The 2011 Tohoku Earthquake ...

released about 600 million times more energy than the atomic bomb dropped on Hiroshima

3



APPLYING the 5 fundamental concepts 2011 Tohoku Earthquake

1

Science helps us predict hazards.

When we return to the Tohoku earthquake at the end of this chapter you will learn about precursor events leading up to the 2011 quake, as well as the scientific data that led to preliminary forecasting and an underestimation of the maximum size of the event.

2

Knowing hazard risks can help people make decisions.

Large earthquakes are known to occur at subduction zones, the frequency of which can be predicted through scientific investigation and therefore earthquake hazard is amenable to risk analysis. However, as the 2011 Tohoku event illustrates, gaps in scientific data and invalid assumptions can lead to an underestimate of the potential earthquake risk.

Earthquakes

2011 Tohoku Earthquake

As you recall from the previous chapter, the movement of Earth's tectonic plates around the globe has reshaped the continents and ocean basins over the past few billion years. Moving at an average speed of about 5 cm (~2 in.) per year, you might think that we would be completely unaware that the plates are in motion. This would be true if movement between adjacent plates was smooth and continuous, but it is not. Rather than gradual imperceptible movement, plates move episodically in large pulses every few hundred years or so. These large episodic movements of the plates cause the violent ground shaking we know as an *earthquake*. The island country of Japan is located just 200 km (~124 mi.) west of the Japan Trench, where the Pacific plate is subducting beneath the Eurasian plate at a rate of about 9 cm (~3.5 in.) per year (Figure 3.1).[1] The convergence of these two plates means Japan experiences frequent large earthquakes.

On March 11, 2011, the strongest recorded earthquake to hit Japan, and one of the top five largest earthquakes ever documented, struck 72 km (~45 mi.) offshore of the Tohoku region of Japan's main island (Figure 3.1). Although Japan has the worlds most advanced system for detecting earthquakes,[2] and scientists had forecast a large earthquake for the Tohoku region, the 2011 quake was significantly greater than was considered possible. Fifteen times more powerful that the

< Tohoku Earthquake Devastated Fukashima, Japan
Military helicopters fly over tsunami inundated and burning coastal Japan following the 2011 earthquake. *(US Navy)*

Earthquakes are serious natural hazards that affect people across the globe, sometimes at long distances from where the quakes occur. They are especially dangerous because seismologists, the scientists who study earthquakes, cannot predict them in time for evacuations or other precautions.

After reading this chapter, you should be able to:

LEARNING Objectives

LO:1 Compare and contrast the different types of faulting.

LO:2 Explain the formation of seismic waves.

LO:3 Summarize the processes that lead to an earthquake and the release of seismic waves.

LO:4 Differentiate between the magnitude scales used to measure earthquakes.

LO:5 Identify global regions at most risk for earthquakes, and describe the effects of earthquakes.

LO:6 Describe how earthquakes are linked to other natural hazards.

LO:7 Discuss the important natural service functions of earthquakes.

LO:8 Explain how human beings interact with and affect the earthquake hazard.

LO:9 Discuss the United States governmental approach to minimizing the effects of earthquakes.

LO:10 Propose ways to minimize seismic risk and suggest adjustments we can make to protect ourselves.

3

Linkages exist between natural hazards.

Most of the destruction and loss of life due to the 2011 Tohoku earthquake was not due to the earthquake, but rather a tsunami triggered by the quake, which caused widespread coastal flooding of the Tohoku region (northeast) of Japan (see Chapter 4).

4

Humans can turn hazardous events into disasters.

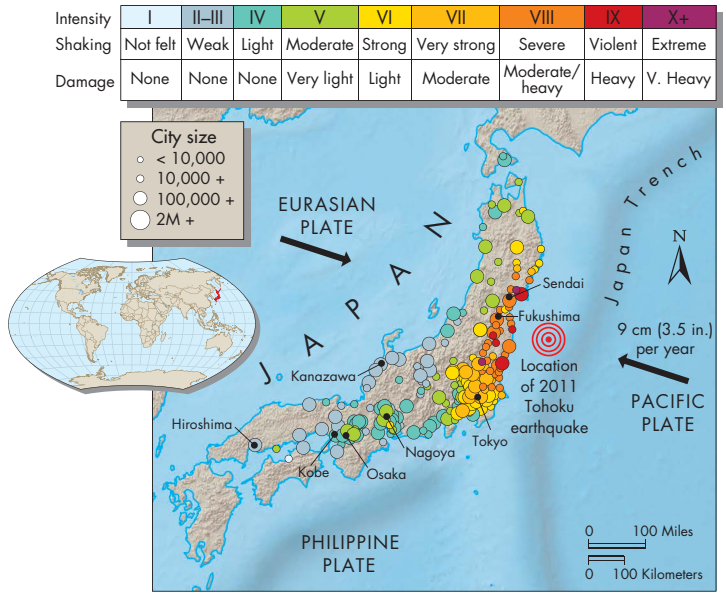
In 2004, Indonesia was struck by a similarly large earthquake and tsunami, but while Japan's population has remained constant since 1900, Indonesia's has grown fivefold in the last century, making the 2004 Indian Ocean earthquake one of the most deadly recorded natural disaster (see Chapter 4).

5

Consequences of hazards can be minimized.

At the end of the chapter, you will learn about how widespread building and infrastructure collapse during the less powerful 1995 Kobe earthquake led to better earthquake building codes in Japan that minimized loss of life and damage during the 2011 Tohoku earthquake.

1906 earthquake that destroyed San Francisco (Table 3.1), the 2011 Tohoku earthquake released about 600 million times more energy than the atomic bomb dropped on Hiroshima at the end of World War II. In just a few minutes a 500 km (~310 mi.) long section of the Pacific plate moved as much as 40–60 m (~130–200 ft.) toward the northwest beneath Japan.[1] Shaking was felt across much of the island and lasted as long as six minutes in some locations (Figure 3.1). Had this earthquake occurred in a country where buildings are less well engineered, the loss of life due to structural collapse would have been significantly greater. In fact, the greatest loss of life was caused by another natural hazard linked to the quake—specifically, a large ocean wave triggered by the earthquake, known as a *tsunami*, which swept inland killing 93 percent of the 16,000 people who died that day (see Chapter 4).[3]



▲ FIGURE 3.1 Shaking and Damage During the Tohoku Earthquake

Japan sits at the junction of three different tectonic plates. In 2011, the Pacific plate surged northwestward beneath the Eurasian plate and Japan, triggering the Tohoku earthquake, causing severe shaking and damage across most of the main island of Honshu. Intensity scale is described in Section 3.3 of this chapter. *(Based on "Poster of the Great Tohoku Earthquake (northeast Honshu, Japan) of March 11, 2011 – Magnitude 9.0," USGS, available at http://earthquake.usgs.gov/earthquakes/eqarchives/poster/2011/20110311.php)*

3.1 Introduction to Earthquakes

Worldwide, people feel an estimated 1 million earthquakes a year. However, few of these quakes are noticed very far from their source, and even fewer are considered major earthquakes. Table 3.1 lists significant earthquakes in the United States in the past 200 years. Even if you have never experienced an earthquake, you may wonder what actually happens when one occurs. To understand the effects of earthquakes and where earthquakes occur, we first need to learn about what causes earthquakes.

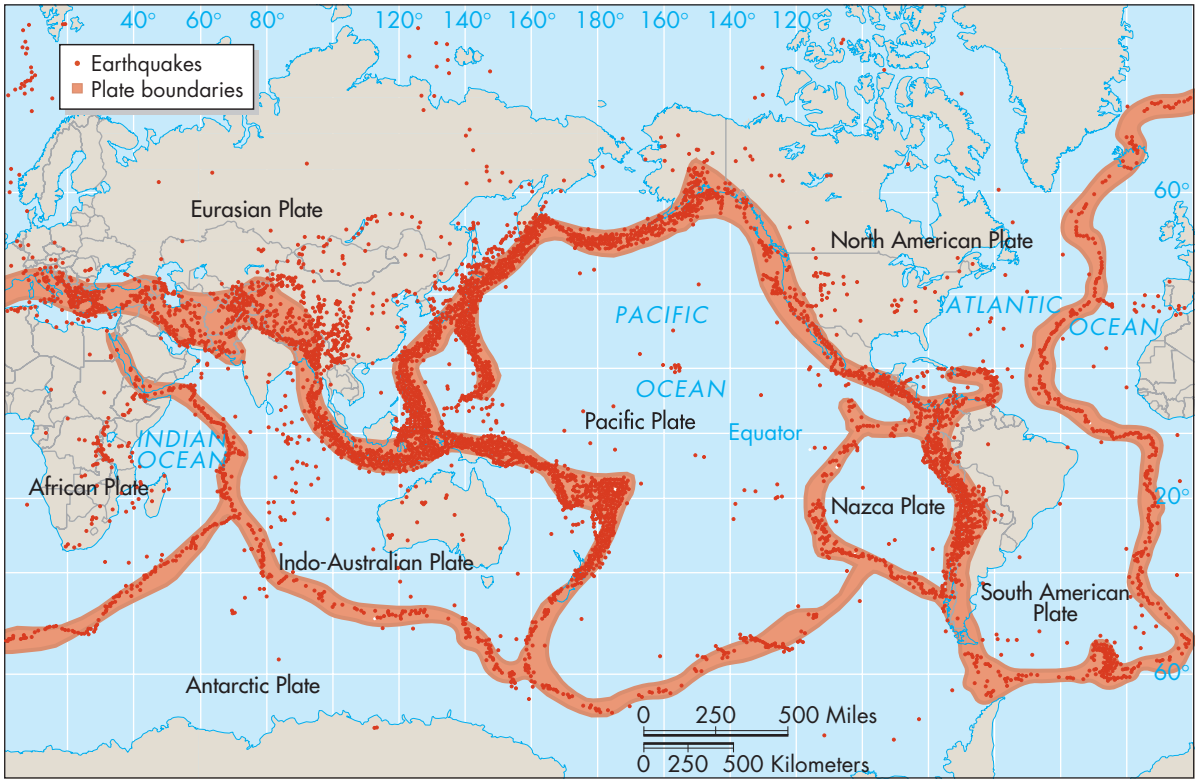
As discussed in Chapter 2, Earth is a dynamic, evolving system in which the movement of tectonic plates results in the formation and destruction of ocean basins, and the uplift of mountains. These processes are most active along the boundaries of lithospheric plates where *faulting* occurs (Figure 3.2).

▼ TABLE 3.1 Significant Earthquakes in the United States

Year	Locality	Damage (millions of dollars)	Number of Deaths
1811–1812	New Madrid, Missouri	Unknown	Unknown
1886	Charleston, South Carolina	23	60
1906	San Francisco, California (includes deaths from fire)	524	>3000
1925	Santa Barbara, California	8	13
1933	Long Beach, California	40	115
1940	Imperial Valley, California	6	9
1952	Kern County, California	60	12
1959	Hebgen Lake, Montana (damage to timber and roads)	11	28
1964	Prince William Sound, Alaska (includes tsunami deaths and damage near Anchorage and on U.S. West Coast)	500	125

Year	Locality	Damage (millions of dollars)	Number of Deaths
1965	SeattleTacoma, Washington	13	7
1971	Sylmar (San Fernando), California	553	65
1983	Coalinga, California	31	0
1983	Borah Peak, central Idaho	15	2
1987	Whittier Narrows, California	358	8
1989	Loma Prieta (San Francisco area), California	6000	63
1992	Landers, California	271	3
1994	Northridge, California	20,000	60
2001	Nisqually (Puget Sound), Washington	2300	1
2002	Denali Fault, southcentral Alaska	(sparsely populated area)	0
2006	Kiholo Bay, Hawaii, Hawaii	200	0
2010	Southernmost California and northern Mexico	100	several in Mexico
2011	Central Virginia	200	0
2014	South Napa Valley, California	5001	

Source: U.S. Geological Survey Earthquake Hazards Program (http://earthquakes.usgs.gov).

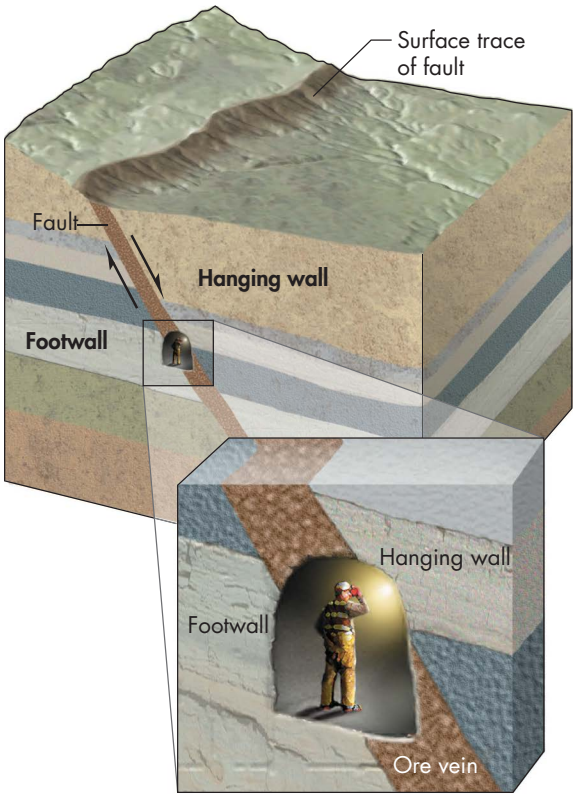


▲ FIGURE 3.2 Earthquake Distribution

Map showing the global distribution of moderate to large earthquakes (1963–88). Notice that most earthquakes occur along plate boundaries (shaded area), in contrast to intraplate earthquakes (isolated dots), which are infrequent. *(From the USGS National Earthquake Information Center)*

FAULTS AND FAULTING

Earthquakes occur along a plane of weakness in Earth's crust known as a **fault**, which is common along plate boundaries. A fault is a semiplanar fracture or fracture system where rocks have been displaced; that is, Earth's crust on one side of the fracture or fracture system has moved relative to the other side. Geologists use centuries-old mining terminology to describe the rocks that are displaced across faults, because many early underground mines were dug into the Earth along inclined surfaces to mine mineralized ore veins along fault zones. Specifically, the block below the fault plane where the miner would stand is known as the **footwall**, whereas the block above the fault plane where a lantern could be hung is known as the **hanging wall** (Figure 3.3).

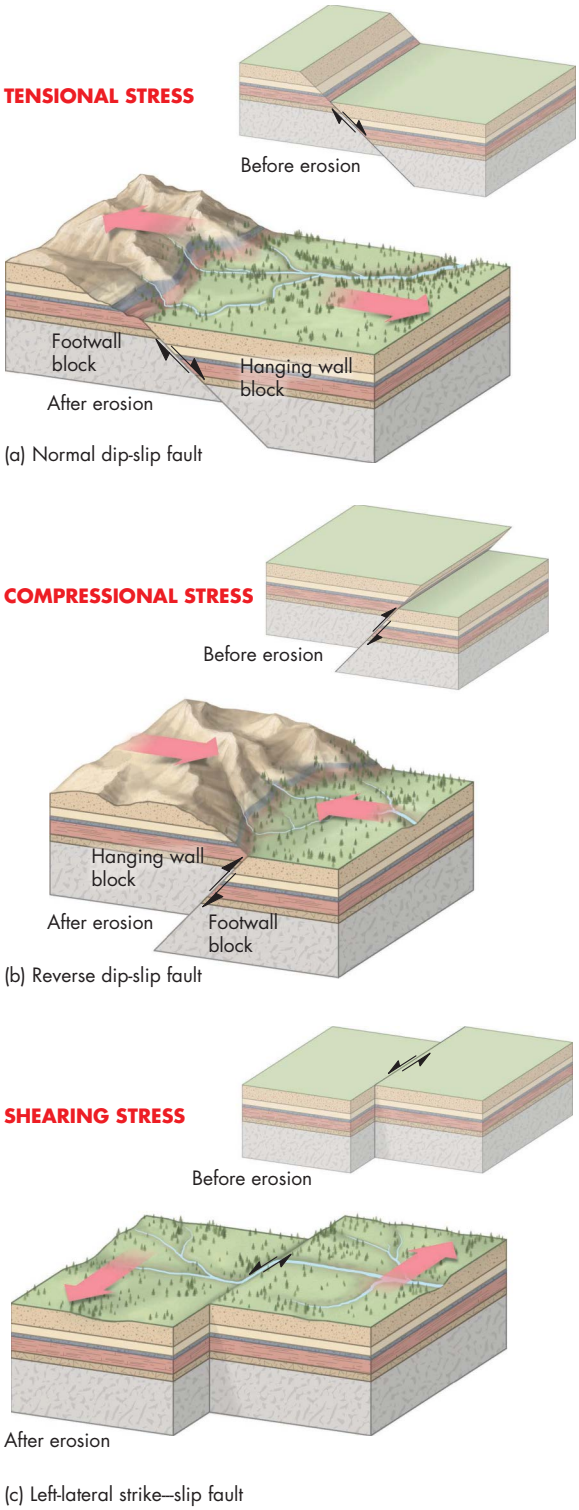


▲ FIGURE 3.3 Basic Fault Features
Block diagram of a dip-slip fault illustrating several basic fault features. Because dip-slip faults are inclined (not vertical), rocks to the right of the fault are above the fault, whereas rocks to the left are below the fault. The hanging wall is defined as the block of rocks that lies above the fault where a miner hangs his lantern, while the block of rocks below the fault that the miner stands on is known as the footwall. *(Based on "Crustal Deformation," GeoPhysics at Ohio University)*

The process of fault rupture, or *faulting*, can be compared to sliding one rough board past another. Friction along the boundary between the boards may temporarily slow their motion, but rough edges break off and motion occurs at various places along the plane. Similarly, one lithospheric plate moving past another is slowed by friction along the fault plane that separates the plates. This "braking action" stresses the rocks along the fault, and as a result, these rocks undergo strain or deformation. When the stresses on rocks exceed their strength, that is, their ability to withstand the force, the rocks rupture and are permanently displaced along the fault plane. Put another way, **stress** is a force that results from plate tectonic movements and **strain** is the change in shape or location of the rocks due to the applied stress. As you recall from Chapter 2, there are three different types of plate boundaries (convergent, divergent, and transform); therefore, there are three different types of stress—*tensional*, *compressional*, and *shearing*—and three primary types of faults (Figure 3.4).

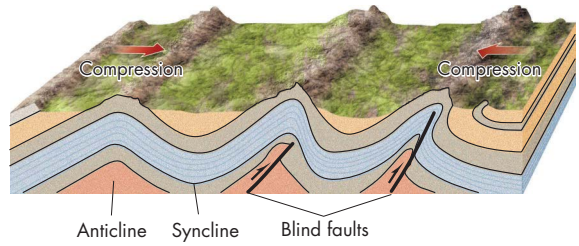
Fault Types Faults are distinguished by the direction in which rocks on either side are displaced. A *dip-slip* fault offsets rocks in a vertical motion due to compressional or tensional stresses, whereas a **strike-slip fault** offsets blocks of crust in a horizontal direction due to shearing stress. A **normal fault** is a type of fault identified by downward movement of the hanging wall relative to the footwall (Figure 3.4a). This movement is caused by tensional stress, which results in extension and thinning of Earth's crust typical of divergent plate boundaries. By contrast, a **reverse fault** is identified by an upward relative movement of the hanging wall due to compression, which results in shortening and thickening of Earth's crust typical of convergent plate boundaries (Figure 3.4b). Unlike reverse and normal dip-slip faults, which are inclined or said to have a dip, a strike-slip fault is close to vertical and, therefore, does not have a hanging wall or a footwall. But similar to a dip-slip fault, a reversal in the orientation of the stresses on either side of the fault will result in two different types of strike-slip faults. Because strike-slip faults offset Earth's crust laterally or in a horizontal motion, strike-slip faults are either right-lateral or left-lateral. The example in Figure 3.4c shows a stream that has been offset by left-lateral faulting. You can determine this by imagining you are paddling your kayak along the river—it does not matter whether you are paddling upstream or downstream—and when you arrive at the fault, you will need to turn to the left in order to get to the part of the stream that has been left-laterally offset.

Until recently it was thought that most active faults could be mapped because their most recent earthquake would cause a surface rupture. However, we now know



< FIGURE 3.4 Types of Geologic Faults

Three common types of faults and their effects on the landscape. Large red arrows on the surface of the block diagrams show the stress directions, while the black arrows along the fault show relative offset (strain) across the fault. Blocks above are shown after movement on the fault with no erosion, whereas the blocks below show effects of erosion. (a) A normal dip-slip fault in which the hanging wall on the right side of the fault has dropped down. (b) A reverse dip-slip fault in which the hanging wall above the fault has moved up. (c) Strike-slip fault with horizontal displacement along the fault plane. This particular example shows left-lateral displacement.



∧ FIGURE 3.5 Blind Faults

Blind reverse faults accommodate compressional stresses by offsetting rock layers at depth and by folding near to Earth's surface. The upward folds are called anticlines and downward folds are called synclines. *(Modified after Lutgens, F, and Tarbuck, E. 1992.* Essentials of geology, *4th ed. New York: Macmillan.)*

that some active faults, referred to as *blind faults*, do not extend to the surface (Figure 3.5). This discovery has made it more difficult to evaluate the earthquake hazard in some areas. For example, the 1994 Northridge earthquake, which killed 60 people and caused at least $20 billion in property damages, occurred on a previously unknown active blind fault that caught the geologists working in the Los Angeles Basin completely by surprise. Since 1994, the earthquake hazard community has become focused on locating these structures in densely urbanized areas. Although blind faults do not offset rocks at the surface, geologists often locate them by identifying folds at the surface known as *anticlines and synclines* (Figure 3.5).

3.1 CHECK your understanding

1. If you were looking at the two blocks on either side of a fault, how would you differentiate the hanging wall from the footwall?
2. What types of stresses are responsible for normal, reverse, and strike-slip faulting?
3. How would you tell the difference between a strike-slip and a dip-slip fault?

3.2 The Earthquake Processes

Most geologists consider a particular fault to be an *active fault* if it has moved during the past 10,000 years of the Holocene Epoch. The Holocene, the most recent epoch of the Quaternary Period of Earth's geologic history, is preceded by the Pleistocene Epoch of the Quaternary Period. Much of our present-day landscape developed during the Quaternary Period. Faults that show evidence of movement during the Pleistocene but not the Holocene Epoch are classified as *potentially active* (Table 3.2).

Faults that have not moved during the past 2 million years are generally classified as *inactive*. However, we emphasize that it is often difficult to prove when a fault was last active, especially where no historical record of earthquakes exists. In many cases geologists must determine the **paleoseismicity** of the fault, that is, the prehistoric record of earthquakes. They do so by determining the age of the most recent faulted or folded sediments. Because the faults themselves are often buried just below our feet or are blind, determining paleoseismicity often involves excavating a paleoseismic trench across the active fault to expose the deformation (Figure 3.6).



FIGURE 3.6 Paleoseismic Trench
Paleoseismic trench excavated across folded sediments above a blind fault in Southern California. *(Duane E. DeVecchio)*

THE EARTHQUAKE CYCLE

Observations of the 1906 San Francisco earthquake led to a hypothesis known as the **earthquake cycle**. The earthquake cycle proposes that there is a drop in elastic strain after an earthquake and an accumulation of strain before the next event.

As stated previously, strain is deformation resulting from stress. *Elastic strain* may be thought of as deformation that is not permanent, provided that the stress is eventually released. When the stress is released, the elastically deformed material returns to its original shape. If the stress is not released and continues to increase, the deformed material will eventually rupture, making the deformation permanent. For example, when you apply tensional stress to a rubber band—sometimes called an elastic—it stretches but will return to its original shape when the stress is released. However, if you apply too much stress, the rubber band will break and be permanently deformed. When it breaks, the broken band often

TABLE 3.2 Terminology for Faults Based on Last Activity

Geologic Age				Start of Time Interval	Fault Activity
Era	Period	Epoch		(in Years before Present)	
Cenozoic			Historic	200	Active
		Holocene	Prehistoric	10,000[a]	
	Quaternary	Pleistocene		1,650,000[a]	Potentially active
	Tertiary			65,000,000	
Pre-Cenozoic time				4,600,000,000 (age of Earth)	Inactive

[a] Dates used for regulatory purposes. Actual dates for these geologic time intervals have changed (see Chapter 1).

Source: Based on California State Mining and Geology Board Classification, 1973.

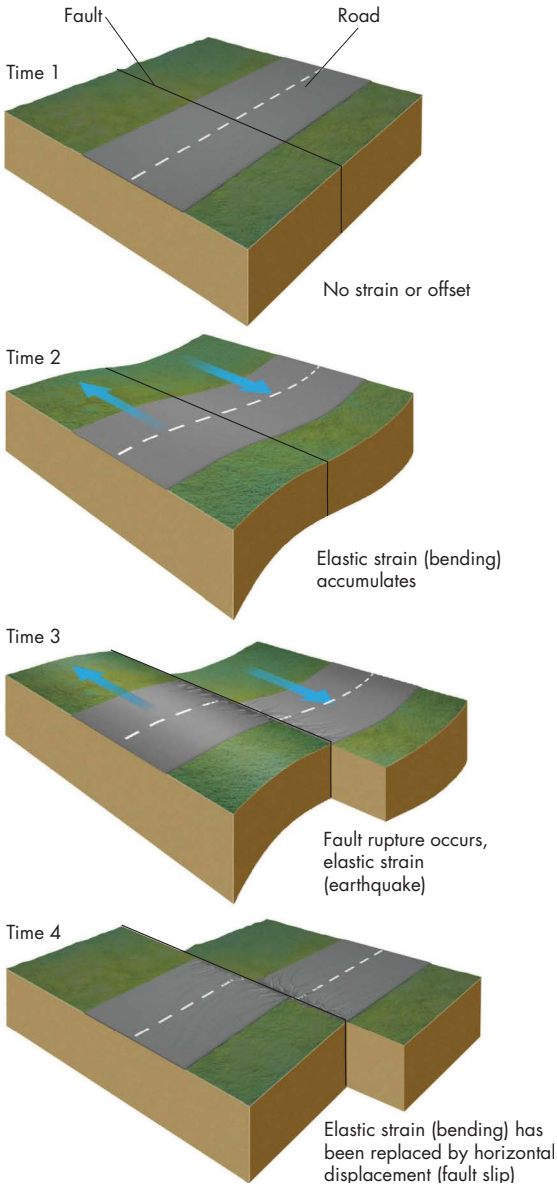


FIGURE 3.7 Elastic Rebound
Idealized diagram showing buildup and release of elastic strain on a right-lateral strike-slip fault due to continuously applied shear stress. At time 1, stress is applied, but there is no significant accumulation of strain or deformation along the fault. At time 2, accumulation of elastic strain within the rocks has caused the road to become curved. Elastic strain will continue to build until the maximum strength of the rocks along the fault is surpassed causing the fault to rupture. At time 3, fault rupture begins and elastic energy is released causing offset of the two fault blocks across the fault. The offset of the road indicates the amount of displacement. Time 4 is immediately following the fault rupture showing rebound of the elastic strain and permanent fault offset. Progression from time 1 to time 4 may take hundreds to thousands of years.

shoots across the room, releasing the pent-up energy with a "snap." Earthquakes along faults are caused by a very similar process where tectonic stresses are applied to rocks. The rocks deform elastically until a critical point is reached and the fault slips, releasing the stored elastic energy in a process know as *elastic rebound* (Figure 3.7).

Seismologists speculate that a typical earthquake cycle has three or four stages.[4] The first stage is a long period of inactivity along a segment of a geologic fault. In the second stage, accumulated elastic strain produces small earthquakes. A third stage, consisting of *foreshocks*, may occur only hours or days prior to the next large earthquake. Foreshocks are small- to moderate-sized earthquakes that occur before the main event. However, in some cases, this third stage may not occur. Finally, the fourth stage is the *mainshock*, the major earthquake, and its aftershocks.[4] An *aftershock* is a smaller earthquake occurring near the location of the mainshock anywhere from a few minutes to a year or so following the main event.

Following the mainshock of an earthquake, news reports generally give information about where the earthquake was located. This location, known as the **epicenter**, is the place on the surface of Earth above where the ruptured rocks broke to produce the earthquake. The point of initial breaking or rupturing within the Earth is known as the **focus**, or *hypocenter*, of the earthquake and is directly below the epicenter (Figure 3.8). When a rupture begins, displacement of rocks starts at the focus and

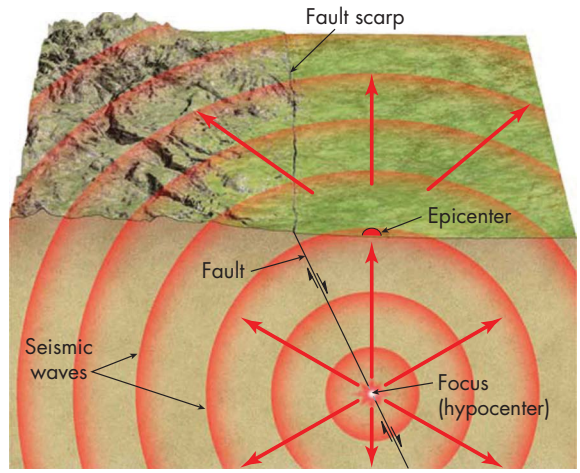


FIGURE 3.8 Basic Earthquake Features
The epicenter of an earthquake is the surface location directly above the focus, which is where movement on the fault begins. During large earthquakes, displacement may propagate from the focus to the surface causing surface deformation to occur, known as a fault scarp. *(Tarbuck, Edward J., Lutgens, Frederick K., and Tasa, Dennis G. Earth: An introduction to physical geology, 11th ed., © 2014, p. 363. Reprinted and electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)*

then propagates up, down, and laterally along the fault plane during the earthquake. The sudden rupture of the rocks produces shock waves, called *seismic waves*, which cause ground shaking.

SEISMIC WAVES

When a fault ruptures, rocks break apart suddenly and violently, releasing stored elastic strain energy in the form of **seismic waves**. These waves radiate outward in all directions from the focus, like ripples on a pond after a pebble hits the water. It is the strong motion from seismic waves as they pass through the ground beneath our feet that we perceive as an *earthquake*, cracking the ground and damaging buildings and other structures. The term *earthquake* also refers to the fault rupture that gives rise to the waves.

Some of the seismic waves generated by the fault rupture travel within the body of the Earth, known as *body waves*, whereas others travel along the surface and are known as *surface waves*. There are two types of body waves: P waves and S waves.

P waves, also called compressional or primary waves, are the faster of the two (Figure 3.9a). They can travel through solids, liquids, and gases. P waves travel much more quickly through solids than through liquids; the average velocity for P waves through Earth's crust is 6 km (~3.7 mi.) per second, in contrast to 1.5 km (~0.9 mi.) per second through water. Interestingly, when P waves reach Earth's surface and are transmitted into the air, some people and animals may be able to hear a fraction of the seismic waves.[5] However, the sound that most people hear when an earthquake is approaching is the loud noise of objects vibrating, not the actual P wave.

S waves, also called shear or secondary waves, can travel only through solid materials (Figure 3.9b). They travel more slowly than P waves and have an average velocity through Earth's crust of 3 km (~1.9 mi.) per second. S waves produce an up-and-down motion (sideways shear) at right angles to the direction that the wave is moving. This movement is similar to the whipping back and forth of a large jump rope being held by two people on a playground. When liquids are

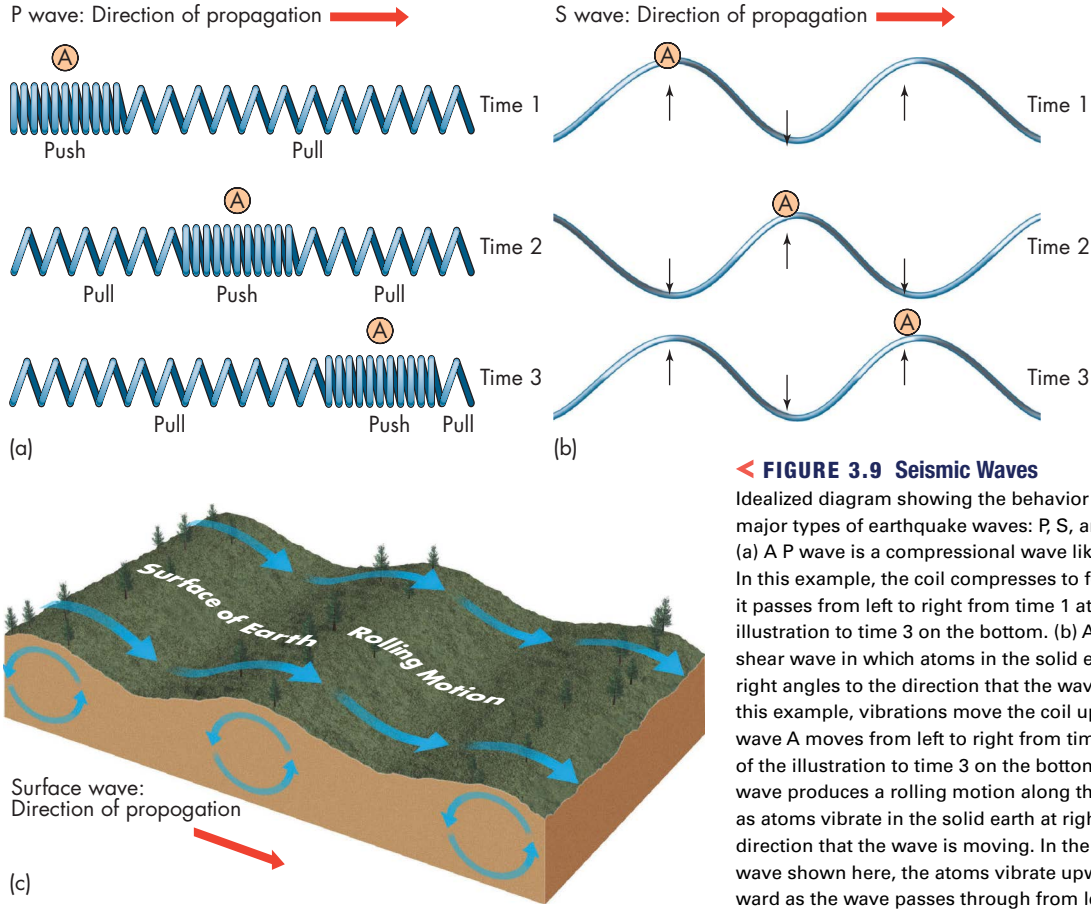


FIGURE 3.9 Seismic Waves
Idealized diagram showing the behavior of the three major types of earthquake waves: P, S, and surface. (a) A P wave is a compressional wave like a sound wave. In this example, the coil compresses to form wave A as it passes from left to right from time 1 at the top of the illustration to time 3 on the bottom. (b) An S wave is a shear wave in which atoms in the solid earth vibrate at right angles to the direction that the wave is moving. In this example, vibrations move the coil up and down as wave A moves from left to right from time 1 at the top of the illustration to time 3 on the bottom. (c) A surface wave produces a rolling motion along the land surface as atoms vibrate in the solid earth at right angles to the direction that the wave is moving. In the type of surface wave shown here, the atoms vibrate upward and downward as the wave passes through from left to right.

subjected to sideways shear, they are unable to spring back, which explains why S waves can't move through liquids.

When P and S waves reach the land surface, complex *surface waves* form and move along Earth's surface. These waves travel more slowly than either P or S waves, and they cause much of the damage near the epicenter. Because surface waves have a complex horizontal and vertical ground movement or rolling motion, they may crack walls and foundations of buildings, bridges, and roads (Figure 3.9c). People caught near the epicenter of a strong earthquake have reported seeing these waves rippling across the land surface. One type of surface wave, called a *Love wave*, causes horizontal shaking that is especially damaging to building foundations.

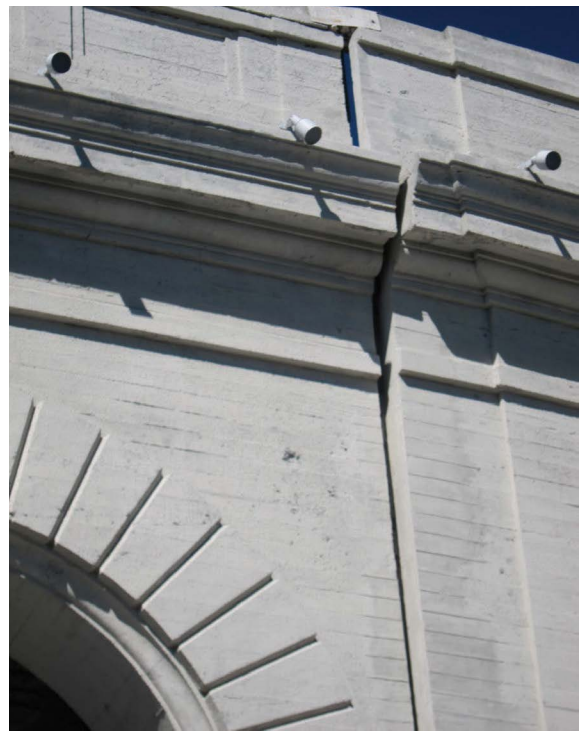
TECTONIC CREEP AND SLOW EARTHQUAKES

Some active faults exhibit **tectonic creep**, that is, gradual movement along a fault that is not accompanied by perceptible earthquakes. For example, tectonic creep along the Cascadia subduction zone beneath southwestern British Columbia and the state of Washington produces *slow earthquakes*, which are not felt and only recently have been detected.[6] Also called *fault creep*, this process can slowly damage roads, sidewalks, building foundations, and other structures (Figure 3.10). Tectonic creep has damaged culverts under the University of California at Berkeley football stadium. Movement of 2.2 cm (~1 in.) was measured beneath the stadium in only 11 years, and periodic repairs have been necessary as the cracks developed.[7] More rapid tectonic creep has been recorded on the Calaveras Fault near Hollister, California. There, a winery on the fault is slowly being pulled apart at about 1 cm (~0.4 in.) per year.[8] Just because a fault creeps does not mean that damaging earthquakes will not occur along the fault. Often the rate of creep is a relatively small portion of the total slip rate on a fault; periodic sudden displacements that produce earthquakes can also be expected.

Slow earthquakes are similar to other earthquakes in that they are produced by fault rupture. The big difference is that the rupture, rather than being nearly instantaneous, can last from days to months. Slow earthquakes are a newly recognized fundamental Earth process. They are recognized through analysis of continuous geodetic measurement or geographic positioning systems (GPS), similar to the devices used in automobiles to identify location. These instruments can differentiate horizontal movement in the millimeter range and have been used to observe surface displacements from slow earthquakes. When slow earthquakes occur frequently, say every year or so, their total contribution to changing Earth's surface to produce mountains may be significant over geologic time.[9]



(a)



(b)

▲ FIGURE 3.10 Tectonic Creep

(a) Slow, continual movement along the San Andreas fault has split this concrete drainage ditch at Almaden Vineyards south of Hollister, California. For scale, there is a person's shoe and blue pant leg in the upperleft corner of the image. *(James A. Sugar/ National Geographic Creative)*; (b) creep along the Hayward fault (a branch of the San Andreas fault) is slowly deforming the football stadium at the University of California, Berkeley. The stadium has been redesigned to accommodate this offset along this vertical opening in the stadium wall. *(Duane E. DeVecchio)*

3.1 CASE study

2015 Nepal (Gorkha) Earthquake: Forecasting a Catastrophe

Nepal is an Asian country that lies along the steep slopes of the Himalayan Mountains, which result from the collision between the Eurasian and Indian plates (Figure 3.11). The large earthquake that struck on April 25, 2015 below the Gorkha District of Nepal killed more than 9,000 people and was expected. For years, experts had been warning that the capital city of Kathmandu was overdue for a powerful earthquake that could decimate the rapidly growing city. In fact, a team of about 50 earthquake scientists and social scientists had gathered in Kathmandu just one week before the event to discuss the impact and ensuing catastrophe that would follow a large magnitude earthquake that scientists felt was imminent.[10]

The gap in historically large earthquakes west of Kathmandu between 1505 and 1866 was what concerned scientists (Figure 3.11). With a convergence rate of about 45 mm/yr, many meters of elastic strain would have accumulated over the past few hundred years (see Section 3.2). This meant that a powerful earthquake was overdue to release the accumulated strain. The 2015 earthquake caused the Eurasian plate to lurch southward over the Indian Plate by as much as 5 m (16 ft.) along 150 km (93 mi.) zone between the epicenters of the 2015 and 1866 events (Figure 3.11). The ground shaking was intense and uplifted the Kathmandu Valley by as much as 1 m (~3 ft.).[11]

With about 10 percent of the population of Nepal living within the Kathmandu Valley and the adjacent steep slopes of the highlands, the devastation of April 25 was just what the scientists had predicted.[10] Building collapse was the primary cause of death in urban environments, which was expected due to a lack of strict earthquake construction codes for homes and civil buildings. Many towns were shaken to complete destruction (Figure 3.12), whereas others were completely wiped away by massive landslides triggered by shaking of the steep slopes.[12] An avalanche triggered by the earthquake killed 21 people on Mount Everest more than 20 km (130 mi.) away, making it the deadliest day in the mountain's history.[13]

For Nepal the 2015 earthquake was catastrophic. The damage is estimated to be in excess of $10 billion or about half of Nepal's gross domestic production (GDP).[14]

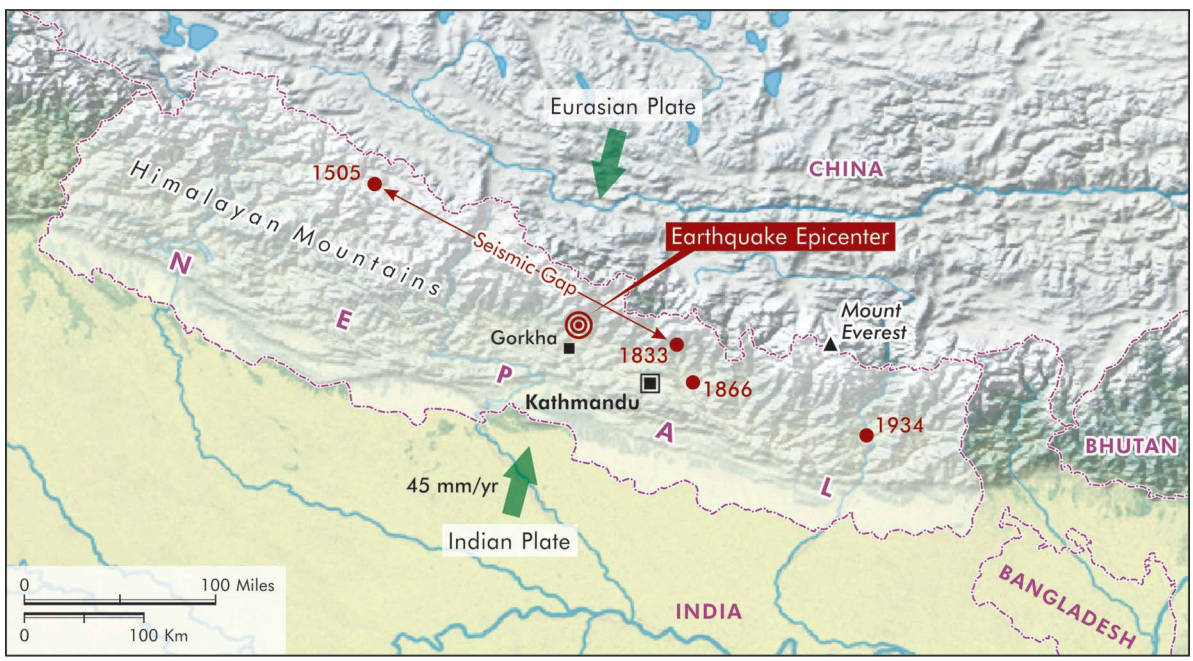


FIGURE 3.11 Forecasting an Earthquake
Along one of the most active plate boundaries in the world between the Eurasian Plate and the Indian Plate, the absence of historic earthquakes (red dots) within the seismic gap northwest of Kathmandu led scientists to believe that the 2015 Nepal earthquake was eminent.



FIGURE 3.12 Earthquake Flattened Town
Numerous small towns in the highlands surrounding Kathmandu were not only shaken to the ground by the 2015 Nepal earthquake, but also bombarded by falling rock from the slopes above. *(Courtesy of Kristen Cook)*

Although billions of dollars have been pledged from around the world to help rebuild, two years after the disaster many tens of thousands of Nepalis are facing a third monsoon season living in temporary habitations.

Although the 2015 Nepal earthquake and its effects were anticipated, it is not possible at this time for scientists to predict earthquakes. As you will learn in the coming sections of this chapter, scientists often speak in probabilities of an earthquake event occurring within a given time frame rather than prediction of a specific time and date.

3.2 CHECK your understanding

1. How are active and potentially active faults defined?
2. Explain the earthquake cycle.
3. Where does the energy that produces seismic waves come from?
4. What is the difference between the epicenter and focus of an earthquake?
5. What is the difference in the rates of travel of P, S, and surface waves?

3.3 Earthquake Shaking

Three important factors determine the shaking you will experience during an earthquake: (1) earthquake magnitude, (2) your location in relation to the epicenter and direction of rupture, and (3) local soil and rock conditions. In general, strong shaking may be expected from earthquakes of moderate *magnitude* or larger (Table 3.3).

TABLE 3.3 Global Frequency of Earthquakes by Descriptor Classification

Descriptor	Average Magnitude	Annual Number of Events
Great	8 and higher	1
Major	7–7.9	14
Strong	6–6.9	146
Moderate	5–5.9	1344
Light	4–4.9	13,000 (estimated)
Minor	3–3.9	130,000 (estimated)
Very Minor	2–2.9	1,300,000 (estimated) (approx. 150 per hour)

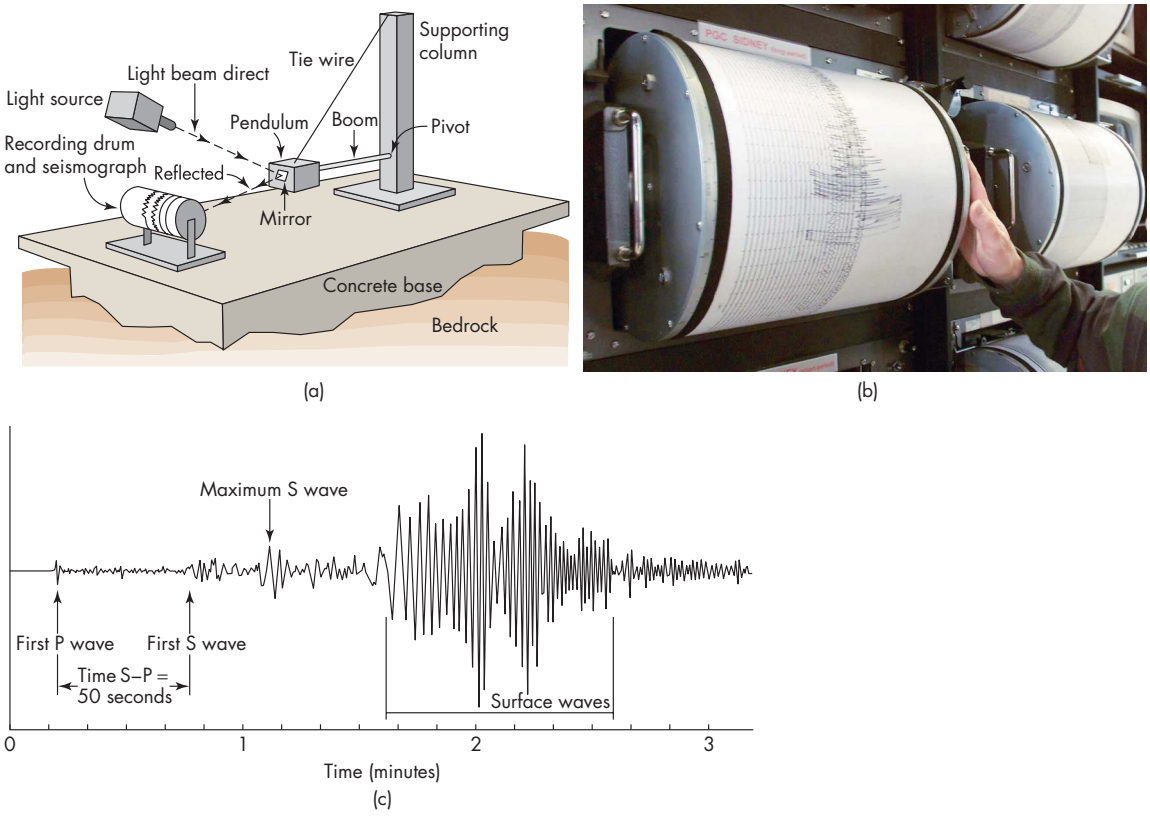
Source: U.S. Geological Survey, "Earthquake Statistics," 2000–15, https://earthquake.usgs.gov/earthquakes/browse/stats.php. Accessed 7/21 /2017.

EARTHQUAKE MAGNITUDE

In addition to the epicenter location, news reports also provide a decimal number (e.g., 6.8) that refers to the size or magnitude of the earthquake. Immediately following an earthquake, the first magnitude estimates were made using the **Richter scale**, developed in 1935 by the famous seismologist Charles Richter. The Richter magnitude of an earthquake is determined by measuring the maximum amount of ground shaking due to the S wave. Ground motion, in either a vertical or horizontal direction, is recorded by an instrument known as a **seismograph** or *seismometer* (Figure 3.13a).

The Richter scale is logarithmic, which means that the increase from one integer to the next is not linear. For example, the ground displacement during a magnitude 6.0 earthquake is approximately 10 times as great as displacement during a magnitude 5.0 quake. As you will learn later in this section, the amount of ground shaking at any one location is strongly affected by numerous variables and, therefore, a Richter magnitude is specific to only one location. Multiple seismographs that detect an earthquake will record differing Richter magnitudes depending on where they are located, giving what is known as a *local magnitude*. In other words, Richter magnitudes are not an absolute measurement of the size of an earthquake and, therefore, not well suited for comparing earthquake sizes around the world.

In order to determine the absolute size of an earthquake, the **moment magnitude scale** was developed in the 1970s. The moment magnitude is a measurement of the actual energy released during the earthquake.



▲ FIGURE 3.13 Seismograph

(a) Simplified illustration showing how a seismograph works. *(Based on information from Southern California Earthquake Center)* (b) Modern seismograph at the Pacific Geoscience Centre near Victoria, British Columbia, showing a recording drum on which a seismogram is made. The earthquake is the February 28, 2001, Nisqually, Washington, earthquake (**M** 6.8). *(AP Photo/Victoria Times Colonist, Ian McKain)* (c) Idealized seismogram for an earthquake. The P, S, and surface waves can be identified by changes in the amplitude of the waves on the graph. (d) Differences in arrival time and amount of shaking at three seismic stations located from 38 to 356 km (~24 to 221 mi.) from the 1994 Northridge, California, earthquake. As you get farther away from the epicenter, the seismic waves take longer to reach the seismograph and the amplitude of the waves on the seismograph decreases. In general, the greater the amplitude of the waves on the seismogram, the stronger is the shaking of the ground. *(Based on information from Southern California Earthquake Center)*

The moment magnitude is determined from an estimate of the area that moved along a fault plane during the quake, the amount of movement or slippage along the fault, and the strength of the rocks near the focus of the quake. Unlike the Richter magnitude, which can be determined immediately following the quake, moment magnitude estimates can take days to months to calculate precisely. Because of this the Richter and moment magnitude scales are used in tandem, where immediately following an earthquake scientists will supply local Richter magnitudes to the media, while moment magnitude calculations are still being made. This is why news reports of the magnitude of an earthquake often change over the course of days to months.

Except for very large earthquakes, the magnitude on the Richter scale is approximately equal to moment magnitude. Because of this correlation, we will refer to the size of an earthquake simply as its magnitude, **M**, without designating Richter or moment magnitude.

It is interesting to look at how often earthquakes of various magnitudes occur. Earthquakes are given descriptive adjectives based on their magnitude (see Table 3.3). For example, most damaging earthquakes are described as major (**M** 7–7.9) or strong (**M** 6–6.9). *Major earthquakes* are capable of causing widespread and serious damage. *Strong earthquakes* can also cause considerable damage depending on their location and the nature of earth materials. Fortunately, the most powerful *great earthquakes* (**M** 8 or higher) are uncommon; the worldwide average is one per year (Table 3.3). In contrast, more than 3,500 very minor earthquakes with a magnitude of less than 3 occur each day. Most of these quakes are too small or too remote to be felt by people.

The amount of ground motion produced by an earthquake is related to its magnitude, depth, and the geologic environment in which it occurs. As earthquake magnitudes increase, the amount of ground motion changes less drastically than the amount of energy released (Table 3.4). As this table illustrates, the difference between a **M** 6 and a **M** 7 earthquake is considerable. Although the amount of ground motion, or shaking, from a **M** 7 earthquake is 10 times as great as that from a **M** 6 earthquake, the amount of energy released is 32 times as much! The energy released from a **M** 6 earthquake is about equivalent to a 30 kiloton nuclear explosion, compared to about a 1 megaton explosion for a **M** 7 earthquake. Another way of looking at this: It would take 32 **M** 6 earthquakes to release as much energy as one **M** 7 quake.

TABLE 3.4 Change in Ground Motion and Energy Released from an Incremental Change in Earthquake Magnitude

Units of Magnitude Change	Ground Motion Change[a]	Change in Amount of Energy Released
1	10 times	About 32 times
0.5	3.2 times	About 5.5 times
0.3	2 times	About 3 times
0.1	1.3 times	About 1.4 times

[a] As reflected in the maximum amplitude of S waves on a standard seismograph. Amplitude is the distance that a seismic wave is displaced from a baseline (zero line) that is established when no seismic waves are detected.

Source: U.S. Geological Survey, "Earthquake Facts and Statistics," 2010, http://earthquake.usgs.gov/earthquakes/eqarchives/year/eqstats.php. Accessed 7/12/2013.

EARTHQUAKE INTENSITY

The moment magnitude scale provides a quantitative way of comparing earthquakes. In contrast, earthquake intensity is often indicated with the qualitative **Modified Mercalli Intensity scale**. The 12 categories on this scale are assigned Roman numerals (Table 3.5). Each category contains a description of how people perceived the shaking from a quake and the extent of damage to buildings and other human-made structures. For example, the 1971 Sylmar earthquake in California's San Fernando Valley had a single magnitude (**M** 6.7) but its Mercalli intensity varied from I to XI, depending on distance from the epicenter and on local geologic conditions (Figure 3.14). Because building codes are



FIGURE 3.14 Intensity of Shaking
Modified Mercalli Intensity map for the 1971 Sylmar, California, earthquake (**M** 6.7), determined after the earthquake. The red and orange areas experienced the most intense shaking. See Table 3.5 for an explanation of the Roman numerals. *(U.S. Geological Survey. 1974. Earthquake Information Bulletin 6[5])*

TABLE 3.5 Abbreviated Modified Mercalli Intensity Scale

Intensity	Effects
I	Felt by few people under especially favorable conditions.
II	Felt by only a few persons at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing vehicles may rock slightly. Vibration feels like the passing of a truck.
IV	Felt indoors by many, outdoors by few during the day. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation of a heavy truck striking building; standing vehicles rock noticeably.
V	Felt by nearly everyone; many awakened. Some dishes and windows broken. Unstable objects overturned.
VI	Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	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; some chimneys broken. Noticed by vehicle drivers.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse; damage great in poorly built structures; fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned. Disturbs vehicle drivers.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Underground pipes broken.
X	Some well-built wooden structures are destroyed; most masonry and frame structures with foundations destroyed; train rails bent.
XI	Few, if any, masonry structures remain standing. Bridges destroyed. Underground pipelines taken out of service. Train rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Lines of sight and level are distorted. Objects thrown into the air.

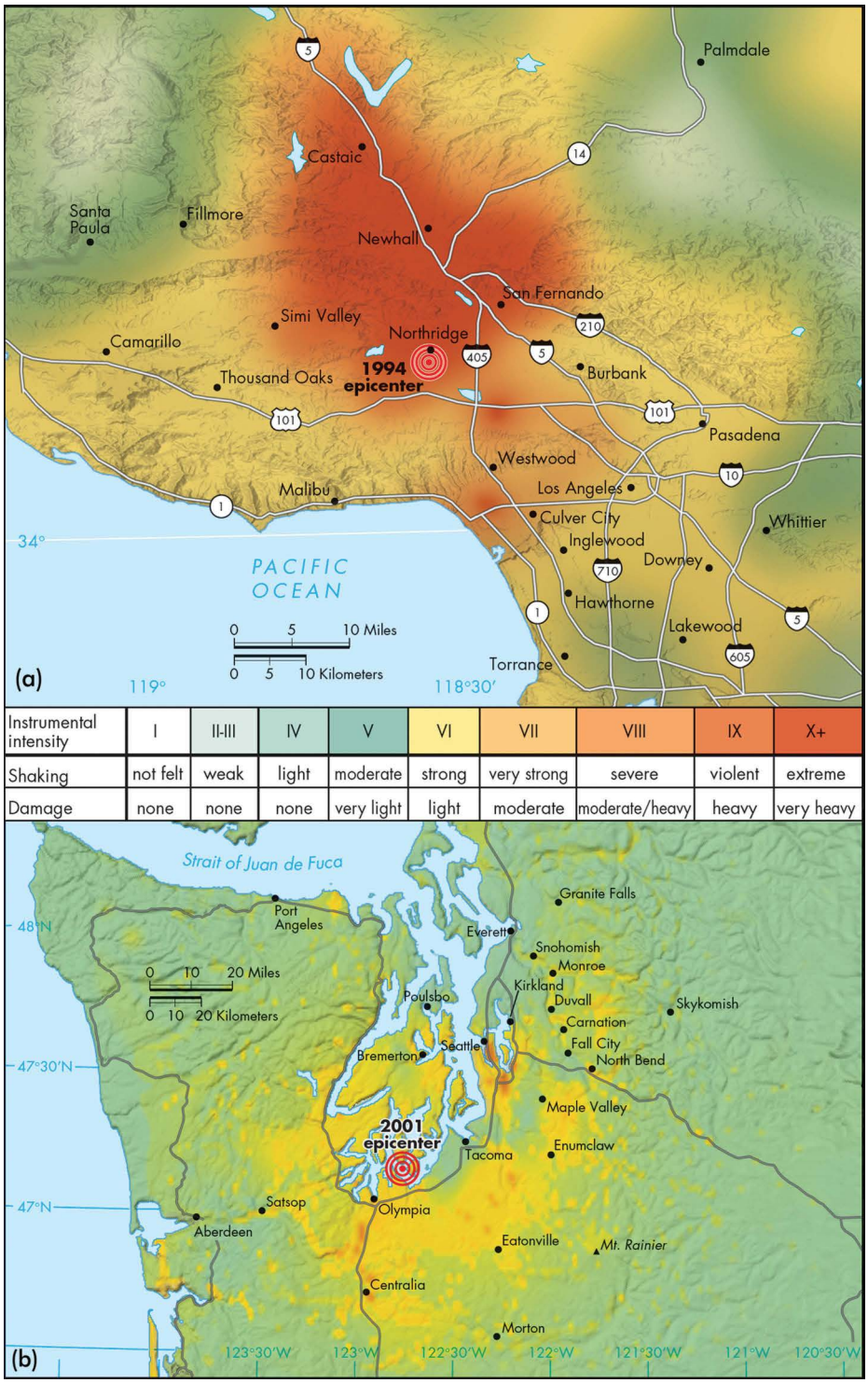
Source: Based on U.S. Geological Survey Earthquake Hazards Program https://earthquake.usgs.gov/learn/topics/mag_vs_int.php. Accessed 7/21/17.

not the same worldwide, Mercalli intensity can also vary from country to country—generally greater where human-made structures are less well constructed (see Case Study 3.2: Earthquake Catastrophes).

Earthquake intensities are commonly shown on maps. Conventional modified Mercalli intensity maps, like that shown in Figure 3.15, take days or even weeks to complete. They are based on questionnaires sent to residents near the epicenter, newspaper articles, and reports from damage assessment teams.

Recently the U.S. Geological Survey (USGS) began experimenting with the use of the Internet to collect intensity information. The USGS website "Did You Feel It?" (https://earthquake.usgs.gov/data/dyfi/) solicits email reports from people in the United States who have recently felt an earthquake (see Figure 3.25). These reports are used to prepare an online *community Internet intensity map* that is updated every few minutes after a large earthquake.

Quickly determining where the damage is most severe is one of the major challenges during a damaging earthquake. This information is now available in parts of California, the Pacific Northwest, and Utah, where there are dense networks of high-quality seismograph stations. These networks transmit direct measurements of ground motion as soon as the shaking stops. This information is known as *instrumental intensity*, and it is used to immediately produce a *shake map* that shows both intensity of shaking and potential damage. Figure 3.15 shows shake maps for the 1994 **M** 6.7 Northridge, California, earthquake and the 2001 **M** 6.8 Nisqually earthquake centered in Puget Sound, Washington. The technology to produce and distribute shake maps in the minutes following an earthquake was made available in 2002.[15] The cost of seismographs is small relative to damages from earthquake shaking, and the arrival of emergency personnel is critical in the first minutes and hours following an earthquake if people in collapsed buildings are to be rescued. The shake map is also useful for locating areas where gas lines and other utilities are likely to be damaged. Clearly, the use of this technology, especially in our urban areas vulnerable to earthquakes, is a desirable component of our preparedness for earthquakes.



▲ FIGURE 3.15 Shake Maps: Differences in Real-Time Instrumental Intensity of Shaking
(a) Instrumental Intensity map for the 1994 Northridge, California, earthquake (**M** 6.7) prepared as the earthquake occurred. *(U.S. Geological Survey and courtesy of David Wald)*; (b) The 2001 Nisqually, Washington, earthquake (**M** 6.8). *(Pacific Northwest Seismograph Network, University of Washington)*

DEPTH OF FOCUS

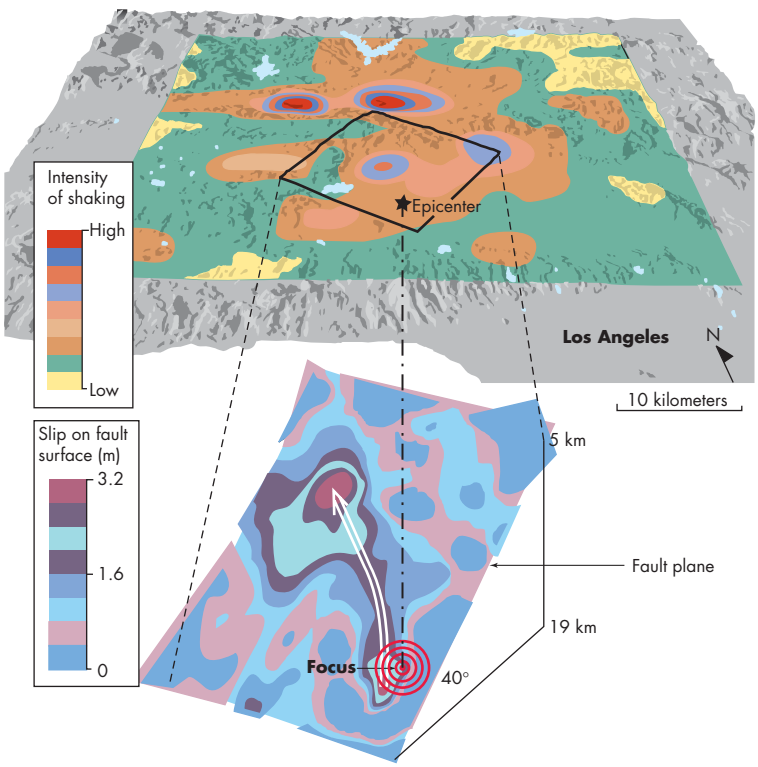
In addition to distance, the depth of an earthquake influences the amount of shaking. Recall that the place within Earth where the earthquake starts is the focus. In general, the deeper the focus of the earthquake, the less shaking that will occur at the surface. The seismic waves lose much of their energy before they reach the surface when the earthquake is relatively deep. This loss of energy, referred to as *attenuation*. For example, attenuation occurred in the 2001 Nisqually, Washington, earthquake (**M** 6.8) (Figure 3.15b). The Nisqually quake occurred along the Cascadia subduction zone at a depth of 52 km (~32 mi.). In comparison, there was less attenuation and more shaking in the 1994 Northridge quake (**M** 6.7), which had a shallower focus depth of 19 km (~12 mi.), but a very similar magnitude (Figure 3.15a).

DIRECTION OF RUPTURE

A third factor that influences the amount of shaking is the direction that the rupture moves along the fault during the earthquake. Although rupture may proceed in many directions from the focus, the path of greatest rupture can focus earthquake energy. This behavior, known as *directivity*, contributes to the amplification of seismic waves and thus to increased shaking. For example, in the 1994 Northridge quake, the path of greatest rupture on the fault was to the northwest (Figure 3.16). This trend caused the most intense shaking to occur northwest of the epicenter rather than directly over the focus.

DISTANCE TO THE EPICENTER

To determine the distance to the epicenter, it must first be located using information about the P and S waves detected by seismographs (see Figure 3.13a and b). The written or digital record of these waves is called a *seismogram*. On a seismogram, the P and S waves appear as an oscillating line that looks similar to an electrocardiograph (ECG) of a person's heartbeat (see Figure 3.13c). Because P waves travel faster than S waves, they will always appear first on a seismogram. Seismologists read the seismogram and use the difference between the time that the first P and S waves arrive (S–P) from a quake to determine how far away the epicenter is. For example, in Figure 3.13c, the S waves arrived 50 seconds after the P waves. This 50-second delay would occur if both types of waves traveled from an epicenter about 420 km (~261 mi.) away. Seismographs scattered across the globe will thus record different arrival times for P and S waves from an earthquake. The seismograph stations that are



< FIGURE 3.16 Direction of Rupture Toward the Area of Most Intense Shaking
Aerial view of the Los Angeles region from the south showing the epicenter and intensity of shaking of the **M** 6.7 1994 Northridge earthquake. The red area in the center of the bull's-eye patterns 10 km (~6 mi.) northwest of the epicenter had the most intense shaking. The bottom of the figure shows the focus and the section of the fault plane that ruptured during the quake. Colors on the fault plane show how much slippage occurred. Greatest slippage is in the reddish-purple bull's-eye pattern northwest of the focus. Rupture started at the focus and followed the direction of the white arrow to the northwest. *(U.S. Geological Survey, "USGS Response to an Urban Earthquake, Northridge '94," U.S. Geological Survey Open File Report 96–263, 1996)*



FIGURE 3.17 Locating an Earthquake
Generalized concept of how the epicenter of an earthquake is located. First, the distance to the event is determined from information on seismograms from at least three seismic stations. Those distances are then used to draw circles around the seismic stations. The point where the circles come together is the epicenter, in this case the epicenter of the 2001 El Salvador earthquake. Accurate location of the epicenter is not always as simple as in this hypothetical example.

farthest from the epicenter will observe the greatest difference between P and S wave arrival times. This relationship was observed for the 1994 Northridge, California, earthquake (see Figure 3.13d).

The difference between P and S arrival times at seismographs in different locations can be used to pinpoint the epicenter of an earthquake. To accomplish this, a distance to the epicenter is calculated for each of three seismographs, and the respective values are used for the radius of a circle drawn around each seismic station. These circles will intersect in one location—the epicenter. The process of locating a feature using distances from three points is called *triangulation*. Thus, the epicenter of an earthquake in Central America can be located by triangulation from seismic stations in Honolulu, Hawaii; Berkeley, California; and San Juan, Puerto Rico (Figure 3.17).

LOCAL GEOLOGIC CONDITIONS

The nature of the local earth materials and local geologic structure strongly influences the amount of ground motion. Earth materials of various types behave differently in an earthquake. This difference is related to their degree of consolidation. Seismic waves move faster

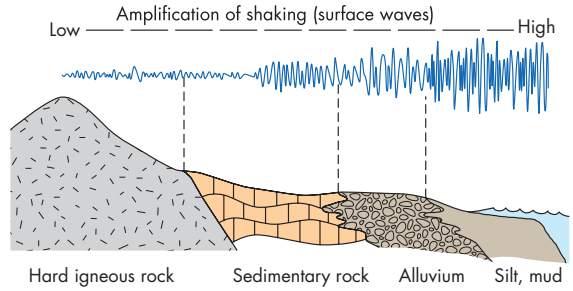
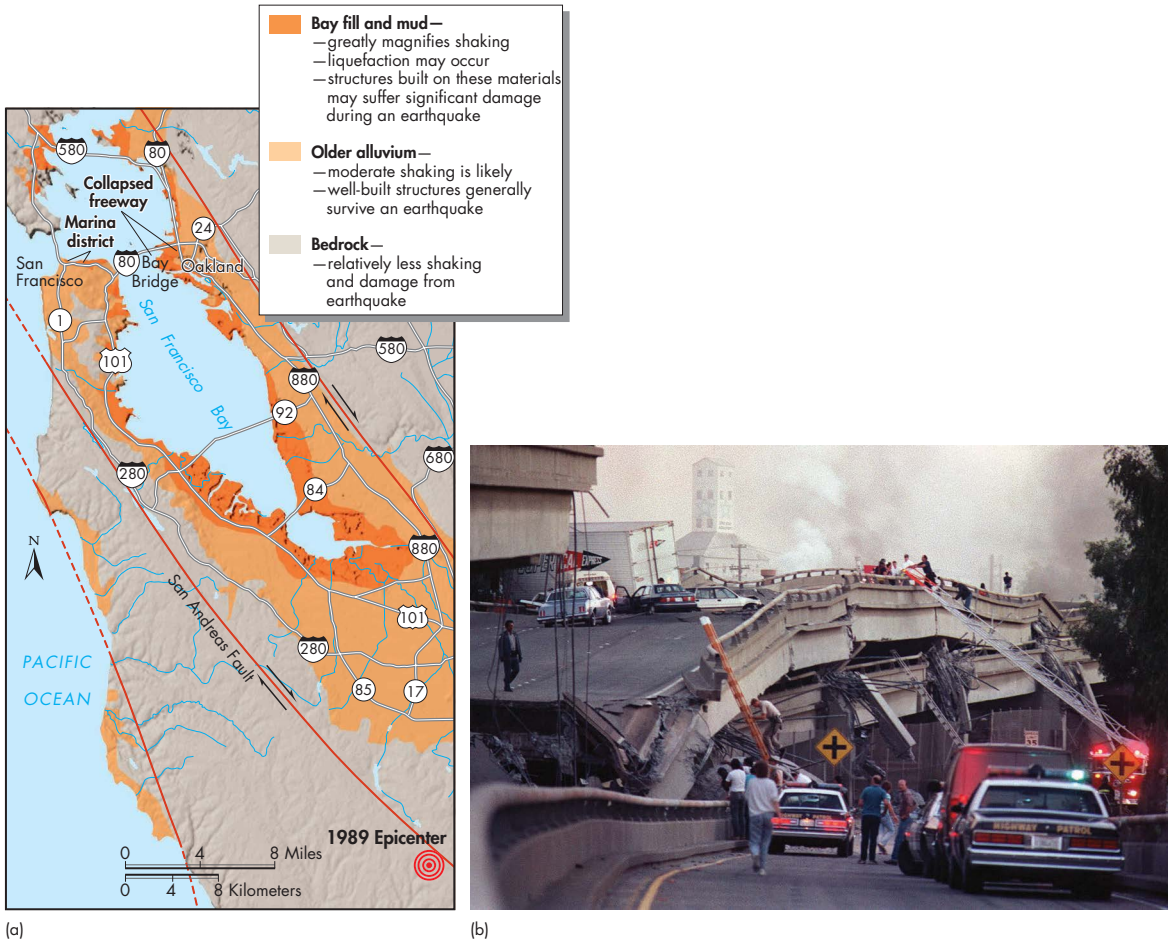


FIGURE 3.18 Material Amplification of Shaking
Generalized relationship between near-surface earth material and amplification of shaking during an earthquake. The material amplification is highest in water-saturated sediment.

through consolidated bedrock than they do through unconsolidated sediment or soil. They slow even further if the unconsolidated material has high water content. For example, seismic waves typically slow down as they move from bedrock to stream deposits of sand and gravel, called *alluvium*, and then slow again as they move through coastal deposits of mud. As P and S waves slow down, the energy that was once directed forward is transferred to the vertical motion of the surface waves (Figure 3.18). This effect, known as **material amplification**, strongly influences the amount of ground motion experienced in an earthquake.

For example, in the 1989 Loma Prieta earthquake (**M** 6.9) in northern California, the most severe ground shaking was experienced along the shore of San Francisco Bay (Figure 3.19a). Intense ground motion caused the collapse of sections of the upper deck of the eastern span of the Bay Bridge and the Nimitz Freeway in Oakland, killing 41 people, and caused extensive damage in the Marina district of San Francisco (Figure 3.19b and 3.19c). The portion of the freeway that collapsed was built on bay fill, mud that had been dumped into San Francisco Bay to create new land. Likewise, the Marina district was created after the 1906 San Francisco earthquake by filling in the shoreline with debris from damaged buildings and with mud pumped from the bottom of the bay.[16] The unconsolidated nature of the bay fill and mud, combined with its high water content, caused the increased shaking. Amazingly, the effects of material amplification meant that the greatest shaking occured 65 km (~40 mi.) north of the epicenter near San Francisco (Figure 3.19a). Following the Loma Preita earthquake it was clear to geologists and engineers that the eastern span of the Bay Bridge was not earthquake safe and that a new bridge would need to be constructed. The new bridge span cost $6.5 billion and took nearly 25 years to complete, not becoming open for traffic until 2013 (Figure 3.19d).

The deaths of more than 8,000 people in the 1985 Mexico City earthquake (**M** 8.0) provide yet another



▲ FIGURE 3.19 Loma Prieta Earthquake

(a) Map of earth materials in the San Francisco Bay region, showing the San Andreas fault zone and the epicenter of the 1989 **M** 6.9 earthquake (southeastern part of map). The most severe shaking was on the muddy bay shore (bright orange) where there are natural deposits of mud and the bay has been filled in to create new land. (b) Shaking caused the collapse of the Nimitz Freeway (I-880) in Oakland, which was built above bay fill and mud deposits. *(Tom Van Dyke/MCT/Newscom)* (c) Damage to buildings in the Marina district of San Francisco resulting from poorly supported first floor that has shifted due to intense shaking caused by material amplification. *(John K. Nakata/USGS)* (d) Completed in 2013 the eastern span of the Bay Bridge stands in front of the old bridge deemed not earthquake safe following the 1989 earthquake. *(Getty)*

tragic example of material amplification. This quake further demonstrated that buildings constructed on materials that are likely to accentuate and increase seismic shaking are extremely vulnerable to earthquakes, even if the event is centered several hundred kilometers away. Much of Mexico City is built on mud deposits from ancient Lake Texcoco. When seismic waves struck the unconsolidated mud, the amplitude of surface shaking appears to have increased by a factor of 4 or 5. More than 500 buildings fell down from the intense shaking.[17] In many buildings, the amplified shaking collapsed upper floors onto lower ones like a stack of pancakes.[18] Local geologic structures can also influence the amount of shaking. For example, troughlike geologic structures, such as synclines and fault-bounded sedimentary basins, can focus seismic waves the way a magnifying lens focuses sunlight. This causes severe shaking in some areas and less intense shaking in others.

3.2 CASE study

Earthquake Catastrophes: Lessons Learned

Catastrophic earthquakes are devastating events that can destroy large cities and take thousands of lives in a matter of seconds. A sixteenth-century earthquake in China reportedly claimed 850,000 lives. More recently, a 1923 earthquake near Tokyo killed 143,000 people, and a 1976 earthquake in China killed several hundred thousand. In 2005 a catastrophic earthquake struck northern Pakistan. Although the epicenter was in Pakistan, extensive damage also occurred in Kashmir and India (Figure 3.20a). More than 80,000 people were killed, and over 30,000 buildings collapsed. A catastrophic continental earthquake occurred in China's



(a) (b) (c) (d)

FIGURE 3.20 Earthquake Damage

(a) Survivors rescue an injured neighbor from a collapsed building in Balakot, Pakistan, in 2005. *(FAROOQ NAEEM/AFP/Getty Images)* (b) Collapsed buildings from 2008 earthquake in China that killed about 87,500 people. *(AP Photo/Greg Baker)* (c) Collapsed apartment building in foreground due to an earthquake in Italy, in 2009. *(Orlando/ZUMA Press/Newscom)* (d) The brown area in the center of this image is the landslide that buried more than 500 homes in the Las Colinas neighborhood of Santa Tecla, a western suburb of San Salvador, the capital of El Salvador. The landslide was triggered by a January 2001 earthquake. *(USGS)*

Sichuan Province in 2008, killing about 87,500 people. Some villages were completely buried by landslides, and more than 5 million buildings collapsed (Figure 3.20b).[19,20,21] On January 12, 2010, an earthquake struck Haiti and killed about 240,000 people (see Figure 1.1).[22] The recent earthquakes that took thousands of lives have a common dominator: They all caused tremendous loss of life because the buildings people were in collapsed. Homes, schools, hospitals, and industrial buildings were subject to collapse in strong shaking because they were not constructed with earthquakes in mind, or the required construction codes were ignored, presumably to save money. In short, most deaths were human induced. We have experience with strong shaking in California (Northridge in 1994), and more recently in Chile (February 27, 2010), where an earthquake about 500 times as strong as the Haiti earthquake only a month earlier killed not hundreds of thousands but hundreds. An earthquake several times smaller than the Northridge quake struck the town of L'Aquila in Italy in 2009, and many of the buildings there collapsed, killing about 300 people (Figure 3.20c). A similar earthquake in California probably would have caused very few deaths, if any. The Italian event was a catastrophe because the buildings were not constructed to sustain moderate seismic shaking.

Building regulations and zoning played an important role in determining the extent of damage from these earthquakes, as they did in the 2011 Tohoku earthquake (see Applying the Fundamental Concepts). Other factors, such as depth of the earthquake rupture and the nature of the soil and rock at and near the surface, were also important in explaining the pattern of damage. However, the dominant factor linked to the number of deaths was the degree to which buildings could withstand the shaking. Criminal complaints have been lodged against some construction companies when experts conclude that poor building materials were used or building codes were ignored. The pattern of damage following some earthquakes supports these complaints—many older homes were shaken, but not damaged, whereas newer homes were reduced to rubble.

Finally, a catastrophic 2001 earthquake in El Salvador illustrates that the number of casualties can be linked to where, not just how, structures were built. The Las Colinas neighborhood in Santa Tecla suffered the greatest loss of life from quake-related landslides, mainly from one giant slide (Figure 3.20d). The extensive damage appears to have resulted from building homes below a slope of loose earth material and from poor land-use practices. Balsamo Ridge, the hill above the community, is composed of unstable volcanic ash and other granular materials that are susceptible to landslides. Local authorities and environmentalists also claim that deforestation and greed were directly responsible for intensifying the disaster. Residents of Las Colinas had pleaded with the government to block construction of mansions on the hillside above them. The residents correctly argued that fewer plants covering the bare ground would leave them vulnerable to landslides. Their pleas were ignored, the mansions went up, and during the earthquake, the slopes came down.

Although we cannot control the geologic environment or the depth of an earthquake, there is much we can do to avoid excessive damage and loss of life. The deaths in Haiti, Italy, El Salvador, and China are especially tragic because much of the devastation could have been avoided if building regulations had been enforced, and protecting lives had been more important than building cheaper structures or making more money. Sound planning techniques and earthquake engineering of buildings can prevent unnecessary damage and loss of life. For examples, the 1989 Loma Prieta earthquake near San Francisco killed about 63 people, but a similar earthquake in Pakistan, India, or Mexico could kill at least several tens of thousands of people. The difference is that homes in California are constructed to better withstand earthquake shaking.[21] The lesson here is that areas with many buildings properly designed and built to withstand shaking, as in Chile and California, result in far fewer deaths from collapsed buildings than areas where construction is substandard.[23]

3.3 CHECK your understanding

1. What does moment magnitude measure? How is it different from a Richter magnitude?
2. How do seismologists locate earthquakes?
3. How does the depth of an earthquake's focus relate to shaking and damage?
4. What types of earth materials amplify seismic waves?
5. How is material amplification related to earthquake damage?
6. What is the primary cause of an earthquake catastrophe due to a moderate size earthquake?

3.4 Geographic Regions at Risk from Earthquakes

Earthquakes are not randomly distributed. Most occur in well-defined zones along the boundaries of Earth's tectonic plates (see Figure 3.2). In the United States, the areas with the highest earthquake risk include the Pacific coastal areas of California, Oregon, Washington,

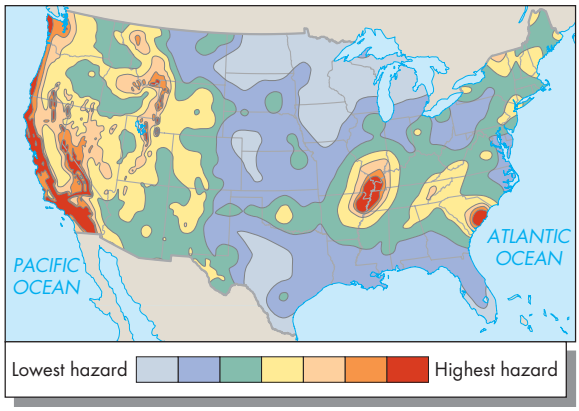


FIGURE 3.21 Seismic Hazard in Contiguous United States
A probabilistic approach to the seismic hazard in the contiguous United States. Colors indicate level of hazard. *(From U.S. Geological Survey Fact Sheet FS-131–02, 2002)*

Alaska, and Hawaii; an area along the California–Nevada border; and the territories of Puerto Rico and the Virgin Islands (Figure 3.21). For Canada, the risk is greatest in British Columbia and the Yukon Territory (Figure 3.22). This distribution is not surprising, since, with the exception of Hawaii, these areas are on or very close to plate boundaries. What may be more surprising are the high-risk zones in South Carolina, the central Mississippi River Valley, and the St. Lawrence River Valley. These areas are not close to present-day plate boundaries, but they have experienced large *intraplate earthquakes*.

PLATE BOUNDARY EARTHQUAKES

Earthquakes occur along all three types of plate boundaries—convergent, divergent, and transform. The world's great earthquakes with magnitude greater than **M** 9 are usually associated with subduction zones (see Applying the Fundamental Concepts). In the past 100 years, earthquakes greater than **M** 9 have been associated with subduction along what is called the "megathrust" that helps define the zone. These events are called **megathrust earthquakes**. The great Chile earthquake of 1960 was a megathrust event of **M** 9.5 that killed about 1,650 people. The earthquake occurred before the concept of subduction and the theory of plate tectonics had been proposed. The 2010 **M** 8.8 Chile earthquake, while smaller than the 1960 event, was most likely on the megathrust fault system that defines the down-going slab in the subduction zone offshore. According to the U.S. Geological Survey, the 2010 earthquake was generated at the gently sloping fault that separates the down-going Nazca plate to the east from the overriding South American plate to the west (Figure 3.23). The regional rate of convergence between the two plates is about 7 cm

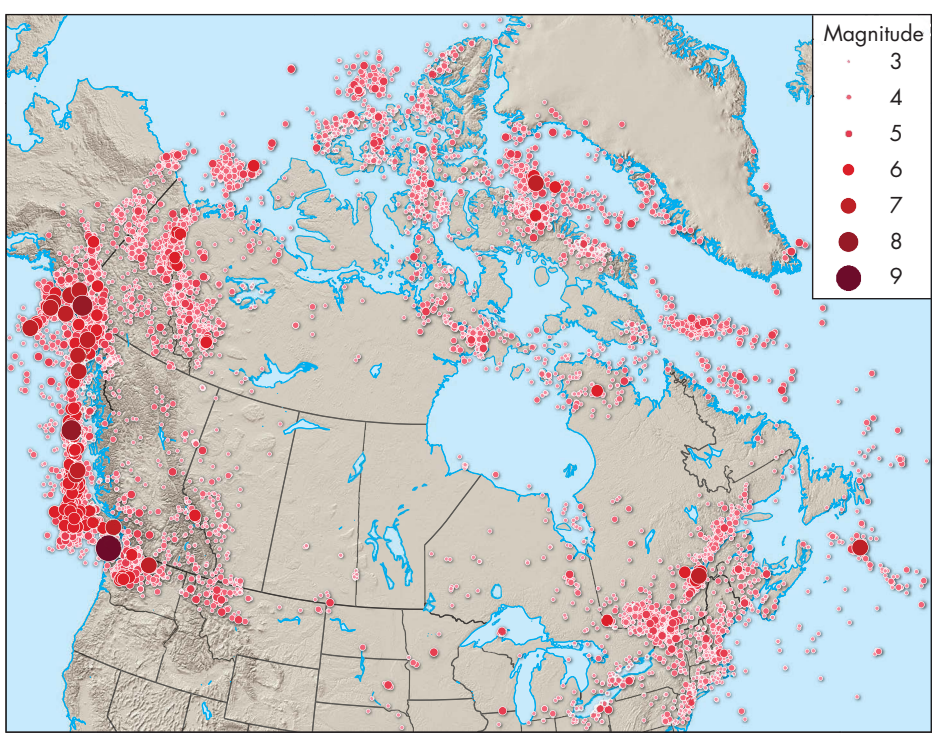
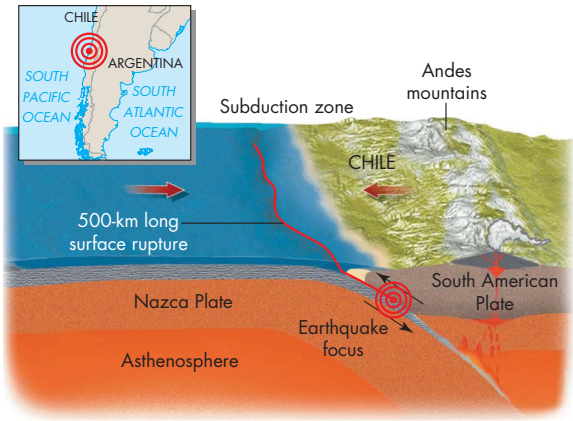


FIGURE 3.22 Historic Earthquakes in or near Canada
Map of earthquake epicenters greater than **M** 3 between 1627 and 2012. *(Reproduced with the permission of Natural Resources Canada 2013, courtesy of Earthquakes Canada)*



▲ FIGURE 3.23 2010 Chile Megathrust Earthquake
The largest recorded earthquakes are known to happen along subduction zones, like the (M 9.5) 1960 and (M 8.8) 2010 Chile quakes, when the interface between the overriding plate (South American) and subducting plate (Nazca) ruptures. *(Based on Lutgens, F., and Tarbuck, E.,* Essentials of Geology. *New York: Macmillan, 1992; From the CIA World Factbook)*

(~2.7 in.) per year. The mostly offshore rupture exceeded 500 km (~310 mi.) parallel to the coast (along the subduction zone). The rupture began deep (35 km or 22 mi.) beneath the coast and spread to the west, north, and south. As the rupture propagated, the fault slip generated intense earthquake shaking. This earthquake killed about 500 people. Fault slip warped the ocean floor, generating a damaging local tsunami in Chile's coastal areas (see Case Study 3.3: Survivor Story).[24]

In the western United States, earthquakes are common along the transform San Andreas fault zone and the convergent Cascadia and Aleutian subduction zones. Whereas California and Alaska are famous for their earthquakes, Nevada, Utah, Idaho, Montana, Wyoming, Oregon, and Washington also experience quakes.

As you recall from Chapter 2, California straddles two lithospheric plates: the Pacific plate west of the San Andreas fault zone, and the North American plate to the east (see Figure 2.1). The motions of these plates in essentially opposite directions along the San Andreas and related faults result in frequent damaging earthquakes. The 1989 Loma Prieta earthquake (**M** 6.9) on the San Andreas fault system south of San Francisco caused 63 deaths, 3,757 injuries, and an estimated $5.6 billion in property damage (see Figure 3.19). Both deaths and injuries would have been significantly greater if many people had not stayed home to avoid the crowds and congestion of the third game of the World Series in Oakland. Neither the Loma Prieta earthquake nor the Northridge earthquake (**M** 6.7) was considered a great earthquake. A great earthquake (**M** 8 and higher) occurring today in a densely populated part of Southern California could inflict $100 billion in damage and kill several thousand people.[25] Thus, neither quake was the anticipated "big one" in California. Both plate boundary earthquakes were initially puzzling because they did not produce a surface rupture. They demonstrated how much we still need to learn about earthquake processes.

This story about the Loma Prieta quake illustrates how observing a sequence of events related to an earthquake does not mean that we understand the causes behind them:

> Shortly before the quake struck, a two-year-old boy was out playing in his yard and discovered how to turn on the lawn sprinklers. His mother was not amused and took him to his room for disobeying her instructions. Shortly after she had returned to the yard, the Earth began to tremble violently. She heard her child yell and ran back into the house to find him terrified. He then remained very quiet until his father came home from work. On seeing his father, the child's first words were an emotional "Daddy, don't turn on the sprinkler!"[26]

The more we know about the probable location, magnitude, and effects of an earthquake, the better we can estimate the damage that is likely to occur and make the necessary plans for minimizing loss of life and property.

INTRAPLATE EARTHQUAKES

Although much less common than plate boundary earthquakes, intraplate earthquakes can be large and extremely damaging. Because they occur less often, there is generally a lack of preparedness, and buildings may not be able to withstand strong shaking. At least two earthquakes greater than **M** 7.5 occurred in the winter of 1811–12 in the central Mississippi Valley (Figure 3.24). The quakes nearly destroyed the town of New Madrid, Missouri, and killed an unknown number of people. They were felt in nearly every city of eastern North America from New Orleans to Quebec City in Canada, an area of more than a million square miles.[27] Seismic waves from these quakes rang church bells in Boston, more than 1600 km (~1000 mi.) away! Associated ground motion produced intense surface deformation over a wide area from Memphis, Tennessee, 230 km (~140 mi.) north of the earthquakes, to the confluence of the Mississippi and Ohio Rivers. As a result, forests were flattened, fractures in the ground opened so wide that people had to cut down trees to cross them, and land sank several meters, causing local flooding. Journal and newspaper reports also indicate that local uplift of the land surface actually caused the Mississippi River to reverse its flow for a short time.[28]

CASE study

3.3 Survivor Story

Magnitude 8.8 Earthquake and Tsunami on the Coast of Chile

Barry Keller (Figure 3.3.A) is a consulting geologist, hydrologist, and geophysicist who earned his Ph.D. at the University of California at Santa Barbara. He contributes to professional projects encompassing everything from industrial to governmental applications. He has more than 25 years of academic and professional experience in geological reconnaissance, earthquake seismology, geophysical exploration, soil and groundwater investigation and remediation, storm water management, dredge material study design, and hazardous waste planning. Dr. Keller has a home in Santa Barbara and another in Pichilemu, a beach town in central Chile known as a surfer's paradise. It is a rare opportunity for a professional who knows the science of earthquakes to write from personal experience. The following is Dr. Keller's story.

Strong earthquakes are a recurring hazard in some parts of the world, including the rim of the Pacific Ocean. Surviving a strong earthquake entails two basic phases: The first is surviving the shaking itself, and the second is surviving the following days when basic infrastructure such as roads, water, electricity, and telephones may be out of service.

First Phase: The most important way to prepare to survive strong shaking is to build strong buildings, as well as well-designed roads, water storage facilities, and other infrastructure. The time of day that an earthquake occurs and where people happen to be are also important factors affecting the number of fatalities and injuries.

Second Phase: Storage of emergency supplies such as food, water, candles, flashlights with batteries, and generators with fuel are very helpful in the days following an earthquake. To this might be added cash, since our ubiquitous sources of money, ATMs, do not work when the power is out.

My wife, Rosemarie, and I survived the **M** 8.8 earthquake and accompanying tsunami on



< FIGURE 3.3.A Survivors of the 2010 Chilean Earthquake
Barry Keller and his wife Rosie in front of the Golden Gate Bridge in San Francisco near one of Dr. Keller's field study sites. *(Edward A. Keller)*

the coast of central Chile in February 2010. The west coast of South America is above the subduction zone in which various oceanic plates are consumed beneath the South American continental plate, so very large earthquakes are a recurring fact of life. This particular part of the subduction zone had not ruptured in more than 100 years and so was identified as a "seismic gap" likely to have a "BIG ONE."

As a geophysicist who studies such risks for environmental reviews, I was well aware of the seismic gap and the potential for large earthquakes and tsunamis when we built our house in Pichilemu (Figure 3.3.B), a beach resort and surfing destination on the coast at 34.5° south latitude, which is similar to the north latitude of central California. Accordingly, the house was designed for seismic safety, built of poured concrete and concrete block with lots of rebar. It is on a hill at about 120 m (~400 ft.) elevation, well above the elevations typically reached by tsunamis.

In the dark of that very early Saturday morning, I was already awake, having gone to the bathroom and checked my watch at 3:22 A.M. The quake occurred at 3:34 A.M. The motion may have built up for a few seconds, then was VERY strong for about a minute—I was quickly thinking "This is for real!" I tried to check my watch again (as my seismology professor, Charlie Richter, taught us!), but the lights went out. Pretty strong motion was felt for about two to three more minutes. When the quake "went off," I started to regain my belief that my life expectancy was more than a few seconds and that my roof was NOT about to collapse; it was quite interesting to me as a geologist who studies such risks. However, it was quite terrifying to most other people, including my wife.

The feeling of the strong motion was similar to flying in a plane through severe turbulence but with more high-frequency jolts. I sat on the corner of the bed, holding on. The good news is that the house came through with no structural damage. However, items on shelves were strewn all over and there was lots of broken glass on the floor, so it is good advice to put on shoes before walking around in the dark in such a situation.

Within minutes, lots of people came up the hill to the roundabout at the bottom of our driveway. Many more were on the next hill over, the official evacuation spot. The lessons of the Sumatra tsunami were taken to heart by the Chilenos, and most people rapidly headed for high ground. It was a calm night with a full moon, which made evacuation easier, and people stayed until dawn. People continued to camp on both hills for several days.

That night, information was minimal; one local radio station was broadcasting, but without outside news, and an AM station from Argentina was on the air, again with minimal news. It was Sunday before we knew the extent of the damage in the rest of the country.

The tsunami struck the coast within 20 minutes of the earthquake. Damage at Pichilemu included complete destruction of a surf school (*Escuela de Surf*), restaurant, and cabañas at Punta de Lobos, a famous surf spot. In the lower downtown part of Pichilemu, there was widespread flooding, but the tsunami did not hit with enough force to destroy buildings. Only one life was lost, a child camped on the beach, so the evacuation was very effective, especially considering that this was the final weekend of



< FIGURE 3.3.B The Keller Home in Pichilemu, Chile
The home was constructed with poured concrete and rebar to strengthen the structure in case of an earthquake, and it is situated at 120 m (~400 ft.) elevation, well above the height of an earthquake-generated tsunami. *(Edward A. Keller)*

summer vacation and there were lots of people at the coast.

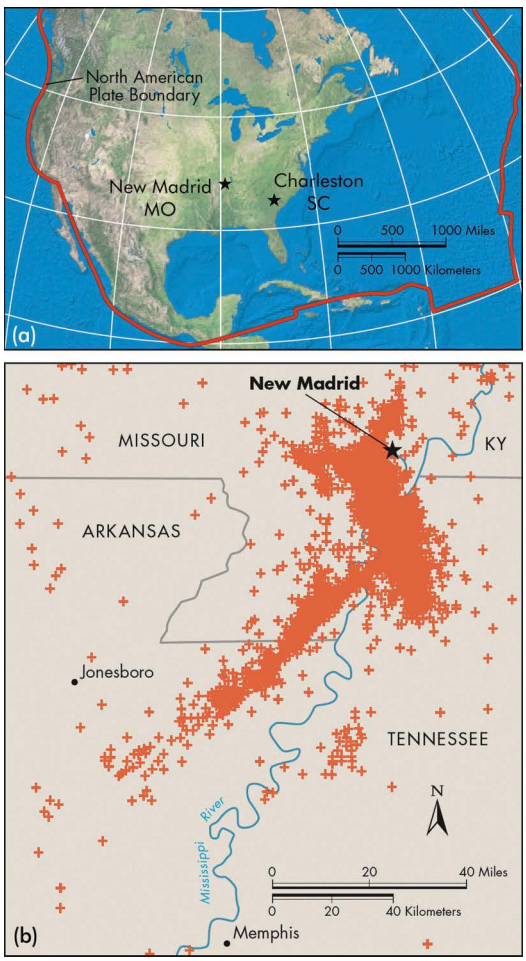
Farther south along the coast there was much more destruction from the tsunami, including severe damage to a Chilean Navy base at Talcahuano harbor, near Concepción.

We had no electricity for two days (until we left for Santiago—it stayed out three more days). My house has a booster pump for water, so without power we had no water pressure—although we had plenty of water in a storage tank (I have a boat bilge pump to get the water out, but it is very slow) and I had lots of bottles of water stashed, because the power goes out often. We had cell phones the first day, but then (according to the local scuttlebutt) the gasoline for the emergency generator ran out, so the phones went out.

Aftershocks were generally pretty sharp, with almost continuous motion for many hours. Daily aftershocks continued for weeks, including an **M** 6.9 very local one that cracked some plaster at our house. The aftershocks were nerve-wracking, especially for the nongeologists, and caused a great deal of mental stress for the local populace, if not much physical damage.

Most modern structures fared well in the quake, minimizing loss of life. Many older adobe structures were damaged, including historic churches, government buildings, a museum, and the funeral parlor. However, at 3:30 A.M. on a Saturday morning, most such structures were not occupied, again minimizing loss of life. The timing was also fortuitous for major roads, which suffered cracking and fallen bridges but, with little traffic at that hour, no loss of life.

—EDWARD A. KELLER



< FIGURE 3.24 Intraplate Seismic Zone

(a) The cities of New Madrid, Missouri, and Charleston, South Carolina, were the sites of several large earthquakes even though the cities are located thousands of kilometers from the nearest North American plate boundary (red lines). (b) The New Madrid seismic zone, highlighted here by earthquake epicenter locations since 1974 (red crosses), is the most earthquake prone region in the United States east of the Rocky Mountains. *(U.S. Geological Survey)*

These earthquakes occurred along the New Madrid seismic zone, a seismically active portion of a geologic structure known as the Mississippi Embayment (Figure 3.24b). The embayment is a downwarped area of Earth's crust where the lithosphere is relatively thin. At least two hypotheses exist to explain this: (1) Thinning took place near the end of the Proterozoic eon, around 600 million years ago, when a divergent plate boundary developed in the southeastern United States; and (2) the thinning is related to the passage of the North American Plate over a mantle hot spot during the Cretaceous period, around 95 million years ago. In either case, the observations of landforms and rates of uplift in the Mississippi Valley indicate that the seismic activity is recent, perhaps less than 10,000 years ago.

The *recurrence interval*, or time between events, for large earthquakes in the Mississippi Embayment is estimated to be several hundred years.[28,29] With material amplification, the New Madrid seismic zone appears to be capable of producing intensities commonly associated with great earthquakes in California. Thus, the interior of the North American Plate is far from

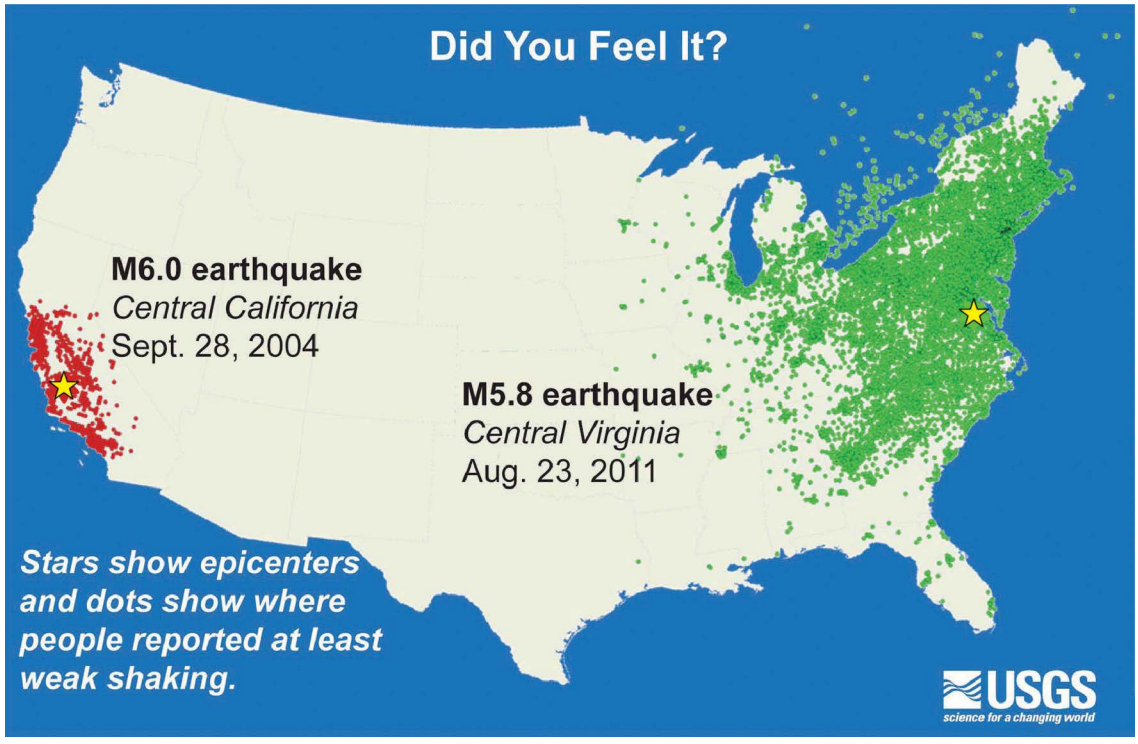
"stable." In recognition of this, the Federal Emergency Management Agency (FEMA) and affected states and municipalities have adopted a new building code designed to mitigate major earthquake hazards.

Another large, damaging intraplate earthquake (**M** ~7.3) occurred on the night of August 31, 1886, near Charleston, South Carolina (Figure 3.24a). This earthquake killed about 60 people and damaged or destroyed most buildings in Charleston. More than 102 buildings were completely destroyed and nearly 14,000 chimneys fell, many because of poor construction following a great fire in 1838. The quake was felt from Canada to Cuba and as far west as Arkansas.[27] Effects of the earthquake were reported at distances exceeding 1000 km (~620 mi.) from the epicenter.

Intraplate earthquakes in the rest of the United States are generally more damaging and felt over a much larger area than similar magnitude earthquakes in California (Figure 3.25). Because the rocks in the eastern United States are generally stronger and less fractured, they can more efficiently transmit earthquake waves. Empirical data from the 2011 **M** 5.8 Central Virginia earthquake suggest that more than 50 million people in the eastern United States (about one-third of the country) felt the quake. The Central Virginia earthquake also triggered a landslide 245 km (~150 mi.) from the epicenter, which is four times farther away than previous studies of worldwide earthquakes of the same size. Based on what they have learned from this event, earthquake scientists at the United States Geological Survey suggest equations used to calculate ground shaking may need to be modified.[30]

3.4 CHECK your understanding

1. How do plate boundary and intraplate earthquakes differ?
2. Why are earthquakes on the East Coast felt by more people than on the West Coast?



▲ FIGURE 3.25 Plate Boundary vs. Intraplate Earthquakes
U.S. Geological Survey Community Internet Intensity Map for two recent earthquakes (epicenters shown with yellow stars). Different color dots show the locations of people who submitted online responses to the "Did You Feel It?" website for either the Central Valley plate boundary earthquake (red dots) or the Central Virginia intraplate earthquake (green dots). Although the two quakes were similar in magnitude, the intraplate earthquake was felt over a much larger area than was the plate boundary quake. *(From "New Evidence Shows Power of East Coast Earthquakes: Virginia Earthquake Triggered Landslides at Great Distances," USGS 2012, www.usgs.gov/newsroom/article.asp?id=3447#.Ui9caRZyHdk)*

3.5 Effects of Earthquakes and Linkages with Other Natural Hazards

Shaking is not the only cause of death and damage during earthquakes. Many earthquakes cause other hazards and are thus an excellent example of how natural hazards are often linked. The primary effects of an earthquake are those caused directly by fault movement, such as ground shaking and its effects on people and structures, and surface rupture. Secondary effects are those that subsequently result from the faulting and shaking. These include liquefaction of the ground, regional changes in land elevation, landslides, fire, tsunamis, and disease. We will discuss the effects of tsunamis, large ocean waves that are often generated by earthquakes, in Chapter 4.

SHAKING AND GROUND RUPTURE

The immediate effects of a catastrophic earthquake can include violent ground shaking accompanied by widespread surface rupture and displacement of Earth's surface. Although most surface cracks produced by earthquakes are the result of liquefaction and landslides (discussed later), a major surface rupture may occur along the fault that was the source for the earthquake. This rupture commonly creates a low cliff, called a **fault scarp**, which may extend for kilometers along the fault (Figure 3.26). It is clear from the figure why you would not want to build your house directly along the trace of where the fault intersects Earth's surface. However, in many cases it is unavoidable, and some human-made structures must be built across known faults. In these cases, precautions must be taken to minimize the effects of ground rupture (see Case Study 3.4: Denali Fault Earthquake).

The 1906 San Francisco earthquake (**M** 7.8) produced 6.5 m (~21 ft.) of horizontal displacement along the San Andreas fault north of San Francisco. Studies following the quake indicate that portions of the bay area reached a maximum Modified Mercalli intensity of XI.[5] At this intensity, rapid surface movements can snap and uproot large trees and knock people to the ground. This level of shaking may damage or collapse large buildings, bridges, dams, tunnels, pipelines, and other rigid structures.[31]

The great 1964 Prince William Sound, Alaska, earthquake (**M** 9.2) caused extensive damage to transportation systems, railroads, airports, and buildings. Both the 1989 Loma Prieta (**M** 6.9) and 1994 Northridge earthquakes (**M** 6.7) were much smaller than the great Prince William Sound earthquake, yet the damage they caused was far more costly. In inflation-adjusted dollars, the Loma Prieta quake was five times as costly as the Alaska quake and the Northridge quake was 20 times as costly. With losses of at least $20 billion, the Northridge earthquake was one of the most expensive hazardous events in U.S. history.[17]

The Northridge earthquake caused so much damage because there were so many human-made structures there to be damaged. Most of the destruction was in the San Fernando Valley northwest of Los Angeles (see Figure 3.15), a highly urbanized area with a high population density that experienced intense shaking.

Violent ground shaking can be especially damaging to buildings if the horizontal motion is particularly strong or if the frequency of the shaking matches the



< FIGURE 3.26 Fault Scarp
This small cliff, called a fault scarp, was produced by the rupturing of Earth's crust during the 1992 **M** 7.3 Landers earthquake in California. The rupture could be traced for a distance of 70 km (~43 mi.) across the Mojave Desert. *(NOAA)*

natural vibrational frequency of the building. Shaking is commonly measured as *ground acceleration* and is compared to the overall acceleration of gravity. The matching of vibrational frequencies is called **resonance** and can affect buildings a significant distance away from the epicenter. One- and two-story buildings typically have high vibrational frequencies, in contrast to tall buildings that have low vibrational frequencies. In general, high shaking frequencies damage low buildings and low shaking frequencies damage tall buildings.

Ground shaking can also be a significant hazard to dams and levees (see Applying the Fundamental Concepts). Partial failure of the Van Norman Dam in the 1971 **M** 6.7 Sylmar earthquake came perilously close to flooding more than 80,000 people downstream of the dam.[17] Parts of the dam slid into the reservoir, which fortunately at the time was only about half full of water. People living downstream were evacuated, and the water level was lowered in the reservoir as a precaution. Likewise, in northern California, ground shaking from an earthquake in the San Francisco Bay area could produce intense shaking in the Sacramento River Delta. This shaking could cause the failure of levees along the river, resulting in widespread flooding and potential disruption of the water supply to Southern California.

3.4 CASE study

The Denali Fault Earthquake: Estimating Potential Ground Rupture Pays Off

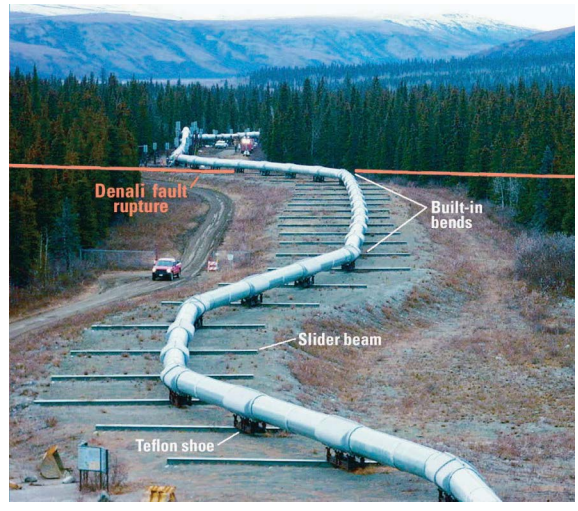
On November 3, 2002, a magnitude 7.9 earthquake occurred in early afternoon on the Denali fault in a remote section of south-central Alaska (Figure 3.27a). Historical movement along the fault was primarily horizontal (right-lateral strike-slip), and the 2002 earthquake was no exception. Along the fault zone, the quake produced a surface rupture approximately 340 km (~210 mi.) in length and a horizontal displacement of up to 8 m (~26 ft.). Although the quake caused thousands of landslides, intense shaking, and many areas of liquefaction, there was little structural damage and no deaths—primarily because few people live in the affected area.[32]

The Denali fault earthquake demonstrated the value of seismic hazard assessments for geologic faults. Geologists studied the fault in the early 1970s as part of planning for the Trans-Alaskan pipeline. Where the pipeline crosses the Denali fault, the investigators determined that the fault zone is several hundred meters wide and could experience a 6 m (~20 ft.) horizontal displacement in a **M** 8 earthquake.

These estimates were used in the engineering design of the pipeline across the fault zone. In anticipation of a future earthquake, the pipeline was elevated



(a)



(b)

▲ FIGURE 3.27 Trans-Alaska Oil Pipeline Survives M 7.9 Earthquake

(a) In its construction, the Alaskan oil pipeline was designed to withstand several meters of horizontal displacement where it crossed the Denali fault south of Fairbanks. That design was put to the test in 2002 when it shifted horizontally 4.3 m (~14 ft.) during the **M** 7.9 Denali fault earthquake. (b) Built-in bends of the pipeline on slider beams with Teflon shoes accommodated the earthquake rupture as designed. This was strong confirmation of the importance of estimating potential ground rupture and taking action to mitigate it. *(U.S. Geological Survey/U.S. Department of the Interior)*

on long horizontal steel beams with Teflon shoes that allowed it to slide horizontally up to 6 m (~20 ft.). These slider beams were installed along a zigzag path for the pipeline for added flexibility and horizontal movement during an earthquake (Figure 3.27b). As anticipated, the 2002 earthquake occurred within the mapped fault zone and caused the pipeline to shift horizontally about 4.3 m (~14 ft.). Because of advanced engineering design, the pipeline suffered little damage and there was no oil spill from the quake.

Although the $3 million cost for the design and construction of the pipeline across the fault may have seemed excessive in 1970, in retrospect it was money well spent. Today the pipeline delivers approximately 11 percent of the domestic oil supply for the United States and transports more than half a million barrels of oil each day. A pipeline break caused by an earthquake would have a significant and costly impact on our oil supply. Current estimates are that the repair of the pipeline and cleanup of the oil spill alone would cost several million dollars.[33]

LIQUEFACTION

During earthquakes, intense shaking can cause a near-surface layer of water-saturated sand to change rapidly from a solid to a liquid. This effect, called **liquefaction**, is most common in **M** 5.5 and greater earthquakes when there is strong shaking in Holocene sediment, that is, deposits less than about 10,000 years old.[31] Layers of solid sand can liquefy into a soupy mixture of sand and water as seismic waves pass through the earth material. Vibrations from the passing seismic waves increase water pressure in the space between sand grains. When the water pressure exceeds the downward-directed pressure from the overlying material, the sand grains and other objects buried in the sand effectively "float," like pieces of vegetables suspended in a thick stew. This creates a sand slurry that flows upward, often squirting through cracks to the surface. Once the shaking slows and the water pressure decreases, the liquefied sediment re-compacts and becomes solid again. A similar change from solid to liquid and back to solid again can also occur in "quicksand" on a beach or river sand bar. Liquefaction in earthquakes commonly causes the land surface to shift or subside.

The liquefaction of sand layers about 10 m (~30 ft.) below the surface has caused four-story apartment buildings to tip over, highway bridges to collapse, and dams to fail (Figure 3.28). It has also brought empty underground tanks, pipelines, and bridge pilings floating to the surface (see Applying the Fundamental Concepts).[34] Liquefaction can cause slope failure and ground subsidence over large areas. One amazing indicator of liquefaction are "sand volcanoes," small mounds of sand formed at the surface where water from liquefied layers squirts out of the ground.

REGIONAL CHANGES IN LAND ELEVATION

Vertical deformation of the land surface is a hazard linked to some large earthquakes. This deformation includes both regional uplift and subsidence of Earth's



< FIGURE 3.28 Building Collapse from Liquefaction
These apartment buildings collapsed as a result of liquefaction of sandy sediment beneath Niigata, Japan, in 1964. The **M** 7.5 earthquake that caused the liquefaction killed 26 people. *(NOAA)*

surface. These changes in elevation can cause substantial damage in coastal areas and along streams and can raise or lower the groundwater table.

The great 1964 Prince William Sound earthquake (**M** 9.2) provided a dramatic example of regional deformation in Alaska. This quake caused vertical deformation over an area of more than 250,000 km^2 (~97,000 $mi.^2$), a land surface slightly larger than the state of Vermont.[35] Within this area, uplift of as much as 10 m (~30 ft.) exposed and killed coastal marine life, lifted docks out of the water, and shifted the shoreline away from fish canneries and neighboring homes. In other areas, subsidence of as much as 2.4 m (~8 ft.) resulted in the partial flooding of several communities. Both the uplift and subsidence produced changes in the groundwater table.

LANDSLIDES

Two of the most closely linked natural hazards are earthquakes and landslides. Earthquakes are one of the most common triggers for landslides in hilly and mountainous areas. Landslides triggered by earthquakes can be extremely destructive and cause great loss of life. For example, a giant landslide triggered by the 1970 Peru earthquake buried the cities of Yungay and Ranrahirca. An estimated 20,000 of the 70,000 people who died in the quake were killed by the landslide. Both the 1964 Alaska earthquake and the 1989 Loma Prieta earthquake caused extensive landslide damage to buildings, roads, and other structures. The 1994 Northridge earthquake and associated aftershocks triggered thousands of landslides.

A giant landslide from the side of a mountain was triggered by the 2015 Gokha earthquake (Figure 3.29).



FIGURE 3.29 Earthquake-Triggered Landslides
Before (above) and after (below) images of the village of Langtang, which was completely buried by a massive landslide that was triggered by the 2015 Gorkha earthquake (see Case Study 3.1). *(David Breahshears/GlacierWorks)*

Thousands of other landslides were also triggered by the earthquake, most of which were on the steep slopes of the Himalayan Mountains.

The 2008 **M** 7.9 earthquake in China caused many landslides. Large landslides buried villages and blocked rivers, forming "earthquake lakes" that produced a serious flood hazard, should the landslide dam fail by overtopping or erosion. Channels were excavated to slowly drain lakes and reduce the flood hazard.[36]

As mentioned in Case Study 3.2, a large landslide associated with the January 2001 El Salvador earthquake (**M** 7.7) buried the community of Las Colinas, killing hundreds of people (see Figure 3.20d). Tragically, the landslide might have been avoided if the slope that failed had not been cleared of vegetation to construct luxury homes.

FIRES

Fire is another major hazard linked to earthquakes. Shaking of the ground and surface displacements can break electrical power and natural gas lines, thus starting fires. The threat from fire is even greater because firefighting equipment may be damaged; streets, roads, and bridges may be blocked; and essential water mains broken. In individual homes and other buildings, appliances such as gas water heaters may be knocked over, causing gas leaks that are ignited. Earthquakes in both Japan and the United States have been accompanied by devastating fires (Figure 3.30). As discussed in the introduction to Chapter 2, the San Francisco earthquake of 1906 has repeatedly been referred to as the "San Francisco Fire" because 80 percent of the damage was caused by firestorms that ravaged the city for several days. The 1989 Loma Prieta earthquake also caused large fires in the Marina district of San Francisco.

Most fires after an earthquake are not wildfires because they start in urban areas where gas and electrical lines are located. However, in a warm, dry area such as Southern California, it is possible for an urban fire to spread to wild lands, causing a wildfire.

DISEASE

Outbreaks of diseases are sometimes associated with large earthquakes. They may be caused by a loss of sanitation and housing, contaminated water supplies, disruption of public health services, and the disturbance of the natural environment. Earthquakes also rupture sewer and water lines, causing water to become polluted by disease-causing organisms.

An interesting example of how an earthquake-related disturbance can result in a disease outbreak occurred in Southern California. Desert soils in the southwestern United States and northwestern Mexico contain spores of a fungus that causes a respiratory illness known as *valley fever*. Landslides from the 1994 Northridge earthquake raised large volumes of desert dust containing these fungal spores. Winds carried the dust and spores to urban areas such as Simi Valley, where an outbreak of valley fever occurred. More than 200 cases of the disease were diagnosed within eight weeks after the earthquake, 16 times the normal number of cases. Fifty of these people were hospitalized and three died.[37]



< FIGURE 3.30
Earthquake and Fire
Fires associated with the 1995 **M** 6.9 Kobe, Japan, earthquake caused extensive damage to the city. *(The Asahi Shimbun via Getty Images)*

3.5 CHECK your understanding

1. What are the effects of earthquake induced liquefaction?
2. What is tectonic subsidence?
3. Why do disease outbreaks sometimes follow major earthquakes and other large natural disasters?

3.6 Natural Service Functions of Earthquakes

When we are confronted with the death and destruction caused by large earthquakes, it is difficult to imagine that there could be any benefits from such disasters. However, earthquakes, like many other natural hazards, do provide natural service functions. They contribute to the development of groundwater and energy resources, the formation and exposure of valuable mineral resources, and the development of landforms.

GROUNDWATER AND ENERGY RESOURCES

Geologic faults produced by earthquakes strongly influence the underground flow of water, oil, and natural gas (see Figure 1.15). Fault zones with coarsely broken earth materials can act as preferential paths for fluid movement. These faults may serve as conduits for the downward flow of surface water or as zones through which groundwater comes back to the surface as springs. Barton Springs in Austin, Texas, is one of many major springs that discharge from fault zones.

In other settings, faulting creates natural underground dams to slow or redirect the flow of water, oil, or natural gas. These dams develop where faulting pulverizes rock to form an impervious clay barrier and where faulting moves impervious earth materials alongside earth materials containing water, oil, or natural gas. Such subsurface dams are responsible for oases in arid areas of Southern California and for many underground accumulations of oil and gas in Texas, Oklahoma, Alberta, and elsewhere.

MINERAL RESOURCES

Faulting related to earthquakes may be responsible for the accumulation or exposure of economically valuable minerals. Mineral deposits commonly develop along cracks associated with faulting. These mineral-filled cracks, called *veins*, can be the source of precious metals such as gold, silver, and platinum (see Figure 3.3). Veins associated with large fault zones may produce enough minerals to be economically viable for extraction.

LANDFORM DEVELOPMENT

Earthquakes can form scenic landforms over long intervals of geologic time. Uplifts of earth materials along geologic faults can produce hills, rugged mountain ranges, and coastal terraces. A spectacular example of the role that earthquakes have played in creating scenic landforms is found in Grand Teton National Park in northwestern Wyoming. In the past several million years, earthquakes along faults both inside and outside the park have allowed the Teton Range to rise and Jackson Hole to subside, creating a scenic mountain front.

The fault zones themselves may become part of landforms if they contain broken rock that is more easily eroded than earth materials in surrounding areas. Easily eroded fault zones commonly become valleys cut by streams and rivers. For example, the course of the Hudson River in southeastern New York appears to be controlled by geologic faulting in the underlying bedrock, and the Rio Grande Rift Valley in New Mexico is the result of normal faulting.

FUTURE EARTHQUAKE HAZARD REDUCTION

Frequent small earthquakes may help prevent larger ones in the same area. If we assume that small earthquakes release pent-up energy, then the reduction in elastic strain may lower the chance of a devastating earthquake along a particular fault. In fact, scientists try to identify areas along active faults that have not experienced earthquakes in a long time. As discussed later, these areas, called "seismic gaps," can have the greatest potential for producing large earthquakes in the future.[4]

3.6 CHECK your understanding

1. Summarize how earthquakes can be beneficial.

3.7 Human Interaction with Earthquakes

As a natural hazard, an earthquake cannot be prevented or controlled; we can only devise ways to minimize the death and destruction it causes. That does not mean, however, that we cannot cause earthquakes ourselves. In fact,

several human activities are known to increase or cause earthquake activity. Damage from these earthquakes is regrettable, but the lessons learned may help control or stop large catastrophic earthquakes in the future.

EARTHQUAKES CAUSED BY HUMAN ACTIVITY

The actions of people have caused earthquakes in three ways:[39]

- Loading the Earth's crust, as in building a dam and reservoir
- Injecting liquid waste deep into the ground through disposal wells
- Creating underground nuclear explosions.

Water Reservoirs Construction of a large, deep reservoir behind a dam on a river may create, or induce, earthquakes. The huge weight of the water in a new reservoir can create or extend fractures in adjacent rock and increase water pressure in the surrounding groundwater. These effects may produce new faults or lubricate and activate existing faults. In the United States, several hundred local tremors occurred in the decade following the completion of Hoover Dam and the filling of Lake Mead in Arizona and Nevada. Most of these quakes were very small, but one was **M** 5 and two were about **M** 4.[38] In India and China, reservoir filling has triggered earthquakes with a magnitude greater than 6.0. Two of these quakes killed hundreds of people and severely damaged the reservoir dams.[31]

Deep Waste Disposal In the early 1960s, an unplanned experiment by the U.S. Army provided the first direct evidence that injecting fluids into Earth can cause earthquakes. From April 1962 to November 1965, the Denver, Colorado, area experienced several hundred earthquakes, far more than normally occur over this length of time. The largest quake (**M** 4.3) caused

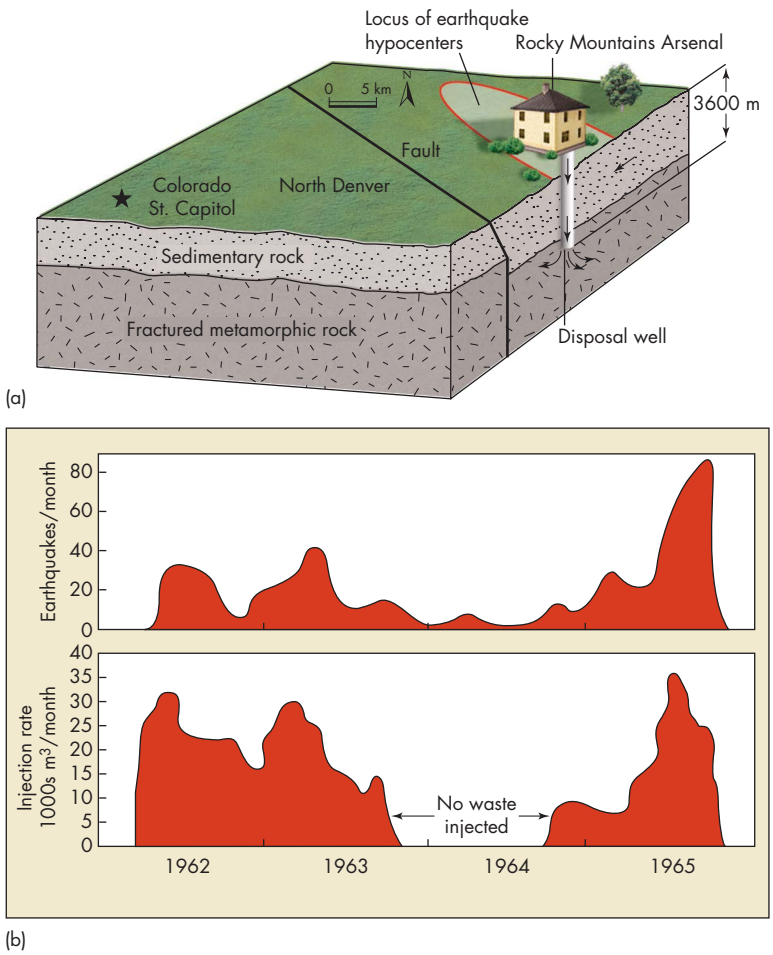


FIGURE 3.31 Human-Caused Earthquakes in Colorado
(a) A red line encompasses the area where most of the earthquakes occurred and a natural fault is present about 10 km (~6.2 mi.) southwest of the disposal well. (b) Injection of waste stopped in 1966; the well was permanently sealed in 1986. Earthquake activity has settled back to the natural frequency. An earthquake of magnitude 4.2 occurred in 1982, suggesting the faulting remains active. Data from www.geosurvey.state.co.us. Rocky Mountain Arsenal—The most famous example of induced earthquakes. Accessed 12/5/10. *(Adapted from Evans, D. M., "Man-made Earthquakes in Denver," Geotimes 10: 11–18, 1966. Reprinted by permission of American Geosciences Institute.)*

sufficient shaking to knock bottles off shelves in stores. Geologist David Evans traced the source of the earthquakes to the Rocky Mountain Arsenal, a chemical weapons plant on the northeast side of Denver. Liquid waste from the plant was being injected under pressure down a deep disposal well 3600 m (~11,800 ft.) into Earth. The injected liquid increased underground fluid pressure and caused slippage of numerous fractures in metamorphic rock. Evans demonstrated a high correlation between the rate of waste injection and the location and timing of the earthquakes. When the injection of waste stopped, so did the earthquakes (Figure 3.31).[39] Deep well injection has also triggered earthquakes in Ohio and Texas.[40,41]

Recognizing that the injection of fluids into Earth could trigger an earthquake was an important development because it drew attention to the relationship between fluid pressure and earthquakes. Subsequent studies of subduction zones and active fold belts suggest that high fluid pressures are present in many areas where earthquakes occur. One hypothesis is that fluid pressure rises in an area until rocks break, triggering an earthquake and discharging fluid upward. After the event, fluid pressure begins to build up again, beginning another cycle.

Nuclear Explosions Underground tests of nuclear weapons in Nevada have triggered numerous earthquakes with magnitudes as large as 6.3.[38] An analysis of the aftershocks suggests that these explosions may have released some natural strain within Earth. This has led to discussions by scientists as to whether nuclear explosions might be used to prevent large earthquakes by releasing strain before it reaches a critical point. Even if such techniques were feasible and legal liability and environmental issues were resolved, the explosive release of strain on one fault might trigger unanticipated earthquakes on other faults.

3.7 CHECK your understanding

1. How can humans cause earthquakes?

3.8 Minimizing the Earthquake Hazard

One important reason why earthquakes cause great damage and loss of life is that they often strike without warning. Because of this, a great deal of research is being devoted to anticipating earthquakes. The best we can do at present is to forecast the likelihood that an earthquake will occur in a particular area or on a particular segment of a fault. These forecasts use probabilistic methods to determine the risk. A forecast will say that an earthquake of a given magnitude or intensity has a high probability of occurring in a given area or fault segment within a specified number of years. These forecasts assist planners who are considering seismic safety measures or people who are deciding where to live. However, long-term forecasts do not help residents of a seismically active area anticipate and prepare for a specific earthquake. An actual prediction specifying the time and place of an earthquake would be much more useful, but the ability to make such predictions has eluded us. Predicting earthquakes depends to a large extent on observation of natural phenomena or changes in Earth that precede an event.

THE NATIONAL EARTHQUAKE HAZARD REDUCTION PROGRAM

In the United States, the USGS as well as university and other scientists are developing a National Earthquake Hazard Reduction Program. The major goals of the program are listed here:[42]

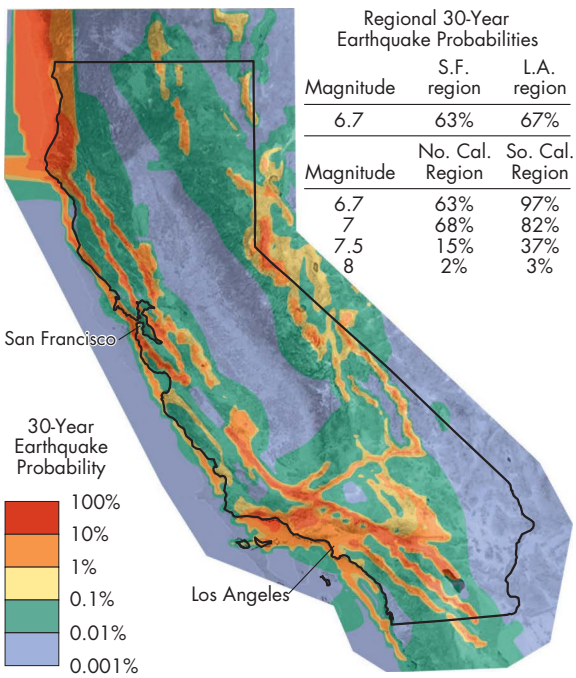
- Develop *an understanding of the earthquake source.* This goal requires obtaining information about the physical properties and mechanical behavior of faults and developing quantitative models of the physics of the earthquake process.
- Determine *earthquake potential.* This goal requires detailed study of seismically active regions to determine their paleoseismicity, identify active faults, and determine rates of deformation (see Case Study 3.5: A Closer Look). This information is used to calculate probabilistic forecasts and to develop methods for intermediate- and short-term predictions of earthquakes.
- Predict *effects of earthquakes.* This goal requires obtaining information needed to predict ground rupture and shaking and an earthquake's effects on buildings and other structures. This information is used to evaluate losses associated with the earthquake hazard (see Case Study 3.6: Professional Profile).
- Apply *research results.* The program educates individuals, communities, states, and the nation about earthquake hazards. This goal requires better planning for earthquakes and ways to reduce loss of life and property.

ESTIMATION OF SEISMIC RISK

Several types of hazard maps are used to communicate earthquake risk. The simplest maps indicate relative hazard by showing the locations of epicenters of historic earthquakes of various magnitudes. More

informative maps communicate the probability of a particular event or the amount of shaking likely to occur. For example, a seismic-shaking hazard map of California (Figure 3.32) shows areas in purple through red that have a chance of experiencing a damaging earthquake in a 30-year period. Within the colored area, the red and orange regions have the greatest seismic hazard because they are likely to experience the most intense shaking in the next 30 years. Regional earthquake-hazard maps are also helpful in establishing property zoning restrictions and determining insurance rates. Figure 3.33 shows the probability of a **M** 6.7 or larger earthquake occurring on faults in the San Francisco Bay region. There is a 62 percent probability of at least one **M** 6–7 or greater earthquake occurring before 2032.[43] The probability is based on past earthquake activity, fault displacement, and slip rate.

In addition to mapping, the state of California is now classifying faults as a method for assessing seismic risk. Geologic faults are classified based on the maximum moment magnitude that the fault can produce and the slip rate of the fault. Slip rate is determined by the amount of movement along a fault averaged over thousands of years and numerous earthquakes. It is not actual slippage that takes place along a fault each year. Although classifying faults provides more information than simply determining if a fault has been active in the past 10,000 years, the long-term slip rates of most major faults in North America are unknown or determined only by information collected at one or two sites.[44]



▲ FIGURE 3.32 Probabilities of damaging (> M 6.7) Earthquakes in California Over Next 30 Years
(Field, E. H., Milner, K. R., and the 2007 Working Group on California Earthquake Probabilities. 2008. Forecasting California's earthquakes—What can we expect in the next 30 years? U.S. Geological Survey Fact Sheet. 2008–2027)

SHORT-TERM PREDICTION

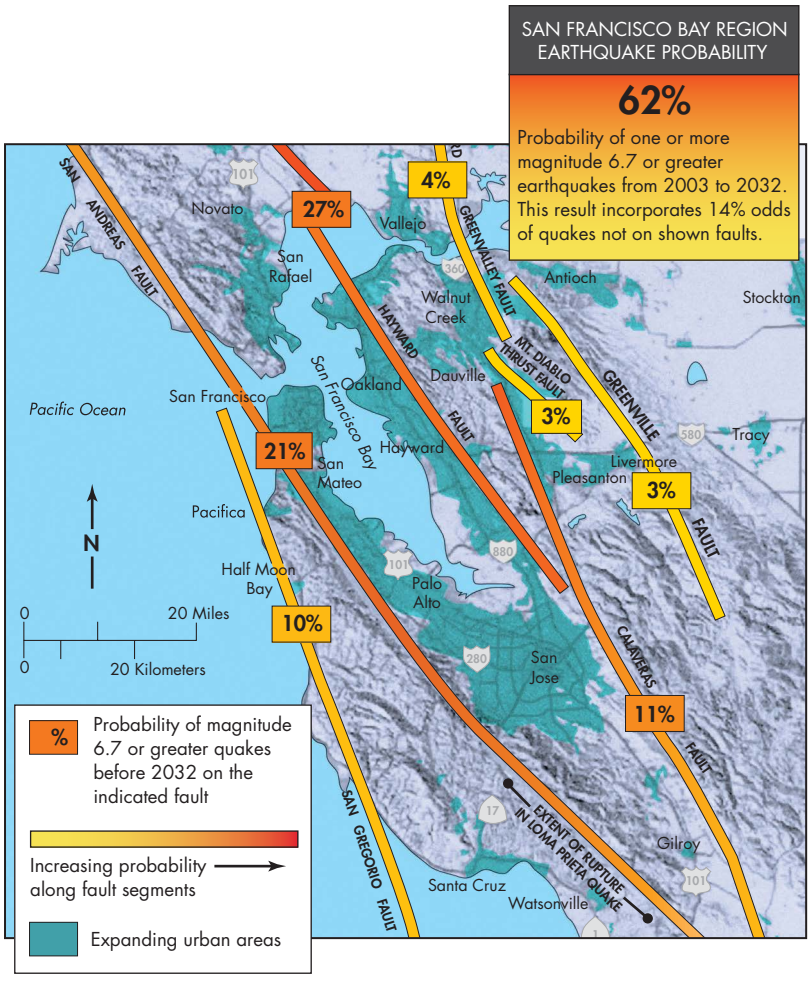
The short-term prediction of earthquakes is an active area of research. Predictions must rely on *precursors*, events or changes that occur before the mainshock of the earthquake. Unlike a forecast, a true earthquake prediction specifies a relatively short time period (days to weeks) in which the event is likely, an estimated magnitude for the quake, a relatively limited geographic area, and a probability of occurrence. The basic procedure for predicting earthquakes was once thought to be as easy as "one-two-three."[45] First, deploy instruments to detect potential precursors of a future earthquake; second, detect and recognize the precursors that indicate when and how big an earthquake will be; and third, after reviewing the data, publicly predict the earthquake. Unfortunately, earthquake prediction is much more complex than first thought.

Japanese seismologists made the first attempts at earthquake prediction using the frequency of small *microearthquakes* (**M** < 2), repetitive surveys to detect tilting of the land surface, and measurements of changes in the local magnetic field of Earth. They found that earthquakes in the areas they studied were nearly always accompanied by swarms of microearthquakes several months before the major shocks. Furthermore, they found that ground tilt correlated strongly with earthquake activity.[38]

Chinese scientists predicted a major earthquake (**M** 7.0) in 1975, saving thousands of lives. Although this prediction appears to have been successful by chance, because Chinese scientists had issued many unsuccessful predictions and also subsequently failed to predict major quakes, the result was beneficial.[32] The predicted earthquake destroyed or damaged about 90 percent of the buildings in Haicheng, China. Most of the town's 9000 people were saved because of a massive evacuation from potentially unsafe housing.

The short-term prediction was based primarily on a series of progressively larger foreshocks that began four days prior to the main event.

Unfortunately, foreshocks do not precede most large earthquakes, and there is no method for distinguishing a foreshock from any other earthquake. In 1976, one of the deadliest earthquakes in recorded history (**M** 7.5) struck near the mining town of Tangshan, China, killing more than 240,000 people. There were no foreshocks.



< FIGURE 3.33 Shaking-Hazard Map

Probability of at least one **M** 6.7 or greater earthquake occurring before 2032 on any fault in the San Francisco Bay region. Small colored boxes show the probabilities of the quake occurring on each of the major faults. *(From U.S. Geological Survey Fact Sheet 039–03)*

In addition to foreshocks, many phenomena have been proposed as precursors for earthquakes. They range from lunar tides to unusual animal behavior. Reports of animal behavior have included unusual barking of dogs, chickens that refuse to lay eggs, horses or cattle that run in circles, rats perched on power lines, and snakes crawling out in the winter and freezing. To date, no scientific studies show a correlation between unusual animal behavior or lunar tides and earthquakes. Earthquake prediction is still a complex problem. Even if reliable precursors can be identified, dependable short-range predictions are many years away. Such predictions, if they are possible, will most likely be based upon precursory phenomena such as the following:

- Patterns and frequency of earthquakes, such as foreshocks discussed earlier with the predicted Haicheng earthquake
- Deformation of the ground surface
- Seismic gaps along faults
- Geophysical and geochemical changes in Earth.

Ground Deformation Changes in the land elevation, referred to as *uplift* and *subsidence*, that occur rapidly or are unusual may help predict earthquakes. For example, more than 120 km (~75 mi.) of the western Japanese coast experienced several centimeters of slow uplift in the decade prior to the 1964 Niigata earthquake (**M** 7.5).[50] A similar uplift occurred over a five-year period prior to the 1983 Sea of Japan earthquake (**M** 7.7).[46,51]

Uplifts of 1 to 2 m (~3 to 7 ft.) also preceded large Japanese earthquakes in 1793, 1802, 1872, and 1927. These uplifts were recognized by sudden withdrawals of the sea from the land. On the morning of the 1802 earthquake, the sea suddenly withdrew about 300 m (~980 ft.) in response to an uplift of about 1 m (~3 ft.). Four hours later, the earthquake struck, destroying many houses and uplifting the land another meter.[50]

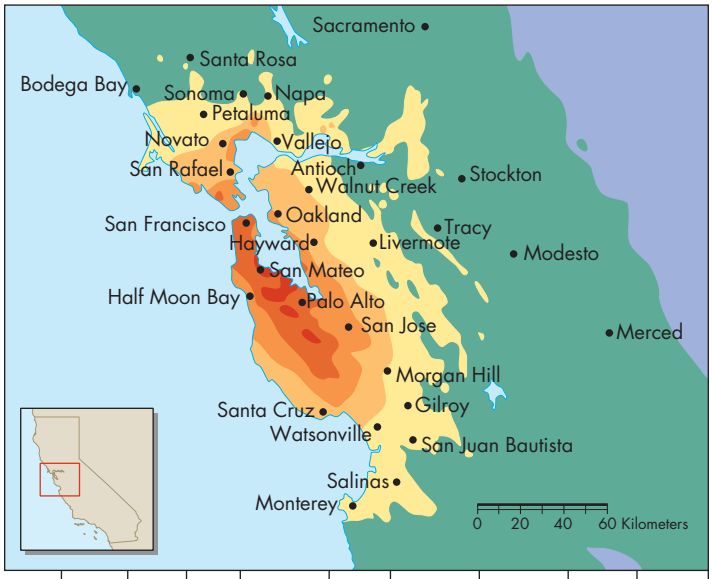
3.5 A Closer Look

CASE study

Paleoseismic Earthquake Hazard Evaluation

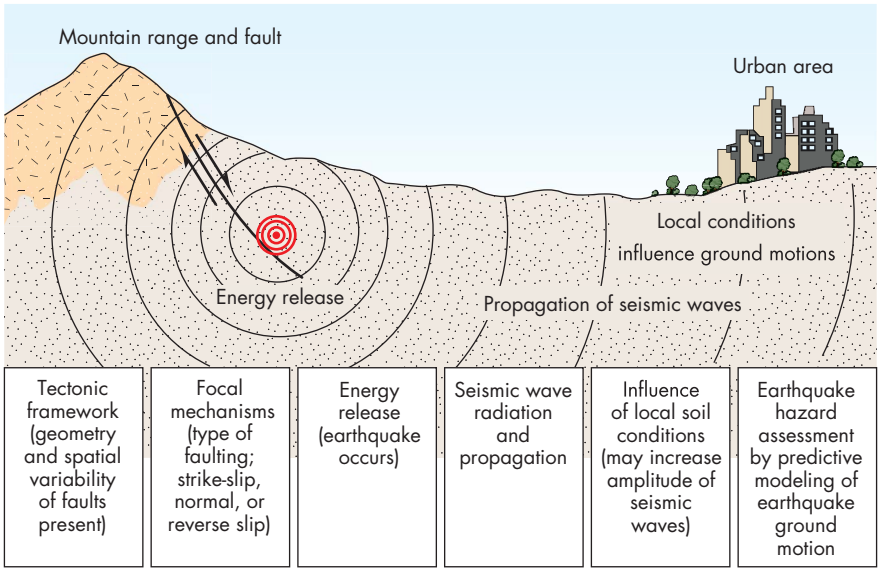
Earthquake hazard assessment is primarily meant to safeguard against loss of life and major structural failures rather than limit damage or maintain functional aspects of society, including roads and utilities.[46] The basic philosophy behind the seismic hazard evaluation is to find what is known as a **design basis ground motion**, defined as the ground motion that has a 10 percent chance of being exceeded in a 50-year period (equivalent to 1 in 475 chance of being exceeded each year). This is determined in California by a series of maps showing strong motion PGA (peak ground acceleration) for earthquake waves of 0.3-second period for one- and two-story buildings, and 1.0-second period for taller buildings.[47] The USGS makes predictions for peak acceleration and velocity of shaking using an earthquake-planning scenario for a particular fault. Figure 3.5.A shows a scenario for a **M** 7.2 event on the San Andreas fault in San Francisco.[48]

Assessing the earthquake hazard at a particular site includes identifying the **tectonic framework** (geometry and spatial pattern of faults or seismic sources) in order to predict earthquake slip rate and ground motion (Figure 3.5.B). Predicting slip rate and ground motion can be illustrated by a hypothetical example of a dam and reservoir site (Figure 3.5.C). The objective is to predict strong ground motion at the dam from several seismic sources (faults) in the area. The tectonic framework shown consists of a north-dipping reverse fault and an associated fold (anticline) located north of the dam, as well as a right-lateral strike-slip fault located south of the



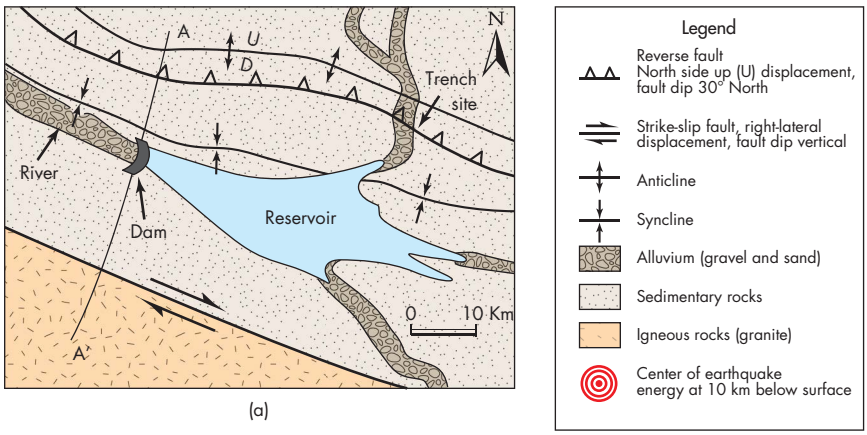
Perceived shaking	Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential damage	none	none	none	Very light	Light	Moderate	Moderate /Heavy	Heavy	Very Heavy
Instrumental intensity	I	II–III	IV	V	VI	VII	VIII	IX	X+

FIGURE 3.5.A Earthquake Planning Scenario
This scenario is for a **M** 7.2 event on the San Andreas fault in San Francisco, California. Instrumental Intensity refers to the Mercalli scale (see Table 3.5). *(From Implications for Earthquake Hazard in the San Francisco Bay Area, US Geological Survey Open File Report 03–214. By Working Group on California Earthquake Probabilities 2003. http://seismo.berkeley. edu/~rallen/teaching/eps256-s07/WG02SumCh1Ch2.pdf)*

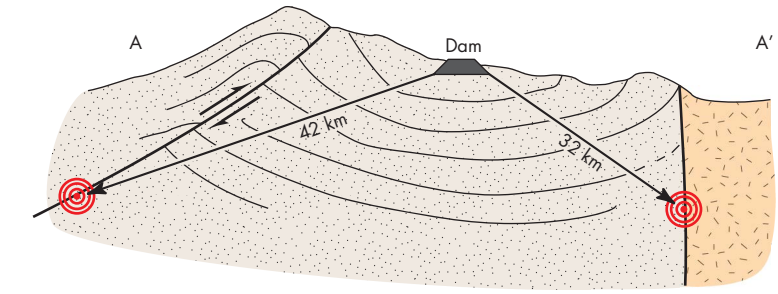


< FIGURE 3.5.B Assessment of Earthquake Hazard by Modeling of Ground Motion

(Based on A. Vogel and K. Brandes (eds.), Earthquake prognostics. Brannschweig/ Weisbaden: Friedr. Vieweg & Sohn, 1–13)



(a)



M_w = 6.5 Consistent with rupture length of 30 km and slip of 1 m

M_w = 7 Consistent with rupture length of 50 km and slip of 2 m

(b)

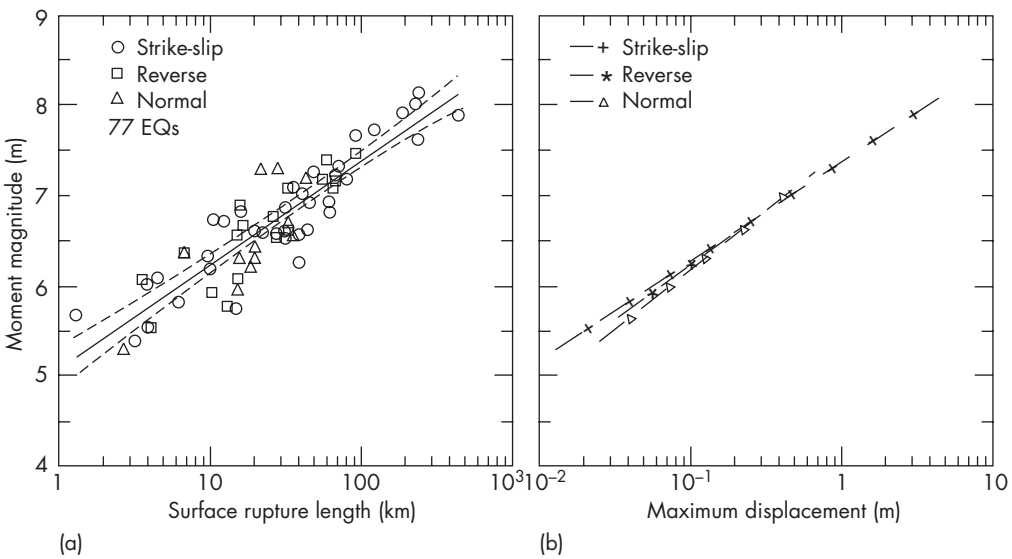
< FIGURE 3.5.C Tectonic Framework for a Hypothetical Dam Site

(a) Geologic map of hypothetical paleoseismic earthquake hazard evaluation site. (b) Cross-section A–A', showing seismic sources and distances of possible ruptures to the dam. See (a) for location of cross-section.

dam. Figure 3.5.C is a cross-section through the dam, illustrating the geologic environment, including several different earth materials, folds, and faults. Assuming that earthquakes would occur at depths of approximately 10 km (~6 mi.), the distances from the dam to the two seismic sources (the reverse fault and the strike-slip fault) are 42 km and 32 km (~27 mi. and 20 mi.), respectively. Thus, for this area, two focal mechanisms are possible: reverse faulting and strike-slip faulting.

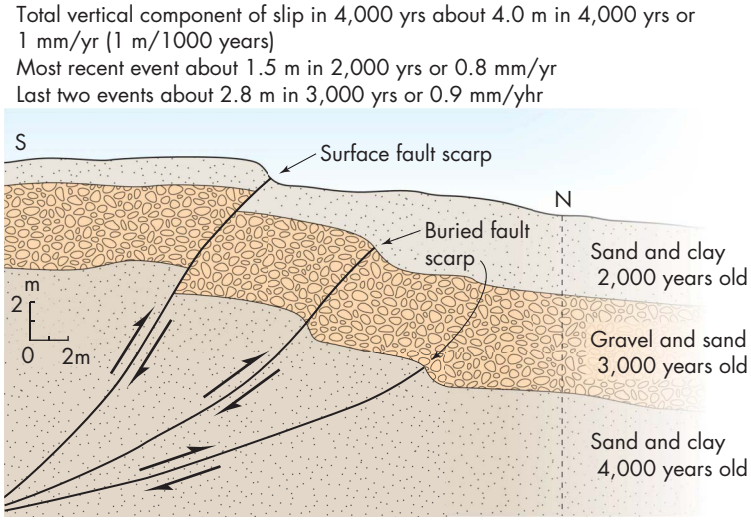
Another step in the process is to estimate the largest earthquakes likely to occur on these faults. Assume that fieldwork in the area revealed ground rupture and other evidence of faulting in the past, suggesting that, on the strike-slip fault, approximately 50 km (~31 mi.) of fault length might rupture in a single event with right-lateral strike-slip motion of 2 m (~6.6 ft.). The fieldwork also revealed that the largest rupture likely on the reverse fault would be 30 km (~18.6 mi.) of fault length with vertical displacement of about 1.5 m (~5 ft.). Given this information, the magnitudes of possible earthquake events can be estimated from graphs such as those shown in Figure 3.5.D.[45] Fifty kilometers (~31 mi.) of surface rupture are associated with an earthquake of approximately **M** 7. Similarly, for the reverse fault with surface rupture length of 30 km (~19 mi.) the magnitude of a possible earthquake is estimated to be **M** 6.5. Notice that in the first graph the regression line predicting the moment magnitude is for strike-slip, normal, and reverse faults. Statistical analyses have suggested that the relation between moment magnitude and length of surface rupture is not sensitive to the style of faulting.[49]

Slip rate (the vertical component) and average return period can be estimated from geologic data collected in a trench excavated across a fault. Figure 3.5.E shows the stratigraphy (trench log) for the site shown in Figure 3.5.C. The slip rate is about 1 mm/yr (1 m per 1,000 years), and the average return period is about 1,300 years.



▲ FIGURE 3.5.D Relationship between Moment Magnitude of an Earthquake and Deformation

Data for 77 events were used to estimate potential earthquake magnitude based on (a) surface rupture length and (b) maximum displacement. (a) Solid line is the "best-fit" or regression line, and dashed lines are error bars at significant difference between the lines. *(Adapted from Wells, Donald L., and Coppersmith, Kevin J. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America, 84(4): 992 (figure 9), August 1994. Reprinted by permission of the authors.)*



< FIGURE 3.5.E Paleoseismic Trench Log
Trench exposes sedimentary layers that have been deformed by faulting. Numerical dating of these sediments can provide information about the timing and rate of deformation. Location of the trench site is shown on Figure 3.5.C.

Seismic Gaps Areas along an active fault zone that are likely to produce large earthquakes but that have not produced one recently are known as *seismic gaps*. These areas are believed to be temporarily inactive while they store elastic strain for future large earthquakes (see Case Study 3.1).[4] The seismic-gap concept was the basis for what may have been the first scientific, long-term earthquake forecast. In 1883, the multitalented USGS geologist G. K. Gilbert forecast a catastrophic earthquake for the Salt Lake City segment of the Wasatch fault based on evidence of its inactivity.[32] Since 1965, the seismic-gap concept has been used successfully in intermediate-range forecasts for at least 10 large plate-boundary earthquakes. One of these quakes took place in Alaska, three in Mexico, one in South America, and three in Japan. In the contiguous United States, seismic gaps along the San Andreas fault in California include one near Fort Tejon that last ruptured in 1857 and one along the Coachella Valley, a segment that has not produced a great earthquake for several hundred years. Both gaps are likely to produce a great earthquake in the next few decades.[4,52]

Geophysical and Geochemical Phenomena

Local changes in Earth's gravity, magnetic field, and ability to conduct electrical currents have been associated with earthquakes. Changes have also been observed in groundwater levels, temperature, and chemistry.[52] Many of these changes may occur before an earthquake as rocks expand and fracture and as the fractures fill with water. For example, changes in the ability of earth materials to conduct an electrical current, referred to as *electrical resistivity*, have been reported before earthquakes in the United States, Eastern Europe, and China.[47] Also, significant increases in the radon content of well water were reported in the month or so prior to the 1995 Kobe, Japan, earthquake (**M** 6.9).[53]

THE FUTURE OF EARTHQUAKE PREDICTION

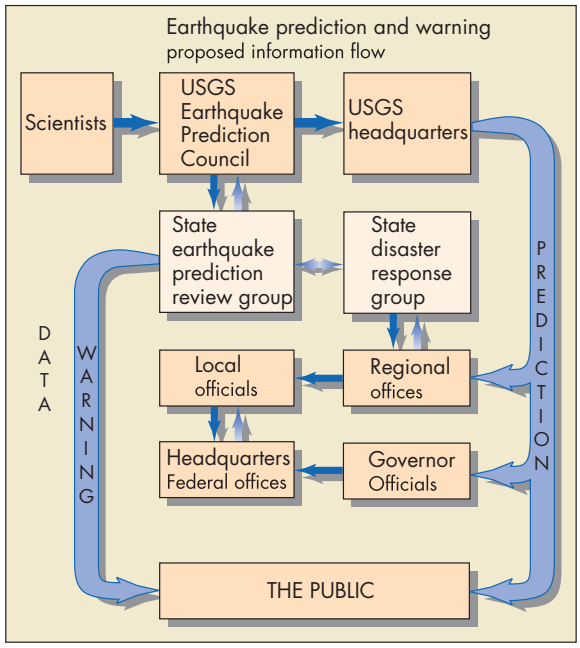
We are still a long way from a working, practical methodology to reliably predict earthquakes. However, a good deal of information is currently being gathered concerning possible precursor phenomena associated with earthquakes. To date, the most useful precursor phenomena have been patterns of earthquakes, particularly foreshocks, and recognition of seismic gaps. Optimistic scientists around the world today believe that we will eventually be able to make consistent long-range forecasts (decades to centuries), intermediate-range forecasts (months to decades), and short-range predictions (hours to weeks) for the general locations and magnitudes of large, damaging earthquakes.

Although progress on short-range earthquake prediction has not matched expectations, intermediate- to

long-range forecasting, including hazard evaluation and probabilistic analysis of areas along active faults, has progressed faster than expected (see Case Study 3.6: Professional Profile).[54] For example, the 1983 Borah Peak earthquake (**M** 6.9) on the Lost River fault in central Idaho has been lauded as a success story for intermediate-range earthquake hazard evaluation. Previous evaluation had suggested that the fault was active.[55] The earthquake killed two people and caused approximately $15 million in damages. Movement during the earthquake created a fault scarp several meters high and numerous ground fractures along a 36 km (~22 mi.) rupture zone. Investigation after the earthquake found that the new fault scarp and fractures were superimposed on previously existing fault scarps, validating the usefulness of careful mapping of scarps produced by prehistoric earthquakes. Remember—where the ground has broken before, it is likely to break again!

We hope eventually to be able to predict earthquakes. Because of this hope, nearly 30 years ago, the USGS established a plan for issuing earthquake predictions and more urgent earthquake warnings (Figure 3.34). This plan requires independent scientific review before information is transmitted to government officials and the public.

Government officials and news media that give publicity and thus credence to predictions that have not been scientifically reviewed do a great disservice to the community. This precept was demonstrated in 1990 when a pseudoscientific prediction for an earthquake in New Madrid, Missouri, was acted on by some government and business leaders and publicized by local, state, and national media—even after the prediction was rejected by the National Earthquake Prediction Evaluation Council.[56] Schools and businesses closed, public events were canceled, people evacuated their homes, and more than 30 television and radio vans converged on the predicted epicenter.[57] Widely publicizing earthquake predictions that have not been independently vetted by seismologists is the geologic equivalent of yelling "fire" in a crowded movie theater.



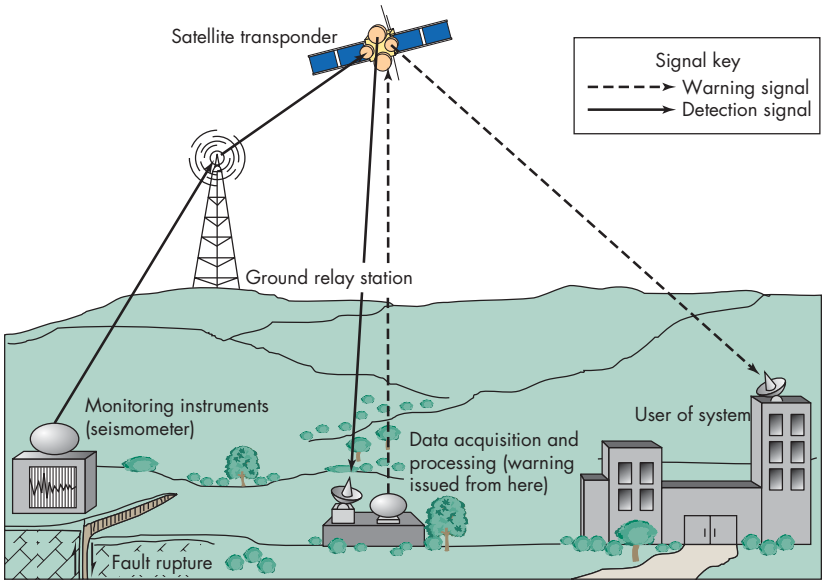
▲ FIGURE 3.34 Issuing a Prediction or Warning
Flowchart for the U.S. plan for issuance of an earthquake prediction and warning. The plan calls for a National Earthquake Prediction Evaluation Council of seismologists from government agencies, universities, and the private sector to evaluate predictions and warnings before they are passed on to state and local officials and the public. *(From McKelvey, V. E. 1976.* Earthquake prediction—*opportunity to avert disaster. U.S. Geological Survey Circular 729)*

EARTHQUAKE WARNING SYSTEMS

Technically it is feasible to develop an earthquake warning system that would provide up to about 1 minute of warning to the Los Angeles area prior to the arrival of damaging earthquake waves from an event several hundred kilometers away. Such a system would be based on the principle that radio waves travel much faster than seismic waves. For nearly 15 years, the Japanese have had such a system that provides earthquake warnings for their high-speed trains; derailment of one of their "bullet" trains by an earthquake could kill hundreds of people (see Applying the Fundamental Concepts).

A proposed system for California involves a sophisticated network of seismometers and transmitters along the San Andreas fault. This system would first sense motion associated with a large earthquake and then send a warning to Los Angeles, which would then relay the warning to critical facilities, schools, and the general population (Figure 3.35). The warning time would range from as little as 15 seconds to as long as 1 minute depending on the location of the earthquake epicenter. This interval could be enough time for many people to shut down machinery and computers and take cover.[58] Remember that an earthquake warning system is not a prediction tool because it warns that an earthquake has already occurred.

Because the warning time is so short, some people believe that the damage to scientific credibility caused by false alarms would be far greater than the benefits of a brief warning. In the Japanese system, it is estimated that around 5 percent of the warnings turn out to be false alarms. Others have expressed concern for liability issues resulting from false alarms, warning system failures, and damage and suffering resulting from actions taken as the result of false early warnings.



< FIGURE 3.35 Earthquake Warning
Idealized diagram showing an earthquake warning system using radio waves, which travel faster than seismic waves. Once an earthquake is detected, a signal is sent ahead of the seismic shaking to warn people and facilities. The warning time, generally measured in seconds, depends on how far away an earthquake occurs. It could be long enough to shut down critical facilities and for people to take cover. *(Based on Holden, R., Lee, R., and Reichle, M. 1989. Technical and economic feasibility of an earthquake warning system in California, California Division of Mines and Geology Bulletin 101)*

3.8 CHECK your understanding

1. What kinds of information are useful in assessing seismic risk?
2. What kinds of phenomena may be precursors for earthquakes?
3. What is the difference between an earthquake prediction and a forecast?

3.9 Perception of and Adjustment to the Earthquake Hazard

PERCEPTION OF THE EARTHQUAKE HAZARD

The experience that Earth is not so firm in places is disconcerting to people who have felt even a moderate earthquake. The large number of people, especially children, who suffered mental distress following the San Fernando and Northridge earthquakes in California attests to the emotional and psychological effects of earthquakes. These events caused a number of families to move away from Los Angeles.

One community's experience with a large earthquake does not always translate into increased preparedness for a community in another area. For example, in the 1994 Northridge earthquake (**M** 6.7), intense shaking caused part of the local seismograph network to malfunction. This malfunction delayed emergency response efforts because the exact location of the epicenter was not immediately available. The intense shaking also caused many unreinforced freeway bridges and buildings to collapse. A year later, the residents of Kobe, Japan, experienced nearly identical problems in a **M** 6.9 earthquake. Delays caused by communication problems and infrastructure damage kept the government from mounting a quick and effective response to the disaster. Even though Japan is one of the most earthquake-prepared countries in the world, much of the emergency relief in the Kobe quake did not arrive until about 10 hours after the earthquake!

Another example of the problems our modern society experiences with earthquakes comes from two large (**M** 7.6 and **M** 7.2) quakes in Turkey in 1999. Turkey was second only to China in the number of lethal earthquakes in the twentieth century. The first of the 1999 earthquakes occurred on August 17 and leveled thousands of concrete buildings. One-quarter of a million people were left homeless, and more than 17,000 people died. Although Turkey has a relatively high standard for new construction to withstand earthquakes, many modern buildings collapsed from the intense seismic shaking while older buildings were left standing (Figure 3.36). As with the experience of the residents of Ahmedabad, India, in the 2001 Bhuj earthquake (**M** 7.7), there is suspicion in Turkey that poor construction practices contributed to the collapse of the newer buildings. There were allegations that some of the Turkish contractors bulldozed collapsed

Andrea Donnellan, Earthquake Forecaster

Andrea Donnellan (Figure 3.6.A) talks about earthquakes the same way meteorologists talk about the weather: as dynamic, interconnected systems with their own peculiar set of rules. So it is only appropriate that she refers to her work as earthquake "forecasting."

Specifically, Donnellan and her colleagues have installed hundreds of high-precision global positioning system (GPS) receivers across Southern California, a network known as the Southern California Integrated GPS Network (SCIGN), in order to study movements in the tectonic plates. The receivers, which Donnellan says are more highly sophisticated than commercial GPS devices such as those used in cell phones, can measure millimeter-scale slips for faults and give scientists valuable data for understanding how and why earthquakes take place. Donnellan's work goes far beyond studying just the earthquakes themselves. In fact, most of the work occurs in between all the moving and shaking. "I look at the quiet part of the earthquake cycle," Donnellan said. "Each earthquake changes where the next earthquake will be."

Like meteorologists, Donnellan and her colleagues have reproduced earthquake systems using supercomputers in order to understand how the dynamic systems change over time. "My focus is on modeling earthquake systems," she said. "We want to treat it like weather, where the system is always changing."

But Donnellan's research consists of far more than just sitting in front of a computer all day. In fact, her studies have taken her to places around the globe, from Antarctica to Mongolia to Bolivia, to name a few. Her current research has taken her across much of Southern California, where she and her team are studying the San Andreas fault.

Back in the lab, Donnellan is also involved in an ambitious project called QuakeSim, in which scientists are developing sophisticated, state-of-the-art computer models of earthquake systems. She said the results of the project will eventually be accessible to anyone and that schools are already using some of the software for educational purposes.

In terms of practical implications, Donnellan's research is already giving scientists a much clearer idea of where earthquakes may next strike, allowing communities to prepare much further in advance. Although, like the weather, earthquakes will probably never be totally predictable, a close study of the ever-shifting activity beneath the ground by Donnellan and her colleagues is making the picture a lot clearer.

— CHRIS WILSON



< FIGURE 3.6.A Geophysicist Develops Earthquake Forecasting Method

Dr. Andrea Donnellan, deputy manager of NASA's Jet Propulsion Laboratory Earth and Space Sciences Division, leads a team of scientists working on earthquake forecasting. She was co-winner of Women in Aerospace's 2003 Outstanding Achievement Award and twice a finalist in the NASA astronaut selection process. *(NASA)*



FIGURE 3.36 Collapse of Buildings in Turkey
Damage to the town of Golcuk in western Turkey from the **M** 7.6 Izmit earthquake in August 1999. The very old mosque on the left remains standing, whereas many modern buildings collapsed. *(AP Photo/Enric Marti)*

buildings soon after the earthquake to remove evidence of shoddy construction. If that was true, those contractors also tied up bulldozers that could have been used to help rescue people trapped in other collapsed buildings.

The lessons learned from Northridge, Kobe, and Turkey are bitter ones. Our modern society is vulnerable to catastrophic loss from large earthquakes. Older, unreinforced concrete buildings or buildings not designed to withstand strong ground motion are most vulnerable. In Kobe, reinforced concrete buildings constructed with improved seismic building codes experienced little damage compared to those constructed earlier. Minimizing the hazard requires new thinking about it.

COMMUNITY ADJUSTMENTS TO THE EARTHQUAKE HAZARD

Since it is clearly impossible to avoid all human habitation in earthquake-prone areas, certain steps must be taken by countries, states, communities, and individuals to adjust to the earthquake hazard. These steps include careful location of critical facilities, structural protection, education, and increased insurance and relief measures. Individuals can also take steps to protect themselves. The extent to which these adjustments occur depends in part on people's perception of the hazard.

Location of Critical Facilities Buildings and other structures, often referred to as *facilities*, that are critical to the community must be located as safely as possible. These structures include hospitals, schools, utility plants, communication systems, and police and fire stations. Selecting safe locations first requires site-specific investigation of earthquake hazards such as the liquefaction, ground motion, and landslide potential. This involves *microzonation*, the detailed location and land-use planning of areas having various earthquake hazards. Microzonation is necessary because the ground's response to seismic shaking can vary greatly within a small area. In urban areas, where individual property values may exceed millions of U.S. dollars, detailed maps of ground response are required to accomplish microzonation. These maps help engineers and architects design buildings and other structures that can better withstand seismic shaking. Clearly, microzonation requires a significant investment of time and money; however, it provides the basic information needed to adequately predict the ground motion at a specific site. Although we may never be able to prevent injury and death from earthquakes, we can reduce the number of casualties through the safe location of critical facilities.

Structural Protection The often-repeated statement "earthquakes don't kill people, buildings kill people" succinctly expresses the importance of building design and construction in reducing the hazard of earthquakes. In regions where there is a significant earthquake hazard, buildings, bridges, pipelines, and other structures must be constructed to withstand at least moderate shaking. To accomplish this, communities must adopt and enforce building codes with earthquake sections similar to those in the International Building Code and International Residential Code. In establishing seismic provisions in building codes, engineers try to balance reducing risk to human life with the high construction costs of earthquake-resistant design.[44]

Of equal importance to seismic provisions in building codes is the inspection and strengthening of existing structures to withstand the ground motion of large earthquakes. Making engineering changes to existing structures, referred to as *retrofitting*, is a costly but extremely important activity (Figure 3.37). For example, a recent study showed that more than half of the hospitals in Los Angeles County could collapse in a large earthquake.[44] The cost of retrofitting these buildings is likely to be more than $8 billion. Retrofitting is especially critical in developing countries and in U.S.



FIGURE 3.37 Seismic Retrofit of University Building
The cross braces and horizontal bracing on the building exterior were added to University Hall on the University of California, Berkeley, campus to help the structure withstand shaking in the next major earthquake. *(Robert H. Blodgett)*

communities such as Memphis, Tennessee, that have only recently included earthquake-resistant design in their building codes.

Earthquake-resistant design and retrofitting of buildings, which first began in the 1920s, has generally been successful in the United States. The effect of these improvements in construction can be appreciated by comparing two events of approximately equal magnitude: the 1988 Armenia (**M** 6.8) and the 1994 Northridge (**M** 6.7) earthquakes. The loss of life and destruction in Armenia was staggering (at least 25,000 people were killed, compared with 60 in California) and some towns near the epicenter were almost totally destroyed. Most buildings in Armenia were constructed of unreinforced concrete and instantly crumbled into rubble, crushing or trapping their occupants. This is not to say that the Northridge quake was not a catastrophe—it certainly was: 25,000 people were left homeless, several freeway overpasses collapsed, at least 8,000 people were injured, and many billions of dollars in damages to buildings and other structures occurred. However, since most buildings in the Los Angeles Basin are constructed with wood frames or reinforced concrete, thousands of deaths in Northridge were avoided.

Education As with most other natural hazards, education is an important component of preparedness at the community level. This educational effort could include the public distribution of pamphlets and videos; workshops and training sessions for engineers, architects, geologists, and community planners; and the availability of information on the Internet. In areas of high seismic or tsunami risk, education also takes place through earthquake and tsunami drills in schools and earthquake disaster exercises for government officials and emergency responders.

An excellent example of educating those at great risk from earthquake hazards is Mexico's annual preparedness exercise. The mock earthquake drill is conducted each year on September 19, which is the anniversary day of the devastating 1985 Mexico city earthquake that killed more than 8,000 people (see Section 3.1). The drill is designed to teach participaints proper building evacuation procedures given an assumed 40 second warning period prior to hypothetical ground shaking (Figure 3.38a). Coincidentally, just 2 hours after the 2017 annual earthquake preparedness drill, earthquake warning sirens went off a second time. Fifteen seconds later strong ground shaking rocked Mexico City, triggered by an **M** 7.1 earthquake with an epicenter 120 km (~75 mi.) to the south. Although collapsing buildings claimed the lives of 370 people (Figure 3.38b), countless citizen reports credit the mock earthquake drills for helping them to safely evacuate following the second round of sirens that day.

Increased Insurance and Relief Measures Insurance and relief measures are vital to help a community, state, or country recover from an earthquake. Losses from a major earthquake can be huge. This fact was graphically demonstrated in the 1906 San Francisco earthquake (**M** 7.8) when only 6 of the 65 insurance companies were able to pay their liabilities in full.[5] Although risk assessment and the insurance industry have greatly improved in the past century, the potential losses from a large earthquake in a densely urbanized area such as Los Angeles, the San Francisco



(a)



(b)

▲ FIGURE 3.38 Mexico Remembrance and Preparadness

Every year the country of Mexico conducts earthquake drills on September 19, the anniversary day of the 1985 Mexico City earthquake that killed thousands. (a) Civilians conducting building evacuation preparedness drills at 11 A.M. (b) Structural collapse of a building 2 hours after the earthquake drill due to the 2017 Central Mexico earthquake.

Bay area, Seattle, New York City, or Boston are enormous. The $15.3 billion in insurance claims paid in the 1994 Northridge quake (**M** 6.7) does not come close to the $200 billion estimate of losses in the 1995 Kobe quake (**M** 6.9).[17] The state of California has partially addressed this problem with state-subsidized earthquake insurance through the nonprofit California Earthquake Authority. Even with state subsidies, barely 25 percent of California residents have earthquake insurance, in part because of the high deductible.[17] Unlike flood insurance and crop insurance, there is no federally subsidized earthquake insurance. Federal officials and the insurance industry have yet to agree on a national strategy to deal with catastrophic earthquake loss.

Development of methods to estimate the potential impact of earthquakes is important to insurance companies, government agencies, and homeowners.[59] Estimates of losses from earthquakes and other hazards can now be accomplished with "Hazards U.S." (HAZUS), a FEMA computer program. This free software can be downloaded from the FEMA website for use on a personal computer.

PERSONAL ADJUSTMENTS: BEFORE, DURING, AND AFTER AN EARTHQUAKE

Individual actions before, during, and after a major earthquake can reduce casualties and property damage. Close to 150 million people in 39 U.S. states live in seismically active areas. In damage alone, billions of dollars could be saved if our buildings and contents were better secured to withstand shaking from earthquakes.

If you live in a seismically active area, a home safety check could increase the probability that you and your property survive a large earthquake. This inspection should include checking chimneys and foundations for reinforcement and the security of large objects, such as water heaters, that might fall over in an earthquake.[60] Probably the most important thing is to plan exactly what you will do should a large earthquake occur. This plan might include teaching your family to "drop, cover, and hold on," which means to "drop" to the ground; take "cover" under a sturdy desk, table, or bed away from falling objects; and "hold on" to something until the shaking stops. Contrary to some suggestions, standing in most doorways is not a good option.[5] Preparations should also include maintaining an adequate stock of bottled water, food, medical supplies, batteries, and spare cash.[60]

During the quake, remember what you have learned in this chapter. P waves will arrive first, causing initial vibrations followed by heavy shaking from the S and surface waves. If there has been at least 20 seconds between the P and S waves, then the quake is from a distant source. The noise of the ground vibrating will be deep and loud and may begin suddenly like a loud clap of thunder if you are close to the epicenter.[52] Books, dishes, glass, furniture, and other objects may come crashing down. Car alarms will go off, and there may be explosive flashes from electrical transformers and falling power lines. The length of shaking will vary with the magnitude. For example, shaking during the **M** 6.7 Northridge quake lasted around 15 seconds, whereas shaking during the **M** 7.8 San Francisco quake lasted nearly 2 minutes.

After the shaking stops, you may feel dizzy and sick.[61] Take several deep breaths, look around, and then leave the building only after the shaking stops, carefully watching for fallen and falling objects. More injuries occur when people attempt to move to a different location inside a building or try to leave. Turn off the main gas line and do not light matches or lighters. Move to an open area, away from fallen power lines and buildings or trees that might fall during aftershocks. The number and intensity of aftershocks are also related to the magnitude of the quake. For example, in the **M** 6.9 Loma Prieta quake, there were 2 **M** 5, 4 **M** 4, and 65 **M** 3 aftershocks.[62] The largest aftershock is typically at least one magnitude value lower than the mainshock. Overall, the most hazardous period for aftershocks is in the minutes, hours, and days following the mainshock. Both the number and the intensity of aftershocks will generally decrease in the days and weeks following the mainshock.

The good news is that in most developed countries, large earthquakes are survivable. In areas of greatest hazard, such as California, buildings are generally constructed to withstand earthquake shaking, and wood-frame houses seldom collapse. In the United States, earthquake-proof construction is progressively less common as one moves from west to east. Many brick houses, buildings, and other structures in New England, New York City, and Washington, DC, will not withstand shaking in a large earthquake.[26] Therefore, it is important to be well informed and prepared for earthquakes.

3.9 CHECK your understanding

1. What kinds of adjustments can a community make to the earthquake hazard?
2. What is retrofitting?
3. List personal adjustments you can make to prepare for an earthquake.

APPLYING the 5 Fundamental Concepts

2011 Tohoku Earthquake

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

Japan, which is about the size of California, and the United States both experience about 1,000 moderate (>**M** 5) earthquakes each year. However, over the past two decades Japan has been hit by 19 major quakes (**M** 7–7.9), whereas the United States has experienced only three during this same interval, all in sparsely populated Alaska. Although less frequent, Japan also experiences **M** 8 earthquakes every few years. With the regular occurrence of such significant earthquakes, and Japan's technological capability and wealth, it is no surprise that many consider Japan to be the world's best-equipped country in earthquake preparedness.[2] Modern structures built in Japan are extremely well engineered to resist ground shaking, and the country hosts the world's densest seismometer network, which is used for forecasting, locating, and studying earthquakes. In addition, the seismometer network is linked to an advance earthquake-warning system, and Japan's people are rigorously drilled on what to do when an earthquake warning is given. Japan's high level of earthquake preparedness represents an evolving process that has grown out of decades of lessons learned from devastating earthquakes, with the 2011 Tohoku earthquake providing the most recent lesson.

Although relatively small compared to the Tohoku earthquake, the **M** 6.8 Kobe earthquake that struck Japan in 1995 killed about 6,500 people, about 90 percent of whom perished beneath collapsed buildings. Even though new seismic building codes had been introduced in 1981, homes, buildings, freeways, and bridges constructed before that time were not required to upgrade to the new code. This led to widespread collapse and toppling of critical roadways, which greatly inhibited the damage control and search-and-rescue operations following the quake (Figure 3.39). Japan's realization that it was not as prepared as it or the world



FIGURE 3.39 Damage from 1995 Kobe Earthquake
Eighteen 3.1-m (~10 ft.) diameter columns fail due to intense ground shaking during the Kobe Earthquake causing 630 m (~0.4 mi.) of the Hanshin elevated expressway to topple, scattering automobiles into the city below. Failure of critical infrastructure such as this severely limited the rescue effort. *(Yoshiaki Nagashima/Pacific Press Service/Alamy)*

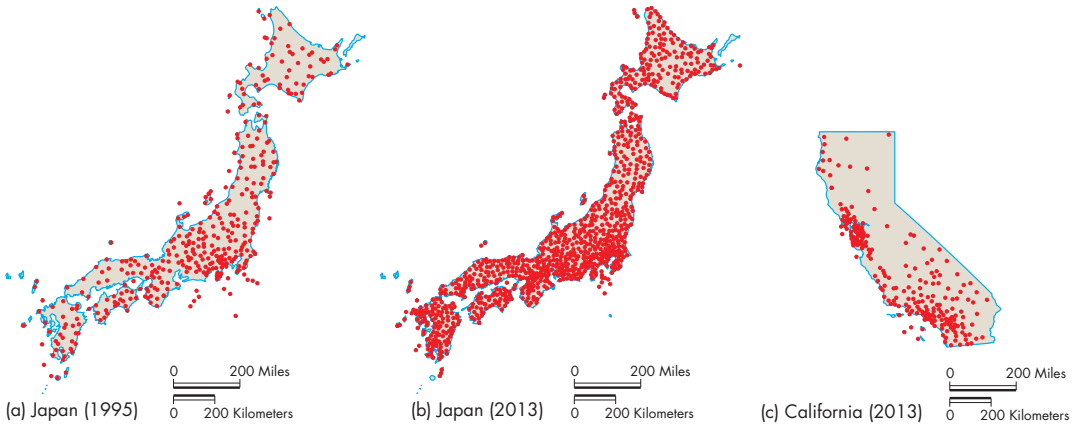
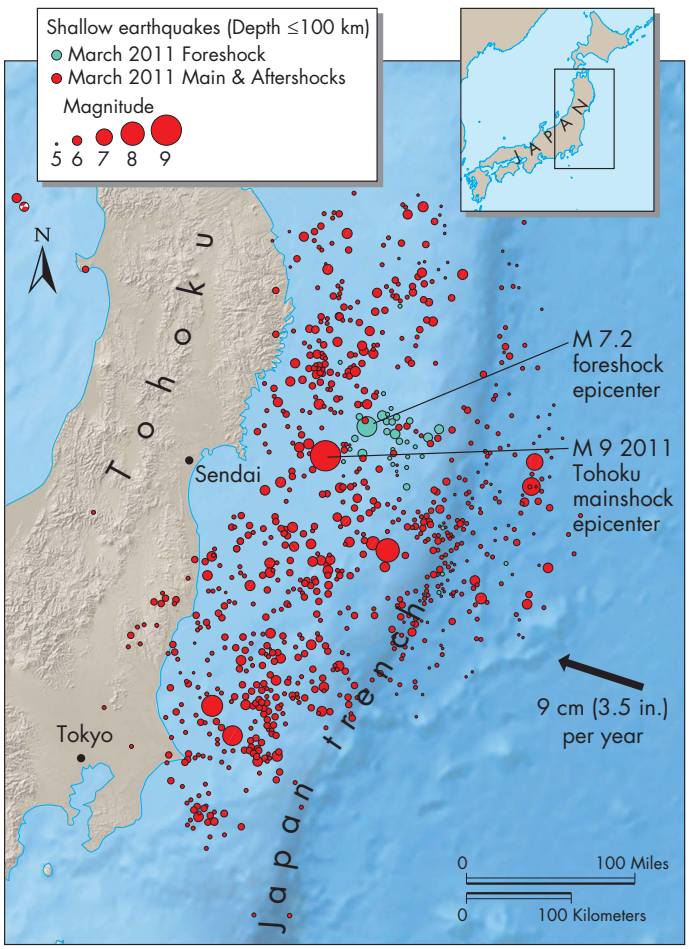


FIGURE 3.40 Seismometer Networks

Following the Kobe earthquake, (a) the deficient seismometer network emplace during the 1995 quake network was significantly upgraded *(Okada, Y., et al. "Recent Progress of Seismic Observation Networks in Japan: Hi-net, F-net, K-net and KiK-net,"* Earth Planets Space *56: 15–28, 2004. Reprinted by permission of Terrapub.)* (b) *(From "Next Steps: Improving the Sensor Network," USGS, http://earthquake.usgs.gov/research/earlywarning/nextsteps.php)* (c) Seismometer network in California, the most dense network in the United States, for comparison. *(From "Next Steps: Improving the Sensor Network," USGS, http://earthquake.usgs.gov/research/earlywarning/nextsteps.php)*



believed led to a more proactive approach to minimizing the effects of earthquakes. This included significant spending increases to retrofit older buildings and infrastructure throughout the country and an investment of $1 billion in research and development for an early warning system, which included an overhaul of Japan's seismometer network (Figure 3.40). Fifteen years later Japan would be tested again—this time by a much larger quake.

Two days before the Tohoku earthquake on March 9, 2011, the seismic network detected a **M** 7.2 earthquake east of the Tohoku region of Japan (Figure 3.41). Because the frequency and size of earthquakes for this region over the past 1,100 years was relatively well known, the timing and size of this earthquake came as no surprise to the

FIGURE 3.41 2011 Tohoku Earthquake Sequence

Epicenteral foreshock and aftershock locations surrounding the mainshock of the 2011 Tohoku earthquake with respect to the big island of Japan. *(Based on Ammon, C. J., Lay, T., Kanamori, H., and Cleveland, M., "A Rupture Model of the 2011 of the Pacific Coast of Tohoku Earthquake," Earth Planets Space 63: 693–96, 2011)*

seismologists.[63] In fact, earthquake forecasting along this part of the subduction zone estimated a 60–70 percent chance of an **M** 7 quake occurring in the next 20 years; in earthquake forecasting, this is like saying an earthquake could happen any day.[64] Therefore, there was no reason to suspect that this earthquake was a foreshock to an imminent quake that would be 500 times more powerful than the earthquake history suggested. For the next 50 hours small foreshocks continued, until March 11 at 2:46 P.M. Japan time, when the frictional forces keeping the Pacific plate from sliding under the Eurasian plate were overcome. In a geological instant the Pacific plate lurched northwestward beneath Japan as much as 40–60 m (~130–200 ft.), releasing the stored elastic strain energy that had likely accumulated over the past 1,000–1,200 years and producing the **M** 9.0 Tohoku mainshock (Figure 3.41).[63] Not only was the size of the earthquake significantly larger than the maximum size that seismologists had predicted—it also produced a larger than predicted tsunami (see Chapter 4: Applying the Fundamental Concepts). Although seismologists significantly underestimated the maximum potential earthquake magnitude for the region, the lessons learned from the 1995 Kobe earthquake and development of the early warning system was about to save thousands of lives.[2]

Just 8 seconds after the first P waves from the Tohoku earthquake were confirmed by the seismometer network, an automated alert went out to 124 television stations and 52 million telephones. Across the country critical infrastructure systems such as power plants and Japan's famous bullet trains automatically shut down upon receiving the alert. For the cities closest to the Tohoku epicenter, like Sendai (Figure 3.41), the alert provided about 10 seconds of early warning before the slower, more destructive S waves arrived. This was enough time for the earthquake-prepared citizens to take immediate shelter as they had practiced. The 9 million people living in the capitol city of Tokyo 373 km (~232 mi.) to the south received about 80 seconds of early warning before very strong ground motion was felt.[2]

Since the Tohoku earthquake in 2011 about 10,000 aftershocks were recorded, with about 2,000 occurring within seven days of the mainshock. Some of the aftershocks were even large enough to trigger the early warning system again, with 39 aftershocks having magnitudes greater than **M** 6, three of which were greater than **M** 7 (Figure 3.41).

Buildings, bridges, and other critical facilities built or retrofited since 1995 withstood the ground shaking extremely well with few buildings having collapsed as a direct result of shaking. However superficial damage and minor structural damage were widespread. Even though many of the buildings with structural damage will need to be demolished, the fact that they did not completely collapse allowed occupants within to escape with their lives unlike 15 years earlier during the Kobe earthquake.



FIGURE 3.42 Damage Due to Liquefaction
Manholes to underground sewer system forced through overlying sidewalks due to ground surface subsidence (lowering) caused by liquefaction. *(Koki Nagahama/Getty Images)*

In fact, the overall resilience of the structures is particularly impressive considering that the earthquake building codes for the region near the epicenter were based on the predicted maximum earthquake magnitude, which had been grossly underestimated.

Outside of tsunami damage, liquefaction and landsliding triggered by ground shaking were responsible for a significant portion of the damage to buildings, roads, and subsurface utilities such as water, gas, and sewage pipes. Subsidence of the ground surface due to liquefaction was particularly destructive (Figure 3.42) and widespread, with about 6,000 homes needing to be demolished due to liquefaction damage, some as far away as Tokyo. The extent of the liquefaction damage surprised many earthquake hazard experts worldwide, raising questions about whether building codes in Japan, as well as the United States, adequately account for this hazard in urban areas.[65] The Tohoku earthquake also triggered about 4000 landslides along the east coast of Japan, most in sparsely populated mountainous regions.[66] However, about 20 people were killed by landslides, some of whom died when a landslide caused an earthen dam to collapse unleashing a flood on the community below.

The 2011 Tohoku earthquake and lessons learned preceding and following the quake are excellent examples of our unending struggle to understand, predict, prepare, and survive Earth's natural hazards. Over the past 20 years Japan has invested tens of billions of dollars in this struggle. The cost of the 2011 Tohoku earthquake and tsunami is estimated to be more than $200 billion, making it the most expensive natural disaster in history. Did Japan's investment pay off? Could the effects have been better minimized? The answer to both these questions is clearly *yes*! Like the lessons learned from the Kobe earthquake, which clearly saved thousands of lives in 2011, lessons from the Tohoku quake will undoubtedly save countless future lives, not only in Japan but also worldwide. The data recorded by Japan's seismometer network have provided the first detailed record of a megathrust earthquake. From this record, seismologists have already learned more about why both the earthquake and the tsunami were larger than predicted and expect that the data will greatly improve global earthquake forecasting.

Following the success of Japan's early warning system in 2011, United States experts have begun an aggressive push to acquire funds to implement a similar system along the West Coast. On March 11, 2013, a pilot early warning system in California detected a **M** 4.7 earthquake 160 km (~100 mi.) south of Pasadena (near Los Angeles) and alerted Caltech seismologists in Pasadena 30 seconds before minor shaking was felt. A robust early warning system for the entire state of California would cost about $80 million and could be operating within five years, but no substantial funds for this program have yet been approved.

APPLYING THE 5 FUNDAMENTAL CONCEPTS

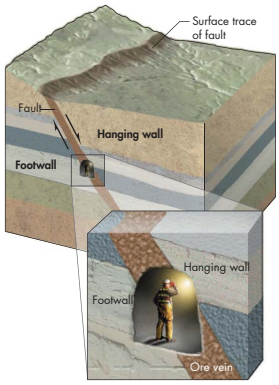
1. Discuss Japan's successes and shortcomings in forecasting the 2011 Tohoku earthquake, using the earthquake history of the region and the application of modern tools used to detect precursory events.
2. Compare and contrast the seismic hazard to the citizens of the United States living on the west Coast of California to those living in Japan.
3. Explain the links between the Tohoku earthquake and other natural hazards. How do the effects of the earthquake and linked natural hazards compare?
4. Similar in size to Japan, California is growing at a rate higher than the national average and by 2100 its population could be about the size of Japan's population today. Discuss how rapid population growth in California combined with its current level of earthquake hazard preparedness could lead to a catastrophe if an event similar to the Tohoku earthquake struck the United States West Coast.
5. Summarize and evaluate Japan's strategy for minimizing the effects of earthquakes following the 1999 Kobe earthquake, which has earned the country the title "best equipped country in earthquake preparedness."

CONCEPTS in review

3.1 Introduction to Earthquakes

LO:1 Compare and contrast the different types of faulting.

- Earthquakes are common along tectonic plate boundaries where faulting is common.
- Faults are fractures where rocks on one side of the fracture have been offset with respect to rocks on the other side.
- Displacement is caused by compressional, tensional, or shearing stresses. Displacement can be mainly horizontal, as along a strike-slip fault, or mainly vertical, as on a dip-slip fault.



KEY WORDS
fault (p. 68), **footwall** (p. 68), **hanging wall** (p. 68), **normal fault** (p. 68), **reverse fault** (p. 68), **strain** (p. 68), **stress** (p. 68), **strike-slip fault** (p. 68)

3.2 The Earthquake Processes

LO:2 Explain the formation of seismic waves.

- A fault is usually considered active if it has moved during the past 10,000 years and potentially active if it has moved during the past 2 million years.
- Before an earthquake, elastic strain builds up in the rocks on either side of a fault as the sides pull in different directions. When the stress exceeds the strength of the rocks, they rupture, producing elastic rebound.
- Released elastic strain energy radiates outward in all directions from the ruptured surface of the fault in the form of seismic waves.
- Seismic waves are vibrations that compress (P) or shear (S) the body of Earth or travel across the ground as surface waves. Although P waves travel the fastest, the S and surface waves cause most of the shaking and damage. Some faults exhibit tectonic creep, a slow displacement not accompanied by felt earthquakes.



KEY WORDS
earthquake cycle (p. 70), **epicenter** (p. 71), **focus** (p. 71), **P waves** (p. 72), **paleoseismicity** (p. 70), **S waves** (p. 72), **seismic waves** (p. 72), **tectonic creep** (p. 73)

3.3 Earthquake Shaking

LO:3 Summarize the processes that lead to an earthquake and the release of seismic waves.

LO:4 Differentiate between the magnitude scales used to measure earthquakes.

- Large earthquakes release a tremendous amount of energy. Seismologists measure this energy on a magnitude (**M**) scale. On this scale, an increase from one whole number to the next represents a tenfold increase in the amount of shaking and a 32-fold increase in the amount of energy released.

- Earthquake intensity varies with the severity of shaking and is affected by proximity to the epicenter, the local geological environment, and the engineering of structures.
- Buildings highly subject to damage are those that (1) are constructed on unconsolidated sediment, artificially filled land, or water-saturated sediment, all of which tend to amplify shaking; (2) are not designed to withstand significant horizontal acceleration of the ground; or (3) have natural vibrational frequencies that match the frequencies of the seismic waves.

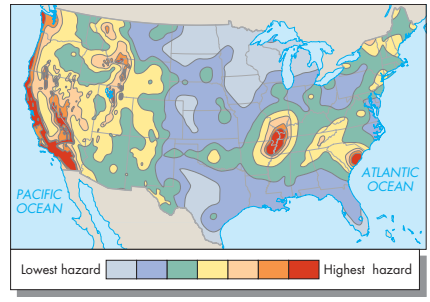


KEY WORDS
material amplification (p. 81), **Modified Mercalli Intensity scale** (p. 77), **moment magnitude scale** (p. 75), **Richter scale** (p. 75), **seismograph** (p. 75)

3.4 Geographic Regions at Risk from Earthquakes

LO:5 Identify global regions at most risk for earthquakes, and describe the effects of earthquakes.

- Most earthquakes occur on faults near tectonic plate boundaries, such as the San Andreas fault in California, the Cascadia subduction zone in the Pacific Northwest, and the Aleutian subduction zone in Alaska.
- Intraplate earthquakes are also common in Hawaii, the western United States, the southern Appalachians and South Carolina, and in the northeastern United States.
- Some of the largest historic earthquakes in North America occurred within the plate in the central Mississippi Valley in the early 1800s.



KEY WORD
megathrust earthquake (p. 85)

3.5 and 3.6 Effects of Earthquakes and Linkages with Other Natural Hazards Natural Service Functions of Earthquakes

LO:6 Describe how earthquakes are linked to other natural hazards.

LO:7 Discuss the important natural service functions of earthquakes.

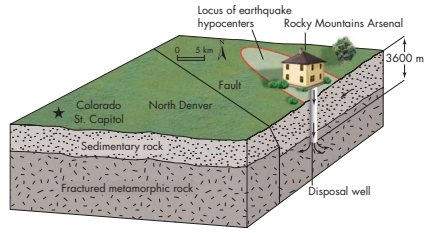
- The primary effect of an earthquake is violent ground motion accompanied by fracturing, which may shear or collapse large buildings, bridges, dams, tunnels, pipelines, levees, and other structures.
- Other effects include liquefaction, regional subsidence, uplift of the land, landslides, fires, tsunamis, and disease.
- Earthquakes provide natural service functions such as enhancing groundwater and energy resources and exposing or contributing to the formation of valuable minerals deposits.



KEY WORDS
fault scarp (p. 91), **liquefaction** (p. 93), **resonance** (p. 92)

3.7 Human Interaction with Earthquakes

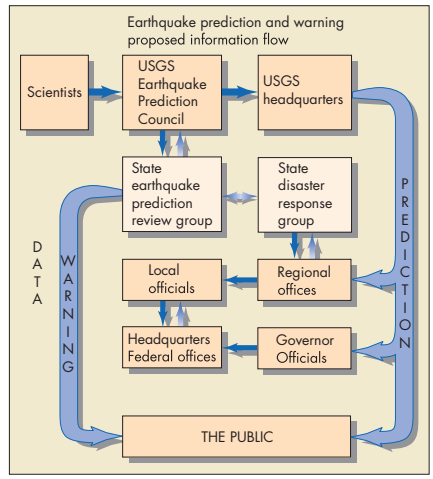
LO:8 Explain how human beings interact with and affect the earthquake hazard.



- Human activity has locally increased earthquake activity by fracturing rock and increasing water pressure underground below large water reservoirs, by raising fluid pressure in faults and fractures through the deep-well disposal of liquid waste, and by setting off underground nuclear explosions.
- Understanding how we have caused earthquakes may eventually help us control or stop large natural earthquakes.

3.8 Minimizing the Earthquake Hazard

LO:9 Discuss the United States governmental approach to minimizing the effects of earthquakes.



- Reducing earthquake hazards requires detailed mapping of geologic faults, the cutting of trenches to determine earthquake frequency, and detailed mapping and analysis of earth materials sensitive to shaking.
- Adjustments to earthquake hazards include improving structural design to better withstand shaking, retrofitting existing structures, microzonation of areas of seismic risk, and updating and enforcing building codes.
- To date, scientists have been able to make long- and intermediate-term forecasts for earthquakes using probabilistic methods but not consistent, accurate short-term predictions. A potential problem of predicting earthquakes is that their pattern of occurrence is often variable with clusters of events separated by longer periods of time with reduced earthquake activity.
- Early warning systems have been shown to be effective in Japan, but no such system exists in the United States or Canada.

KEY WORD
tectonic framework (p. 101)

3.9 Perception of and Adjustment to the Earthquake Hazard

LO:10 Propose ways to minimize seismic risk and suggest adjustments we can make to protect ourselves.



- Warning systems and earthquake prevention are not yet reliable alternatives to earthquake preparedness. More communities must develop emergency plans to respond to a predicted or unexpected catastrophic earthquake. Such plans should include earthquake education, disaster response, drills, and improved insurance coverage.
- At a personal level, individuals who live in or visit areas of seismic risk can learn how to "duck, cover, and hold on" before the next large earthquake. Preparation both reduces the earthquake hazard and eases recovery.

CRITICAL thinking questions

1. You live in an area that has a significant earthquake hazard. Public officials, the news media, and citizens are debating whether an earthquake warning system should be developed. Some people are worried that false alarms will cause a lot of problems, and others point out that the response time may be very long. What are your views on this issue? Should public funds be used to finance an earthquake warning system, assuming such a system is feasible? What are potential implications if a warning system is not developed and a large earthquake results in damage that could have been partially avoided with a warning system in place?
2. You are considering buying a home on the California coast. You know that earthquakes are common in the area. What questions would you ask before purchasing the home? For example, consider the effects of earthquakes, the relationship of shaking to earth material, and the age of the structure. What might you do to protect yourself (both financially and physically) if you decide to buy the house?
3. You are working for the Peace Corps in a developing country where most of the homes are built out of unreinforced bricks. There has not been a large damaging earthquake in the area for several hundred years, but earlier there were several earthquakes that killed thousands of people. How would you present the earthquake hazard to the people living where you are working? What steps might be taken to reduce the hazard?

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