SIX

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Earthquakes and Related Phenomena

Learning Objectives

The study of earthquakes is an exciting field with significant social consequences including potential catastrophic loss of life; damage or loss of homes, large buildings, and infrastructure such as roads, train tracks, airports, dams, and power plants; disruption of people's lives; and loss of income. In this chapter we focus on the following learning objectives:

- Understand the relationship of earthquakes to faulting
- Understand how the magnitude of an earthquake is determined
- Know the types of earthquake waves, their properties, and how strong ground motion is produced
- Understand how seismic risk is estimated
- Know the major effects of earthquakes
- Know how an earthquake may produce a tsunami
- Understand the components of the earthquake cycle
- Understand the methods that could potentially predict earthquakes
- Understand the processes of earthquake hazard reduction and how people adjust to and perceive the hazard

Los Angeles earthquake Collapse of a freeway in the Los Angeles area as the result of the 1994 Northridge earthquake. *(Les Stone/Corbis/Sygma)*

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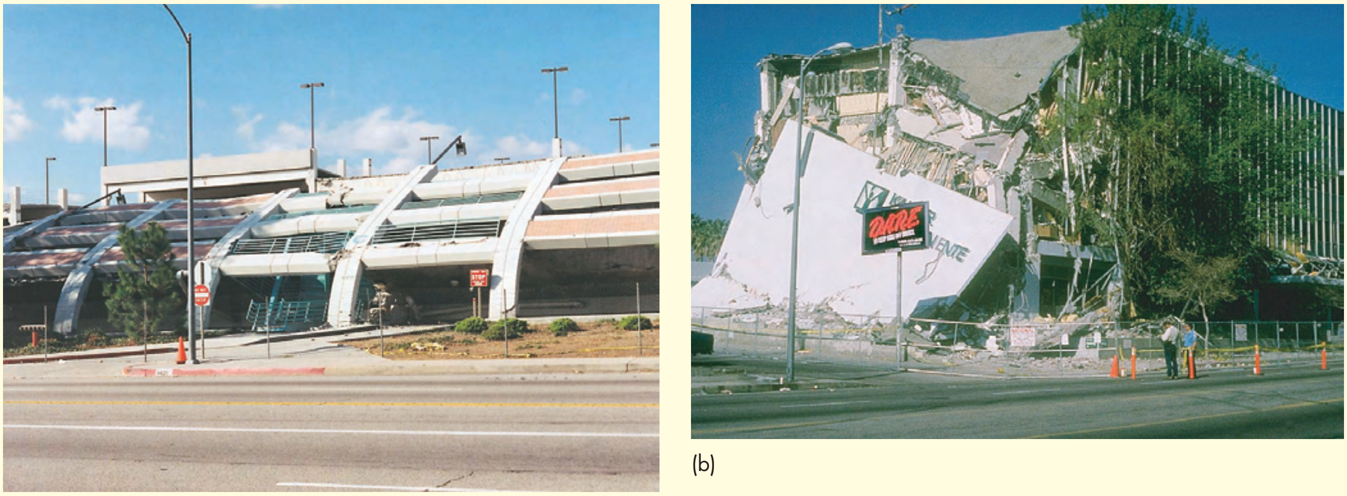
CASE HISTORY | Northridge, 1994

The 1994 Northridge earthquake that struck the Los Angeles area on January 17 was a painful wake-up call to southern Californians. The earthquake killed 57 people and caused about $40 billion in property damage. Several sections of freeways were heavily damaged, as were parking structures and more than 3,000 buildings (Figure 6.1). The Northridge earthquake is one in a series of moderate-sized earthquakes that have recently occurred in southern California.

The rupture of rocks that produced the Northridge earthquake was initiated on a steep fault at a depth of approximately 18 km (11 mi). The rupture quickly propagated upward (northward and westward) but did not reach the surface, stopping at a depth of several kilometers. At the same time, the rupture progressed laterally in a mostly westward direction, 20 km (12.5 mi). The geometry of the fault movement is shown in Figure 6.2. The movement produced uplift and folding of part of the Santa Susana Mountains, a few kilometers north of Northridge.[1]

The Northridge earthquake terrified people, especially children. The shaking, which lasted about 15 seconds, was intense; people were thrown out of bed, objects flew across rooms, chimneys tumbled, walls cracked, and Earth groaned and roared with each passing earthquake wave. When the shaking stopped, people had little time to recover before strong aftershocks started.



(a)

(b)

Figure 6.1 **Earthquake in Los Angeles urban region** Damage from the 1994 Northridge, California, earthquake. (a) A parking structure. *(R. Forrest Hopson)* (b) Damage to the Kaiser Permanente Building. *(A. G. Sylvester)*

6.1 Introduction to Earthquakes

There are approximately 1 million earthquakes a year that can be felt by people somewhere on Earth. However, only a small percentage of these can be felt very far from their source. Earthquakes can be compared with one another by the energy they release, their *magnitude,* or by their intensity of shaking, referred to as ground motion, and the resulting impact on people and society. Table 6.1 lists selected major earthquakes that have struck the United States since the early nineteenth century.

6.2 Earthquake Magnitude

When a news release is issued about an earthquake, it generally gives information about where the earthquake started, known as the epicenter. The **epicenter** is the location on the surface of Earth above the **focus,** which is the point at depth where the rocks ruptured to produce the earthquake (Figure 6.3). The news also reports **moment magnitude,** which is a measure of the energy released by the earthquake. The moment magnitude is based in part upon important physical characteristics,

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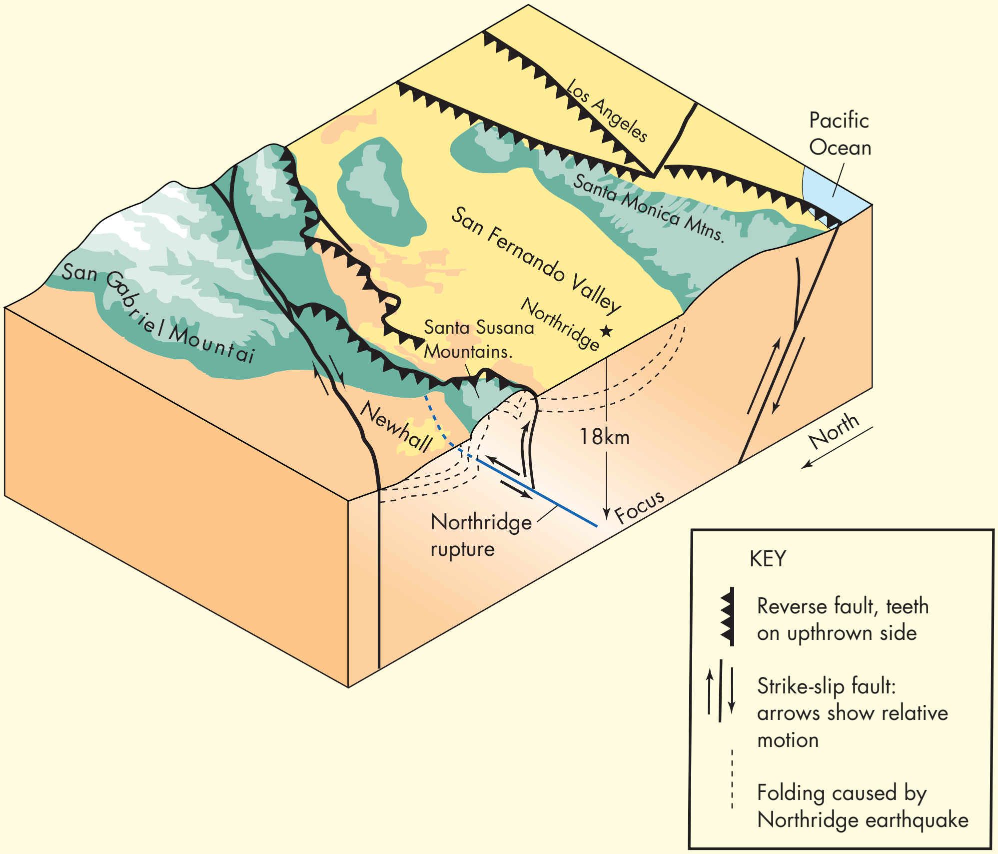

Figure 6.2 **Details of an earthquake** Block diagram showing the fault that produced the 1994 Northridge earthquake. During the earthquake, the Santa Susana Mountains were folded, uplifted 38 cm (15 in.), and moved 21 centimeters (8.2 in.) to the northwest. *(Courtesy of Pat Williams, Lawrence Livermore Laboratory)*

including the area that ruptured along a fault plane during an earthquake, the amount of movement or fault slip during an earthquake, and the rigidity of the rocks.

Before the use of moment magnitude, *Richter magnitude,* named after the famous seismologist Charles Richter, was used to describe the energy released by an earthquake. Richter magnitude is based upon the *amplitude,* or size, of the largest seismic wave produced during an earthquake. A *seismograph* is an instrument that records earthquake displacements; seismographs produce *seismographic records,* or *seismograms*. The amplitude recorded is converted to a magnitude on a logarithmic scale; that is, each integer increase in Richter magnitude represents a tenfold increase in amplitude. For example, a Richter magnitude 7 earthquake produces a displacement on the seismogram 10 times larger than does a magnitude 6. Although the Richter magnitude remains the best known earthquake scale to many people, earthquake scientists, known as *seismologists,* do not commonly use it. For large, damaging earthquakes the Richter magnitude is approximately equal to the moment magnitude, which is more commonly used today. In this book we will simply refer to the size of an earthquake as its magnitude, M, without designating a Richter or moment magnitude.

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TABLE 6.1 Selected Major 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	524	700
1925	Santa Barbara, California	8	13
1933	Long Beach, California	40	115
1940	Imperial Valley, California	6	9
1952	Kern County, California	60	14
1959	Hebgen Lake, Montana (damage to timber and roads)	11	28
1964	Alaska and U.S. West Coast (includes tsunami damage from earthquake near Anchorage)	500	131
1965	Puget Sound, Washington	13	7
1971	San Fernando, California	553	65
1983	Coalinga, California	31	0
1983	Central Idaho	15	2
1987	Whittier, California	358	8
1989	Loma Prieta (San Francisco), California	5,000	62
1992	Landers, California	271	1
1994	Northridge, California	40,000	57
2001	Seattle, Washington	2,000	1
2002	South-Central Alaska	(sparsely populated area)	0

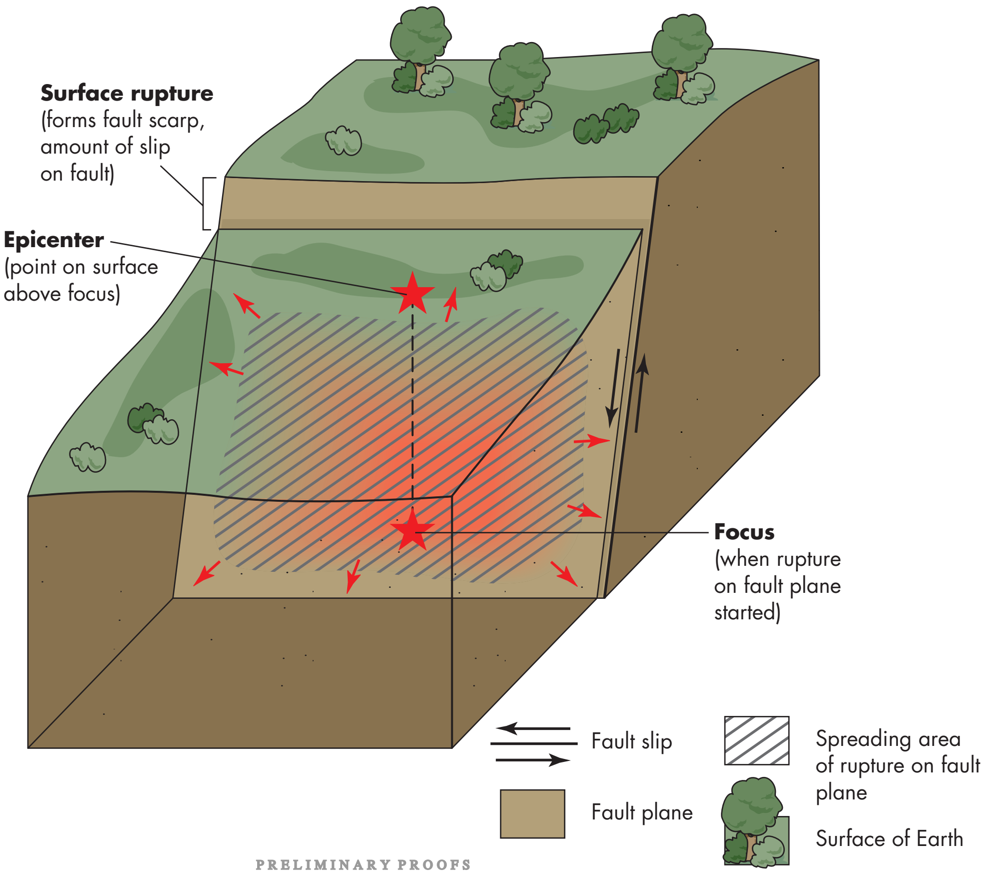

Figure 6.3 Basic earthquake features Block diagram showing fault plane, amount of displacement, rupture area, focus, and epicenter. Rupture starts at the focus and propagates up, down, and laterally. During a major to giant earthquake, slip may be 2 to 20 meters along a fault length of 100 or more kilometers. Rupture area may be 1,000 square kilometers or more.

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TABLE 6.2 Worldwide Magnitude and Frequency of Earthquakes by Descriptor Classification

Descriptor	Magnitude	Average Annual No. of Events
Great	8 and Higher	1
Major	7–7.9	18
Strong	6–6.9	120
Moderate	5–5.9	800
Light	4–4.9	6,200 (estimated)
Minor	3–3.9	49,000 (estimated)
Very minor	<3.0	Magnitude 2–3 about 1,000 per day
		Magnitude 1–2 about 8,000 per day

U.S. Geological Survey. 2000. *Earthquakes, facts and statistics*. http://neic.usgs.gov. Accessed 1/3/00.

TABLE 6.3 Relationships between Magnitude, Displacement, and Energy of Earthquakes

Magnitude Change	Ground Displacement Change[1]	Energy Change
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

[1] Displacement, vertical or horizontal, that is recorded on a standard seismograph.

Source: U.S. Geological Survey. 2000. *Earthquakes, facts and statistics*. neic.usgs.gov. Accessed 1/3/00.

The magnitude and frequency of earthquakes worldwide are shown in Table 6.2. An event of magnitude (M) 8 or above is considered a *great earthquake,* capable of causing widespread catastrophic damage. In any given year there is a good chance that one M 8 event will occur somewhere in the world. A M 7 event is a *major earthquake,* capable of causing widespread and serious damage. Magnitude 6 signifies a *strong earthquake* that can cause considerable damage, depending upon factors such as location, surface materials, and quality of construction. Ground motion can be recorded as the displacement or actual separation of rocks produced by an earthquake. Relationships between change in magnitude and change in displacement and energy are shown in Table 6.3. This table illustrates that the difference between a M 6 and a M 7 earthquake is considerable. A M 7 earthquake releases about 32 times more energy than a M 6 earthquake and the amount of displacement, or ground motion, is 10 times greater. If we compare a M 5 with a M 7 earthquake the differences are much greater. The energy released is about 1,000 times greater. The topic of earthquake magnitude is introduced here to help compare the severity of earthquakes. We will return to a more detailed discussion of this topic later in this chapter when earthquake processes are discussed.

Earthquake Catastrophes

Catastrophic, or great, 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 1985, an earthquake originating beneath the Pacific

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Figure 6.4 **Earthquake damage** (a) This elevated road collapsed as a result of intense seismic shaking associated with the 1995 Kobe, Japan, earthquake. *(Naoto Hosaka/Getty Images Inc.)* (b) Collapsed buildings, Balakot, Pakistan, from M 7.6 earthquake in 2005. *(AP/Wide World Photos)*

(a)

(b)

Ocean off Mexico (M 8.1) caused 10,000 deaths in Mexico City, several hundred kilometers from the source. Exactly one year after Northridge, the January 17, 1995, Kobe, Japan, earthquake (M 7.2) killed more than 5,000 and injured 27,000 people while destroying 100,000 buildings and causing over $100 billion in property damages (Figure 6.4a). The January 26, 2001, Gujarat, India, earthquake (M 7.7) killed as many as 30,000 people, injured 166,000, damaged or destroyed about 1 million homes, and left 600,000 people homeless. An earthquake on October 8, 2005, of M 7.6, struck northern Pakistan. Although the epicenter was in Pakistan, extensive damage also occurred in Kashmir and India (Figure 4.b). Over 80,000

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people were killed and over 30,000 buildings collapsed. Entire villages were destroyed, some buried by landslides triggered by the violent shaking.[2,3]

6.3 Earthquake Intensity

A qualitative way of comparing earthquakes is to use the **Modified Mercalli Scale,** which describes 12 divisions of intensity based on observations concerning the severity of shaking during an earthquake (Table 6.4). Intensity reflects how people perceived the shaking and how structures responded to the shaking. Whereas a particular earthquake has only one magnitude, different levels of intensity may be assigned to the same earthquake at different locations, depending on proximity to the epicenter and local geologic conditions. Figure 6.5 is a map showing the spatial variability of intensity for the 1971 San Fernando earthquake (M 6.6). Such maps, produced from questionnaires sent to residents in the epicentral region after an earthquake, are a valuable, although crude, index of ground shaking.

One of the major challenges during a damaging earthquake is to quickly determine where the damage is most severe. An approach now being used is known as a **shake map** that shows the extent of potential damaging shaking following an earthquake. Data for a shake map are recorded from a dense network of high-quality seismograph stations. When seismic data are received at seismographic stations, the areas with the severest shaking are known within a minute or so after the shaking has ceased. This information is critical to direct an effective emergency response to those areas. The maps in Figure 6.6 show the shake map for the 1994 Northridge, California, earthquake (M 6.7), and the 2001 M 6.8 Seattle, Washington, earthquake. Notice that the magnitudes of the two earthquakes are very similar, but the intensity of shaking was greater for

TABLE 6.4 Modified Mercalli Intensity Scale (abridged)

Intensity	Effects
I	Felt by very few people.
II	Felt by only a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration feels like the passing of a truck.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound; sensation like heavy truck striking building; standing motor cars rock noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, and so on, broken; a few instances of cracked plaster; unstable objects overturned; disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage is slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures; panel walls thrown out of frame structures; fall of chimneys, factory stacks, columns, monuments, walls; heavy furniture overturned; sand and mud ejected in small amounts; changes in well water; disturbs persons driving cars.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings are shifted off foundations. Ground cracked conspicuously. Underground pipes are broken.
X	Some well-built wooden structures are destroyed; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water is splashed over banks.
XI	Few, if any (masonry) structures remain standing. Bridges are destroyed. Broad fissures are formed in ground. Underground pipelines are taken out of service. Earth slumps and land slips on soft ground occurs. Train rails are bent.
XII	Damage is total. Waves are seen on ground surfaces. Lines of sight and level distorted. Objects are thrown upward into the air.

Source: From Wood and Neuman, 1931, by U.S. Geological Survey, 1974, *Earthquake Information Bulletin* 6(5): 28.

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Figure 6.5 **Intensity of shaking** Modified Mercalli Intensity Map for the 1971 San Fernando Valley, California, earthquake (M 6.6), determined after the earthquake. *(U.S. Geological Survey, 1974,* Earthquake Information Bulletin *6[5])*

the Northridge earthquake. The technology to produce and distribute shake maps in the minutes following an earthquake was made available in 2002.[4] 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 very useful in helping locate 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 very desirable component of our preparedness for earthquakes.

6.4 Plate Boundary Earthquakes

California, which straddles two lithospheric plates that are moving past one another, experiences frequent damaging earthquakes. The 1989 Loma Prieta earthquake (M 7.1) on the San Andreas fault system south of San Francisco killed 62 people and caused $5 billion in property damage. Neither the Loma Prieta earthquake nor the Northridge earthquake (M 6.7) was considered a great earthquake. It has been estimated that a great earthquake occurring today in a densely populated part of southern California could inflict $100 billion in damage and kill several thousand people. Thus, the Northridge quake, as terrible as it was, was not the anticipated "big one." Given that earthquakes have the proven potential for producing a catastrophe, earthquake research is primarily dedicated to understanding earthquake processes. 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.

Interplate earthquakes are those between two plates, initiated near plate boundaries and producing nearly continuous linear or curvilinear zones in which most seismic activity takes place (Figure 6.7). Most large U.S. earthquakes are interplate earthquakes in the West, particularly near the North American and Pacific plate boundaries (Table 6.1). However, large damaging *intraplate earthquakes,* located within a single plate, can occur far from plate boundaries.

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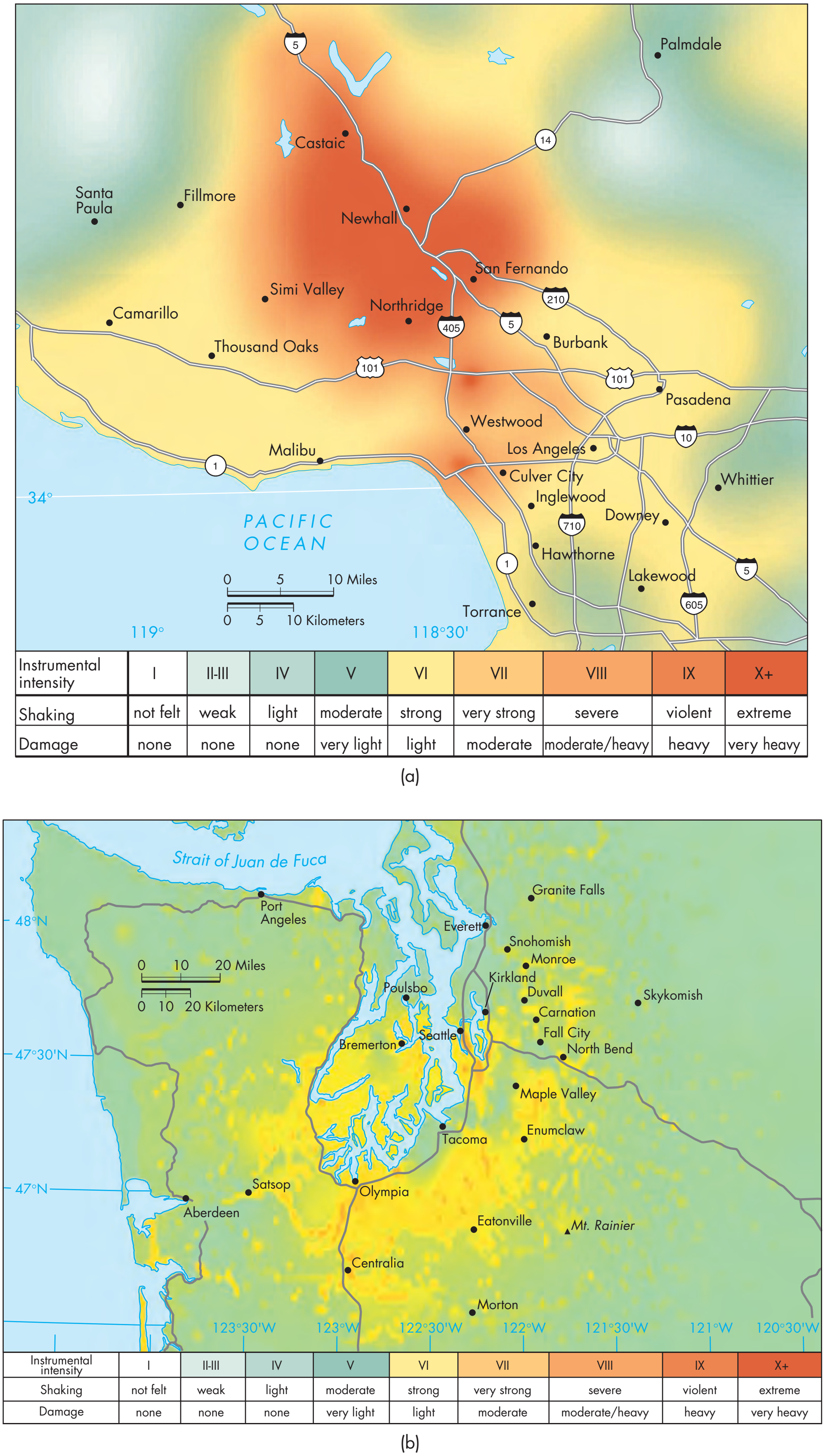

Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Damage	none	none	none	very light	light	moderate	moderate/heavy	heavy	very heavy

Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Damage	none	none	none	very light	light	moderate	moderate/heavy	heavy	very heavy

Figure 6.6 Real-time intensity of shaking (a) Shake map for the 1994 Northridge, California, earthquake (M 6.7) determined after the earthquake occurred. *(U.S. Geological Survey, and courtesy of David Wald)* (b) The 2001 Seattle, Washingon, earthquake (M 6.8). *(Pacific Northwest Seismograph Network, University of Washington)*

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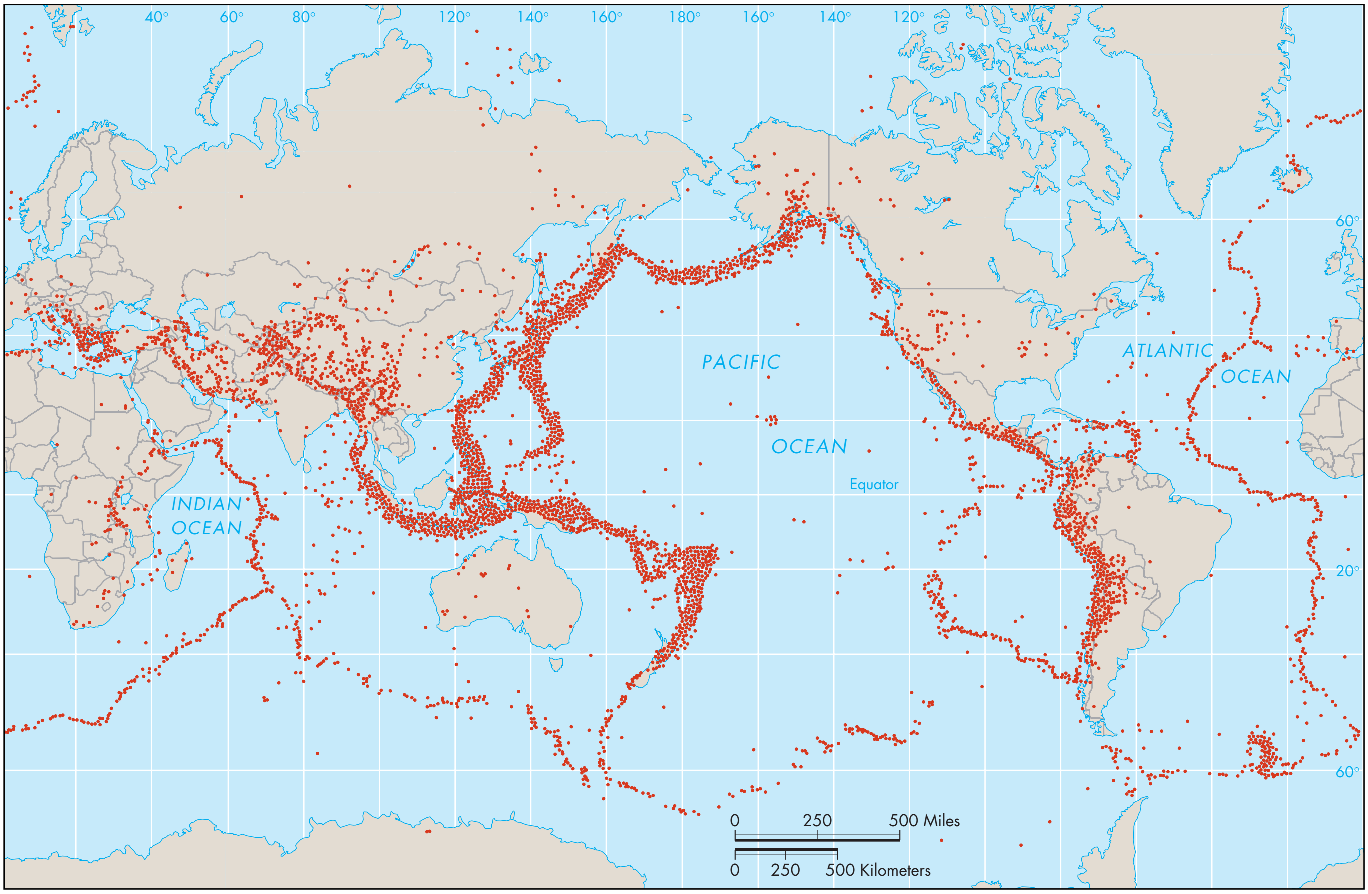

Figure 6.7 **Earthquakes at plate boundaries** Map of global seismicity (1963–1988), delineating plate boundaries and earthquake belts shown in Figure 6.9. Brown dots represent individual earthquakes. For the locations and names of Earth's tectonic plates refer to Figure 2.4. *(Courtesy of National Earthquake Information Center)*

6.5 Intraplate Earthquakes

Intraplate earthquakes with M 7.5+ that occurred in the winter of 1811–1812 in the central Mississippi Valley nearly destroyed the town of New Madrid, Missouri, while killing an unknown number of people. These earthquakes rang church bells in Boston! Seismic shaking produced intense surface deformation over a wide area from Memphis, Tennessee, north to the confluence of the Mississippi and Ohio Rivers. During the earthquakes, 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 in some areas, causing flooding. It was reported that the Mississippi River actually reversed its flow during shaking. The earthquakes occurred along a seismically active structure known as the New Madrid seismic zone, which underlies the geologic structure known as the Mississippi River Embayment (Figure 6.8). The embayment is a downwarped area of Earth's crust where the lithosphere is relatively weak. The recurrence interval, or time between events, for major earthquakes in the embayment is estimated to be about 500 years.[5,6] Even in this "stable" interior of the North American plate, the possibility of future damage demands that the earthquake hazard in the area be considered when facilities such as power plants and dams are being designed and built. It is believed that the New Madrid seismic zone is a young, perhaps less than 10,000 year old, zone of deformation. The rate of

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Figure 6.8a New Madrid seismic zone Location is thousands of kilometers from the nearest plate boundary (red lines).

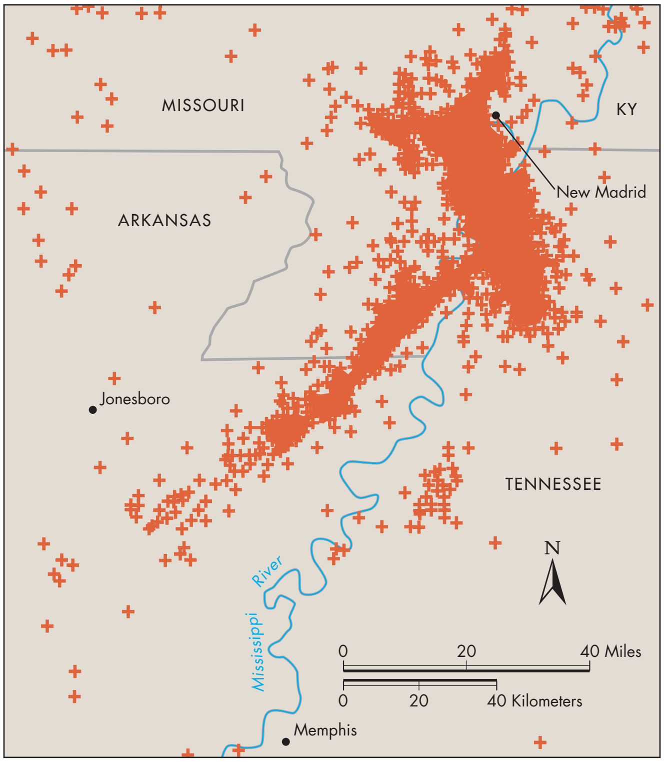

Figure 6.8b This zone is the most earthquake-prone region in the United States east of the Rocky Mountains. Locations of recorded minor earthquakes since 1974 are shown as crosses. *(U.S. Geological Survey)*

uplift is sufficient to produce significant topographic relief over a period of several hundred thousand years. The fact that topography of the uplifted region in the Mississippi River floodplain area is very minor supports the hypothesis that this is a very young fault system or one that has been recently reactivated. The New Madrid seismic zone is capable of producing great earthquakes and is the object of intensive research.

Another large damaging intraplate earthquake (M 7.5) occurred on August 31, 1886, near Charleston, South Carolina. The earthquake killed about 60 people and damaged or destroyed most buildings in Charleston. Effects of the earthquake were reported at distances exceeding 1,000 km (620 mi).

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Intraplate earthquakes in the eastern United States are generally more damaging and felt over a much larger area than a similar magnitude earthquake in California. The reason is that the rocks in the eastern United States are generally stronger and less fractured and can more efficiently transmit earthquake waves than rocks in the west.

6.6 Earthquake Processes

Our discussion of global tectonics established that Earth is a dynamic, evolving system. Earthquakes are a natural consequence of the processes that form the ocean basins, continents, and mountain ranges of the world. Most earthquakes occur along the boundaries of lithospheric plates (Figures 6.7 and 6.9).

Faulting

The process of fault rupture, or *faulting*, can be compared to sliding two rough boards past one another. Friction along the boundary between the boards, analogous to a fault plane, may temporarily slow their motion, but rough edges break off and motion occurs at various places along the plane. For example, lithospheric plates that are moving past one another are slowed by friction along their boundaries. As a result, rocks along the boundary undergo strain, or deformation, resulting from stress produced by the movement. When stress on the rocks

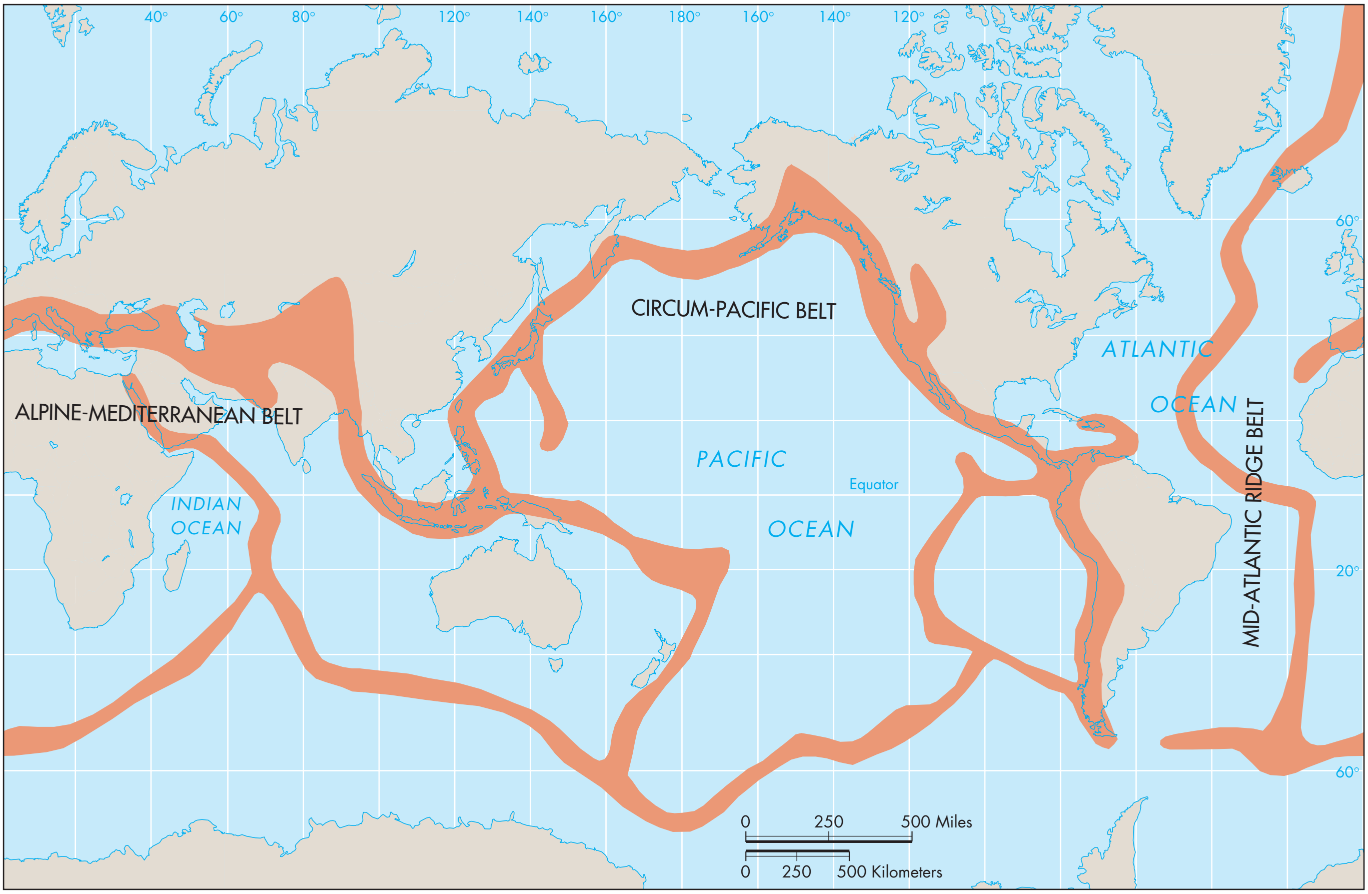

Figure 6.9 **Earthquake belts** Map of the world showing the major earthquake belts as shaded areas. *(National Oceanic and Atmospheric Administration)*

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exceeds their strength, the rocks rupture, forming a fault and producing an **earthquake.** A **fault** is a fracture or fracture system along which rocks have been displaced; that is, one side of the fracture or fracture system has moved relative to the other side. The long-term rate of movement is known as the *slip rate* and is often recorded as millimeters per year (mm/yr) or meters per 1,000 years (m/ky). During a major to great earthquake, displacements of several meters may suddenly occur along a fault. When a rupture begins it starts at the focus and then grows or propagates up, down, and laterally along the fault plane during an earthquake. (See Figure 6.3.) The sudden rupture of the rocks produces shock waves called earthquake waves, or *seismic waves,* that shake the ground. In other words, the pent-up energy of the strained rocks is released in the form of an earthquake. Faults are therefore *seismic sources,* and identifying them is the first step in evaluating the risk of an earthquake, or seismic risk in a given area.

Fault Types

The major types of faults, based on the direction, or sense of the relative displacement, are shown on Figure 6.10. A *strike-slip fault* is one in which the sides of the fault are displaced horizontally; a strike-slip fault is called *right-lateral* if the right-hand side moves toward you as you sight, or look along the fault line, and *left-lateral* if the left-hand side moves toward you. A fault with vertical displacement is referred to as a *dip-slip fault*. A dip-slip fault may be a *reverse fault* or a *normal fault,* depending on the geometry of the displacement. Geologists use interesting terminology to distinguish reverse and normal faults. Notice in Figure 6.10 that there are two blocks separated by the fault plane. One way to remember the terminology for the two blocks is to imagine you are walking up the fault plane, like walking up a hill. The block you would be standing on is called the foot-wall, and the other block is called the hanging-wall. If the fault displacement is such that the hanging-wall moves up relative to the foot-wall, the fault is called a *reverse fault*. When the fault plane of a reverse fault has an angle of less than 45 degrees it is called a *thrust fault*. If the hanging-wall moves down relative to the foot-wall the fault is called a *normal fault*. Reverse and thrust fault displacement are associated with crustal shortening, whereas normal fault displacement is associated with crustal extension.

The faults shown in Figure 6.10 generally produce surface displacement or rupture. However, there are also *buried faults,* usually associated with folded rocks. Displacement and rupture of buried faults do not propagate to the surface even in large earthquakes, as was the case with the Northridge earthquake.

The relationship of a buried reverse fault to rock folding is shown in Figure 6.11. Shortening of a sequence of sedimentary rocks has produced folds called anticlines and synclines. *Anticlines* are arch-shaped folds; *synclines* are bowl-shaped folds. In this illustration, anticlines form ridges and synclines form basins at the surface of the ground. Notice that in the cores of two of the anticlines on the right, buried faulting has occurred. Faulting during earthquakes causes anticlinal mountains to be uplifted, whereas subsidence, or sinking of the ground surface, may occur in synclinal valleys.

Until recently it was thought that most active faults could be mapped because their most recent earthquake would cause surface rupture. Discovering that some faults are buried and that rupture does not always reach the surface has made it more difficult to evaluate the earthquake hazard in some areas.

Active Faults

Most geologists consider a particular fault to be an *active fault* if it can be demonstrated to have moved during the past 10,000 years, the Holocene epoch. The Quaternary period, spanning approximately the past 1.65 million years, is the most recent period of geologic time, and most of our landscape has been produced during that time (see Table 1.1). Fault displacement that has occurred during the Pleistocene

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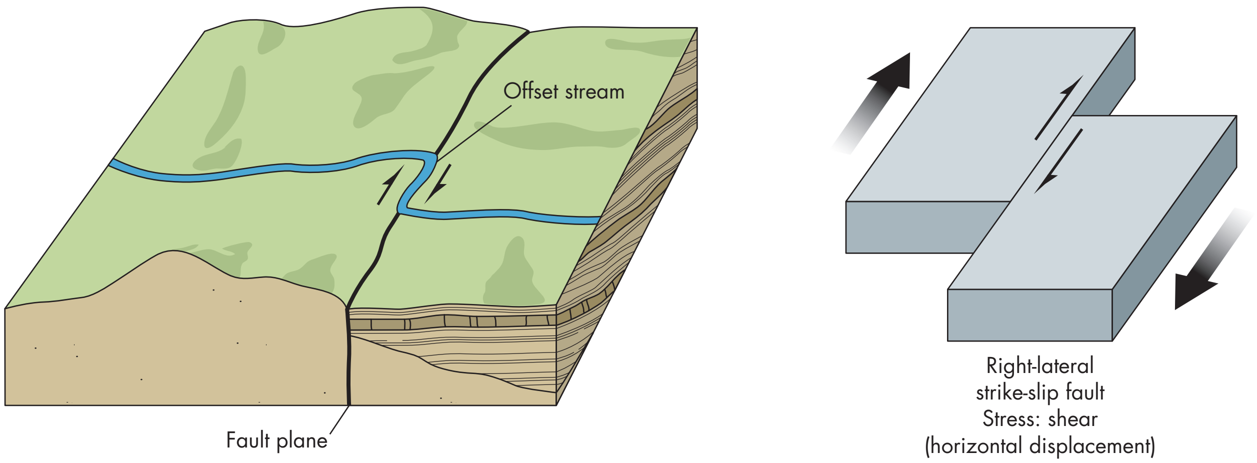
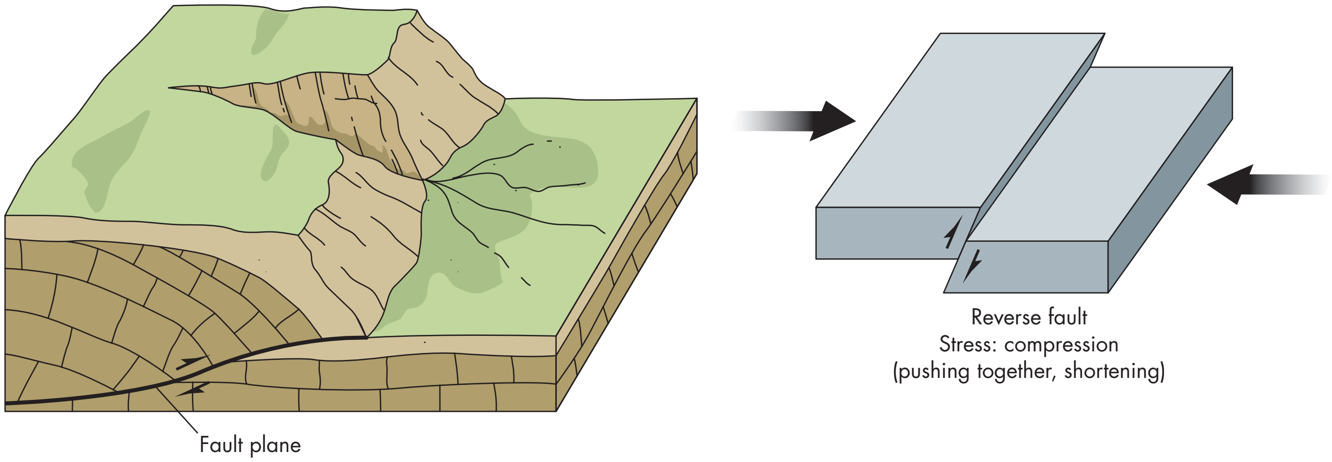
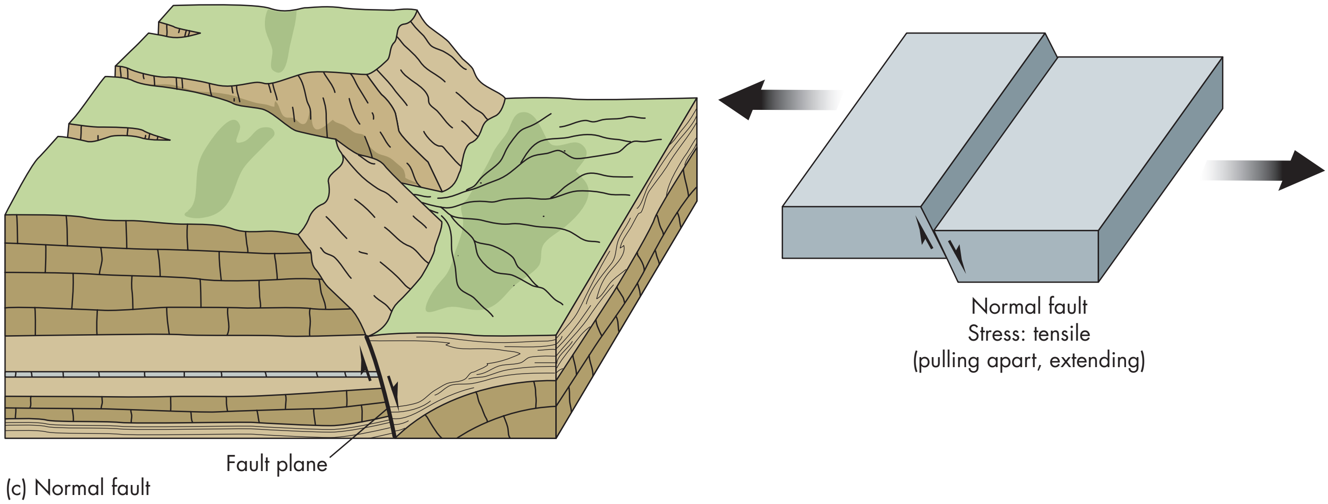


(a) Right-lateral strike-slip fault



(b) Reverse (thrust) fault



(c) Normal fault

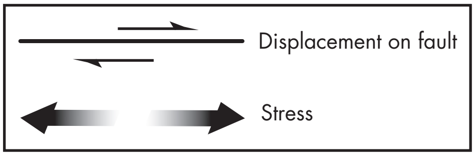


Figure 6.10 **Faulting changes the land** Types of fault movement and effects on the landscape based on the sense of motion relative to the fault.

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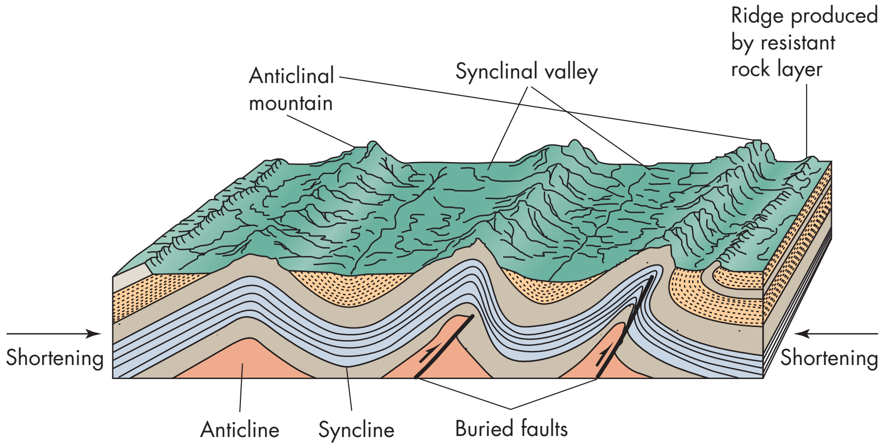

Figure 6.11 **Buried faults** Block diagram illustrating several types of common folds and buried reverse faults with possible surface expressions such as anticlinal mountains and synclinal valleys. *(Modified after Lutgens, F., and Tarbuck, E. 1992.* Essentials of geology, *4th ed. New York: Macmillan)*

epoch of the Quaternary period, approximately 1.65 million to 10,000 years ago, but not in the Holocene, is classified as *potentially active* (Table 6.5).

Faults that have not moved during the past 1.65 million years are generally classified as *inactive*. However, we emphasize that it is often difficult to prove the activity of a fault in the absence of easily measured phenomena such as historical earthquakes. Demonstrating that a fault is active may require determining the past earthquake history, or *paleoseismicity,* on the basis of the geologic record. This determination involves identifying faulted Earth materials and determining when the most recent displacement occurred.

Tectonic Creep

Some active faults exhibit **tectonic creep,** that is, gradual displacement that is not accompanied by felt earthquakes. The process can slowly damage roads, sidewalks, building foundations, and other structures. Tectonic creep has damaged culverts under the football stadium of the University of California at Berkeley and periodic repairs have been necessary as the cracks developed. Movement of approximately 3.2 cm (1.3 in.) was measured in a period of 11 years. More rapid rates of tectonic creep have been recorded on the Calaveras fault zone, a segment of the San Andreas fault, near Hollister, California. At one location, a winery situated on the fault is slowly being pulled apart at about 1 cm (0.4 in.) per year (Figure 6.12). Damages resulting from tectonic creep generally occur along narrow fault zones subject to slow, continuous displacement.

TABLE 6.5 **Terminology Related to Recovery of Fault Activity**

GEOLOGIC AGE			Years before Present	Fault Activity
Era	Period	Epoch		
Cenozoic	Quaternary	Historic Holocene	200 10,000	Active
		Pleistocene	1,650,000	Potentially active
	Tertiary	Pre-Pleistocene	65,000,000	Inactive
	Pre-Cenozoic time		4,500,000,000	
	Age of Earth			

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

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Figure 6.12 **Tectonic creep** This concrete culvert at the Almandea vineyards in Hollister, California, is being split by creep on the San Andreas fault. *(James A. Sugar/NGS Image Collection)*

Slow Earthquakes

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. The moment magnitude of slow earthquakes can be in the range of 6 to 7 because a large area of rupture is often involved, although the amount of slip is generally small (a centimeter or so). Slow earthquakes are a newly recognized fundamental Earth process. They are recognized through analysis of continuous geodetic measurement or GPS, similar to the devices that are used in automobiles to identify your 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 the surface of the earth to produce mountains over geologic time may be significant.[7]

6.7 Earthquake Shaking

Three important factors determine the shaking you will experience during an earthquake: (1) earthquake magnitude; (2) your distance from the epicenter; and (3) local soil and rock conditions. If an earthquake is of moderate magnitude (M 5 to 5.9) or larger, then strong motion or shaking may be expected. It is the strong motion from earthquakes that cracks the ground and makes Earth "rock and roll" to damage buildings and other structures.

Types of Seismic Waves

Some of the seismic waves generated by fault rupture travel within Earth and others travel along the surface. The two types of seismic waves that travel with a velocity of several kilometers per second through rocks are primary (P) and secondary (S) waves (see Figure 6.13a, b).

P waves, also called compressional waves, are the faster of the two and can travel through solid, liquid, and gaseous materials (see Figure 6.13a). The velocity of P waves through liquids is much slower. Interestingly, when P waves are propagated into the atmosphere, they are detectable to the human ear. This fact explains the observation that people sometimes *hear* an earthquake before they feel the shaking caused by the arrival of the slower surface waves.[8]

S waves, also called shear waves, can travel only through solid materials. Their speed through rocks such as granite is approximately one-half that of P waves. S waves produce an up-and-down or side-to-side motion at right angles to the direction of wave propagation, similar to the motion produced in a clothesline by pulling it down and letting go (see Figure 6.13b). Because liquids cannot spring

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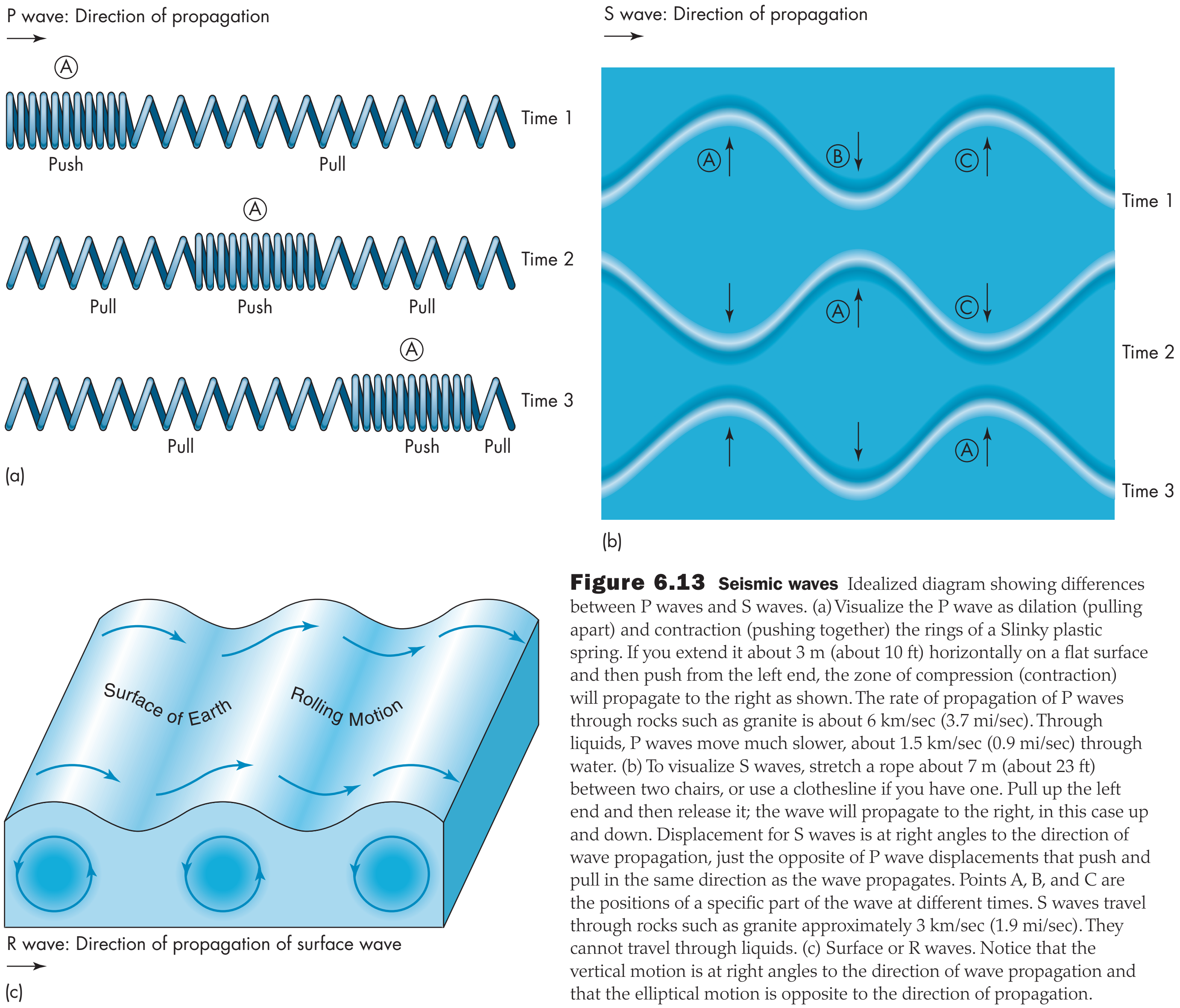

Figure 6.13 **Seismic waves** Idealized diagram showing differences between P waves and S waves. (a) Visualize the P wave as dilation (pulling apart) and contraction (pushing together) the rings of a Slinky plastic spring. If you extend it about 3 m (about 10 ft) horizontally on a flat surface and then push from the left end, the zone of compression (contraction) will propagate to the right as shown. The rate of propagation of P waves through rocks such as granite is about 6 km/sec (3.7 mi/sec). Through liquids, P waves move much slower, about 1.5 km/sec (0.9 mi/sec) through water. (b) To visualize S waves, stretch a rope about 7 m (about 23 ft) between two chairs, or use a clothesline if you have one. Pull up the left end and then release it; the wave will propagate to the right, in this case up and down. Displacement for S waves is at right angles to the direction of wave propagation, just the opposite of P wave displacements that push and pull in the same direction as the wave propagates. Points A, B, and C are the positions of a specific part of the wave at different times. S waves travel through rocks such as granite approximately 3 km/sec (1.9 mi/sec). They cannot travel through liquids. (c) Surface or R waves. Notice that the vertical motion is at right angles to the direction of wave propagation and that the elliptical motion is opposite to the direction of propagation. Surface waves are often the most damaging of the seismic waves.

back when subjected to this type of motion, called sideways shear, S waves cannot move through liquids.[8]

When seismic waves reach the surface, complex **surface waves** (R waves) are produced. Surface waves, which move along Earth's surface, travel more slowly than either P or S waves and cause much of the earthquake damage to buildings and other structures. Damage occurs because surface waves have a complex horizontal and vertical ground movement or rolling motion that may crack walls and foundations of buildings, bridges, and roads. An important surface wave is the R wave, shown in Figure 6.13c. The rolling motion moves in the direction opposite to that of the wave, or propagation, and the vertical motion, or amplitude, is at right angles to the direction of propagation.

Seismograph

The *seismogram* is the written or digital record of an earthquake. In written form, it is a continuous line that shows vertical or horizontal Earth motions received at a seismic recording station and recorded by a seismograph. The components of a simple seismograph are shown in Figure 6.14a, and a photograph of a modern seismograph is shown in Figure 6.14b. An idealized written record, or seismogram,

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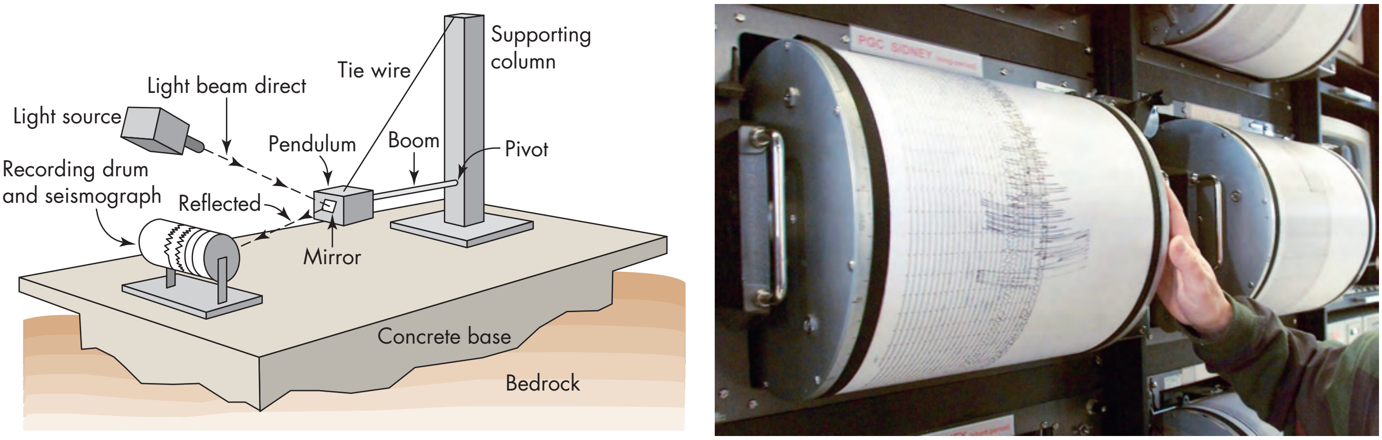
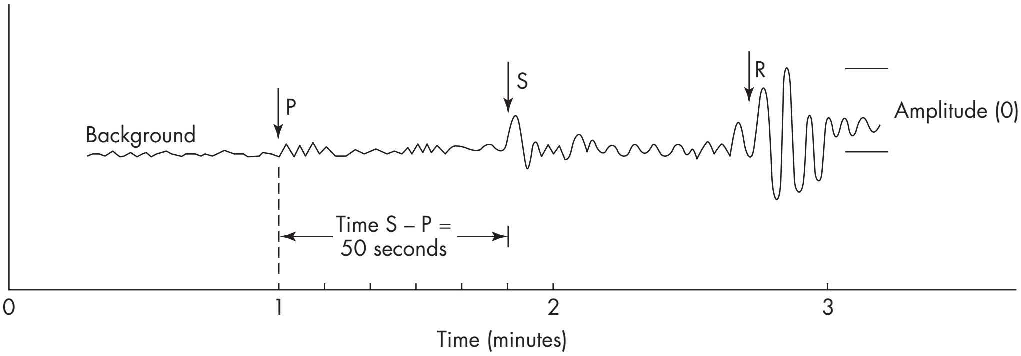


(a) (b)



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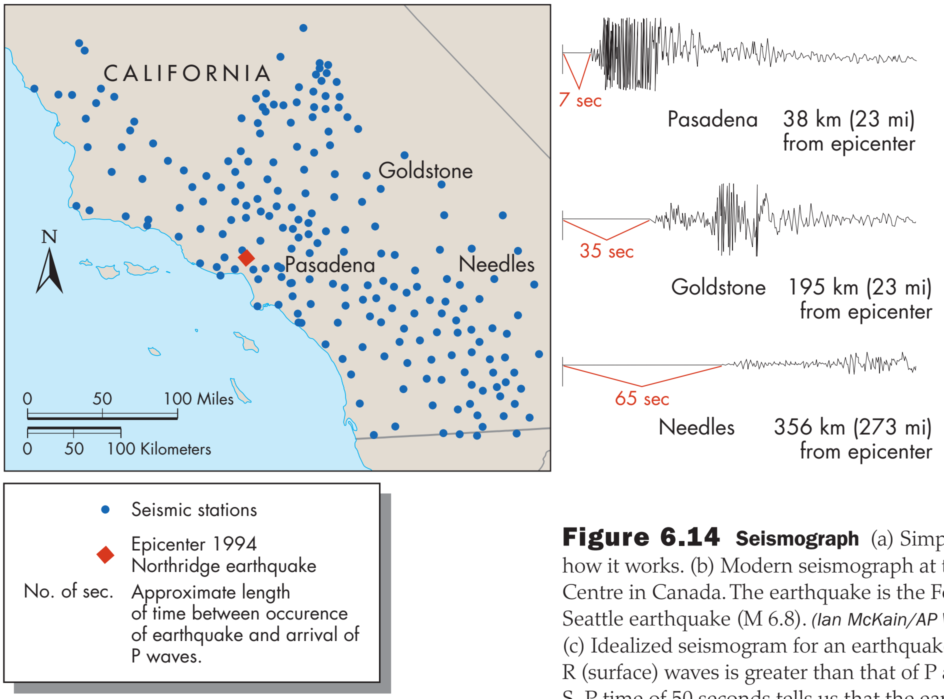

(d)

Figure 6.14 **Seismograph** (a) Simple seismograph showing how it works. (b) Modern seismograph at the Pacific Geoscience Centre in Canada. The earthquake is the February 28, 2001, Seattle earthquake (M 6.8). *(Ian McKain/AP Wide World Photos)* (c) Idealized seismogram for an earthquake. The amplitude of the R (surface) waves is greater than that of P and the S waves. The S–P time of 50 seconds tells us that the earthquake epicenter was about 420 km (261 mi) from the seismograph. (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. Notice that, with distance, the time of arrival of shaking increases and the amplitude of shaking decreases. *(Modified from Southern California Earthquake Center)*

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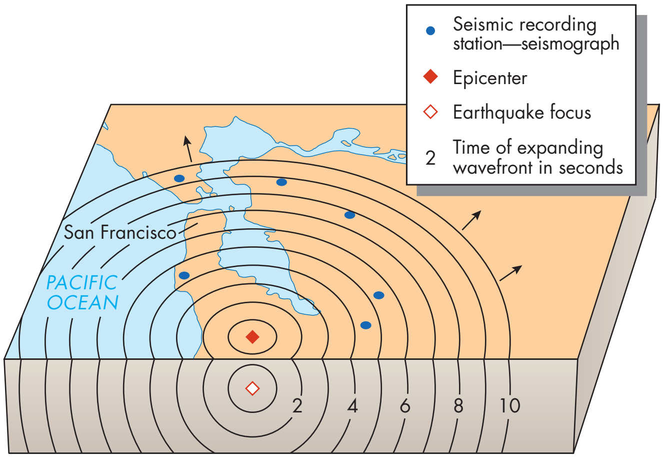

Figure 6.15 **Locating an earthquake** Idealized diagram of San Francisco, California, region with expanding wavefront of seismic waves from the focus of an earthquake. The arrival of waves at seismic recording stations may be used to mathematically calculate the location of the epicenter and its depth of focus. *(U.S. Geological Survey)*

is shown in Figure 6.14c. Notice that for Figure 6.14c the P waves arrive 50 seconds before the S waves and about 1 minute 40 seconds before the surface (R) waves. R waves have the largest amplitude and often cause the most damage to buildings.

The effect of distance on the seismogram is shown in Figure 6.14d for the 1994 M 6.7 Northridge, California, earthquake. Three seismographs from close to the epicenter at Pasadena (38 km or 24 mi) to far away at Needles (356 km or 221 mi) are shown. The shaking starts with the arrival of the P wave. Notice that the shaking arrives sooner and is more intense at Pasadena than at Needles.

The difference in arrival times at seismographs (S − P) can be used to locate the epicenter of an earthquake. Locating an epicenter requires at least three seismograms from three locations. For example, the S − P value of 50 seconds on Figure 6.14c suggests that the distance between the epicenter and the seismograph was about 420 km (261 mi). This is calculated algebraically using the S − P value and the velocity for P and S waves mentioned earlier; however, this calculation is beyond the scope of our discussion. Although we now know that the epicenter was about 420 km (261 mi) from the seismograph, this distance could be in any direction. When the records from seismographs from numerous seismic stations are analyzed using computer models, the epicenter for an earthquake can be located. The model is used to calculate the travel times of seismic waves to each seismograph from various depths of focus (Figure 6.15). Distances and depths to the focus are adjusted to provide the best fit of the data from all the seismographs. By a process of approximation, the location of the epicenter and depth to the focus are determined.

Frequency of Seismic Waves

Another important characteristic of earthquakes and their seismic waves is their frequency, measured in cycles per second, or hertz (Hz). To understand wave frequency, visualize water waves traveling across the surface of the ocean, analogous to seismic waves. If you are at the end of a pier and record the time when each wave peak moves by you toward shore, the average time period between wave peaks is the *wave period* and is usually measured in seconds. Consider the passing of each wave by you to be one cycle. If one wave passes the end of the pier on its way toward the shore every 10 seconds, the wave period is 10 seconds and there are 6 waves per minute. The frequency of the waves in cycles per second is 1 cycle divided by 10 seconds, or 0.1 Hz. Returning to earthquake waves, most P and S waves have frequencies of 0.5 to 20 Hz, or one-half to 20 cycles per second. Surface waves have lower frequencies than P and S waves, often less than 1 Hz.

Why is the wave frequency important? During an earthquake seismic waves with a wide range of frequencies are produced, and intense ground motion near the epicenter of a large earthquake is observed. High-frequency shaking causes low buildings to vibrate, and low-frequency shaking causes tall buildings to

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vibrate. It is the vibrating or shaking that damages buildings. Two points are important in understanding the shaking hazard: (1) Near the epicenter, both shorter buildings and taller buildings may be damaged by high- and low-frequency seismic waves. (2) With increasing distance from the epicenter the high-frequency waves are weakened or removed by a process called *attenuation*. Rapid shaking dies off quickly with distance. As a result, nearby earthquakes are often described as "jolting" and far-away earthquakes as "rolling." Low-frequency seismic waves of about 0.5 to 1.0 Hz can travel long distances without much attenuation. Therefore, they can damage tall buildings far from the epicenter. This fact has importance in planning to reduce earthquake damages and loss of life. Tall buildings need to be designed to withstand seismic shaking even if they are located hundreds of kilometers from large faults that are capable of producing strong to great earthquakes.

Material Amplification

Different Earth materials, such as bedrock, alluvium (sand and gravel), and silt and mud, respond differently to seismic shaking. For example, the intensity of shaking or strong ground motion of unconsolidated sediments may be much more severe than that of bedrock. Figure 6.16 shows how the *amplitude* of shaking, or the vertical movement, is greatly increased in unconsolidated sediments such as silt and clay deposits. This effect is called **material amplification.**

The Mexico City earthquake (M 8.1) demonstrated that buildings constructed on materials likely to accentuate and increase seismic shaking are extremely vulnerable to earthquakes, even if the event is centered several hundred kilometers away. Although seismic waves originating offshore initially contained many frequencies, those arriving at the city were low-frequency waves of about 0.5 to 1.0 Hz. It is speculated that when seismic waves struck the lake beds beneath Mexico City, the amplitude of shaking may have increased at the surface by a factor of 4 or 5. Figure 6.17 shows the geology of the city and the location of the worst damage. The intense regular shaking caused buildings to sway back and forth, and eventually many of them pancaked as upper stories collapsed onto lower ones.[9]

The potential for amplification of surface waves to cause damage was again demonstrated with tragic results during the 1989 Loma Prieta earthquake (M 7.1), which originated south of San Francisco. Figure 6.18 shows the epicenter and the areas that greatly magnified shaking. The collapse of a tiered freeway, which killed 41 people, occurred on a section of roadway constructed on bay fill and mud (Figure 6.19). Less shaking occurred where the freeway was constructed on older, stronger alluvium; in these areas the structure survived. Extensive damage

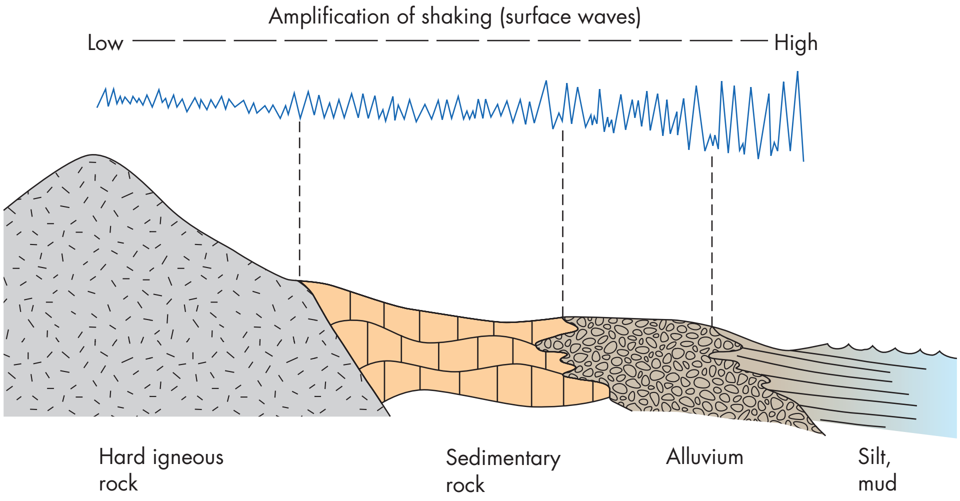

Figure 6.16 Amplification of shaking Generalized relationship between near-surface Earth material and amplification of shaking during a seismic event.

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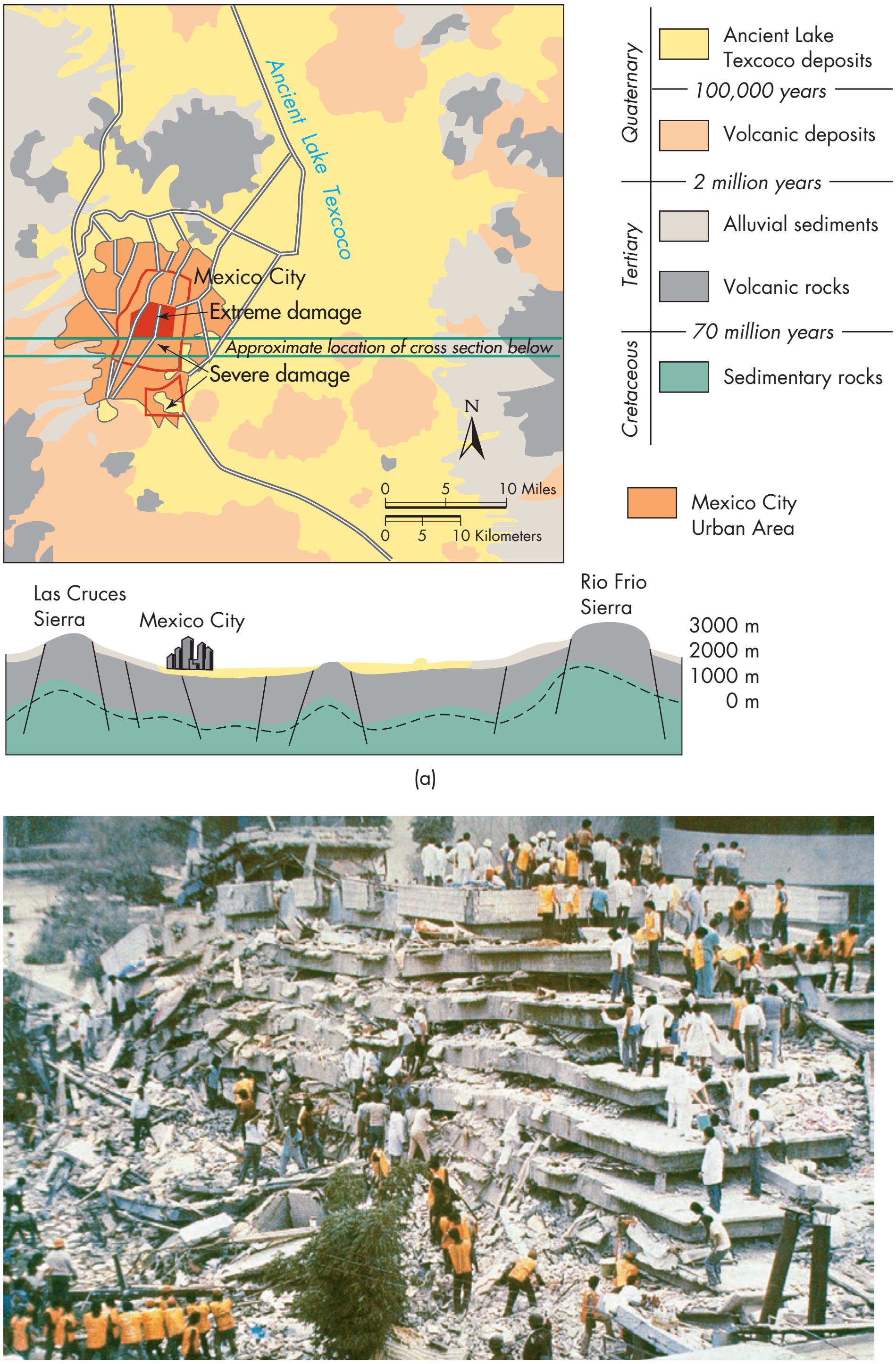

Figure 6.17 **Earthquake damage to Mexico City** (a) Generalized geologic map of Mexico City showing the ancient lake deposits where the greatest damage occurred. The zone of extreme damage is represented by the solid red area, and the severe damage zone is outlined in red. (b) One of many buildings that collapsed during the 1985 (M 8.1) earthquake. *(Both courtesy of T. C. Hanks and Darrell Herd/U.S. Geological Survey)*

was also recorded in the Marina district of San Francisco (Figure 6.20). This area was primarily constructed on bay fill and mud as well as debris dumped into the bay during the cleanup following the 1906 earthquake.[10]

Directivity

Rupture of rocks on a fault plane starts at a point and radiates, or propagates, from that point. The larger the area of rupture the larger the earthquake. **Directivity,** another amplification effect, results because the intensity of seismic shaking increases in the direction of the fault rupture. For example, fault rupture of the 1994

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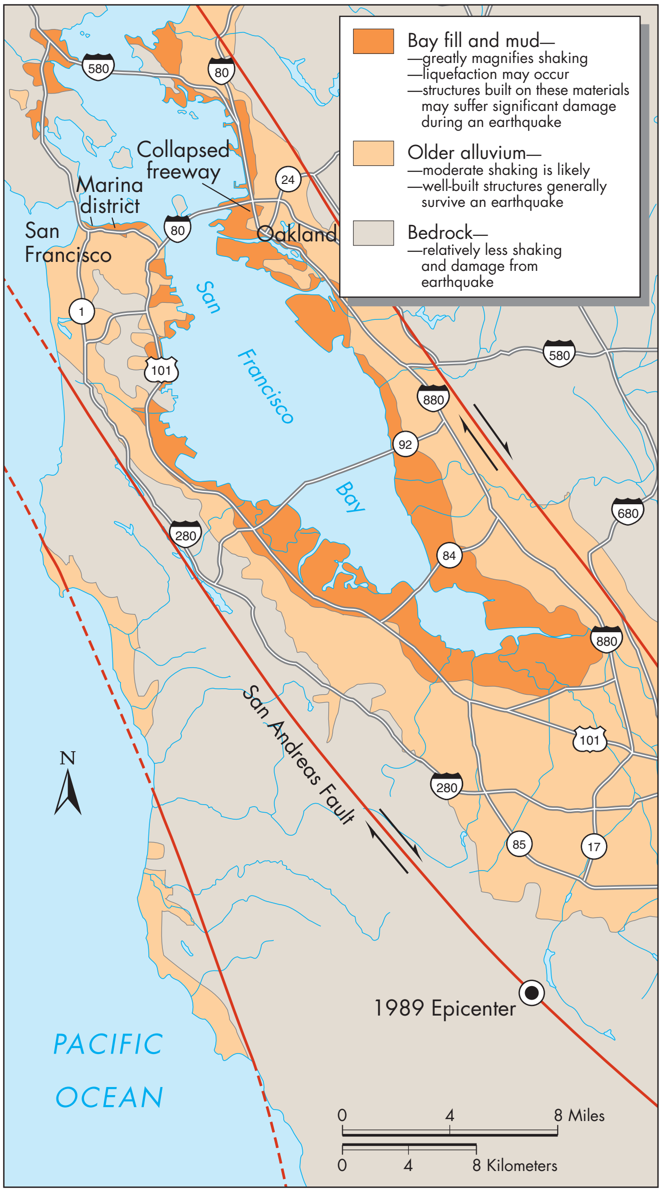
Figure 6.18 **Loma Prieta earthquake** San Francisco Bay region, showing the San Andreas fault and the epicenter of the 1989 earthquake, which had a magnitude of 7.1. The most severe shaking was on bay fill and mud, where a freeway collapsed and the Marina district was damaged. *(Modified after T. Hall. Data from U.S. Geological Survey)*



Northridge earthquake was up (north) and to the west, resulting in stronger ground motions from seismic shaking to the northwest (Figure 6.21). The stronger ground motion to the northwest is believed to have resulted from the movement of a block of Earth, the hanging-wall block, upward and to the northwest.[2]

Ground Acceleration During Earthquakes

Strong ground motion from earthquakes may be described in terms of the speed or velocity at which primary, secondary, and surface waves travel through rocks or across the surface of Earth. In general, these waves move a few kilometers per second. This velocity is analogous to the units used to describe the speed at which you drive a car, for example, 100 km per hour (62 mi per hour). Earthquake waves, however, travel much faster than cars, at a velocity of about 20,000 km (12,428 mi) per hour, similar to that of the U.S. Space Shuttle when it orbits Earth. Damage to structures from strong ground motion is related to both the amplitude of seismic surface waves and to the rate of velocity change of the seismic waves with time. The rate of change of velocity with time is referred to as acceleration. You may have learned in physical science that the acceleration of gravity is 9.8 meters

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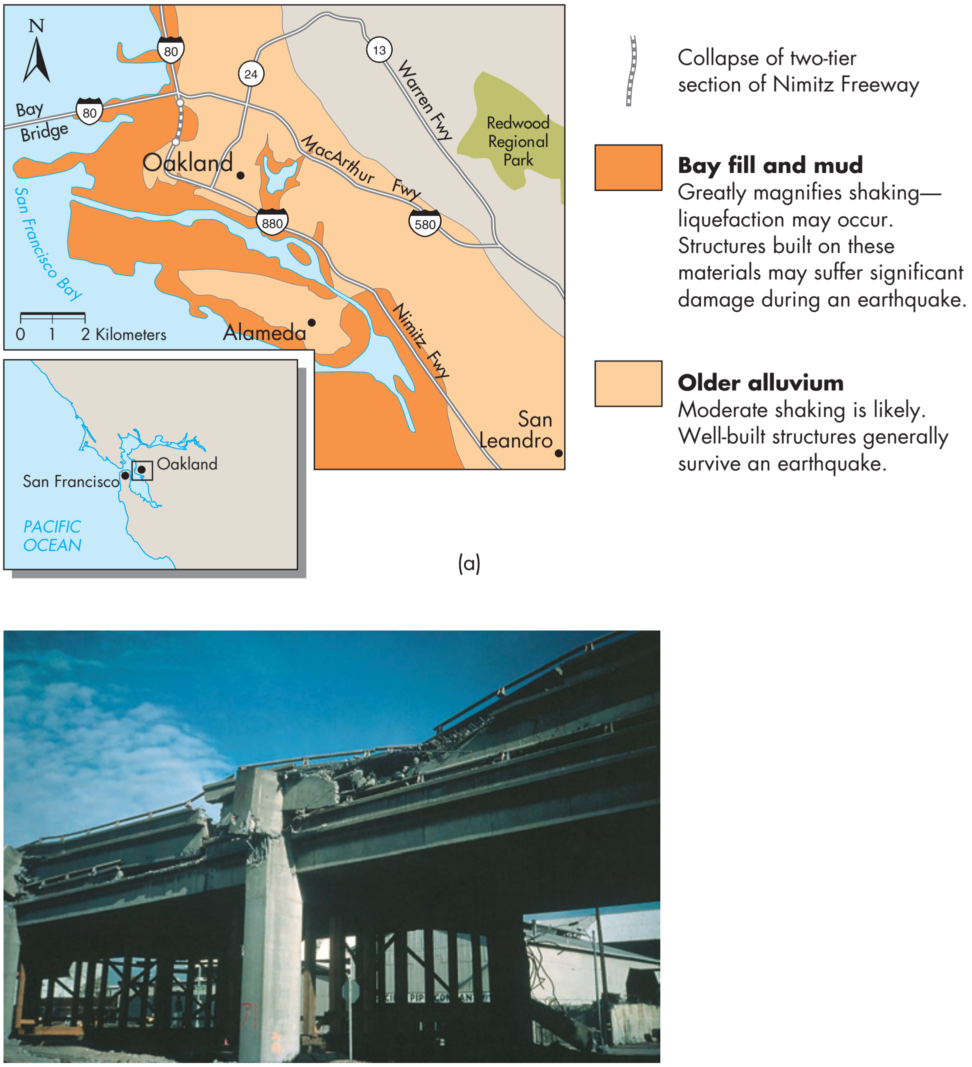

(a)

(b)

Figure 6.19 Collapse of a freeway (a) Generalized geologic map of part of the San Francisco Bay showing bay fill and mud and older alluvium. *(Modified after Hough, S. E., et al. 1990. Nature 344(6269): 853–55. Copyright © Macmillan Magazines Ltd., 1990. Used by permission of the author)* (b) Collapsed freeway as a result of the 1989 earthquake. *(Courtesy of Dennis Laduzinski)*

Figure 6.20 Earthquake damage Damage to buildings in the Marina district of San Francisco resulting from the 1989 M 7.1 earthquake. *(John K. Nakata/ U.S. Geological Survey)*

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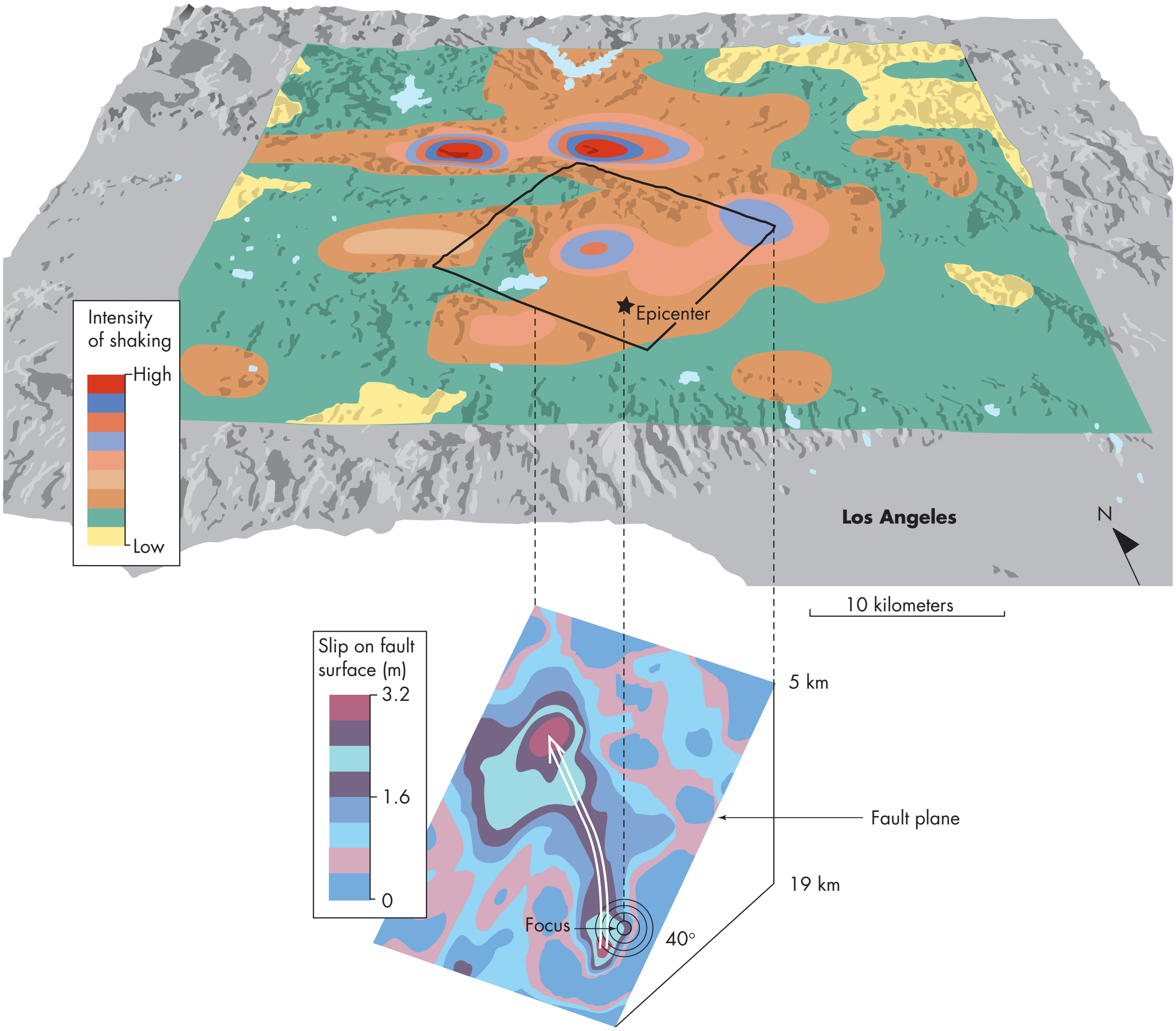

Figure 6.21 **Epicenter and rupture path** Aerial view of the Los Angeles region from the south showing the epicenter of the M 6.7 1994 Northridge earthquake, showing peak ground motion in centimeters per second and the fault plane in its subsurface position. The path of the rupture is shown, along with the amount of slip in meters along the fault plane. The area that ruptured along the fault plane is approximately 430 km^2 (166 mi^2) and the fault plane is dipping at approximately 40 degrees to the south-southwest. Notice that the maximum slip and intensity of shaking both occur to the northwest of the epicenter. The fault rupture apparently began at the focus in the southeastern part of the fault plane and proceeded upward and to the northwest as shown by the arrow. *(U.S. Geological Survey. 1996.* USGS response to an urban earthquake, Northridge '94. *U.S. Geological Survey Open File Report 96–263)*

per second per second (written as 9.8 m/sec^2, or 32 ft/sec^2). This acceleration is known as 1 *g*. If you parachute from an airplane and free fall for several seconds, you will experience the acceleration of gravity (1 *g*), and by the end of the first second of free fall, your velocity will be 9.8 m/sec. At the end of 2 seconds of free fall, your velocity will be about 20 m/sec, and it will be about 30 m/sec at the end of 3 seconds. This increase, or rate of change, in velocity with time is the acceleration. Earthquake waves cause the ground to accelerate both vertically and horizontally, just as your car accelerates horizontally when you step on the gas pedal. Specially designed instruments called accelometers measure and record the acceleration of the ground during earthquakes. The units of acceleration in earthquake studies

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Figure 6.22 Buildings collapse in Russia Rows of prefabricated, unreinforced, five-story apartment buildings destroyed by the 1995 earthquake that struck the island of Sakhalin in Russia (M 7.5). *(Tanya Makeyeva/AP/Wide World Photos)*

are in terms of the acceleration of gravity. If the ground accelerates at 1 *g*, the value is 9.8 m/sec^2. If the acceleration of the ground is 0.5 *g*, the value is roughly 5 m/sec^2. One reason we are interested in acceleration of the ground from earthquakes is that when engineers design buildings to withstand seismic shaking, the building design criteria are often expressed in terms of a maximum acceleration of the ground, since it is the horizontal acceleration of the ground that causes most damage to buildings. For example, earthquakes with M 6.0 to 6.9, typical magnitudes for strong southern California earthquakes, will produce horizontal accelerations of about 0.3 to 0.7 *g*, with localized values near the epicenter exceeding 1.0 *g*. Horizontal accelerations in excess of about 0.3 *g* cause damage to some buildings, and at 0.7 *g* damage is widespread, unless buildings are designed and constructed to withstand strong ground motion. Therefore, if we wish to design buildings to withstand M 6 to 6.9 earthquakes, we need to conservatively design them to withstand ground accelerations of about 0.6 to 0.7 *g*. To put this in perspective, consider that homes constructed of adobe, which are common in rural Mexico, South America, and the Middle East, can collapse under a horizontal acceleration of 0.1 *g*.[8] Unreinforced, prefabricated concrete buildings are also very vulnerable, at 0.2 to 0.3 *g*, as was tragically illustrated in the 1995 Sakhalin, Russia, earthquake (M 7.5). Two thousand of the 3,000 people in the town of Neftegorsk were killed when 17 prefabricated apartment buildings collapsed into rubble (Figure 6.22).

Depth of Focus

Recall that the point or area within Earth where the earthquake rupture starts is called the focus (see Figure 6.3). The depth of focus of an earthquake varies from just a few kilometers deep to almost 700 km (435 mi) below the surface. The deepest earthquakes occur along subduction zones, where slabs of oceanic lithosphere sink to great depths. The 2001 Seattle, Washington, earthquake (M 6.8) is an example of a relatively deep earthquake. Although the Seattle event was a large quake, about the same size as the 1994 Northridge earthquake, the focus was deeper, at

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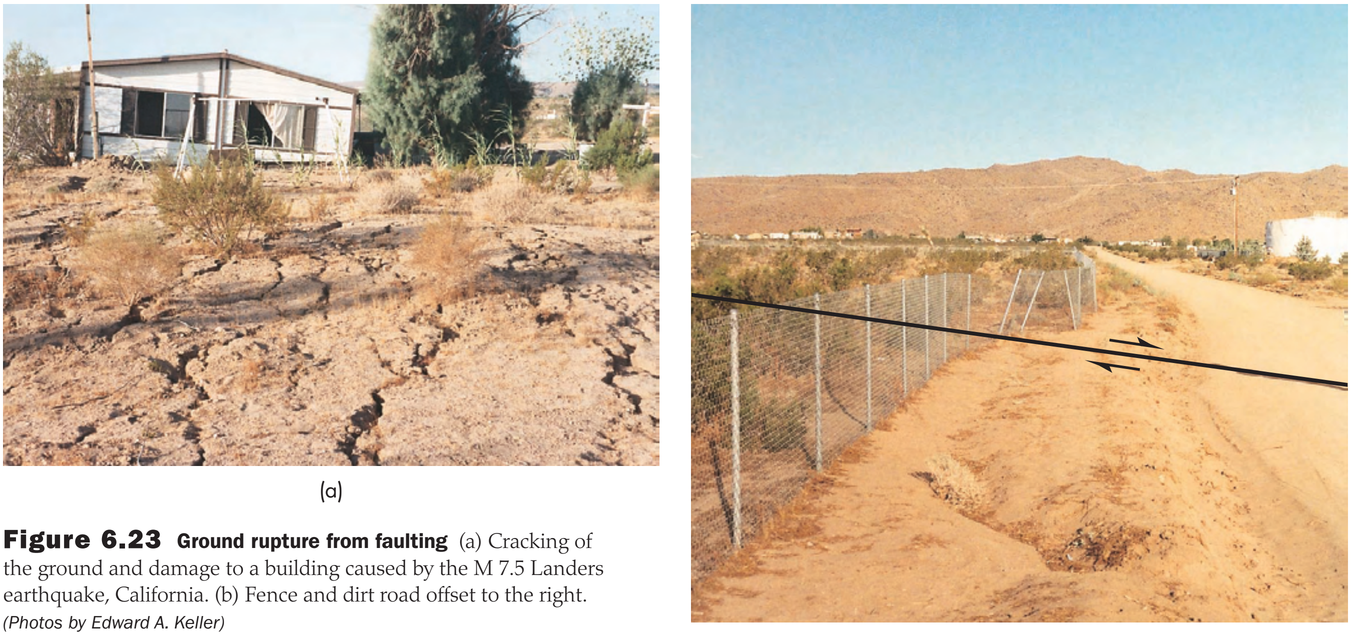

Figure 6.23 **Ground rupture from faulting** (a) Cracking of the ground and damage to a building caused by the M 7.5 Landers earthquake, California. (b) Fence and dirt road offset to the right. *(Photos by Edward A. Keller)*

about 52 km (32 mi) beneath Earth's surface. The focus was within the subducting Juan de Fuca plate along a normal fault (see Figure 2.10). Seismic waves had to move up 52 km (32 mi) before reaching the surface, and they lost much of their energy in the journey. As a result, the earthquake caused relatively little damage for its magnitude. In contrast, most earthquakes in southern California have focal depths of about 10 to 15 km (6 to 9 mi), although deeper earthquakes have occurred. These relatively shallow earthquakes are more destructive than deeper earthquakes of comparable magnitude because they are deep enough to generate strong seismic shaking, yet sufficiently close to the surface to cause strong surface shaking. A M 7.5 earthquake on strike-slip faults in the Mojave Desert near Landers, California, in 1992 had a focal depth of less than 10 km (6 mi). This event caused extensive ground rupture for about 85 km (53 mi).[11] Local vertical displacement exceeded 2 m (6.5 ft), and extensive lateral displacements of about 5 m (16 ft) were measured (Figure 6.23). If the Landers event had occurred in the Los Angeles Basin, extensive damage and loss of life would have occurred.

6.8 Earthquake Cycle

Observations of the 1906 San Francisco earthquake (M 7.7) led to a hypothesis known as the **earthquake cycle.** The earthquake cycle hypothesis proposes that there is a drop in elastic strain after an earthquake and a reaccumulation of strain before the next event.

Strain is deformation resulting from stress. *Elastic strain* may be thought of as deformation that is not permanent, provided that the stress is released. When the stress is released, the deformed material returns to its original shape. If the stress continues to increase, the deformed material eventually ruptures, making the deformation permanent. For example, consider a stretched rubber band or a bent archery bow; continued stress will snap the rubber band or break the bow. When a stretched rubber band or bow breaks, it experiences a rebound, in which the broken ends snap back, releasing their pent-up energy. A similar effect, referred to as *elastic rebound,* occurs after an earthquake (Figure 6.24). At time 1, rocks on either side of a fault segment have no strain built up and show no deformation. At time 2, elastic strain begins to build, caused by the tectonic forces that pull the rocks in

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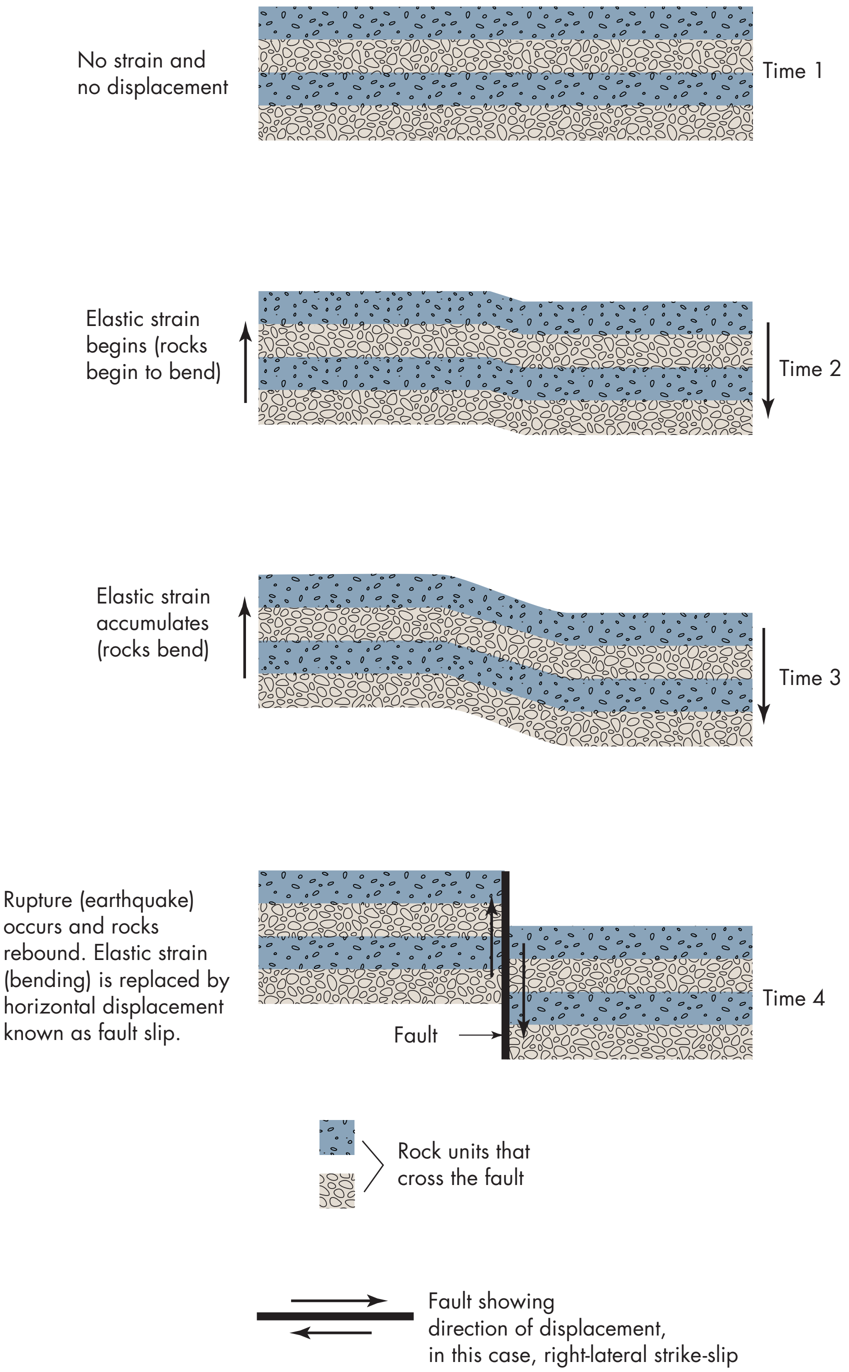

Figure 6.24 Earthquake cycle Idealized diagram illustrating the earthquake cycle. From time 1 to time 4 may take from hundreds to thousands of years.

opposite directions, referred to as shear stress. The rocks begin to bend. At time 3, elastic strain is accumulating, and the rocks have bent; however, they are still held together by friction. When the deformed rocks finally rupture, at time 4, the stress is released and the elastic strain suddenly decreases as the sides of the fault "snap" into their new, or permanently deformed, position. After the earthquake, it takes time for sufficient elastic strain to accumulate again to produce another rupture.[12]

Stages of the Earthquake Cycle

It is speculated that a typical earthquake cycle has three or four stages. The first is a long period of seismic inactivity following a major earthquake and associated *aftershocks*, earthquakes that occur anywhere from a few minutes to a year or so

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after the main event. This is followed by a second stage characterized by increased seismicity, as accumulated elastic strain approaches and locally exceeds the strength of the rock. The accumulated elastic strain initiates faulting that produces small earthquakes. The third stage of the cycle, which may occur only hours or days before the next large earthquake, consists of *foreshocks*. Foreshocks are small to moderate earthquakes that occur before the main event. For example, a M 6 earthquake may have foreshocks of about M 4. In some cases, this third stage may not occur. After the major earthquake, considered to be the fourth stage, the cycle starts over again.[12] Although the cycle is hypothetical and periods between major earthquakes are variable, the stages have been identified in the occurrence and reoccurrence of large earthquakes.

6.9 Earthquakes Caused by Human Activity

Several human activities are known to increase or cause earthquake activity. Damage from these earthquakes is regrettable, but the lessons learned may help to control or stop large catastrophic earthquakes in the future. Three ways that the actions of people have caused earthquakes are

- Loading the Earth's crust, as in building a dam and reservoir
- Disposing of waste deep into the ground through disposal wells
- Setting off underground nuclear explosions

Reservoir-Induced Seismicity

During the 10 years following the completion of Hoover Dam on the Colorado River in Arizona and Nevada, several hundred local tremors occurred. Most of these were very small, but one was M 5 and two were about M 4.[12] An earthquake in India, approximately M 6, killed about 200 people after the construction and filling of a reservoir. Evidently, fracture zones may be activated both by the increased load of water on the land and by increased water pressure in the rocks below the reservoir, resulting in faulting.

Deep Waste Disposal

From April 1962 to November 1965 several hundred earthquakes occurred in the Denver, Colorado, area. The largest earthquake was M 4.3 and caused sufficient shaking to knock bottles off shelves in stores. The source of the earthquakes was eventually traced to the Rocky Mountain Arsenal, which was manufacturing materials for chemical warfare. Liquid waste from the manufacturing process was being pumped down a deep disposal well to a depth of about 3,600 m (11,800 ft). The rock receiving the waste was highly fractured metamorphic rock, and injection of the new liquid facilitated slippage along fractures. Study of the earthquake activity revealed a high correlation between the rate of waste injection and the occurrence of earthquakes. When the injection of waste stopped, so did the earthquakes (Figure 6.25).[13] Fluid injection of waste as an earthquake trigger was an important occurrence because it directed attention to the fact that earthquakes and fluid pressure are related.

Nuclear Explosions

Numerous earthquakes with magnitudes as large as 5.0 to 6.3 have been triggered by underground nuclear explosions at the Nevada Test Site. Analysis of the aftershocks suggests that the explosions caused some release of natural tectonic strain. This led to discussions by scientists as to whether nuclear explosions might be used to prevent large earthquakes by releasing strain before it reached a critical point.

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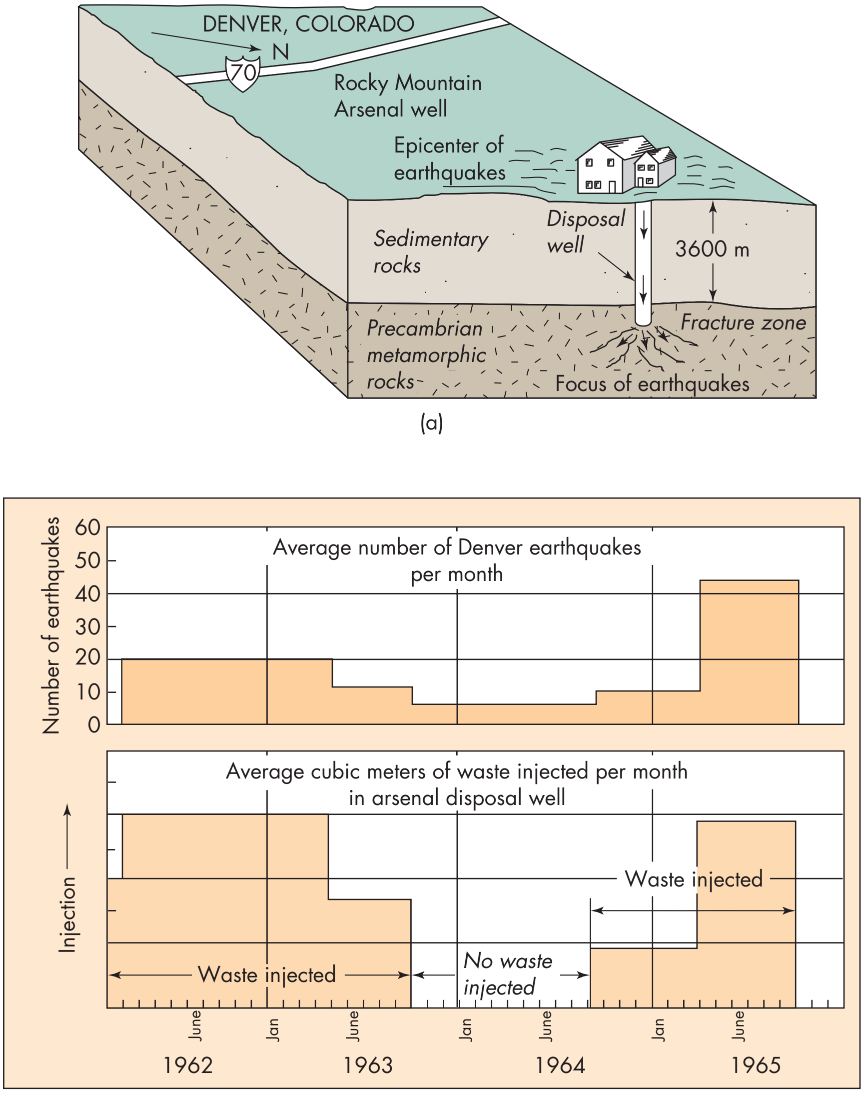

(a)

(b)

Figure 6.25 Human-caused earthquakes (a) Generalized block diagram showing the Rocky Mountain Arsenal well. (b) Graph showing the relationship between earthquake frequency and the rate of injection of liquid waste. *(After Evans, D. M. 1966.* Geotimes *10. Reprinted by permission)*

6.10 Effects of Earthquakes

Shaking is not the only cause of death and damage in earthquakes: Catastrophic earthquakes have a wide variety of destructive effects. Primary effects, those caused directly by fault movement, include ground shaking and its effects on people and structures and surface rupture. Secondary effects induced by the faulting and shaking include liquefaction of the ground, landslides, fires, disease, tsunamis, and regional changes in land elevation.

Shaking and Ground Rupture

The immediate effects of a catastrophic earthquake can include violent ground shaking accompanied by widespread surface rupture and displacements. Surface rupture with a vertical component produces a *fault scarp*. A fault scarp is a linear, steep slope that looks something like a curb on a street. Fault scarps are often approximately 1 m (3.3 ft) or more high and extend for a variable distance, from a few tens of meters to a few kilometers along a fault (Figure 6.26). The 1906 San Francisco earthquake (M 7.7) produced 6.5 m (21.3 ft) of horizontal displacement, or fault-slip, along the San Andreas fault north of San Francisco and reached a

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Figure 6.26 **Fault scarp** Produced by the 1992 M 7.5 Landers earthquake in California. *(Edward A. Keller)*

maximum Modified Mercalli Intensity of XI.[8] At this intensity, surface accelerations can snap and uproot large trees and knock people to the ground. The shaking may damage or collapse large buildings, bridges, dams, tunnels, pipelines, and other rigid structures. The great 1964 Alaskan earthquake (M 8.3) caused extensive damage to transportation systems, railroads, airports, and buildings. The 1989 Loma Prieta earthquake (M 7.1) was much smaller than the Alaska event, yet it caused about $5 billion of damage. The 1994 Northridge earthquake (M 6.7) caused 57 deaths while inflicting about $40 billion damage, making it one of the most expensive hazardous events ever in the United States. *The Northridge earthquake caused so much damage because there was so much there to be damaged.* The Los Angeles region is highly urbanized with high population density, and the seismic shaking was intense.

Liquefaction

Liquefaction is the transformation of water-saturated granular material, or sediments, from a solid to a liquid state. During earthquakes liquefaction may result from compaction of sediments during intense shaking. Liquefaction of near-surface water-saturated silts and sand causes the materials to lose their strength and to flow. As a result, buildings may tilt or sink into the liquefied sediments while tanks or pipelines buried in the ground may rise buoyantly.[14]

Landslides

Earthquake shaking often triggers many landslides, a comprehensive term for several types of hillslope failure, in hilly and mountainous areas. These can be extremely destructive and can cause great loss of life, as demonstrated by the 1970 Peru earthquake. In that event, more than 70,000 people died, and of those, 20,000 people were killed by a giant landslide that buried the cities of Yungan and Ranrahirca. Both the 1964 Alaskan earthquake and the 1989 Loma Prieta earthquake caused extensive landslide damage to buildings, roads, and other structures. The 1994 Northridge earthquake and aftershocks triggered thousands of landslides. A giant landslide from the side of a mountain was triggered by the 2002 Alaska earthquake (Figure 6.27). Thousands of other landslides were also triggered by the earthquake. Most were on the steep slopes of the Alaska Range.

A large landslide associated with the January 13, 2001, El Salvador earthquake (M 7.6) buried the community of Las Colinas, killing hundreds of people. Tragically, the landslide could probably have been avoided if the slope that failed had not

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Figure 6.27 **Earthquake-triggered landslides** This giant landslide was one of thousands triggered by the 2002 (M 7.9) Alaskan earthquake. Landslide deposits cover part of the Black Rapids Glacier *(U.S. Geological Survey)*

previously been cleared of vegetation for the construction of luxury homes. (We will discuss landslides in greater detail in Chapter 9.)

Fires

Fire is a major hazard associated with earthquakes. Shaking of the ground and surface displacements can break electrical power and gas lines, thus starting fires. In individual homes and other buildings, appliances such as gas heaters may be knocked over, causing gas leaks that could be ignited. The threat from fire is intensified because firefighting equipment may become damaged and essential water mains may be broken during an earthquake. Earthquakes in both Japan and the United States have been accompanied by devastating fires (Figure 6.28). The San Francisco earthquake of 1906 has been repeatedly referred to as the

Figure 6.28 **Earthquake and fire** Fires associated with the 1995 Kobe, Japan, earthquake caused extensive damage to the city. *(CORBIS)*

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"San Francisco Fire," and in fact 80 percent of the damage from that event 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.

Disease

Landslides from the 1994 Northridge earthquake raised large volumes of dust, some of which contained fungi spores that cause valley fever. Winds carried the dust and spores to urban areas including Simi Valley, where an outbreak of valley fever occurred during an 8-week period after the earthquake. Two hundred cases were diagnosed, which is 16 times the normal infection rate; of these, 50 people were hospitalized and three died.[1] Earthquakes can rupture sewer and water lines, causing water to become polluted by disease-causing organisms. The death of animals and people buried in earthquake debris also produces potential sanitation problems that may result in an outbreak of disease.

Regional Changes in Land Elevation

Vertical deformation, including both uplift and subsidence, is another effect of some large earthquakes. Such deformation can cause regional changes in groundwater levels. The great 1964 Alaskan earthquake (M 8.3) caused regional uplift and subsidence.[15] The uplift, which was as much as 10 m (33 ft), and the subsidence, which was as much as 2.4 m (7.8 ft), caused effects ranging from severely disturbing or killing coastal marine life to changes in groundwater levels. In areas of uplift, canneries and fishermen's homes were displaced above the high-tide line, rendering docks and other facilities inoperable. The subsidence resulted in flooding of some communities. In 1992 a major earthquake (M 7.1) near Cape Mendocino in northwestern California produced approximately 1 m (3.3 ft) of uplift at the shoreline, resulting in the death of marine organisms exposed by the uplift.[16]

6.11 Tsunami

Tsunamis (the Japanese word for "large harbor waves") are produced by the sudden vertical displacement of ocean water.[17] Tsunamis are a serious natural hazard that can cause a catastrophe thousands of kilometers from where they originate. They may be triggered by several types of events such as large earthquakes that cause rapid uplift or subsidence of the seafloor; underwater landslides that may be triggered by an earthquake; collapse of part of a volcano that slides into the sea; submarine volcanic explosion; and impact in the ocean of an extraterrestrial object such as an asteroid or comet. Asteroid impact can produce a "Mega" tsunami about 100 times as high as the largest tsunami produced by an earthquake and put hundreds of millions of people at risk.[17] Fortunately, the probability of a large impact is very low. Of the above potential causes, tsunamis produced by earthquakes are by far the most common.

Damaging tsunamis in historic time have been relatively frequent and until recently confined to the Pacific Basin. Recent examples include

- The 1960 (M 9+) Chile earthquake that triggered a tsunami killing 61 people in Hawaii after traveling for 15 hours across the Pacific Ocean.
- The 1964 (M 8.3) Alaskan earthquake that generated a deadly tsunami that killed about 130 people in Alaska and California.
- The 1993 (M 7.8) earthquake in the sea of Japan that generated a tsunami that killed 120 people on the island of Okushiri, Japan.
- The 1998 (M 7.1) Papua New Guinea earthquake and submarine landslide that triggered a tsunami that killed more than 2,100 people.
- The 2004 (M 9) Sumatran earthquake that generated a tsunami that killed about 250,000 people (see A Closer Look: Indonesian Tsunami).

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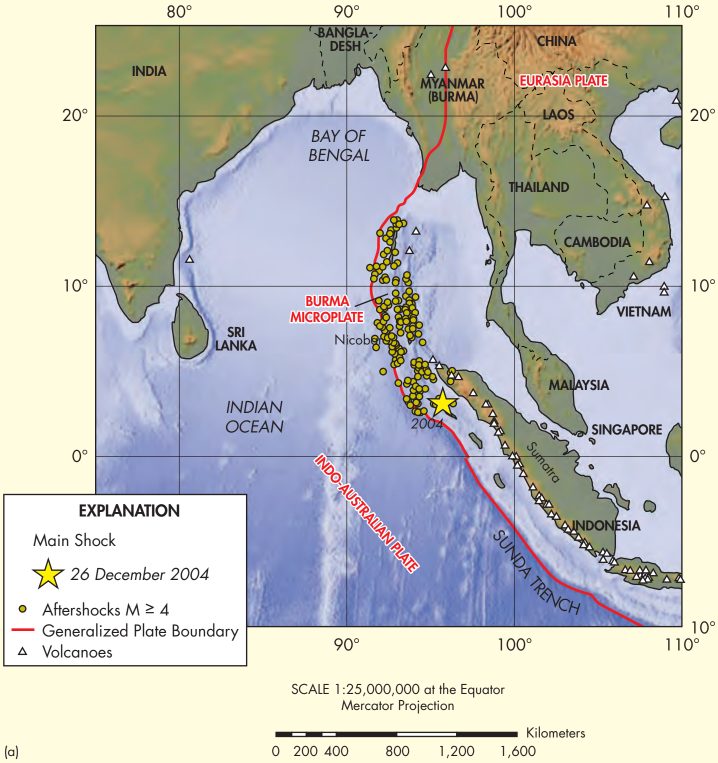
A CLOSER LOOK | Indonesian Tsunami

The Indonesian tsunami of 2004 made us aware of these giant waves and the destruction they can cause. Within a span of only a few hours, about 250,000 people were killed and millions were displaced as coastal area after coastal area around the Indian Ocean was struck by the series of tsunami waves.

The largest earthquake on Earth in the past 4 decades struck on the morning of Sunday, December 26, 2004, just off the Indonesian island of Sumatra (Figure 6.A). That earthquake caused the most damaging tsunami in recorded history. The magnitude of the earthquake was 9.0, and it



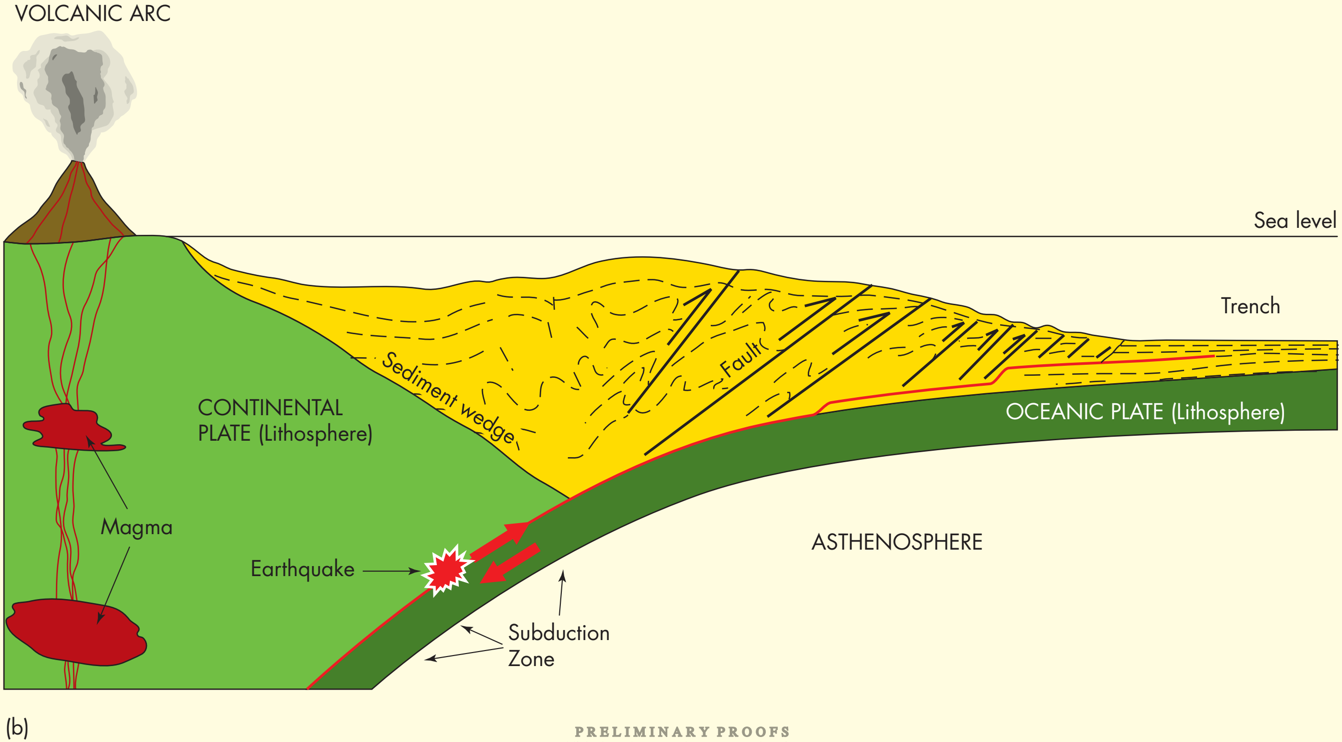


Figure 6.A **Geologic setting** (a) of the Indonesian tsunami. *(Modified after U.S. Geological Survey)* (b) Idealized cross section of where a subduction zone earthquake might occur. *(Modified from United Kingdom Hydrographic Office)* Also see Figure 2.5.

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occurred on the plate boundary where the giant Indo-Australian Plate is being subducted beneath the smaller Burma Plate near Sumatra. The fault rupture was what is known as a "megathrust event" on the subduction zone, which dips gently (about 10°) to the northeast. Shaking from the earthquake lasted several minutes and displacement on the rupture surfaces (faults) between the plates was about 15 meters (50 feet). The total length of the rupture was about 1,200 kilometers (750 miles). The bottom of the sea was displaced by the earthquake to the west-southwest about 15 meters horizontally and several meters vertically. Displacement of the sea bottom disturbed and displaced the overlying waters of the Indian Ocean and a series of tsunami waves were generated. The effect is like throwing a giant boulder in your bathtub and watching the rings or waves of water spread out. In this case, though, the boulder came up from the bottom, but the result was the same and waves radiated outward moving at high speed across the Indian Ocean.

There was no warning system for tsunamis in the Indian Ocean as there are for the Pacific, and people were by and large caught by surprise. Warning by United States scientists, who recognized that a very large earthquake that could potentially produce a tsunami had occurred, was issued to the United States government as well as some governments in the region where the earthquake occurred. Unfortunately, the warnings were not timely enough for countries to take action, and warnings were complicated by the fact that there are insufficient linkages between the United States and other governments of the region. Had it been possible for warnings to be issued, thousands of lives could have been saved because the tsunami waves in some instances took several hours to reach the coastlines where people died. Even a warning of a half an hour or so would have been sufficient to move many people from low-lying coastal areas and saved many, many lives.[17] The first sensor on the seafloor to detect a tsunami for the Indian Ocean was in place by the end of 2006 and others will follow. Sirens are now in place along some coastal areas around the Indian Ocean to warn people if a tsunami is coming.

Over three-quarters of the deaths were in Indonesia, which suffered from both intense shaking from the earthquake that caused the tsunami and the tsunami itself. The site of the magnitude 9 earthquake and the generation of the tsunami and its travel over several hours with the number of deaths are shown on Figure 6.B. Notice that the time from generation

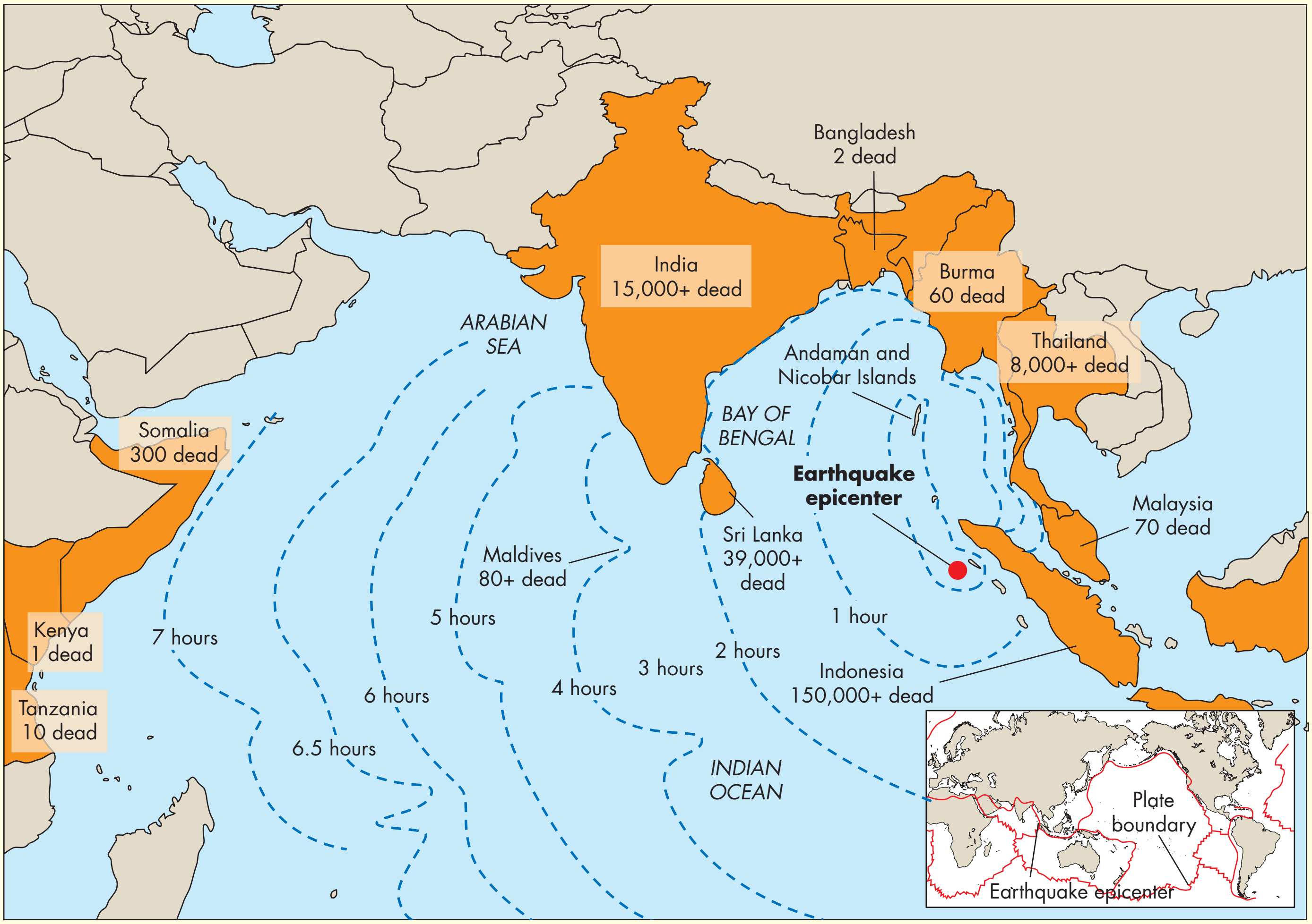

Figure 6.B **Tsunami in December 2004 killed several hundred thousand people in Indonesia** This map shows the epicenter of the magnitude 9 earthquake that produced the Indonesian tsunami. Shown are the movement out of tsunami waves that devastated many areas in the Indian Ocean. Notice that the waves took approximately 7 hours to reach Somalia, where almost 300 people were killed. Most of the deaths were in Indonesia, where the waves arrived only about 1 hour after the earthquake. *(NOAA)*

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of the tsunami to its arrival in Somalia was about 7 hours. In India, it was 2 hours, and earlier and later in other places depending on distance from the earthquake.

The coastal area of Banda Aceh, Indonesia, was nearly destroyed, as shown in before and after photographs (Figure 6.C). The destruction was a result of earthquake shaking, tsunami, and subsidence of the land from earthquake deformation.

Tourist areas in the region were hard hit, especially in Thailand, where several thousand tourists were killed. Figure 6.D shows the approaching wave in Phuket, Thailand. Some people seem to be mesmerized by the approaching waves while others are running in panic. On at least two beaches, everything wasn't quite as bleak. About 100 tourists and other people were saved when a 10 year-old British girl sounded the warning in time for a beach in Thailand to be evacuated. She had previously reviewed a lesson in school about plate tectonics, earthquakes, and tsunamis. As part of that lesson, she learned that sometimes the sea recedes prior to the arrival of a tsunami. That is precisely what she observed and she warned her mother, eventually screaming, to get off the beach, that they were in danger. She convinced her mother as well as others on the beach and people in the hotel where they stayed. The beach was successfully evacuated. Her mother later stated she did not even know what a tsunami was, but that her daughter's school lesson had saved the day, for them at least. In a second case, a scientist staying at a Sri Lanka hotel witnessed a small wave rise up and inundate the swimming pool. This was followed by a 7 meter drop in sea


(a)


(b)

Figure 6.C Nearly complete destruction associated with Indonesian tsunami of 2004 (a) Banda Aceh before December 23, 2004. *(Digital Globe)* (b) Two days after the tsunami that struck the Indonesian provincial capital of Banda Aceh on the northern end of the island of Sumatra. Nearly all of the development has been damaged or destroyed. Notice along the top of the photograph the beach with the extensive erosion leaving what appears to be a number of small islands where a more continuous coast was formerly. Subsidence caused by the earthquake as well as the tsunami caused the destruction and changes in land elevation. *(Digital Globe)*

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level. The scientist recognized that a big wave was coming and sounded the alarm. The hotel manager used a megaphone to warn people to get off the beach. Many people had gone down to the beach out of curiosity to see the exposed seafloor. When the big 7-meter wave arrived, most people were near stairs and escaped to higher floors. No hotel staff or guests were killed, but several people on the ground floor were swept out and survived by clinging to palm trees in the hotel garden.[18]

Some native people in Indonesia have a collective memory of tsunamis. When the earthquake occurred, some applied that knowledge and moved to high ground, saving entire small tribes on some islands.

Elephants saved a small group of about 12 tourists in Thailand from the 2004 tsunami.[19] Elephants that give tourists rides started trumpeting about the time the M 9 earthquake struck off the island of Sumatra. They became agitated again about 1 hour later. Those elephants that were not taking tourists for rides broke loose from their strong chains and headed inland. Elephants that had tourists aboard for a ride didn't respond to their handlers and climbed a hill behind a beach resort where about 4,000 people were killed by the tsunami. When handlers recognized the advancing tsunami, additional tourists were lifted onto the elephants, which used their trunks to place the people on their backs (tourists usually mount elephants from a wooden platform), and moved inland. Tsunami waves surged about 1 km (0.5 mi) inland up from the beach. The elephants stopped just beyond where the waves ended their destructive path.

The question is, did the elephants know something that people did not? Animals have sensory ability that differs from humans. It's possible they heard the earthquake as it generated sound waves with low tones called infrasonic sound generated by the earthquake. Some people are also able to sense sound waves but don't generally perceive them

Figure 6.D **Tourists running for their lives** Man in foreground is looking back at the tsunami rushing toward him that is higher than the building. The location is Phuket, Thailand. Many of the people living there, as well as the tourists, did not initially think the wave would inundate the area where they were and when the waves arrived they thought they would be able to outrun the rising water. In some cases people did escape, but all too often people were drowned. *(ZUMA Press)*

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as a hazard. The elephants may also have sensed the motion as the land vibrated from the earthquake. They fled inland, which was the only way they could go. This is apparently what happened, but the linkages between the elephants' sensory ability and their behavior is speculative. Nevertheless, the end result was a few lives were saved.[19]

Tropical ecology played a role in determining tsunami damage. Where the maximum intensity of the tsunami impact occurred, massive destruction of the coast was inevitable. In other areas, the damage was not uniform. Some coastal villages were destroyed while others were much less damaged. Those villages that were spared destruction were generally protected from the energy of tsunami waves by mangrove forest or several rows of plantation trees that shielded the villages, lessening the impact of the waves.[20]

The role of education of people living along shorelines that are susceptible to tsunamis is important. Lives would have been saved had more people recognized from Earth's behavior that a tsunami was likely. Those people experiencing a large earthquake would have known that a tsunami might be coming and move to higher ground. Thousands of miles away where the earthquake waves would not be felt, the Earth still provides signals of what may happen. The example of the schoolgirl clearly shows this: Telling people that if the water suddenly recedes, quickly exposing the sea bottom, you might expect it to come back as a tsunami wave. This would be their signal to move to higher ground. People should also be informed that tsunamis are seldom one wave but are in fact a series of waves with later ones sometimes being more damaging than earlier ones. The education of people close to where a tsunami may originate is particularly important as waves may arrive in 10–15 minutes following an earthquake. Geologists have warned that it is likely that another large tsunami will be generated by earthquakes off shore of Indonesia in the next few decades.

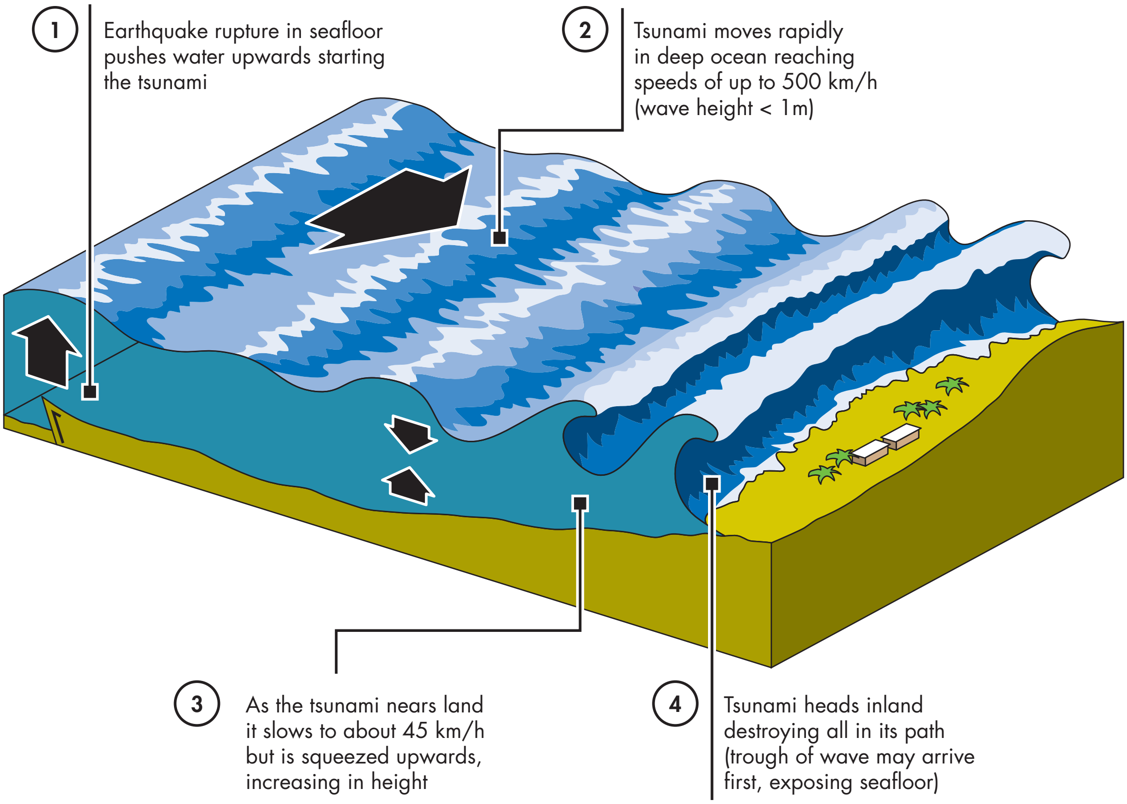

Figure 6.29 **Tsunami damage** Idealized diagram showing the process of how a tsunami is produced by an earthquake. *(Modified after United Kingdom Hydrographic Office)*

How Do Earthquakes Cause a Tsunami? The processes that generate a tsunami from an earthquake are generalized in Figure 6.29. Faulting that ruptures the seafloor and displaces the overlying water starts the process. Generally, a M 7.5 or greater earthquake is necessary to generate a damaging tsunami.

Tsunami waves are relatively low in open ocean, being less than a meter high, but they travel at speeds of jet aircraft (750 km/hr, 500 mi/hr). When a tsunami wave strikes the coast, the energy of the wave is compressed in the shallow waters

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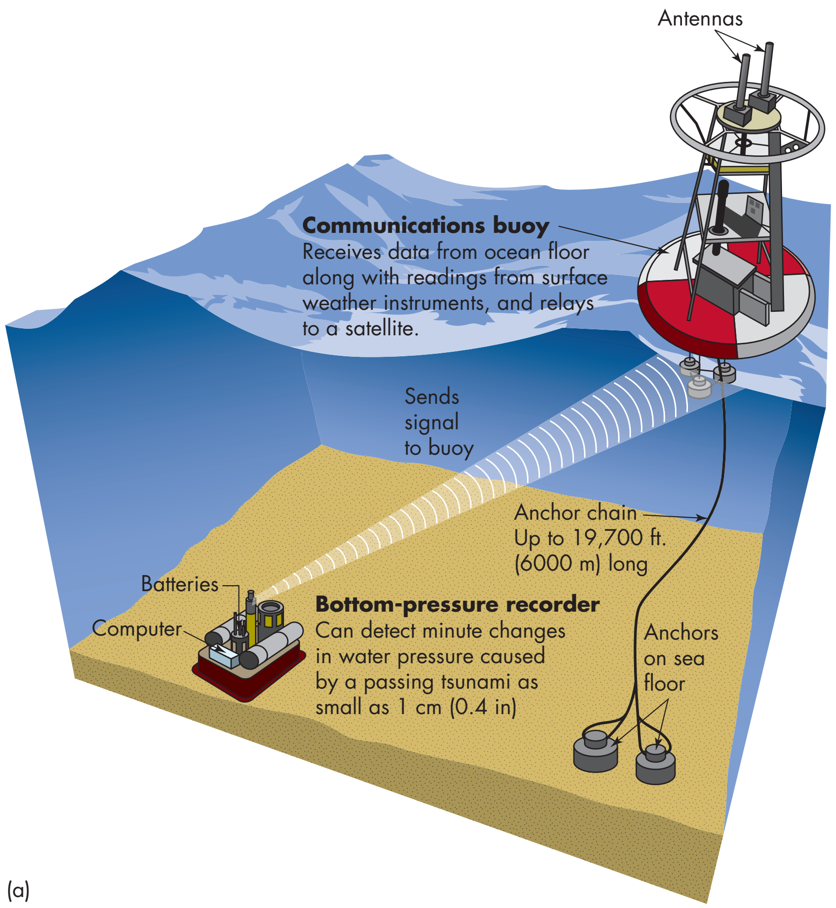

Figure 6.30 **Tsunami warning system** (a) A surface buoy and bottom sensor to detect a tsunami. (b) Travel time (each band in one hour) for a tsunami generated in Hawaii. The wave arrives in Los Angeles in about 5 hours. It takes about 12 hours for the waves to reach South America. Locations of six existing tsunami instruments are shown. Others are being planned for the Atlantic and Caribbean. *(NOAA)*

and the height of the wave increases dramatically. Tsunami waves come in as a series and later waves may be higher than earlier ones. When the water from a wave retreats from the land, flowing back to sea, the return flow can be as dangerous as an incoming wave.[17]

After an earthquake that produces a tsunami, the arrival time of waves can be estimated to within plus or minus 1.5 minutes per hour of travel time. This information has been used to produce a tsunami warning system in the Pacific Ocean. A surface buoy with a bottom sensor (Figure 6.30a) to detect a tsunami helps provide data to make a map showing arrival times around the Pacific Ocean. The map in Figure 6.30b is for a tsunami traveling from Hawaii.

6.12 Earthquake Risk and Earthquake Prediction

The great damage and loss of life associated with earthquakes are due in part to the fact that they often strike without warning. A great deal of research is being devoted to anticipating earthquakes. The best we can do at present is to use probabilistic methods to determine the risk associated with a particular area or with a particular segment of a fault. Such determinations of risk are a form of long-term prediction: We can 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 predictions assist planners who are considering seismic safety measures or people who are deciding where to live. However, long-term prediction does not help residents of a seismically active area to anticipate and

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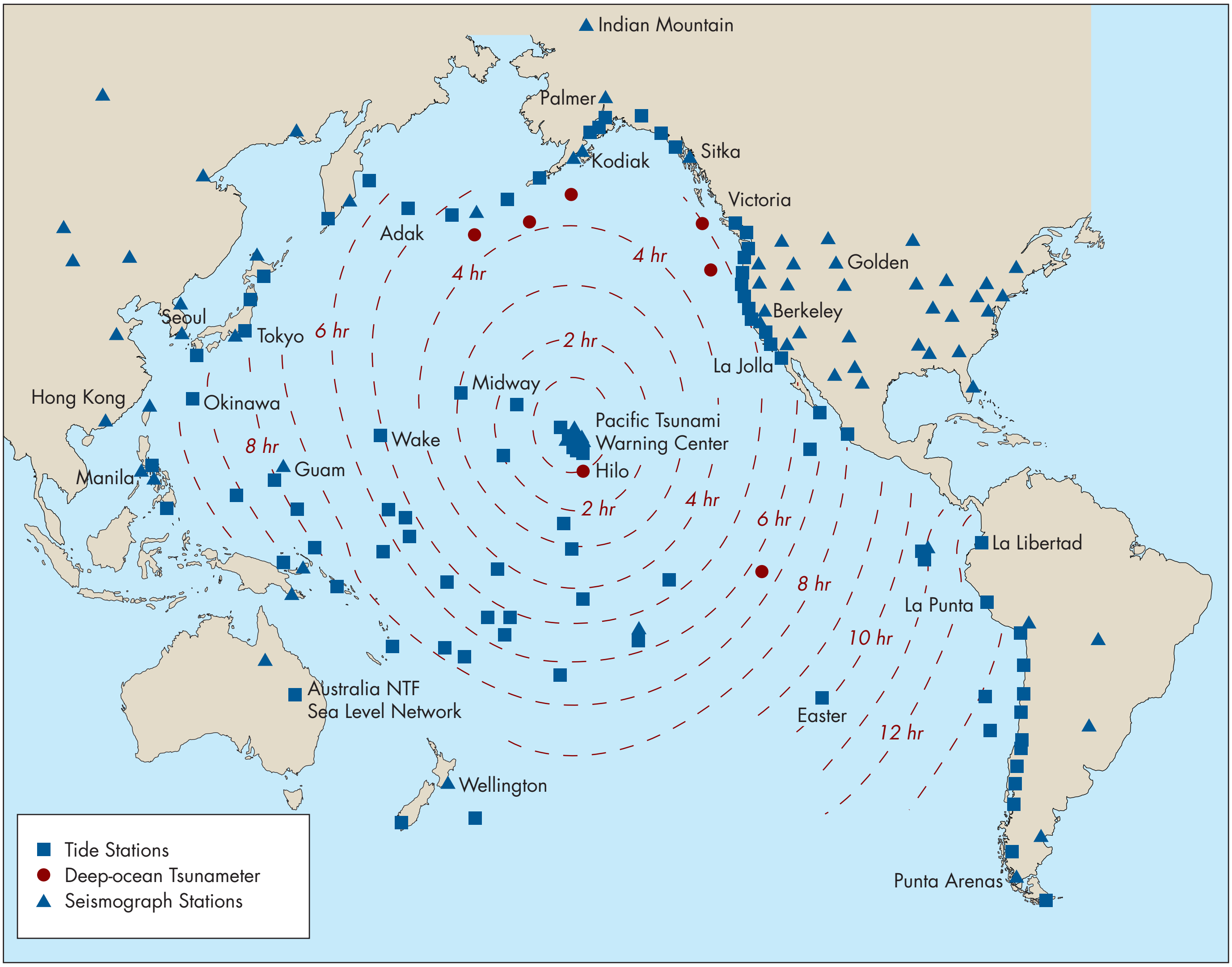

(b)

Figure 6.30 *(Continued)*

prepare for a specific earthquake over a period of days or weeks before an event. Short-term prediction specifying the time and place of the earthquake would be much more useful, but the ability to make such predictions has eluded us. Predicting imminent earthquakes depends to a large extent on observation of precursory phenomena, or changes preceding the event.

Estimation of Seismic Risk

The earthquake risk associated with particular areas is shown on seismic hazard maps, which are prepared by scientists. Some of these maps show relative hazard, that is, where earthquakes of a specified magnitude have occurred. However, a preferable method of assessing seismic risk is to calculate the probability of either a particular event or of the amount of shaking likely to occur. Figure 6.31a shows an earthquake hazard map for the United States. It was prepared on the basis of the probability of horizontal ground motion. The darkest areas on the map represent the regions of greatest seismic hazard, because it is those areas that will have the highest probability of experiencing the greatest seismic shaking. Regional earthquake hazard maps are valuable; however, considerably more data are necessary to evaluate hazardous areas in order to assist in the development of building codes and the determination of insurance rates. Figure 6.31b shows the

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Figure 6.31 Earthquake hazard map (a) A probabilistic approach to the seismic hazard in the United States. Colors indicate level of hazard. (b) Probability of at least one M 6–7 or greater earthquake occurring before 2032 on a particular fault and entire region for the San Francisco Bay region. *(From U.S. Geological Survey Fact Sheets FS-131-02, 2002, and 039-03, 2004)*

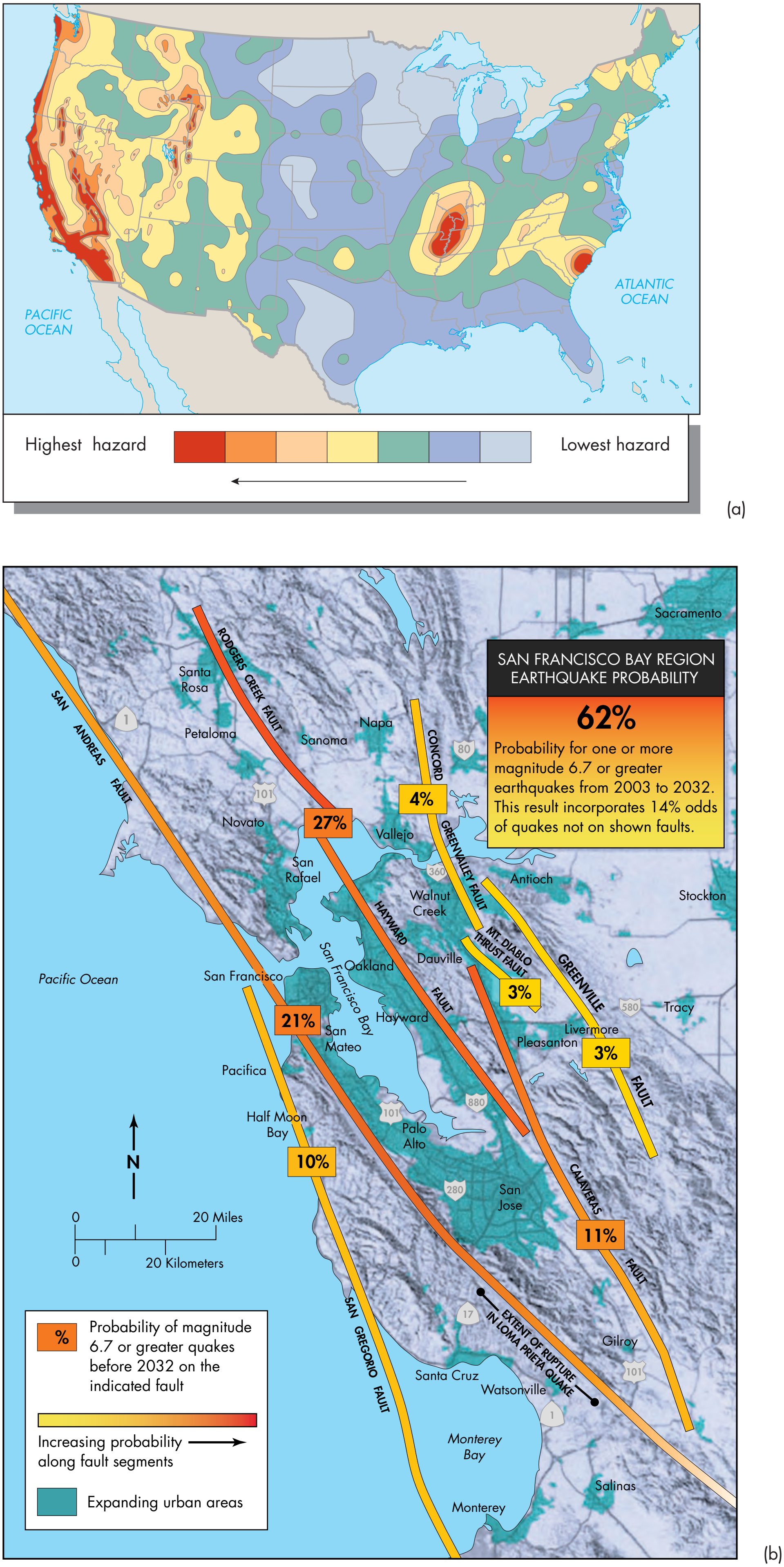

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TABLE 6.6 Fault (Seismic Source) Type in California

Based on slip rate and potential earthquake a fault could produce. Type B collectively produce most of the damage in California because there are many more Type B faults than Type A, and Type C faults, while common, produce smaller earthquakes.

		DEFINITION[1]	
Fault Type	Description	Maximum Moment Magnitude, M[3]	Slip Rate, SR (mm/yr)[3]
A	Faults that are capable of producing large-magnitude events and that have a high rate of seismic activity[2]	$M \geq 7.0$	$SR \geq 5$
B	All faults other than Types A and C	$M \geq 7.0$	$SR < 5$
		$M < 7.0$	$SR > 2$
		$M \geq 6.5$	$SR < 2$
C	Faults that are not capable of producing large-magnitude earthquakes and that have a relatively low rate of seismic activity	$M < 6.5$	$SR \leq 2$

[1] Both maximum moment magnitude and slip rate conditions must be satisfied concurrently when determining the seismic source type.

[2] Subduction sources shall be evaluated on a site-specific basis.

[3] $\geq$ means greater than or equal to; $<$ means less than.

Source: From *1997 California Uniform Building Code*, Table 16-U.

probability of a M 6.7 or larger earthquake from 2003 to 2032 occurring on faults in the San Francisco Bay region. There is a combined 62 percent probability of at least one M 6 to 7 or greater earthquake occurring before 2032.[21] In addition, the state of California now classifies faults on the basis of the slip rate of the fault and the maximum moment magnitude earthquake the fault can produce (Table 6.6). An example of a type A fault would be the San Andreas fault. The majority of faults in California that produce damaging earthquakes are type B. This results because there are many type B faults in California and they can produce strong major earthquakes (Table 6.2). This system of classification is thought to be more important than simply demonstrating whether a fault is active. Most known active faults in California have been classified by type.

Short-Term Prediction

The short-term prediction, or *forecast*, of earthquakes is an active area of research. Similar to a weather forecast, an earthquake forecast specifies a relatively short time period in which the event is likely to occur and assigns it a probability of occurring. The basic procedure for predicting earthquakes was once thought to be as easy as "one-two-three."[22] First, deploy instruments to detect potential precursors of a future earthquake; second, detect and recognize the precursors in terms of when an earthquake will occur and how big it will be; and third, after review of your data, publicly predict the earthquake. Unfortunately, earthquake prediction is much more complex than first thought.[22]

The Japanese made the first attempts at earthquake prediction with some success, using the frequency of microearthquakes (M less than 2), repetitive surveys of land levels, and a change in the local magnetic field of Earth. They found that earthquakes in the areas they studied were nearly always accompanied by swarms of microearthquakes that occurred several months before the major shocks. Furthermore, ground tilt was correlated strongly with earthquake activity.

Chinese scientists made the first successful prediction of a major earthquake in 1975. The February 4, 1975, Haicheng earthquake (M 7.3) destroyed or damaged about 90 percent of buildings in the city, which had a population of 9,000. The short-term prediction was based primarily on a series of foreshocks that began 4 days before the main event. On February 1 and 2, several shocks with a magnitude of less than 1 occurred. On February 3, less than 24 hours before the main shock, a foreshock of M 2.4 occurred, and in the next 17 hours, eight shocks with a

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magnitude greater than 3 occurred. Then, as suddenly as it began, the foreshock activity became relatively quiet for 6 hours until the main earthquake occurred.[23] Haicheng's population of 9,000 was saved by the massive evacuation from potentially unsafe housing just before the earthquake.

Unfortunately, foreshocks do not always precede large earthquakes. In 1976, one of the deadliest earthquakes in recorded history struck near the mining town of Tanshan, China, killing several hundred thousand people. There were no foreshocks. Earthquake prediction is still a complex problem, and it will probably be many years before dependable short-range prediction is possible. Such predictions most likely will be based upon precursory phenomena such as

- Patterns and frequency of earthquakes, such as the foreshocks used in the Haicheng prediction
- Preseismic deformation of the ground surface
- Emission of radon gas
- Seismic gaps along faults
- Anomalous animal behavior (?)

Preseismic Deformation of the Ground Surface

Rates of uplift and subsidence, especially when they are rapid or anomalous, may be significant in predicting earthquakes. For more than 10 years before the 1964 earthquake near Niigata, Japan (M 7.5), there was a broad uplift of Earth's crust of several centimeters near the Sea of Japan coast. Similarly, broad slow uplift of several centimeters occurred over a 5 year period before the 1983 Sea of Japan earthquake (M 7.7).[24]

Preinstrument uplifts of 1 to 2 m (3.3 to 6.6 ft) preceded large Japanese earthquakes in 1793, 1802, 1872, and 1927. Although these uplifts are not well understood, they could have been indicators of the impending earthquakes. These uplifts were recognized by sudden withdrawals of the sea from the land, often as much as several hundred meters in harbors. For example, on the morning of the 1802 earthquake, the sea suddenly withdrew about 300 m (984 ft) from a harbor in response to a preseismic uplift of about 1 m (3.3 ft). Four hours later the earthquake struck, destroying many houses and uplifting the land another meter, causing the sea to withdraw an even greater distance.[25]

Emission of Radon Gas

The levels of radon, a radioactive gas, have been observed to increase significantly before some earthquakes. It is believed that before an earthquake rocks expand, fracture, and experience an influx of water. Radon gas, which is naturally present in rocks, moves with the water. There was a significant increase in radon gas measured in water wells a month or so before the 1995 Kobe, Japan, earthquake (M 7.2).[26]

Seismic Gaps

Seismic gaps are defined as areas along active fault zones or within regions that are likely to produce large earthquakes but have not caused one recently. The lack of earthquakes is believed to be temporary; furthermore, these areas are thought to store tectonic strain and are thus candidates for future large earthquakes.[27] Seismic gaps have been useful in medium-range earthquake prediction. At least 10 large plate boundary earthquakes have been successfully forecast from seismic gaps since 1965, including one in Alaska, three in Mexico, one in South America, three in Japan, and one in Indonesia. In the United States, seismic gaps along the San Andreas fault include one near Fort Tejon, California, that last ruptured in 1857 and one along the Coachella Valley, a segment that has not produced a great

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earthquake for several hundred years. Both gaps are likely candidates to produce a great earthquake in the next few decades.[12,27]

Anomalous Animal Behavior (?)

Anomalous animal behavior has often been reported before large earthquakes. Reports have included dogs barking unusually, chickens refusing to lay eggs, horses or cattle running in circles, rats perching on power lines, and snakes crawling out in the winter and freezing. Anomalous behavior of animals was evidently common before the Haicheng earthquake.[23] Years ago it was suggested that sometime in the future we might have animals such as ground squirrels or snakes in cages along faults, and that somehow they would tell us when an earthquake was likely to occur in the near future. Undoubtedly, some animals are much more sensitive to Earth movements and possible changes in Earth before an earthquake or landslide than are people. However, the significance and reliability of animal behavior are very difficult to evaluate. There is little research going on to further explore anomalous animal behavior in the United States, but it remains one of the interesting mysteries surrounding earthquakes.

6.13 Toward Earthquake Prediction

We are still a long way from a working, practical methodology to reliably predict earthquakes.[28] 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 seismic gaps. Optimistic scientists around the world today believe that we will eventually be able to make consistent long-range forecasts (tens to a few thousand years), medium-range predictions (a few years to a few months), and short-range predictions (a few days or hours) for the general locations and magnitudes of large, damaging earthquakes.

Although progress on short-range (days to months) earthquake prediction has not matched expectations, medium- to long-range forecast (years to decades) based on probability of an earthquake occurring on a particular fault has progressed faster than expected. The October 28, 1983, Borah Peak earthquake in central Idaho (M 7.3) has been lauded as a success story for medium-range earthquake hazard evaluation. Previous evaluation of the Lost River fault suggested that the fault was active.[29] The earthquake killed two people and caused approximately $15 million in damages. Fault scarps up to several meters high and numerous ground fractures along the 36 km (22 mi) rupture zone of the fault were produced as a result of the earthquake. The important fact was that the scarp and faults produced during the earthquake were superimposed on previously existing fault scarps, validating the usefulness of careful mapping of scarps produced from prehistoric earthquakes. Remember; where the ground has broken before, it is likely to break again!

6.14 Sequence of Earthquakes in Turkey: Can One Earthquake Set Up Another?

There is considerable controversy regarding patterns of repetitive earthquakes. That is, do earthquakes on a given fault have return periods that are relatively constant with relatively constant-magnitude earthquakes, or do they tend to occur in clusters over a period of several hundred to several thousands of years? Some faults evidently do produce earthquakes of similar magnitude over relatively

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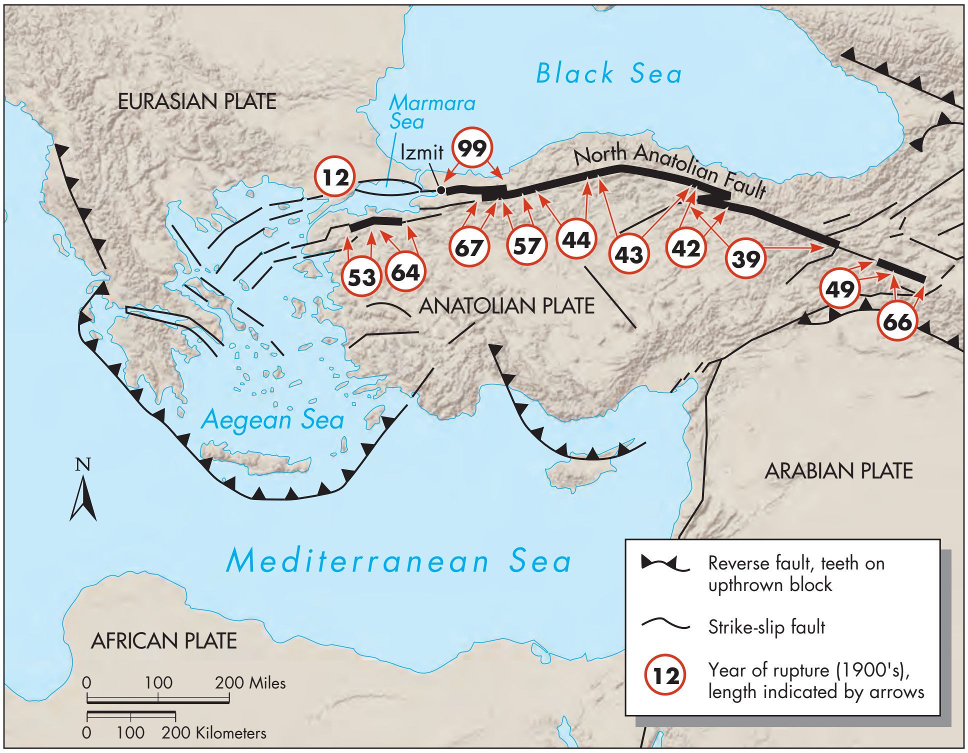

Figure 6.32 Sequence of earthquakes Earthquakes (M greater than 6.7) on the North Anatolian fault in the twentieth century. Events of 1992 and 1951 are not shown. Year 1999 shows the rupture length of two events combined (Izmit, August; and Duzce, November). *(Modified after Reilinger, R., Toksot, N., McClusky, S., and Barka, A. 2000. 1999 Izmit, Turkey earthquake was no surprise.* GSA Today *10(1):1–5)*

constant return periods. However, as we learn more about individual faults, we learn that there is a great deal of variability concerning magnitudes of earthquakes and their return periods for a given fault system. For example, in the twentieth century a remarkable series of earthquakes with magnitude greater than 6.7 generally occurred from east to west on the north Anatolian fault in Turkey, resulting in surface ruptures along a 1,000 km (621 mi) section of the fault (Figure 6.32). Two events in 1999—the Izmit (M 7.4) and the Duzce (M 7.1) earthquakes—were particularly severe, causing billions of dollars in property damage and thousands of deaths. The sequence of earthquakes has been described as a "falling-domino scenario," in which one earthquake sets up the next, eventually rupturing nearly the entire length of the fault in a cluster of events.[30,31] Clusters of earthquakes that form a progressive sequence of events in a relatively short period of time are apparently separated by a period of no earthquakes for several hundred years. A similar sequence or clustering may be occurring along the fault bordering the Sumatra Plate boundary that produced the 2004 tsunami. Three earlier large earthquakes from 1600 to 1833, discovered from the geologic record, preceded the 2004 event, and a M 8.7 event occurred in 2005. That earthquake did not produce a tsunami, but collapsed buildings and took about 1,000 lives.[3] Understanding processes related to clustering of earthquakes along a particular fault is very important if we are to plan for future seismic events in a given region. The fact that there may not have been a large damaging earthquake for several hundred years may not be as reassuring as we once thought.

6.15 The Response to Earthquake Hazards

Responses to seismic hazards in earthquake-prone areas include development of hazard-reduction programs, careful siting of critical facilities, engineering and land-use adjustments to earthquake activity, and development of a warning system. The extent to which these responses occur depends in part on people's perception of the hazard.

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Earthquake Hazard-Reduction Programs

In the United States, the U.S. Geological Survey (USGS) as well as university and other scientists are developing a National Earthquake Hazard Reduction Program. The major goals[28] of the program are to

- ***Develop an understanding of the earthquake source.*** This requires an understanding of the physical properties and mechanical behavior of faults as well as development of quantitative models of the physics of the earthquake process.
- ***Determine earthquake potential.*** This determination involves characterizing seismically active regions, including determining the rates of crustal deformation, identifying active faults, determining characteristics of paleoseismicity, calculating long-term probabilistic forecasts, and finally, developing methods of intermediate- and short-term prediction of earthquakes.
- ***Predict effects of earthquakes.*** Predicting effects includes gathering of the data necessary for predicting ground rupture and shaking and for predicting the response of structures that we build in earthquake-prone areas and evaluating the losses associated with the earthquake hazard. (See A Closer Look: The Alaska Earthquake of 2002 and the Value of Estimating Potential Ground Rupture.)
- ***Apply research results.*** The program is interested in transferring knowledge about earthquake hazards to people, communities, states, and the nation. This knowledge concerns what can be done to plan better for earthquakes and reduce potential losses of life and property.

Adjustments to Earthquake Activity

The mechanism of earthquakes is still poorly understood; therefore, such adjustments as warning systems and earthquake prevention are not yet reliable alternatives. There are, however, reliable protective measures we can take:

- ***Structural protection,*** including the construction of large buildings and other structures such as dams, power plants, and pipelines able to accommodate moderate shaking or surface rupture. This measure has been relatively successful in the United States. (See A Closer Look: The Alaska Earthquake of 2002 and the Value of Estimating Potential Ground Rupture.) The 1988 Armenia earthquake (M 6.8) was somewhat larger than the 1994 Northridge event (M 6.7), but the loss of life and destruction in Armenia were staggering. At least 45,000 people were killed, compared with 57 in California, and near-total destruction occurred in some towns near the epicenter. Most buildings in Armenia were constructed of unreinforced concrete and instantly crumbled into rubble, crushing or trapping their occupants. The 2005 Pakistan M 7.6 earthquake killed over 80,000 people. Many of the deaths occurred as apartment buildings with little or no steel reinforcement collapsed to resemble a stack of pancakes.[3] This is not to say that the Northridge earthquake was not a catastrophe. It certainly was; the Northridge earthquake left 25,000 people homeless, caused the collapse of several freeway overpasses, injured approximately 8,000 people, and inflicted many billions of dollars in damages to structures and buildings (Figure 6.1). However, since most buildings in the Los Angeles Basin are constructed with wood frames or reinforced concrete, thousands of deaths were avoided in Northridge.
- ***Land-use planning,*** including the siting of important structures such as schools, hospitals, and police stations in areas away from active faults or sensitive Earth materials that are likely to increase seismic shaking. This planning involves zoning the ground's response to seismic shaking on a block-by-block basis. Zoning for earthquakes in land-use planning is necessary

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A CLOSER LOOK

The Alaska Earthquake of 2002 and the Value of Estimating Potential Ground Rupture

On November 3, 2002, a magnitude 7.9 earthquake occurred in early afternoon on the Denali fault in south-central Alaska. That event produced approximately 340 km of surface rupture with maximum right-slip displacement of just over 8 meters (Figure 6.E) The earthquake struck a remote part of Alaska where few people live, and although it caused thousands of landslides and numerous examples of liquefaction and intense shaking, little structural damage and no deaths were recorded.[32]

The Denali fault earthquake demonstrated the value of seismic hazard and earthquake hazard evaluation. The fault was studied in the early 1970s as part of an evaluation of the Trans-Alaskan pipeline that today supplies approximately 17 percent of the domestic oil supply for the United States. Where the pipeline crosses the Denali fault, geologists determined that the fault zone was several hundred meters wide and might experience a 6-meter horizontal displacement from a magnitude 8 earthquake. These estimates were used in design of the pipeline, which included long horizontal steel beams with teflon shoes which allow the pipeline to slide horizontally approximately 6 meters. This was associated with a zigzag pattern of the pipeline that allows, along with the steel beams, the horizontal movement (Figure 6.E). The 2002 earthquake occurred within the mapped zone of the fault and sustained about 4.3 meters (14 feet) of right-lateral strike-slip. As a result the pipeline suffered little damage and there was no oil spill. The cost in 1970 of the engineering and construction that allowed the fault slip was about $3 million. Today, that looks very cost effective considering that approximately $25 million worth of oil per day is transported via the pipeline. If the pipeline had been ruptured, then the cost of repair and cleanup of the environment might have cost several hundred million dollars.[33]

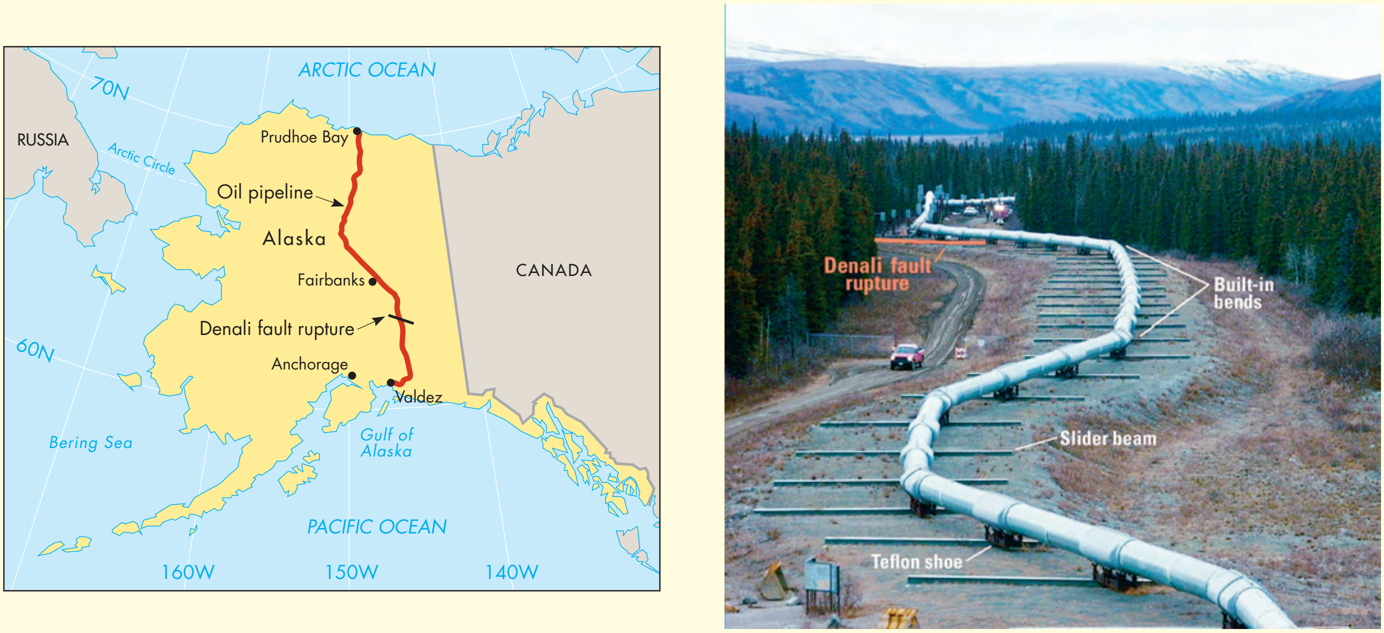

Figure 6.E **A Trans-Alaska oil pipeline survives (M 7.9) earthquake** The Alaskan pipeline was designed to withstand several meters of horizontal displacement on the Denali fault. The 2002 earthquake caused a rupture of 4.3 m (14 ft) beneath the pipeline. The built-in bends on slider beams with teflon shoes accommodated the rupture as designed. This was strong confirmation of the value of estimating potential ground rupture and taking action to remove the potential threat and damage. *[Alyeska Pipeline Service Company (ASPC)]*

because ground conditions can change quickly in response to shaking. In urban areas, where property values may be as high as millions to billions of dollars per block, we need to produce detailed maps of ground response to accomplish zonation. These maps will assist engineers when designing buildings and other structures that can better withstand seismic shaking. Clearly, zonation requires a significant investment of time and money; however, the first step is to develop methods that adequately predict the ground motion from an earthquake at a specific site.

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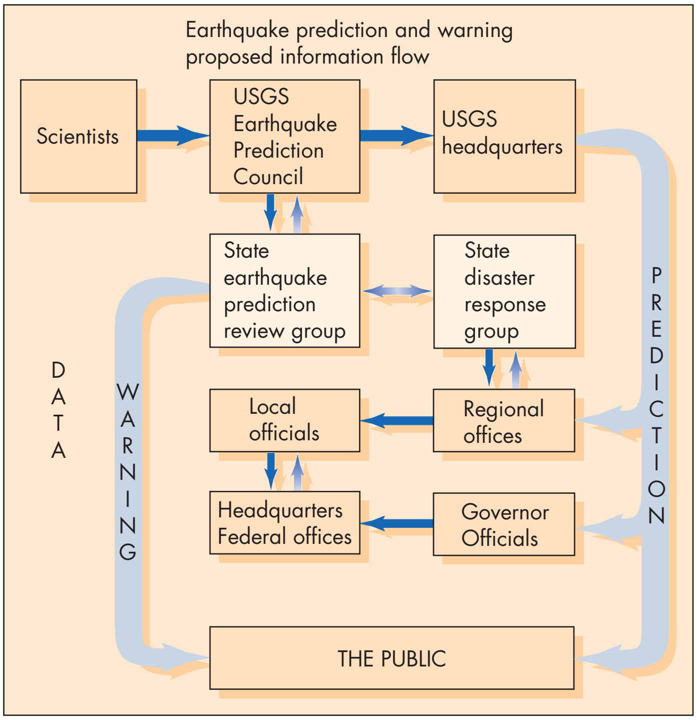

Figure 6.33 **Issuing a prediction or warning** A federal plan for issuance of earthquake predictions and warning: the flow of information. *(From McKelvey, V. E. 1976.* Earthquake prediction—Opportunity to avert disaster. *U.S. Geological Survey Circular 729)*

- ***Increased insurance and relief measures*** to help adjustments after earthquakes. After the 1994 Northridge earthquake, total insurance claims were very large, and some insurance companies terminated earthquake insurance.

We hope eventually to be able to predict earthquakes. The federal plan for issuing prediction and warning is shown on Figure 6.33. Notice how it is related to the general flow path for issuance of a disaster prediction shown in Figure 5.14. The general flow of information moves from scientists to a prediction council for verification. Once verified, a prediction that a damaging earthquake of a specific magnitude would occur at a particular location during a specified time would be issued to state and local officials. These officials are responsible for issuing a warning to the public to take defensive action that, one hopes, has been planned in advance. Potential response to a prediction depends upon lead time, but even a few days would be sufficient to mobilize emergency service, shut down important machinery, and evacuate particularly hazardous areas.

Earthquake Warning Systems

Technically, it is feasible to develop an earthquake warning system that would provide up to about 1 minute's warning to the Los Angeles area before the arrival of damaging earthquake waves from an event several hundred kilometers away. This type of system is based on the principle that the warning sent by a radio signal via satellite relay travels much faster than seismic waves. The Japanese have had a system for nearly 20 years that provides earthquake warnings for their high-speed trains; train derailment by an earthquake could result in the loss of hundreds of lives. 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 6.34). The warning time would vary from as little as 15 seconds to as long as about 1 minute, depending on the location of the epicenter of the earthquake. This could be enough time for people to shut down machinery and computers and take cover.[34] Note that this earthquake warning system is not a prediction tool; it only warns that an earthquake has already occurred.

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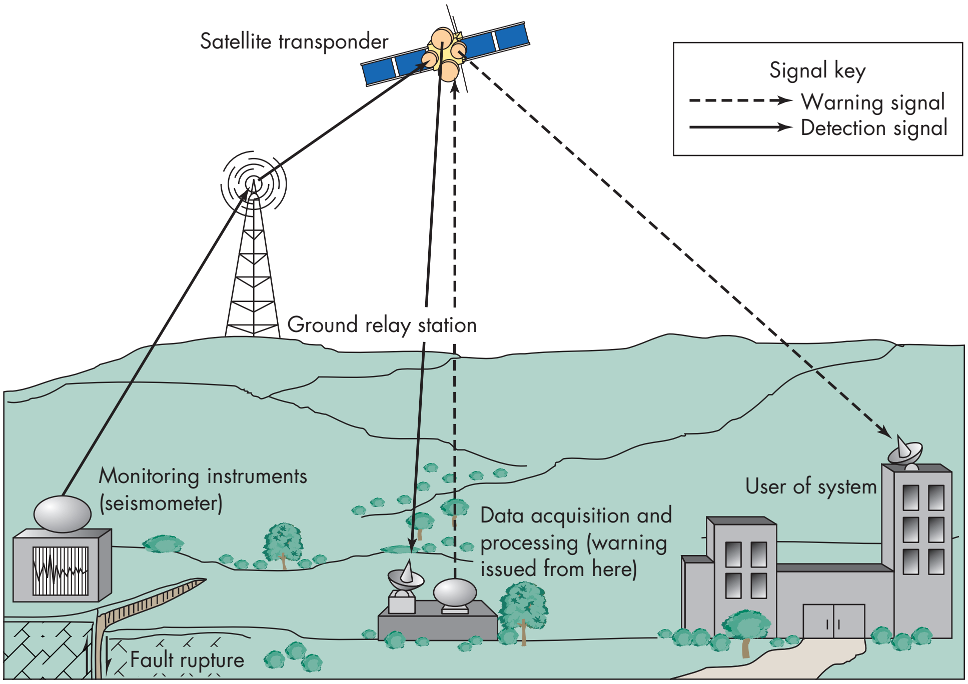

Figure 6.34 Earthquake warning Idealized diagram showing an earthquake warning system. Once an earthquake is detected, a signal is sent ahead of the seismic shaking to warn people and facilities. The warning time depends on how far away an earthquake occurs. It could be long enough to shut down critical facilities and for people to take cover. *(After Holden, R., Lee, R., and Reichle, M. 1989.* California Division of Mines and Geology Bulletin *101)*

A potential problem with a warning system is the chance of false alarms. For the Japanese system, the number of false alarms is less than 5 percent. However, because the warning time is so short, some people have expressed concern as to whether much evasive action could be taken. There is also 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 warning.

Perception of Earthquake Hazard

The fact that terra firma is not so firm in places is disconcerting to people who have experienced even a moderate earthquake. The large number of people, especially children, who suffered mental distress after the San Fernando and Northridge earthquakes attests to the emotional and psychological effects of earthquakes. These events were sufficient to influence a number of families to move away from Los Angeles.

The Japanese were caught off guard by the 1995 Kobe earthquake, and the government was criticized for not mounting a quick and effective response. Emergency relief did not arrive until about 10 hours after the earthquake! They evidently believed that their buildings and highways were relatively safe compared with those that had failed in Northridge, California, one year earlier.

As mentioned earlier, a remarkable sequence of earthquakes in Turkey terminated in 1999 with two large damaging earthquakes (Figure 6.32). The first occurred on August 17 and leveled thousands of concrete buildings. Six hundred thousand people were left homeless, and approximately 38,000 people died as a result of the earthquake. Some of the extensive damage to the town of Golcuk in western Turkey is shown in Figure 6.35. Note that the very old mosque on the left is still standing, whereas many modern buildings collapsed, suggesting that earlier construction was more resistant to earthquakes. Although Turkey has a relatively high standard for new construction to withstand earthquakes, there is fear that poor construction was a factor in the collapse of the newer buildings from intense seismic shaking. It has been alleged that some of the Turkish contractors bulldozed the rubble from collapsed buildings soon after the earthquake, perhaps in an effort to remove evidence of shoddy construction. If that allegation is true,

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Figure 6.35 **Collapse of buildings in Turkey** Damage to the town of Golcuk in western Turkey from the M 7.4 earthquake of August 1999. The very old mosque on the left remains standing, whereas many modern buildings collapsed. *(Enric Marti/AP/Wide World Photos)*

these contractors also tied up bulldozers that could have been used to help rescue people trapped in collapsed buildings.

The lessons learned from Northridge, Kobe, Turkey, and Pakistan were bitter ones that illuminate our modern society's vulnerability to catastrophic loss from large earthquakes. Older, unreinforced concrete buildings or buildings not designed to withstand strong ground motion are most susceptible to damage. In Kobe, reinforced concrete buildings constructed post-1990 with improved seismic building codes experienced little damage compared with those constructed in the mid-1960s or earlier. Minimizing the hazard requires new thinking about the hazard. In addition, microzonation is instrumental in the engineering response to design structures that are less vulnerable to ground motion from earthquakes.

Personal and Community Adjustments: Before, During, and After an Earthquake

A group of individuals living in an area define a community, whether it is a village, town, or city. In areas with an earthquake hazard, it is important for people to prepare for the hazard in terms of what can be done before, during, and after an earthquake.

At the community level, one important aspect of earthquake preparedness is enforcing building codes such as the Uniform Building Code of California. The objective of the earthquake section of the code is to provide a safeguard against loss of life and major structural failures through better design of buildings to withstand earthquake shaking. Another important task is the inspection of older buildings to determine if a "retrofit" is necessary to increase the strength of the building in order to better withstand earthquakes. In fact, the State of California has regulated building retrofits. A recent study concluded that many of the hospitals in southern California are in need of extensive and costly retrofitting.

Education is also an important component of earthquake preparedness at the community level. Government, state, and local agencies prepare pamphlets and videos concerning the earthquake hazard and help ensure that this information is distributed to the public. Workshops and training meetings concerning the most up-to-date information to minimize earthquake hazards are available to professionals in engineering, geology, and planning. A great deal of information at the community level is also available on the World Wide Web from a variety of sources, including the U.S. Geological Survey and scientific organizations such as

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the Southern California Earthquake Center, as well as other agencies interested in earthquake hazard reduction.[35]

In schools, it is important to practice what is sometimes called the "earthquake drill": everyone pretends that an earthquake is happening and students "duck, cover, and hold." After about 15 or 20 seconds, students emerge from their duck-and-cover location, take five slow, deep breaths, practice calming down, and then walk to a designated safe area.

At the personal level in homes and apartments, it is estimated that billions of dollars of damages from earthquakes could be avoided if our buildings and contents were better secured to withstand shaking from earthquakes. Before an earthquake occurs, homeowners and apartment dwellers should complete a thorough check of the building, including rooms, foundations, garages, and attics. The following are some items of a home safety check.[35]

- Be sure your chimney has been reinforced to withstand shaking from earthquakes. After the 1994 Northridge earthquake, one of the most commonly observed types of damage was collapsed chimneys.
- Be sure your home is securely fastened to the foundation and that there are panels of plywood between the wooden studs in walls. Make sure that large openings such as garage doors with a floor above are adequately braced.
- Within the house, be sure that anything that is heavy enough to hurt you if it falls on you, or is fragile and expensive, is secured. There are ways to secure tabletop objects, television sets, tall furniture, and cabinet doors.
- Large windows and sliding doors may be covered with strong polyester (Mylar®) films to make them safer and reduce the hazard from broken glass that is shattered during earthquakes.
- Ensure that your gas water heater is strapped to the building so that it will not fall over and start a fire. If necessary, change to flexible gas connections that can withstand some movement.

Probably the most important and rational thing you can do before an earthquake is to prepare a plan of exactly what you will do should a large earthquake occur. This might include the following points.[35]

- Teach everyone in your family to "duck, cover, and hold." For each room in your home, identify safe spots such as a sturdy desk or table or strong interior walls.
- Instruct everyone who might be home how to turn off the gas. However, the gas should be turned off only if a leak is detected through either hearing or smelling the leaking gas.
- After an earthquake, out-of-area phone calls are often much easier to place and receive than local calls. Therefore, establish an out-of-area person who can be contacted.
- Be sure you have necessary supplies such as food, water, first-aid kit, flashlights, and some cash to tide you over during the emergency period when it may be difficult to obtain some items.
- Canvass your neighborhood and identify elderly or disabled neighbors who may need your help should an earthquake occur, and help educate others in the neighborhood about how to prepare their own plans.

During an earthquake, the strong ground motion will greatly restrict your motion, and, as a result, your strategy is to "duck, cover, and hold." Given your knowledge of earthquakes, you may also try to recognize how strong the earthquake is likely to be and to predict what may happen during the event. For example, you know there will be several types of waves including P, S, and surface waves. The P waves will arrive first, and you may even hear them coming. However, the S and R waves, which soon follow, have bigger displacement and cause most of the damage. The length of shaking during an earthquake will vary

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with the magnitude. For example, during the 1994 Northridge earthquake, the shaking lasted approximately 15 seconds, but the time of shaking in a great earthquake may be much longer. For example, during the 1906 San Francisco earthquake, shaking lasted nearly 2 minutes. In addition to the "duck, cover, and hold" strategy, you need to remain calm during an earthquake and try to protect yourself from appliances, books, and other materials that may slide or fly across the room. A good strategy would be to crouch under a desk or table, roll under a bed, or position yourself in a strong doorway. During the earthquake, there may be explosive flashes from transformers and power poles, and you must obviously avoid downed power lines. At all costs, resist the natural urge to panic.[35]

After the shaking stops, take your deep breaths and organize your thinking in accordance with the plan you developed. Check on your family members and neighbors, check for gas leaks and fires. Your telephones should be used only for emergency calls. Examine your chimney, as chimneys are particularly prone to failure from earthquakes. The chimney may separate from the roof or the walls along the side of the chimney. If you are caught in a theater or stadium during a large earthquake, it is important to remain in your seat and protect your head and neck with your arms; do not attempt to leave until the shaking has stopped. Remain calm and walk out slowly, keeping a careful eye out for objects that have fallen or may fall. If you are in a shopping mall, it is important to "duck, cover, and hold," away from glass doors and display shelves of books or other objects that could fall on you. If you are outdoors and an earthquake occurs, it is prudent to move to a clear area where you can avoid falling trees, buildings, power lines, or other hazards. If you are in a mountainous area, be aware of landslide hazards, since earthquakes often generate many slides that may occur during and for some time after the earthquake. If you are in a high-rise building, you need to "duck, cover, and hold" as in any indoor location, avoiding any large windows. It is likely that the shaking may activate fire alarms and water sprinkler systems. Streets lined with tall buildings are very dangerous locations during an earthquake; glass from these buildings often shatters and falls to the street below, becoming razor-sharp shards that can cause serious damage and death to people below.[35]

Finally, after an earthquake, be prepared for aftershocks. There is a known relationship between the magnitude of the primary earthquake and the distribution of aftershocks in hours, days, months, or even years following the earthquake. If the earthquake has a magnitude of about 7, then several magnitude 6 aftershocks can be expected. Many magnitude 5 and 4 events are likly to occur. In general, the number and size of aftershocks decrease with time from the main earthquake event, and the most hazardous period is in the minutes, hours, and days following the main shock.

The good news concerning living in earthquake country in the United States is that large earthquakes are survivable. Our buildings are generally constructed to withstand earthquake shaking, and our woodframe houses seldom collapse. It is, however, important to be well informed and prepared for earthquakes. For that reason it is extremely important to develop and become familiar with your personal plan of what to do before, during, and after an earthquake.

SUMMARY

Large earthquakes rank among nature's most catastrophic and devastating events. Most earthquakes are located in tectonically active areas where lithospheric plates interact along their boundaries, but some large damaging intraplate earthquakes also occur.

A fault is a fracture or fracture system along which rocks have been displaced. 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, giving rise to seismic, or earthquake, waves that shake the ground.

Strike-slip faults exhibit horizontal displacement and are either right- or left-lateral. Dip-slip faults exhibit vertical displacement and are either normal or reverse. Some faults are buried and do not rupture the surface even when their movement causes large earthquakes. Recently a new fundamental earth process known as slow earthquakes has been discovered. Slow earthquakes may last from days to months with large areas of fault rupture, but small displacements.

A fault is usually considered active if it has moved during the past 10,000 years and potentially active if it has moved

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during the past 1.65 million years. Some faults exhibit tectonic creep, a slow displacement not accompanied by felt earthquakes.

The area within Earth where fault rupture begins is called the focus of the earthquake and can be from a few kilometers to almost 700 km (435 mi) deep. The area of the surface directly above the focus is called the epicenter. Seismic waves of different kinds travel away from the focus at different rates; much of the damage from earthquakes is caused by surface waves. The severity of shaking of the ground and buildings is affected by the frequency of the seismic waves and by the type of Earth material present. Buildings on unconsolidated sediments or landfill, which tend to amplify the shaking, are highly subject to earthquake damage.

The magnitude of an earthquake is a measure of the amount of energy released. The measure of the intensity of an earthquake, the Modified Mercalli Scale, is based on the severity of shaking as reported by observers and varies with proximity to the epicenter and local geologic and engineering features. Following an earthquake, shake maps based on a dense network of seismographs can quickly show areas where potentially damaging shaking occurred. This information is needed quickly to assist emergency efforts. Ground acceleration during an earthquake is important information necessary to design structures that can withstand shaking.

The hypothesized earthquake cycle for large earthquakes has four stages. A period of seismic inactivity, during which elastic strain builds up in the rocks along a fault, is followed by a period of increased seismicity as the strain locally exceeds the strength of the rocks, initiating local faulting and small earthquakes. The third stage, which does not always occur, consists of foreshocks. The fourth stage is the major earthquake, which occurs when the fault segment ruptures, producing the elastic rebound that generates seismic waves.

Human activity has caused increasing earthquake activity by loading Earth's crust through construction of large reservoirs; by disposal of liquid waste in deep disposal wells, which raises fluid pressures in rocks and facilitates movement along fractures; and by setting off underground nuclear explosions. The accidental damage caused by the first two activities is regrettable, but what we learn from all the ways we have caused earthquakes may eventually help us to control or stop large earthquakes.

Effects of earthquakes include violent ground motion accompanied by fracturing, which may shear or collapse large buildings, bridges, dams, tunnels, and other rigid structures. Other effects include liquefaction, landslides, fires, and regional subsidence and uplift of landmasses as well as regional changes in groundwater levels. Large to great submarine earthquakes can generate a damaging catastrophic tsunami.

Prediction of earthquakes is a subject of serious research. To date, long-term and medium-term earthquake prediction based on probabilistic analysis has been much more successful than short-term prediction. Long-term prediction provides important information for land-use planning, developing building codes, and engineering design of critical facilities. Some scientists believe that we will eventually be able to make long-, medium-, and short-range predictions based on previous patterns and frequency of earthquakes as well as by monitoring the deformation of land, the release of radon gas, and existing seismic gaps. Although not currently being pursued, reports suggest that anomalous animal behavior before an earthquake may offer potential aid in earthquake prediction. A potential problem of predicting earthquakes is that their pattern of occurrence is often variable, with clustering or sequencing of events separated by longer periods of time with reduced earthquake activity.

Reduction of earthquake hazards will be a multifaceted program, including recognition of active faults and Earth materials sensitive to shaking and development of improved ways to predict, control, and adjust to earthquakes, including designing structures to better withstand shaking. Warning systems and earthquake prevention are not yet reliable alternatives, but more communities are developing emergency plans to respond to a predicted or unexpected catastrophic earthquake. Seismic zoning, including microzonation and other methods of hazard reduction, are active areas of research. At a personal level, there are steps an individual can take before, during, and after an earthquake to reduce the hazard and ease recovery.

Revisiting Fundamental Concepts

Human Population Growth

Human population growth, especially in large cities in seismically active regions, is placing more and more people and property at risk from earthquakes.

Sustainability

Minimizing the damages from earthquakes to public and private property is a component of sustainable development. The goal is to produce stable communities that are less likely to experience catastrophic losses as a result of poor earthquake preparation.

Earth as a System

Earthquakes are produced by Earth's internal tectonic systems. Landforms, including ocean basins and mountains, are the products of continental movement and resultant earthquakes. Mountains cause changes to atmospheric processes that create deserts and regional patterns of rainfall and thus affect vegetation and erosion. This is an example of the principle of environmental unity: One change, in this case the development of mountains, causes a chain of other events.

Hazardous Earth Processes, Risk Assessment, and Perception

We cannot control processes that produce earthquakes, but how we perceive the earthquake hazard greatly influences the actions we take to minimize the risk of loss of life. If we perceive earthquakes as a real risk to our lives and those of our family and friends, we will take the necessary steps to prepare for future earthquakes.

Scientific Knowledge and Values

Scientific knowledge about earthquakes in terms of how they are produced, where and why they occur, and how to design buildings to better withstand earthquake shaking has grown

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dramatically in recent years. Important lessons were learned from the 1999 earthquakes in Turkey that killed about 38,000 people. Turkey has relatively high building standards, and more of their buildings should have survived the quakes. Some people believe that improper construction contributed significantly to the loss of buildings. Contractors may have destroyed evidence of inadequate construction after the earthquake occurred. Community values result in building regulations that help reduce earthquake losses. If buildings are properly constructed to withstand earthquakes, then catastrophes such as the Turkey earthquakes that caused terrible and unacceptable loss of life may be fewer in number in the future.

Key Terms

directivity (p. 181)
earthquake (p. 173)
earthquake cycle (p. 186)
epicenter (p. 162)
fault (p. 173)
focus (p. 162)
liquefaction (p. 190)
material amplification (p. 180)
Modified Mercalli Scale (p. 167)
moment magnitude (p. 162)
P waves (p. 176)
shake map (p. 167)
slow earthquakes (p. 176)
surface wave (p. 177)
S waves (p. 176)
tectonic creep (p. 175)
tsunamis (p. 192)

Review Questions

1. What is the difference between the focus and the epicenter of an earthquake?
2. How is Richter magnitude determined?
3. What is moment magnitude?
4. What factors determine the Modified Mercalli Scale?
5. What are the main differences between the Richter, Moment Magnitude, Modified Mercalli, and Instrumental scales?
6. Define a fault.
7. What are the major types of fault?
8. What is the difference between an anticline and a syncline?
9. How do we define an active fault?
10. What is tectonic creep?
11. What are the main types of seismic wave?
12. Describe the motion of P, S, and R waves. How do their physical properties account for their effects?
13. What is a shake map, how is it produced, and why are they important?
14. What is material amplification?
15. Define the earthquake cycle, and illustrate it with a simple example.
16. How has human activity caused earthquakes?
17. What are some of the major effects of earthquakes?
18. What is a tsunami and how are most produced?
19. What are some of the precursory phenomena likely to assist us in predicting earthquakes?
20. What are the major goals of earthquake hazard-reduction programs?
21. What are the main adjustments people make to seismic activity and the occurrence of earthquakes?

Critical Thinking Questions

1. Assume you are working for the Peace Corps and are in a developing country where most of the homes are built out of unreinforced blocks or 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?
2. You live in an area that has a significant earthquake hazard. There is ongoing debate as to 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 not be very long. What are your views? Do you think it is a responsibility of public officials 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 partially been avoided with a warning system in place?

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