Mount Nyiragongo is a volcano located in Virunga National Park in the Democratic Republic of the Congo. Mount Nyiragongo has a molten lake of lava in the crater of its summit, obscured here by steam. Nyiragongo’s lava is unusually runny, flowing downslope at speeds up to 100 km/h (62 mph). The volcano has twice sent lava streams down into nearby villages and into the city of Goma. (© Last Refuge/Robert Harding Picture Library/Age Fotostock Inc.)
To learn more about this type of volcano, turn to Section 14.1.

LIVING PHYSICAL GEOGRAPHY

➤ What is a tsunami?
➤ Why do some volcanoes explode violently?
➤ What causes earthquakes?
➤ What was the “Year without a Summer”?
PART III • TECTONIC SYSTEMS: BUILDING THE LITHOSPHERE

THE BIG PICTURE Earth’s hot interior and its moving crust create volcanoes and earthquakes. These phenomena shape the surface of the crust and present hazards for people.

LEARNING GOALS After reading this chapter, you will be able to:

14.1 Describe three main types of volcanoes and major landforms associated with each.
14.2 Explain the hazards volcanoes pose and which geographic areas are most at risk.
14.3 Explain what causes earthquakes.
14.4 Describe the types of seismic waves produced by earthquakes, how earthquakes are ranked, and what can be done to reduce our vulnerability to earthquakes.
14.5 Assess the potential links between large volcanic eruptions, Earth’s physical systems, and people.

THE HUMAN SPHERE: Deadly Ocean Waves

JUST BEFORE 8:00 A.M. ON DECEMBER 26, 2004, the seafloor off the coast of the island of Sumatra, in Indonesia, was thrust upward 5 m (16 ft) in a magnitude 9.1 earthquake. This earthquake was the third strongest in recorded history. The movement of the seafloor heaved an estimated 30 km$^3$ (7.2 mi$^3$) of seawater upward, creating a series of waves that radiated across the Indian Ocean. Such large ocean waves triggered by an earthquake or other natural disturbance of the ocean floor are called tsunamis.

In the open ocean, the waves traveled at nearly the speed of a jetliner (800 km/h or 500 mph), but they went largely undetected because they had a wavelength (the distance between wave crests) of hundreds of kilometers. Thus, the thousands of boats in the Indian Ocean did not detect the waves as they passed underneath.

As the waves approached shallow water, however, the wavelengths decreased and the height of the waves grew up to 15 m (50 ft) high in some regions. Some coastal areas even experienced 30 m (100 ft) waves. The waves devastated coastal areas along the Indian Ocean, particularly in regions nearest the earthquake. Most of the city of Banda Aceh, on Sumatra (Figure 14.1), was destroyed.

In response to this catastrophe, the Indian Ocean Tsunami Warning System, similar to one already active in the Pacific Ocean, was developed and activated in June of 2006. Cell-phone users can access a free app that is connected to the detection system and provides real-time data and warnings. It is hoped that with this system in place, another catastrophic loss of life can be avoided.

This chapter focuses on geologic hazards, or geohazards: hazards presented to people by the physical Earth. Examples of geohazards include volcanic eruptions, earthquakes, and tsunamis. We first examine volcano types as well as the behavior of volcanoes and the hazards they present. We next explore earthquakes and the dangers they pose for people. Finally, we take a look at the global reach of large volcanic eruptions and their effects on human societies.

*Answers to the Living Physical Geography questions are found on page 000.
14.1 About Volcanoes

Describe three main types of volcanoes and major landforms associated with each.

Volcanoes shape Earth’s crust. They can pour cubic kilometers of lava onto Earth’s surface to build new islands and landmasses. They form beautiful snow-capped peaks that have inspired humans for generations, and they provide nutrient-rich soils that plants thrive in. Volcanoes can also be extremely dangerous and cause catastrophic loss of human life.

Active volcanoes—those that have erupted in the last 10,000 years and could erupt again—pose the greatest danger to human life. Volcanoes that have not erupted for 10,000 years or more, but could awaken again, are considered dormant or inactive. An extinct volcano is one that has not erupted for tens of thousands of years and can never erupt again.

Three Types of Volcanoes

Volcanoes are surface landforms created by accumulations of the materials they emit over time. Although they take on many shapes and sizes, most volcanoes can be categorized as either stratovolcanoes, shield volcanoes, or cinder cones.

A stratovolcano, or composite volcano, is a large, potentially explosive, cone-shaped volcano composed of alternating layers of lava and pyroclasts. Pyroclasts, or pyroclastic materials, encompass any fragmented solid material that is ejected from a volcano. Pyroclasts range in size from ash—pulverized rock particles and solidified droplets of lava that form a fine powder—to large boulders. Stratovolcanoes are the most conspicuous type of volcano. Their cones can tower over landscapes, as shown in Figure 14.2.

A shield volcano is a broad, domed volcano formed from many layers of fluid basaltic lava.
Shield volcanoes are much larger than stratovolcanoes. In fact, they are so large that they can be difficult to identify as volcanoes from the ground. Instead, they look like a broad, gently sloped horizon.

Cinder cones are small, cone-shaped volcanoes consisting of pyroclasts that settle at the angle of repose. The steepest angle at which loose sediments can settle.

Cinder cones are small, cone-shaped volcanoes consisting of pyroclasts that settle at the angle of repose: the steepest angle at which loose sediments can settle. The steepness of the slope of a cinder cone ranges from 25 to 35 degrees, depending on the size of the pyroclasts that were ejected during their formation. Cinder cones can form in any volcanic setting, but particularly on the flanks or at the bases of stratovolcanoes and shield volcanoes.

Most cinder cones are less than 400 m (1,300 ft) high, and they are roughly symmetrical. They are roughly symmetrical. Many cinder cones erupt for a few decades or less, then become extinct. Structurally, cinder cones are the simplest of the three types of volcanoes, as illustrated in Figure 14.4.

Cinder cones are the smallest type of volcano. Figure 14.5 illustrates and compares the differences in the extents of the three volcano types.

What Do Volcanoes Make?
Active stratovolcanoes and shield volcanoes make and eject a variety of physical materials, ranging in size from fine ash to large boulders, and they create landforms from small volcanic craters to vast
lava fields. Here we discuss three categories of volcanic products: lavas, pyroclasts and gases, and volcanic landforms.

**Molten Rock: Lava**

Lava is one of the most conspicuous products of volcanic activity. Lava comes only from volcanoes or volcanic fissures in the ground. Lava flows range from fast-moving sheets of basaltic lava to blocky, glowing boulders that slowly push and tumble across a landscape. Lava also forms cohesive masses of molten rock thick enough to plug a volcanic vent.

The thickness of a material is called its viscosity. The higher a material’s viscosity, the more resistant it is to flowing. The viscosity of lava is controlled by many factors, including its temperature, gas content, crystal content, and silica (SiO₂) content. Silica plays an important role in determining lava viscosity because it forms long chains of molecules that bind the lava together.

Three types of lava can be classified according to their silica content and temperature: mafic, intermediate, and felsic. Mafic lava has a temperature of about 1,000°C to 1,200°C (1,800°F to 2,200°F), has a silica content of 50% or less, has a low viscosity, and flows easily. Mafic lava builds shield volcanoes. When mafic lava solidifies into smooth, billowy lobes over the surface, it is called pāhoehoe (Figure 14.6A). When it takes on a blocky, rough surface, it is called ‘a‘ā.

Intermediate lava has a temperature of about 800°C to 1,000°C (1,500°F to 1,800°F), a silica content between 50% and 70%, and a medium viscosity (Figure 14.6B). Andesitic lava, often called blocky lava because of its blocky texture as it moves downslope, is one type of intermediate lava. Stratovolcanoes are composed mostly of intermediate lava and felsic lava.

Of the three lava types, felsic lava has the coolest temperature, at about 650°C to 800°C (1,200°F to 1,500°F), and the highest silica content, 70% or more. Its resulting high viscosity restricts its ability to flow. Plug domes, which may block volcanic vents, are composed of viscous felsic lava (Figure 14.6C).

---

**FIGURE 14.5** Volcano sizes. A typical cinder cone, Mount Fuji, and the Big Island of Hawai‘i (composed of five fused shield volcanoes) are drawn to scale to show their relative sizes. Much of Hawai‘i is submerged beneath the ocean, so the immense size of its shield volcanoes is hidden.

**FIGURE 14.6** Three types of lava. (A) Mafic lava has a low viscosity and flows in streams or sheets downslope. This volcanologist (a scientist who studies volcanoes) is sampling pāhoehoe in Hawai‘i Volcanoes National Park, on the island of Hawai‘i. (B) Intermediate lava is more viscous than mafic lava and resists movement. This photo shows the blocky consistency of intermediate lava on Mount Etna, Sicily. (C) Thick, felsic lava has formed a plug dome in the volcanic vent of Mount St. Helens. (top, © David R. Frazier/Science Source; center, © Tom Pfeiffer/www.volcanodiscovery.com; bottom, USGS/photo by John S. Pallister)
What determines the amount of silica in magma? Two main factors determine its silica content: the makeup of the solid mantle material from which the magma first melted and the type of rock the magma passes through on its way to the surface of the crust. For example, as magma migrates through granitic crust in a subduction zone, it will partially melt the surrounding granite through which it is passing (see Section 13.2). Granite is high in silica and will be mixed into the magma, creating a felsic magma. On the other hand, magma migrating up through basaltic oceanic crust, as it does at a hot spot, becomes mafic lava that spills from a volcano (Figure 14.7). Mafic lava that erupts beneath the ocean forms pillow lava (Figure 14.7B). Because most volcanic activity on Earth occurs at divergent plate boundaries along mid-ocean ridges, pillow lavas are the most geographically widespread but least seen lava formations. In time, pillow-lava accumulations can grow to considerable size and even form new islands. The formation of the Hawaiian Islands began with pillow lava.

**Blown into the Air: Pyroclasts and Gases**

Explosive volcanic eruptions produce pyroclasts with a wide range of sizes, shapes, and consistencies. Some common types of pyroclasts are described here.

- **Volcanic ash:** Volcanic eruptions can spray droplets of lava high into the air, which solidify as they cool. In powerful explosive eruptions, existing rock from the volcano can also be pulverized into a fine powder and ejected into the atmosphere. These materials constitute volcanic ash, which is very fine-grained and soft to the touch.

- **Lapilli and pumice:** Two other types of pyroclasts are lapilli and pumice. Both are formed from intermediate and felsic lava. Lapilli are marble- to golf ball–sized cooled fragments of lava (Figure 14.8A). Because most volcanic activity on Earth occurs at divergent plate boundaries along mid-ocean ridges, lapilli are the most geographically widespread but least seen lava formations. In time, lapilli accumulate to considerable size and even form new islands. The formation of the Hawaiian Islands began with pillow lava.

- **Volcanic bombs and blocks:** A volcanic bomb is a streamlined fragment of lava ejected from a volcano that cooled and hardened as it was still moving through the air. A volcanic block is a fragment of rock from the volcano’s cone that is ejected during an explosive eruption (Figure 14.9).

- **Volcanic gases:** By volume, about 8% of most magma is gas. Gas is not a pyroclastic material, but gas emissions produce pyroclasts. As gas forcefully exits a volcano, it blasts lava and rock debris into the air, generating pyroclasts. Gas in magma expands as the magma migrates toward the surface of the crust, where there is less pressure. At the surface, the gases in magma expand rapidly, creating an explosion.
Aside from their role in generating pyroclasts, volcanic gases are not usually lethal to people. The main gases emitted by volcanoes are water vapor, carbon dioxide, sulfur dioxide, and hydrogen sulfide (\( \text{H}_2\text{O}, \text{CO}_2, \text{SO}_2, \text{and H}_2\text{S} \)). Where volcanic gases are concentrated, however, they can be lethal. An example of this occurred near Lake Nyos, in Cameroon, in western Africa, in 1986. Lake Nyos is located on an inactive volcano. A magma chamber below the lake leaks CO\(_2\) into the lake. Occasionally, the CO\(_2\) is released from the lake in a sudden outgassing event. In August 1986, the lake is thought to have emitted about 1.6 million tons of CO\(_2\), suffocating 1,700 people and 3,500 head of livestock.

**FIGURE 14.9 Bombs and blocks.** (A) This volcanic bomb was found in the Pinacate Volcanic Field in northwestern Sonora, Mexico. Its typical streamlined shape is the result of airflow around it as it cooled in flight. (B) The flanks of Licancabur volcano, near the town of San Pedro de Atacama in central Chile, are littered with blocks that once made up the volcano, but were torn from it during an eruption.

(A. © Peter L. Kresan; B. © Paul Harris/AWL Images/Getty Images)
Columbia Plateau
The Columbia Plateau formed from flood basalts, it is 500 m (1,640 ft) thick in places and covers some 220,000 km² (85,000 mi²).

Columbia Plateau
Siberian Traps
Flood basalts cover extensive areas of Siberia in central Eurasia. The word trap is derived from the Swedish word trappa, which means stairs, alluding to the stairlike appearance of flood basalts. The Siberian Traps are 250 million years old and cover about 2 million km² (770,000 mi²). They are 3,500 m (11,500 ft) thick in places.

Deccan Traps
Ellora Caves, in northwestern Maharashtra State, India, are a World Heritage Site. Ellora is one of hundreds of archaeological sites carved into the flood basalts of the Deccan Plateau of India, also called the Deccan Traps. The Deccan Traps cover 500,000 km² (200,000 mi²) and are more than 2,000 m (6,500 ft) thick. They were formed 68 million years ago.


FIGURE 14.10 Columnar jointing. This photo shows a small portion of the island of Staffa, in the Inner Hebrides of northwestern Scotland. Most of Staffa is composed of mafic lava that slowly cooled 55 million years ago, allowing time for columnar jointing to form. Here, the joints mainly sit perpendicular to the cooling surface. (© Photo by Lady of the Dawn/Flickr Open/Getty Images)

FIGURE 14.11 Large igneous provinces. All of these large igneous provinces were formed where mantle plumes formed geologic hot spots. Most of the eruptions that formed them caused global climate change, and some even caused global mass extinction events when they rapidly elevated atmospheric CO₂ levels. (left, © Peter L. Kresan; center, © Serguei Fomine/Global Look/Corbis; right, © Tony Waltham/Robert Harding/Getty Images)
After the Lava Cools: Volcanic Landforms

Volcanic landforms are typically very conspicuous on Earth's surface. Some common volcanic landforms, in addition to volcanic mountains, are columnar jointing, large igneous provinces, and calderas.

Columnar jointing: As basaltic lava cools and hardens into rock, cracks and weak planes in the rock, called joints, develop. A geometric jointing pattern called columnar jointing, shown in Figure 14.10, sometimes forms, in which angular columns result from joint formation in the lava during cooling.

Large igneous provinces: Large igneous provinces (LIPs) are accumulations of basaltic lava that cover extensive geographic areas. If you have ever driven through eastern Washington and Oregon, you drove over the Columbia Plateau. The rocks of the Columbia Plateau superficially resemble sedimentary rocks, but they are flood basalts, lava flows that poured onto the crust over several million years. The Columbia Plateau flows formed between 17 million and 6 million years ago and created a large igneous province. There are several dozen large igneous provinces around the world (Figure 14.11).

Calderas: After an eruption, the emptied magma chamber can collapse, forming a large circular depression called a caldera (from the Spanish word for "cauldron"). The process of caldera formation is illustrated in Figure 14.12. Calderas can be many kilometers in diameter. They usually have flat bases and steep slopes. Calderas can be mistaken for meteor impact craters, but the two can be differentiated because each leaves different types of evidence (Picture This, page 12).
14.2 Pele’s Power: Volcanic Hazards

Explain the hazards volcanoes pose and which geographic areas are most at risk.

In Hawaiian myth, Pele is the volcano goddess. She is said to reside in the summit caldera of Kilauea on the island of Hawai‘i. Pele embodies the many facets of volcanoes, ranging from life-sustaining benevolence to destructive malevolence. In this section, we turn to Pele’s malevolent side and examine the main geohazards that volcanoes present.

Two Kinds of Eruptions: Effusive and Explosive

Shield volcanoes, such as those found on Hawai‘i, present little threat to human life. Shield volcanoes have nonexplosive effusive eruptions that emit more lava than gases. Mafic lava from shield volcanoes usually flows slowly downhill and can be avoided.

Stratovolcanoes, on the other hand, are potentially serious geohazards. Their eruptions are called explosive eruptions. An explosive eruption is violent and yields large amounts of pyroclasts. Stratovolcanoes may produce effusive outpourings of mafic lava like shield volcanoes, but they are also capable of exploding violently with little warning.

Explosive eruptions send rock, ash, and volcanic gases high into the troposphere, or even into the stratosphere. In the troposphere, rain washes the volcanic material out in a few days or weeks. There is no rainfall in the stratosphere, however, so once ash and sulfur gases enter the stratosphere, they can remain suspended there for five years or more. These materials can encircle the globe and cause climate cooling for a few years (see Section 6.2).
Large explosive eruptions result when gas-rich felsic magma migrates upward through the crust and encounters less pressure, which causes it to expand rapidly. Once the magma and gases begin expanding, the surrounding magma chamber is enlarged, allowing more gas to expand and further enlarge the magma chamber. This process can unfold over the course of minutes to hours and can result in a catastrophic explosive eruption.

Island volcanoes can become particularly explosive when seawater migrates into the magma chamber, as might occur after an earthquake. As water comes into contact with the intense heat, it turns to vapor and expands rapidly and explosively. Figure 14.13 shows an explosive volcanic eruption in which the force of the expanding gases and collapsing magma chamber sent ash billowing high into the atmosphere.

**Ranking Volcanic Eruption Strength**

The **volcanic explosivity index (VEI)** ranks volcanic eruption magnitude based on the amount of material a volcano ejects during an eruption. A VEI 5 eruption emits more than 1 km³ (0.24 mi³) of pyroclastic material into the atmosphere, and a VEI 6 eruption emits more than 10 km³ (24 mi³). During the last 10,000 years, there have been about 50 VEI 6 eruptions. The eruption of Tambora, described in Geographic Perspectives, was the only VEI 7 eruption in historic times. Figure 14.14 compares large historical eruptions to the colossal prehistoric eruption of the Yellowstone caldera, 640,000 years ago.

**The Two Greatest Threats: Lahars and Pyroclastic Flows**

Stratovolcanoes are among the most dangerous geohazards on the planet. Lava flows from these volcanoes are not their biggest threat because their lava usually flows slowly, so people can escape. The two greatest volcanic hazards are lahars and pyroclastic flows. Together, they account for about half of the volcano-related deaths in any given year.

**Torrents of Mud: Lahars**

A lahar (a Javanese word that means “mudflow” or “debris flow”) is a mudflow that results when a snow-capped stratovolcano erupts. A lahar is a thick slurry of mud, ash, water, and other debris that moves rapidly down the volcano’s flank. Lahars can travel tens of kilometers down the slopes of volcanic explosivity index (VEI)

An index used to rank volcanic eruptions based on the amount of material a volcano ejects during an eruption.

lahar

A thick slurry of mud, ash, water, and other debris that flows rapidly down a snow-capped stratovolcano when it erupts.
volcanoes and into the flatlands below, where people may reside. Lahars are not hot. Their danger lies in the fact that they move quickly and can engulf whole villages in minutes. Figure 14.15 shows a lahar that engulfed Plymouth, the former capital city of Montserrat, an island in the Caribbean Sea.

**Blazing Clouds: Pyroclastic Flows**

Pyroclastic flows (also called *nuées ardentes*, meaning “blazing clouds”) are rapidly moving avalanches of gas and ash. Pyroclastic flows are one of the greatest volcanic hazards because they can travel at speeds up to 700 km/h (450 mph) and they can be as hot as 500°C (930°F). At night, these avalanches can glow orange from their intense heat. The largest flows can travel hundreds of kilometers from the volcanic vent. Figure 14.16 shows a pyroclastic flow on Mount Merapi in Indonesia.

Lahars and pyroclastic flows are by far the most significant geohazards volcanoes present, but they are not the only ones. Volcanoes can also produce large earthquakes, dangerous lava flows, and smothering ashfalls. Picture This explores an unusual and unfortunate volcanic event that happened in Italy many centuries ago.
In 79 CE, on the morning of August 24, a series of earthquakes shook the region near the Italian city of Pompeii. At about 1:00 p.m., a menacing black ash cloud billowed up 25 km (15 mi) and shrouded Pompeii (and the nearby city of Herculaneum) in blackness. Eruptions continued for a week. As many as 16,000 people may have died, crushed under the weight of ash as rooftops collapsed or asphyxiated as they were buried alive. The town was entombed beneath 6 m (18 ft) of ash.

In 1749, mysterious terra cotta roof tiles were found beneath farm fields where a canal was being dug, hinting at a lost city beneath. It was not until the late 1880s that archaeologists began to excavate the ash to reveal the ruins of Pompeii beneath. As they were digging, they found many mysterious cavities in the ash. When these cavities were injected with plaster, shapes of people were revealed.

Mount Vesuvius, which was responsible for the destruction of Pompeii, is still alive and active. It last erupted for a period of 31 years, from 1913 to 1944. Since then, it has been silent. Fully aware of the risk posed by the volcano, the Italian government has offered up to 30,000 euros (US$40,000) to each of the 500,000 people living in the "red zone" of the volcano (the area of greatest hazard) to move farther away. Most have declined this offer.

Consider This

1. When did Mount Vesuvius last erupt? How do you think the number of people living around the volcano then compares with the local population today?
2. If given the opportunity, would you live in the red zone of Vesuvius or another such risky zone? Explain.
Can Scientists Predict Volcanic Eruptions?

Because volcanoes can be such a serious geohazard, predicting their eruptions would save many lives. Scientists can sometimes predict an eruption within weeks or months if a volcano gives warning signs. The monitoring of Mount St. Helens, in Washington State, is a good example of the process of monitoring warning signs and successfully anticipating an eruption, as illustrated in Figure 14.17.

Figure 14.17 Scientific Inquiry: Can scientists predict dangerous volcanic eruptions? Careful monitoring of Mount St. Helens allowed scientists to predict its eruption in 1980 and warn people to get out of harm’s way. Changes in the gases emitted by a volcano, widening cracks, swelling of the volcano’s surface, and increasing earthquake activity can all be signs that magma is moving upward through the magma chamber. Given the growing body of data that pointed to an impending eruption, scientists urged local authorities to close the mountain to the public before the eruption, saving thousands of lives. (1. USGS, photo by Thomas Casadevall; 2. U.S. Geological Survey, photo by Lyn Topinka; 3. U.S. Geological Survey, photo by Lyn Topinka; 4. U.S. Geological Survey, photo by F. W. Lipman; 5. U.S. Geological Survey, Volcano Hazards Program, photo by Mike Doukas)

1. Scientists take gas samples to understand how magma is moving beneath the ground.
2. Surface cracks are measured. Widening of cracks could indicate that magma is rising up through the magma chamber.
4. Scientists measure surface swelling from a distance.
5. The May 1980 eruption of Mount St. Helens was not a surprise. Scientists collected data and closely monitored the volcano before its eruption.
The Pacific Ring of Fire

Plate tectonic theory provides the framework to understand why volcanic landforms occur where they do. All volcanoes are found where the mantle is melted into magma, namely, at or near mid-ocean ridges (divergent plate boundaries), subduction zones (convergent plate boundaries), continental rifts, and hot spots (see Sections 12.3 and 12.4).

More than 60% of the Pacific Ocean’s margins, totaling some 40,000 km (25,000 mi), are subduction zones with active and dangerous stratovolcanoes. These volcanoes make up the Pacific Ring of Fire (see Section 12.3). Although shield volcanoes are found in the Pacific Ring of Fire, explosive stratovolcanoes are the most common type of volcano there. Many of them are dormant, but there are also many active and dangerous stratovolcanoes. Figure 14.18 provides an eruption history for some of the more active stratovolcanoes in the Pacific Ring of Fire.

Volcán de Colima, Mexico

Volcán de Colima is one of Mexico’s most active volcanoes. It generated a catastrophic VEI 5 eruption on January 17, 1913. Today, some 300,000 people live within about 40 km (25 mi) of the volcano, which puts them at risk in the event of another major eruption.

Mount Merapi, Indonesia

Mount Merapi is Indonesia’s most active volcano. It has erupted almost continually over the last 450 years. Volcanic gases and steam can be seen at the summit almost every day of the year. Merapi produced a VEI 4 eruption in October 2010 that killed 150 people and displaced 320,000. A mandatory government evacuation order just before the eruption averted what would have been a catastrophic loss of life.

Whakaari/White Island, New Zealand

Whakaari/White Island is New Zealand’s most active volcano. Seventy-five percent of the volcano lies submerged in the ocean; only the peak (standing at 321 m or 1,053 ft above sea level) can be seen.
14.3 Tectonic Hazards: Faults and Earthquakes

Explain what causes earthquakes.

On Friday, March 11, 2011, seismographs around the world began detecting one of the largest earthquakes in recorded history, now called the 2011 Tōhoku earthquake. The shaking began at 2:46 p.m. local time. The earthquake was calculated at magnitude 9.0, a colossal event. There are more than 1 million detectable earthquakes on the planet each year, and this single 9.0 event released more energy than all of the others combined. Only four other recorded earthquakes have been larger. The earthquake focus was 32 km (20 mi) deep and 128 km (80 mi) from Sendai, on the island of Honshu, Japan. The aftershocks that followed for weeks were as powerful as magnitude 7.2.

The damage caused by the earthquake and its aftershocks was made much worse by a tsunami that reduced the low-lying coastal regions in its path to ruins (see the Human Sphere section at the beginning of this chapter to learn about tsunamis). To make matters even worse, local nuclear power plants survived the shaking, but were not designed to be flooded by salt water. After they were flooded, they leaked radiation, which traveled across the Northern Hemisphere. Bringing the damaged nuclear plants under control and stopping radiation leaks have been among the greatest challenges brought by this earthquake. As of 2014, radiation continues to leak from the Fukushima Daiichi nuclear power plant into the Pacific Ocean.

Faulting and Earthquakes

Although usually less noticeable than volcanic hazards, earthquakes are as dangerous as volcanoes, or even more so. The 2011 Tōhoku earthquake, like all earthquakes, occurred when Earth’s crust broke along a geologic fault, which is a fracture in the crust where movement and earthquakes occur (see Section 12.4).

Most earthquakes are too small to be felt by people. Only seismographs can detect them. Many
of those that do shake the ground strongly occur in remote areas, such as the deep seafloor, and are harmless to people. Very rarely, a massive earthquake, such as the Tôhoku earthquake, occurs near a populated region, causing catastrophic loss of life and structural damage to the built environment.

Three Types of Faults

There are three basic types of faults: normal faults, reverse faults, and strike-slip faults (Figure 14.19). A normal fault is a result of tensional force (extension) as two pieces of Earth’s crust, called fault blocks, are pulled apart. As a result, one fault block slips downward in relation to the other fault block. A reverse fault results from compressional force, which pushes one block upward in relation to another block. Under certain circumstances, reverse faults are also called thrust faults. A strike-slip fault occurs where one block moves horizontally in relation to another block as a result of shearing (lateral) force.

Reverse and normal faults create a fault scarp, or cliff face, that results from the vertical movement of the fault blocks. Strike-slip faults create little up or down block movement. Where strike-slip faults cross orchards, streams, roads, sidewalks, and other linear features, those features may be offset by fault movement. Left-lateral strike-slip faults occur when, from the perspective of either block, the opposite block moves to the left. Right-lateral strike-slip faults, as shown in Figure 14.20, occur when the opposite block moves to the right.

Fault scarps indicate that a normal or reverse fault is at work, and offset features indicate that a strike-slip fault is present. Like much of the western United States, California and Nevada have many fault systems with all three fault types, as shown in Figure 14.21.

**Figure 14.20** Right-lateral strike-slip fault. On September 4, 2010, the magnitude 7.1 Canterbury earthquake struck South Island, New Zealand. The tire tracks on this dirt road once connected. This fault is a right-lateral strike-slip fault because the opposite side moved to the right. (© Kate Pedley Photography)

**Figure 14.21** Fault map of California and Nevada. (A) The North American and Pacific plates are fractured by many fault systems in the western United States. (B) In the Great Basin Desert of Nevada, the crust is being rifted and stretched, creating a series of normal faults oriented north-south and resulting in horst and graben topography. The fault blocks have rotated slightly as the crust has been stretched. Portions of the blocks form grabens (valleys), and portions of them form horsts (mountain ranges), as illustrated here. The photograph shows Nevada’s snow-capped Wheeler Peak, part of one of the many mountain ranges in Nevada produced by a rotated and tilted block. (Bruce Gervais)

- **Normal fault**
  - The result of tensional force as two fault blocks move apart, causing one fault block to slip downward in relation to the other fault block.

- **Reverse fault**
  - The result of compressional force as two fault blocks are pushed together, causing one block to move upward in relation to another block.

- **Strike-slip fault**
  - The result of shearing force as one block moves horizontally in relation to another block.

- **Fault scarp**
  - A cliff face resulting from the vertical movement of a reverse or normal fault.
How Do Faults Generate Earthquakes?

When subjected to geologic stresses, fault blocks usually do not move smoothly past one another. Instead, friction between them causes them to stick together, and stress energy builds up in the crust. Eventually, the geologic stress exceeds the friction, the crust breaks (either along a preexisting fault or along a new fault), and the blocks move. As each block moves, the built-up stress energy is released and travels through the crust as seismic waves, resulting in an earthquake.

Elastic-rebound theory describes how fault blocks bend, break, and rebound back to their original shape as they move in relation to one another. The blocks may become stuck again from friction, then slip again in this stick-slip process. The focus is the location of initial movement along a fault during an earthquake. The epicenter is the location on the ground’s surface immediately above the focus of the earthquake and is usually the area of greatest shaking. These concepts are illustrated in Figure 14.22.

What Are Foreshocks and Aftershocks?

Small foreshock earthquakes sometimes precede large earthquakes. Foreshocks may be caused by smaller cracks developing as the deformed and stressed crust is about to fail. Going back to the bending stick analogy used in Figure 14.22, as the stick bends, small splinters of wood may form—these are the foreshocks. They may indicate that the stick is about to break—or that the rocks are about to fault. The breaking of the stick represents the main earthquake.

Very commonly, especially with large earthquake events, smaller earthquakes called aftershocks follow the main shock. Aftershocks occur because the blocks are settling into their new positions after they have been moved. Most aftershocks are much smaller than the main earthquake and occur on the same fault as the initial earthquake. Occasionally, aftershocks occur on different faults nearby.

Geographic Patterns of Earthquakes

Most earthquakes occur along plate boundaries in seismic belts. Plate boundaries give rise to earthquakes because of the interactions between moving plates that occur there. Figure 14.23 explains some major characteristics of earthquakes at different types of plate boundaries.
Describe the types of seismic waves produced by earthquakes, how earthquakes are ranked, and what can be done to reduce our vulnerability to earthquakes.

No two earthquakes are exactly alike. After people have been in an earthquake, they may describe “rolling” or “up-and-down” or “sideways” movement. Earthquakes generate several different types of seismic waves. The movements people experience depend on the dominant type of seismic waves passing through the ground beneath them and the type of ground underfoot. Seismic waves can be categorized by where they travel and how they move through the crust, as illustrated in Figure 14.24.

\( P \) waves are fast-traveling compressional waves that move through the body of Earth. They are always the first to arrive after an earthquake. They are soon followed by \( S \) waves, which move perpendicularly to the direction they travel through the body of Earth. \( L \) waves and \( R \) waves, which move through the crust at Earth’s surface, arrive last and produce the greatest shaking (Figure 14.25).

The seismic waves detected at the earthquake focus always reach the epicenter first and, normally, shake the ground there the most. Ground shaking usually decreases with distance from the epicenter because the crust absorbs seismic wave energy.

**Detecting Earthquakes**

The instruments used to detect, measure, and record ground shaking are called **seismographs** (or **seismometers**). Before the digital era, seismographs consisted of a swinging pendulum that recorded...
Seismic waves. Seismic waves can be categorized in two ways: by where they travel and by how they move.

**Categories of Seismic Waves**

**Categories Based on Where Waves Travel:**
- Body waves pass through the “body” of Earth.
- Surface waves travel near the surface of the crust.

**Categories Based on How Waves Move:**
- Compressional waves produce movement that goes back and forth in a direction parallel to the direction of the traveling waves.
- Shear waves move back and forth perpendicular to the direction the waves are traveling.

**Earthquake Intensity**

Earthquake intensity is determined by the amount of damage an earthquake causes to physical structures. The Mercalli intensity scale (or Mercalli scale) was developed in 1902 by the Italian scientist Giuseppe Mercalli as a means to estimate the intensity of shaking. No instruments are used to rank earthquakes on the Mercalli scale; instead, the scale is subjectively based on the observed damage done to structures. Later, the Mercalli intensity scale was developed into the modified Mercalli intensity (MMI) scale. In this system, earthquakes are ranked using Roman numerals, ranging from I to XII (Table 14.1).

There is no single MMI value for a given earthquake. Instead, locations progressively farther away from the epicenter experience less shaking as the seismic waves dissipate with distance, so each location is given its own MMI value. Figure 14.27 provides a modified Mercalli intensity map of the 2010 Haiti earthquake.

The distance seismic waves travel through the crust depends in large part on the integrity of the crust. In the western United States, for example,
**FIGURE 14.26** Seismographs. Seismographs are anchored to the ground and record Earth movement on paper. The paper record is called a seismogram. (A) Traditional seismographs consist of a box attached to bedrock. Inside the box is a heavy pendulum with an ink pen attached to it. When the ground shakes, the pendulum remains stationary, recording the movement on a seismogram. (B) Modern electronic seismographs use a stationary magnet and a wire coil to generate an electronic signal. Greater Earth movement creates a stronger voltage that moves the needle more. (B. © Zephyr/Science Source)

![Seismograph Diagram](image1)

**FIGURE 14.27** Intensity rankings for the 2010 Haiti earthquake. Color is used in a continuous gradation to denote the intensity of ground shaking during the January 12, 2010, Haiti earthquake. Red areas experienced the greatest shaking. Port-au-Prince, which was close to the epicenter, experienced an intensity of VIII, “very strong to violent.” Many structures there collapsed on people (inset photo). The death toll for this event is estimated by the USGS to be 100,000. (left, U.S. Geological Survey, Earthquake Hazards Program; right, © Thony Belizaire/AFP/Getty Images)

![Intensity Map and Inset Photo](image2)
many faults separate sections of the crust, and seismic waves do not travel as far as they would if the crust were not fractured. In the eastern United States, seismic waves tend to travel greater distances because there are fewer faults.

Another factor that influences the intensity of an earthquake is the composition of the ground. Loose, wet sediments deposited by rivers or human-made landfills are susceptible to liquefaction. Liquefaction is the transformation of solid sediments into an unstable slurry by ground shaking. Buildings resting on top of sediments may sink during liquefaction, as Figure 14.28 shows, unless their supporting piles are anchored in more stable ground, such as bedrock.

Earthquake Magnitude
Earthquake magnitude is determined from measurements of ground movement using seismographs. More ground movement creates higher-magnitude earthquakes. Each earthquake is given a single magnitude number that indicates the maximum shaking at the epicenter. Scientists can calculate earthquake magnitude from any seismograph on Earth if its distance from the epicenter is correctly established.

In 1935, the American geologist Charles Richter developed the Richter scale to quantify earthquake magnitudes using seismographic measurements. Richter’s system had limitations that have been addressed by several newer scales. One of these is the moment magnitude scale, an earthquake ranking system based on the amount of ground movement produced.

The moment magnitude scale relies on seismographic data to quantify ground movement. The scale also uses other types of data, such as how much the fault slipped, the amplitude of the ground movement (its up-and-down and back-and-forth extent), and the physical characteristics of the rocks at the epicenter. It takes several weeks to collect data and calculate the moment magnitude scale because scientists have to go out and inspect the ground for indications of the extent of movement.

Although there is no upper limit to the moment magnitude scale, no earthquake exceeding magnitude 10.0 has ever been recorded. The strongest earthquake ever recorded, which occurred in Chile in 1960, was a magnitude 9.5.

What Do Magnitude Numbers Mean?
Earthquake magnitude indicates both how much the ground shakes and how much energy is released:

1. Ground shaking: With each whole-number increase in magnitude, 10 times more ground movement occurs. A magnitude 5 earthquake shakes the ground 10 times more than a magnitude 4 earthquake and 100 times (10 × 10, or 10²) more than a magnitude 3 earthquake.

2. Energy released: With each unit of increase in magnitude, about 32 times more energy is released. A magnitude 5 earthquake releases about 32 times more energy than a magnitude 4 earthquake and about 1,024 times (32 × 32, or 32²) more energy than a magnitude 3 earthquake (Crunch the Numbers).

CRUNCH THE NUMBERS: Calculating Ground Shaking and Energy Released during an Earthquake
Compared with a magnitude 2 earthquake,

1. How much more ground shaking occurs during a magnitude 5 earthquake?
2. How much more energy is released during a magnitude 5 earthquake?
3. How much more ground shaking occurs during a magnitude 7 earthquake?
4. How much more energy is released during a magnitude 7 earthquake?
The amount of energy released by a large earthquake is phenomenal. Comparing earthquake magnitude with familiar events, or kilograms of TNT, allows us to put the power of earthquakes into perspective (Figure 14.29).

Living with Earthquakes
When you think about it, earthquakes in and of themselves are not much to be feared. Imagine that you are picnicking in an open, grassy field when a strong earthquake occurs. What would happen? You would first experience up-and-down movement with the arrival of P waves, then you would experience side-to-side movement with the following S waves. Then the R waves and L waves would move the ground up and down and sideways. Your drinks would spill, and you might be tossed into the air. The sensation would be disorienting and exhilarating or terrifying, depending on your perspective. But you would probably not get hurt.

The same strong earthquake, occurring in a populated area, could bring death to thousands as structures collapse, bridges fail, bricks and glass rain down from above, and gas mains burst into flames. By itself, ground movement is not the problem—the structures that fail during ground movement create the hazard (Figure 14.30).

Earthquakes are as old as Earth’s crust itself. As long as Earth’s mantle moves the crust’s plates, there will be earthquakes. So we have to learn to live with them. But what are our options?

**Figure 14.29** Energy equivalent of earthquake magnitude. The 1906 San Francisco earthquake released as much energy as the 1980 Mount St. Helens eruption (or 56 billion kg of TNT).

**Figure 14.30** Earthquake damage. (A) L-wave shearing caused this freeway overpass to collapse in Kobe, Japan, in 1995 during a magnitude 6.9 earthquake. (B) Intense R-wave shaking lasted 3 minutes in February 2010 during the 8.8 magnitude earthquake near Santiago, Chile. This overpass structure failed, overturning these cars. (A. © JIJI PRESS /AFP/Getty Images; B. © AP Photo/David Lillo)
Saving Lives
Because many lives are lost when built structures fail during earthquakes, engineers have redesigned structures to better withstand ground shaking. In the United States, building codes require that engineers build structures in accordance with the seismic risk for the region, and older structures must be retrofitted with steel support to make them safer. These building codes have made earthquakes far less of a hazard than before. Unfortunately, many countries do not have such building codes, and their residents are at risk from the collapse of buildings in earthquakes.

Another effective means of saving lives is to give earthquake warnings. Electrons in copper wire travel far faster than seismic waves in Earth's crust. Thus, after an earthquake occurs, an automated system of alerts can be broadcast electronically. For example, after the 2011 Tohoku earthquake, people living in Tokyo, 370 km (230 mi) from the epicenter, had 80 seconds to shut off gas mains, stop trains, and seek shelter. These actions saved many lives. The USGS is developing an earthquake warning system in Southern California. This system could give downtown Los Angeles 50 seconds of warning time if a major earthquake occurred along the nearby San Andreas Fault.

Responsibility for earthquake safety also rests with every individual who lives where earthquakes are common. Table 14.2 lists some of the important ways individuals can prepare themselves for an earthquake.

### Table 14.2: AT A GLANCE: Earthquake Preparedness

<table>
<thead>
<tr>
<th>HEAVY ITEMS</th>
<th>Secure unstable heavy items, such as bookshelves, to walls and check for other objects that could become a hazard during shaking.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAFE PLACES</td>
<td>Identify safe places indoors and outdoors you can quickly get to.</td>
</tr>
<tr>
<td>SHUTOFFS</td>
<td>Learn and then teach other family members how to turn off gas, electricity, and water to your home. Gas leaks are a common source of fires after an earthquake has struck.</td>
</tr>
<tr>
<td>SURVIVAL KIT</td>
<td>Keep a survival kit in a safe place. It should include a flashlight, radio, batteries, first-aid kit, emergency food and water, nonelectric can opener, essential medicines, and shoes.</td>
</tr>
</tbody>
</table>

Predicting Earthquakes
Scientists cannot predict earthquakes. Many seismologists believe we will never be able to predict earthquakes because their precise timing and location are largely random. Seismologists are much better at determining long-term seismic probabilities than at making short-term predictions. For example, they know that a 6.7 earthquake has a 99% probability of happening in California within the next three decades, and they know where the probability of such an event is highest (Figure 14.31).

The seismic risk of an area is determined by considering many factors, including the seismic probability, the types of faults present, how active those faults have been in recorded history, and the number of people living near them. This highlights a twist of events in which scientists were prosecuted for failing to adequately warn the public of an earthquake.
Faulting Scientists

At 3:32 a.m. on April 6, 2009, a magnitude 6.3 earthquake struck L’Aquila, Italy, destroying large portions of the city and killing 309 people. Most of Italy has a high seismic probability, and large earthquakes are certainly not unheard of there. The L’Aquila earthquake was unusual in one important way: Six scientists and a former government official were blamed for the disaster and charged with involuntary manslaughter.

There were many foreshocks before the main earthquake. The six government scientists assured the public that there was no imminent danger. Their reasoning, now known to be incorrect, was that with each little earthquake, the stress on the plates was gradually easing. Six days before the disaster, one of the scientists even told the town’s residents, who were increasingly on edge from the foreshocks, to relax and have a glass of wine.

The prosecutors representing the families of the victims based their accusations on the failure of the scientists to evaluate the seismic risk and communicate it to the public. “They were obligated to evaluate the degree of risk given all these [foreshocks],” said a prosecutor, “and they did not.” The defendants based their defense largely on the fact that scientists cannot predict earthquakes and argued that they should not be held accountable for acts of Mother Nature. They also claimed that the ruling would set a dangerous precedent. The defendants were found guilty and sentenced to six years in jail.

Residents affected by the earthquake applauded the verdict.

Consider This

1. Do you agree that the scientists should have been held accountable for this disaster and prosecuted? Explain.

2. What other natural hazards might present a similar situation and similar liability for scientists?

3. If scientists were held legally liable for bad predictions of natural disasters, how might the future of their scientific fields be affected?
The Gothic horror novel *Frankenstein* and physical geography are linked in a surprising way. The novel’s author, Mary Shelley, was vacationing on Lake Geneva in Switzerland in the summer of 1816. The weather was uncharacteristically cold, gloomy, and stormy, so her vacation was spent confined indoors with her husband and friends. They held a contest writing ghost stories to see who could best express how they felt about their miserable situation. Shelley won, and *Frankenstein* was born. Little did Shelley know that her inspiration was due to the eruption of Tambora, a volcano 12,300 km (7,600 mi) away on the island of Sumbawa, east of Java, the year before.

Tambora (elevation 2,850 m or 9,350 ft) is part of the Sunda Arc, the volcanic island arc that makes up part of Indonesia. Subduction of the Indo-Australian plate beneath the Eurasian plate formed the Sunda Arc, which is the most volcanically active and dangerous section of the Pacific Ring of Fire. Three particularly notable volcanoes in the Sunda Arc are Krakatau, Toba, and Tambora (Figure 14.32).

Krakatau’s most recent big eruption was in 1883. It was a VEI 6 eruption that killed over 36,000 people. Toba’s eruption about 73,000 years ago was one of the largest known volcanic eruptions in Earth’s history. Scientists estimate that it had a magnitude of VEI 8 and believe that it caused significant climate change worldwide as ash veiled the Sun and cooled the planet for as much as several centuries. **Tambora’s most recent big eruption, in 1815, holds the dubious distinction of causing the greatest known human death toll of any volcanic eruption.**

**The Waking Giant**

In 1812, after centuries of sleep, Tambora awoke with a series of blasts that could be heard over hundreds of miles. These massive detonations culminated in an 1815 eruption of colossal proportions. At about 7:00 p.m. on April 10, 1815, a VEI 7 eruption occurred that could be heard as far away as South Asia, some 2,600 km (1,600 mi) away. Similar eruptions thundered during the night and into the next day. Mount Tambora was blown apart by the force of these blasts and was reduced in height by almost 1.5 km (1 mi). A column of ash punched into the stratosphere and reached an altitude of 43 km (27 mi), nearly to the base of the mesosphere. Thick ash rained down to the north (Figure 14.33). Up to 100,000 people died in the immediate vicinity of Tambora, both directly in pyroclastic flows and indirectly in tsunamis, as well as from starvation resulting from crop failure.

Today, Tambora continues to show signs of life. In August 2011, the mountain erupted small amounts of ash into the atmosphere. Earthquakes are common, indicating shifting magma and gas in the...
magma chamber. Surprisingly, few of the 3,000 or so people living on the flanks of the volcano today even know about the 1815 eruption and the loss of life that occurred. Some 130 million people now live on the nearby island of Java. A similar eruption today would bring catastrophic loss of life. Scientists are carefully monitoring Tambora for signs of reawakening.

**Tambora’s Wide Reach**

Stratovolcano eruptions ranked VEI 7 put more than 100 km$^3$ (25 mi$^3$) of ash, as well as an estimated 400 million tons of sulfur gases, into the atmosphere. When sulfur combines with water, it creates droplets of sulfuric acid. These droplets can remain suspended in the stratosphere for several years. The ash and sulfuric acid droplets reflect and absorb solar radiation in the stratosphere and cool Earth’s surface (see Section 6.2). Climatologists have coined the term *volcanic winter* to describe the cooling effects of large volcanic eruptions.

**The Year without a Summer**

The year 1816 was nicknamed the Year without a Summer or Eighteen-Hundred-and-Froze-to-Death because it was unusually cold in both eastern North America and northern Europe (*Figure 14.34*, page 30). North America, Europe, Argentina, South Africa, India, and China all experienced unusually cold summers in 1816. The average summer temperature in the northeastern United States was about 3°C to 6°C (5°F to 10°F) below average. There was snow in New England in every month of the year in 1816.

Unfortunately, Tambora’s effects on humanity were not limited to unseasonable snowstorms. Tambora triggered crop failure and disease outbreaks and changed rainfall patterns as well.

**Crop Failure**

Crop failure was widespread, leading to hunger and starvation in New England, the United Kingdom, Germany, and across much of Europe. There is almost no vintage 1816 wine from Europe because the grape harvests were destroyed by the low temperatures. New England experienced an unusual number of killing frosts and record low agricultural harvests during the summer of 1816.

Many European cities had already been shaken politically by the Napoleonic Wars, and the food shortages after the eruption of Tambora sparked social unrest, riots, arson, and looting. Britain
even stopped collecting income taxes in 1816 in response to food shortages and a hungry and volatile populace.

**Typhus Outbreak**
Tambora is blamed for a typhus epidemic between 1816 and 1819 in Europe. It is thought to have started in Ireland, spread to England, and then moved south into continental Europe. Some 65,000 people lost their lives in this epidemic. People were vulnerable to this disease because of the poor nutrition resulting from crop losses caused by the eruption.

**Indian Monsoon**
Tambora’s aerosols in the upper atmosphere are thought to have changed the Asian monsoon rainfall pattern (see Section 4.4), causing widespread crop failures, severe hunger, and greater susceptibility to diseases. Cholera outbreaks and famine occurred in 1816 in the Bengal region of eastern India because rainfall from the monsoon came late and heavy, causing severe flooding. The cholera outbreak spread into parts of Europe, China, and Russia as people traveled between regions and transmitted the disease.

The atmosphere, biosphere and people, lithosphere, and hydrosphere are all connected in ways that are sometimes challenging to see until an event like Tambora reveals these connections.
To complete these problems, first read the chapter. Then open the Chapter 14 “Workbook Problems” folder to “fly” to each of the problems listed below and answer the questions. Be sure to keep your “Borders and Labels” layer activated. Refer to Appendix 4 on page 000 if you need help using Google Earth.

**PROBLEM 14.1** This placemark lands on Volcán de Colima in Mexico. Pan around and carefully examine the summit crater.

1. **What kind of volcano is this?**
   a. Stratovolcano       c. Cinder cone
   b. Shield volcano      d. Plug dome

2. **Zoom in. What landform is visible in Colima’s summit crater?**
   a. A plug dome         c. A cinder cone
   b. A lahar             d. A shield volcano

**PROBLEM 14.2** This placemark highlights a volcanic landform.

1. **What is the name of this volcanic landform?**
   a. A plug dome         c. A cinder cone
   b. A lahar             d. A caldera

2. **Is it active?**
   a. Yes                b. No

3. **What kind of volcano can make such a landform?**
   a. A stratovolcano
   b. A shield volcano
   c. Both a stratovolcano and a shield volcano

4. **Zoom out. Where is this?**
   a. Iran               c. Greece
   b. Turkey            d. Italy

**PROBLEM 14.3** This placemark is on a coastal location. Note that the historical imagery feature is activated in the upper portion of your screen. It shows an aerial photo for 07/22/2010. (If it is not activated, be sure to activate it.)

1. **Which of the following best describes the condition of the surface on 07/22/2010?**
   a. There is nothing unusual about the surface.
   b. The surface has been slightly disturbed by some natural event.
   c. The surface has been destroyed by some natural event.

2. **Now move the historical imagery slider to the right and stop when the date reads 03/31/2011. Wait while the aerial photo for this date loads. Which of the following best describes the situation on the ground on this date?**
   a. There is nothing unusual about the surface.
   b. The surface has been slightly disturbed by some natural event.
   c. The surface has been destroyed by some natural event.

3. **Zoom out. Where is this location?**
   a. Russia               d. China
   b. North Korea         
   c. Japan

**PROBLEM 14.4** This placemark highlights a large circular lake.

1. **Given the subject of this chapter, what process formed this lake?**
   a. A caldera formed after a magma chamber collapsed. Later, it filled with water.
   b. An asteroid created this crater, which filled with water.
   c. A large igneous province was eroded into a bowl, then filled with water.
   d. A cinder cone crater filled with water.

2. **Zoom in to the island in the lake. What is the name of the island landform found inside the lake?**
   a. A shield volcano  c. A cinder cone
   b. A stratovolcano  d. A plug dome

3. **Zoom out. Where is this lake?**
   a. Oregon          c. California
   b. Washington     d. Idaho

**PROBLEM 14.5** This placemark lands on a large volcano in Mexico.

1. **What is the name of this volcano? (Make sure your Borders and Labels layer is activated.)**
   a. Popocatépetl  c. Mount Tlaloc
   b. Iztaccihuatl   d. La Malinche

2. **What kind of volcano is this?**
   a. Shield volcano  c. Cinder cone
   b. Stratovolcano  d. Plug dome

3. **Can this volcano produce explosive eruptions?**
   a. Yes                b. No

4. **There is a large city to the northwest. What city is it?**
   a. Veracruz  c. Zacatlán
   b. Puebla    d. Mexico City

5. **How many kilometers away is this city?**
   a. 70 km        c. 120 km
   b. 90 km       d. 200 km

**PROBLEM 14.6** This placemark lands on a volcano in Iceland. Zoom out, tilt, and pan around to get a sense of this volcano’s shape and dimensions.

1. **What kind of volcano is this?**
   a. Shield volcano  c. Cinder cone
   b. Stratovolcano  d. Plug dome

2. **Is this volcano likely to produce explosive eruptions?**
   a. Yes                b. No
PROBLEM 14.7  Activate the ShakeMap overlay in this folder. This problem features the 2010 Haiti earthquake.

1. The placemark points to the epicenter. How strong was the shaking at the epicenter?
   a. Weak  
   b. Moderate  
   c. Very strong  
   d. Violent  

2. What was the potential damage at the epicenter?
   a. Light  
   b. Moderate  
   c. Heavy  

3. Find Port-au-Prince to the east. How far in kilometers was Port-au-Prince from the epicenter?
   a. 20 km  
   b. 27 km  
   c. 38 km  
   d. 48 km  

4. How strong was the shaking in Port-au-Prince?
   a. Light  
   b. Moderate  
   c. Very strong  
   d. Extreme  

5. What was the potential damage level?
   a. Light  
   b. Moderate  
   c. Heavy  

PROBLEM 14.8  This placemark highlights a volcano that produced a VEI 6 eruption in 1991.

1. Approximately how much material did this volcano eject during that eruption?
   a. 1 km³  
   b. 10 km³  
   c. 100 km³  
   d. 1,000 km³  

2. What is the name of this volcano?
   a. Pinatubo  
   b. Hekla  
   c. Tambora  
   d. Krakatau  

3. Which of the following best describes this volcano’s activity level?
   a. Active  
   b. Dormant  
   c. Extinct  

4. Double-click Marker 1 in this problem’s folder. What is this marker highlighting?
   a. Lapilli  
   b. A lahar  
   c. Liquefaction  
   d. Ash  

PROBLEM 14.9  Activate the ShakeMap overlay in this folder if it is not already activated. This problem features the 2011 Tōhoku earthquake in Japan.

1. What earthquake ranking scale is provided in this overlay?
   a. The moment magnitude scale  
   b. The Richter scale  
   c. The Mercalli intensity scale  

2. The placemark points to the epicenter of the earthquake. How far was the epicenter from Tokyo, the world’s most populous city?
   a. 100 km  
   b. 175 km  
   c. 375 km  
   d. 450 km  

3. What was the approximate level of ground shaking in Tokyo?
   a. Strong  
   b. Very strong  
   c. Severe  
   d. Violent  

4. What kind of damage was potentially sustained in Tokyo?
   a. Light  
   b. Moderate  
   c. Heavy  

PROBLEM 14.10  Deactivate any open overlays. This placemark lands on Wallace Creek in California. The placemark points to the San Andreas Fault, running mostly east-west in this view. The stream runs roughly north to south on the screen. Note the change of direction of the stream where it crosses the San Andreas Fault.

1. What kind of fault caused the stream to change direction?
   a. Normal fault  
   b. Reverse fault  
   c. Strike-slip fault  

2. What pattern of deformation is seen in this stream?
   a. Offset  
   b. S wave  
   c. Liquefaction  
   d. Stick-slip  

3. Which of the following best describes this specific fault type?
   a. Right-lateral fault  
   b. Left-lateral fault  
   c. Fault block  

CHAPTER 14 Study Guide

Focus Points

14.1 About Volcanoes
Types of volcanoes: There are three main types of volcanoes: stratovolcanoes, shield volcanoes, and cinder cones.
Lava: Lava, the most conspicuous product of volcanic activity, ranges from runny mafic to thick felsic lava.
Pyroclasts: Volcanoes eject materials into the air ranging in size from fine ash to large blocks.
Gases: Gases, particularly carbon dioxide and water vapor, are a significant component of volcanic emissions.
Volcanic landforms: Landforms resulting from volcanism include columnar jointing, flood basalts, and calderas.

14.2 Pele's Power: Volcanic Hazards
Shield volcanoes: Shield volcanoes have gentle, effusive eruptions.
Stratovolcanoes: Stratovolcanoes erupt both effusively and explosively. Explosive eruptions occur when gas in the magma chamber expands rapidly.
Volcanic geohazards: Lahars and pyroclastic flows are the two greatest threats posed by stratovolcanoes.
Eruption prediction: Scientists can sometimes predict a volcanic eruption by monitoring gas emissions and earthquake activity.
Pacific Ring of Fire: The Pacific Ring of Fire has the greatest number of explosive stratovolcanoes on the planet.

14.3 Tectonic Hazards: Faults and Earthquakes
Fault types: Faults occur as normal faults, reverse faults, and strike-slip faults.
Fault indicators: Fault scarps indicate normal and reverse faults. Offset features indicate strike-slip faults.
Earthquakes: Earthquakes are caused when the crust suddenly breaks and releases built-up stress energy in the form of seismic waves.
Seismic belts: Earthquakes occur mainly in seismic belts that coincide with plate boundaries.

14.4 Unstable Crust: Seismic Waves
Intensity and magnitude: Earthquake intensity is determined by the amount of damage done to built structures, and earthquake magnitude is determined by the degree of measured ground shaking.
Earthquake prediction: Scientists cannot predict earthquakes.
Saving lives: Building codes and retrofitting greatly strengthen buildings and save human lives.

14.5 Geographic Perspectives: The World's Deadliest Volcano
Tambora: The 1815 eruption of Tambora was the strongest and deadliest volcanic eruption in recorded history.

Key Terms
a'a, 24
active volcano, 5
aftershock, 20
angle of repose, 6
ash (volcanic), 5
block (volcanic), 8
bomb (volcanic), 8
caldera, 11
cinder cone, 6
columnar jointing, 11
effusive eruption, 12
epicenter, 20
extinct volcano, 5
fault scarp, 19
focus, 20
géologé, 4
joint, 11
lahar, 13
lapilli, 8
large igneous province (LIP), 11
liquefaction, 24
modified Mercalli intensity (MMI) scale, 22
moment magnitude scale, 24
normal fault, 19
pāhoehoe, 7
pumice, 8
pyroclast, 5
pyroclastic flow (or nuée ardente), 14
reverse fault, 19
seismograph (or seismometer), 22
shield volcano, 5
stratovolcano (or composite volcano), 5
tsunami, 4
Volcanic Explosivity Index (VEI), 13

Concept Review

The Human Sphere: Deadly Ocean Waves
1. What is a tsunami? How are tsunamis generated? Why are they geohazards?
2. What are the three kinds of volcanoes? Which is the smallest volcano type and which is the largest? Describe how each is built up.
3. What are the three types of lava? Explain how each behaves and what causes it to behave that way.
4. Give examples of the types of materials volcanoes produce. Briefly describe each.
5. What is a joint? What is columnar jointing? In which kind of lava can it be found?
6. What is a large igneous province? Give three examples of where they can be found.
7. What is a caldera and how does it form?

14.2 Pele's Power: Volcanic Hazards
8. What are the two types of volcanic eruptions, and what controls which type of eruption will occur?
9. What is the VEI?
10. What are the two most deadly products of volcanic eruptions? Explain why each is so hazardous.
12. What is the Pacific Ring of Fire? Explain the kind of volcanoes found there and why they are deadly.

14.3 Tectonic Hazards: Faults and Earthquakes
13. Describe the three types of faults. What is the direction of force and the type of movement associated with each?
14. Explain how an earthquake forms using the terms stress and friction. What is elastic rebound theory in this context? What is the stick-slip process?
15. Define and briefly explain the following terms: focus, epicenter, and seismic waves.
16. What is a foreshock? What is an aftershock? What causes them?
17. Describe the geographic pattern of earthquakes worldwide. Where do most earthquakes occur?

14.4 Unstable Crust: Seismic Waves
18. Compare a body wave to a surface wave. Where does each travel?
19. Compare a compressional wave with a shear wave. What kind of movement does each produce?
20. What scientific instrumentation is used to measure ground shaking?
21. Compare P waves, S waves, L waves, and R waves in terms of the sequence of their arrival after an earthquake and the strength of the ground shaking they cause.
22. What does the Mercalli scale indicate about an earthquake? What evidence does it use to rank earthquakes?
23. What information about an earthquake does the moment magnitude scale provide?
24. What is liquefaction? On what kind of ground does it occur?

Critical-Thinking Questions
1. Are you vulnerable to volcanic hazards where you live? If you are unsure, how would you find out?
2. Is there a risk of an earthquake occurring where you live? If you do not know, what kinds of questions could you ask to find out?
3. If a VEI 6 or greater eruption occurred today, what effects do you think it would have locally (where you live) and globally?
4. Do you think scientists will ever be able to predict accurately when a given region will be hit by an earthquake?
5. In Sri Lanka, many elephants ran to high ground minutes before the 2004 tsunami struck, even though their unknowing riders ordered them to stop. Similarly, there are many eyewitness accounts of animals such as horses and dogs acting strangely or panicking minutes before an earthquake strikes. What do you think animals may be sensing that humans and scientific instruments are not sensing? Do you think scientists should pursue further research into this area, or would it be a waste of money?

Test Yourself
Take this quiz to test your chapter knowledge.

1. True or false? Shield volcanoes produce effusive eruptions.
2. True or false? Lava viscosity is in large part the result of the silica content of the lava.
3. True or false? Lava is one of the most deadly hazards of volcanoes.
4. True or false? S waves travel fastest and are the first to arrive after an earthquake.
5. Multiple choice: Which of the following is not associated with explosive volcanic eruptions?
   a. Stratovolcano
   b. Felsic magma
   c. Caldera formation
   d. Large igneous province

6. Multiple choice: Which of the following types of seismic waves produces a rolling movement on the surface of Earth’s crust?
   a. P waves
   b. S wave
   c. L waves
   d. R waves

7. Multiple choice: About how much more ground shaking does a magnitude 8 earthquake create than a magnitude 5 earthquake?
   a. 100 times more
   b. 1,000 times more
   c. 10,000 times more
   d. 100,000 times more

8. Multiple choice: Which of the following is not a type of pyroclast?
   a. Bombs
   b. Ash
   c. Lapilli
   d. Lava flows

9. Fill in the blank. A ____________ is a slurry of mud created when a snow-capped volcano erupts.
10. Fill in the blank. The ____________ is the point directly over an earthquake’s focus.
Further Reading


Answers to Living Physical Geography Questions

1. What is a tsunami? A tsunami is a giant ocean wave triggered by a natural event, usually an earthquake. When these waves reach shallow coastal waters, they can grow to great heights and devastate coastal areas.
2. Why do some volcanoes explode violently? Volcanoes explode violently when gas in magma expands rapidly as the magma migrates upward toward the crust and experiences less pressure.
3. What causes earthquakes? When crust under stress suddenly breaks and moves, ripples of energy travel outward and shake the ground.
4. What was the “Year without a Summer”? The year 1816 was named the “Year without a Summer” in eastern North America because of the cooling effects of aerosols from the Tambora eruption in the stratosphere.