# Earthquakes

CHAPTER

11

*Aftermath of a devastating tsunami at the coastal town of Banda Aceh on the Indonesian island of Sumatra, December 26, 2004. (Photo by Mark Pearson/ Alamy)*

On October 17, 1989, at 5:04 P.M. Pacific daylight time, millions of television viewers around the world were settling in to watch the third game of the World Series. Instead, they saw their television sets go black as tremors hit San Francisco's Candlestick Park. Although the earthquake was centered in a remote section of the Santa Cruz Mountains, 100 kilometers to the south, major damage occurred in the Marina District of San Francisco.

The most tragic result of the violent shaking was the collapse of some double-decked sections of Interstate 880, also known as the Nimitz Freeway. The ground motions caused the upper deck to sway, shattering the concrete support columns along a mile-long section of the freeway. The upper deck then collapsed onto the lower roadway, flattening cars as if they were aluminum cans. This earthquake, named the Loma Prieta quake for its point of origin, claimed 67 lives.

In mid-January 1994, less than five years after the Loma Prieta earthquake devastated portions of the San Francisco Bay area, a major earthquake struck the Northridge area of Los Angeles. Although not the fabled "Big One," this moderate, 6.7-magnitude earthquake left 51 dead, more than 5000 injured, and tens of thousands of households without water and electricity. The damage exceeded $40 billion and was attributed to an unknown fault that ruptured 18 kilometers (11 miles) beneath Northridge.

The Northridge earthquake began at 4:31 A.M. and lasted roughly 40 seconds. During this brief period the quake terrorized the entire Los Angeles area. In the three-story Northridge Meadows apartment complex, 16 people died when sections of the upper floors collapsed onto the first-floor units. Nearly 300 schools were seriously damaged, and a dozen major roadways buckled. Among these were two of California's major arteries—the Golden State Freeway (Interstate 5), where an overpass collapsed completely and blocked the roadway, and the Santa Monica Freeway. Fortunately, these roadways had practically no traffic at this early morning hour.

In nearby Granada Hills, broken gas lines were set ablaze while the streets flooded from broken water mains. Seventy homes burned in the Sylmar area. A 64-car freight train derailed, including some cars carrying hazardous cargo. But it is remarkable that the destruction was not greater. Unquestionably, the upgrading of structures to meet the requirements of building codes developed for this earthquake-prone area helped minimize what could have been a much greater human tragedy.

## What Is an Earthquake?

GEODe EARTH
Earthquakes
▸ What Is an Earthquake?

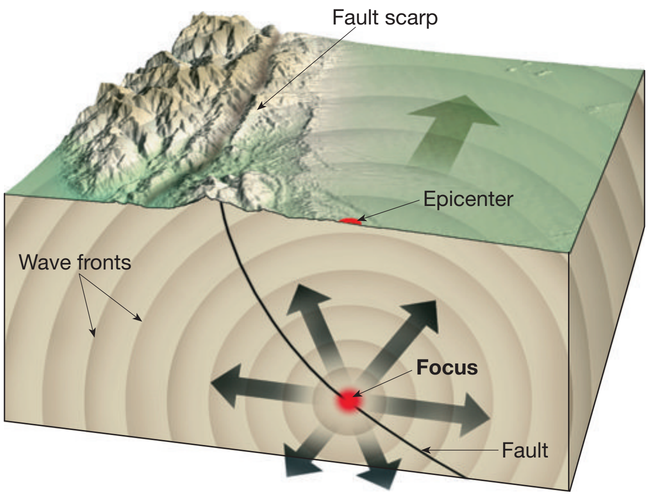
An **earthquake** is the vibration of Earth produced by the rapid release of energy (Figure 11.1). Most often, earthquakes are caused by slippage along a fault in Earth's crust. The energy released radiates in all directions from its source, called the **focus** (*foci* = a point) or **hypocenter,** in the form of waves. These waves are analogous to those produced when a stone is dropped into a calm pond (Figure 11.2). Just as the impact of the stone sets water waves in motion, an earthquake generates seismic waves that radiate throughout Earth. Even though the energy dissipates rapidly with increasing distance from the focus, sensitive instruments located around the world record the event.

More than 30,000 earthquakes that are strong enough to be felt occur worldwide annually. Fortunately, most are minor tremors and do very little damage. Generally, only about 75 significant earthquakes take place each year, and many of these occur in remote regions. However, occasionally a large earthquake occurs near a large population center. Under these conditions, an earthquake is among the most destructive natural forces on Earth.

**FIGURE 11.1** Destruction caused by a major earthquake that struck northwestern Turkey on August 17, 1999. More than 17,000 people perished. (Photo by Yann Arthus-Bertrand/Peter Arnold, Inc.)

The shaking of the ground, coupled with the liquefaction of some soils, wreaks havoc on buildings and other structures. In addition, when a quake occurs in a populated area, power and gas lines are often ruptured, causing numerous fires. In the famous 1906 San Francisco earthquake, much of the damage was caused by fires (Figure 11.3). They quickly became uncontrollable when broken water mains left firefighters with only trickles of water.

**FIGURE 11.2** Earthquake focus and epicenter. The focus is the zone within Earth where the initial displacement occurs. The epicenter is the surface location directly above the focus.




## Earthquakes and Faults

The tremendous energy released by atomic explosions or by volcanic eruptions can produce an earthquake, but these events are relatively weak and infrequent. What mechanism produces a destructive earthquake? Ample evidence exists that Earth is not a static planet. We know that Earth's crust has been uplifted at times, because we have found numerous ancient wave-cut benches many meters above the level of the highest tides. Other regions exhibit evidence of extensive subsidence. In addition to these vertical displacements, offsets in fence lines, roads, and other structures indicate that horizontal movement is common (Figure 11.4). These movements are usually associated with large fractures in Earth's crust called **faults.**

Typically, earthquakes occur along preexisting faults that formed in the distant past along zones of weakness in Earth's crust. Some are very large and can generate major earthquakes. One example is the San Andreas Fault, which is a transform fault boundary that separates two great sections of Earth's lithosphere: the North American plate and the Pacific plate. This extensive fault zone trends in a northwesterly direction for nearly 1300 kilometers (780 miles), through much of western California.



**FIGURE 11.3** San Francisco in flames after the 1906 earthquake. (Reproduced from the collection of the Library of Congress) Inset photo shows fire triggered when a gas line ruptured during the Northridge earthquake in Southern California in 1994. (AFP/Getty Images)

Other faults are small and produce only minor and infrequent earthquakes. However, the vast majority of faults are inactive and do not generate earthquakes at all. Nevertheless, even faults that have been inactive for thousands of years can rupture again if the stresses acting on the region increase sufficiently.

In addition, most faults are not perfectly straight or continuous; instead, they consist of numerous branches and smaller fractures that display kinks and offsets. Such a pattern is displayed in Figure 10.B (p. 290), which shows that the San Andreas Fault is actually a system that consists of several large faults (innumerable small fractures are not shown).

Most of the motion along faults can be satisfactorily explained by the plate tectonics theory, which states that large slabs of Earth's lithosphere are in continual slow motion. These mobile plates interact with neighboring plates, straining and deforming the rocks at their margins. In fact, it is along faults associated with plate boundaries that most earthquakes occur. Furthermore, earthquakes are repetitive: As soon as one is over, the continuous motion of the plates adds strain to the rocks until they fail again.

## Discovering the Cause of Earthquakes

The actual mechanism of earthquake generation eluded geologists until H. F. Reid of Johns Hopkins University conducted a study following the great 1906 San Francisco earthquake. The earthquake was accompanied by horizontal surface displacements of several meters along the northern portion of the San Andreas Fault. Field investigations determined that during this single earthquake, the Pacific plate lurched as much as 4.7 meters (15 feet) northward past the adjacent North American plate.

The mechanism for earthquake formation that Reid deduced from this information is illustrated in Figure 11.5. In part A of the figure, you see an existing fault, or break in the rock. In part B, tectonic forces ever so slowly deform the crustal rocks on both sides of the fault, as demonstrated by the bent features. Under these conditions, rocks are bending and storing elastic energy, much like a wooden stick does if bent. Eventually, the frictional resistance holding the rocks in place is overcome. As slippage occurs at the weakest point (the focus), displacement will exert stress farther along the fault, where additional slippage will release the built-up strain (Figure 11.5C). This slippage allows the deformed rock to "snap back." The vibrations we know as an earthquake occur as the rock elastically returns to its original shape. The "springing back" of the rock was termed **elastic rebound** by Reid because the rock behaves elastically, much like a stretched rubber band does when it is released.

**FIGURE 11.4** Slippage along a fault produced an offset in this orange grove east of Calexico, California. (Photo by John S. Shelton)

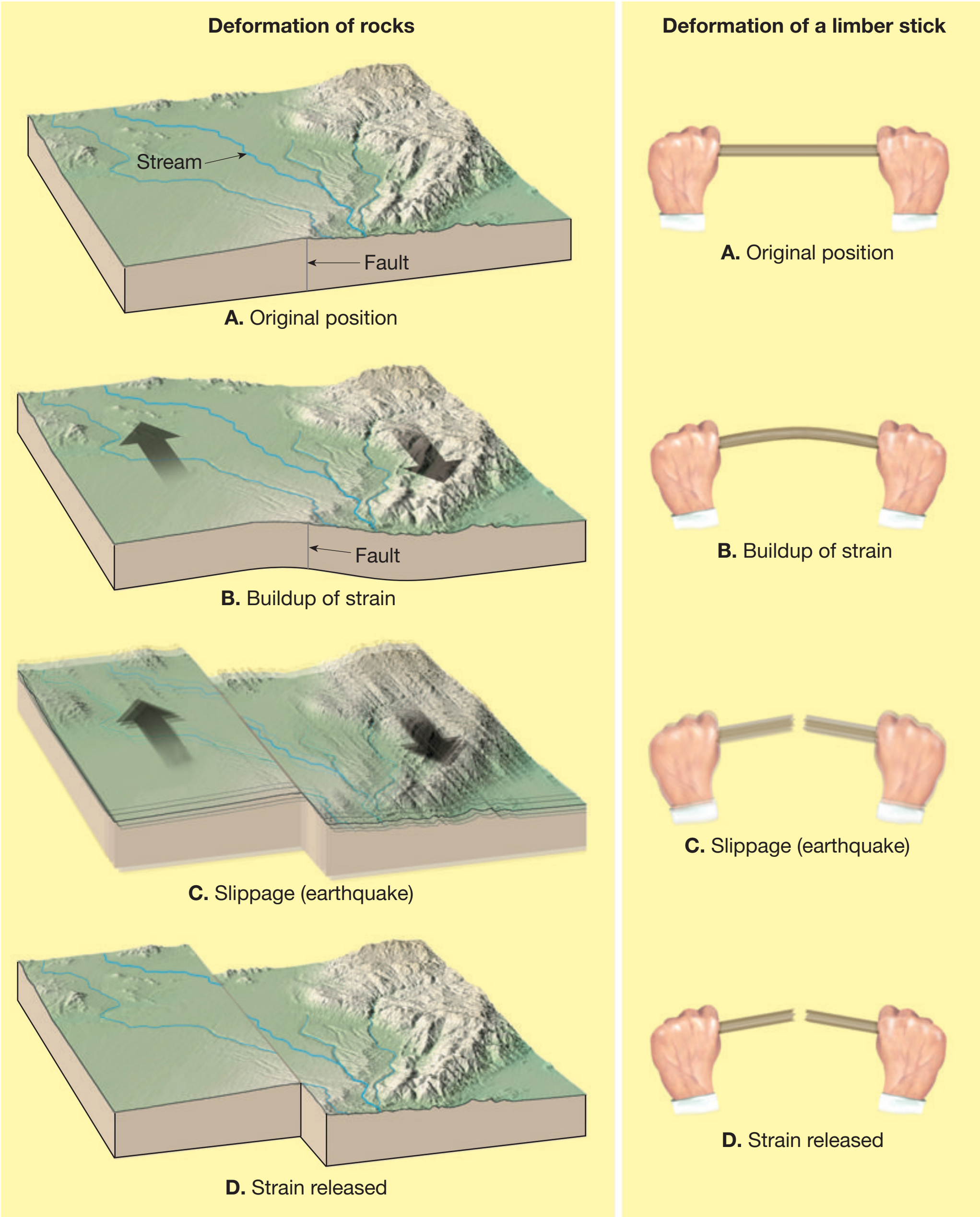



**FIGURE 11.5** Elastic rebound. As rock is deformed, it bends, storing elastic energy. Once strained beyond its breaking point, the rock cracks, releasing the stored-up energy in the form of earthquake waves.

In summary, most earthquakes are produced by the rapid release of elastic energy stored in rock that has been subjected to great stress. Once the strength of the rock is exceeded, it suddenly ruptures, causing the vibrations of an earthquake. Earthquakes most often occur along existing faults whenever the frictional forces on the fault surfaces are overcome.

## Foreshocks and Aftershocks

The intense vibrations of the 1906 San Francisco earthquake lasted about 40 seconds. Although most of the displacement along the fault occurred in this rather short period, additional movements along this and other nearby faults lasted for several days following the main quake. The adjustments that follow a major earthquake often generate smaller earthquakes called **aftershocks.** Although these aftershocks are usually much weaker than the main earthquake, they can sometimes destroy already badly weakened structures. This occurred, for example, during a 1988 earthquake in Armenia. A large aftershock of magnitude 5.8 collapsed many structures that had been weakened by the main tremor.

In addition, small earthquakes called **foreshocks** often precede a major earthquake by days or, in some cases, by as much as several years. Monitoring of these foreshocks has been used as a means of predicting forthcoming major earthquakes, with mixed success. We will consider the topic of earthquake prediction in a later section of this chapter.

# Earthquake Rupture and Propagation

We know that the forces (stresses) that cause sudden slippage along faults are ultimately caused by the motions of Earth's plates. It is also clear that most faults are locked, except for brief, abrupt movements that accompany an earthquake rupture. The primary reason most faults are locked is that the confining pressure exerted by the overlying crust is enormous. Because of this, the fractures in the crust are essentially squeezed shut.

Eventually, the stresses that cause the fault to rupture overcome the frictional resistance to slippage. What actually triggers the initial rupture is still not completely understood. Nevertheless, this event marks the beginning of an earthquake.

Recall that an earthquake begins at a location (at depth) along a fault plane called the focus. Although earthquakes begin at a single point, they involve the slippage along an extended fault surface. Stated another way, the initial rupture begins at the focus and propagates (travels) away from the source, sometimes in both horizontal directions along the fault, but often only in one direction. According to one model, the slippage at any one location along a fault is achieved almost instantaneously, "in the blink of an eye." In addition, at any given time, slippage is confined to only a narrow zone along the fault, which continually travels forward. As this zone of rupture proceeds, it can slow down, speed up, or even jump to a nearby fault segment.

During small earthquakes, the total slippage occurs along a comparatively small fault surface, or a small segment of a larger fault. Thus, the rupture zone is able to propagate quickly, and the earthquake is short-lived. By contrast, large earthquakes involve slippage along a large segment of a fault, occasionally a few hundred kilometers in length, and thus last much longer. For example, the propagation of the rupture zone along a 300-kilometer-long fault would take about 1.5 minutes. Therefore, the accompanying strong vibrations produced by a large earthquake would not only be stronger but would also last longer than the vibrations produced by a small earthquake.

An analogy to the propagation of an earthquake rupture can be made with the development of a crack in a windshield. Imagine a rock hits one corner of your auto's windshield, and a crack develops that rapidly travels across the windshield (a distance of 2 meters) in one-tenth of a second. Now visualize a windshield 300 kilometers (300,000 meters) in width that represents a large segment of a fault. A crack propagating from end to end of that windshield and traveling at the same rate as the crack in your windshield would be en route for roughly four hours. Obviously, an earthquake's propagation is much more rapid and its scale considerably greater than a crack in a windshield.

Having reviewed how earthquake ruptures propagate, the question that follows is, "Why do earthquakes stop rather than continuing along the entire fault?" Evidence suggests that slippage most often stops when the rupture reaches a section of the fault where the rocks have not been sufficiently strained to overcome frictional resistance. This could occur in a section of the fault that has recently experienced an earthquake. The rupture may also stop if it encounters a sufficiently large kink, or an offset along the fault plane.

## San Andreas Fault: An Active Earthquake Zone

The San Andreas is undoubtedly the most studied fault system in the world. Over the years, investigations have shown that displacement occurs along discrete segments that are 100 to 200 kilometers long. Further, each fault segment behaves somewhat differently from the others. A few sections of the San Andreas exhibit a slow, gradual displacement known as **fault creep,** which occurs relatively smoothly and therefore with little noticeable seismic activity. Other segments slip at somewhat regular intervals, producing small- to moderate-sized earthquakes.

Still other segments remain locked and store elastic energy for a few hundred years before rupturing in great earthquakes. The latter process is described as *stick-slip* motion, because the fault exhibits alternating periods of locked behavior followed by sudden slippage and release of strain. It is estimated that great earthquakes should occur about every 50 to 200 years along those sections of the San Andreas Fault that exhibit stick-slip motion. This knowledge is useful when assigning a potential earthquake risk to a given segment of the fault zone.

The tectonic forces along the San Andreas Fault zone that were responsible for the 1906 San Francisco earthquake are still active. Currently, laser beams and techniques that employ the Global Positioning System (GPS) are used to measure the relative motion between the opposite sides of this fault. These measurements reveal a displacement of 2 to 5 centimeters (1 to 2 inches) per year. Although this seems slow, it produces substantial movement over millions of years. To illustrate, in 30 million years this rate of displacement would slide the western portion of California northward so that Los Angeles, on the Pacific plate, would be adjacent to San Francisco on the North American plate! More important in the short term, a displacement of just 2 centimeters per year produces 2 meters of offset every 100 years. Consequently, the 4 meters of displacement produced during the 1906 San Francisco earthquake should occur at least every 200 years along this segment of the fault zone. This fact lies behind California's concern for making buildings earthquake-resistant in anticipation of the inevitable "Big One."

Earthquakes that occur along strike-slip faults, such as the faults that comprise the San Andreas fault system, are generally shallow, having focus depths less than 20 kilometers (12 miles). For example, the 1906 San Francisco earthquake involved movement within the upper 15 kilometers of Earth's crust, and even the comparatively deep 1989 Loma Prieta earthquake had a focus depth of only 19 kilometers. The main reason for the shallow activity in this region is that earthquakes occur only where rocks are rigid and exhibit elastic behavior. Recall from Chapter 10 that at depth, where temperatures and confining pressures are high, rocks display *ductile deformation.* In these environments, when the strength of the rock is exceeded, it deforms by various flow mechanisms that produce slow gradual slippage without storing elastic strain. Thus, rocks at depth are generally not capable of generating an earthquake. The major exception occurs at convergent plate boundaries, where cool lithosphere is being subducted. (For more information on the San Andreas Fault, refer to Box 10.2.)

## Seismology: The Study of Earthquake Waves

GEODe EARTH
Earthquakes
▸ Seismology

The study of earthquake waves, **seismology** (*seismos* = shake, *ology* = the study of) dates back to attempts made by the Chinese almost 2000 years ago to determine the

**FIGURE 11.6** Ancient Chinese seismograph. During an Earth tremor, the dragons located in the direction of the main vibrations would drop a ball into the mouths of the frogs below.

direction from which these waves originated. The seismic instrument used by the Chinese was a large hollow jar that probably contained a mass suspended from the top (Figure 11.6). This suspended mass (similar to a clock pendulum) was connected in some fashion to the jaws of several large dragon figurines that encircled the container. The jaws of each dragon held a metal ball. When earthquake waves reached the instrument, the relative motion between the suspended mass and the jar would dislodge some of the metal balls into the waiting mouths of frogs directly below.

The Chinese were probably aware that the first strong ground motion from an earthquake is directional, and when it is strong enough, all poorly supported items will topple over in the same direction. Apparently the Chinese used this fact, plus the position of the dislodged balls, to detect the direction to an earthquake's source. However, the complex motion of seismic waves makes it unlikely that the actual direction to an earthquake was determined with any regularity.

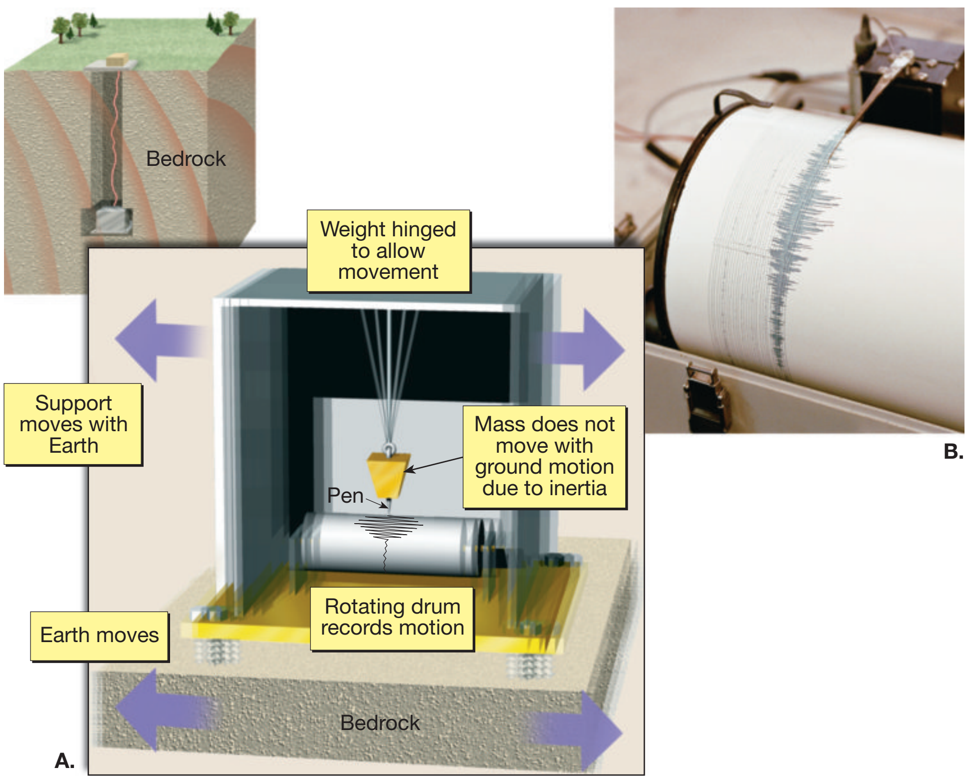
In principle, at least, modern **seismographs** (*seismos* = shake, *graph* = write), instruments that record seismic waves, are not unlike the device used by the early Chinese. Seismographs have a mass freely suspended from a support that is attached to the ground (Figure 11.7). When the vibration from a distant earthquake reaches the instrument, the **inertia*** (*iners* = idle) of the mass keeps it relatively stationary while Earth and support move. The movement of Earth in relation to the stationary mass is recorded on a rotating drum or magnetic tape.

Earthquakes cause both vertical and horizontal ground motion; therefore, more than one type of seismograph is needed. The instrument shown in Figure 11.7 is designed so that the mass is permitted to swing from side to side and thus detects horizontal ground motion. Usually two horizontal seismographs are employed, one oriented north–south and the other placed with an east–west orientation. Vertical ground motion can be detected if the mass is suspended from a spring, as shown in Figure 11.8.

To detect very weak earthquakes, or a great earthquake that occurred in another part of the world, seismic instruments are typically designed to magnify ground motion. Conversely, some instruments are designed to withstand the violent shaking that occurs very near the earthquake source.

*Inertia: Simply stated, objects at rest tend to stay at rest, and objects in motion tend to remain in motion unless either is acted upon by an outside force. You probably have experienced this phenomenon when you tried to stop your automobile quickly and your body continued to move forward.

**FIGURE 11.7** Principle of the seismograph. **A.** The inertia of the suspended mass tends to keep it motionless, while the recording drum, which is anchored to bedrock, vibrates in response to seismic waves. Thus, the stationary mass provides a reference point from which to measure the amount of displacement occurring as the seismic wave passes through the ground. **B.** Seismograph recording earthquake tremors. (Photo courtesy of Zephyr/Photo Researchers, Inc.)



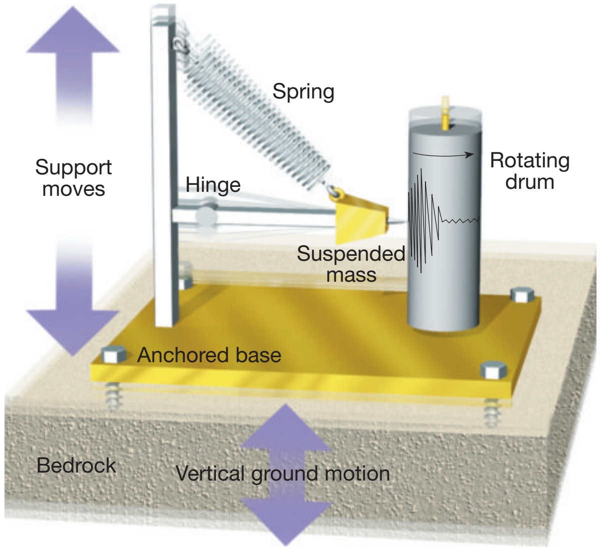



**FIGURE 11.8** Seismograph designed to record vertical ground motion.

The records obtained from seismographs, called **seismograms** (*seismos* = shake, *gramma* = what is written), provide a great deal of information concerning the behavior of seismic waves. Simply stated, seismic waves are elastic energy that radiates out in all directions from the focus. The propagation (transmission) of this energy can be compared to the shaking of gelatin in a bowl, which results as some is spooned out. Whereas the gelatin will have one mode of vibration, seismograms reveal that two main groups of seismic waves are generated by the slippage of a rock mass. One of these wave types travels along the outer part of Earth. These are called **surface waves.** Others travel through Earth's interior and are called **body waves.** Body waves are further divided into two types, called **primary,** or **P, waves** and **secondary** or **S, waves.**

Body waves are divided into P and S waves by their mode of travel through intervening materials. P waves are "push-pull" waves—they push (compress) and pull (expand) rocks in the direction the wave is traveling (Figure 11.9A). Imagine holding someone by the shoulders and shaking that person. This push-pull movement is how P waves move through Earth. This wave motion is analogous to that generated by human vocal cords as they move air to create sound. Solids, liquids, and gases resist a change in volume when compressed and will elastically spring back once the force is removed. Therefore, P waves, which are compressional waves, can travel through all these materials.

On the other hand, S waves "shake" the particles at right angles to their direction of travel. This can be illustrated by fastening one end of a rope and shaking the other end, as shown in Figure 11.9B. Unlike P waves, which temporarily change the *volume* of intervening material by alternately compressing and expanding it, S waves temporarily change the *shape* of the material that transmits them. Because fluids (gases and liquids) do not respond elastically to changes in shape, they will not transmit S waves.

## *Students Sometimes Ask . . .*

*How often do earthquakes occur?*

All the time—in fact, there are literally thousands of earthquakes daily! Fortunately, the majority of them are too small to be felt by people (see Table 11.2, p. 308), and many of them occur in remote regions. Their existence is known only because of sensitive seismographs.

The motion of surface waves is somewhat more complex. As surface waves travel along the ground, they cause the ground and anything resting upon it to move, much like ocean swells toss a ship. In addition to their up-and-down motion, surface waves have a side-to-side motion similar to an S wave oriented in a horizontal plane. This latter motion is particularly damaging to the foundations of structures.

By observing a "typical" seismic record, as shown in Figure 11.10, you can see a major difference among these seismic waves: P waves arrive at the recording station first, then S waves, and then surface waves. This is a consequence of their speeds. To illustrate, the velocity of P waves through granite within the crust is about 6 kilometers per second. S waves under the same conditions travel at 3.6 kilometers per second. Differences in density and elastic properties of the rock greatly influence the velocities of these waves. Generally, in any solid material, P waves travel about 1.7 times faster than S waves, and surface waves can be expected to travel at 90 percent of the velocity of the S waves.

In addition to velocity differences, also notice in Figure 11.10 that the height or, more correctly, the amplitude of these wave types varies. The S waves have a slightly greater amplitude than do the P waves, while the surface waves, which cause the greatest destruction, exhibit an even greater amplitude. Because surface waves are confined to a narrow region near the surface and are not spread throughout Earth as P and S waves are, they retain their maximum amplitude longer. Surface waves also have longer periods (time interval between crests); therefore, they are often referred to as **long waves,** or **L waves.**

As we shall see, seismic waves are useful in determining the location and magnitude of earthquakes. In addition, seismic waves provide a tool for probing Earth's interior.

# Locating the Source of an Earthquake

GEODe EARTH
**Earthquakes**
▸ **Locating the Source of an Earthquake**

Recall that the *focus* is the place within Earth where earthquake waves originate. The **epicenter** (*epi* = upon, *centr* = a point)is the location on the surface directly above the focus (see Figure 11.2).

The difference in velocities of P and S waves provides a method for locating the epicenter. The principle used is

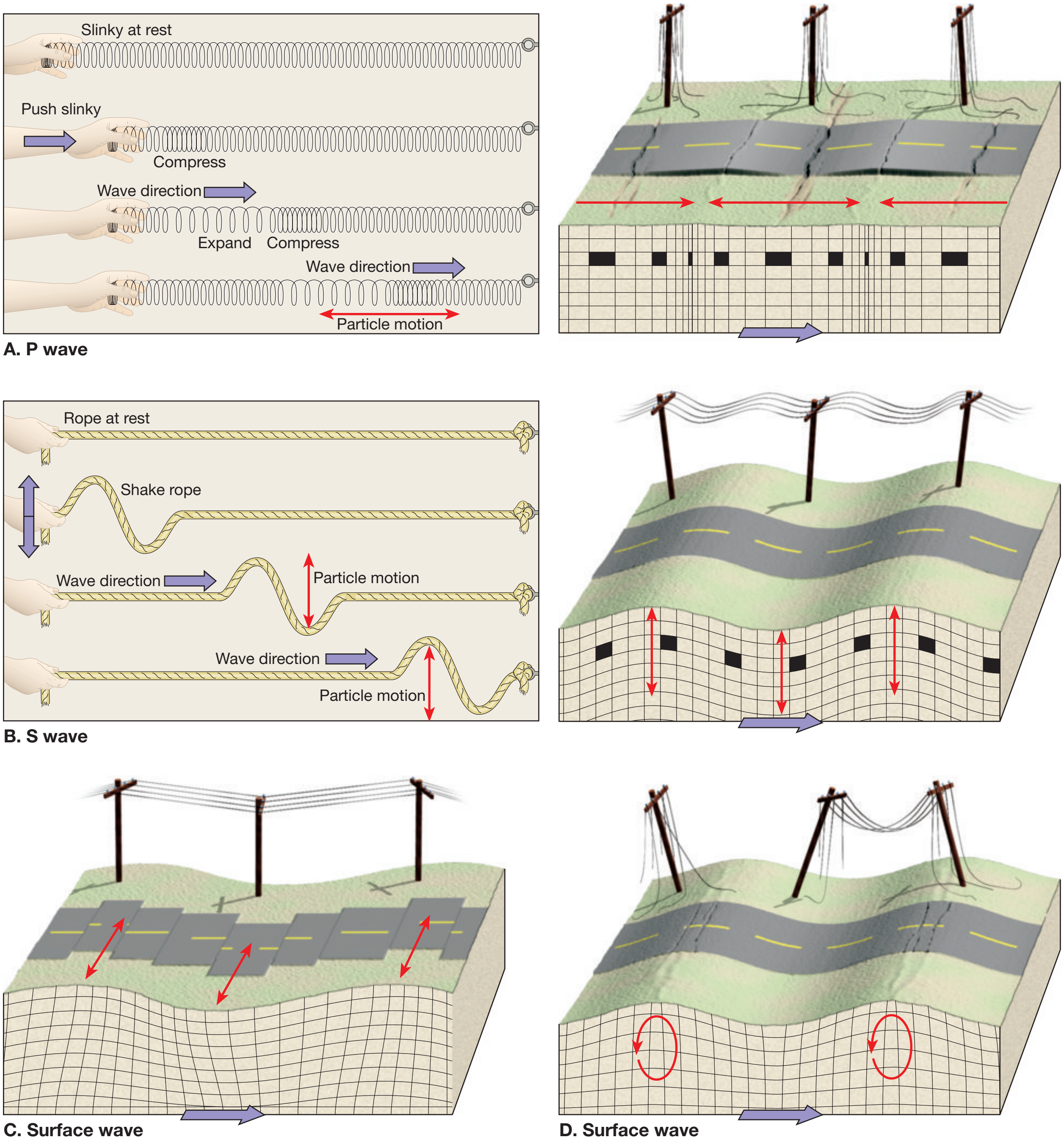



**FIGURE 11.9** Types of seismic waves and their characteristic motion. (Note that during a strong earthquake, ground shaking consists of a combination of various kinds of seismic waves.) **A.** As illustrated by a slinky, P waves are compressional waves that alternately compress and expand the material through which they pass. The back-and-forth motion produced as compressional waves travel along the surface can cause the ground to buckle and fracture, and may cause power lines to break. **B.** S waves cause material to oscillate at right angles to the direction of wave motion. Because S waves can travel in any plane, they produce up-and-down and sideways shaking of the ground. **C.** One type of surface wave is essentially the same as that of an S wave that exhibits only horizontal motion. This kind of surface wave moves the ground from side to side and can be particularly damaging to the foundations of buildings. **D.** Another type of surface wave travels along Earth's surface much like rolling ocean waves. The arrows show the elliptical movement of rock as the wave passes.

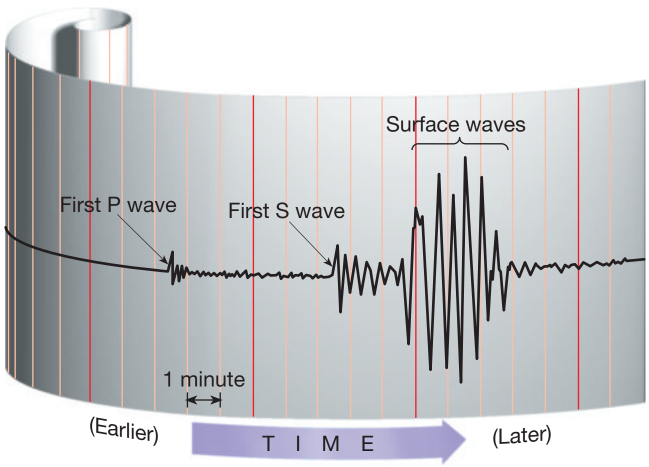


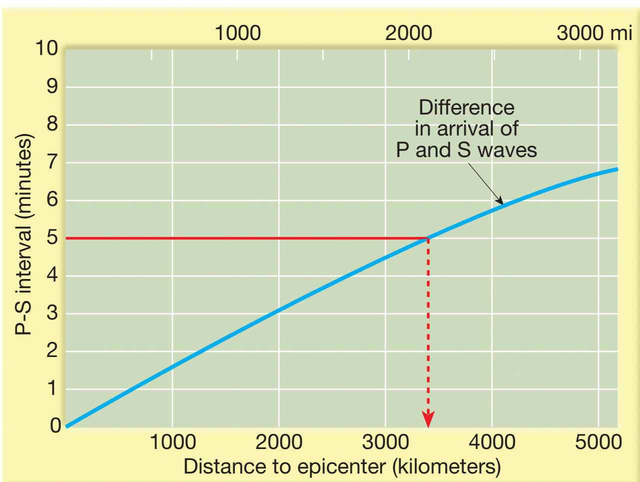

**FIGURE 11.10** Typical seismogram. Note the time interval (about 5 minutes) between the arrival of the first P wave and the arrival of the first S wave.

analogous to a race between two autos, one faster than the other. The P wave always wins the race, arriving ahead of the S wave. But the greater the length of the race, the greater will be the difference in the arrival times at the finish line (the seismic station). Therefore, the greater the interval measured on a seismogram between the arrival of the first P wave and the first S wave, the greater the distance to the earthquake source.

A system for locating earthquake epicenters was developed by using seismograms from earthquakes whose epicenters could be easily pinpointed from physical evidence. From these seismograms, travel-time graphs were constructed (Figure 11.11). The first travel-time graphs were greatly improved when seismograms became available from nuclear explosions, because the precise location and time of detonation were known.

Using the sample seismogram in Figure 11.10 and the travel-time curve in Figure 11.11, we can determine the distance separating the recording station from the earthquake in two steps: (1) Using the seismogram, determine the time interval between the arrival of the first P wave and the first S wave, and (2) using the travel-time graph, find the P–S interval on the vertical axis and use that information to determine the distance to the epicenter on the horizontal axis. From this information, we can determine that this earthquake occurred 3400 kilometers (2100 miles) from the recording instrument.

**FIGURE 11.11** A travel-time graph is used to determine the distance to the epicenter. The difference in arrival times of the first P and S waves in the example is 5 minutes. Thus, the epicenter is roughly 3400 kilometers (2100 miles) away.




Now we know the *distance*, but what *direction?* The epicenter could be in any direction from the seismic station. As shown in Figure 11.12, the precise location can be found when the distance is known from three or more different seismic stations. On a globe, we draw a circle around each seismic station. Each circle represents the epicenter distance for each station. The point where the three circles intersect is the epicenter of the quake. This method is called *triangulation.*

## Earthquake Belts

About 95 percent of the energy released by earthquakes originates in a few relatively narrow zones that wind around the globe (Figure 11.13). The greatest energy is released along a path around the outer edge of the Pacific Ocean known as the *circum-Pacific belt.* Included in this zone are regions of great seismic activity such as Japan, the Philippines, Chile, and numerous volcanic island chains, as exemplified by the Aleutian Islands.

Another major concentration of strong seismic activity runs through the mountainous regions that flank the Mediterranean Sea and continues through Iran and on past the Himalayan complex. Figure 11.13 indicates that yet another continuous belt extends for thousands of kilometers

**FIGURE 11.12** An earthquake epicenter is located using the distances obtained from three or more seismic stations.

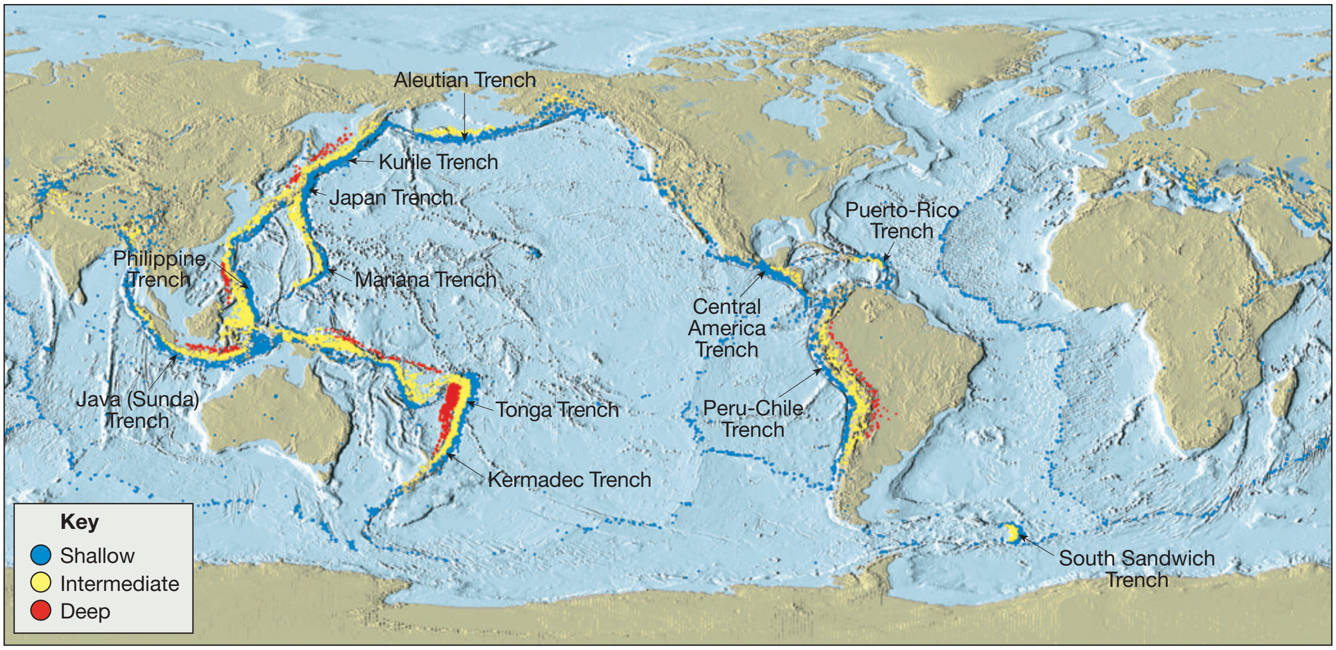



**FIGURE 11.13** Distribution of shallow-, intermediate-, and deep-focus earthquakes. Note that deep-focus earthquakes occur only in association with convergent plate boundaries and subduction zones. (Data from NOAA)

through the world's oceans. This zone coincides with the oceanic ridge system, which is an area of frequent but low-intensity seismic activity.

The areas of the United States included in the circum-Pacific belt lie adjacent to California's San Andreas Fault and along the western coastal regions of Alaska, including the Aleutian Islands. In addition to these high-risk areas, other sections of the United States are regarded as regions where strong earthquakes are likely to occur (see Box 11.1).

## Earthquake Depths

Evidence from seismic records reveals that earthquakes originate at depths ranging from 5 to about 700 kilometers. In a somewhat arbitrary fashion, earthquake foci have been classified by their depth of occurrence. Those with points of origin within 70 kilometers of the surface are referred to as *shallow,* while those generated between 70 and 300 km are considered *intermediate,* and those with a focus greater than 300 km are classified as *deep.* About 90 percent of all earthquakes occur at depths of less than 100 km, and nearly all very damaging earthquakes appear to originate at shallow depths.

Recall that the 1906 San Francisco earthquake involved movement within the upper 15 km of Earth's crust, whereas the 1964 Alaskan earthquake had a focal depth of 33 km. Seismic data reveal that while shallow-focus earthquakes have been recorded with Richter magnitudes of 8.6, the strongest intermediate-depth quakes have had values below 7.5, and deep-focus earthquakes have not exceeded 6.9 in magnitude.

When earthquake data were plotted according to geographic location and depth, several interesting observations were noted. Rather than a random mixture of shallow and deep earthquakes, some very definite patterns emerged (Figure 11.13). Earthquakes generated along the oceanic ridge system always have a shallow focus, and none are very strong. Further, it was noted that almost all deep-focus earthquakes occurred in the circum-Pacific belt, particularly in regions situated landward of deep-ocean trenches.

Studies conducted in the Pacific basin established the fact that foci depths increase with increasing distance from deep-ocean trenches. Notice in Figure 11.13 that in South America the foci depths increase landward of the Peru–Chile trench. These seismic regions, called **Wadati-Benioff zones** after the two scientists who were the first to extensively study them, dip at an average angle of about 45 degrees to the surface. Why should earthquakes be oriented along a narrow zone that plunges almost 700 kilometers into Earth's interior? We will consider this question later in the chapter.

# Measuring the Size of Earthquakes

Historically, seismologists have employed a variety of methods to obtain two fundamentally different measures that describe the size of an earthquake—intensity and magnitude. The first of these to be used was **intensity—**a measure of the degree of earthquake shaking at a given locale based on the amount of damage. With the development of seismographs, it became clear that a quantitative measure of an earthquake based on seismic records rather than uncertain personal estimates of damage was desirable. The measurement that was developed, called **magnitude,** relies on calculations that use data provided by seismic records (and other

BOX 11.1 ▶ PEOPLE AND THE ENVIRONMENT

## Earthquakes East of the Rockies

The majority of earthquakes occur near plate boundaries, as exemplified by California and Japan. However, areas distant from plate boundaries are not necessarily immune. A team of seismologists recently estimated that the probability of a damaging earthquake east of the Rocky Mountains during the next 30 years is roughly two-thirds as likely as an earthquake of comparable damage in California. Like all earthquake-risk assessments, this prediction is based in part on the geographic distribution and average rate of earthquake occurrences in these regions.

At least six major earthquakes have occurred in the central and eastern United States since colonial times. Three of them, having estimated Richter magnitudes of 7.5, 7.3, and 7.8, were centered near the Mississippi River Valley in southeastern Missouri. Occurring over a three-month period in December 1811, January 1812, and February 1812, these earthquakes and numerous smaller tremors destroyed the town of New Madrid, Missouri. They also triggered massive landslides, damaged a six-state area, altered the course of the Mississippi River, and enlarged Tennessee's Reelfoot Lake.

The distance over which these earthquakes were felt is truly remarkable. Chimneys were downed in Cincinnati and Richmond, and even Boston residents—1770 kilometers (1100 miles) to the northeast—felt the tremor. Although destruction from the New Madrid earthquakes was slight compared to the Loma Prieta earthquake of 1989, the Midwest in the early 1800s was sparsely populated. Memphis, near the epicenter, had not yet been established, and St. Louis was a small frontier town. Other damaging earthquakes—Aurora, Illinois (1909), and Valentine, Texas (1931)—remind us that the central United States is vulnerable.

The greatest historical earthquake in the eastern states occurred in Charleston, South Carolina, in 1886. This one-minute event caused 60 deaths, numerous injuries, and great economic loss within 200 kilometers (120 miles) of Charleston. Within 8 minutes strong vibrations shook the upper floors of buildings in Chicago and St. Louis, causing people to rush outdoors. In Charleston alone more than a hundred buildings were destroyed, and 90 percent of the remaining structures were damaged. It was difficult to find a chimney that was still standing (Figure 11.A).

New England and adjacent areas have experienced sizable shocks since colonial times, including the 1683 quake in Plymouth and the 1755 quake in Cambridge, Massachusetts. Since records have been kept, New York State has experienced more than 300 earthquakes large enough to be felt by humans.

These eastern and central earthquakes occur far less frequently than do those in California. Yet the shocks east of the Rockies have generally produced structural damage over a larger area than tremors of similar magnitude in California. The reason is that the underlying bedrock in the central and eastern United States is older and more rigid. As a result, seismic waves travel greater distances with less attenuation than in the western United States. For similar earthquakes, the region of maximum ground motion in the East may be up to 10 times larger than in the West. Consequently, the higher rate of earthquakes in the West is partly balanced by more widespread damage in the East.

Despite recent geologic history, Memphis, the largest population center in the area of the New Madrid earthquake, lacks adequate provision for earthquakes in its building code. Worse, Memphis rests on unconsolidated floodplain deposits, so its buildings are more susceptible to damage. A 1985 federal study concluded that a 7.6-magnitude earthquake in this area could cause an estimated 2500 deaths, collapse 3000 structures, cause $25 billion in damages, and displace a quarter of a million people in Memphis alone.


**FIGURE 11.A** Damage to Charleston, South Carolina, caused by the August 31, 1886, earthquake. Damage ranged from toppled chimneys and broken plaster to total collapse. (Photo courtesy of U.S. Geological Survey)

techniques) to estimate the amount of energy released at the source of the earthquake.

At it turns out, both intensity and magnitude provide useful, although quite different, information about earthquake strength. Consequently, both measures are still used to describe the relative sizes of earthquakes.

## Intensity Scales

Until a little more than a century ago, historical records provided the only accounts of the severity of earthquake shaking and destruction. Using these descriptions—which were compiled without any established standards for reporting—

made accurate comparisons of earthquake sizes difficult, at best.

Perhaps the first attempt to “scientifically” describe the aftermath of an earthquake came following the great Italian earthquake in 1857. By systematically mapping effects of the earthquake, a measure of the strength and distribution of ground motion was established. The map generated by this study employed lines to connect places of equal damage and hence equal intensity (Figure 11.14). Using this technique, zones of intensity were identified, with the zone of highest intensity located near the center of maximum ground shaking and often (but not always) the source of seismic waves.

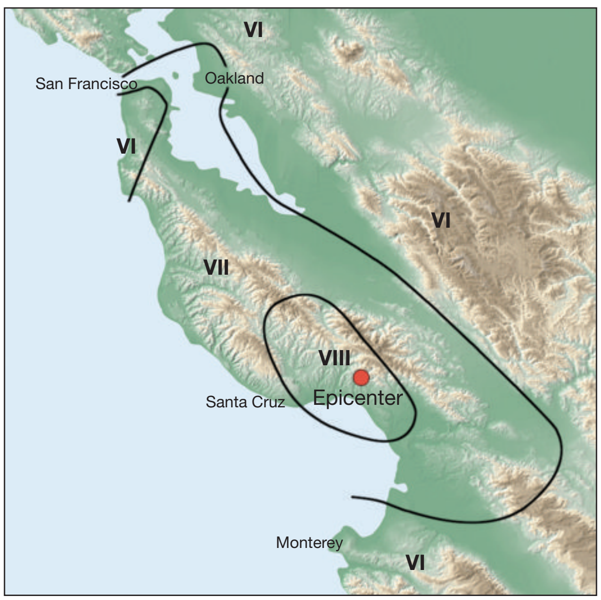
In order to standardize the study of earthquake severity, workers developed various intensity scales that considered damage done to buildings, as well as individual descriptions of the event, and secondary effects—landslides and the extent of ground rupture. By 1902, Giuseppe Mercalli had developed a relatively reliable intensity scale, which in a modified form is still used today (Figure 11.14). The **Modified Mercalli Intensity Scale,** shown in Table 11.1, was developed using California buildings as its standard, but it is appropriate for use throughout most of the United States and Canada to estimate the strength of an earthquake. For example, if some well-built wood structures and most masonry buildings are destroyed by an earthquake, a region would be assigned an intensity of X on the Mercalli scale (Table 11.1).

Despite their usefulness in providing seismologists with a tool to compare earthquake severity, particularly in regions where there are no seismographs, intensity scales have severe drawbacks. In particular, intensity scales are based on effects (largely destruction) of earthquakes that depend not only on the severity of ground shaking but also on factors such as population density, building design, and the nature of surface materials. The modest 6.9-magnitude earthquake in Armenia in 1988 was extremely destructive, mainly because of inferior building construction, whereas the 1985 Mexico City quake was deadly because of the soft sediment upon which the city rests. Thus, the destruction wrought by earthquakes may not be a true measure of the earthquake’s actual size.

**TABLE 11.1 Modified Mercalli Intensity Scale**

| | |
|---|---|
| I | Not felt except by a very few under especially favorable circumstances. |
| II | Felt only by a few persons at rest, especially on upper floors of buildings. |
| III | Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. |
| IV | During the day, felt indoors by many, outdoors by few. Sensation like heavy truck striking building. |
| V | Felt by nearly everyone, many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed. |
| VI | Felt by all; many frightened and run outdoors. Some heavy furniture moved; few instances of fallen plaster or damaged chimneys. Damage slight. |
| VII | Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures. |
| VIII | Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures (fall of chimneys, factory stacks, columns, monuments, walls). |
| IX | Damage considerable in specially designed structures. Buildings shifted off foundations. Ground cracked conspicuously. |
| X | Some well-built wooden structures destroyed. Most masonry and frame structures destroyed. Ground badly cracked. |
| XI | Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. |
| XII | Damage total. Waves seen on ground surfaces. Objects thrown upward into air. |

**FIGURE 11.14** Zones of destruction associated with the Loma Prieta, California, earthquake of 1989 using the Modified Mercalli Intensity Scale. Roman numerals show the intensity categories. The zone of maximum intensity roughly corresponds to the epicenter. Even higher intensities were experienced at a few sites in San Francisco and Oakland where local conditions amplified the seismic waves. (Data from Plafker and Galloway)




## Magnitude Scales

In order to compare earthquakes across the globe, a measure was needed that does not rely on parameters that vary considerably from one part of the world to another, such as types of construction. As a consequence, a number of magnitude scales were developed.

***Richter Magnitude*** In 1935 Charles Richter of the California Institute of Technology developed the first magnitude scale using seismic records to estimate the relative sizes of earthquakes. As shown in Figure 11.15 (top), the **Richter scale** is based on the amplitude of the largest seismic wave (P, S, or surface wave) recorded on a seismogram. Because seismic waves weaken as the distance between the earthquake focus and the seismograph increases (in a manner

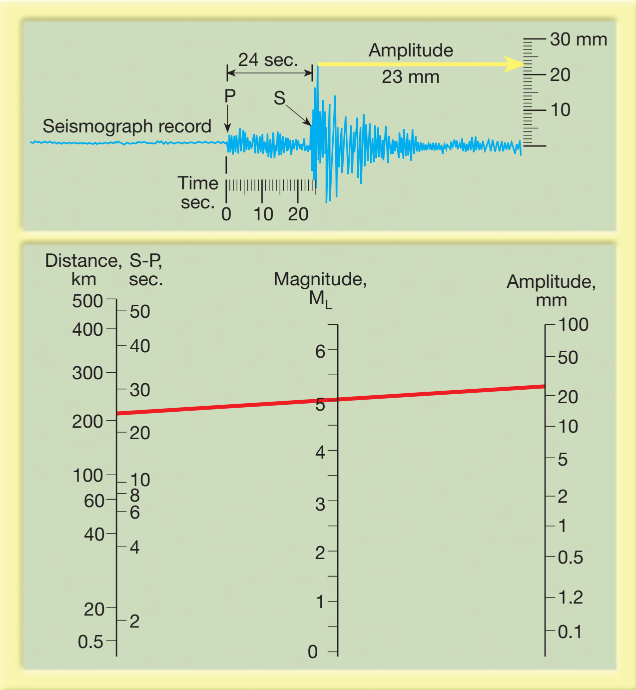



**FIGURE 11.15** Illustration showing how the Richter magnitude of an earthquake can be determined graphically using a seismograph record from a Wood-Anderson instrument. First, measure the height (amplitude) of the largest wave on the seismogram (23 mm) and then the distance to the focus using the time interval between S and P waves (24 seconds). Next, draw a line between the distance scale (left) and the wave amplitude scale (right). By doing this, you should obtain the Richter magnitude ($M_L$) of 5. (Data from California Institute of Technology)

**TABLE 11.2 Earthquake Magnitudes and Expected World Incidence**

| Richter Magnitudes | Effects Near Epicenter | Estimated Number per Year |
|---|---|---|
| <0.2 | Generally not felt, but recorded. | 600,000 |
| 2.0–2.9 | Potentially perceptible. | 300,000 |
| 3.0–3.9 | Felt by some. | 49,000 |
| 4.0–4.9 | Felt by most. | 6200 |
| 5.0–5.9 | Damaging shocks. | 800 |
| 6.0–6.9 | Destruction in populous regions. | 266 |
| 7.0–7.9 | Major earthquakes. Inflict serious damage. | 18 |
| 8.0 | Great earthquakes. Cause extensive destruction to communities near epicenter. | 1.4 |

similar to light), Richter developed a method that accounted for the decrease in wave amplitude with increased distance. Theoretically, as long as the same, or equivalent, instruments were used, monitoring stations at various locations would obtain the same Richter magnitude for every recorded earthquake. (Richter selected the Wood-Anderson seismograph as the standard recording device.) In practice, however, different recording stations often obtained slightly different Richter magnitudes for the same earthquake—a consequence of the variations in rock types through which the waves traveled.

Although the Richter scale has no upper limit, the largest magnitude recorded on a Wood-Anderson seismograph was 8.9. These great shocks released approximately $10^{26}$ ergs of energy—roughly equivalent to the detonation of 1 billion tons of TNT. Conversely, earthquakes with a Richter magnitude of less than 2.0 are not felt by humans. With the development of more sensitive instruments, tremors of a magnitude of minus 2 were recorded. Table 11.2 shows how Richter magnitudes and their effects are related.

Earthquakes vary enormously in strength, and great earthquakes produce wave amplitudes that are thousands of times larger than those generated by weak tremors. To accommodate this wide variation, Richter used a *logarithmic scale* to express magnitude, where a *tenfold* increase in wave amplitude corresponds to an increase of 1 on the magnitude scale. Thus, the amount of ground shaking for a 5-magnitude earthquake is 10 times greater than that produced by an earthquake having a Richter magnitude of 4.

In addition, each unit of Richter magnitude equates to roughly a *32-fold energy increase.* Thus, an earthquake with a magnitude of 6.5 releases 32 times more energy than one with a magnitude of 5.5, and roughly 1000 times more energy than a 4.5-magnitude quake (Table 11.3). A major earthquake with a magnitude of 8.5 releases millions of times more energy than the smallest earthquakes felt by humans.

***Other Magnitude Scales*** Richter's original goal was modest in that he only attempted to rank the earthquakes of southern California (shallow-focus earthquakes) into groups of large, medium, and small magnitude. Hence, Richter magnitude was designed to study nearby (or local) earthquakes and is denoted by the symbol ($M_L$)—where M is for *magnitude* and L is for *local.*

The convenience of describing the size of an earthquake by a single number that could be calculated quickly from seismograms makes the Richter scale a powerful tool. Further, unlike intensity scales that could only be applied to populated areas of the globe, Richter magnitudes could be assigned to earthquakes in more remote regions and even to events that occurred in the ocean basins. As a result, the method devised by Richter was adapted to a number of different seismographs located throughout the world. In time, seismologists modified Richter's work and developed new magnitude scales.

However, despite their usefulness, none of these "Richter-like" magnitude scales are adequate for describing very large earthquakes. For example, the 1906 San Francisco earthquake and the 1964 Alaskan earthquake had roughly the same Richter magnitudes. However, based on the size of the fault zone and the amount of displacement observed, the Alaskan earthquake released considerably more energy than the San Francisco quake. Thus, the Richter scale (as well as the other related magnitude scales) are said to be

**TABLE 11.3 Earthquake Magnitude and Energy Equivalence**

| Earthquake Magnitude | Energy Released* (Millions of Ergs) | Approximate Energy Equivalence |
|---|---|---|
| 0 | 630,000 | 1 pound of explosives |
| 1 | 20,000,000 | |
| 2 | 630,000,000 | Energy of lightning bolt |
| 3 | 20,000,000,000 | |
| 4 | 630,000,000,000 | 1000 pounds of explosives |
| 5 | 20,000,000,000,000 | |
| 6 | 630,000,000,000,000 | 1946 Bikini atomic bomb test<br>1994 Northridge Earthquake |
| 7 | 20,000,000,000,000,000 | 1989 Loma Prieta Earthquake |
| 8 | 630,000,000,000,000,000 | 1906 San Francisco Earthquake<br>1980 Eruption of Mount St. Helens |
| 9 | 20,000,000,000,000,000,000 | 1964 Alaskan Earthquake<br>1960 Chilean Earthquake |
| 10 | 630,000,000,000,000,000,000 | Annual U.S. energy consumption |

* For each unit increase in magnitude, the energy released increases about 31.6 times.
*Source:* U.S. Geological Survey.

*saturated* for large earthquakes because they cannot distinguish between the size of these events.

***Moment Magnitude*** In recent years seismologists have been employing a more precise measure called **moment magnitude** ($M_W$), which can be calculated using several techniques. In one method the moment magnitude is calculated from field studies using a combination of factors that include the average amount of displacement along the fault, the area of the rupture surface, and the shear strength of the faulted rock—a measure of how much strain energy a rock can store before it suddenly slips and releases this energy in the form of an earthquake (and heat). For example, the energy involved in a 3-meter displacement of a rock body along a rupture a few hundred kilometers long would be much larger than that produced by a 1-meter displacement along a 10-kilometer-long rupture (assuming comparable rupture depths).

The moment magnitude can also be readily calculated from seismograms by examining very long period seismic waves. The values obtained have been calibrated so that small- and moderate-sized earthquakes have moment magnitudes that are roughly equivalent to Richter magnitudes. However, moment magnitudes are much better for describing very large earthquakes. For example, on the moment magnitude scale, the 1906 San Francisco earthquake, which had a Richter magnitude of 8.3, would be demoted to 7.9 on the moment magnitude scale, whereas the 1964 Alaskan earthquake with an 8.3 Richter magnitude would be increased to 9.2. The strongest earthquake on record is the 1960 Chilean earthquake, with a moment magnitude of 9.5.

Moment magnitude has gained wide acceptance among seismologists and engineers because: (1) it is the only magnitude scale that estimates adequately the size of very large earthquakes; (2) it is a measure that can be derived mathematically from the size of the rupture surface and the amount of displacement, thus it better reflects the total energy released during an earthquake; and (3) it can be verified by two independent methods—field studies that are based on measurements of fault displacement and by seismographic methods using long-period waves.

### Students Sometimes Ask . . .

*Do moderate earthquakes decrease the chances of a major quake in the same region?*

No. This is due to the vast increase in release of energy associated with higher-magnitude earthquakes (see Table 11.3). For instance, an earthquake with a magnitude of 8.5 releases millions of times more energy than the smallest earthquakes felt by humans. Similarly, thousands of moderate tremors would be needed to release the huge amount of energy equal to one "great" earthquake.

## Earthquake Destruction

The most violent earthquake ever recorded in North America—the Good Friday Alaskan earthquake—occurred at 5:36 P.M. on March 27, 1964. Felt throughout that state, the earthquake had a moment magnitude ($M_W$) of 9.2 and reportedly lasted 3 to 4 minutes. This brief event left 131 people dead, thousands homeless, and the economy of the state badly disrupted. Had the schools and business districts been open, the toll surely would have been higher. Within 24 hours of the initial shock, 28 aftershocks were recorded, 10 of which exceeded a magnitude of 6 on the Richter scale. The location of the epicenter and the towns that were hardest hit by the quake are shown in Figure 11.16.

Many factors determine the degree of destruction that will accompany an earthquake. The most obvious is the magnitude of the earthquake and its proximity to a populated area. Fortunately, most earthquakes are small and occur in remote regions of Earth. However, about 20 major earthquakes are reported annually, one or two of which can be catastrophic.

During an earthquake, the region within 20 to 50 kilometers (12.5 to 30 miles) of the epicenter ordinarily will experience roughly the same degree of ground shaking, but beyond this limit the vibration deteriorates rapidly. Occasionally

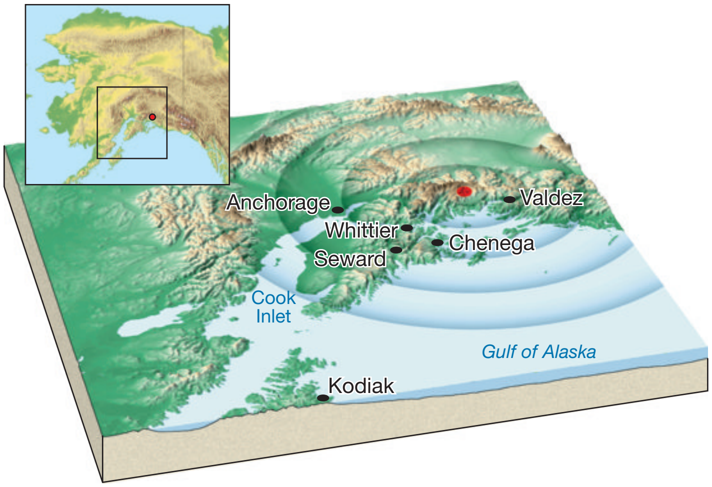



**FIGURE 11.16** Region most affected by the Good Friday earthquake of 1964. Note the location of the epicenter (red dot). (After U.S. Geological Survey)

during earthquakes that occur in the stable continental interior, such as the New Madrid earthquake of 1811, the area of influence can be much larger. The epicenter of this earthquake was located directly south of Cairo, Illinois, and the vibrations were felt from the Gulf of Mexico to Canada, and from the Rockies to the Atlantic Seaboard.

## Destruction from Seismic Vibrations

The 1964 Alaskan earthquake provided geologists with new insights into the role of ground shaking as a destructive force. As the energy released by an earthquake travels along Earth's surface, it causes the ground to vibrate in a complex manner by moving up and down as well as from side to side. The amount of structural damage attributable to the vibrations depends on several factors, including (1) the intensity and (2) the duration of vibrations, (3) the nature of the material upon which the structure rests, and (4) the design of the structure.

All of the multistory structures in Anchorage were damaged by the vibrations. The more flexible wood-frame residential buildings fared best. However, many homes were destroyed when the ground failed. A striking example of how construction variations affect earthquake damage is shown in Figure 11.17. You can see that the steel-frame building on the left withstood the vibrations, whereas the poorly designed J.C. Penney building was badly damaged. Engineers have learned that unreinforced masonry buildings are the most serious safety threat in earthquakes.

Most large structures in Anchorage were damaged, even though they were built according to the earthquake provisions of the Uniform Building Code. Perhaps some of that destruction can be attributed to the unusually long duration of this earthquake. Most quakes consist of tremors that last less than a minute. For example, the 1994 Northridge earthquake was felt for about 40 seconds, and the strong vibrations of the 1989 Loma Prieta earthquake lasted less than 15 seconds. But the Alaska quake reverberated for 3 to 4 minutes.

***Amplification of Seismic Waves*** Although the region within 20 to 50 kilometers of the epicenter will experience about the same intensity of ground shaking, the destruction varies considerably within this area (see Box 11.2). This difference is mainly attributable to the nature of the ground on which the structures are built. Soft sediments, for example, generally amplify the vibrations more than solid bedrock. Thus, the buildings located in Anchorage, which were situated on unconsolidated sediments, experienced heavy structural damage. By contrast, most of the town of Whittier, although much nearer the epicenter, rests on a firm foundation of granite and hence suffered much less damage. However, Whittier was damaged by a tsunami (described in the next section).

***Liquefaction*** In areas where unconsolidated materials are saturated with water, earthquake vibrations can generate a phenomenon known as **liquefaction** (*liqueo* = to be fluid, *facio* = to make).Under these conditions, what had been a stable soil turns into a mobile fluid that is not capable of supporting buildings or other structures (Figure 11.18). As a result, underground objects such as storage tanks and sewer lines may literally float toward the surface of their newly liquefied environment. Buildings and other structures may settle and collapse. During the 1989 Loma Prieta earthquake, in San Francisco's Marina District, foundations failed and geysers of sand and water shot from the ground, indicating that liquefaction had occurred (Figure 11.19).

**FIGURE 11.17** Damage caused to the five-story J.C. Penney Co. building, Anchorage, Alaska. Very little structural damage was incurred by the adjacent building. (Courtesy of NOAA/Seattle)

BOX 11.2 ▸ UNDERSTANDING EARTH

## Wave Amplification and Seismic Risks

Much of the damage and loss of life in the 1985 Mexico City earthquake occurred because downtown buildings were constructed on lake sediment that greatly amplified the ground motion. To understand why this happens, recall that as seismic waves pass through Earth, they cause the intervening material to vibrate much as a tuning fork when it is struck. Although most objects can be "forced" to vibrate over a wide range of frequencies, each has a natural period of vibration that is preferred. Different Earth materials, like different-length tuning forks, also have different natural periods of vibration.*

Ground-motion amplification results when the supporting material has a natural period of vibration (frequency) that matches that of the seismic waves. A common example of this phenomenon occurs when a parent pushes a child on a swing. When the parent periodically pushes the child in rhythm with the frequency of the swing, the child moves back and forth in a greater and greater arc (amplitude). By chance, the column of sediment beneath Mexico City had a natural period of vibration of about 2 seconds, matching that of the strongest seismic waves. Thus, when the seismic waves began shaking the soft sediments, a *resonance* developed, which greatly increased the amplitude of the vibrations. This amplification resulted in vibrations that exhibited 40 centimeters (1.3 feet) of back-and-forth ground motion every 2 seconds for nearly 2 minutes. Such movement was too intense for many poorly designed buildings in the city. In addition, intermediate-height structures (5 to 15 stories) sway back and forth with a period of about 2 seconds. Thus, resonance also developed between these buildings and the ground, with the result that most of the building failures occurred to structures in this height range (Figure 11.B).

Sediment-induced wave amplification is also thought to have contributed significantly to the failure of the two-tiered Cypress section of Interstate 880 during the 1989 Loma Prieta earthquake (Figure 11.C). Studies conducted on the 1.4-kilometer section that did collapse showed that it was built on San Francisco Bay mud. Another section of this interstate that was damaged but did not collapse was constructed on firmer alluvial materials.

*To demonstrate the natural period of vibration of an object, hold a ruler over the edge of a desk so that most of it is not supported by the desk. Start it vibrating, and notice the noise it makes. By changing the length of the unsupported portion of the ruler, the natural period of vibration will change accordingly.


**FIGURE 11.B** During the 1985 Mexican earthquake, multistory buildings swayed back and forth as much as 1 meter. Many, including the hotel shown here, collapsed or were seriously damaged. (Photo by James L. Beck)

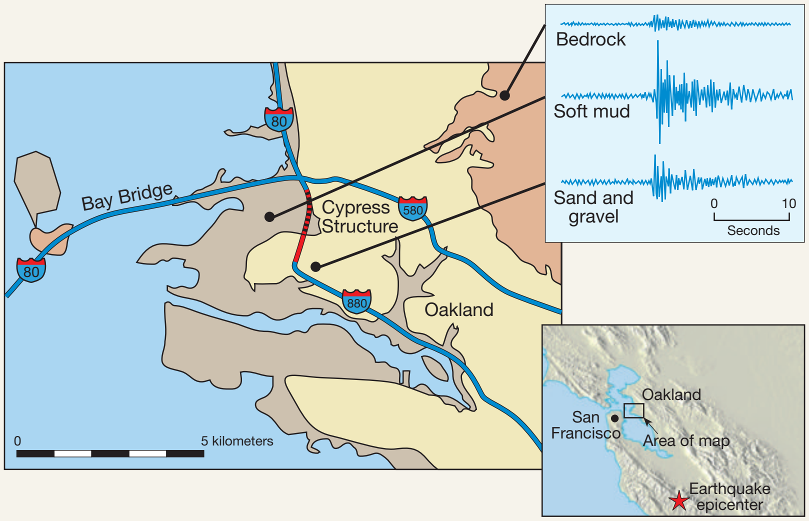



**FIGURE 11.C** The portion of the Cypress Freeway structure in Oakland, California, that stood on soft mud (dashed red line) collapsed during the 1989 Loma Prieta earthquake. Adjacent parts of the structure (solid red) that were built on firmer ground remained standing. Seismograms from an aftershock (upper right) show that shaking is greatly amplified in the soft mud as compared to the firmer materials.

**FIGURE 11.18** Effects of liquefaction. This tilted building rests on unconsolidated sediment that behaved like quicksand during the 1985 Mexican earthquake. (Photo by James L. Beck)

***Seiches*** The effects of great earthquakes may be felt thousands of kilometers from their source. Ground motion may generate *seiches,* the rhythmic sloshing of water in lakes, reservoirs, and enclosed basins such as the Gulf of Mexico. The 1964 Alaskan earthquake, for example, generated 2-meter waves off the coast of Texas, which damaged small craft, while much smaller waves were noticed in swimming pools in both Texas and Louisiana.

Seiches can be particularly dangerous when they occur in reservoirs retained by earthen dams. These waves have been known to slosh over reservoir walls and weaken the structure, thereby endangering the lives of those downstream.

## What Is a Tsunami?

Large undersea earthquakes occationally set in motion massive waves of water called **seismic sea waves,** or **tsunami.*** (*tsu* = harbor, *nami* = waves). These destructive waves often are called "tidal waves" by the media. However, this name is inappropriate, because these waves are not created nor influenced by the tidal effect of the Moon or Sun. Most tsunami result from vertical displacement along a fault located on the ocean floor, or from a large underwater landslide triggered by an earthquake (Figure 11.20).

Once formed, a tsunami resembles the ripples formed when a pebble is dropped into a pond. In contrast to ripples, tsunami advance across the ocean at amazing speeds between 500 and 950 kilometers per hour. Despite this striking characteristic, a tsunami in the open ocean can pass undetected because its height is usually less than 1 meter and the distance between wave crests is great, ranging from 100 to 700 kilometers. However, upon entering shallower coastal waters, these destructive waves are slowed down and the water begins to pile up to heights that occasionally exceed 30 meters (Figure 11.20). As the crest of a tsunami approaches the shore, it appears as a rapid rise in sea level with a turbulent and chaotic surface. Tsunami can be very destructive (Figure 11.21).

Usually the first warning of an approaching tsunami is a relatively rapid withdrawal of water from beaches. Some residents living near the Pacific basin have learned to heed this warning and move to higher ground, because about 5 to 30 minutes later, the retreat of water is followed by a surge capable of extending hundreds of meters inland. In a successive fashion, each surge is followed by rapid oceanward retreat of the water.

*Seismic sea waves were given the name *tsunami* by the Japanese, who have suffered a great deal from them. The term *tsunami* is now used worldwide.

**FIGURE 11.19** Liquefaction. **A.** These "mud volcanoes" were produced by the Loma Prieta earthquake of 1989. They formed when geysers of sand and water shot from the ground, an indication that liquefaction occurred. (Photo by Richard Hilton, courtesy of Dennis Fox) **B.** Students experiencing the nature of liquefaction. (Photo by Marli Miller)

**A.**

**B.**

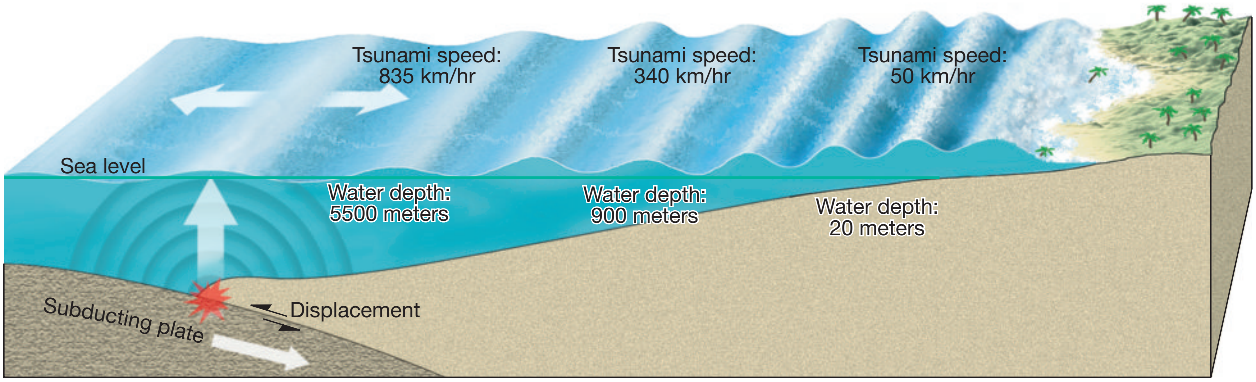



**FIGURE 11.20** Schematic drawing of a tsunami generated by displacement of the ocean floor. The speed of a wave correlates with ocean depth. As shown, waves moving in deep water advance at speeds in excess of 800 kilometers per hour. Speed gradually slows to 50 kilometers per hour at depths of 20 meters. Decreasing depth slows the movement of the wave. As waves slow in shallow water, they grow in height until they topple and rush onto shore with tremendous force. The size and spacing of these swells are not to scale.

**FIGURE 11.21** A massive earthquake of magnitude 9.0 off the Indonesian island of Sumatra sent a tsunami racing across the Indian Ocean and Bay of Bengal on December 26, 2004. **A.** Unsuspecting foreign tourists, who at first walked on the sand after the water receded, now rush toward shore as the first of six tsunami start to roll toward Hat Rai Lay Beach near Krabi in southern Thailand. (AFP/Getty Images Inc.) **B.** The Indonesian town of Banda Aceh, ten days after the tsunami. (Photo by Berbar Halin/Sipa Press)

**A.**

**B.**

The tsunami generated in the 1964 Alaskan earthquake inflicted heavy damage to the communities in the vicinity of the Gulf of Alaska, completely destroying the town of Chenega. Kodiak was also heavily damaged and most of its fishing fleet destroyed when a seismic sea wave carried many vessels into the business district. The deaths of 107 persons have been attributed to this tsunami. By contrast, only nine people died in Anchorage as a direct result of the vibrations.

Tsunami damage following the Alaskan earthquake extended along much of the west coast of North America, and despite a one-hour warning, 12 people perished in Crescent City, California, where all of the deaths and most of the destruction were caused by the fifth wave. The first wave crested about 4 meters (13 feet) above low tide and was followed by three progressively smaller waves. Believing that the tsunami had ceased, people returned to the shore, only to be met by the fifth and most devastating wave, which superimposed upon high tide crested about 6 meters higher than the level of low tide.

***Tsunami Damage from the 2004 Indonesian Earthquake*** A massive undersea earthquake of moment magnitude 9.0 occurred near the island of Sumatra on December 26, 2004, and sent waves of water racing across the Indian Ocean and Bay of Bengal (Figure 11.21A). This tsunami was one of the deadliest natural disasters of any kind in modern times, claiming more than 230,000 lives. As water surged several kilometers inland, cars and trucks were flung around like toys in a bathtub, and fishing boats were rammed into homes. In some locations, the backwash of water dragged bodies and huge amounts of debris out to sea.

The destruction was indiscriminate, destroying luxury resorts and poor fishing hamlets on the Indian Ocean coast (Figure 11.21B). Devastation was most severe along the southeast coast of Sri Lanka, in the Indonesian province of Aceh, in the Indian state of Tamil Nada, and on Thailand's resort island of Phuket. Damages were reported as far away as the Somalia coast of Africa, 4100 kilometers (2500 miles) west of the earthquake epicenter.

The killer waves generated by this massive quake achieved heights as great as 10 meters (33 feet) and struck many unprepared areas within three hours of the event. Although the Pacific basin contains deep-sea buoys and tide gauges that can spot tsunami waves at sea, the Indian Ocean does not. (The deep-sea buoys have pressure sensors that detect changes in pressure as the earthquake's energy travels through the ocean, and tide gauges measure the rise and fall in sea level.) The rarity of tsunami in the Indian Ocean also contributed to the lack of preparedness for such an event. It should come as no surprise that the countries of India, Indonesia, and Thailand have announced plans to establish a tsunami warning system for the Indian Ocean.

*Tsunami Warning System* In 1946, a large tsunami struck the Hawaiian Islands without warning. A wave more than 15 meters (50 feet) high left several coastal villages in shambles. This destruction motivated the U.S. Coast and Geodetic Survey to establish a tsunami warning system for coastal areas of the Pacific. From seismic observatories throughout the region, large earthquakes are reported to the Tsunami Warning Center in Honolulu. Scientists at the Center use tidal gauges to determine whether a tsunami has formed. Within an hour a warning is issued. Although tsunami travel very rapidly, there is sufficient time to evacuate all but the region nearest the epicenter. For example, a tsunami generated near the Aleutian Islands would take five hours to reach Hawaii, and one generated near the coast of Chile would travel 15 hours before reaching Hawaii (Figure 11.22).

## Landslides and Ground Subsidence

In the 1964 Alaskan earthquake, the greatest damage to structures was from landslides and ground subsidence triggered by the vibrations. At Valdez and Seward, the violent shaking caused deltaic materials to experience liquefaction; the subsequent slumping carried both waterfronts away. Because of the threat of recurrence, the entire town of Valdez was relocated about 7 kilometers away on more stable ground. In Valdez, 31 people on a dock died when it slid into the sea.

Most of the damage in the city of Anchorage was also attributed to landslides. Many homes were destroyed in Turnagain Heights when a layer of clay lost its strength and over 200 acres of land slid toward the ocean (Figure 11.23). A

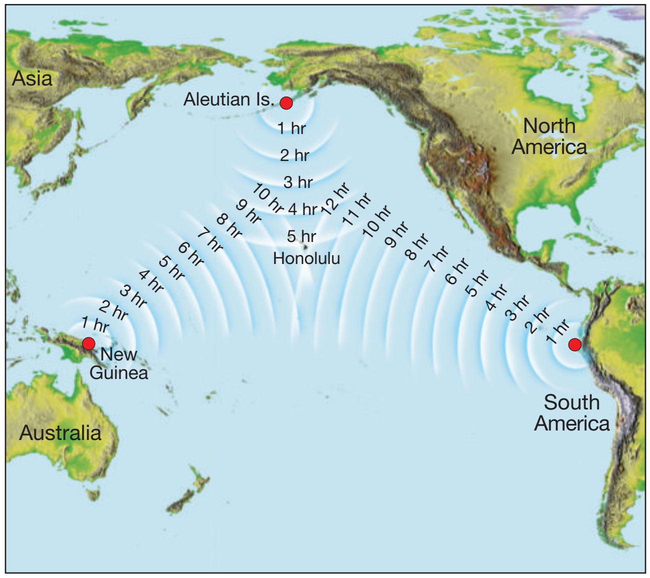
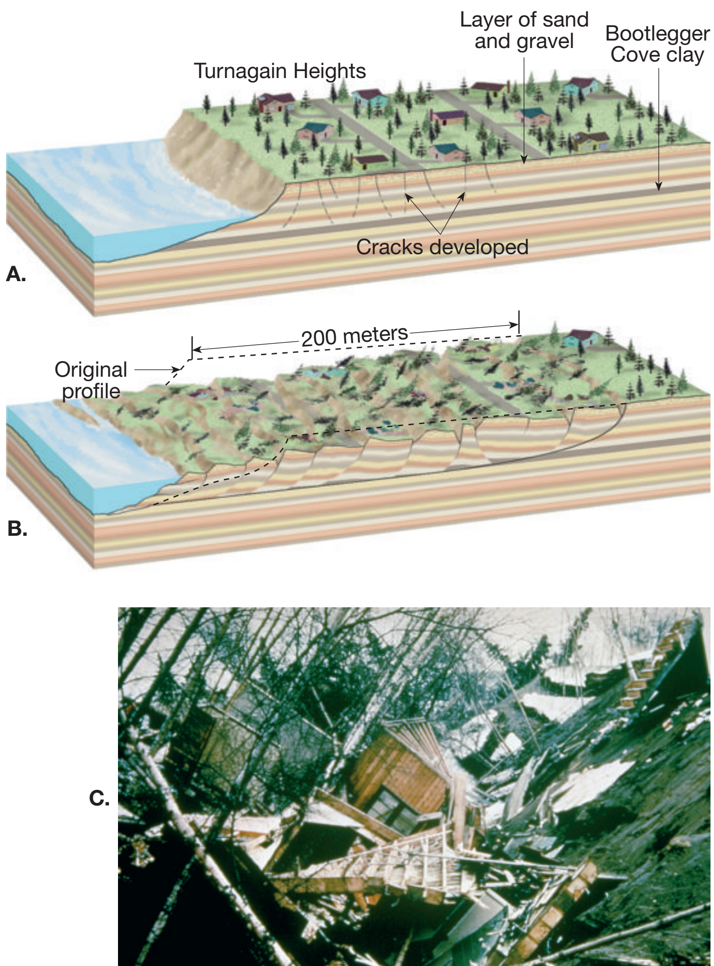



**FIGURE 11.22** Tsunami travel times to Honolulu, Hawaii, from selected locations throughout the Pacific. (Data from NOAA)

**FIGURE 11.23** Turnagain Heights slide caused by the 1964 Alaskan earthquake. **A.** Vibrations from the earthquake caused cracks to appear near the edge of the bluff. **B.** Within seconds blocks of land began to slide toward the sea on a weak layer of clay. In less than 5 minutes, as much as 200 meters of the Turnagain Heights bluff area had been destroyed. **C.** Photo of a small portion of the Turnagain Heights slide. (Photo courtesy of U.S. Geological Survey)



portion of this spectacular landslide was left in its natural condition as a reminder of this destructive event. The site was appropriately named "Earthquake Park." Downtown Anchorage was also disrupted as sections of the main business district dropped by as much as 3 meters (10 feet).

### Fire

The 1906 earthquake in San Francisco reminds us of the formidable threat of fire. The central city contained mostly large, older wooden structures and brick buildings. Although many of the unreinforced brick buildings were extensively damaged by vibrations, the greatest destruction was caused by fires, which started when gas and electrical lines were severed. The fires raged out of control for three days and devastated over 500 blocks of the city (see Figure 11.3). The problem was compounded by the initial ground shaking, which broke the city's water lines into hundreds of unconnected pieces.

The fire was finally contained when buildings were dynamited along a wide boulevard to provide a fire break, the same strategy used in fighting a forest fire. Although only a few deaths were attributed to the San Francisco fire, such is not always the case. A 1923 earthquake in Japan triggered an estimated 250 fires, which devastated the city of Yokohama and destroyed more than half the homes in Tokyo. More than 100,000 deaths were attributed to the fires, which were driven by unusually high winds.

## Can Earthquakes Be Predicted?

The vibrations that shook Northridge, California, in 1994 inflicted 57 deaths and about $40 billion in damage (Figure 11.24). This was from a brief earthquake (about 40 seconds) of moderate rating ($M_W$ 6.7). Seismologists warn that earthquakes of comparable or greater strength will occur along the San Andreas Fault, which cuts a 1300-kilometer (800-mile) path through the state. The obvious question is: Can earthquakes be predicted?

### Short-Range Predictions

The goal of short-range earthquake prediction is to provide a warning of the location and magnitude of a large earthquake within a narrow time frame. Substantial efforts to achieve this objective are being put forth in Japan, the United States, China, and Russia—countries where earthquake risks are high (Table 11.4). This research has concentrated on monitoring possible *precursors*—phenomena that precede and thus provide a warning of a forthcoming earthquake. In California, for example, seismologists are measuring uplift, subsidence, and strain in the rocks near active faults. Some Japanese scientists are studying anomalous animal behavior that may precede a quake. Other researchers are monitoring changes in groundwater levels, while still others are trying to predict earthquakes based on changes in the electrical conductivity of rocks.

**FIGURE 11.24** Damage to Interstate 5 caused by the January 17, 1994, Northridge earthquake. (Photo by Tom McHugh/Photo Researchers, Inc.)

## *Students Sometimes Ask . . .*

***I've heard that the safest place to be in a house during an earthquake is in a doorframe. Is that really the best place to be while an earthquake is occurring?***

It depends. If you're on the road, stay away from tunnels, underpasses, and overpasses. Stop in a safe area and stay in your vehicle until the shaking stops. If you happen to be outside during an earthquake, stand away from buildings, trees, and telephone and electric lines. If you're inside, remember to *duck, cover, and hold.* When you feel an earthquake, *duck* under a desk or sturdy table. Stay away from windows, bookcases, file cabinets, heavy mirrors, hanging plants, and other heavy objects that could fall. Stay under *cover* until the shaking stops. And, *hold* on to the desk or table: If it moves, move with it.

An enduring earthquake image of California is a collapsed adobe home with the doorframe as the only standing part. From this came the belief that a doorway is the safest place to be during an earthquake. This is true only if you live in an old, unreinforced adobe house. In modern homes, doorways are no stronger than any other part of the house and usually have doors that will swing and can injure you. You'd be safer under a table.

Among the most ambitious earthquake experiments is one being conducted along a segment of the San Andreas Fault near the town of Parkfield in central California. Here, earthquakes of moderate intensity have occurred on a regular basis about once every 22 years since 1857. The most recent rupture was a 5.6-magnitude quake that occurred in 1966. With the next event already significantly "overdue," the U.S. Geological Survey has established an elaborate monitoring network. Included are creepmeters, tiltmeters, and bore-hole strain meters that are used to measure the accumulation and release of strain. Moreover, 70 seismographs of various designs have been installed to record foreshocks as well as the main event. Finally, a network of distance-measuring devices that employ lasers measures movement across the fault (Figure 11.25). The object is to identify ground movements that may precede a sizable rupture.

One claim of a successful short-range prediction was made by Chinese seismologists after the February 4, 1975, earthquake in Liaoning Province. According to reports, very few people were killed, although more than 1 million lived near the epicenter, because the earthquake was predicted and the population was evacuated. Recently, some Western seismologists have questioned this claim and suggest

**TABLE 11.4 Some Notable Earthquakes**

| Year | Location | Deaths (est.) | Magnitude† | Comments |
|---|---|---|---|---|
| 1556 | Shensi, China | 830,000 | | Possibly the greatest natural disaster. |
| 1755 | Lisbon, Portugal | 70,000 | | Tsunami damage extensive. |
| *1811–1812 | New Madrid, Missouri | Few | 7.9 | Three major earthquakes. |
| *1886 | Charleston, South Carolina | 60 | | Greatest historical earthquake in the eastern United States. |
| *1906 | San Francisco, California | 1500 | 7.8 | Fires caused extensive damage. |
| 1908 | Messina, Italy | 120,000 | | |
| 1923 | Tokyo, Japan | 143,000 | 7.9 | Fire caused extensive destruction. |
| 1960 | Southern Chile | 5700 | 9.5 | Possibly the largest-magnitude earthquake ever recorded. |
| *1964 | Alaska | 131 | 9.2 | Greatest North American earthquake. |
| 1970 | Peru | 66,000 | 7.8 | Great rockslide. |
| *1971 | San Fernando, California | 65 | 6.5 | Damage exceeded $1 billion. |
| 1975 | Liaoning Province, China | 1328 | 7.5 | First major earthquake to be predicted. |
| 1976 | Tangshan, China | 240,000 | 7.6 | Not predicted. |
| 1985 | Mexico City | 9500 | 8.1 | Major damage occurred 400 km from epicenter. |
| 1988 | Armenia | 25,000 | 6.9 | Poor construction practices. |
| *1989 | Loma Prieta, California | 62 | 6.9 | Damages exceeded $6 billion. |
| 1990 | Iran | 50,000 | 7.3 | Landslides and poor construction practices caused great damage. |
| 1993 | Latur, India | 10,000 | 6.4 | Located in stable continental interior. |
| *1994 | Northridge, California | 57 | 6.7 | Damages in excess of $40 billion. |
| 1995 | Kobe, Japan | 5472 | 6.9 | Damage estimated to exceed $100 billion. |
| 1999 | Izmit, Turkey | 17,127 | 7.4 | Nearly 44,000 injured and more than 250,000 displaced |
| 1999 | Chi-Chi, Taiwan | 2300 | 7.6 | Severe destruction; 8700 injuries. |
| 2001 | El Salvador | 1000 | 7.6 | Triggered many landslides. |
| 2001 | Bhuj, India | 20,000 | 7.9 | 1 million or more homeless. |
| 2003 | Bam, Iran | 41,000 | 6.6 | Ancient city with poor construction. |
| 2004 | Indian Ocean | 230,000 | 9.0 | Devastating tsunami damage. |
| 2005 | Pakistan/Kashmir | 86,000 | 7.6 | 69,000 injured, 4 million homeless, many landslides. |

* U.S. earthquakes.
† Widely differing magnitudes have been estimated for some of these earthquakes. When available, moment magnitudes are used.
*Source:* U.S. Geological Survey

**FIGURE 11.25** Lasers used to measure movement along the San Andreas Fault. (Photo by John K. Nakata/U.S. Geological Survey)

instead that an intense swarm of foreshocks, which began 24 hours before the main earthquake, may have caused many people to evacuate spontaneously. Further, an official Chinese government report issued 10 years later stated that 1328 people died and 16,980 injuries resulted from this earthquake.

One year after the Liaoning earthquake, at least 240,000 people died in the Tangshan, China, earthquake, which was not predicted. The Chinese have also issued false alarms. In a province near Hong Kong, people reportedly left their dwellings for over a month, but no earthquake followed. Clearly, whatever method the Chinese employ for short-range predictions, it is *not* reliable.

In order for a prediction scheme to warrant general acceptance, it must be both accurate and reliable. Thus, *it must have a small range of uncertainty as regards to location and timing, and it must produce few failures or false alarms.* Can you imagine the debate that would precede an order to evacuate a large city in the United States, such as Los Angeles or San Francisco? The cost of evacuating millions of people, arranging for living accommodations, and providing for their lost work time and wages would be staggering.

Currently, *no reliable method exists* for making short-range earthquake predictions. In fact, except for a brief period of optimism during the 1970s, the leading seismologists of the past 100 years have generally concluded that short-range earthquake prediction is *not* feasible. To quote Charles Richter, developer of the well-known magnitude scale, "Prediction provides a happy hunting ground for amateurs, cranks, and outright publicity-seeking fakers." This statement was validated in 1990 when Iben Browning, a self-proclaimed expert, predicted that a major earthquake on the New Madrid fault would devastate an area around southeast Missouri on December 2 or 3. Many people in Missouri, Tennessee, and Illinois rushed out to buy earthquake insurance. Some schools and factories closed, while people as far away as northern Illinois stayed home rather than risk traveling to work. The designated date passed without even the slightest tremor.

## Long-Range Forecasts

In contrast to short-range predictions, which aim to predict earthquakes within a time frame of hours or at most days, long-range forecasts give the probability of a certain magnitude earthquake occurring on a time scale of 30 to 100 years or more. Stated another way, these forecasts give statistical estimates of the expected intensity of ground motion for a given area over a specified time frame. Although long-range forecasts may not be as informative as we might like, these data are important for updating the Uniform Building Code, which contains nationwide standards for designing earthquake-resistant structures.

Long-range forecasts are based on the premise that earthquakes are repetitive or cyclical, like the weather. In other words, as soon as one earthquake is over, the continuing motions of Earth's plates begin to build strain in the rocks again until they fail once more. This has led seismologists to study historical records of earthquakes to see if there are any discernible patterns so that the probability of recurrence might be established.

With this concept in mind, a group of seismologists plotted the distribution of rupture zones associated with great earthquakes that have occurred in the seismically active regions of the Pacific Basin. The maps revealed that individual rupture zones tended to occur adjacent to one another without appreciable overlap, thereby tracing out a plate boundary. Recall that most earthquakes are generated along plate boundaries by the relative motion of large crustal blocks. Because plates are in constant motion, the researchers predicted that over a span of one or two centuries, major earthquakes would occur along each segment of the Pacific plate boundary.

When the researchers studied historical records, they discovered that some zones had not produced a great earthquake in more than a century. These quiet zones, called **seismic gaps,** were identified as probable sites for major earthquakes in the next few decades (Figure 11.26). In the 25 years since the original studies were conducted, some of these gaps have ruptured (see Box 11.3). Included in this group is the zone that produced the earthquake that devastated portions of Mexico City in September 1985.

Another method of long-term forecasting, known as *paleoseismology* (*palaois* = an- cient, *seismos* = shake, *ology* = the study of), has been implemented. One technique involves the study of layered deposits that were offset by prehistoric seismic disturbances. To date, the most complete investigation that employed this method focused on a segment of the San Andreas Fault about 50 kilometers (30 miles) northeast of Los Angeles. Here the drainage of Pallet Creek has been repeatedly disturbed by successive ruptures along the fault zone.

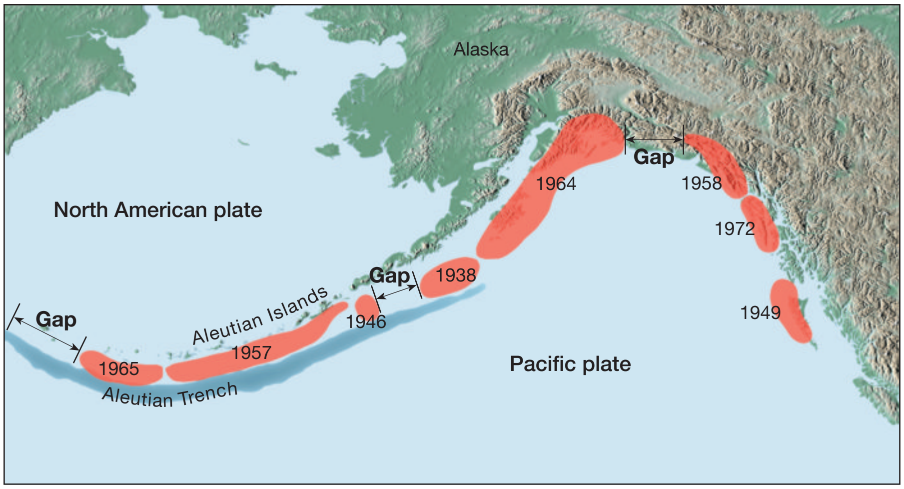



**FIGURE 11.26** The distribution of rupture areas of large, shallow earthquakes from 1930 to 1979 along the southwestern coast of Alaska and the Aleutian Islands. The three seismic gaps denote the most likely locations for the next large earthquakes along this plate boundary. (After J. C. Savage et al., U.S. Geological Survey)

Ditches excavated across the creek bed have exposed sediments that had apparently been displaced by nine large earthquakes over a period of 1400 years. From these data it was determined that a great earthquake occurs here an average of once every 140 to 150 years. The last major event occurred along this segment of the San Andreas Fault in 1857. Thus, roughly 140 years have elapsed. If earthquakes are truly cyclic, a major event in southern California seems imminent. Such information led the U.S. Geological Survey to predict that there is a 50 percent probability that an earthquake of magnitude 8.3 will occur along the southern San Andreas Fault within the next 30 years.

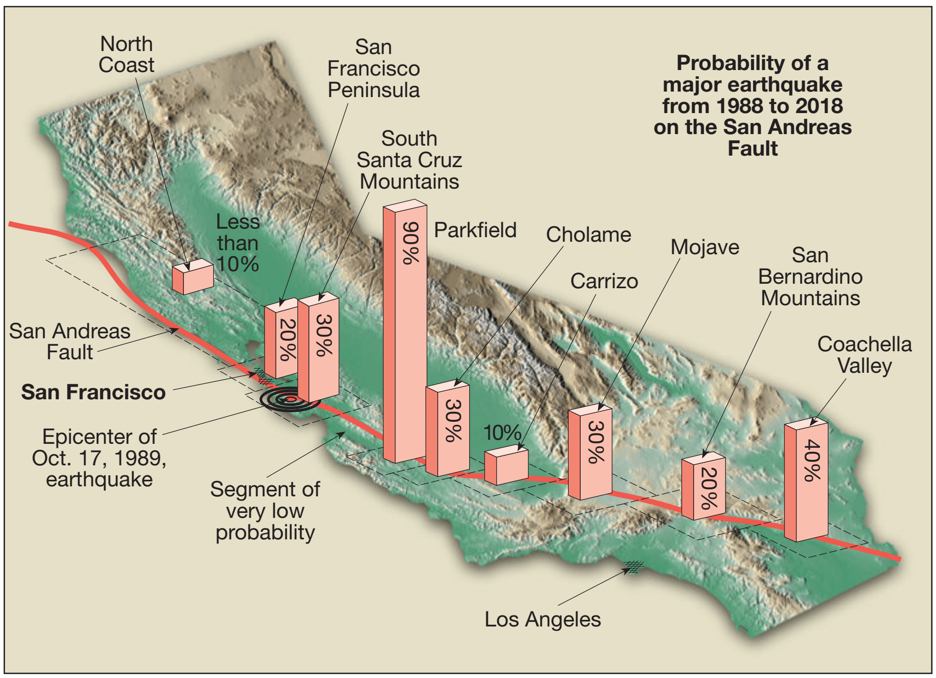
Using other paleoseismology techniques, researchers recently discovered strong evidence that very powerful earthquakes (magnitude of 8 or larger) have repeatedly struck the Pacific Northwest over the past several thousand years. The most recent event occurred about 300 years ago. As a result of these findings, public officials have taken steps to strengthen some of the region's existing dams, bridges, and water systems. Even the private sector responded. The U.S. Bancorp building in Portland, Oregon, was strengthened at a cost of $8 million and now exceeds the standards of the Uniform Building Code.

Another U.S. Geological Survey study gives the probability of a rupture occurring along various segments of the San Andreas Fault for the 30 years between 1988 and 2018 (Figure 11.27). From this investigation, the Santa Cruz Mountains region was given a 30 percent probability of producing a 6.5-magnitude earthquake during this time period. In fact, the region experienced the Loma Prieta quake in 1989, of 6.9 magnitude.

The region along the San Andreas Fault given the highest probability (90 percent) of generating a quake is the Parkfield section. This area has been called the "Old Faithful" of earthquake zones because activity here has been very regular since record-keeping began in 1857. In late September 2004, a magnitude 6.0 earthquake again struck this area. Although the event was more than a decade overdue, it did demonstrate the potential usefulness of long-range forecasts. Another section between Parkfield and the Santa Cruz Mountains is given a very low probability of generating an earthquake. This area has experienced very little seismic activity in historical times; rather, it exhibits a slow, continual movement known as *fault creep.* Such movement is beneficial because it prevents strain from building to high levels in the rocks.

In summary, it appears that the best prospects for making useful earthquake predictions involve forecasting magnitudes and locations on time scales of years or perhaps even decades. These forecasts are important because they provide information used to develop the Uniform Building Code and to assist in land-use planning.

**FIGURE 11.27** Probabilities of a major earthquake between 1988 and 2018 along the San Andreas Fault.



# Earthquakes: Evidence for Plate Tectonics

**Earthquakes**
**▸ Evidence at Plate Boundaries**

No sooner had the basic outline of the plate tectonics theory been formulated than researchers from various branches of the geosciences began to test its validity. One of the first efforts was undertaken by a group of seismologists, who were able to demonstrate a good fit between the newly developed plate tectonics model and the global distribution of earthquakes shown in Figure 11.13. In particular, these scientists were able to account for the close association between deep-focus earthquakes and subduction zones.

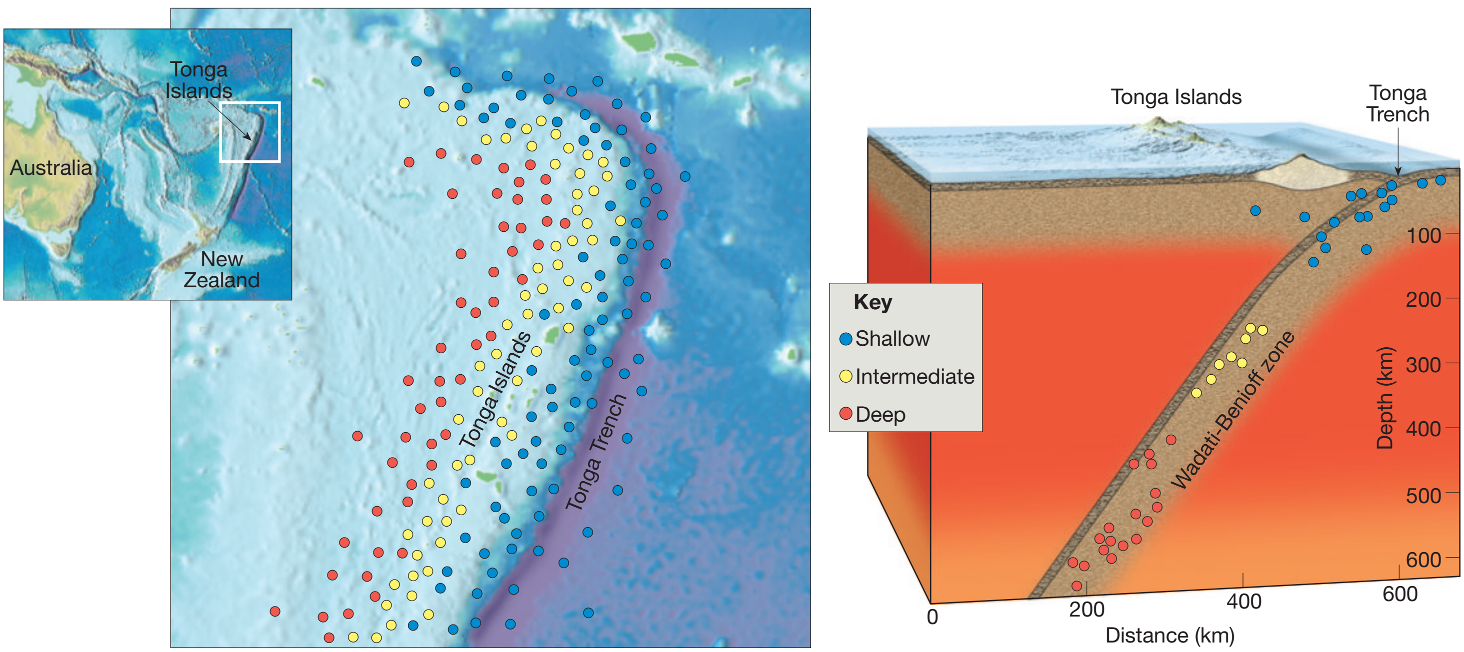
Based on our understanding of the mechanism that generates most earthquakes, one could predict that earthquakes should occur only in Earth's cool, rigid, outermost layer. Recall that as these rocks are deformed, they bend and store elastic energy—like a stretched rubber band. Once the rock is strained sufficiently, it ruptures, releasing the stored energy as the vibrations of an earthquake. By contrast, the hot mobile rocks of the asthenosphere are not capable of storing elastic energy and, therefore, should not generate earthquakes. Yet earthquakes having depths of nearly 700 kilometers (435 miles) are known.

The unique connection between deep-focus earthquakes and oceanic trenches was established through studies conducted in the Tonga Islands. When the depth of earthquake foci and their location within the Tonga arc are plotted, the pattern shown in Figure 11.28 emerges. Most shallow-focus earthquakes occur within or adjacent to the trench, whereas intermediate- and deep-focus earthquakes occur toward the Tonga Islands.

In the plate tectonics model, deep-ocean trenches form where dense slabs of oceanic lithosphere plunge into the mantle (Figure 11.28). Shallow-focus earthquakes are produced in response to the bending and fracturing of the lithosphere as it begins its descent, or as the subducting slab interacts with the overriding plate. As the slab descends farther into the asthenosphere, deeper-focus earthquakes are generated by other mechanisms. Much of the available evidence suggests that the earthquakes occur in the relatively cool subducting slab rather than in the ductile rocks of the mantle. Very few earthquakes have been recorded below 700 kilometers, possibly because the subducting slab has been heated sufficiently to lose its rigidity.

Additional evidence supporting the plate tectonics model came from observations that *only* shallow-focus earthquakes occur along divergent and transform fault boundaries. Recall that along the San Andreas Fault most earthquakes occur in the upper 20 kilometers (12 miles) of the crust. Because oceanic trenches are the only places where cold slabs of oceanic crust plunge to great depths, these should be the only sites of deep-focus earthquakes. Indeed, the absence of deep-focus earthquakes along oceanic ridges and transform faults supports the theory of plate tectonics.

**FIGURE 11.28** Idealized distribution of earthquake foci in the vicinity of the Tonga Trench. Note that the intermediate- and deep-focus earthquakes occur only within the sinking lithosphere. (Modified after B. Isacks, J. Oliver, and L. R. Sykes)



BOX 11.3 ▶ UNDERSTANDING EARTH

# A Major Earthquake in Turkey

On August 17, 1999, at 3:02 A.M. local time, northwestern Turkey was shaken by a moment magnitude ($M_W$) 7.4 earthquake, catching most people in their sleep. The epicenter was 10 kilometers southeast of Ismit in a region that is the industrial center and most densely populated part of the country (see chapter opening photo). Istanbul and its 13 million people are just 70 kilometers (43 miles) to the west.

According to official government estimates, the earthquake killed more than 17,000 people and injured nearly 44,000 (Figure 11.D). More than 250,000 people were forced out of their damaged homes and were sheltered in 120 makeshift "tent cities." Estimates of property losses by the World Bank approached $7 billion. Liquefaction and ground shaking were the dominant causes of damage, but surface faulting and landslides were also responsible for substantial death and destruction. It was the most devastating earthquake to strike Turkey in 60 years.

**FIGURE 11.D** Earthquake damage near Ismit, Turkey, 1999. (Photo courtesy of CORBIS/SYGMA)

Turkey is a geologically active region that frequently experiences large earthquakes. Most of the country is part of a small block of continental lithosphere known as the Turkish microplate. This small plate is caught between the northward-moving Arabian and African plates and the relatively stable Eurasian plate (Figure 11.E). The August 1999 earthquake occurred along the western end of the 1500-kilometer- (930-mile-) long North Anatolian fault system. This fault has much in common with California's San Andreas Fault. Both are right-lateral strike-slip faults having similar lengths and similar long-term rates of movement.* Also like its North American counterpart, the North Anatolian Fault is a transform plate boundary.

The fact that a large earthquake occurred along this portion of the North Anatolian Fault did not come as a complete surprise. Based on historical records, the region of the epicenter had been identified as a *seismic gap*, a "quiet zone" along the fault where strain had been building for perhaps 300 years. Moreover, during the preceding 60 years an interesting pattern of seismic activity had developed. Beginning in 1939 with a ($M_W$) 7.9 quake that produced about 350 kilometers of ground rupture, seven earthquakes had broken the fault progressively from east to west as shown in Figure 11.F.

Researchers now understand that as each earthquake occurred, it loaded the zone to the west with additional stress. That is, as a quake released stress on the section of the fault it broke, it transferred stress to adjacent segments. The next segment in line to break is west of Ismit, near Istanbul. It could happen relatively soon. In the sequence since 1939, no earthquake waited longer than 22 years, and some came within a year of the one before.

The 1999 earthquake near Ismit, Turkey, demonstrated the awesome power of a large earthquake and the immense human suffering that can occur when an earthquake strikes an urban area. Although no one knows for sure where or when the next major quake will occur in the region, it appears that the 1999 earthquake near Ismit increased the risk for those living near Istanbul.

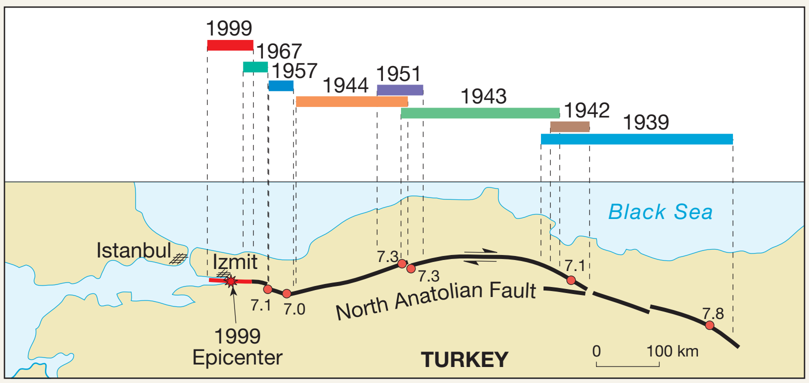
*Recall that if a person is looking across a right-lateral strike-slip fault during an earthquake, that person would see the opposite side move to the right.

## Summary

- *Earthquakes* are vibrations of Earth produced by the rapid release of energy from rocks that rupture because they have been subjected to stresses beyond their limit. This energy, which takes the form of waves, radiates in all directions from the earthquake's source, called the *focus.* The movements that produce most earthquakes occur along large fractures, called *faults,* that are usually associated with plate boundaries.
- Along a fault, rocks store energy as they are bent. As slippage occurs at the weakest point (the focus), displacement will exert stress farther along a fault, where additional slippage will occur until most of the built-up


**FIGURE 11.E** Earthquakes in Turkey are caused by the northward movement of the Arabian and African plates against the Eurasian plate, squeezing the small Turkish microplate westward. Movement is accommodated along two major strike-slip faults—the North Anatolian Fault and the East Anatolian Fault.

**FIGURE 11.F** This map depicts the sequential westward progression of large earthquakes along the North Anatolian Fault between 1939 and 1999. The epicenter and magnitude of each is noted. The length of each colored segment shows the extent of surface rupture along the fault for each event.




strain is released. An earthquake occurs as the rock elastically returns to its original shape. The "springing back" of the rock is termed *elastic rebound.* Small earthquakes, called *foreshocks,* often precede a major earthquake. The adjustments that follow a major earthquake often generate smaller earthquakes called *aftershocks.*

- Two main types of *seismic waves* are generated during an earthquake: (1) *surface waves,* which travel along the outer layer of Earth, and (2) *body waves,* which travel through Earth's interior. Body waves are further divided into *primary,* or *P, waves,* which push (compress) and pull (expand) rocks in the direction the wave is traveling, and *secondary,* or *S, waves,* which "shake" the particles in rock at right angles to their direction of travel. P waves can travel through solids, liquids, and gases. Fluids (gases and liquids) will not transmit S waves. In any solid material, P waves travel about 1.7 times faster than do S waves.

- The location on Earth's surface directly above the focus of an earthquake is the *epicenter.* An epicenter is determined using the difference in velocities of P and S waves. Using the difference in arrival times between P and S waves, the distance separating a recording station from the earthquake can be determined. When the distances are known from three or more seismic stations, the epicenter can be located using a method called *triangulation.*
- *A close correlation exists between earthquake epicenters and plate boundaries.* The principal earthquake epicenter zones are along the outer margin of the Pacific Ocean, known as the *circum-Pacific belt,* and through the world's oceans along the *oceanic ridge system.*
- Seismologists use two fundamentally different measures to describe the size of an earthquake—intensity and magnitude. *Intensity* is a measure of the degree of ground shaking at a given locale based on the amount of damage. The *Modified Mercalli Intensity Scale* uses damages to buildings in California to estimate the intensity of ground shaking for a local earthquake. *Magnitude* is calculated from seismic records and estimates the amount of energy released at the source of an earthquake. Using the *Richter scale,* the magnitude of an earthquake is estimated by measuring the *amplitude* (maximum displacement) of the largest seismic wave recorded. A logarithmic scale is used to express magnitude, in which a tenfold increase in ground shaking corresponds to an increase of 1 on the magnitude scale. *Moment magnitude* is currently used to estimate the size of moderate and large earthquakes. It is calculated using the average displacement of the fault, the area of the fault surface, and the sheer strength of the faulted rock.
- The most obvious factors determining the amount of destruction accompanying an earthquake are the magnitude of the earthquake and the proximity of the quake to a populated area. Structural damage attributable to earthquake vibrations depends on several factors, including (1) wave amplitudes, (2) the duration of the vibrations, (3) the nature of the material upon which the structure rests, and (4) the design of the structure. Secondary effects of earthquakes include *tsunami,* landslides, ground subsidence, and fire.
- Substantial research to predict earthquakes is under way in Japan, the United States, China, and Russia—countries where earthquake risk is high. No reliable method of short-range prediction has yet been devised. Long-range forecasts are based on the premise that earthquakes are repetitive or cyclical. Seismologists study the history of earthquakes for patterns so their occurrences might be predicted. Long-range forecasts are important because they provide information used to develop the Uniform Building Code and to assist in land-use planning.
- The distribution of earthquakes provides strong evidence for the theory of plate tectonics. One aspect involves the close association between deep-focus earthquakes and subduction zones. Additional evidence involves the fact that only shallow-focus earthquakes occur at divergent and transform fault boundaries.

## Review Questions

1. What is an earthquake? Under what circumstances do earthquakes occur?
2. How are faults, foci, and epicenters related?
3. Who was first to explain the actual mechanism by which earthquakes are generated?
4. Explain what is meant by *elastic rebound.*
5. Faults that are experiencing no active creep may be considered "safe." Rebut or defend this statement.
6. Describe the principle of a seismograph.
7. List the major differences between P and S waves.
8. P waves move through solids, liquids, and gases, whereas S waves move only through solids. Explain.
9. Which type of seismic wave causes the greatest destruction to buildings?
10. Using Figure 11.11, determine the distance between an earthquake and a seismic station if the first S wave arrives 3 minutes after the first P wave.
11. Most strong earthquakes occur in a zone on the globe known as the _____.
12. Deep-focus earthquakes occur several hundred kilometers below what prominent features on the deep-ocean floor?
13. Distinguish between the Mercalli scale and the Richter scale.
14. For each increase of 1 on the Richter scale, wave amplitude increases _____ times.
15. An earthquake measuring 7 on the Richter scale releases about _____ times more energy than an earthquake with a magnitude of 6.
16. List three reasons that the moment magnitude scale has gained popularity among seismologists.
17. List four factors that affect the amount of destruction caused by seismic vibrations.
18. What factor contributed most to the extensive damage that occurred in the central portion of Mexico City during the 1985 earthquake? (see Box 11.2.)
19. The 1988 Armenian earthquake had a Richter magnitude of 6.9, less than the 1994 Northridge California

earthquake. Nevertheless, the loss of life was far greater in the Armenian event. Why?

**20.** In addition to the destruction created directly by seismic vibrations, list three other types of destruction associated with earthquakes.

**21.** What is a tsunami? How is one generated?

**22.** Cite some reasons why an earthquake with a moderate magnitude might cause more extensive damage than a quake with a high magnitude.

**23.** Can earthquakes be predicted?

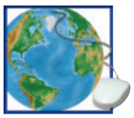
**24.** What is the value of long-range earthquake forecasts?

**25.** Briefly describe how earthquakes can be used as evidence for the theory of plate tectonics.

## Key Terms

aftershock (p. 299)
body wave (p. 302)
earthquake (p. 296)
elastic rebound (p. 298)
epicenter (p. 302)
fault (p. 287)
fault creep (p. 300)
focus (p. 296)
foreshock (p. 297)
hypocenter (p. 296)
inertia (p. 301)
intensity (p. 305)
liquefaction (p. 310)
long (L) waves (p. 302)
magnitude (p. 305)
Modified Mercalli Intensity Scale (p. 307)
moment magnitude (p. 309)
primary (P) waves (p. 302)
Richter scale (p. 307)
secondary (S) waves (p. 302)
seismic gaps (p. 317)
seismic sea wave (p. 312)
seismogram (p. 302)
seismograph (p. 301)
seismology (p. 333)
surface wave (p. 302)
tsunami (p. 312)
Wadati–Benioff zones (p. 305)

## Web Resources



The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

**http://www.prenhall.com/tarbuck**

## GEODe: Earth

*GEODe: Earth* makes studying faster and more effective by reinforcing key concepts using animation, video, narration, interactive exercises and practice quizzes. A copy is included with every copy of *Earth.*