a dormant volcano reawakens, rising magma fractures rock above. At first, the fracturing slowly increases the rate of seismic activity; then both the fracturing and seismic activity accelerate a few days prior to an eruption. *(Adapted from Kilburn, C. R. J., and Sammonds, P. R., "Maximum Warning Times for Imminent Volcanic Eruptions," Geophysical Research Letters 32: L24313, 2005. Copyright © 2005. Reprinted with permission of Wiley Inc.)*

toward an eruption. However, once the trend has been recognized, there will still be several days before the eruption occurs. Unfortunately, this short warning time may be insufficient for a large-scale evacuation. Thus, to forecast eruptions it may be best to use seismic activity in concert with other eruption precursors discussed later. It is fortunate that, in contrast to earthquakes, volcanic eruptions always provide warning signs.[34]

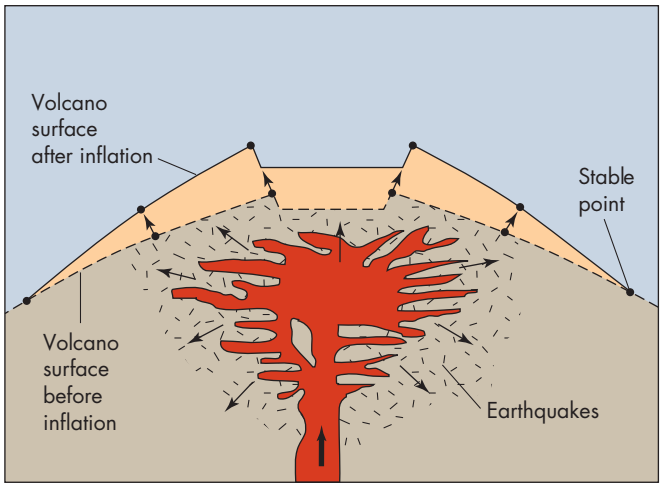
Thermal, Magnetic, and Hydrologic Monitoring

Prior to a volcanic eruption, a large volume of magma accumulates in a holding reservoir beneath the volcano. The hot material changes the local magnetic, thermal, hydrologic, and geochemical conditions. As the surrounding rocks heat up, the rise in temperature of the rocks at the surface may be detected by satellite remote sensing or infrared aerial photography. Increased heat may melt snowfields or glaciers; thus, periodic remote sensing of a volcanic chain may detect new hot places related to volcanic activity. This method was used with some success at Mount St. Helens prior to the main eruption in 1980.

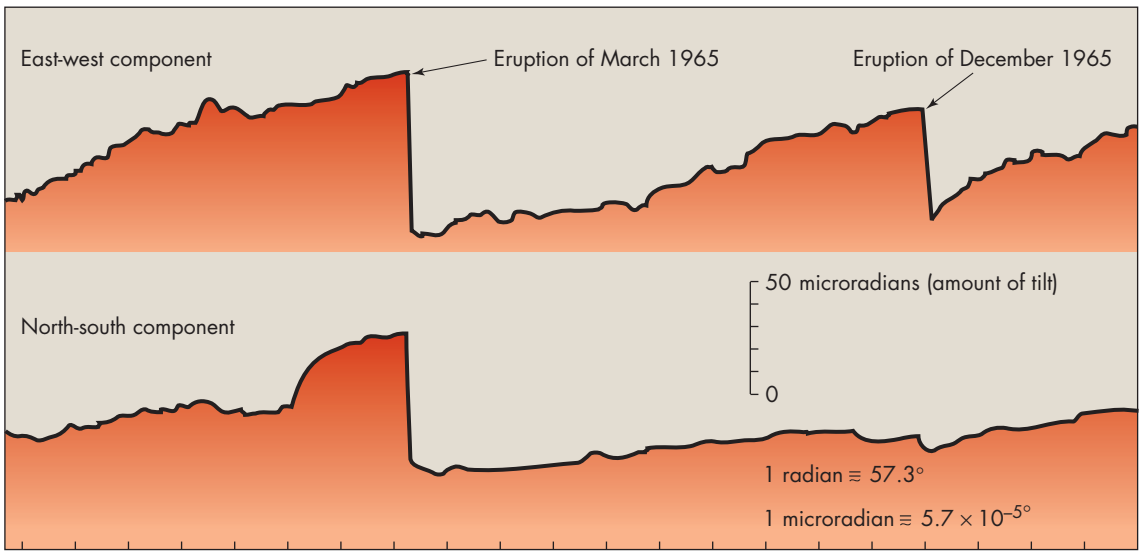
When older volcanic rocks are heated by new magma, magnetic properties, originally imprinted when the older rocks cooled and crystallized, may change. These changes can be detailed by ground or aerial magnetic surveys.[13,35]

Land Surface Monitoring Monitoring changes in the land surface and seismic activity of volcanoes has been useful in forecasting some volcanic eruptions. Hawaiian volcanoes, especially Kilauea, have supplied most of the data. The summit of Kilauea tilts and swells prior to an eruption and subsides during the actual outbreak (Figure 5.43). Kilauea also experiences swarms of small earthquakes from the underground movement of magma shortly before an eruption. The tilting of the summit, in conjunction with earthquake swarms, was used to predict a volcanic eruption in the vicinity of the farming community of Kapoho on the flank of the volcano 45 km (~28 mi.) from the summit. As a result, the inhabitants were evacuated before the event, in which lava overran and eventually destroyed most of the village.[36] Because of the characteristic swelling and earthquake activity before eruptions, scientists expect the Hawaiian volcanoes to continue to be more predictable than others.

Monitoring ground movements such as tilting, swelling, and opening of cracks, or changes in the water level of lakes on or near a volcano, can identify movement that might indicate a forthcoming eruption.[13] Today, satellite-based interfrometric synthetic aperature radar (InSAR), and a network of GPS satellite receivers can be used to monitor change in volcanoes, including surface deformation, without sending people into a hazardous



(a)



(b)

< FIGURE 5.43 Inflation and Tilting Before Eruption

(a) Idealized diagram of the Kilauea volcano in Hawaii illustrating inflation and surface tilting as magma moves up. The red area is the underground magma chamber that fills before an eruption. *(Solarfilma ehf)* (b) Graphs showing the tilting of the surface of Kilauea in two directions, the east–west component and the north–south component, from 1964 to 1966. Notice the slow increase in ground tilt before an eruption and rapid subsidence, or lowering of the land surface, during eruption. *(From Fiske, R. S. and Koyanagi R. Y., U.S. Geological Survey Professional Paper 607, 1968)*

area.[37] These tools are capable of measuring millimeter- to centimeter-scale (0.4–4 in.) changes in Earth's surface over spans of days to years.

Monitoring Volcanic Gas Emissions The primary objective of monitoring volcanic gas emissions is to recognize changes in chemical composition (see Case Study 5.4: Professional Profile). Changes in the relative amounts of carbon dioxide and sulfur dioxide, as well as changes in gas emission rates, are thought to correlate with subsurface volcanic processes. These changes may indicate movement of magma toward the surface. This technique was useful in studying eruptions at Mount St. Helens and Mount Pinatubo. The volume of sulfur dioxide emitted from Pinatubo increased more than a million times two weeks before the explosive eruptions.

Geologic History An understanding of the geologic history of a volcano or volcanic system is useful in predicting the types of future eruptions. The primary tool for reconstructing geologic history is geologic mapping of volcanic rocks and deposits. Scientists attempt to determine the age of past lava flows and pyroclastic

CASE study

5.4 Professional Profile

Chris Eisinger, Student of Active Volcanoes

Chris Eisinger (Figure 5.4.A) describes volcanoes the same way he might discuss old, temperamental friends. "For the most part volcanoes are very approachable," he says, "as long as you know their cycles." As a graduate student in the Department of Geological Sciences at Arizona State University, Eisinger has 15 years of firsthand experience with volcanoes. He began as an undergraduate and spent time at the Hawaiian Volcano Observatory and in Indonesia, a region rife with volcanic activity.

But the summit of an active volcano is anything but a breezy affair. On the contrary, volcanoes emit malodorous gases, as Eisinger can attest. "The most distinct things you notice are the fumes," he says. "You get a strong sulfur smell."

If the volcano is near enough to the ocean for lava to flow into the sea, Eisinger also says the runoff creates a steam that is highly acidic, thanks to the high chlorine content of seawater. "Your eyes will water," he observes. "It's typically difficult to breathe and you end up coughing if you're not wearing a gas mask."

Rainstorms can further cloud the air, creating steam when the falling water strikes the hot surface of the lava. At times, visibility for volcanologists studying at the summit is reduced to a few feet.



FIGURE 5.4.A Volcanologist Sampling Molten Sulfur
Volcanologist Chris Eisinger uses a crowbar to hit some molten sulfur on Kawah Ijen volcano in Indonesia. The 200°C (~390°F) molten sulfur is still red hot and will cool to a yellow or green color. *(Chris Eisinger)*

The heavy influx of gases doesn't affect only the eyes and nose. The taste, if one isn't wearing a mask, can be "pretty nasty," Eisinger says, adding that the smell adheres to clothing as well.

For volcanoes in a constant state of eruption, Eisinger notes that there are distinct patterns in the emission cycles. Volcanoes he has visited in Indonesia, for example, would emit a stream of gaseous material every 20 minutes to an hour.

Although most volcanologists are able to remain safe by paying close attention to eruption cycles, fatalities have happened. In August 2000, two volcanologists died at the summit of Semeru on the island of Java in Indonesia when the volcano erupted with no warning.

Active volcanoes also emit low, rumbling sounds, Eisinger says, due largely to subterranean explosions that tend to be muffled. Hawaiian volcanoes are unique in that they also emit an intense hissing sound, "like a jet engine," from the expulsion of gases. Eruptions are often foreshadowed by seismic activity that contributes to the rumble of the explosions. Although Eisinger himself has never witnessed a volcanic eruption of historic order, he noted that accounts of such colossal eruptions as that of Krakatau in 1883 produced reports of a boom that could be heard thousands of miles away.

— CHRIS WILSON

deposits. Geologic mapping, in conjunction with the dating of volcanic deposits at Kilauea, led to the discovery that more than 90 percent of the land surface of the volcano has been covered by lava in only the past 1,500 years. The town of Kalapana, destroyed by lava flows in 1990, might never have been built if this information had been known prior to development because the risk might have been considered too great. The real value of geologic mapping and dating of volcanic events is that it allows hazard maps to be prepared to assist in land-use planning and disaster preparedness.[13] Such maps are now available for a number of volcanoes around the world.

VOLCANIC ALERT OR WARNING

At what point should the public be alerted or warned that a volcanic eruption may occur? This question has been partially addressed by volcanologists and policy makers. The USGS recently established an alert notification system for volcanic activity for use by its five volcanic observatories.[38] This system has two components: ground-based volcano alert levels and aviation-based color code levels (Table 5.4). Each component has four levels and, for most monitored volcanoes and eruptions, the alert and aviation code will be at the

TABLE 5.4 U.S. Geological Survey Volcanic Alert Levels and Aviation Color Codes[a]

Ground Alert Level	Volcanic Condition	Aviation Color Code
NORMAL	1. Typical background, noneruptive state. *Or* 2. If downgraded from higher alert level, activity has ceased and returned to a background, noneruptive state.	GREEN
ADVISORY	1. Elevated unrest above known background level. *Or* 2. If downgraded from a higher alert level, activity has decreased significantly with close monitoring for possible renewed increase.	YELLOW
WATCH	1. Heightened or escalating unrest with increased potential of eruption, time frame uncertain. *Or* 2. Eruption underway with limited hazards; for aviation—no or minor volcanic ash emissions.	ORANGE
WARNING	Hazardous eruption imminent, underway, or suspected; for aviation—significant emission of volcanic ash into atmosphere.	RED

[a] Note: For most eruptions, the ground alert level and aviation color code will be at the same levels; however, for some eruptions there will be a greater hazard on the ground or to aviation, and different levels will be assigned for the two environments.

Source: Modified from http://volcanoes.usgs.gov/activity/alertsystem/icons.php and U.S. Geological Survey Fact Sheet 2006–3139.

same level. For some eruptions, however, the hazard posed to either those on the ground or those in the air will differ and higher alerts or codes will be issued. For example, if a lava flow from Kilauea volcano threatens a subdivision, the Hawaiian Volcano Observatory may issue a warning because a hazardous eruption is underway but only issue an orange aviation code because there are minor volcanic-ash emissions. Likewise, if a volcano erupts on an isolated island in the Aleutians, the Alaska Volcano Observatory may issue a watch because the eruption poses limited hazards on the ground and a red aviation code because of significant emissions of volcanic ash.

Although this system is a good start, the hard questions remain: When should evacuation begin? When is it safe for people to return? These are questions that public officials will have to answer when the USGS issues volcanic watches or warnings. The USGS volcanic observatories monitor approximately 50 of an estimated 170 active volcanoes in Alaska, Hawaii, the western contiguous United States, and the Northern Mariana Islands.[38]

5.8 CHECK your understanding

1. Describe how seismic activity can indicate a forthcoming volcanic eruption.
2. How is land surface monitoring used to detect volcanic activity?
3. Explain the USGS alert notification system for volcanic eruptions.

5.9 Perception of and Adjustment to the Volcanic Hazard

PERCEPTION OF VOLCANIC HAZARDS

Information concerning how people perceive a volcanic hazard is limited. People live near volcanoes for a variety of reasons: (1) They were born there and in the case of some islands, such as the Canary Islands, all land is volcanic; (2) the land is fertile and good for farming; (3) people are optimistic and believe an eruption is unlikely; and (4) they cannot choose where they live—for example, they may be limited by economics. One study of people's perception in Hawaii found that a person's age and length of residence near a volcanic hazard are significant factors in his or her knowledge of the hazard and possible adjustments to it.[39] One reason the evacuation of 60,000 people prior to the 1991 eruption of Mount Pinatubo was successful was that the Philippine government had educated people about the dangers of violent ash eruptions with debris flows. A video depicting these events was widely shown before the eruption, and it helped convince local officials and residents that they faced a real and immediate threat.[4]

The science of volcanoes is becoming well known. However, good science is not sufficient (see Case Study 5.5: Survivor Story). Probably the greatest hazard reduction will come from an increased understanding of human and societal issues that arise during an emerging **volcanic crisis**. A volcanic crisis can develop when scientists predict that an eruption is likely in the near future. In such a crisis, improved communication among scientists, emergency managers, educators, media, and private citizens is particularly important. The goal is to prevent a volcanic crisis from becoming a disaster or catastrophe.[39]

ADJUSTMENTS TO VOLCANIC HAZARDS

Apart from the psychological adjustment to losses, the primary human adjustment to volcanic activity is evacuation. Mount Vesuvius, which devastated the cities of Pompeii and Herculaneum in A.D. 79 (see Figure 5.26), is considered by some to be one of the most hazardous volcanoes on Earth with nearly 3 million people living in the surrounding area. In an attempt to minimize the potential for a future catastrophe if another large eruption were to occur, the Italian government is offering 30,000 euros to anyone living in the 18 towns within the immediate area who is willing to relocate.[40]

ATTEMPTS TO CONTROL LAVA FLOWS

Several methods, such as *hydraulic chilling* and wall construction, have been employed to deflect lava flows away from populated or otherwise valuable areas. These methods have had mixed success. They cannot be expected to modify large flows, and their effectiveness with smaller flows requires further evaluation.

The world's most ambitious hydraulic chilling effort was initiated in January 1973 on the Icelandic island of Heimaey. Basaltic lava flows from Eldfell volcano nearly closed the harbor of Vestmannaeyjar, the island's main town and Iceland's main fishing port. The situation prompted immediate action.

Three favorable conditions existed: (1) Slow movement of the flows allowed the time needed to initiate a control effort; (2) transport by sea and roads allowed the delivery of pipes, pumps, and heavy equipment; and

A Close Call with Mount St. Helens

5.5 Survivor Story

CASE study

For someone who makes his living as a reporter, Don Hamilton was awfully lucky to be nowhere near a telephone on the evening of May 17, 1980 (Figure 5.5.A).

The next day, at 8:32 A.M., Mount St. Helens would explode in one of the largest eruptions in North American history, spewing monstrous proportions of ash that would eventually circle the entire planet and cover the surrounding region in hundreds of feet of debris.

But that evening, Hamilton was sitting on the porch of a lodge on Spirit Lake, no more than 16 km (~10 mi.) from the mountain's peak, visiting the lodge's resident, a local eccentric named Harry Truman. By this point, smaller earthquakes and seismic observations had geologists clamoring about the imminent eruption, and Truman, then 84 years old, had become a minor celebrity for his stalwart refusal to evacuate.

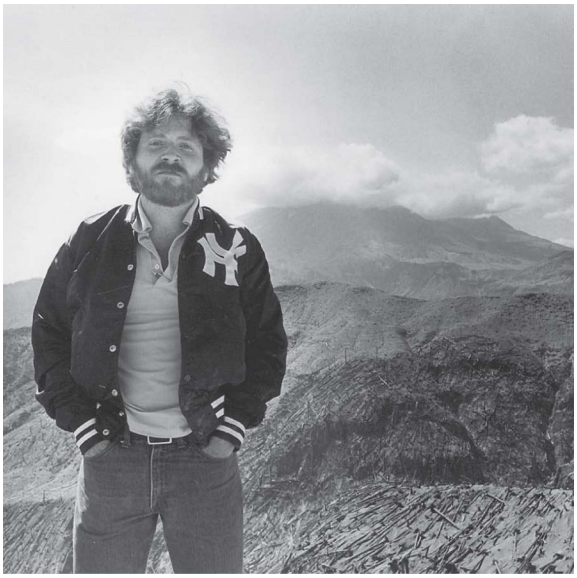
Hamilton was working for the now-defunct *Oregon Journal*, and that night he might have stayed with Truman if he had had a telephone. But Hamilton needed some way to file that day's story.

As it turned out, leaving was a wise decision. When the volcano erupted the very next morning, with Hamilton safely in bed in Portland, it buried Truman and his lodge in a massive landslide of debris and pyroclastic flow.

In the days and weeks leading up to the eruption, Hamilton had witnessed several violent earthquakes while visiting Truman. "I was up there a few times in his lodge, up on his front porch, when some pretty good quakes hit," he said. "I could see the road rippling. It was the weirdest thing I'd ever seen."

By this time the media had already caught up with Truman, who had appeared on the *Today* show and in the *New York Times.* But for all his gusto, Hamilton said, there were cracks in Truman's resolve. "I saw some genuine fear in his face," he recalled. "He looked drawn. His eyes were bugging out a little bit. It made him stop and pay attention."

But in spite of all the warnings, Hamilton thought most people weren't prepared for the sheer magnitude of the eruption. "The geologists were certainly warning us that this was a very dangerous and unstable situation," he said. "But I don't think anybody really anticipated the enormity of what happened. There wasn't a lot of documented history of this kind of thing."



< FIGURE 5.5.A Oregon Reporter who Escaped Death on Mount St. Helens

A fateful decision on May 17, 1980, to leave Harry Truman's lodge on the slopes of Mount St. Helens and return to Portland saved Don Hamilton's life. Don recounted his story nearly 25 years later when Mount St. Helens erupted again in March 2005. *(Don Hamilton)*

Natives of the Pacific Northwest certainly couldn't have been blamed for lack of firsthand experience. At the time, Mount St. Helens had been dormant for more than 120 years.

The day of the eruption, Hamilton and his brother, a photographer for the *Oregon Journal,* went up in a chartered flight and were lucky enough to have a pilot who was willing to loosely interpret the FAA restriction on the airspace around the eruption.

Hamilton described the view from the plane as utterly extraordinary. Prior to the eruption, Mount St. Helens had a rounded peak that had been blown off in the blast. A massive column of volcanic ash rose straight into the cloud ceiling. "It was unbelievable to see this emerge out of the clouds," he said. "The mountain was completely flattened off. It had been a very beautiful, conical top." As they got closer, they saw massive mudflows, as well as cars, trucks, and bridges that had been destroyed. "The road that I'd been going up for two weeks was completely washed out," said Hamilton.

For residents of Portland and many other areas near the blast, ash from the eruption became a regular part of life that summer. "People were wearing surgical masks. It was piled up on the side of the road. It just stayed there all summer," Hamilton recalled. "For that whole summer you just lived with it."

For Hamilton, then 26 years old, the timing couldn't have been worse. "It was the only summer I had a convertible," he said. "I kept the top up most of the time that summer."

—CHRIS WILSON

(3) water was readily available. Initially, the edges and surface of the flow were cooled with water from numerous fire hoses (Figure 5.44).

Then bulldozers were moved up on the slowly advancing flow to make a path for a large water pipe. The plastic pipe did not melt as long as water was flowing in it, and small holes in the pipe allowed the cooling of hot spots along parts of the flow. Watering had little effect the first day, but then the back edge flow began to slow down and in some cases stopped.



(a)



(b)



(c)

< FIGURE 5.44 Fighting Lava Flows

Eruptions of Eldfell volcano on the island of Heimaey, Iceland. (a) Lava fountain buries homes in volcanic cinders. Numerous homes were destroyed by structural collapse or fire. *(Bettmann/CORBIS)* (b) White steam pours from the front of the lava flow as emergency crews use fire hoses to slow the advance of the flow on the town and the precious harbor. *(S Jonasson/FLPA Image Broker/Newscom)* (c) Aerial view taken several months after the eruption shows the town covered in black ash and the harbor that was kept free of lava, partly due to human efforts. *(Scholz/picture-alliance/dpa/AP Images)*

These actions undoubtedly had an important effect on the lava flows from Eldfell volcano. They restricted lava movement, reduced property damage, and allowed the harbor to remain open. When the eruption stopped five months later, the harbor was still usable.[41] In fact, by fortuitous circumstances, the shape of the harbor was actually improved because the cooled lava provided additional protection from the sea. More recent efforts to chill and deflect lava flows on the slope of Mount Etna in Sicily have also had some success.

5.9 CHECK your understanding

1. What methods have been used to control lava flows?
2. Why was the evacuation prior to the Mount Pinatubo eruptions so successful?
3. How has the risk from an eruption of Mount Vesuvius changed in the past two,000 years?

APPLYING the 5 Fundamental Concepts

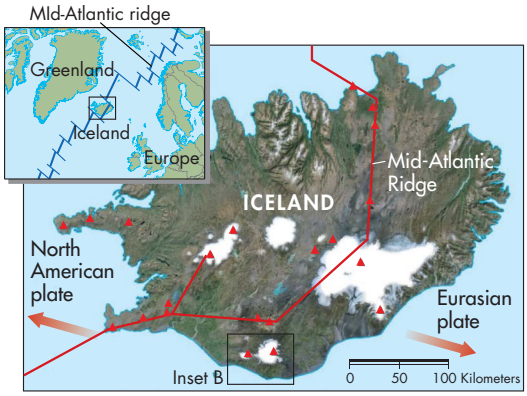
Eyjafjallajökull 2010 Eruption

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

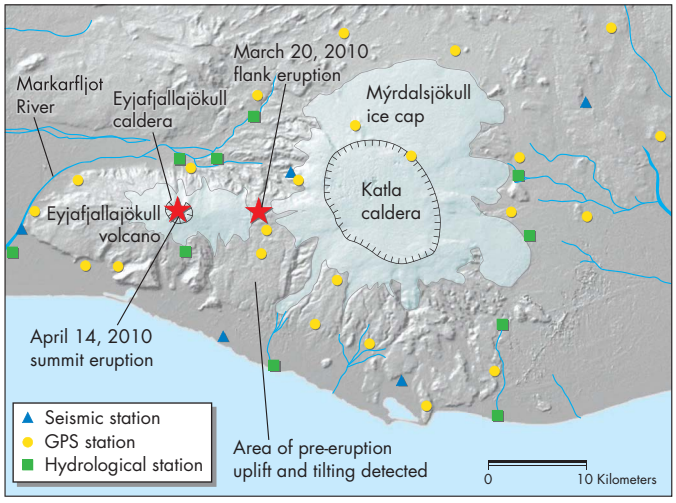
The large number of active volcanoes on Iceland is not surprising given its location on the Mid-Atlantic Ridge. Iceland is literally being ripped apart at a rate of 20 cm (~8 in.) per year (Figure 5.45a)![42] The island also sits atop a hot spot, enhancing magma formation and volcanic activity at the surface—Iceland experiences a volcanic eruption once every three to four years.[1] Fortunately, the process by which magma forms in this setting means that most Icelandic eruptions are generally effusive and have a VEI of no more than 1 (see Table 5.2). This means that the effects of Icelandic volcanic eruptions are typically limited to the island and often go unnoticed by the rest of the world. This all changed with the eruption of Eyjafjallajökull volcano in 2010.

Frequent eruptions means that Iceland's people and government agencies must be constantly prepared. As recently as 2006, the government and citizens of southern Iceland had taken part in a full-scale test of the evacuation plan for an eruption of Katla[43]—Eyjafjallajökull's larger and more active neighbor to the east (Figure 5.45b). The Icelandic Meteorological Office (IMO) also operates a complex array of monitoring and early warning equipment to minimize the effects of volcanic eruptions, including 56 seismic stations and 70 continuous GPS stations that measure earthquake activity and ground displacement indicative of magma movement. An automated network of hydrological stations also provides early warning for jökulhlaups by measuring the amount and temperature of water flowing in rivers downstream of glacially covered volcanoes (Figure 5.45b).[1]

For almost 20 years prior to the 2010 eruption, intermittent deep earthquake activity was recorded throughout the region surrounding the Eyjafjallajökull and Katla volcanoes.[1] By January 2010, however, just three months before the eruption, seismic activity became localized about 5 km (~3.1 mi) east of Eyjafjallajökull's summit crater and earthquake depths were becoming more shallow with time. Concurrently, GPS stations on the southeast flank of the volcano were detecting uplift and tilting (Figure 5.46). Slow at first, by early March the rate of deformation was as much as 5 mm (~0.2 in.) per day. These data left no doubt that magma in the subsurface was rising up from great depths and pooling within the upper 4 km (~2.5 mi.) of the surface. For the next two weeks the volcano



(a)



(b)

▲ FIGURE 5.45 Icelandic Volcano Monitoring

(a) Map showing the location of Iceland's major volcanoes and ice caps. *(Based on Sigmundson, F. et al., "Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption,"* Nature Letters *468: 426–32, 2010)* (b) Monitoring equipment surrounding Eyjafjallajökull and Katla volcanoes on the southern tip of Iceland. See (a) for location. *(Based on Erik Sturkell et al., "Katla and Eyjafjallajökull Volcanoes," Developments in Quaternary Science 13: 521, 2010)*

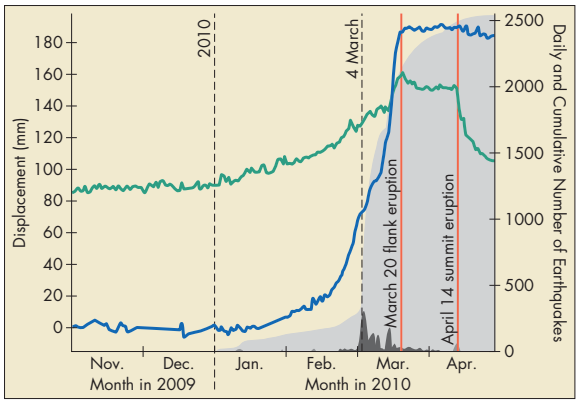
continued to inflate and seismic activity steadily increased with as many as 1,000 earthquakes occurring around March 4 (Figure 5.46).[42]

Eyjafjallajökull's eruption occurred in two phases—an effusive, Icelandic-type eruption phase followed by an explosive phase. The effusive phase began on March 20 with the opening of a 500 m (~1,640 ft.) long fissure on the flank of the volcano 10 km (~6.2 mi.) east of Eyjafjallajökull's caldera (Figure 5.45b). About 500 farm families were immediately evacuated from the area. Fortunately, the fissure opened between the Eyjafjallajökull and Mýrdalsjökull ice caps and the evacuation was suspended after 24 hours of no increased stream flow detected by hydrologic stations.

The effusive phase continued for three weeks and generated a spectacular fire curtain display and lava falls cascading more than 300 m (~985 ft.) down to the local river valleys. Without any obvious hazard, more than 25,000 geotourists visited the volcano to watch the eruption (Figure 5.47).[44] Some visitors actually witnessed the formation of a second fissure, which fortunately opened 200 m (~650 ft.) northwest of the first and not where the crowds had gathered.

After erupting for three straight weeks, 10–20 m (~30–60 ft.) of lava had accumulated around the vent covering 1.5 km^2 (~1 mi^2.). Yet despite this large volume of extruded lava, GPS data showed no evidence for volcano deflation during this phase (Figure 5.46). The lack of deflation indicated a steady inflow of magma, suggesting that the eruption might not end anytime soon. However, on April 12 the lava stopped flowing from the fissures.

For the next 48 hours the seismicity increased beneath Eyjafjallajökull's summit caldera indicating that the magma was working its way to the surface along another path. Then, early in the morning on April 13, an explosive eruption occurred from beneath the 200 m (~650 ft.) thick ice cap (Figure 5.45b). Emergency response plans were enacted and residents on the south side of the volcano were being evacuated by 1:00 A.M. At about 7:00 A.M., hydrologic stations on both the north and the south sides of the volcano detected jökulhlaups, forcing the evacuation of another 800 people in nearby river valleys.[43] Over the next three days several jökulhlaups would be unleashed down the Markarfljót River valley, the largest occurring shortly after the explosive phase began (Figure 5.48a). Fortunately, the floods were relatively small (< 3000 m/s) and flood control structures along the river were able protect some of the roads and agricultural lands in the Valleys (Figure 5.48b). But because the initial floods were charged with debris from the eruption



▲ FIGURE 5.46 GPS and Seismic Data
Seismic and GPS monitoring data showing earthquake activity and surface displacement measurements before and during the 2010 eruption of Eyjafjallajökull volcano. Displacement of two GPS stations (blue and green lines show inflation and deflation of the mountain (left axis), while seismic stations the number of daily (dark gray) and cumulative (light gray) earthquakes since the beginning of 2010. *(Based on Sigmundson, F. et al., "Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption," Nature Letters 468: 426–32, 2010)*

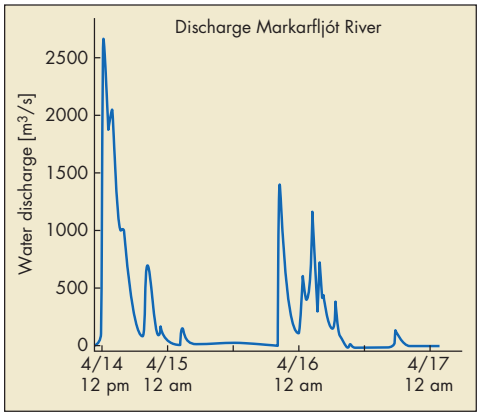
and icebergs from the melting glaciers, some local infrastructure and farms sustained damage (Figure 5.48c).

Unlike the effusive eruption phase, a towering eruption column of ash could be seen rising 9 km (~5.9 mi.) into the atmosphere above Eyjafjallajökull within 24 hours of the eruption (see Figure 5.1a).[45] By April 15, unusually stable high-altitude winds (see jet streams, Chapter 9, section 9.4) blowing toward the southeast carried the ash cloud straight toward Europe (Figure 5.49a). Because volcanic ash can stall and destroy aircraft engines in flight, the Civil Aviation Authority declared a "no fly zone" for any airspace containing more than 4 milligrams per cubic meter of ash. By April 18 most air travel in and out of Europe had been suspended (Figure 5.49b). For more than a week northern Europe's airspace remained closed, stranding countless travelers and costing businesses relying on air travel billions of dollars. This situation persisted until wind patterns changed. Over the next five weeks, the height of the eruption column and the path of the ash varied widely due to changing wind velocities and direction, which meant that temporary airport closures throughout Europe continued through the rest of April and May.

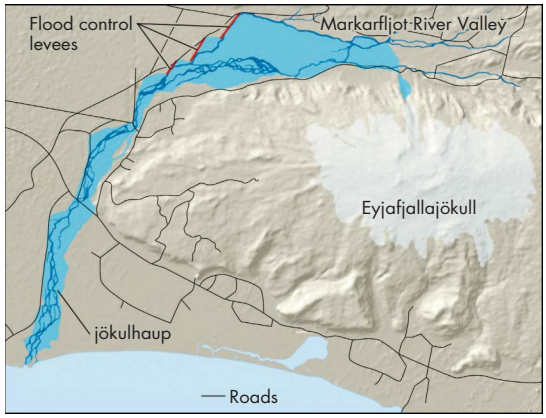
The southerly winds carrying the ash out to sea and causing Europe's woes spared much of Iceland from being blanketed in ash. However, the island's southeastern corner, within about



▲ FIGURE 5.47 Geotourists Witness Fissure Eruption
Eyjafjallajökull volcano draws a crowd during the effusive first phase of the eruption. *(PaKos Photography/Alamy)*



(a)



(b)

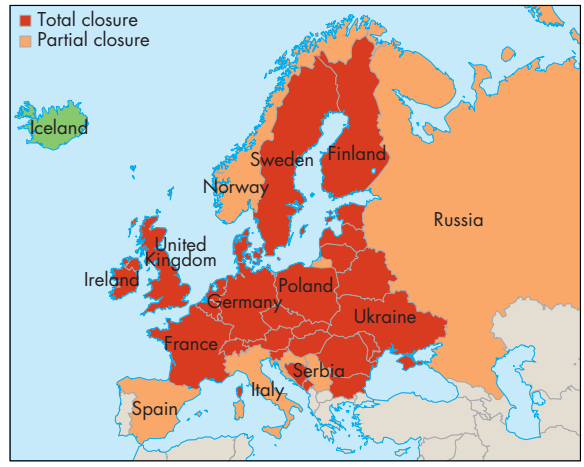


(c)

FIGURE 5.48 Markarfljót River Valley Floods
(a) Hydrograph on the Markarfljót River showing multiple jökulhlaups over a four-day period of the eruption, with the largest occurring on 14 April. *(From Oddur Sigursson et al., "Flood warning system and jökulhlaups-Eyjafjallajökull" (4/7/13), Iceland Meteorological office, http://en.vedur.is/hydrology/articles/nr/2097)* (b) Markarfljót River Valley, showing the area covered by the 14 April jökulhlaup (shaded blue) and the effectiveness of flood control structures (red lines) in minimizing the effects of the torrent of water. (c) Roadway across the Markarfljót River destroyed by jökulhlaup. *(Caters News/ZUMAPRESS/Newscom)*



(a)



(b)

FIGURE 5.49 Ash Shuts Down Air Travel in Europe
(a) Satellite image showing ash cloud from Eyjafjallajökull being carried southward toward Europe. *(NASA)* (b) For 10 days, beginning with the second phase of the eruption on 14 April, the airspace above most of Europe was shut down either partially or completely, affecting an estimated 10 million travelers. *(From "Travel crisis in Europe 2010," http://en.wikipedia.org/wiki/File:Travel_crisis_in_Europe_2010.png)*

20 km (~12.5 mi.) of Eyjafjallajökull, was covered by several centimeters (1–2 inches) of ash, and from April 17 until early April 18 the region was plunged into total darkness by the ash fallout (Figure 5.50).[45] Volcanic lightning within the eruption column during this period was also particularly vigorous with as many as 15 strikes an hour being recorded (see chapter-opener photograph), but it was the accumulation of ash that caused problems for local farmers. Toxic levels of water-soluble fluoride in the ash could

sicken or kill livestock if animals digested or inhaled the fine ash or drunk from contaminated streams. Farmers were therefore told to keep themselves and their animals inside, but this was problematic due to calving season and also confusing because these instructions contradicted the recently practiced Katla evacuation plan, which stated that animals should be released during an eruption.

The unexpectedly large ash column produced during the second phase of the eruption was, in part, due to the interaction of water melted from the ice cap and the erupting lava. Rapid cooling of the hot lava caused explosive fragmenting of the melt during steam explosions, forming fine ash that was carried upward into the eruption column. In addition, the magma erupting from Eyjafjallajökull's caldera had a higher silica content and viscosity than the lava that erupted from the fissures on the flank of the volcano. The 2010 eruptions of Eyjafjallajökull was not declared over until six months later in October. During the volcano's explosive phase, it was estimated that 0.27 km^3 (~0.05 $mi.^3$) of magma erupted, and together with the ash plume height, the explosive power of the eruption ranked as a 3 on the VEI (see Table 5.2).[45] No deaths were directly attributed to the eruption, but two people did die in their travels to witness the effusive phase of the eruption.

Eyjafjallajökull had only erupted twice before in the past thousand years, and eruptions were relatively small.[46] Katla, however, had erupted 20 times over this same interval and the eruptions often included large ash plume. This history combined with a larger ice cap means Katla has always been considered the greater threat. Although most scientists do not believe that the volcanic magma pluming systems of these two volcanoes are linked, the previous two eruptions of Eyjafjallajökull occurred in tandem with Katla eruptions. Therefore, seismic activity surrounding the Katla volcano was closely monitored throughout Eyjafjallajökull's 2010 eruption. Since the 2010 eruption, an increase in seismic activity beneath Katla's caldera indicates that magma is moving within the volcano, leading to concerns about an impending Katla eruption.



▲ FIGURE 5.50 Ash Fallout Endangers Animals
Farmers rescue cattle from toxic volcanic ash fallout southeast of Eyjafjallajökull on 17 April. *(Brynjar Gauti/AP Images)*

APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. What kind of monitoring is done to predict Eyjafjallajökull and Katla eruptions? Figure 5.46 shows some monitoring station data. Discuss how these data changed from January through April and how these changes are related to forecasting and monitoring changes within the volcano.
2. How does the risk presented by Eyjafjallajökull compare to that of Katla? Prior to 2010, the global risk of volcanic eruptions on Iceland was thought to be very low. Explain how and why the 2010 eruption has changed the perceived global risk for future Icelandic eruptions.
3. In addition to the direct effects of the volcanic eruption, such as ash fall and lava flows, several other natural hazards were linked to the eruption. Explain these linkages and discuss the geographic regions that could be affected by the linked hazards.
4. Iceland's very low population density and the volcano's rural setting limited the potentially disastrous effects of the 2010 eruption. How might the local effects of the eruption have been different if the city where you live now was located at the foot of Eyjafjallajökull in April 2010?
5. Discuss the preparedness of Iceland's government and people for volcanic eruptions and the effectiveness of the scientific equipment, evacuation planning, and engineering structures used to mitigate the effects of the eruption (refer to Figures 5.45 and 5.48).

CONCEPTS in review

5.1 Introduction to Volcanism

LO:1 Explain the relationship of volcanoes to plate tectonics.

- Volcanic activity is directly related to plate tectonics. Most volcanoes are located at plate boundaries, where magma is produced in the spreading or sinking of lithospheric plates. Two-thirds of the world's volcanoes are associated with the sinking of lithospheric plates along the Ring of Fire surrounding most of the Pacific Ocean.
- Lava is magma that has been extruded from a volcano. Its viscosity, a characteristic related to the temperature and silica content, and volatile content are important in determining the eruptive style of the different types of volcanoes.
- Magma comes from melting of the asthenosphere. Three ways to melt the asthenosphere are by decompression, addition of volatiles, and addition of heat.
- Features of volcanoes include ven**hield volcano**ts, craters, and calderas.



KEY WORDS

crater (p. 161), **decompression melting** (p. 157), **effusive eruption** (p. 161), **lava** (p. 156), **magma** (p. 156), **magma chamber** (p. 160), **pyroclastic debris** (p. 161), **volatiles** (p. 159), **volcanic vent** (p. 156)

5.2 Volcano Types, Formation, and Eruptive Behavior

LO:2 Identify the different types of volcanoes and their associated features.

- Most explosive volcanic eruptions are from the classic, cone-shaped stratovolcanoes that occur above subduction zones, particularly around the Pacific Rim. These volcanoes are characterized by explosive eruptions and are composed primarily of silica-rich lavas, such as andesite, and pyroclastic deposits.
- Volcanic domes are smaller than stratovolcanoes but develop similarly above subduction zones and are composed of viscous magma. Domes can be explosive or nonexplosive.
- The largest volcanoes, shield volcanoes, are common at mid-ocean ridges such as Iceland, and over mid-plate hot spots such as the Hawaiian Islands. They are characterized by relatively nonexplosive lava flows of basalt.
- Large calderas are created by infrequent, huge, violent eruptions. Following an explosive beginning, they often resurge and may present a volcanic hazard for a million years or longer.



KEY WORDS

caldera (p. 166), **cinder cone** (p. 167), **lava dome** (p. 163), **shield volcano** (p. 165), **stratovolcano** (p. 162), **volcanic explosivity index (VEI)** (p. 162)

5.3 Geographic Regions at Risk from Volcanoes

LO:3 Locate on a map the geographic regions at risk from volcanoes.

- Specific geographic regions of North America at risk from volcanoes include the northwestern coast of California; the western coasts of Oregon and Washington and parts of British Columbia and Alaska, Long Valley, and the Yellowstone National Park area.



5.4 Effects of Volcanoes

LO:4 Describe the effects of volcanoes and how they are linked to other natural hazards.

- Primary effects of volcanic activity include lava flows, pyroclastic hazards, and, occasionally, the emission of poisonous gases.
- Lava flows, which can move as fast as 35 mph, but often move much slower, do not represent a serious hazard for loss of life because they can often be avoided. However, they are not easily diverted so loss of property and land can result from lava flows.
- Pyroclastic hazards include volcanic ash falls, which may cover large areas with carpets of cool ash that can destroy some structures and ruin agricultural land, but loss of life is less common. By contrast, pyroclastic flows travel at very high velocities, are extremely hot, and destroy and kill everything in their path.
- Secondary effects of volcanic activity include debris flows and mudflows, generated when melting snow and ice or precipitation mix with volcanic ash. These flows can devastate an area many kilometers from the volcano. All these effects have occurred in the recent history of the Cascade Range of the Pacific Northwest and will occur there in the future.



KEY WORDS

ash fall (p. 175), **debris flows** (p. 180), **lateral blast** (p. 176), **lava flow** (p. 172), **mudflows** (p. 180), **pyroclastic deposit** (p. 174), **pyroclastic flow** (p. 175), **tephra** (p. 174)

5.5 and 5.6 Linkages between Volcanoes and Other Natural Hazards Natural Service Functions of Volcanoes

LO:5 List the potential benefits of volcanic eruptions.

LO:6 Discuss how humans can minimize the volcanic hazard.

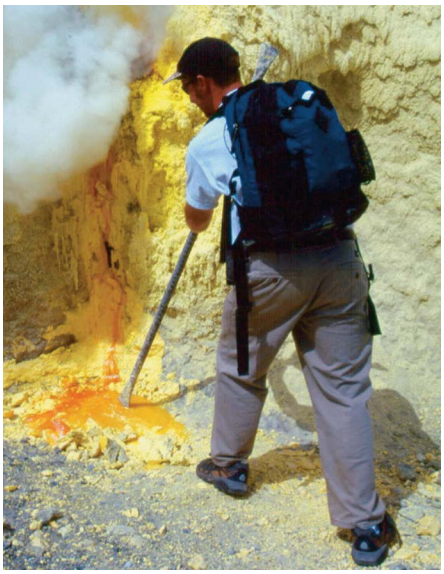
- Volcanoes are linked to other natural hazards such as fire, earthquakes, landslides, and climate change.
- Volcanoes provide fertile soils, a source of power, mineral resources, recreational opportunities, as well as newly created land.



5.7, 5.8, and 5.9 Human Interactions with Volcanoes Minimizing the Volcanic Hazard Perception of and Adjustment to the Volcanic Hazard

LO:7 Recommend adjustments we can make to avoid death and damage from volcanoes.

- Sufficient monitoring of seismic activity; thermal, magnetic, and hydrologic properties; and changes in the land surface, combined with knowledge of the recent geologic history of volcanoes, may eventually result in reliable forecasting of volcanic activity.
- Forecasts of eruptions have been successful, particularly for Hawaiian volcanoes and Mount Pinatubo in the Philippines.
- The U.S. Geological Survey has developed an alert notification system for volcanic activity that has four levels for hazards on land and four color codes for aviation hazards.
- Efforts to meet the goal of reducing volcanic hazards are focusing on human and societal issues of communication; the objective is to prevent a volcanic crisis from becoming a disaster or catastrophe. Worldwide, however, it is unlikely that we will be able to accurately forecast most volcanic activity in the near future.
- Perception of the volcanic hazard is apparently a function of a person's age and length of residency near the hazard. Community-based education plays an important role in informing people about the hazards of volcanoes. Apart from psychological adjustment to losses, the primary human adjustment to volcanic activity is evacuation. Some attempts to control lava flows once an eruption has begun have been successful.



KEY WORD

volcanic crisis (p. 194)

CRITICAL thinking questions

1. While looking through some old boxes in your grandparents' home, you find a sample of volcanic rock collected by your great-grandfather. No one knows where it was collected. You take it to school, and your geology professor tells you that it is a sample of andesite. What might you tell your grandparents about the type of volcano from which it probably came, its geologic environment, and the type of volcanic activity that likely produced it?
2. In our discussion of perception of and adjustment to volcanic hazards, we established that people's perceptions and what they will do in case of an eruption are associated with both their proximity to the hazard and their knowledge of volcanic processes and necessary adjustments. With this association in mind, develop a public relations program that could alert people to a potential volcanic hazard. Keep in mind that the tragedy associated with the eruption of Nevado del Ruiz was in part due to political and economic factors that influenced the apathetic attitude toward the hazard map prepared for that area. Some people were afraid that the hazard map would lower property values in high-risk areas.
3. You are going to take a scout troop to Hawaii to see the Kilauea volcano. Some children have seen

documentaries of the 1980 eruption of Mount St. Helens and are afraid; others are fearless and want to try cooking on a lava flow. What will you tell the fearful scouts? Describe the safety precautions you will follow for all the scouts.

4. Given what you know about the effects of a volcanic eruption and the linked natural hazards, where might you build your house if you were living near a composite volcano such as Mount Rainer in Washington?
5. Do you think our current ability to monitor precursor events and predict an eminent eruption is sufficient for large populations to live on the flank of an active volcano? Why or why not?

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