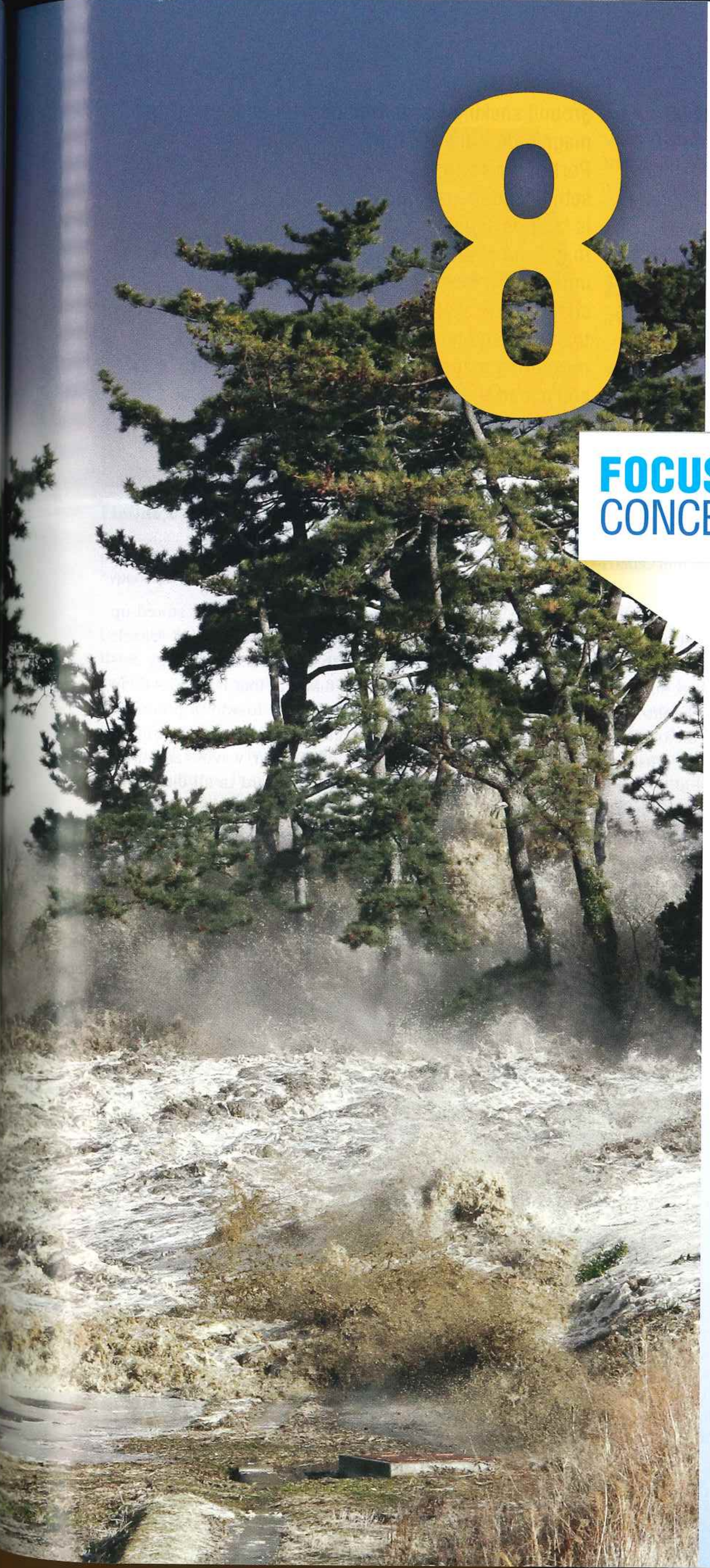
8

Earthquakes and Earth's Interior



FOCUS ON CONCEPTS

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

8.1 Sketch and describe the mechanism that generates most earthquakes.

8.2 Compare and contrast the types of seismic waves and describe the principle of the seismograph.

8.3 Distinguish between intensity scales and magnitude scales.

8.4 List and describe the major destructive forces that can be triggered by earthquake vibrations.

8.5 Locate Earth's major earthquake belts on a world map and label the regions associated with the largest earthquakes.

8.6 Compare and contrast the goals of short-range earthquake predictions and long-range forecasts.

8.7 Explain how Earth acquired its layered structure and briefly describe how seismic waves are used to probe Earth's interior.

8.8 List and describe each of Earth's major layers.

Tsunami striking the coast of Japan on March 11, 2011.
(Photo by Sadatsugu Tomizawa/AFP/Getty Images)

On January 12, 2010, an estimated 316,000 people lost their lives when a magnitude 7.0 earthquake struck the small Caribbean nation of Haiti, the poorest country in the Western Hemisphere. In addition to the staggering death toll, there were more than 300,000 injuries, and more than 280,000 houses were destroyed or damaged.

The quake originated only 25 kilometers (15 miles) from the country's densely populated capital city of Port-au-Prince. It occurred along a San Andreas–like fault at a depth of just 10 kilometers (6 miles). Because of the quake's shallow depth, ground shaking was exceptional for an event of this magnitude. Other factors that contributed to the Port-au-Prince disaster included the city's geologic setting and the nature of its buildings. The city is built on sediment, which is quite susceptible to ground shaking during an earthquake. More importantly, inadequate or nonexistent building codes meant that buildings collapsed far more readily than they should have. At least 52 aftershocks, measuring magnitude 4.5 or greater, jolted the area and added to the trauma survivors experienced for days after the original quake.

8.1 WHAT IS AN EARTHQUAKE?

Sketch and describe the mechanism that generates most earthquakes.

An **earthquake** is ground shaking caused by the sudden and rapid movement of one block of rock slipping past another along fractures in Earth's crust called **faults**. Most faults are locked, except for brief, abrupt movements when sudden slippage produces an earthquake (**FIGURE 8.1**). Faults are locked because the confining pressure exerted by the overlying crust is enormous, causing these fractures in the crust to be "squeezed shut."

Earthquakes tend to occur along preexisting faults where internal stresses have caused the crustal rocks to rupture or break into two or more units. The location where slippage begins is called the **hypocenter**, or **focus**. Earthquake waves radiate from this spot outward into the surrounding rock. The point on Earth's surface directly above the hypocenter is called the **epicenter** (**FIGURE 8.2**).

Large earthquakes release huge amounts of stored-up energy as **seismic waves**—a form of energy that travels through the lithosphere and Earth's interior. The energy carried by these waves causes the material that transmits them to shake. Seismic waves are analogous to waves produced when a stone is dropped into a calm pond. Just as the impact of the stone creates a pattern of circular waves, an earthquake generates waves that radiate outward in all directions from the hypocenter. Although seismic energy dissipates rapidly as it moves away from the quake's hypocenter, sensitive instruments can detect earthquakes even when they occur on the opposite side of Earth.

Thousands of earthquakes occur around the world every day. Fortunately, most are small and cannot be detected by people. Of these, only about 15 strong earthquakes

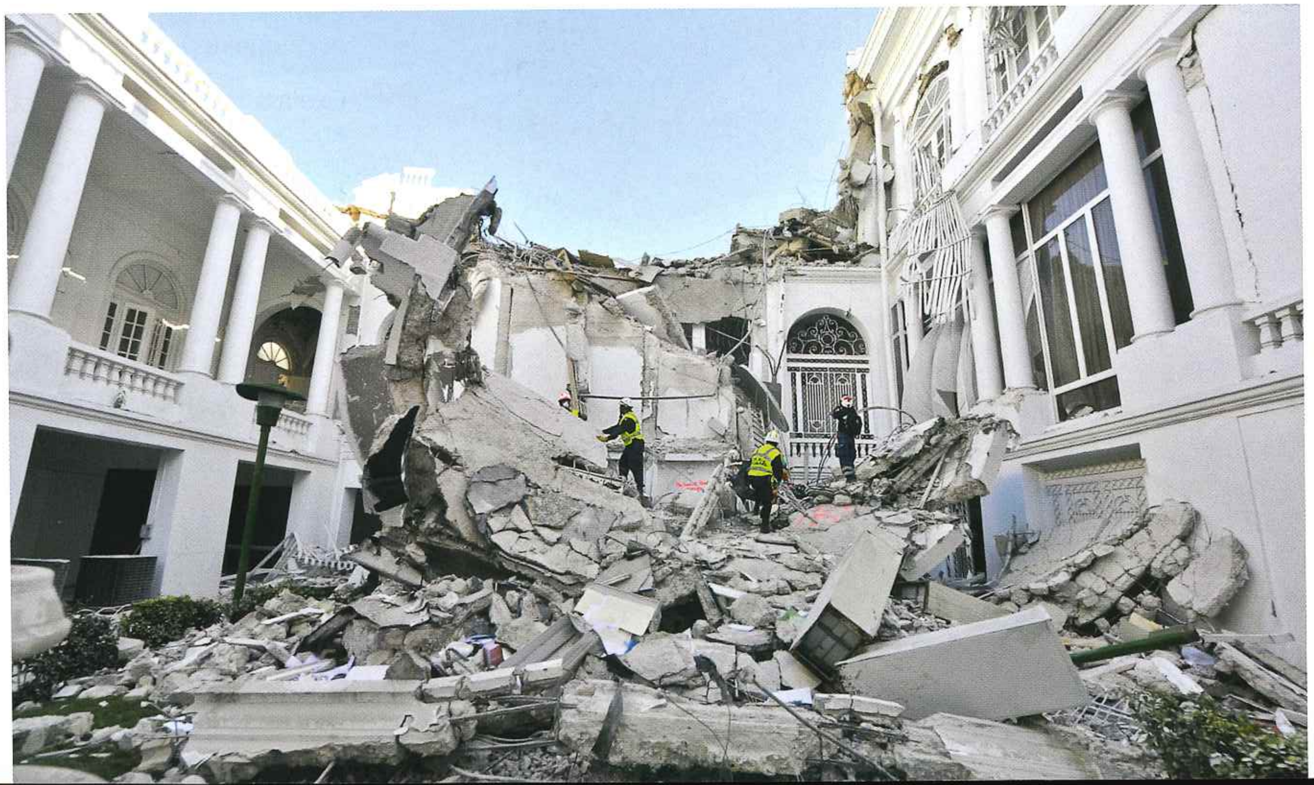


FIGURE 8.1 Presidential Palace Damaged During the 2010 Haiti Earthquake
(Photo by Luis Acosta/Getty Images)

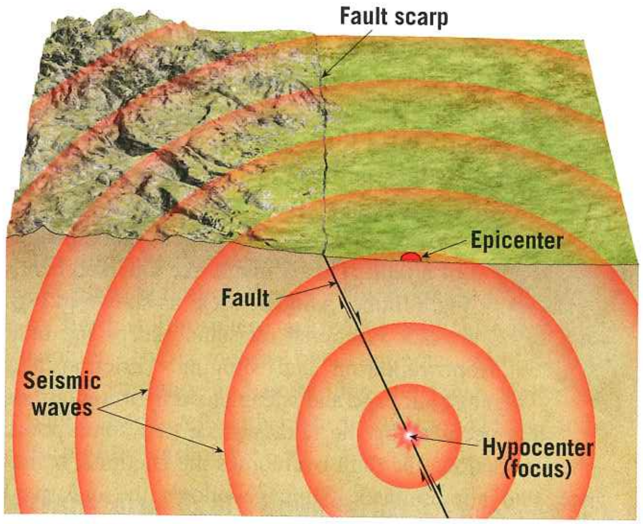


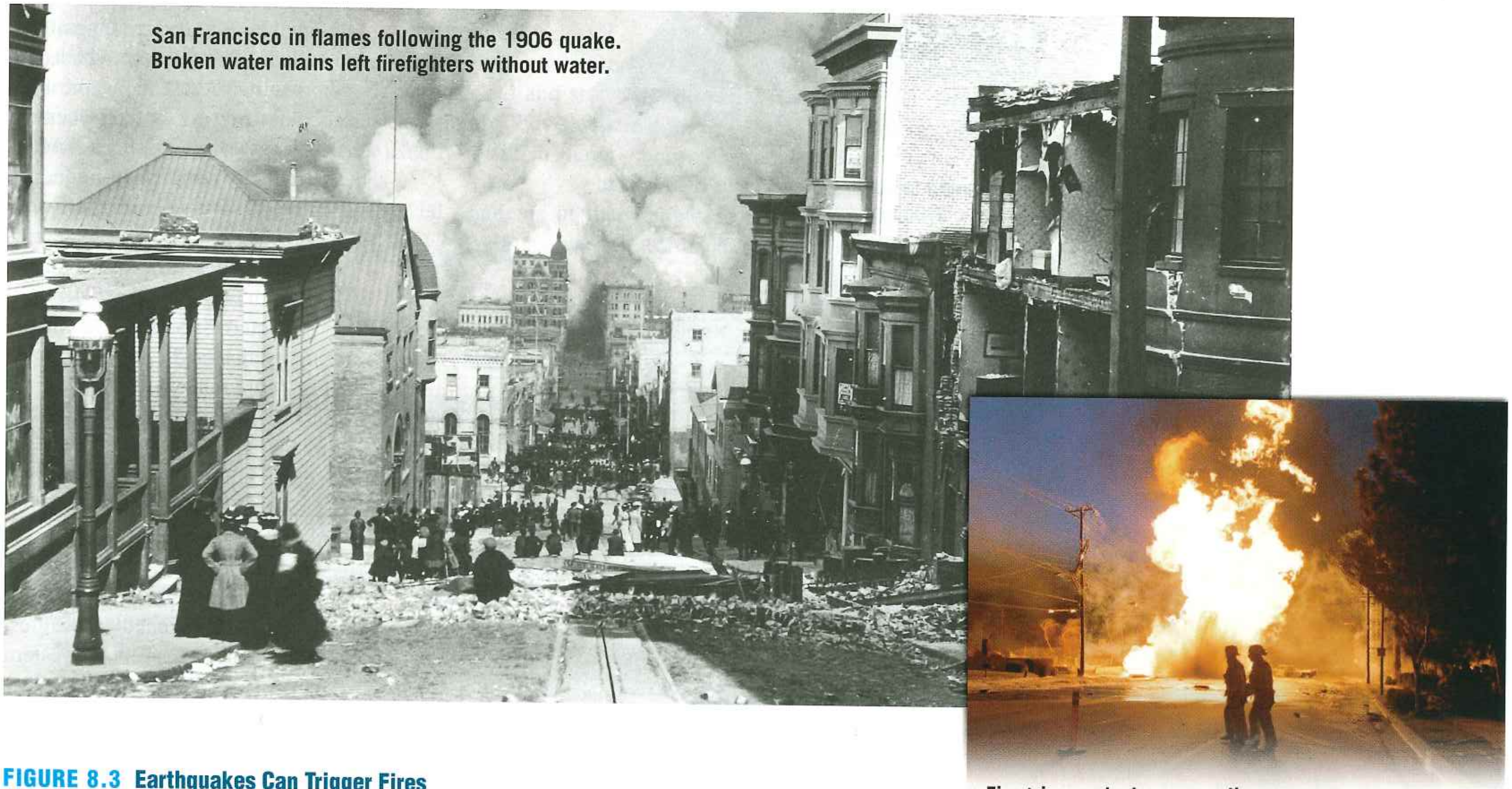
FIGURE 8.2 Earthquake Hypocenter and Epicenter The *hypocenter* is the zone at depth where the initial displacement occurs. The *epicenter* is the surface location directly above the hypocenter.

(magnitude 7 or greater) are recorded each year, many of them occurring in remote regions. Occasionally, a large earthquake is triggered near a major population center. Such events are among the most destructive natural forces on Earth. The shaking of the ground, coupled with the liquefaction of soils, wreaks havoc on buildings, roadways, 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 that became uncontrollable when broken water mains left firefighters with only trickles of water (**FIGURE 8.3**).

Discovering the Causes of Earthquakes

The energy released by volcanic eruptions, massive landslides, and meteorite impacts can generate earthquakelike waves, but these events are usually weak. What mechanism produces a destructive earthquake? As you have learned, Earth is not a static planet. We know that large sections of Earth's crust have been thrust upward because fossils of marine organisms have been discovered thousands of meters above sea level. Other regions, such as California's Death Valley, exhibit evidence of extensive subsidence. In addition to these vertical displacements, offsets in fences, roads, and other structures indicate that horizontal movements between blocks of Earth's crust are also common (**FIGURE 8.4**).

The actual mechanism of earthquake generation eluded geologists until H. F. Reid of Johns Hopkins University conducted a landmark study following the 1906 San Francisco earthquake. This earthquake was accompanied by horizontal surface displacements of several meters along the northern portion of the San Andreas Fault. Field studies determined that during this single earthquake, the Pacific plate lurched as much as 9.7 meters (32 feet) northward, past the adjacent



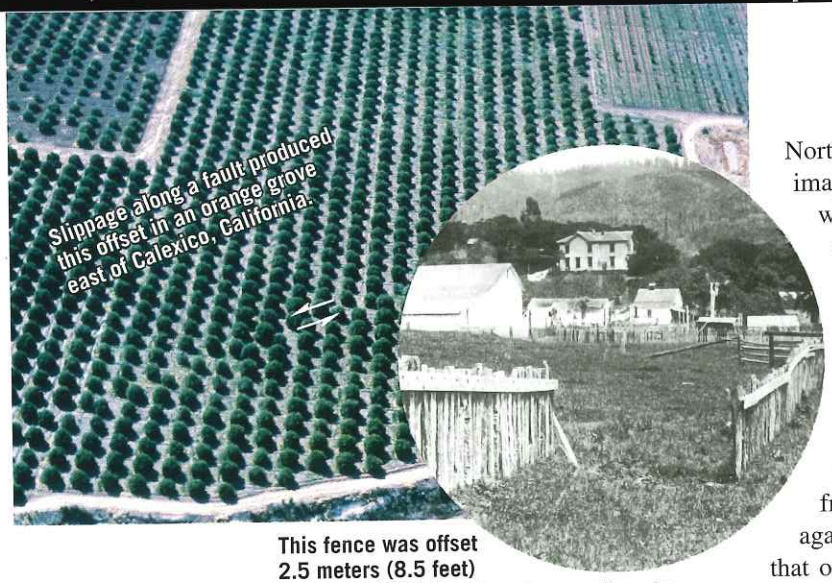
San Francisco in flames following the 1906 quake. Broken water mains left firefighters without water.

Fire triggered when a gas line ruptured during the Northridge earthquake in southern California in 1994.

FIGURE 8.3 Earthquakes Can Trigger Fires

(Reproduced from the collection of the Library of Congress; inset photo by Hal Garb/AFP/Getty Images)

FIGURE 8.4 Displacement of Structures along a Fault (Color photo by John S. Shelton/University of Washington Libraries; inset photo by G. K. Gilbert/USGS)



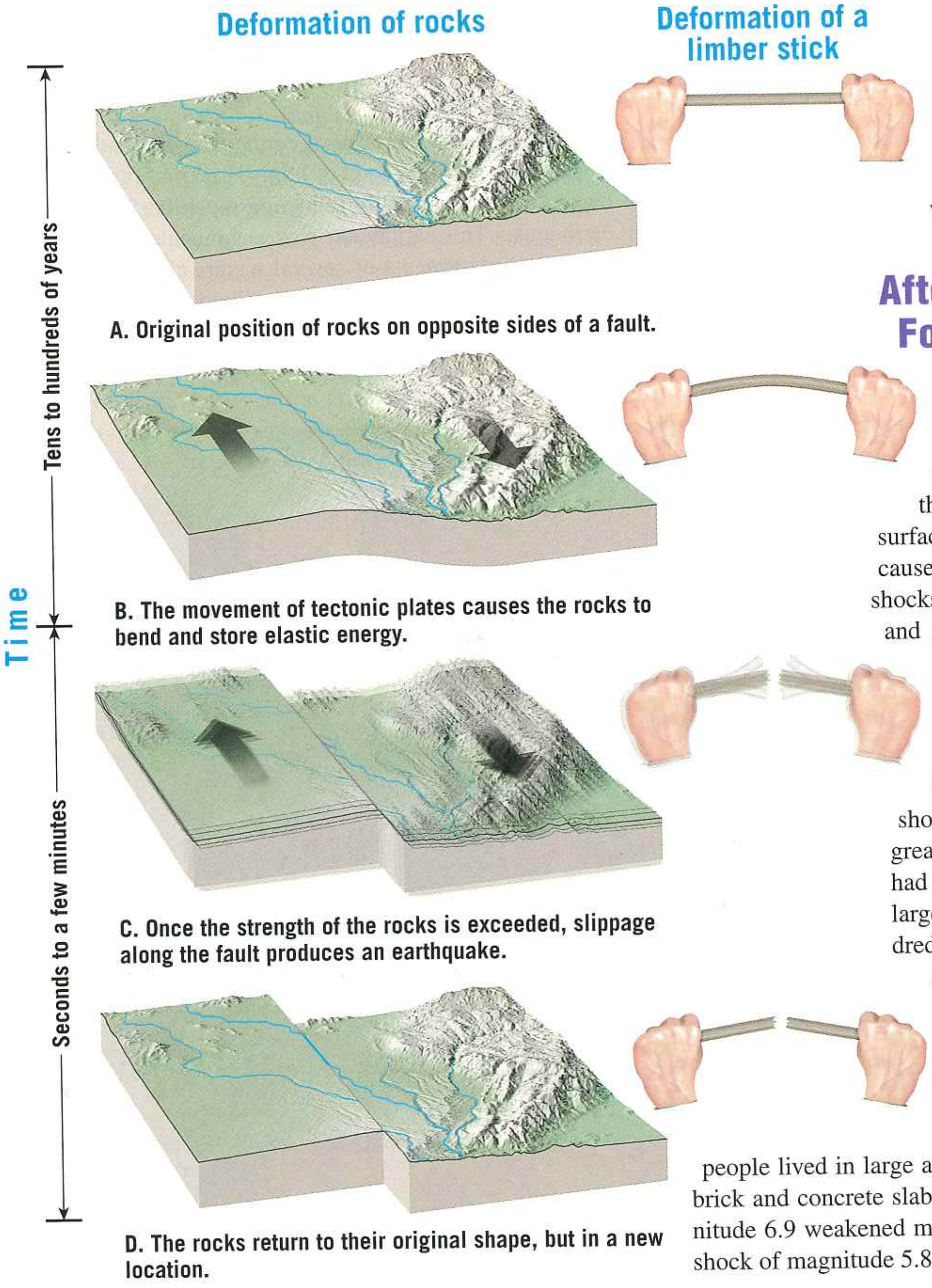
Slippage along a fault produced this offset in an orange grove east of Calexico, California.

This fence was offset 2.5 meters (8.5 feet) during the1906 San Francisco earthquake.

North American plate. To better visualize this, imagine standing on one side of the fault and watching a person on the other side suddenly slide horizontally 32 feet to your right.

What Reid concluded from his investigations is illustrated in **FIGURE 8.5**. Over tens to hundreds of years, differential stress slowly bends the crustal rocks on both sides of a fault. This is much like a person bending a limber wooden stick, as shown in Figure 8.5. Frictional resistance keeps the fault from rupturing and slipping. (Friction acts against slippage and is enhanced by irregularities that occur along the fault surface.) At some point, the stress along the fault overcomes the frictional resistance, and slip initiates. Slippage allows the deformed (bent) rock to "snap back" to its original, stress-free, shape; a series of earthquake waves radiate as it slides (see Figure 8.5C,D). Reid termed the "springing back" **elastic rebound** because the rock behaves elastically, much like a stretched rubber band does when it is released.

SmartFigure 8.5 Elastic Rebound



Deformation of rocks

Deformation of a limber stick

A. Original position of rocks on opposite sides of a fault.

B. The movement of tectonic plates causes the rocks to bend and store elastic energy.

C. Once the strength of the rocks is exceeded, slippage along the fault produces an earthquake.

D. The rocks return to their original shape, but in a new location.

Aftershocks and Foreshocks

Strong earthquakes are followed by numerous earthquakes of lesser magnitude, called **aftershocks**, which are the result of crust along the fault surface adjusting to the displacement caused by the main shock. Aftershocks gradually diminish in frequency and intensity over a period of several months following an earthquake. In a little more than a month following the 2010 Haiti earthquake, the U.S. Geological Survey detected nearly 60 aftershocks with magnitudes of 4.5 or greater. The two largest aftershocks had magnitudes of 6.0 and 5.9, both large enough to inflict damage. Hundreds of minor tremors were also felt.

Although aftershocks are weaker than the main earthquake, they often trigger the destruction of already weakened structures. For example, in northwestern Armenia in 1988, where many people lived in large apartment buildings constructed of brick and concrete slabs, a moderate earthquake of magnitude 6.9 weakened many structures, and a strong aftershock of magnitude 5.8 completed the demolition.

In contrast to aftershocks, small earthquakes called **foreshocks** often, but not always, precede major earthquakes by days or, in some cases, several years. Monitoring of foreshocks to predict forthcoming earthquakes has been attempted with only limited success.

FIGURE 8.6 Transform Fault Boundaries and Large Earthquakes

Faults and Large Earthquakes

The slippage that occurs along faults can be explained by the plate tectonics theory, which states that large slabs of Earth's lithosphere are continually grinding past one another. These mobile plates interact with neighboring plates, straining and deforming the rocks at their edges. Faults associated with plate boundaries are the source of most large earthquakes.

Transform Fault Boundaries Faults in which the dominant displacement is horizontal and parallel to the *strike* (direction) of the fault surface are called **strike-slip faults**. Large strike-slip faults that slice through Earth's lithosphere and accommodate motion between two tectonic plates are called **transform faults**. For example, the San Andreas Fault is a large strike-slip fault that separates the North American plate and the Pacific plate. Most transform faults, including the San Andreas Fault, are not perfectly straight or continuous; instead, they consist of numerous branches and smaller fractures that display kinks and offsets (**FIGURE 8.6**). In addition, geologists have learned that displacement along transform faults occurs in discrete segments that often behave differently from one another. Some sections of the San Andreas Fault exhibit slow, gradual displacement, known as **fault creep**, and produce little seismic shaking. Other segments slip at relatively closely spaced intervals, producing numerous small to moderate earthquakes. Still other segments remain locked and store elastic energy for a few hundred years before they break loose; ruptures on these segments usually result in major earthquakes.

Earthquakes that occur along locked segments of the San Andreas Fault tend to be repetitive: As soon as one is over, strain immediately begins accumulating due to the continuous motion of the plates. Decades or centuries later, the fault fails again.

Faults Associated with Convergent Plate Boundaries Strong earthquakes also occur along large faults associated with convergent plate boundaries. Compressional forces associated with continental collisions that result in mountain building generate many *thrust faults*. Displacement along a thrust fault results in rock above the fault being forced (or *thrust*) over rock below the fault surface, causing an earthquake (**FIGURE 8.7**).

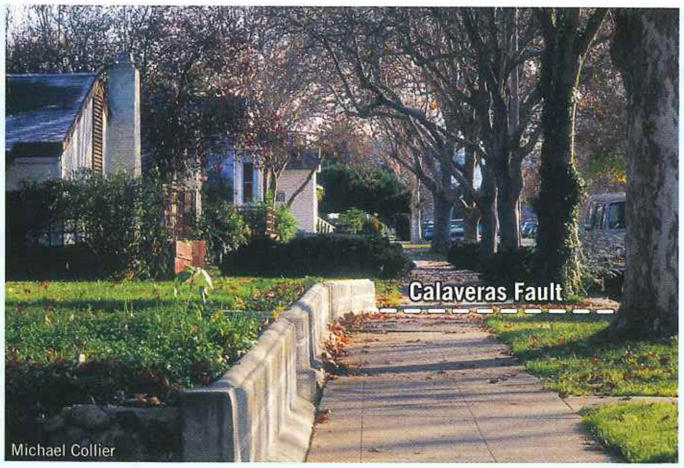
In addition, the plate boundary between a subducting slab of oceanic lithosphere and the overlying plate form a fault referred to as a **megathrust fault** (see Figure 8.7). Because these large thrust faults lie partially beneath the ocean floor, movement along these faults may displace the overlying seawater, generating destructive tsunami. Megathrust faults have produced the majority of Earth's most powerful and destructive earthquakes, including the 2011 Japan quake (M 9.0), the 2004

EYE ON EARTH

The Calaveras Fault, a branch of the San Andreas Fault system, cuts directly through the town of Hollister, California. Rather than being "locked," this section of the fault is slowly slipping, producing noticeable offsets and damage to curbs, sidewalks, roads, and buildings. The concrete wall and sidewalk shown here were straight when they were originally constructed.

QUESTION 1 *What term is used to describe the phenomenon observed in Hollister along the Calaveras Fault?*

QUESTION 2 *Are faults that exhibit this type of slippage considered likely to generate a major earthquake? Explain.*



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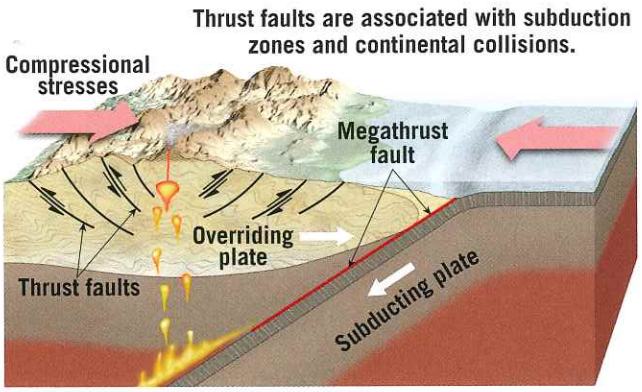


FIGURE 8.7 Megathrust Faults are the Sites of Earth's Largest Earthquakes

Indian Ocean (Sumatra) quake (M 9.1), the 1964 Alaska quake (M 9.2), and the largest earthquake yet recorded, the 1960 Chile quake (M 9.5).

Fault Propagation Slippage along large faults does not occur instantaneously. The initial slip begins at the hypocenter and propagates (travels) along the fault surface, at 2 to 4 kilometers per second—faster than a rifle shot. Slippage on one section of the fault adds strain to the adjacent segment, which may also slip. As this zone of slippage advances, it can slow down, speed up, or even jump to a nearby fault segment. The propagation of the rupture zone along a 300-kilometer- (200-mile-) long fault, for example, takes about 1.5 minutes, as compared to about 30 seconds for a 100-kilometer- (60-mile-) long fault. Earthquake waves are generated at every point along the fault as that portion of the fault begins to slip.

8.1 CONCEPT CHECKS

1 What is an earthquake? Under what circumstances do most large earthquakes occur?
2 How are faults, hypocenters, and epicenters related?
3 Who was the first person to explain the mechanism by which most earthquakes are generated?
4 Explain what is meant by *elastic rebound.*
5 What is the approximate duration of an earthquake that occurs along a 300-kilometer-long fault?
6 Defend or rebut this statement: Faults that do not experience fault creep may be considered safe.
7 What type of faults tend to produce the most destructive earthquakes?

8.2 SEISMOLOGY: THE STUDY OF EARTHQUAKE WAVES

Compare and contrast the types of seismic waves and describe the principle of the seismograph.

FIGURE 8.8 Ancient Chinese Seismograph During an Earth tremor, the dragons located in the direction of the main vibrations would drop a ball into the mouth of a frog below. (Photo by James E. Patterson Collection)

The study of earthquake waves, **seismology**, dates back to attempts made in China almost 2000 years ago to determine the direction from which these waves originated. The earliest known instrument, invented by Zhang Heng, was a large hollow jar that contained a weight suspended from the top (**FIGURE 8.8**). The suspended weight (similar to a clock pendulum) was connected 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.

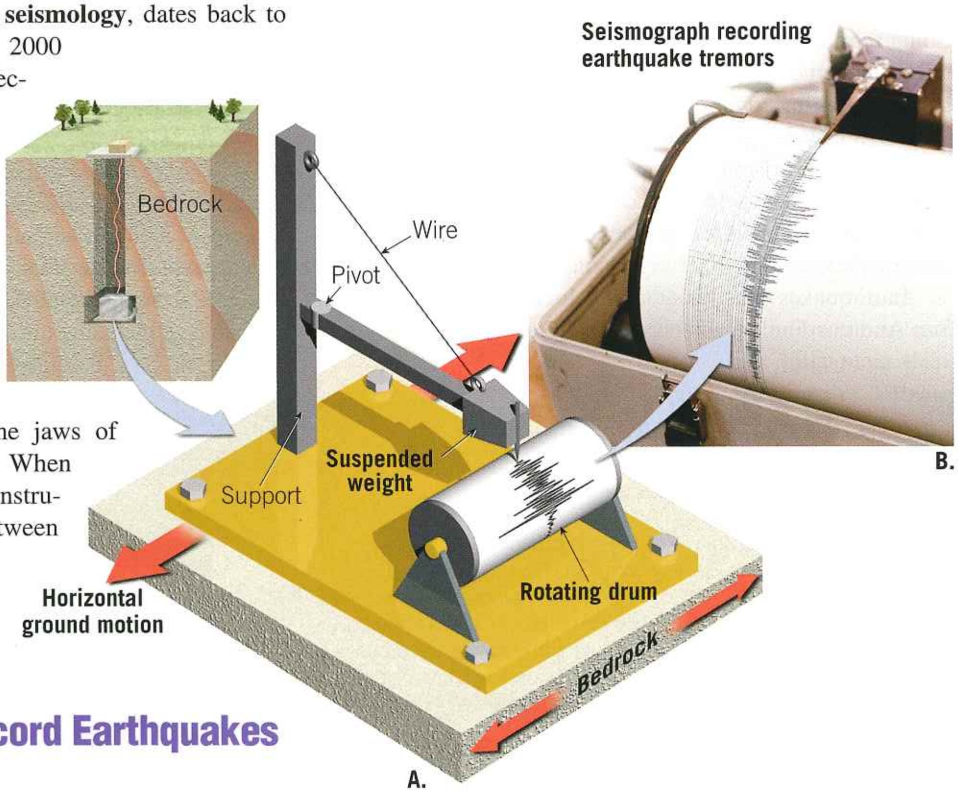
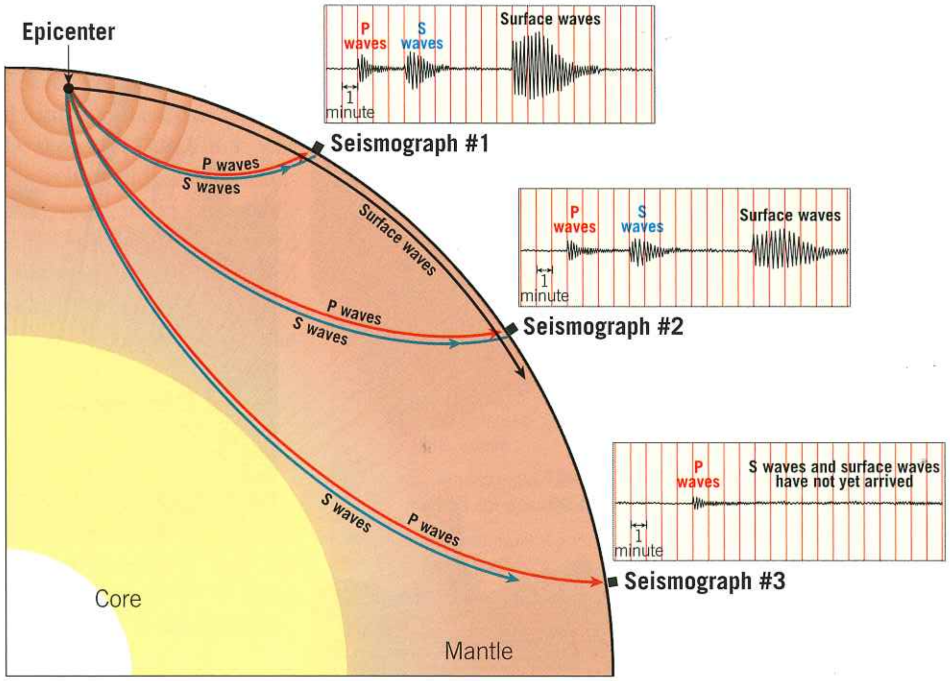


FIGURE 8.9 Principle of the Seismograph The inertia of the suspended weight tends to keep it motionless, while the recording drum, which is anchored to bedrock, vibrates in response to seismic waves. The stationary weight provides a reference point from which to measure the amount of displacement occurring as a seismic wave passes through the ground. (Photo courtesy of Zephyr/Science Source)

Instruments That Record Earthquakes

In principle, modern **seismographs**, or **seismometers**, are similar to the instruments used in ancient China. A seismograph has a weight freely suspended from a support that is securely attached to bedrock (**FIGURE 8.9**). When vibrations from an earthquake reach the instrument, the **inertia** of the weight keeps it relatively stationary, while Earth and the support move. Inertia can be simply described by this statement: Objects at rest tend to stay at rest, and objects in motion tend to remain in motion, unless acted upon by an outside force. You probably have experienced inertia when you have tried to stop your automobile quickly and your body has continued to move forward.

To detect very weak earthquakes or a great earthquake that has occurred in another part of the world, most seismographs are designed to amplify ground motion. In earthquake-prone areas, the instruments used are designed to withstand the violent shaking that can occur near the quake's epicenter.



SmartFigure 8.10 Body Waves (P and S waves) versus Surface Waves P and S waves travel through Earth's interior, while surface waves travel in the layer directly below the surface. P waves are the first to arrive at a seismic station, followed by S waves, and then surface waves.

Seismic Waves

The records obtained from seismographs, called **seismograms**, provide useful information about the nature of seismic waves. Seismograms reveal that two main types of seismic waves are generated by the slippage of a rock mass. One of these wave types, called **surface waves**, travels in the rock layers just below Earth's surface (**FIGURE 8.10**). The other wave types travel through Earth's interior and are called **body waves**.

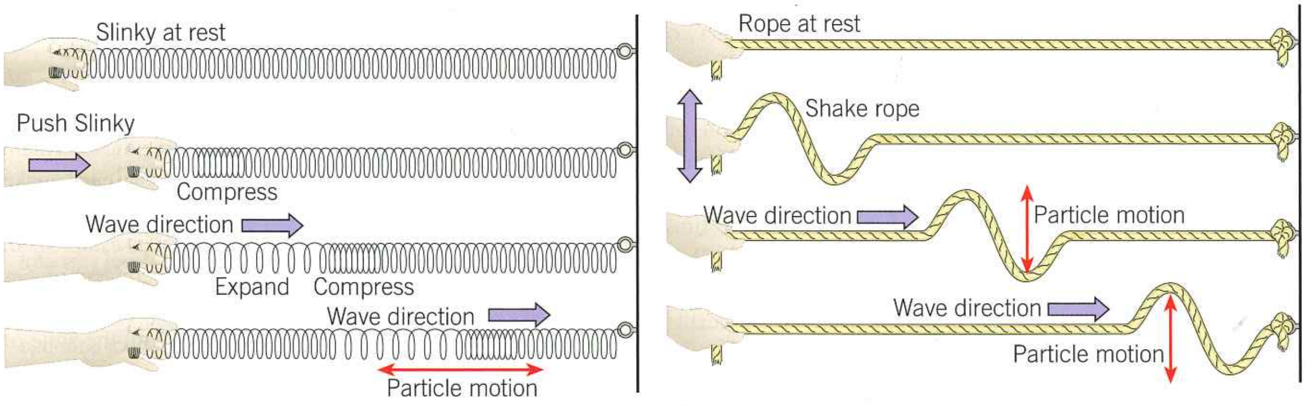
Body Waves

Body waves are further divided into two types—called **primary waves**, or **P waves,** and **secondary waves**, or **S waves**—and are identified by their mode of travel through intervening materials. P waves are "push/pull" waves; they momentarily push (compress) and pull (stretch) rocks in the direction the wave is traveling (**FIGURE 8.11A**). This wave motion is similar to that generated by human vocal cords as they move air back and forth to create sound. Solids, liquids, and gases resist stresses that change their volume when compressed and, therefore, elastically spring back once the stress is removed. Therefore, P waves can travel through all these materials.

By contrast, 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 8.11B**. Unlike P waves, which temporarily change the *volume* of intervening material by alternately squeezing and stretching it, S waves change the *shape* of the material that transmits them. Because fluids (gases and liquids) do not resist stresses that cause changes in shape—meaning fluids do not return to their original shape once the stress is removed—liquids and gases will not transmit S waves.

Surface Waves

There are two types of surface waves. One type causes Earth's surface and anything resting on it

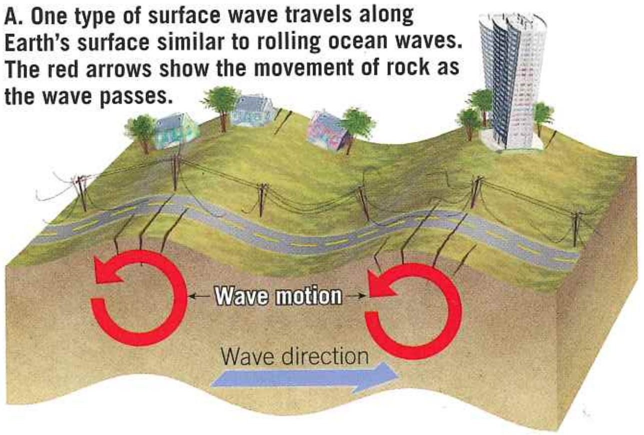

A. As illustrated by a toy Slinky, P waves alternately compress and expand the material through which they pass.

B. S waves cause material to oscillate at right angles to the direction of wave motion.

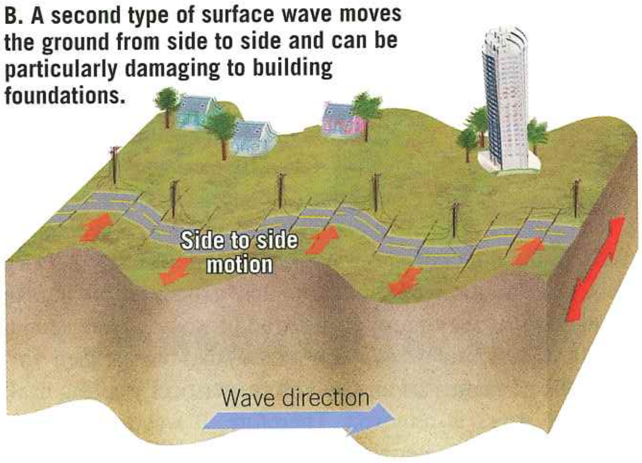
FIGURE 8.11 The Characteristic Motion of P Waves and S Waves During a strong earthquake, ground shaking consists of a combination of various kinds of seismic waves.

FIGURE 8.12 Two Types of Surface Waves

A. One type of surface wave travels along Earth's surface similar to rolling ocean waves. The red arrows show the movement of rock as the wave passes.



B. A second type of surface wave moves the ground from side to side and can be particularly damaging to building foundations.



to move, much as ocean swells toss a ship (**FIGURE 8.12A**). The second type of surface wave causes Earth's materials to move side to side. This motion is particularly damaging to the foundations of structures (**FIGURE 8.12B**).

Body Waves Versus Surface Waves By examining the seismogram shown in **FIGURE 8.13**, you can see that the major difference among seismic waves is their speed of travel. P waves are the first to arrive at a recording station, then S waves, and finally surface waves. Generally, in any solid Earth material, P waves travel about 1.7 times faster than S waves, and S waves are roughly 10 percent faster than surface waves.

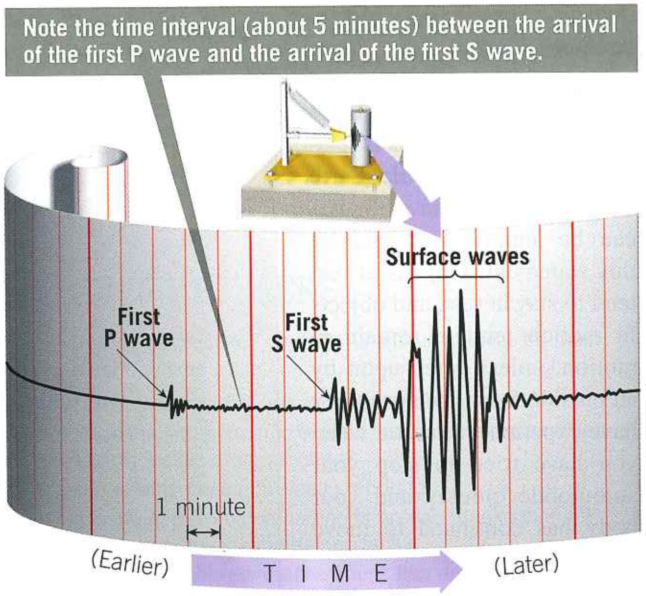

Note the time interval (about 5 minutes) between the arrival of the first P wave and the arrival of the first S wave.

FIGURE 8.13 Typical Seismogram

In addition to velocity differences, notice in Figure 8.13 that the height, or *amplitude*, of these wave types also varies. S waves have slightly greater amplitudes than P waves, and surface waves exhibit even greater amplitudes. Surface waves also retain their maximum amplitude longer than P and S waves. As a result, surface waves tend to cause greater ground shaking and, hence, greater property damage, than either P or S waves.

8.2 CONCEPT CHECKS

1. Describe the principle of the seismograph.
2. List the major differences between P, S, and surface waves.
3. Which type of seismic waves tend to cause the greatest destruction to buildings?

8.3 DETERMINING THE SIZE OF EARTHQUAKES

Distinguish between intensity scales and magnitude scales.

Seismologists use a variety of methods to determine 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 amount of ground shaking at a particular location, based on observed property damage. Later, with the development of seismographs, it became possible to measure ground motion using instruments. This quantitative measurement, called **magnitude**, relies on data gleaned from seismic records to estimate the amount of energy released at an earthquake's source.

Intensity Scales

Until the mid-1800s, historical records provided the only accounts of the severity of earthquake shaking and destruction. Perhaps the first attempt to scientifically describe the aftermath of an earthquake came following the great Italian earthquake of 1857. By systematically mapping effects of the earthquake, a measure of the intensity of ground shaking was established. The map generated by this study used lines to connect places of equal damage and hence equal ground shaking. 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 earthquake epicenter.

In 1902, Giuseppe Mercalli developed a more reliable intensity scale, which in a modified form is still used today. The **Modified Mercalli Intensity scale**, shown in **TABLE 8.1**, was developed using California buildings as its standard. For example, on the 12-point Mercalli Intensity scale, when some well-built wood structures and most masonry buildings are destroyed by an earthquake, the affected area is assigned a Roman numeral X (10). **FIGURE 8.14** shows the zone of destruction for the 1989 Loma Prieta earthquake, where the intensity of ground shaking was based on the Modified Mercalli Intensity scale.

Magnitude Scales

To more accurately compare earthquakes around the globe, scientists searched for a way to describe the energy released by earthquakes that did not rely on factors, such as building practices, that vary considerably from one part of the world to another. As a result, several magnitude scales were developed.

Richter Magnitude In 1935 Charles Richter of the California Institute of Technology developed the first magnitude scale to use seismic records. As shown in **FIGURE 8.15** (top), the **Richter scale** is calculated by measuring the amplitude of the largest seismic wave (usually an S, or surface, wave)

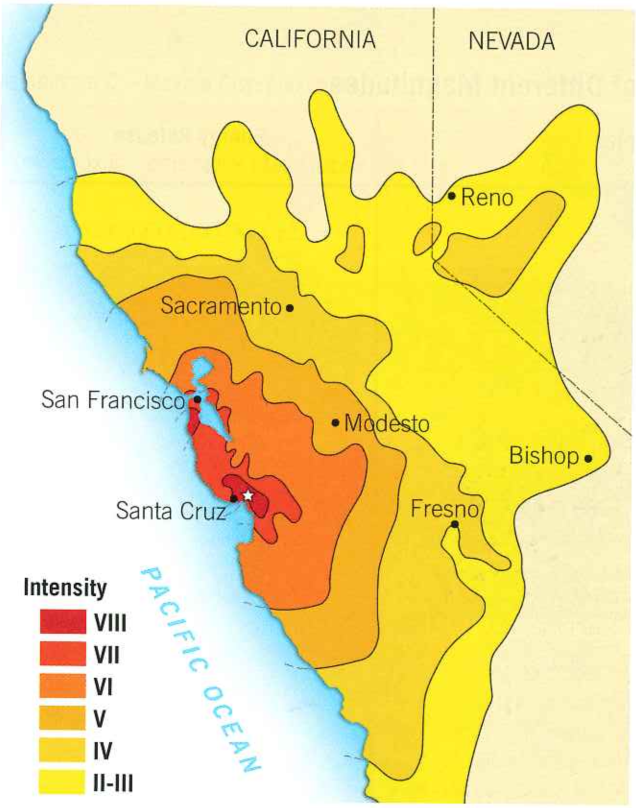
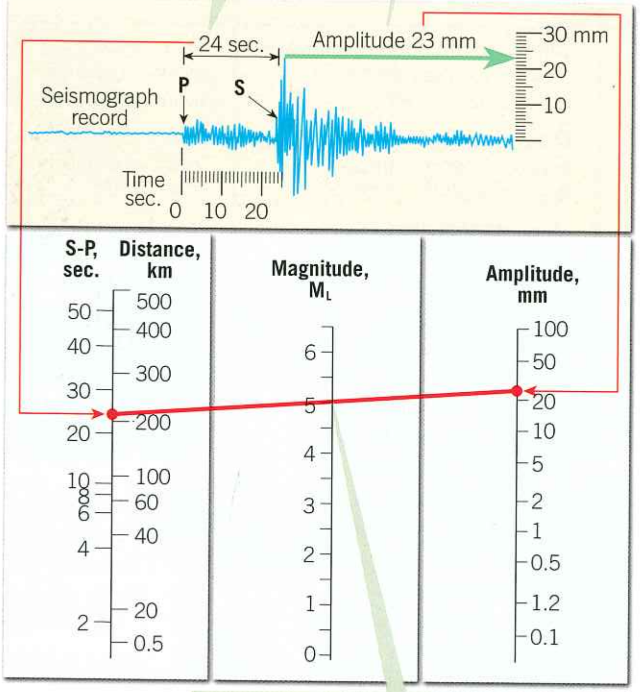


FIGURE 8.14 Seismic Intensity Map, Loma Prieta, 1989
Intensity levels are based on the Modified Mercalli Intensity scale, which uses Roman numerals to represent the intensity categories. The zone of maximum intensity during this event roughly corresponded to the epicenter, but this is not always the case.

TABLE 8.1 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.



1. Measure the height (amplitude) of the largest wave on the seismogram (23 mm) and plot it on the amplitude scale (right).

2. Determine the distance to the earthquake using the time interval separating the arrival of the first P wave and the arrival of the first S wave (24 seconds) and plot it on the distance scale (left).

3. Draw a line connecting the two plots and read the Richter magnitude (M_L 5) from the magnitude scale (center).

FIGURE 8.15 Determining the Richter Magnitude of an Earthquake

FIGURE 8.16 Magnitude versus Ground Motion and Energy Released An earthquake that is one magnitude stronger than another (M 6 versus M 5) produces seismic waves that have a maximum amplitude 10 times greater, and they release about 32 times more energy than the waves of the weaker quake.

Magnitude vs. Ground Motion and Energy

Magnitude Change	Ground Motion Change (amplitude)	Energy Change (approximate)
4.0	10,000 times	1,000,000 times
3.0	1000 times	32,000 times
2.0	100 times	1000 times
1.0	10.0 times	32 times
0.5	3.2 times	5.5 times
0.1	1.3 times	1.4 times

recorded on a seismogram. Because seismic waves weaken as the distance between the hypocenter and the seismograph increases, Richter developed a method that accounts for the decrease in wave amplitude with increasing distance. Theoretically, as long as equivalent instruments are used, monitoring stations at different locations will obtain the same Richter magnitude for each recorded earthquake. In practice, however, different recording stations often obtain slightly different magnitudes for the same earthquake—a consequence of the variations in rock types through which the waves travel.

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, in which a *10-fold* increase in wave amplitude corresponds to an increase of 1 on the magnitude scale. Thus, the intensity of ground shaking for a magnitude 5 earthquake is 10 times greater than that produced by an earthquake having a Richter magnitude of 4 (**FIGURE 8.16**).

In addition, each unit of increase in Richter magnitude equates to roughly a *32-fold increase in the energy released.* 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 (32 × 32) more energy than a magnitude 4.5 quake. A major earthquake with a magnitude of 8.5 releases millions of times more energy than the smallest earthquakes felt by humans (**FIGURE 8.17**).

The convenience of describing the size of an earthquake by a single number that can be calculated quickly from seismograms makes the Richter scale a powerful tool. Seismologists have since modified Richter's work and developed other Richter-like magnitude scales.

Despite its usefulness, the Richter scale is not adequate for describing very large earthquakes. For example, the 1906 San Francisco earthquake and the 1964 Alaska earthquake have roughly the same Richter magnitudes. However, based on the relative size of the affected areas and the associated tectonic changes, the Alaska earthquake released considerably more energy than the San Francisco quake. Thus, the Richter scale is considered *saturated* for major earthquakes because it cannot distinguish among them. Despite this shortcoming, Richter-like scales are still used because they can be calculated quickly.

FIGURE 8.17 Annual Occurrence of Earthquakes with Various Magnitudes

Frequency and Energy Released by Earthquakes of Different Magnitudes

Magnitude (Mw)	Average Per Year	Description	Examples	Energy Release (equivalent kilograms of explosive)
9	<1	**Largest recorded earthquakes–** destruction over vast area massive loss of life possible	Chile, 1960 (M 9.5); Alaska, 1964 (M 9.0); Japan, 2011 (M 9.0)	56,000,000,000,000
8	1	**Great earthquakes–** severe economic impact large loss of life	Sumatra, 2006 (M 8.6); Mexico City, 1980 (M 8.1)	1,800,000,000,000
7	15	**Major earthquakes–** damage ($ billions) loss of life	New Madrid, Missouri 1812 (M 7.7); Turkey, 1999 (M 7.6); Charleston, South Carolina, 1886 (M 7.3)	56,000,000,000
6	134	**Strong earthquakes–** can be destructive in populated areas	Kobe, Japan, 1995 (M 6.9); Loma Prieta, California, 1989 (M 6.9); Northridge, California, 1994 (M 6.7)	1,800,000,000
5	1319	**Moderate earthquakes–** property damage to poorly constructed buildings	Mineral, Virginia, 2011 (M 5.8); Northern New York, 1994 (M 5.8); East of Oklahoma City, Oklahoma, 2011 (M5.6)	56,000,000
4	13,000	**Light earthquakes–** noticeable shaking of items indoors, some property damage	Western Minnesota, 1975 (M 4.6); Arkansas, 2011 (M 4.7)	1,800,000
3	130,000	**Minor earthquakes–** felt by humans, very light property damage, if any	New Jersey, 2009 (M3.0) Maine, 2006 (M3.8)	56,000
2	1,300,000	**Very minor earthquakes–** felt by humans, no property damage		1,800
	Unknown	**Very minor earthquakes–** generally not felt by humans, but may be recorded		56

Data from USGS

Thony Belizaire/AFP/Getty Images

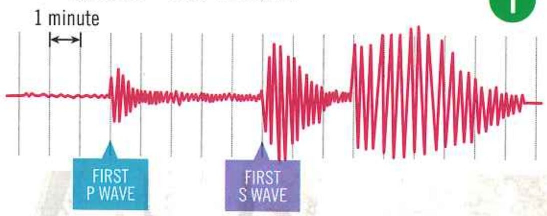
GEOGRAPHICS

Finding the Epicenter of an Earthquake

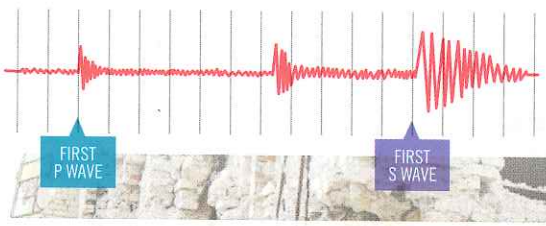
The difference in the velocities of P and S waves provides a method for locating the epicenter of an earthquake. Since P waves travel faster than S waves, the further the epicenter is from the recording instrument, the greater the difference in the arrival times of the first P wave compared to the first S wave.

THREE SEISMOGRAMS

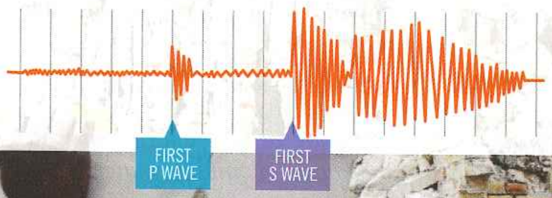
Seismogram A – New York, NY



Seismogram B – Nome, Alaska



Seismogram C – Mexico City, Mexico



STEP 1

Using the seismogram on the left for a seismic recording station in New York, determine the time difference between the arrival of the first P wave and the arrival of the first S wave. In this example, the P-S time interval is 5 minutes.

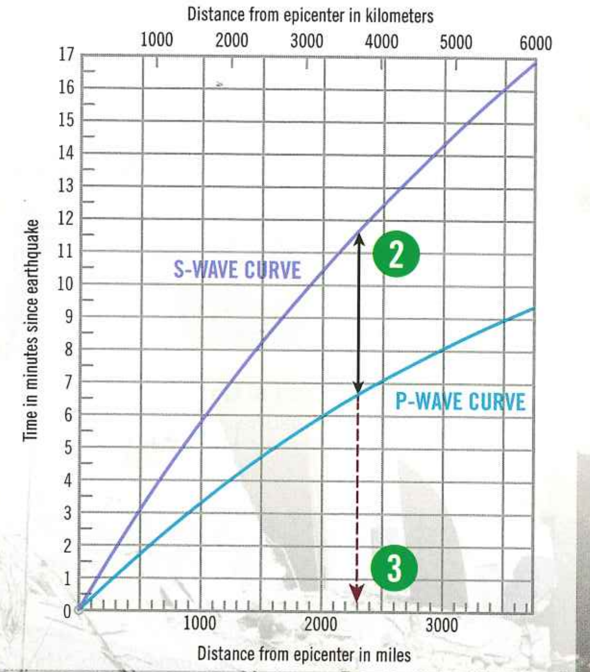
STEP 2

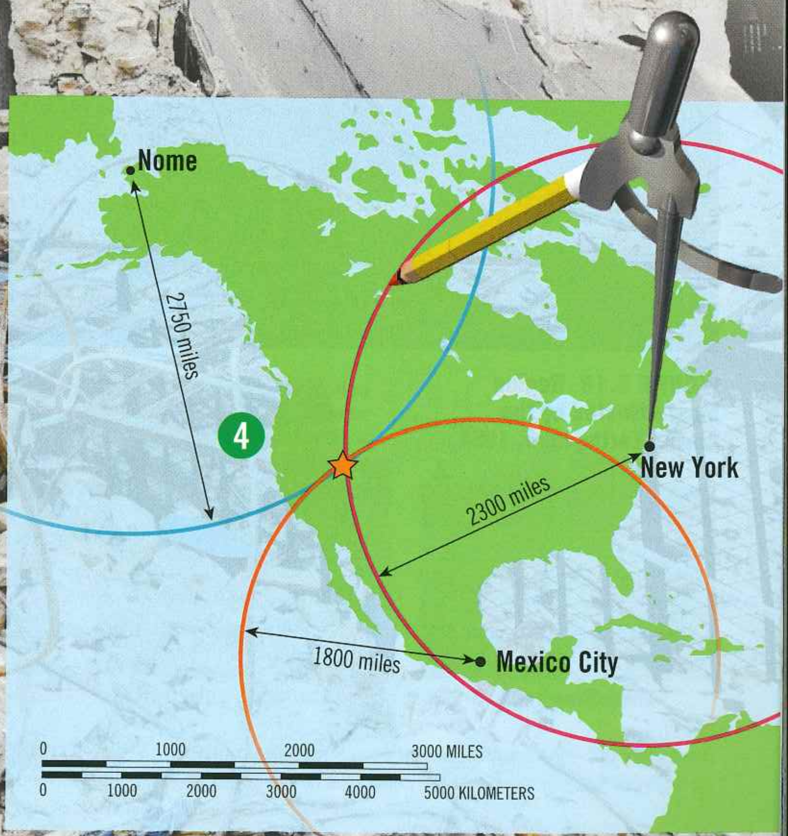
Find the place on the travel-time graph where the vertical separation between the P and S curves is equal to the P-S interval determined in Step 1.

STEP 3

From this position, draw a vertical line that extends to the bottom of the graph and read the distance to the epicenter. The distance from our seismograph in New York to the earthquake epicenter is 2300 miles.

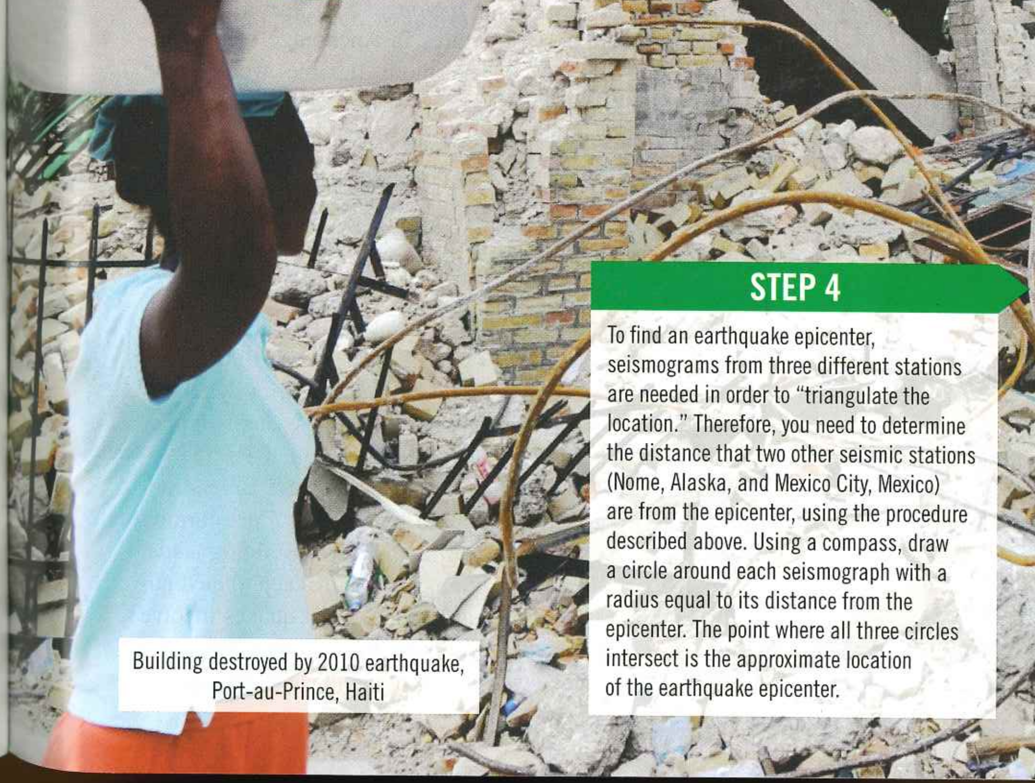
TRAVEL-TIME GRAPH





STEP 4

To find an earthquake epicenter, seismograms from three different stations are needed in order to "triangulate the location." Therefore, you need to determine the distance that two other seismic stations (Nome, Alaska, and Mexico City, Mexico) are from the epicenter, using the procedure described above. Using a compass, draw a circle around each seismograph with a radius equal to its distance from the epicenter. The point where all three circles intersect is the approximate location of the earthquake epicenter.



Building destroyed by 2010 earthquake, Port-au-Prince, Haiti

Thony Belizaire/AFP/Getty Images

Moment Magnitude For measuring medium and large earthquakes, seismologists have come to favor a newer scale, called **moment magnitude** (M_W), which measures the total energy released during an earthquake. Moment magnitude is calculated by determining the average amount of slip on the fault, the area of the fault surface that slipped, and the strength of the faulted rock.

Moment magnitude can also be calculated by modeling data obtained from seismograms. The results are converted to a magnitude number, as in other magnitude scales. In addition, as in the Richter scale, each unit increase in moment magnitude equates to roughly a 32-fold increase in the energy released.

Because moment magnitude estimates the total energy released, it is better for measuring very large earthquakes. Seismologists have recalculated the magnitudes of older, strong earthquakes using the moment magnitude scale. For example, the 1964 Alaska earthquake, which was originally given a Richter magnitude of 8.3, has since been recalculated using the moment magnitude scale, resulting in an upgrade to 9.2. Conversely, the 1906 San Francisco earthquake that was given a Richter magnitude of 8.3, was downgraded to a M_W 7.9. The strongest earthquake on record is the 1960 Chilean subduction zone earthquake, with a moment magnitude of 9.5.

8.3 CONCEPT CHECKS

1. What does the Modified Mercalli Intensity scale tell us about an earthquake?
2. What information is used to establish the lower numbers on the Mercalli scale?
3. How much more energy does a magnitude 7.0 earthquake release than a 6.0 earthquake?
4. Why is the moment magnitude scale favored over the Richter scale?

8.4 EARTHQUAKE DESTRUCTION

List and describe the major destructive forces that can be triggered by earthquake vibrations.

The most violent earthquake ever recorded in North America—the Alaska earthquake—occurred at 5:36 P.M. on March 27, 1964. Felt over most of the state, the earthquake had a moment magnitude (M_W) of 9.2 and lasted 3 to 4 minutes. This event left 128 people dead and thousands homeless, and it badly disrupted the economy of the state. Within 24 hours of the initial shock, 28 aftershocks were recorded, 10 of them exceeding a magnitude of 6. The location of the epicenter and the towns hardest hit by the quake are shown in **FIGURE 8.18**.

Many factors determine the degree of destruction that accompanies an earthquake. The most obvious is *the magnitude of the earthquake and its proximity to a populated area.* During an earthquake, the region within 20 to 50 kilometers (12 to 30 miles) of the epicenter tends to experience roughly the same degree of ground shaking, and beyond that limit, vibrations usually diminish rapidly. Earthquakes that occur in the stable continental interior, such as the New Madrid earthquake of 1811–1812, are generally felt more over a much larger area than those in earthquake-prone areas such as California.

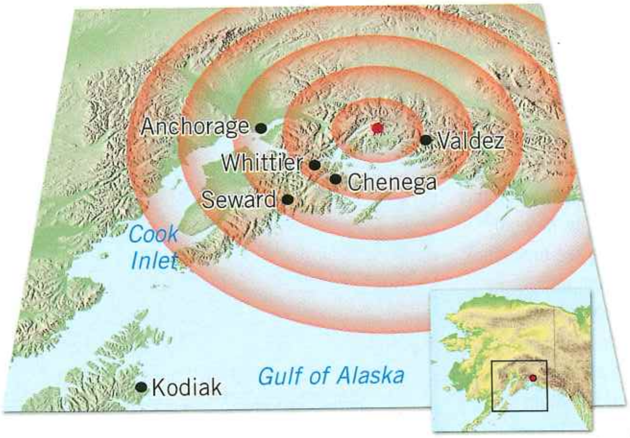


FIGURE 8.18 Region Most Affected by the Alaska Earthquake, 1964

Destruction from Seismic Vibrations

The 1964 Alaska earthquake provided geologists with 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 involving up-and-down as well side-to-side motion. The amount of damage to human-made structures attributable to the vibrations depends on several factors, including (1) *the intensity* and (2) *the duration of the vibrations*, (3) *the nature of the material on which structures rest*, and (4) *the nature of building materials and construction practices of the region.*

All the multi-story structures in Anchorage were damaged by the vibrations. The more flexible wood-frame residential buildings fared best. A striking example of how construction variations affect earthquake damage is shown in **FIGURE 8.19**. You can see that the steel-frame building on the left withstood the vibrations, whereas the poorly designed JCPenney building was badly damaged. Engineers have learned that buildings built of blocks and bricks that are not reinforced with steel rods are the most serious safety threats in earthquakes. Unfortunately, most of the structures in the developing world are constructed of unreinforced concrete slabs and bricks made of dried mud—a primary reason the death toll in poor countries such as Haiti is usually higher than for earthquakes of similar size in the United States.

The 1964 Alaska earthquake damaged most large structures in Anchorage, 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 the earthquake. Most quakes involve tremors that last less than a minute. For example, the 1994 Northridge earthquake was felt for about 40 seconds, and the

FIGURE 8.19 Comparing Damage to Structures The poorly designed five-story JCPenney building in Anchorage, Alaska, sustained extensive damage. The steel-frame adjacent building incurred very little structural damage. (Courtesy of NOAA)

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 near the epicenter experiences about the same intensity of ground shaking, destruction may vary considerably in this area. These differences are usually 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 in Anchorage that were situated on unconsolidated sediments experienced heavy structural damage (**FIGURE 8.20**). In contrast, most of the town of Whittier, although much nearer the epicenter, rested on a firm foundation of solid bedrock and suffered much less damage from seismic vibrations.

Liquefaction The intense shaking of an earthquake can cause loosely packed water-logged materials, such as sandy stream deposits or fill, to be transformed into a substance that acts like fluids. The phenomenon of transforming a somewhat stable soil into mobile material capable of rising toward Earth's surface is known as **liquefaction**. When liquefaction occurs, the ground may not be capable of supporting buildings, and underground storage tanks and sewer lines may literally float toward the surface (**FIGURE 8.21**).

During the 1989 Loma Prieta earthquake, in San Francisco's Marina District, foundations failed, and geysers of sand and water shot from the ground, evidence that liquefaction had occurred (**FIGURE 8.22**).

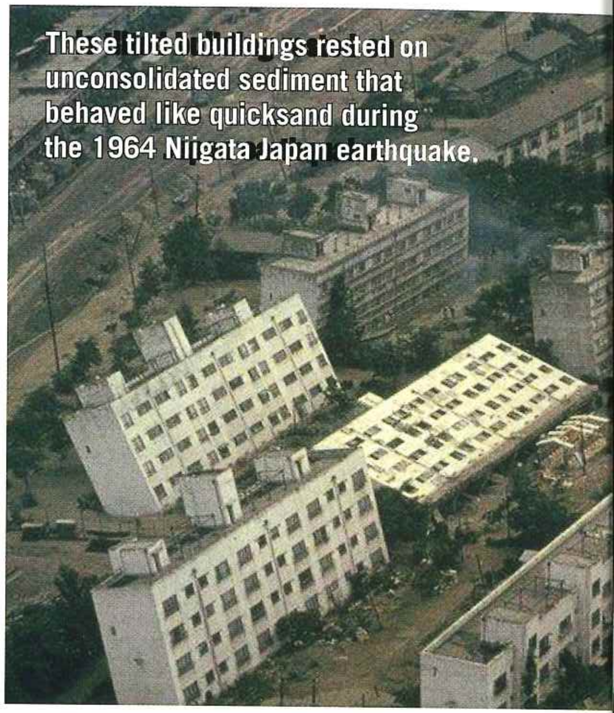


FIGURE 8.21 Effects of Liquefaction on Buildings (Photo courtesy of USGS)

FIGURE 8.20 Ground Failure Caused This Street in Anchorage, Alaska, to Collapse (Photo by USGS)

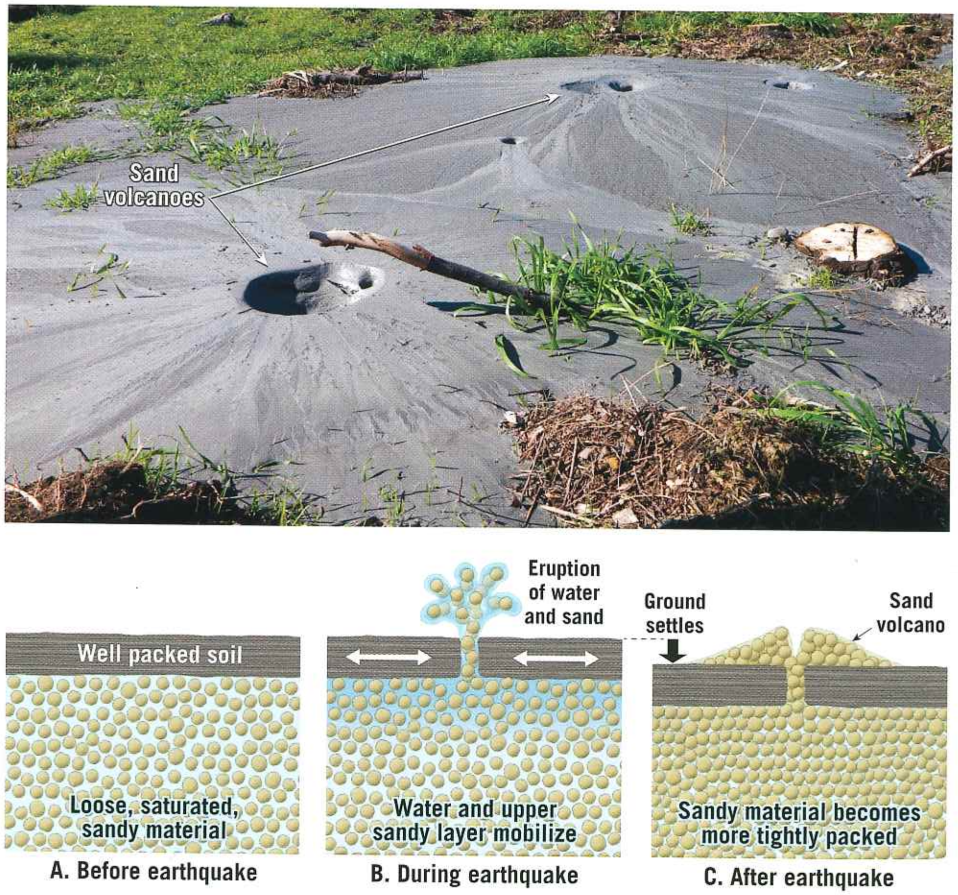
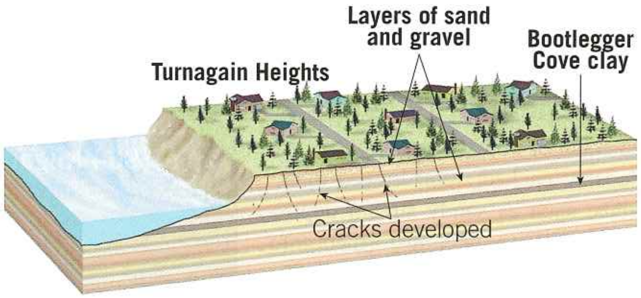


FIGURE 8.22 Liquefaction These "sand volcanoes," produced by the Christchurch New Zealand earthquake of 2011, formed when "geysers" of sand and water shot from the ground, an indication that liquefaction occurred. (Photo by Thorsten Blackwood/AFP Getty Images/Newscom)

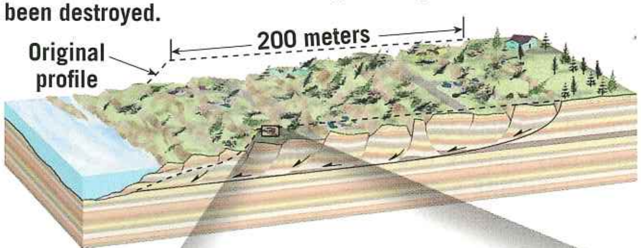
SmartFigure

8.23 Turnagain Heights slide caused by the 1964 Alaska earthquake. (Photo courtesy of U.S. Geological Survey, Denver)

A. Vibrations from the Alaskan earthquake caused cracks to appear near the edge of the Turnagain Heights bluff.



B. Blocks of land began to slide toward the sea on a weak layer called the Bootlegger Cove clay and in less than 5 minutes, as much as 200 meters of the Turnagain Heights bluff area had been destroyed.



C. Photo of a small area of destruction caused by the Turnagain Heights slide.

Liquefaction also contributed to the damage inflicted on San Francisco's water system during the 1906 earthquake. During the 2011 Japan earthquake, liquefaction caused entire buildings to sink several feet.

Landslides and Ground Subsidence

The greatest earthquake-related damage to structures is often caused by landslides and ground subsidence triggered by earthquake vibrations. This was the case during the 1964 Alaska earthquake in Valdez and Seward, where the violent shaking caused coastal sediments to slump, carrying both waterfronts away. In Valdez, 31 people died when a dock slid into the sea. Because of the threat of recurrence, the entire town of Valdez was relocated to more stable ground about 7 kilometers (4 miles) away.

Much of the damage in Anchorage was attributed to landslides. 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 8.23**). A 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

More than 100 years ago, San Francisco was the economic center of the western United States, largely because of gold and silver mining. Then, at dawn on April 18, 1906, a violent earthquake struck, triggering an enormous firestorm (see Figure 8.3). Much of the city was reduced to ashes and ruins. It is estimated that 3000 people died and more than half of the city's 400,000 residents were left homeless.

The historic San Francisco earthquake reminds us of the formidable threat of fire, which started in that quake when gas and electrical lines were severed. The initial ground shaking broke the city's water lines into hundreds of disconnected pieces, which made controlling the fires virtually impossible. The fires, which raged out of control for 3 days, were finally contained when buildings were dynamited along a wide boulevard to provide a fire break, similar to the strategy used in fighting forest fires.

While few deaths were attributed to the San Francisco fires, other earthquake-initiated fires have been more destructive and have claimed many more lives. For example, the 1923 earthquake in Japan triggered an estimated 250 fires, devastating the city of Yokohama and destroying more than half the homes in Tokyo. More than 100,000 deaths were attributed to the fires, which were driven by unusually high winds.

EYE ON EARTH

Water-saturated sandy soil provides students an opportunity to experience the phenomenon of liquefaction. Liquefaction may occur when ground shaking causes a layer of saturated material to lose strength and act like a fluid.

QUESTION 1 *Describe what you think would happen to a structure built on sandy soil that suddenly experienced liquefaction during an earthquake.*

QUESTION 2 *How might a nearly empty underground storage tank be affected by liquefaction of the surrounding soil?*

Marli Miller

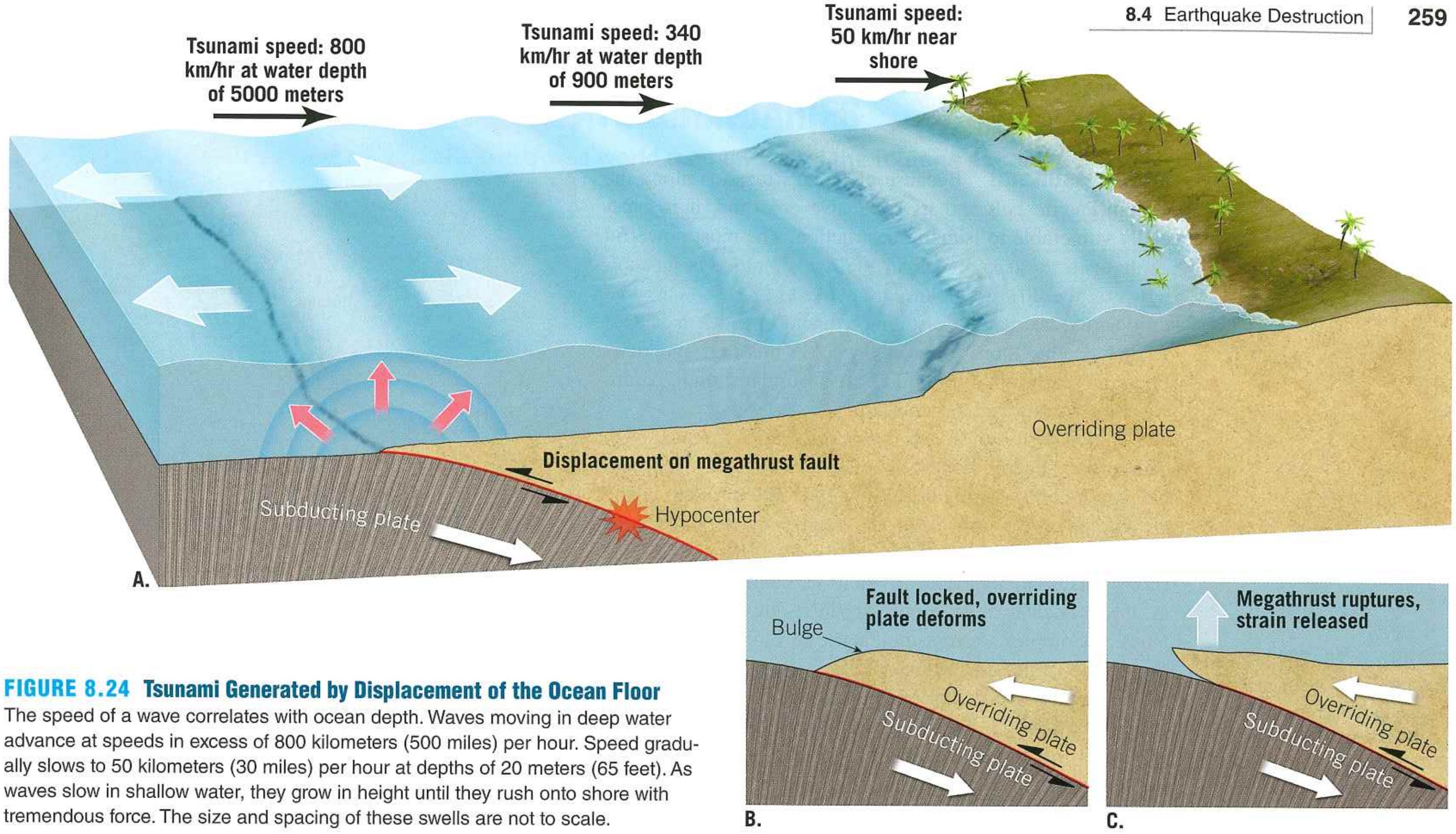


FIGURE 8.24 Tsunami Generated by Displacement of the Ocean Floor The speed of a wave correlates with ocean depth. Waves moving in deep water advance at speeds in excess of 800 kilometers (500 miles) per hour. Speed gradually slows to 50 kilometers (30 miles) per hour at depths of 20 meters (65 feet). As waves slow in shallow water, they grow in height until they rush onto shore with tremendous force. The size and spacing of these swells are not to scale.

What Is a Tsunami?

Major undersea earthquakes occasionally set in motion a series of large ocean waves that are known by the Japanese name **tsunami** (which means "harbor wave"). Most tsunami are generated by displacement along a megathrust fault that suddenly lifts a large slab of seafloor (**FIGURE 8.24**). Once generated, a tsunami resembles a series of ripples formed when a pebble is dropped into a pond. In contrast to ripples, tsunami advance across the ocean at amazing speeds, about 800 kilometers (500 miles) per hour—equivalent to the speed of a commercial airliner. Despite this striking characteristic, a tsunami in the open ocean can pass undetected because its height (amplitude) is usually less than 1 meter, and the distance separating wave crests ranges from 100 to 700 kilometers. However, upon entering shallow coastal waters, these destructive waves "feel bottom" and slow, causing the water to pile up (see Figure 8.24). A few exceptional tsunami have exceeded 30 meters (100 feet) in height. As the crest of a tsunami approaches the shore, it appears as a rapid rise in sea level with a turbulent and chaotic surface; it does not resemble a breaking wave (**FIGURE 8.25**).

The first warning of an approaching tsunami is often the rapid withdrawal of water from beaches, the result of the trough of the first large wave preceding the crest. Some inhabitants of the Pacific basin have learned to heed this warning and quickly move to higher ground. Approximately 5 to 30 minutes after the retreat of water, a surge capable of extending several kilometers inland occurs. In a successive fashion, each surge is followed by a rapid oceanward retreat of the sea. Therefore, people experiencing a tsunami should not return to the shore once the first surge of water retreats.

Tsunami Damage from the 2004 Indonesian Earthquake A massive undersea earthquake of M_W 9.1 occurred near the island of Sumatra on December 26, 2004, sending waves of water racing across the Indian Ocean and Bay of Bengal (see Figure 8.25). It 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 as well as poor fishing hamlets along the Indian Ocean. Damages were reported as far away as the coast of

FIGURE 8.25 Tsunami Generated Off the Coast of Sumatra, 2004 (AFP/Getty Images)

Somalia in Africa, 4100 kilometers (2500 miles) west of the earthquake epicenter.

Japan Tsunami Because of Japan's location along the circum-Pacific belt and its expansive coastline, it is especially vulnerable to tsunami destruction. The most powerful earthquake to strike Japan in the age of modern seismology was the 2011 Tōhoku earthquake (M_W 9.0). This historic earthquake and devastating tsunami resulted in at least 15,861 deaths, more than 3000 people missing, and 6107 injured. Nearly 400,000 buildings, 56 bridges, and 26 railways were destroyed or damaged.

The majority of human casualties and damage were caused by a Pacific-wide tsunami that reached a maximum height of about 40 meters (130 feet) and traveled inland 10 kilometers (6 miles) in the region of Sendai, Japan (**FIGURE 8.26**). The chapter-opening photo (pages 244–245) shows this dramatic event. In addition, meltdowns occurred at three nuclear reactors in Japan's Fukushima Daiichi Nuclear Complex. Across the Pacific in California, Oregon, Peru, and Chile, some loss of life occurred, and several houses, boats, and docks were destroyed. The tsunami was generated when a slab of seafloor located 60 kilometers (37 miles) off the east coast of Japan was suddenly "thrust up" an estimated 5 to 8 meters (16 to 26 feet).

FIGURE 8.26 2011 Japan Tsunami A massive tsunami hit the coastal area of northeastern Japan, March 11, 2011, following a massive 9.0 magnitude earthquake. (Photo by REUTERS/KYODO)

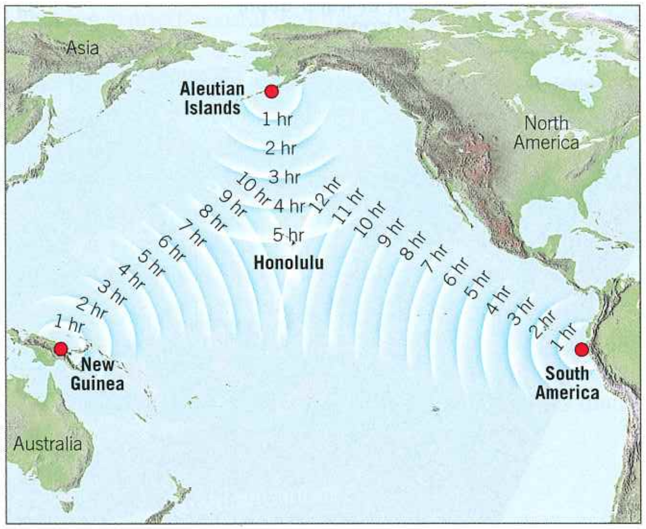


FIGURE 8.27 Tsunami Travel Times Travel times to Honolulu, Hawaii, from selected locations throughout the Pacific. (Data from NOAA)

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 that today includes 26 countries. Seismic observatories throughout the region report large earthquakes to the Tsunami Warning Center in Honolulu. Scientists at the center use deep-sea buoys equipped with pressure sensors to detect energy released by an earthquake. In addition, tidal gauges measure the rise and fall in sea level that accompany tsunami, and warnings are issued within an hour. Although tsunami travel very rapidly, there is sufficient time to warn all except those in the areas nearest the epicenter. For example, a tsunami generated near the Aleutian islands would take 5 hours to reach Hawaii, and one generated near the coast of Chile would travel 15 hours before reaching the shores of Hawaii (**FIGURE 8.27**).

8.4 CONCEPT CHECKS

1. List four factors that affect the amount of destruction that seismic vibrations cause to human-made structures.
2. In addition to the destruction created directly by seismic vibrations, list three other types of destruction associated with earthquakes.
3. What is a tsunami? How are tsunami generated?
4. List at least three reasons an earthquake with a magnitude of 7.0 might result in more death and destruction than a quake with a magnitude of 8.0.

8.5 EARTHQUAKE BELTS AND PLATE BOUNDARIES

Locate Earth's major earthquake belts on a world map and label the regions associated with the largest earthquakes.

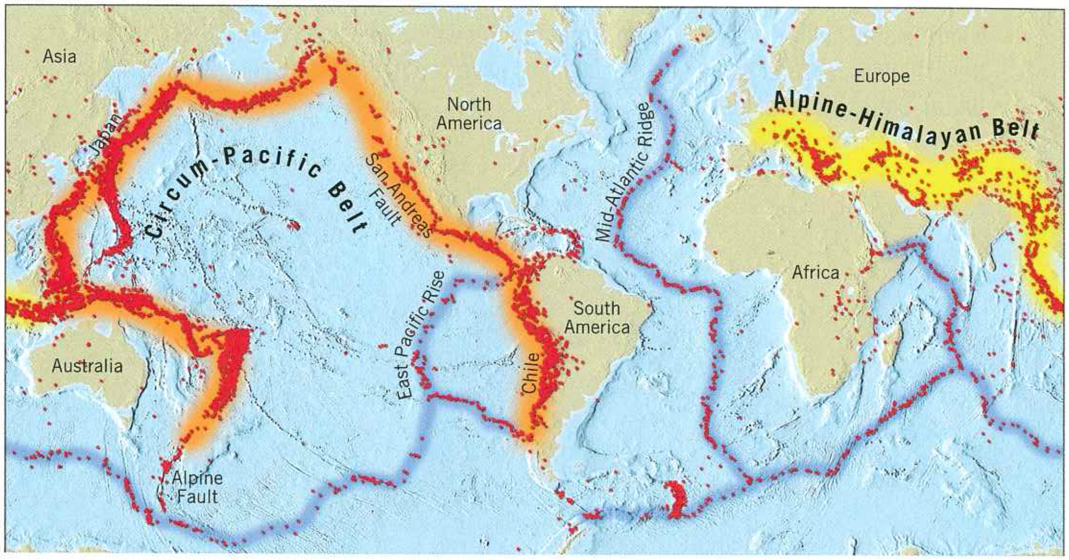


FIGURE 8.28 Global Earthquake Belts Distribution of nearly 15,000 earthquakes with magnitudes equal to or greater than 5 for a 10-year period. (Data from USGS)

About 95 percent of the energy released by earthquakes originates in the few relatively narrow zones, shown in **FIGURE 8.28**. The zone of greatest seismic activity, called the **circum-Pacific belt**, encompasses the coastal regions of Chile, Central America, Indonesia, Japan, and Alaska, including the Aleutian islands (see Figure 8.28). Most earthquakes in the circum-Pacific belt occur along convergent plate boundaries where one plate slides at a low angle beneath another. The contacts between the subducting and overlying plates are *megathrust faults*, along which Earth's largest earthquakes are generated (**FIGURE 8.29**).

There are more than 40,000 kilometers (25,000 miles) of subduction boundaries in the circum-Pacific belt where displacement is dominated by thrust faulting. Ruptures occasionally occur along segments that are nearly 1000 kilometers (600 miles) in length, generating catastrophic *megathrust earthquakes* with magnitudes of (M_W) 8 or greater.

Another major concentration of strong seismic activity, referred to as the *Alpine–Himalayan belt*, runs through the mountainous regions that flank the Mediterranean Sea and extends past the Himalayan Mountains (see Figure 8.28). Tectonic activity in this region is mainly attributed to collisions of the African plate with Eurasia and of the Indian plate with Southeast Asia. These plate interactions created many thrust and strike-slip faults that remain active. In addition, numerous faults located a considerable distance from these plate boundaries have been reactivated as India continues its northward advance into Asia. For example, slippage on a complex fault system in 2008 in the Sichuan Province of China killed at least 70,000 people and left 1.5 million others homeless. The cause was the Indian subcontinent continually shoving the Tibetan Plateau eastward against the rocks of the Sichuan basin.

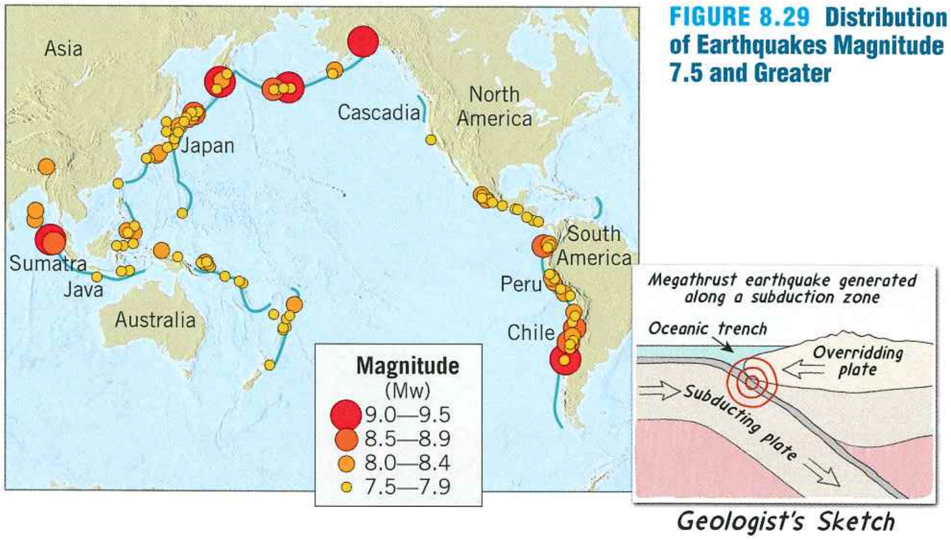


FIGURE 8.29 Distribution of Earthquakes Magnitude 7.5 and Greater

Figure 8.28 shows another continuous earthquake belt that extends for thousands of kilometers through the world's oceans. This zone coincides with the oceanic ridge system, which is an area of frequent but weak seismic activity. As tensional forces pull the plates apart during seafloor spreading, displacement along normal faults generates most of the earthquakes in this zone. The remaining seismic activity is associated with slippage along transform faults located between ridge segments.

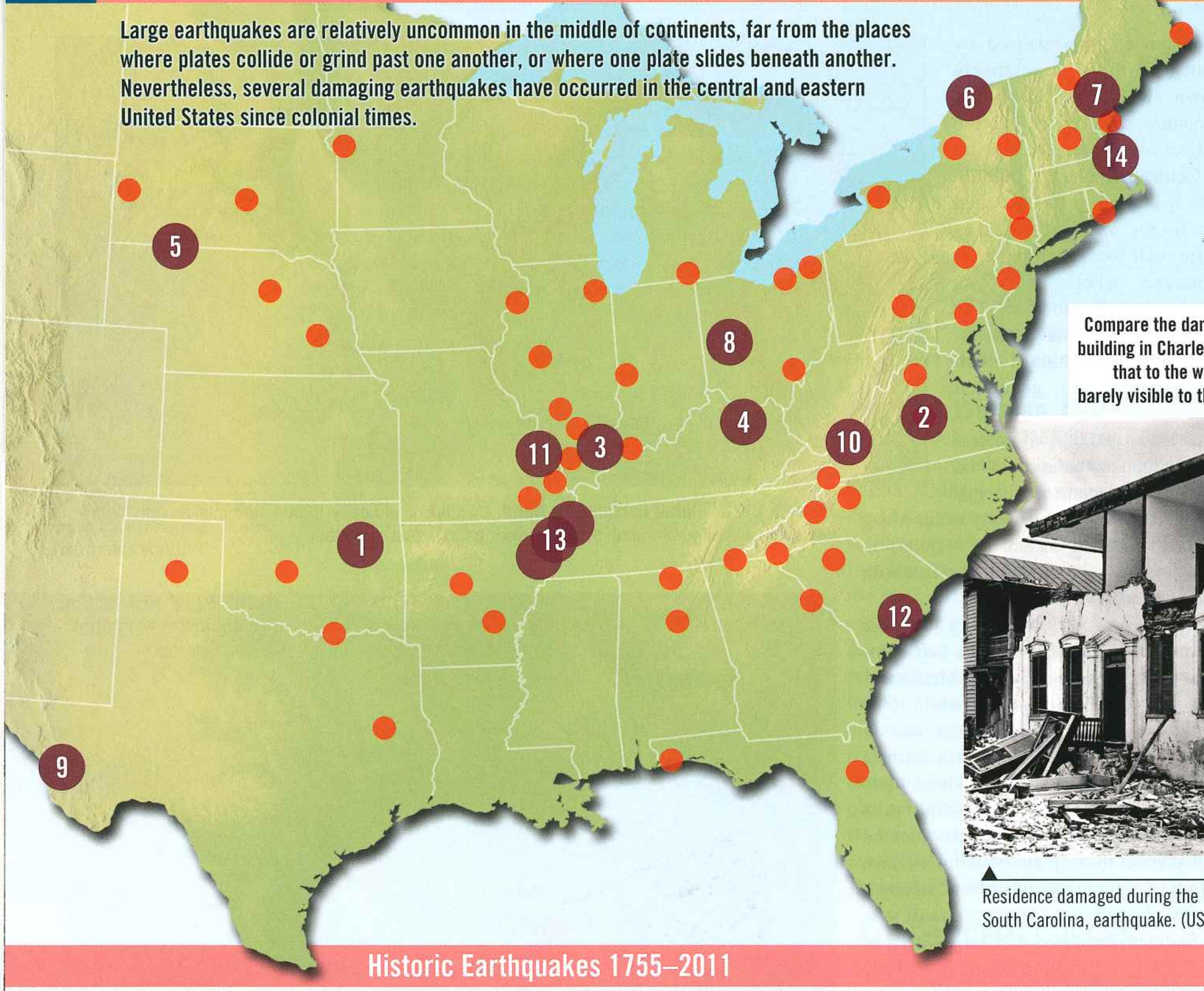
Transform faults and smaller strike-slip faults also run through continental crust, where they may generate large earthquakes that tend to occur on a cyclical basis. Examples include California's San Andreas Fault, New Zealand's Alpine Fault, and Turkey's North Anatolian Fault, which produced a deadly earthquake in 1999.

8.5 CONCEPT CHECKS

1. Where does the greatest amount of seismic activity occur?
2. What type of plate boundary is associated with Earth's largest earthquakes?
3. Name another major concentration of strong earthquake activity.

Historic Earthquakes East of the Rockies

Large earthquakes are relatively uncommon in the middle of continents, far from the places where plates collide or grind past one another, or where one plate slides beneath another. Nevertheless, several damaging earthquakes have occurred in the central and eastern United States since colonial times.



Compare the damage to the brick building in Charleston (below) with that to the wood-frame house barely visible to the building's left.

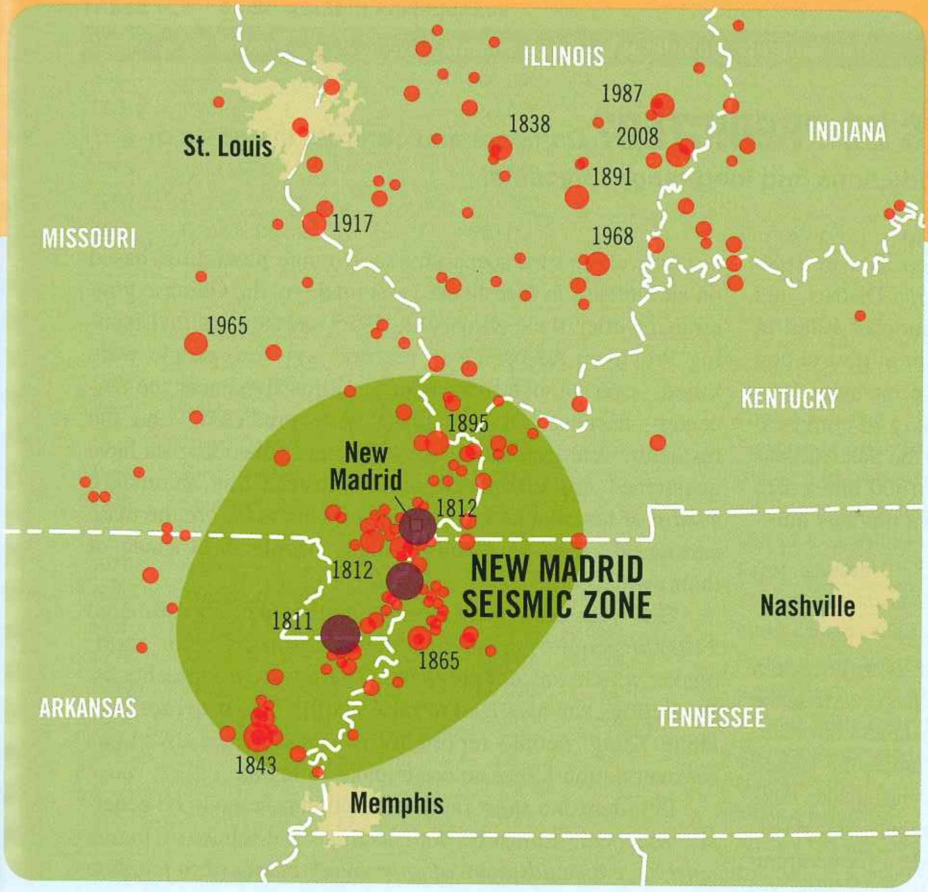
?

Residence damaged during the 1886 Charleston, South Carolina, earthquake. (USGS)

Historic Earthquakes 1755–2011

	LOCATION	DATE	INTENSITY	MAGNITUDE*	COMMENTS
1	East of Oklahoma City	2011	VII	5.6	Fourteen homes destroyed
2	Mineral, Virginia	2011	VII	5.8	Felt by many due to its proximity to large population centers
3	Southeastern Illinois	2008	VII	5.4	Occurred along the Wabash Valley Seismic Zone
4	Northeast Kentucky	1980	VII	5.2	Largest earthquake ever recorded in Kentucky
5	Merriman, Nebraska	1964	VII	5.1	Largest earthquake ever recorded in Nebraska
6	Northern New York	1944	VIII	5.8	Left several structures unsafe for occupancy
7	Ossipee Lake, New Hampshire	1947	VII	5.5	Two earthquakes occurred four days apart
8	Western Ohio	1937	VIII	5.4	Extensive damage to chimneys and plaster walls
9	Valentine, Texas	1931	VIII	5.8	Brick buildings were severely damaged
10	Giles County, Virginia	1897	VIII	5.9	Changed the flow of natural springs
11	Charleston, Missouri	1895	VIII	6.6	Structural damage and liquefaction reported
12	Charleston, South Carolina	1886	X	7.3	Caused 60 deaths, destroyed many buildings
13	New Madrid, Missouri	1811-1812	X	7.7	Three strong earthquakes occurred in remote areas
14	Cape Ann, Massachusetts	1755	VIII	?	Chimneys leveled and brick buildings damaged in Boston

Source: U.S. Geological Survey
*Intensity and magnitudes have been estimated for many of these events.



New Madrid Seismic Zone

Three large earthquakes that were centered near the Mississippi River Valley in southeastern Missouri occurred on December 16, 1811, January 23, 1812, and February 7, 1812. Having estimated magnitudes of 7.7, 7.5, and 7.7, these earthquakes and numerous smaller aftershocks destroyed the town of New Madrid, Missouri. These quakes also triggered massive landslides, inflicted damage in the surrounding states of Illinois, Indiana, Kentucky, Arkansas, and Tennessee and were felt over the entire Midwest because of the rigid bedrock that underlies that region. Chimneys collapsed as far away as Cincinnati, Ohio. Destruction of property from the New Madrid earthquakes was minimal, primarily because the Midwest was sparsely populated in the early 1800s. Memphis, Tennessee, located near the epicenter, had not yet been established, and St. Louis, Missouri, was a small frontier town. Today, these metropolitan areas each have populations that exceed one million residents.

Eric Foltz/Getty Images

Reelfoot Lake, Tennessee, located about 14 miles south of New Madrid, formed in an area of subsidence that was produced during the February 7, 1812, event. Subsidence that exceeded 6 meters (20 feet) in some places occurred on the down-dropped side of the Reelfoot Fault.

The largest historical earthquake in the eastern United States occurred in Charleston, South Carolina, in 1886. This one-minute event resulted in 60 deaths, numerous injuries, and great economic loss within 200 kilometers (120 miles) of Charleston. Minutes after the quake, strong vibrations shook the upper floors of buildings in Chicago, Illinois, and St. Louis, Missouri, causing people to rush outdoors. In Charleston, more than one hundred buildings were destroyed, and 90 percent of the remaining structures were damaged.

(USGS)

8.6 CAN EARTHQUAKES BE PREDICTED?

Compare and contrast the goals of short-range earthquake predictions and long-range forecasts.

The vibrations that shook the San Francisco area in 1989 caused 63 deaths, heavily damaged the Marina District, and caused the collapse of a double-decked section of I-880 in Oakland, California (**FIGURE 8.30**). This level of destruction was the result of an earthquake of moderate intensity (M_W 6.9). Seismologists warn that other earthquakes of comparable or greater strength can be expected along the San Andreas system, which cuts a nearly 1300-kilometer (800-mile) path through the western one-third of the state. An obvious question is: Can these 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 (**TABLE 8.2**). Substantial efforts to achieve this objective have been attempted in Japan, the United States, China, and Russia—countries where earthquake risks are high. This research has concentrated on monitoring possible *precursors*—events or changes that precede a forthcoming earthquake and thus may provide warning. In California, for example, seismologists monitor changes in ground elevation and variations in strain levels near active faults. Other researchers measure changes in groundwater levels, while still others try to predict earthquakes based on an increase in the frequency of foreshocks that precede some, but not all, earthquakes.

Japanese and Chinese scientists have been known to monitor anomalous animal behavior. A few days before the May 12, 2008, earthquake in China's Sichuan Province, the streets of a village near the fault were filled with toads migrating from the mountains. Was this a warning? Perhaps. Walter Mooney, a USGS seismologist, put it best: "Everyone hopes that animals can tell us something we don't know . . . but animal behavior is way too unreliable." Although precursors may exist, we have yet to determine effective ways to interpret and utilize the information.

FIGURE 8.30 Collapse of the Double-decked Section of I-880 This section of a double-decked highway, known as the Cypress Viaduct, collapsed during the 1989 Loma Prieta earthquake. (Photo by Paul Sakuma/AP Photo)

One claim of a successful short-range prediction, based on an increase in foreshocks, was made by the Chinese government after the February 4, 1975, earthquake in Liaoning Province. According to reports, very few people were killed—even though more than 1 million lived near the epicenter—because the earthquake was "predicted," and the residents were evacuated. Some Western seismologists have questioned this claim and suggest instead that an intense swarm of foreshocks, which began 24 hours before the main earthquake, may have caused many people to evacuate of their own accord.

One year after the Liaoning earthquake, an estimated 240,000 people perished in the Tangshan, China, earthquake, which was *not* predicted. There were no foreshocks. Predictions can also lead to false alarms. In a province near Hong Kong, people reportedly evacuated their dwellings for over a month, but no earthquake followed.

In order for a short-range prediction scheme to be generally accepted, it must be both accurate and reliable. Thus, *it must have a small range of uncertainty in regard 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, leading seismologists in the past 100 years have generally concluded that short-range earthquake prediction is not feasible.

Long-Range Forecasts

In contrast to short-range predictions, which aim to predict earthquakes within a time frame of hours or days, long-range forecasts are estimates of how likely it is for an earthquake of a certain magnitude to occur on a time scale of 30 to 100 years or more. 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 are not as informative as we might like, these data are useful for providing important guides for building codes so that buildings, dams, and roadways are constructed to withstand expected levels of ground shaking.

Most long-range forecasting strategies are based on evidence that many large faults break in a cyclical manner, producing similar quakes at roughly similar intervals. In other words, as soon as a section of a fault ruptures, the continuing motions of Earth's plates begin to build strain in the rocks again until they fail once more. Seismologists have therefore studied historical records of earthquakes to see if there are any discernible patterns so that they can establish the probability of recurrence.

TABLE 8.2 **Some Notable Earthquakes**

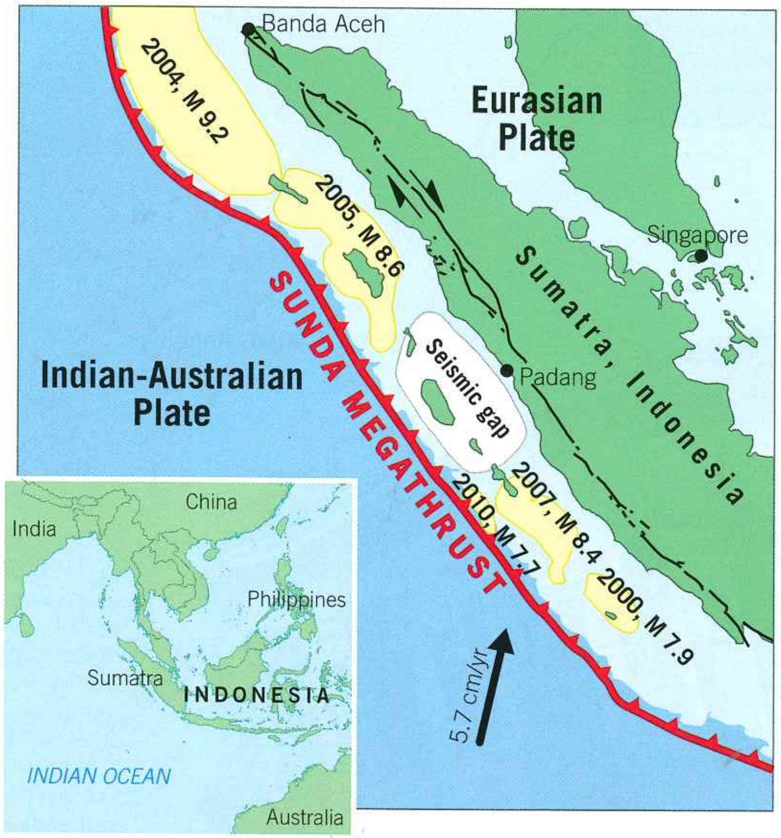
Year	Location	Deaths (est.)	Magnitude*	Comments
856	Iran	200,000		
893	Iran	150,000		
1138	Syria	230,000		
1268	Asia Minor	60,000		
1290	China	100,000		
1556	Shensi, China	830,000		Possibly the greatest natural disaster
1667	Caucasia	80,000		
1727	Iran	77,000		
1755	Lisbon, Portugal	70,000		Tsunami damage extensive
1783	Italy	50,000		
1908	Messina, Italy	120,000		
1920	China	200,000	7.5	Landslide buried a village
1923	Tokyo, Japan	143,000	7.9	Fire caused extensive destruction
1948	Turkmenistan	110,000	7.3	Almost all brick buildings near epicenter collapsed
1960	Southern Chile	5700	9.5	The largest-magnitude earthquake ever recorded
1964	Alaska	131	9.2	Greatest-magnitude North American earthquake
1970	Peru	70,000	7.9	Great rockslide
1976	Tangshan, China	242,000	7.5	Estimates for the death toll are as high as 655,000
1985	Mexico City	9500	8.1	Major damage occurred 400 km from epicenter
1988	Armenia	25,000	6.9	Poor construction practices resulted in many deaths
1990	Iran	50,000	7.4	Landslides and poor construction practices led to great damage
1993	Latur, India	10,000	6.4	Located in stable continental interior
1995	Kobe, Japan	5472	6.9	Damages estimated to exceed $100 billion
1999	Izmit, Turkey	17,127	7.4	Nearly 44,000 injured and more than 250,000 displaced
2001	Gujarat, India	20,000	7.9	Millions homeless
2003	Bam, Iran	31,000	6.6	Ancient city with poor construction
2004	Indian Ocean (Sumatra)	230,000	9.1	Devastating tsunami damage
2005	Pakistan/Kashmir	86,000	7.6	Many landslides; 4 million homeless
2008	Sichuan, China	87,000	7.9	Millions homeless, some towns will not be rebuilt
2010	Port-au-Prince, Haiti	316,000	7.0	More than 300,000 injured and 1.3 million homeless
2011	Japan	20,000	9.0	Majority of the casualties due to a tsunami

* Widely differing magnitudes have been estimated for some of these earthquakes. When available, moment magnitudes are used.

Source: U.S. Geological Survey.

Seismic Gaps Seismologists began to plot the distribution of rupture zones associated with great earthquakes around the globe. The maps revealed that individual rupture zones tend to occur adjacent to one another, without appreciable overlap, thereby tracing out a plate boundary. Because plates are moving at known velocities, the rate at which strain builds can also be estimated.

When these researchers studied historical records, they discovered that some seismic zones had not produced a large earthquake in more than a century or, in some locations, for several centuries. These quiet zones, called **seismic gaps**, are believed to be zones that are storing strain that will be released during a future earthquake. **FIGURE 8.31** shows a patch (seismic gap) of the megathrust fault that lies offshore of Padang, a low-lying city of 800,000 people off the coast of Sumatra that has not ruptured since 1797. Scientists are particularly concerned about this seismic gap because, in 2004, a rupture of an adjacent segment of this megathrust fault that lies to the north generated a tsunami that claimed 230,000 lives.

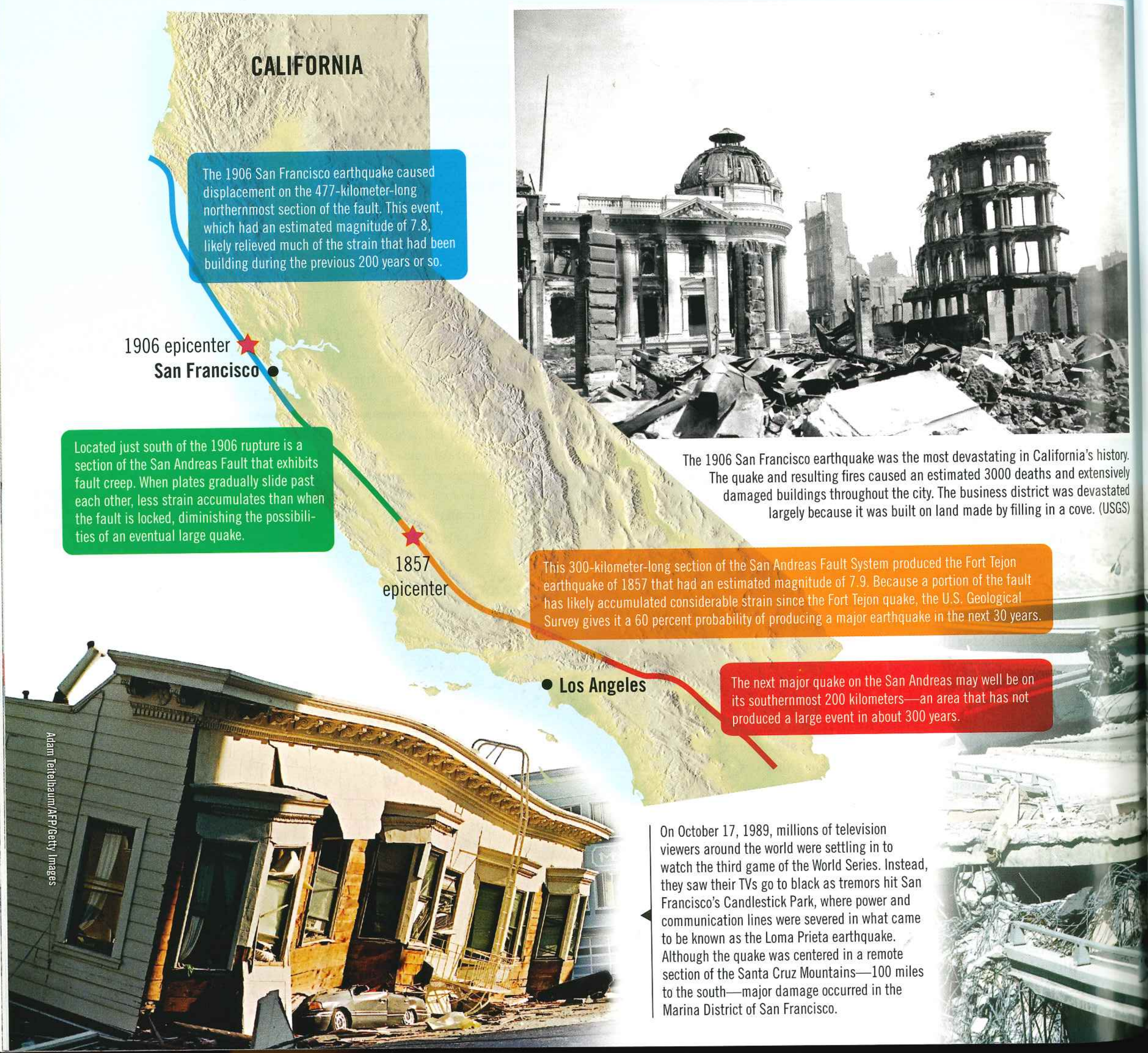


SmartFigure 8.31 **Seismic Gaps: Tools for Forecasting Earthquakes** Seismic gaps are "quiet zones" thought to be inactive zones that are storing elastic strain that will eventually produce major earthquakes. This seismic gap occurs along a patch of the megathrust fault where oceanic lithosphere is being subducted beneath Sumatra, near Padang, a low-lying coastal city with a population of 800,000 people.

GEOGRAPHICS

Seismic Risks on the San Andreas Fault System

California's San Andreas Fault runs diagonally from southeast to northwest for nearly 1300 kilometers (800 miles) through much of the western part of the state. For years researchers have been trying to predict the location of the next "Big One"—an earthquake with a magnitude of 8 or greater—along this fault system.



The 1906 San Francisco earthquake caused displacement on the 477-kilometer-long northernmost section of the fault. This event, which had an estimated magnitude of 7.8, likely relieved much of the strain that had been building during the previous 200 years or so.

Located just south of the 1906 rupture is a section of the San Andreas Fault that exhibits fault creep. When plates gradually slide past each other, less strain accumulates than when the fault is locked, diminishing the possibilities of an eventual large quake.

This 300-kilometer-long section of the San Andreas Fault System produced the Fort Tejon earthquake of 1857 that had an estimated magnitude of 7.9. Because a portion of the fault has likely accumulated considerable strain since the Fort Tejon quake, the U.S. Geological Survey gives it a 60 percent probability of producing a major earthquake in the next 30 years.

The next major quake on the San Andreas may well be on its southernmost 200 kilometers—an area that has not produced a large event in about 300 years.

The 1906 San Francisco earthquake was the most devastating in California's history. The quake and resulting fires caused an estimated 3000 deaths and extensively damaged buildings throughout the city. The business district was devastated largely because it was built on land made by filling in a cove. (USGS)

On October 17, 1989, millions of television viewers around the world were settling in to watch the third game of the World Series. Instead, they saw their TVs go to black as tremors hit San Francisco's Candlestick Park, where power and communication lines were severed in what came to be known as the Loma Prieta earthquake. Although the quake was centered in a remote section of the Santa Cruz Mountains—100 miles to the south—major damage occurred in the Marina District of San Francisco.

Adam Teitelbaum/AFP/Getty Images

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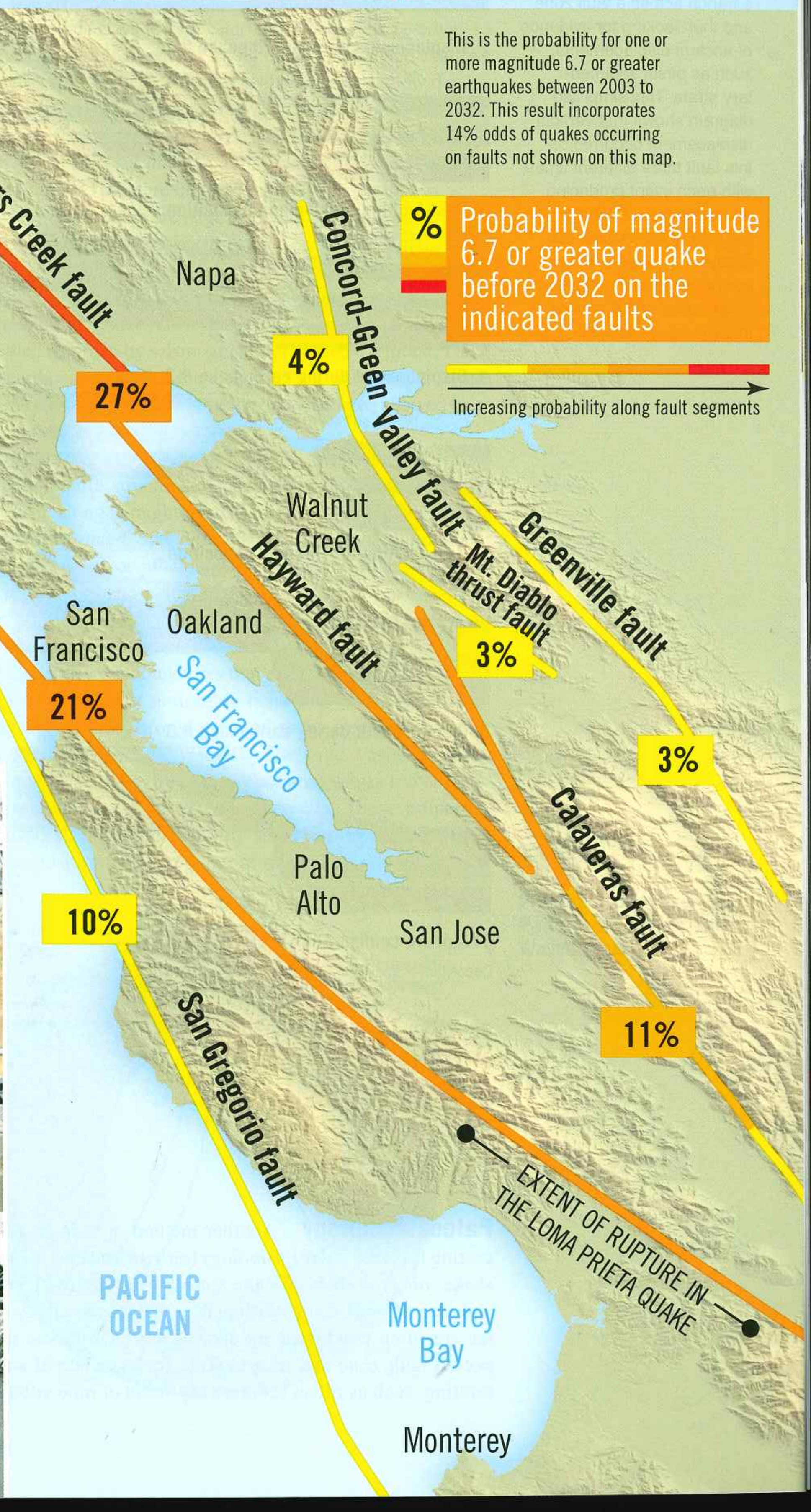
The U.S. Geological Survey concluded that between 2003 and 2032 there is a 62 percent probability of at least one magnitude 6.7 or greater earthquake striking somewhere in the San Francisco Bay area. They also predict that this quake would be roughly comparable to the 1989 Loma Prieta event (MW 6.9) and capable of causing significant damage.

SAN FRANCISCO BAY REGION EARTHQUAKE PROBABILITY 62%

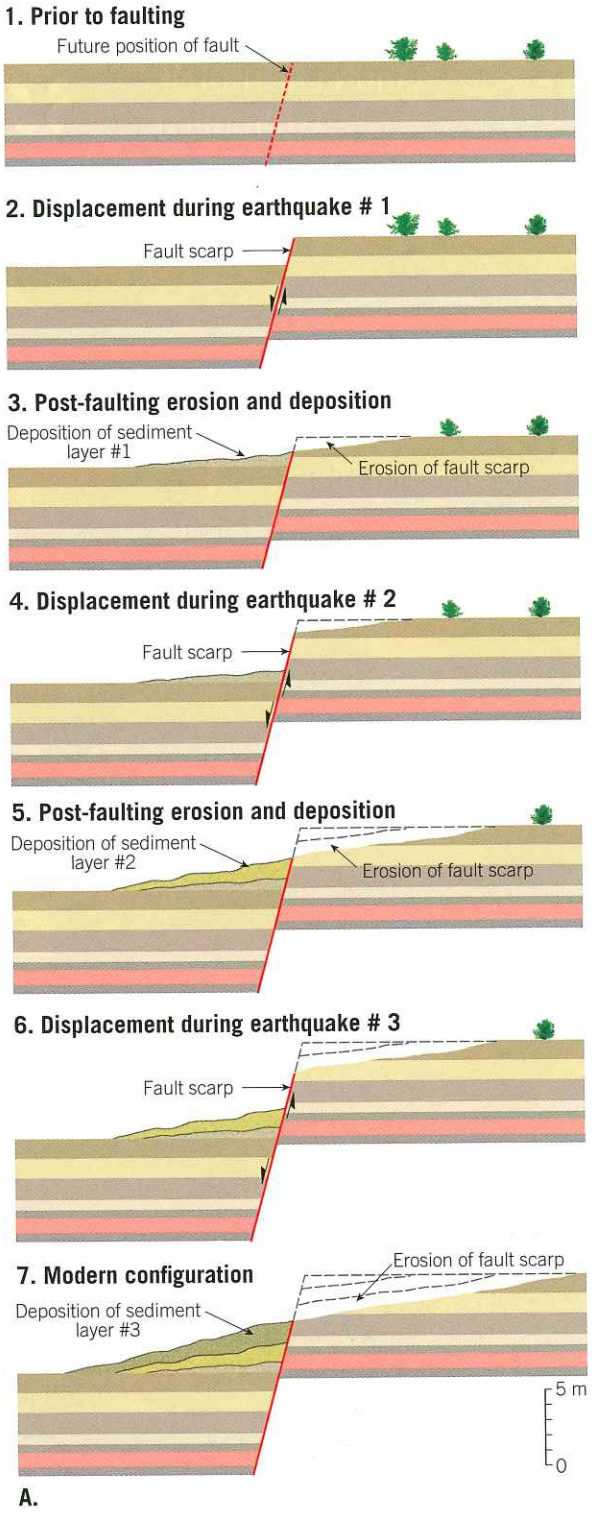
This is the probability for one or more magnitude 6.7 or greater earthquakes between 2003 to 2032. This result incorporates 14% odds of quakes occurring on faults not shown on this map.



In mid-January 1994, less than five years after the Loma Prieta event, the Northridge earthquake struck an area slightly north of Los Angeles. Although not the fabled "Big One," this moderate 6.7-magnitude earthquake claimed the lives of 57 people. Nearly 300 schools were severely damaged, and one dozen major roadways buckled. Among these were two of California's major arteries—sections of the Santa Monica Freeway and the Golden State Freeway (I-5) where an overpass collapsed completely and blocked the highway.

Tom McHugh/Science Source

FIGURE 8.32 Paleoseismology: The Study of Prehistoric Earthquakes These studies are often conducted by digging a trench across a fault zone and then looking for evidence of ancient displacements, such as offset sedimentary strata. This simplified diagram shows that vertical displacement occurred on this fault three different times, with each event producing an earthquake. Based on the size of the vertical displacement, these ancient earthquakes had estimated magnitudes of 6.8 and 7.4. (Photo courtesy of USGS)



B. The events depicted in the accompanying diagram were deciphered by digging a trench (shown here) across the fault zone and studying the displaced sedimentary beds.

Paleoseismology Another method of long-term forecasting involves *paleoseismology* (*paleo* = ancient, *seismos* = shake, *ology* = study of), the study of the timing, location, and size of prehistoric earthquakes. Paleoseismology studies are often conducted by digging a trench across a suspected fault zone and then looking for evidence of ancient faulting, such as offset sedimentary strata or mud volcanoes (**FIGURE 8.32**). A large vertical offset of the layers of sediments indicates a large earthquake. Sometimes buried plant debris can be carbon dated, allowing for the timing of recurrence to be established.

One investigation that used this method focused on a segment of the San Andreas Fault that lies north and east of Los Angeles. At this site, the drainage of Pallet Creek has been repeatedly disturbed by successive ruptures along the fault zone. Trenches excavated across the creek bed have exposed sediments that have been displaced by several large earthquakes over a span of 1500 years. From these data, it was determined that strong earthquakes occur an average of once every 135 years. The last major event, called the Fort Tejon earthquake, occurred on this segment of the San Andreas Fault in 1857, roughly 150 years ago. Because earthquakes occur on a cyclical basis, a major event in southern California may be imminent.

Using other paleoseismology techniques, researchers determined that several powerful earthquakes (magnitude 8 or larger) have repeatedly struck the coastal Pacific Northwest over the past several thousand years. The most recent event, which occurred about 300 years ago, generated a destructive tsunami. As a result of these findings, public officials have taken steps to strengthen some of the region's existing buildings, 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.

8.6 CONCEPT CHECKS

1 Are accurate, short-range earthquake predictions currently possible using modern seismic instruments? Explain.

2 What is the value of long-range earthquake forecasts?

8.7 EARTH'S INTERIOR

Explain how Earth acquired its layered structure and briefly describe how seismic waves are used to probe Earth's interior.

If you could slice Earth in half, the first thing you would notice is that it has distinct layers. The heaviest materials (metals) would be in the center. Lighter solids (rocks) would be in the middle, and liquids and gases would be on top. Within Earth we know these layers as the iron core, the rocky mantle and crust, the liquid ocean, and the gaseous atmosphere. More than 95 percent of the variations in composition and temperature in Earth are due to layering. However, this is not the end of the story. If it were, Earth would be a dead, lifeless cinder floating in space.

There are also variations in composition and temperature with depth, which indicate that the interior of our planet is very dynamic. The rocks of the mantle and crust are in constant motion, not only moving about through plate tectonics but also continuously recycling between the surface and the deep interior. Furthermore, it is from Earth's deep interior that the water and air of our oceans and atmosphere are replenished, allowing life to exist at the surface.

Formation of Earth's Layered Structure

As material accumulated to form Earth (and for a short period afterward), the high-velocity impact of nebular debris and the decay of radioactive elements caused the temperature of our planet to steadily increase. During this time of intense heating, Earth became hot enough that iron and nickel began to melt. Melting produced liquid blobs of heavy metal that sank toward the center of the planet. This process occurred rapidly on the scale of geologic time and produced Earth's dense iron-rich core.

The early period of heating resulted in another process of chemical differentiation, whereby melting formed buoyant masses of molten rock that rose toward the surface and solidified to produce a primitive crust. These rocky materials were rich in oxygen and "oxygen-seeking" elements, particularly silicon and aluminum, along with lesser amounts of calcium, sodium, potassium, iron, and magnesium. In addition, some heavy metals such as gold, lead, and uranium, which have low melting points or were highly soluble in the ascending molten masses, were scavenged from Earth's interior and concentrated in the developing crust. This early period of chemical segregation established the three basic divisions of Earth's interior: (1) the iron-rich *core*, (2) the thin *primitive crust*, and (3) Earth's largest layer, called the *mantle*, which is located between the core and crust.

Probing Earth's Interior: "Seeing" Seismic Waves

Discovering the structure and properties of Earth's deep interior has not been easy. Light does not travel through rock, so we must find other ways to "see" into our planet. The best way to learn about Earth's interior is to dig or drill a hole and examine it directly. Unfortunately, this is possible only at shallow depths. The deepest a drilling rig has ever penetrated is only 12.3 kilometers (8 miles), which is about 1/500 of the way to Earth's center! Even this was an extraordinary accomplishment because temperature and pressure increase rapidly with depth.

Many earthquakes are large enough that their seismic waves travel all the way through Earth and can be recorded on the other side (**FIGURE 8.33**). This means that the seismic waves act like medical x-rays used to take images of a person's insides. About 100 to 200 earthquakes each year are large enough (about M_w 6) to be well recorded by seismographs all around the globe. These large earthquakes provide the means to "see" into our planet and have been the source of most of the data that have allowed us to figure out the nature of Earth's interior.

Interpreting the waves recorded on seismograms in order to identify Earth structures is challenging. Seismic waves do not travel along straight paths; instead, seismic waves are *reflected*, *refracted*, and *diffracted* as they pass through our planet. They reflect off boundaries between different layers, they refract (or bend) when passing from one layer to another layer, and they diffract around any obstacles they encounter (see Figure 8.33). These different wave behaviors have been used to identify the boundaries that exist within Earth.

One of the most noticeable behaviors of seismic waves is that they follow strongly curved paths (see Figure 8.33). This occurs because the velocity of seismic waves generally increases with depth. In addition, seismic waves travel faster when rock is stiffer or less compressible. These properties of stiffness and compressibility are then used to interpret the composition and temperature of the rock. For instance,

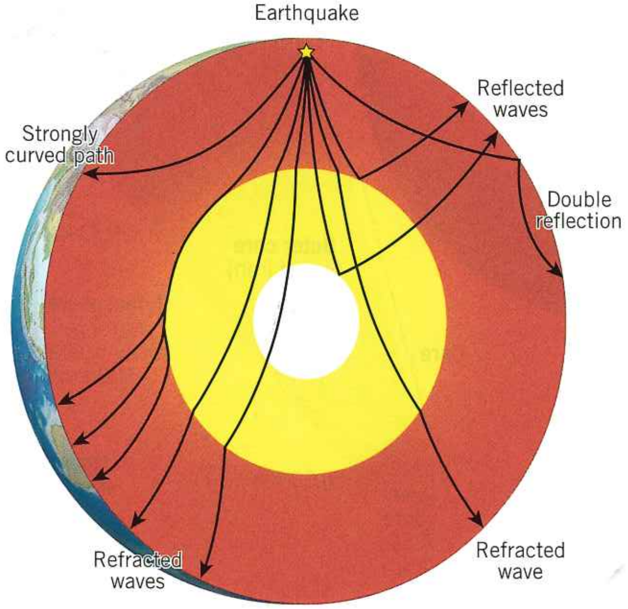


FIGURE 8.33 Possible Paths that Earthquake Waves Take

when rock is hotter, it becomes less stiff (imagine heating up a frozen chocolate bar!), and waves travel more slowly. Waves also travel at different speeds through rocks of different compositions. Thus, the speed at which seismic waves travel can help determine both the kind of rock that is inside Earth and how hot it is.

8.7 CONCEPT CHECKS

1. How did Earth acquire its layered structure?
2. Briefly describe how seismic waves are used to probe Earth's interior.

8.8 EARTH'S LAYERS

List and describe each of Earth's major layers.

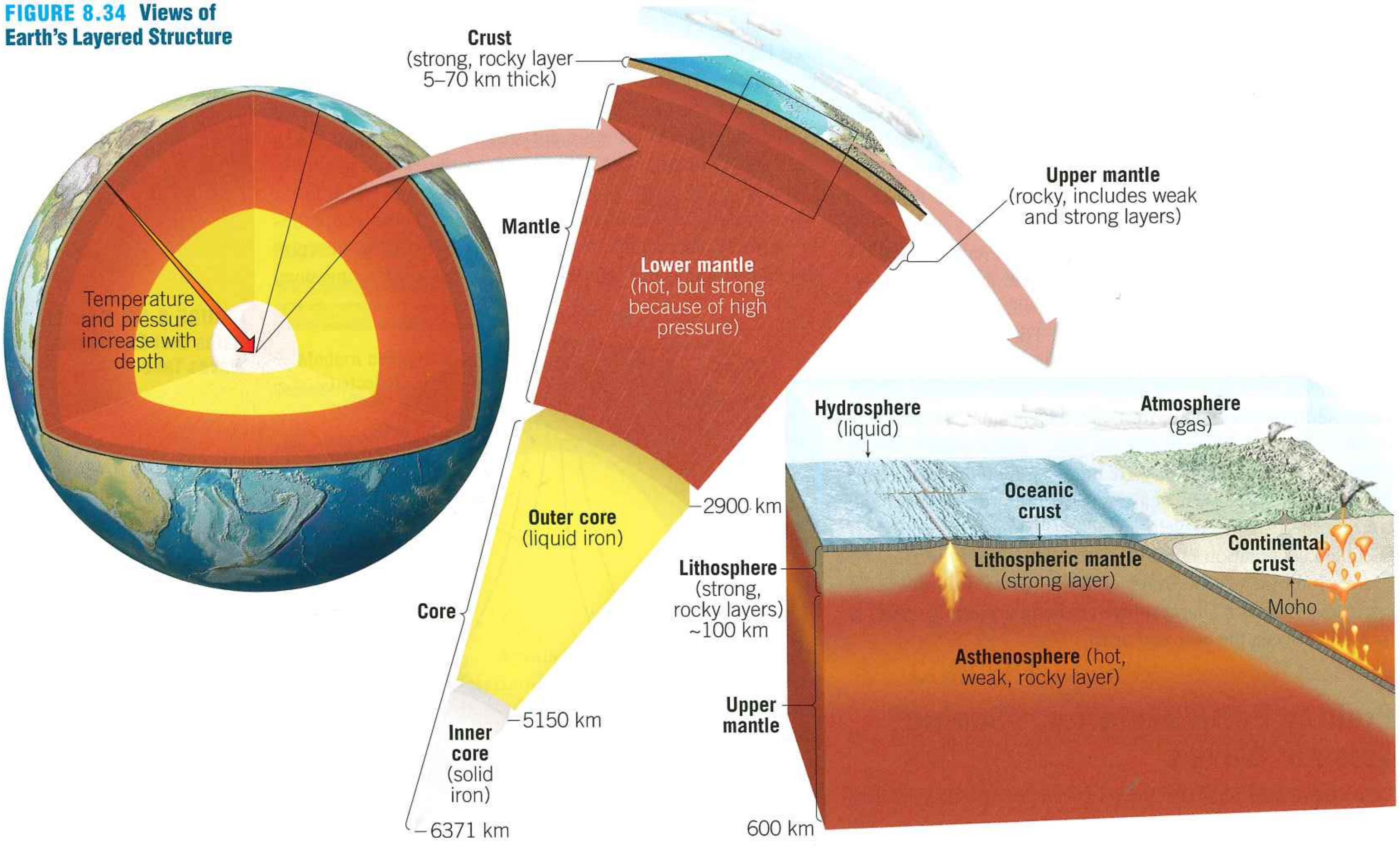
Earth's three compositionally distinct layers—the crust, mantle, and core—can be further subdivided into zones based on physical properties. The physical properties used to define such regions include whether the layer is solid or liquid and how weak or strong it is. Knowledge of both types of layers is essential to our understanding of basic geologic processes, such as volcanism, earthquakes, and mountain building (**FIGURE 8.34**).

Crust

The **crust** is Earth's relatively thin, rocky outer skin, and there are two types: continental crust and oceanic crust. Both share the word *crust*, but the similarity ends there. The oceanic crust is roughly 7 kilometers (4 miles) thick and composed of the dark igneous rock *basalt*. By contrast, the continental crust averages 35 to 40 kilometers (22 to 25 miles) thick but may exceed 70 kilometers (40 miles) in some mountainous regions such as the Rockies and Himalayas. Unlike the oceanic crust, which has a relatively homogeneous chemical composition, the continental crust consists of many rock types. Although the upper crust has an average composition of a *granitic rock* called *granodiorite*, it varies considerably from place to place.

Continental rocks have an average density of about 2.7 grams per cubic centimeter, and some are 4 billion years old. The rocks of the oceanic crust are younger (180 million years or less) and denser (about 3.0 grams per cubic centimeter) than continental rocks.

FIGURE 8.34 Views of Earth's Layered Structure



Mantle

Beneath Earth's crust lies the mantle. More than 82 percent of Earth's volume is contained in the **mantle**, a solid, rocky shell that extends to a depth of about 2900 kilometers (1800 miles). The boundary between the crust and mantle represents a marked change in chemical composition. The dominant rock type in the uppermost mantle is *peridotite*, which is richer in the metals magnesium and iron than the minerals found in either the continental or oceanic crust.

The upper mantle extends from the crust–mantle boundary down to a depth of about 660 kilometers (410 miles). The upper mantle can be divided into two different parts. The top portion of the upper mantle is part of the stiff *lithosphere*, and beneath that is the weaker *asthenosphere*. The **lithosphere** ("sphere of rock") consists of the entire crust and uppermost mantle and forms Earth's relatively cool, rigid outer shell. Averaging about 100 kilometers (62 miles) thick, the lithosphere is more than 250 kilometers (155 miles) thick below the oldest portions of the continents (see Figure 8.34). Beneath this stiff layer to a depth of about 350 kilometers (217 miles) lies a soft, comparatively weak layer known as the **asthenosphere** ("weak sphere"). The top portion of the asthenosphere has a temperature/pressure regime that results in a small amount of melting. Within this very weak zone, the asthenosphere and lithosphere are mechanically detached from each other. The result is that the lithosphere is able to move independently of the asthenosphere.

It is important to emphasize that the strength of various Earth materials is a function of both their composition and the temperature and pressure of their environment. The entire lithosphere does *not* behave like a brittle solid similar to rocks found on the surface. Rather, the rocks of the lithosphere get progressively hotter and weaker (more easily deformed) with increasing depth. At the depth of the uppermost asthenosphere, the rocks are close enough to their melting temperature that they are very easily deformed, and some melting may actually occur. Thus, the uppermost asthenosphere is weak because it is near its melting point, just as hot wax is weaker than cold wax.

From 660 kilometers (410 miles) deep to the top of the core, at a depth of 2900 kilometers (1800 miles), is the lower mantle. Because of an increase in pressure (caused by the weight of the rock above), the mantle gradually strengthens with depth. Despite their strength, however, the rocks within the lower mantle are very hot and capable of very gradual flow.

Core

The composition of the **core** is thought to be an iron–nickel alloy, with minor amounts of oxygen, silicon, and sulfur—elements that readily form compounds with iron. At the extreme pressure found in the core, this iron-rich material has an average density of more than 10 grams per cubic centimeter and is about 13 grams per cubic centimeter at Earth's center. The core is divided into two regions that exhibit very different mechanical strengths. The **outer core** is a liquid layer 2270 kilometers (1410 miles) thick. It is the movement of metallic iron within this zone that generates Earth's magnetic field. The **inner core** is a sphere with a radius of 1216 kilometers (754 miles). Despite its higher temperature, the iron in the inner core is solid due to the immense pressures that exist in the center of the planet.

8.8 CONCEPT CHECKS

1. How do continental crust and oceanic crust differ?
2. Contrast the physical makeup of the asthenosphere and the lithosphere.
3. How are Earth's inner and outer cores different? How are they similar?

8 CONCEPTS IN REVIEW

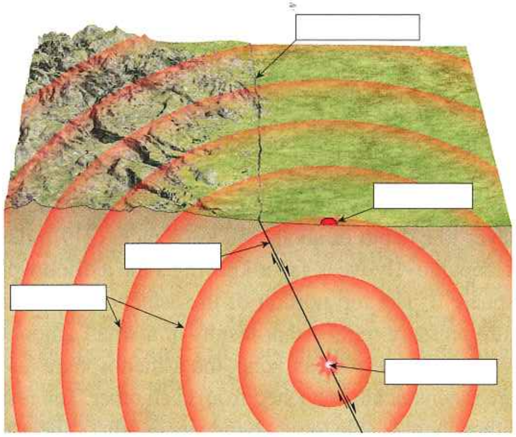
Earthquakes and Earth's Interior

8.1 WHAT IS AN EARTHQUAKE?

Sketch and describe the mechanism that generates most earthquakes.

KEY TERMS: earthquake, fault, hypocenter (focus), epicenter, seismic wave, elastic rebound, aftershock, foreshock, strike-slip fault, transform fault, fault creep, megathrust fault

- Earthquakes are caused by the sudden movement of blocks of rock on opposite sides of faults. The spot where the rock begins to slip is the hypocenter (or focus). Seismic waves radiate from this spot outward into the surrounding rock. The point on Earth's surface directly above the hypocenter is the epicenter.
- Elastic rebound explains why most earthquakes happen: Rock is deformed by movement of Earth's crust. However, frictional resistance keeps the fault locked in place, and the rock bends elastically. Strain builds up until it is greater than the resistance, and the blocks of rock suddenly slip, releasing the pent-up energy in the form of seismic waves. As elastic rebound occurs, the blocks of rock on either side of the fault return to their original shapes, but they are now in new positions.
- Foreshocks are smaller earthquakes that precede larger earthquakes. Aftershocks are smaller earthquakes that happen after large earthquakes, as the crust readjusts to the new, post-earthquake conditions.
- Faults associated with plate boundaries are the source of most large earthquakes.
- The San Andreas Fault in California is an example of a transform fault boundary capable of generating destructive earthquakes.
- Subduction zones are marked by megathrust faults, large faults that are responsible for the largest earthquakes in recorded history. Megathrust faults are also capable of generating tsunami.



Q Label the blanks on the diagram to show the relationship between earthquakes and faults.

8.2 SEISMOLOGY: THE STUDY OF EARTHQUAKE WAVES

Compare and contrast the types of seismic waves and describe the principle of the seismograph.

KEY TERMS: seismology, seismograph (seismometer), inertia, seismogram, surface waves, body waves, P waves (primary waves), S waves (secondary waves)

- Seismology is the study of seismic waves. An instrument called a seismograph measures these waves, using the principle of inertia. While the body of the machine moves with the waves, the inertia of a suspended weight keeps a pen (or an electronic sensor) stationary and records the relative difference between the two. The resulting record of the waves is called a seismogram.
- Seismograms reveal that there are two main categories of earthquake waves: body waves (P waves and S waves) that are capable of moving through Earth's interior and surface waves, which travel only along the upper layers of the crust. P waves are the fastest, S waves are intermediate in speed, and surface waves are the slowest. However, surface waves tend to have the greatest amplitude, while S waves are intermediate, and P waves have the least amplitude. Large-amplitude waves produce the most shaking, so surface waves are responsible for most damage during earthquakes.
- P waves and S waves exhibit different kinds of motion. P waves show compressional motion: They change the volume of the rock as they pass through it. In contrast, S waves impart a shaking motion to rock as they pass through it. This changes the shape of the rock but doesn't alter its volume. As a result, P waves can travel through liquids, but S waves cannot. Liquids can be compressed but not sheared.

Q How could you physically demonstrate the difference between P waves and S waves to a friend who hasn't taken a geology course? (*Caution:* Don't hurt your friend!)

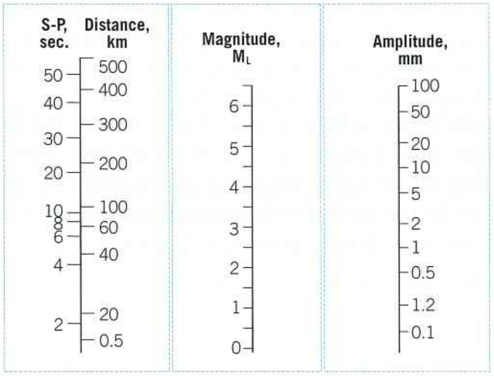
8.3 DETERMINING THE SIZE OF EARTHQUAKES

Distinguish between intensity scales and magnitude scales.

KEY TERMS: intensity, magnitude, Modified Mercalli Intensity scale, Richter scale, moment magnitude

- Intensity and magnitude are different measures of earthquake strength. Intensity measures the amount of ground shaking a place experiences due to an earthquake, and magnitude is an estimate of the actual amount of energy released during the earthquake.
- The Modified Mercalli Intensity scale is a tool for measuring an earthquake's intensity at different locations. The scale is based on verifiable physical evidence to quantify intensity on a 12-point scale. However, it's hard to measure intensity if there are no buildings or people present at a particular location.
- The Richter scale was the first attempt at measuring an earthquake's magnitude. The scale takes into account both the maximum amplitude of the seismic waves measured at a given seismograph and the distance of that seismograph from the earthquake. The Richter scale is logarithmic, meaning that each numerical unit up on the scale represents seismic wave amplitudes that are 10 times greater than those of the next number down. Seismic waves with larger amplitudes possess more energy, so each numerical Richter unit represents about 32 times as much energy release as the next number below it.
- Because the Richter scale does not effectively differentiate between very large earthquakes, the moment magnitude scale was devised. The moment magnitude scale measures the total energy released from an earthquake by considering the strength of the faulted rock, the amount of slip, and the area of the fault that slipped. Moment magnitude is the modern standard for measuring the size of earthquakes.

Q On the Richter scale diagram, first determine the M_L for an earthquake at 400 kilometers distance, with a maximum amplitude of 0.5 millimeters. Second, for this same earthquake (same M_L), determine the amplitude of the biggest waves for a seismograph only 40 kilometers from the hypocenter.



8.4 EARTHQUAKE DESTRUCTION

List and describe the major destructive forces that can be triggered by earthquake vibrations.

KEY TERMS: liquefaction, tsunami

- Several factors influence how much destruction results from an earthquake. The earthquake's magnitude and distance are important, but we must also consider (1) the intensity of the shaking, (2) how long shaking persists, (3) what sort of ground underlies buildings, and (4) building construction standards. Buildings constructed of unreinforced masonry (bricks and blocks) are more likely than other types of buildings to collapse in a quake.
- In general, bedrock-grounded buildings fare better in an earthquake, as loose sediments amplify seismic shaking. A particular hazard occurs with water-logged sediments or soil: When shaken at certain frequencies, the material will flow like a liquid. This phenomenon, called liquefaction, sometimes produces "sand volcanoes." Buildings may also sink into the ground, or underground tanks or sewer lines may float up to the surface when the Earth's subsurface experiences liquefaction.
- Earthquakes may also trigger landslides or ground subsidence, and they may break gas lines, which can initiate devastating fires.
- Tsunami are large ocean waves that form when water is displaced, usually by a megathrust fault rupturing on the seafloor. Crossing the ocean at the speed of a commercial airplane, a tsunami is hardly noticeable in deep water. However, upon arrival in shallower coastal waters, the tsunami slows down and piles up, sometimes producing a wall of water more than 30 meters (100 feet) in height. A tsunami does not look like a curling breaker wave. Instead, it resembles a rapid rise in sea level and may be choked with sediment and other debris. Tsunami warning systems have been established in several ocean basins, including the Pacific.

Q Of the secondary earthquake hazards discussed in this section, which is (are) of the greatest concern in the region where you live? Why?

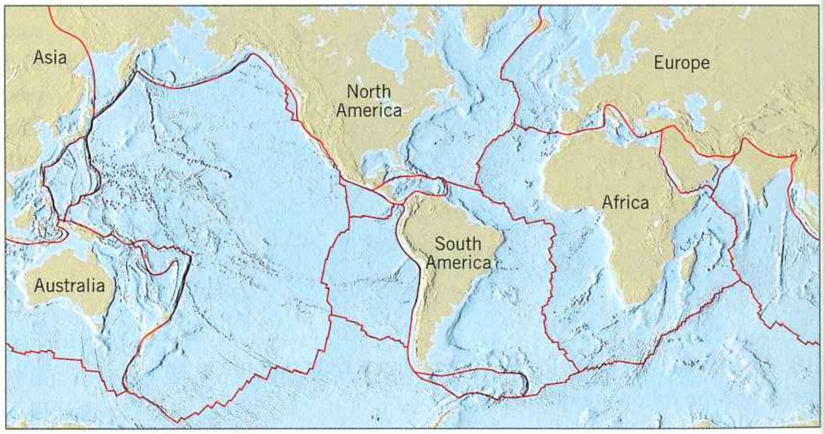
8.5 EARTHQUAKE BELTS AND PLATE BOUNDARIES

Locate Earth's major earthquake belts on a world map and label the regions associated with the largest earthquakes.

KEY TERM: circum-Pacific belt

- Most earthquake energy is released in the circum-Pacific belt, the ring of megathrust faults rimming the Pacific Ocean. Another earthquake belt is the Alpine–Himalayan belt, which runs along the collisional zone between Eurasia and the Indian–Australian and African plates.
- Earth's divergent oceanic ridge system produces another belt of earthquake activity where seafloor spreading generates many frequent quakes of small magnitude. Transform faults in the continental crust, including the San Andreas Fault, can produce large earthquakes.

Q From memory, outline Earth's major earthquake belts on this map. Describe the tectonic stresses responsible for producing each belt.



8.6 CAN EARTHQUAKES BE PREDICTED?

Compare and contrast the goals of short-range earthquake predictions to long-range forecasts.

KEY TERM: seismic gap

- Successful earthquake prediction has been an elusive goal of seismology for many years. Shorter-range predictions (for hours or days) are based on precursor events such as changes in ground elevation or variations in strain levels near a fault. Unfortunately, they haven't been found to be consistently reliable.
- Long-range forecasts (for time scales of 30 to 100 years) are statistical estimates of how likely it is for an earthquake of a given magnitude to occur. Long-range forecasts are useful because they can be used to guide building codes and infrastructure development.
- Scientists have identified seismic gaps, portions of faults that have been storing strain for a long time without releasing it. Knowing the location of seismic gaps can help in the preparation of long-range forecasts. Another tool used in making long-range forecasts is paleoseismology, the study of ancient earthquakes. Because earthquakes occur on a cyclical basis, determining how frequently they have occurred in the past can suggest when they are most likely to occur again.

Q If you were considering moving to a city located in a seismic gap, how would you determine whether it was safe or foolhardy? Which factors would be most influential in your decision?

8.7 EARTH'S INTERIOR

Explain how Earth acquired its layered structure and briefly describe how seismic waves are used to probe Earth's interior.

- The layered internal structure of Earth developed due to gravitational sorting of Earth materials early in the history of the planet. The densest material settled to form the center, while the least dense material rose to form the surface.
- Seismic waves allow geoscientists to "look" into Earth's interior, which would otherwise be invisible to scientific investigation. Like the x-rays used to image human bodies, seismic waves generated by large earthquakes reveal details about Earth's layered structure.

8.8 EARTH'S LAYERS

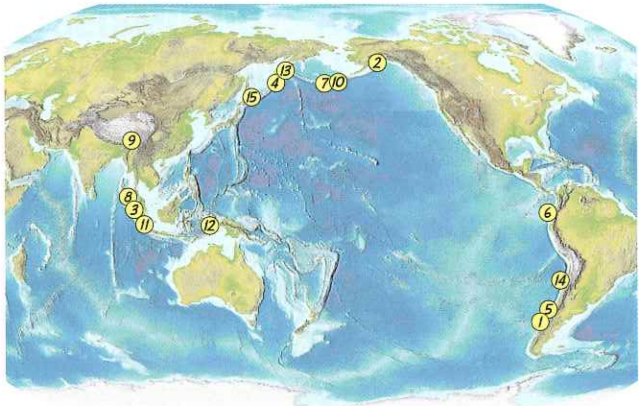
List and describe each of Earth's major layers.

KEY TERMS: crust, mantle, lithosphere, asthenosphere, core, outer core, inner core

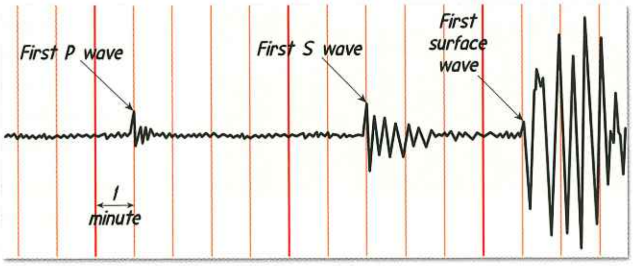
- Earth has two distinct kinds of crust: oceanic and continental. Oceanic crust is thinner, denser, and younger than continental crust. Oceanic crust also readily subducts, whereas the less dense continental crust does not.
- Earth's mantle may be divided by density into upper and lower portions. The uppermost mantle makes up the bulk of rigid lithospheric plates, while a relatively weak layer, the asthenosphere, lies beneath it.
- The composition of Earth's core is likely a mix of iron, nickel, and lighter elements. Iron and nickel are common heavy elements in meteorites, the leftover "building blocks" of Earth. The outer core is dense (around 10 g/cm^3). It is known to be liquid, as S waves cannot pass through it. The inner core is solid and very dense (more than 13 g/cm^3).

GIVE IT SOME **THOUGHT**

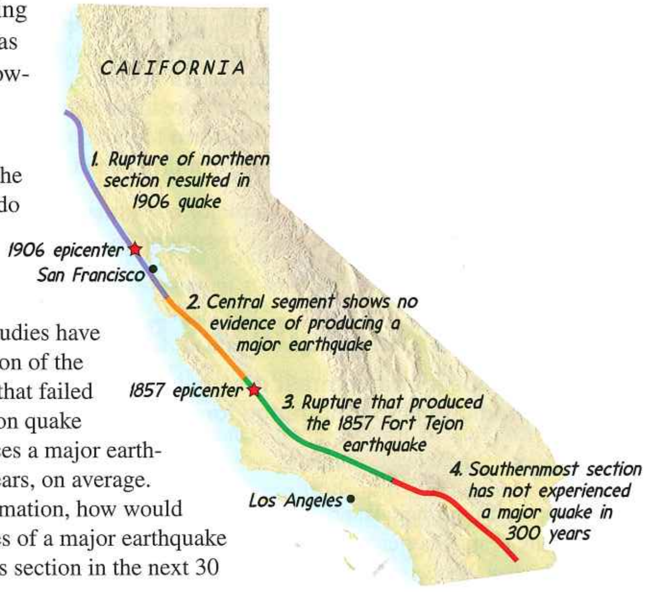
1. Draw a sketch that illustrates the concept of elastic rebound. Develop an analogy other than a rubber band to illustrate this concept.
2. The accompanying map shows the locations of many of the largest earthquakes in the world since 1900. Refer to the map of Earth's plate boundaries in Figure 7.12 (page 218) and determine which type of plate boundary is most often associated with these destructive events.



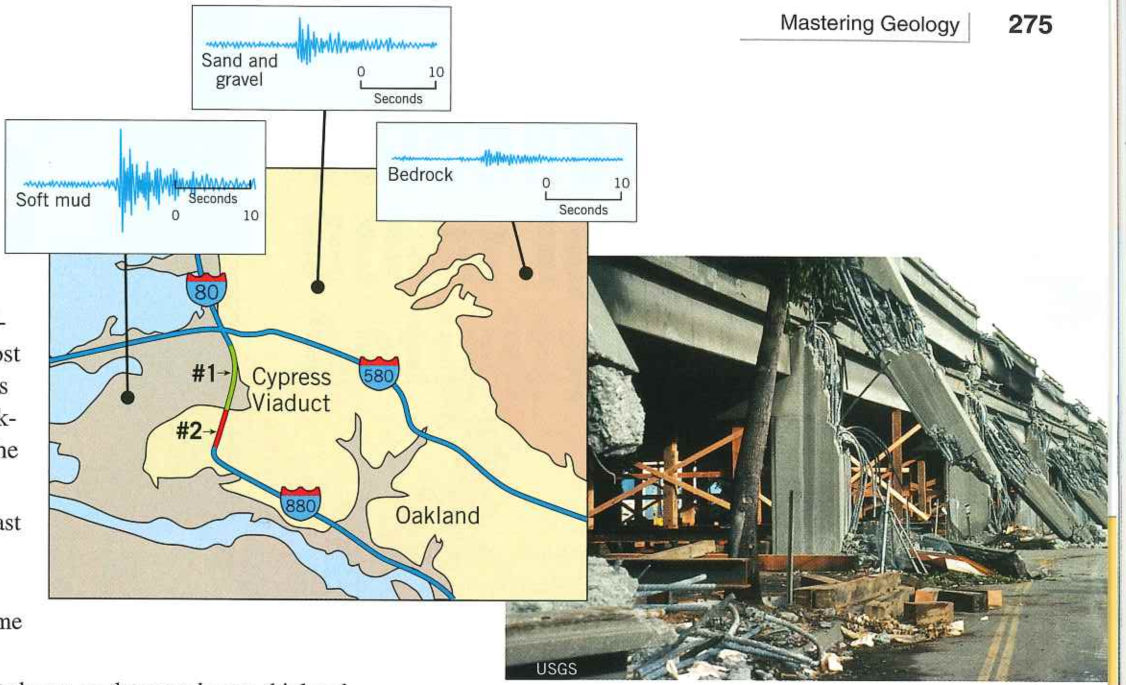
3. Use the seismogram located in the upper right column to answer the following questions:
   a. Which of the three types of seismic waves reached the seismograph first?
   b. What is the time interval between the arrival of the first P wave and the arrival of the first S wave?
   c. Use your answer from Question b and the travel-time graph on page 255 to determine the distance from the seismic station to the earthquake.
   d. Which of the three types of seismic waves had the highest amplitude when they reached the seismic station?



4. You go for a jog on a beach and choose to run near the water, where the sand is well packed and solid under your feet. With each step, you notice that your footprint quickly fills with water but not water coming in from the ocean. What is this water's source? For what earthquake-related hazard is this phenomenon a good analogy?
5. Make a sketch that illustrates why a tsunami often causes a rapid withdrawal of water from beaches before the first surge.
6. Why is it possible to issue a tsunami warning but not a warning for an impending earthquake? Describe a scenario in which a tsunami warning would be of little value.
7. Using the accompanying map of the San Andreas Fault, answer the following questions:
   a. Which of the four segments (1–4) of the San Andreas Fault do you think is experiencing fault creep?
   b. Paleoseismology studies have found that the section of the San Andreas Fault that failed during the Fort Tejon quake (segment 3) produces a major earthquake every 135 years, on average. Based on this information, how would you rate the chances of a major earthquake occurring along this section in the next 30 years? Explain.
   c. Do you think San Francisco or Los Angeles has the greater risk of experiencing a major earthquake in the near future? Defend your selection.



8. The accompanying image shows a double-decked section of Interstate 880 (the Nimitz Freeway) that collapsed during the 1989 Loma Prieta earthquake and caused 42 deaths. About 1.4 kilometers (0.9 mile) of this freeway section, commonly called the Cypress Viaduct, collapsed, while a similar section survived the vibration. Both sections were subsequently demolished and rebuilt as a single-level structure, at a cost of $1.2 billion. Examine the map and seismograms from an aftershock that shows the intensity of shaking observed at three nearby locations to answer the following questions:
   - **a.** What type of ground material experienced the least amount of shaking during the aftershock?
   - **b.** What type of ground materials experienced the greatest amount of ground shaking during the same event?
   - **c.** Which of the two sections of the Cypress Viaduct shown on the map do you think collapsed? Explain.



USGS

9. Strike-slip faults, like the San Andreas Fault, are not perfectly straight but bend gradually back and forth. In some locations, the bends are oriented such that blocks on opposite sides of the fault pull away from each other, as shown in the accompanying sketch. As a result, the ground between the bends sags, forming a depression or basin. These depressions often fill with water.
   - **a.** What name is given to the depression in the accompanying photo?
   - **b.** Describe what would happen if these two blocks began moving in opposite directions.
10. Using the Internet, compare and contrast the 2010 Haiti earthquake with the 2011 Japan earthquake. Include magnitude, type of plate boundary, and extent of destruction. Explain why the Japan earthquake produced a tsunami, while the Haiti quake did not.
11. Describe the two different ways that Earth's layers are defined.
12. Based on the properties of Earth's layers and the mode of travel of body waves, predict the location in Earth's interior where waves should (a) travel fastest and (b) travel slowest. Is there an exception for these generalities? Explain your answers.

Michael Collier

EXAMINING THE **EARTH SYSTEM**

What potentially disastrous phenomenon often occurs when the energy of an earthquake is transferred from the solid earth to the hydrosphere (ocean) at their interface on the floor of the ocean? When the energy from this event is expended along a coast, how might coastal lands and the biosphere be altered?

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