CHAPTER

# 4

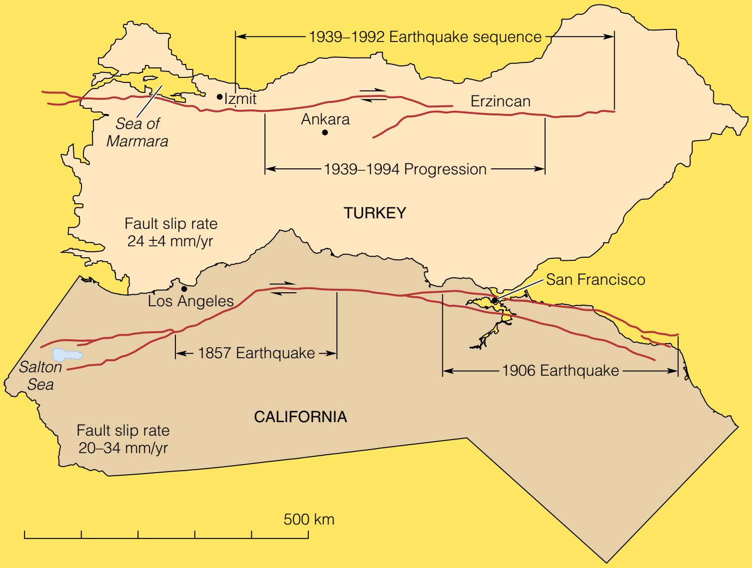
# Earthquakes and Human Activities

*It is useful to be assured that the heavings of the Earth are not the work of deities. These phenomena have a cause of their own.*

Seneca, Roman statesman and philosopher (4 B.C.?–A.D. 65)

ASSOCIATED PRESS, AUGUST 25, 1999 "TURKEY'S PRIME MINISTER has promised stricter building rules to prevent the shoddy construction blamed for the thousands of deaths from last week's massive earthquake. Eight days after the powerful 7.4-magnitude temblor reduced much of western Turkey to rubble, an estimated 200,000 survivors remained camped out in parks and on vacant lots."

The cause of the earthquake was a sudden rupture along northern Turkey's Anatolia fault. The severe ground motion that was generated collapsed hundreds of buildings, many of which had been built below earthquake-resistant standards. Interestingly, the Anatolia fault and California's infamous San Andreas fault have some striking geographic similarities; see ◆Figure 1. Let's hope that is where the likeness ends.

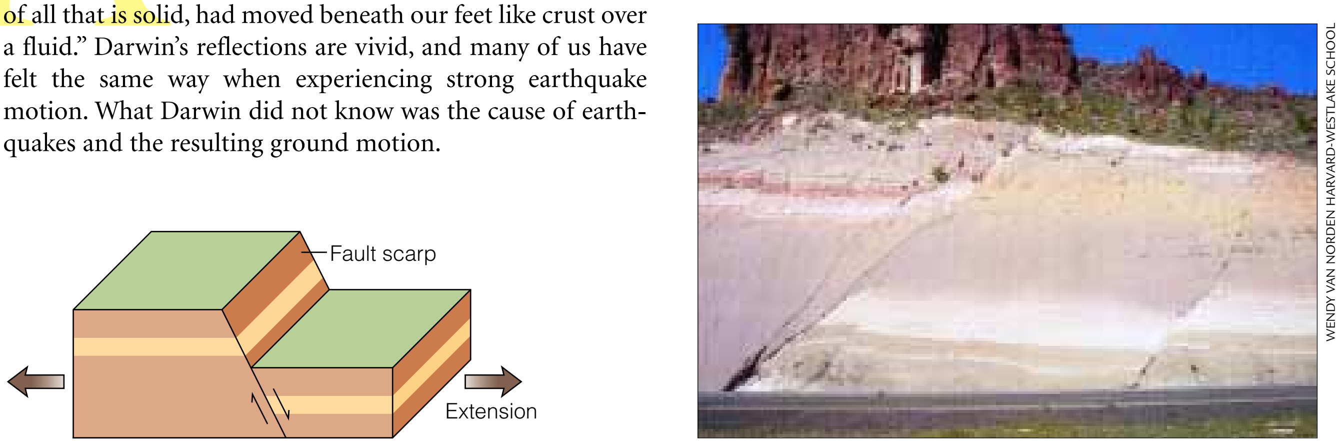


◆ FIGURE 1 *The North Anatolian fault in Turkey and the San Andreas fault in California. The faults have the same sense of motion, are about the same age and length, and are capable of similar-magnitude earthquakes. The earthquake sequences shown on the North Anatolian fault represent events that occurred, one after the other from east to west, along the fault.*

After experiencing an earthquake in Concepción, Chile, in 1835, Charles Darwin noted that “A bad earthquake at once destroys the oldest associations; the world, the very emblem of all that is solid, had moved beneath our feet like crust over a fluid.” Darwin’s reflections are vivid, and many of us have felt the same way when experiencing strong earthquake motion. What Darwin did not know was the cause of earthquakes and the resulting ground motion.

## The Nature of Earthquakes

Earthquakes are the result of abrupt movements on **faults**—fractures in the earth’s lithosphere. The types of faults and the earth forces that cause them are shown in ◆Figure 4.1. The



**(a)** Normal fault

**(b)**

WENDY VAN NORDEN HARVARD-WESTLAKE SCHOOL

**(c)** Reverse fault

**(d)**

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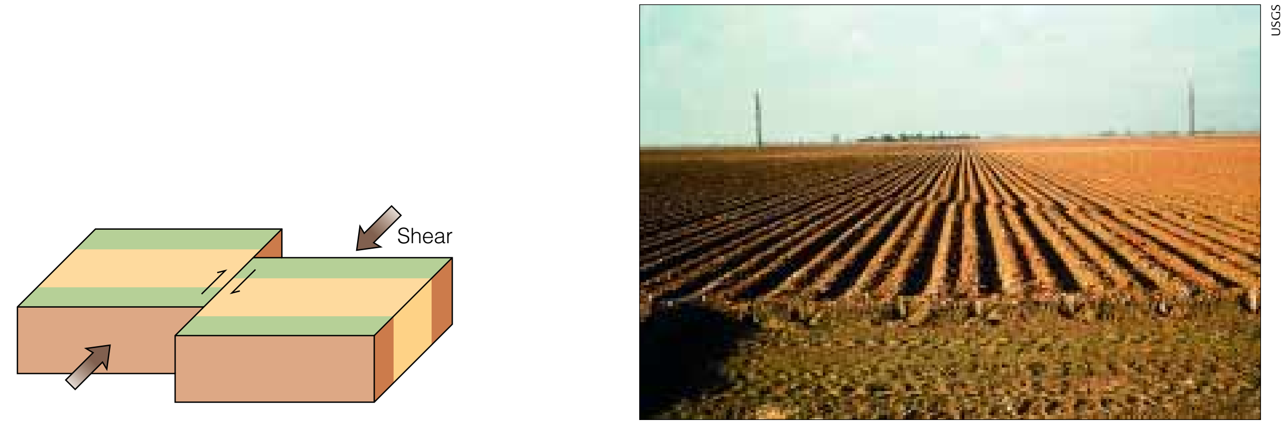
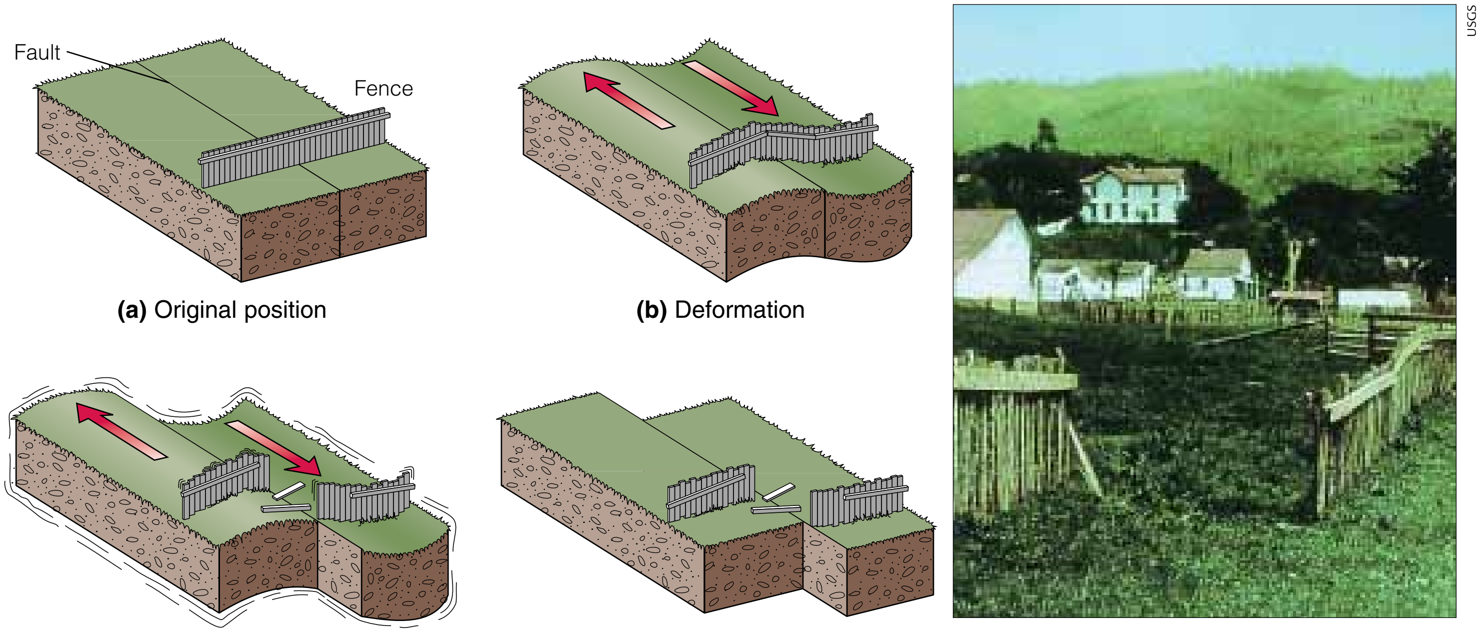


**(e)** Right-lateral strike-slip fault

**(f)**

USGS

◆ FIGURE 4.1 (a) Normal fault geometry and (b) examples in a road cut on I-40 near Kingman, Arizona. The normal fault at the right is in relatively soft sedimentary rocks. Fault at the left is also a normal fault with a small displacement of white sandstone between it and a small fault that shows reverse displacement. (c) Reverse fault geometry and (d) low-angle reverse fault displacing sandstone strata at Wasatch Plateau near Salina, Utah. (e) Right-lateral strike-slip fault geometry and (f) a plowed field displaced by a strike-slip fault in the Imperial Valley, California, in 1979.



(a) Original position

(b) Deformation

(c) Rupture and release of energy

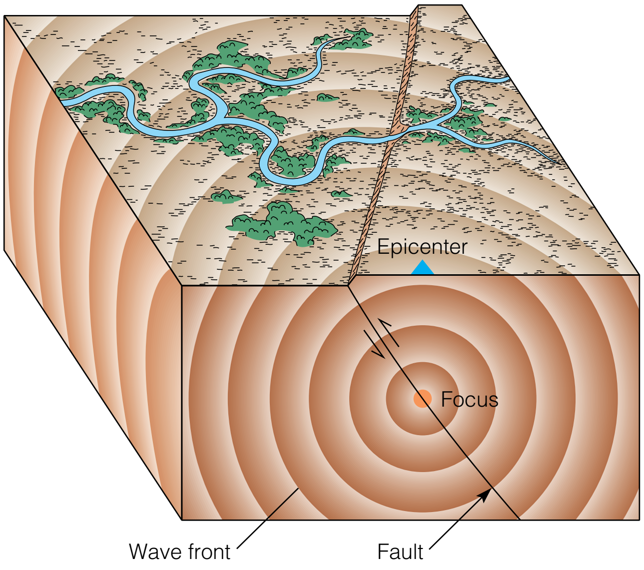
(d) Rocks rebound to original undeformed shape

(e)

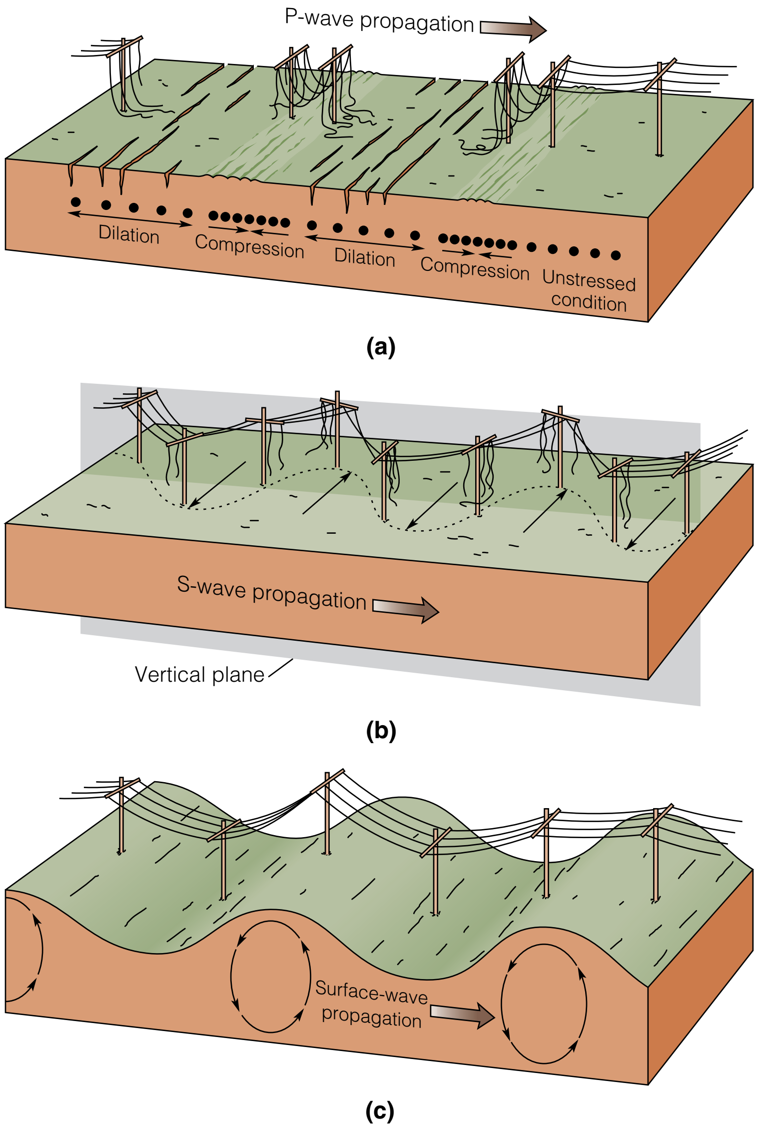
◆ FIGURE 4.2 (a–d) The cycle of elastic-strain buildup and release for a right-lateral strike-slip fault according to Reid's elastic rebound theory of earthquakes. At the instant of rupture, (c), energy is released in the form of earthquake waves that radiate out in all directions. (e) Right-lateral offset of a fence by 2.5 meters (8 ft) by displacement on the San Andreas fault in 1906; Marin County, California.

movements occur as the earth's crustal plates slip past, under, and away from one another. Because the **stress** (force per unit area) that produces **strain** (deformation) can be transmitted long distances in rocks, active faults do not necessarily occur exactly on a plate boundary, but they generally occur in the vicinity of one. The mechanism by which stressed rocks store up strain energy along a fault to produce an earthquake was explained by Harold F. Reid after the great San Francisco earthquake of 1906. Reid proposed a mechanism to explain the shaking, which resulted from movement on the San Andreas fault, known as the **elastic rebound theory** (◆Figure 4.2). According to this theory, when sufficient strain energy has accumulated in rocks, they may rupture rapidly—just as a rubber band breaks when it is stretched too far—and the stored strain energy is released as vibrations that radiate outward in all directions (◆Figure 4.3).

Most earthquakes are generated by movements on faults within the crust and upper mantle that do not produce ruptures at the ground surface. We can thus recognize a point within the earth where the fault rupture starts, the **focus,** and the **epicenter,** the point on the earth surface directly above the focus (Figure 4.3). Elastic waves—vibrations—move out spherically in all directions from the focus and strike the surface of the earth. Damaging earthquake foci are generally within a few kilometers of the earth's surface. Deep-focus earthquakes, on the other hand, those whose foci are 300–700 kilometers (190–440 mi) below the surface, do little or no damage. Earthquake foci are not known below 700 kilometers. This indicates that the mantle at that depth behaves *plastically* due to high temperatures and confining pressures, deforming continuously as ductile substances do, rather than storing up strain energy.



ENVIRONMENTAL
◆ Geology Now™ ACTIVE FIGURE 4.3 The focus of an earthquake is the point in the earth where fault rupture begins, and the epicenter is directly above the focus at the ground surface. Seismic-wave energy moves out in all directions from the focus. (From *Essentials of Geology,* 2nd ed., by R. Wicander and J. Monroe, p. 228, Brooks/Cole, 1999)



ENVIRONMENTAL
◆ **Geology⇌Now™** ACTIVE FIGURE 4.4
Ground motion during passage of earthquake waves. (a) P-waves compress and expand the earth. (b) S-waves move in all directions perpendicular to the wave advance, but only the horizontal motion is shown in this diagram. (c) Surface waves create surface undulations that result from a combination of the retrograde elliptical motions of Rayleigh waves (shown) and Love waves, which move from side to side at right angles to the direction of wave propagation.

The vibration produced by an earthquake is complex, but it can be described as three distinctly different types of waves (◆Figure 4.4). Primary waves, **P-waves,** and secondary waves, **S-waves,** are generated at the focus and travel through the interior of the earth; thus, they are known as **body waves.** They are designated P- and S-waves because they are the first (*p*rimary) and second (*s*econdary) waves to arrive from distant earthquakes. As these body waves strike the earth's surface, they generate surface waves that are analogous to water ripples on a pond.

P-waves (◆Figure 4.4a) are **longitudinal waves;** the solids, liquids, and gases through which they travel are alternately compressed and expanded in the same direction the waves move. Their velocity depends upon the resistance to change in volume (in compressibility) and shape of the material through which they travel. P-waves travel about 300 meters (1,000 ft) per second in air, 300–1,000 meters (1,000–3,000 ft) per second in soil, and faster than 5 kilometers (3 mi) per second in solid rock at the surface. P-wave velocity increases with depth, because the materials composing the mantle and core become less compressible with depth. This increase causes the waves' travel paths to be bowed downward as they move through the earth. P-waves speed through the earth with a velocity of about 10 kilometers (6 mi) per second. At the ground surface they have very small amplitudes (motion) and cause little property damage. Although they are physically identical to sound waves, they vibrate at frequencies below what the human ear can detect. The earthquake noise that has been reported could be P-waves of a slightly higher frequency or some other, related vibrations whose frequencies are in the audible range.

S-waves (◆Figure 4.4b) are **transverse (shear) waves;** they produce ground motion perpendicular to their direction of travel. This causes the rocks through which they travel to be twisted and sheared. These waves have the shape produced when one end of a garden hose or a loosely hanging rope is given a vigorous flip. They can travel only through material that resists shearing—that is, material that resists two forces acting in opposite directions in different planes. Thus, S-waves travel only through solids, because liquids and gases have no shear strength (try piling water in a mound). S-wave ground motion may be largely in the horizontal plane and can result in considerable property damage. S-wave velocity is approximately 5.2 kilometers (3.2 mi) per second from distant earthquakes; hence, they arrive after the P-waves.

Unexpended P- and S-wave energy bouncing off the earth's surface generates the complex surface waves (◆Figure 4.4c). These waves produce a rolling motion at the ground surface. In fact, slight motion sickness is a common response to surface waves of long duration. The waves are the result of a complex interaction of several wave types, the most important of which are *Love waves,* which exhibit horizontal motion normal to the direction of travel, and *Rayleigh waves,* which exhibit retrograde (opposite to the direction of travel) elliptical motion in a plane perpendicular to the ground surface. Surface waves have amplitudes that are greatest in near-surface unconsolidated layers and are the most destructive of the earthquake waves.

## Locating the Epicenter

A **seismograph** is an instrument designed specifically to detect, measure, and record vibrations in the earth's crust (◆Figure 4.5). It is relatively simple in concept (◆Figure 4.6), but some very sophisticated electronic systems have been developed. Seismic data are recorded onto a **seismogram** (◆Figure 4.7). Because seismographs are extremely sensitive to vibrations of any kind, they are installed in quiet areas such as abandoned oil and water wells, cemeteries, and parks.

When an earthquake occurs, the distance to its epicenter can be approximated by computing the difference in P- and S-wave arrival times at various seismograph stations. Although the method actually used by seismologists today is more accurate and determines the depth and location of the quake's focus and its epicenter, what is described here serves to show how seismic-wave arrival times can be used to determine the distance to an epicenter. Because it is known that the two kinds of waves are generated simultaneously at the earthquake focus and that P-waves travel faster than S-waves, it is possible to calculate where the waves started.

Imagine that two trains leave a station at the same time, one traveling at 60 kilometers per hour and the other at 30 km/h, and that the second train passes your house one hour after the first train goes by. If you know their speeds, you can readily calculate your distance from the train station of origin as 60 kilometers. The relationship between distance to an epicenter and arrival times of P- and S-waves is illustrated in ◆Figure 4.8. The epicenter will lie somewhere on a circle whose center is the seismograph and whose radius is the distance from the seismograph to the epicenter. The problem is then to determine where on the circumference of the circle the epicenter is. To learn this, more data are needed: specifically, the distances to the epicenter from two other seismograph stations. Then the intersection of the circles drawn around each of the three stations—a method of map location called *triangulation*—specifies the epicenter of the earthquake (◆Figure 4.9).

**CONSIDER THIS** *You are shopping for a house in earthquake country. How could an isoseismal map of an earthquake whose epicenter was near a house you think you would like to buy be useful? What patterns would you look for when examining the isoseismal map?*

## Earthquake Measurement

### Intensity Scales

The reactions of people (geologists included) to an earthquake typically range from mild curiosity to outright panic. However, a sampling of the reactions of people who have been subjected to an earthquake can be put to good use. Numerical values can be assigned to the individuals' perceptions of earthquake shaking and local damage, which can then be contoured upon a map. One **intensity scale** developed for measuring these perceptions is the 1931 **modified Mercalli scale *(MM).*** The scale's values range from *MM* = I (denoting not felt at all) to *MM* = XII (denoting widespread destruction), and they are keyed to specific U.S. architectural and building specifications. (See Appendix 4.) People's perceptions and responses are compiled from returned questionnaires, and then lines of earthquake intensity, called **isoseismals,** are plotted on maps. Isoseismals enclose areas of equal earthquake damage and can indicate areas of weak rock or soil as well as areas of substandard building construction (◆Figure 4.10a). Such maps have proved useful to planners and building officials in revising building codes and safe construction standards.

Recently a new method of plotting shaking intensities has evolved that is faster and that compares favorably with the questionnaire method. It is the Community Internet Intensity Maps (CIIM), an example of which is shown in Figure 4.10b. The CIIM takes advantage of the Internet, and the time to generate intensity maps drops from months to

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◆ FIGURE 4.5 Seismometer *(left)* and seismogram *(right)* used to demonstrate method of detecting and recording earthquakes. The record on the seismogram is not an earthquake, but represents the seismometer's detection of vibrations from students' footsteps amplified about 2,000 times.

minutes. The responses, which can take place within 3 minutes of the event, are summarized by computer, and an intensity number is assigned to each ZIP code area. This method is particularly useful in areas with sparse seismograph coverage. Although perhaps not as colorful as the map generated by the traditional *MM* intensities obtained by using postal questionnaires, the CIIM values agree well and have actually proved more reliable in areas of low shaking. However, neither method allows comparison of earthquakes with widely spaced epicenters because of local differences in construction practices and local geology.

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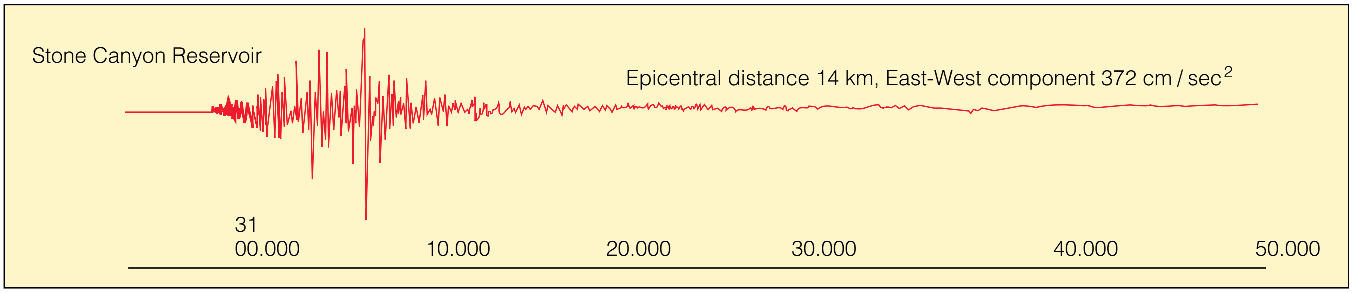
◆ FIGURE 4.6 The first earthquake detector, invented about A.D. 130 by Chinese scholar Chang Heng. Balls held in the dragons' mouths were aligned with a pendulum inside the vase. When an earthquake occurred the pendulum swung and pushed balls into the mouths of the frogs aligned with the pendulum's swing. If the frogs facing north and south contained balls, for example, Chang Heng could say that the earthquake epicenter was north or south of the instrument.

## Richter Magnitude Scale—The Best-Known Scale

The best-known measure of earthquake strength is the **Richter magnitude scale,** which was introduced in 1935 by Charles Richter and Beno Gutenberg at the California Institute of Technology. It is a scale of the energy released by an earthquake and thus, in contrast to the intensity scale, may be used to compare earthquakes in widely separated geographic areas. The Richter value is calculated by measuring the maximum amplitude of the ground motion as shown on the seismogram using a specified seismic wave, usually the surface wave. Next, the seismologist "corrects" the measured amplitude (in microns) to what a "standard" seismograph would record at the station. After an additional correction for distance from the epicenter, the Richter **magnitude** is the common logarithm of that ground motion in microns. For example, a magnitude-4 earthquake is specified as having a corrected ground motion of 10,000 microns ($\log_{10}$ of 10,000 = 4) and thus can be compared to any other earthquake for which the same corrections have been made. It should be noted that because the scale is logarithmic, each whole number represents a ground shaking (at the seismograph site) 10 times greater than the next-lower number. Thus a magnitude-7 produces 10 times greater shaking than a magnitude-6, 100 times that of a magnitude-5, and 1,000 times that of a magnitude-4. Total energy released, on the other hand, varies logarithmically as some exponent of 30. Compared to the energy released by a magnitude-5 earthquake, a $M = 6$ releases 30 times ($30^1$) more energy; a $M = 7$



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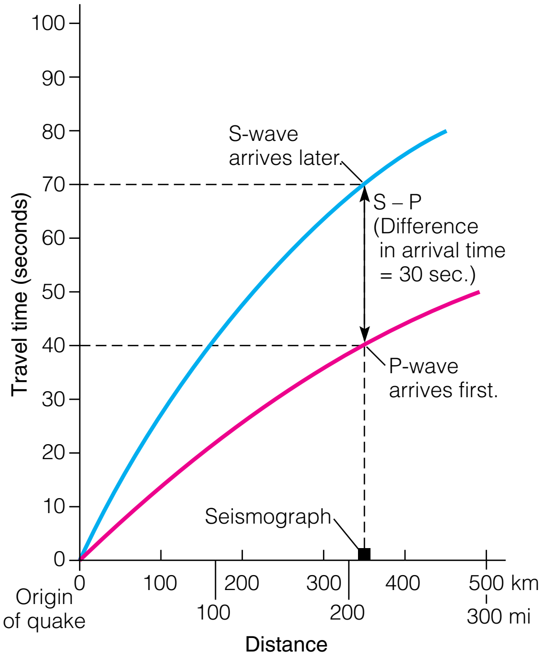
◆ FIGURE 4.7 Seismogram of the main shock of the Northridge earthquake, January 17, 1994. The time in minutes and seconds after 4:00 A.M. appears at the bottom. Distance from the epicenter and direction and ground acceleration at the recording site are also indicated. (Acceleration is explained in the next section.)

releases 900 times ($30^2$) more; and a $M = 8$ releases 27,000 ($30^3$) times more energy (◆Figure 4.11a).

The Richter scale is open-ended; that is, theoretically it has no upper limit. However, rocks in nature do have a limited ability to store strain energy without rupturing, and no earthquake has been observed with a Richter magnitude greater than 8.9—yet.

## Moment Magnitude—The Most Widely Used Scale

Seismologists have abandoned Richter magnitudes in favor of **moment magnitudes** (**$M_w$** or **$M$**) for describing earthquakes. The reason is that Richter magnitudes do not accurately portray the energy released by large earthquakes on faults with great rupture lengths. The seismic waves used to determine the Richter magnitude come from only a small part of the fault rupture and, hence, cannot provide an accurate measure of the total seismic energy released by a very large event.



◆ FIGURE 4.8 Generalized graph of distance versus travel time for P- and S-waves. Note that the P-wave has traveled farther from the origin of the earthquake than the S-wave at any given elapsed time. The curvature of both wave paths is due to increases in velocity with depth (distance from epicenter).

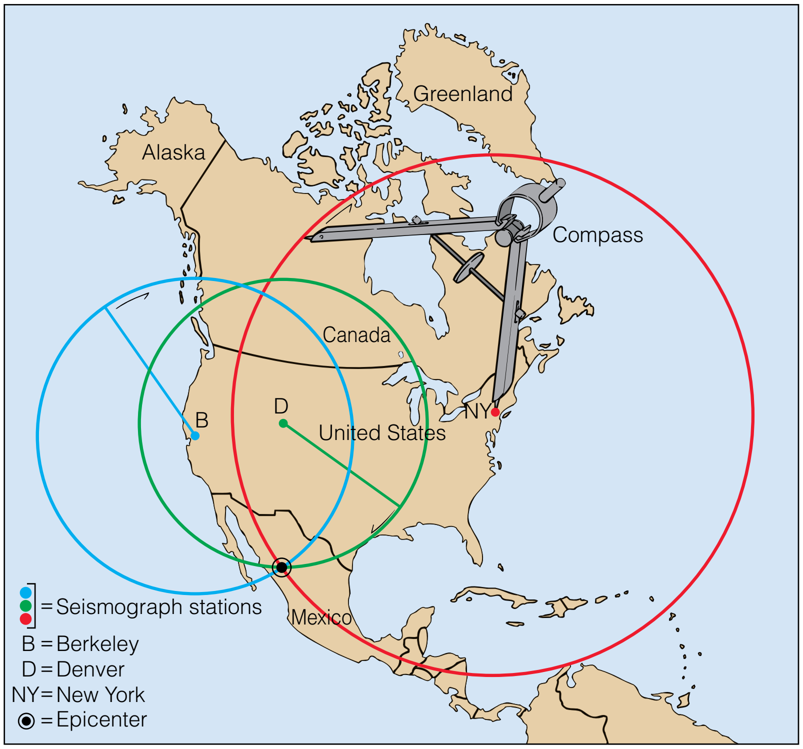
Moment magnitude is derived from seismic moment, $M_0$ (in dyne centimeters), which is proportional to the average displacement (slip) on the fault *times* the rupture area on the fault surface *times* the rigidity of the faulted rock. The amount of seismic energy (in ergs) released from the ruptured fault surface is linearly related to seismic moment by a simple factor, whereas Richter magnitude is logarithmically related to energy. Because of the linear relationship of seismic moment to energy released, the equivalent energy released by other natural and human-caused phenomena can be conveniently compared to earthquakes' moment magnitudes on a graph (◆Figure 4.11b).

Moment magnitudes ($M_w$) are derived from seismic moments ($M_0$) by the formula: $M_w = (\frac{2}{3} \log M_0 - 10.7)$. This table compares the two most commonly used scales for selected significant earthquakes:

| **Earthquake** | **Richter Magnitude** | **Moment Magnitude** |
|---|---|---|
| Chile, 1960 | 8.3 | 9.5 |
| Alaska, 1964 | 8.4 | 9.2 |
| New Madrid, 1812 | 8.7 (est.) | 8.1 (est.) |
| Mexico City, 1985 | 8.1 | 8.1 |
| San Francisco, 1906 | 8.3 (est.) | 7.7 |
| Loma Prieta, 1989 | 7.1 | 7.0 |
| San Fernando, 1971 | 6.4 | 6.7 |
| Northridge, 1994 | 6.4 | 6.7 |
| Kobe, Japan, 1995 | 7.2 JMA* | 6.9 |

*The Richter scale is not used in Japan. The official earthquake scale there is the scale developed by the Japanese Meteorological Agency (JMA).

Confusion arises because some of the earthquake magnitudes are reported as Richter magnitude ($M_L$, teleseismic



◆ ENVIRONMENTAL Geology Now™ ACTIVE FIGURE 4.9 An earthquake epicenter can be closely approximated by triangulation from three seismic stations.

body wave magnitude ($m_b$), duration magnitude ($m_d$), surface wave magnitude ($M_s$), or moment magnitude ($M_w$ or $M$). This is simplified somewhat because most newspapers and the Internet report earthquakes as either Richter or moment magnitude.

At the close of the twentieth century the Chilean earthquake of 1960 ($M_w = 9.5$) still held the record for the greatest seismic moment and energy release ever measured; that is, it had the longest fault rupture and the greatest displacement. The Alaskan earthquake of 1964 had the highest Richter magnitude of the 1900s and theoretically more severe ground motion than the event in Chile. (See ✪ Case Study 4.2 on page 103).

**CONSIDER THIS** *“Then the Lord rained upon Sodom and Gomorrha brimstone and fire. . . . And he overthrew those cities, and all the plain about . . .” (Genesis 19: 24–25). Sodom and Gomorrha are believed to have been located near the modern industrial city of Sedom in Israel at the south end of the Dead Sea. Could some geological event have caused the destruction of these towns? If so, what events might have been possible?*

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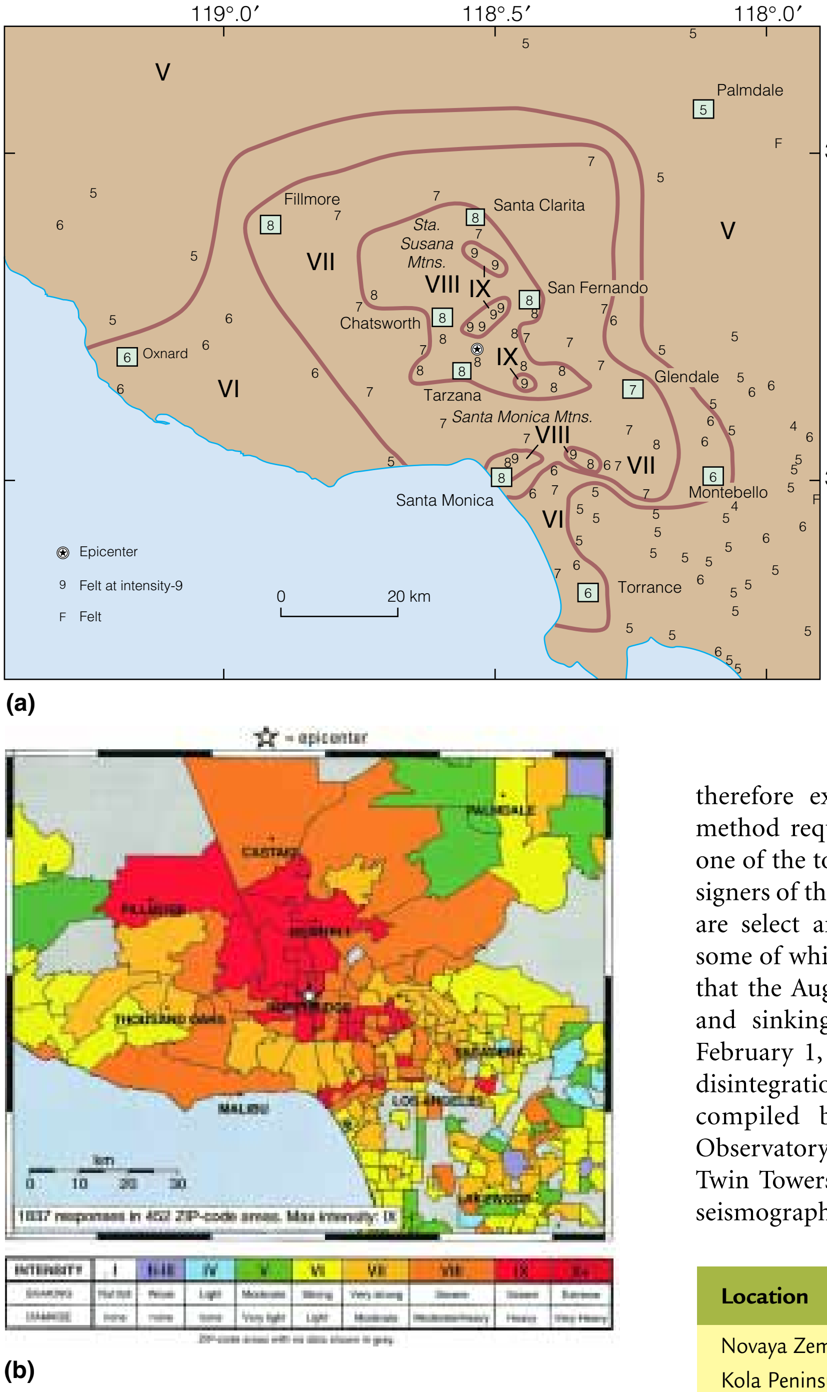
## Fault Creep, the “Nonearthquake”

Some faults move almost continuously, or in short spurts, and do not produce detectable earthquakes. This type of movement, called **fault creep,** is well known but poorly understood. The Hayward fault, which is part of the San Andreas fault system, is an example of a creeping fault. It is just east of the San Andreas fault and runs through the cities of Hayward and Berkeley, California. (It’s on the map in Figure 4.33). Creep along this fault causes displacements of millimeters per year, and is one way that this plate boundary accommodates motion between the Pacific and North American plates. An alternative “accommodation” of plate motion on the San Andreas system is the storage of the strain energy and periodic release as a large displacement on a fault that generates a damaging earthquake. The obvious benefit of a creeping fault does not come without a price, as the residents of Hollister, California, can testify. The “creeping” Calaveras fault runs through their town and, as in Hayward, it gradually displaces curbs, sidewalks, and even residences.

A good strategy in areas subject to fault creep is to map the surface trace of the fault so that it can be avoided in future construction. The University of California–Berkeley Memorial Stadium was built on the Hayward fault before the hazard of fault creep was recognized. The fault creep caused damage to the drainage system that requires periodic maintenance. It is ironic that creep damage occurs at an



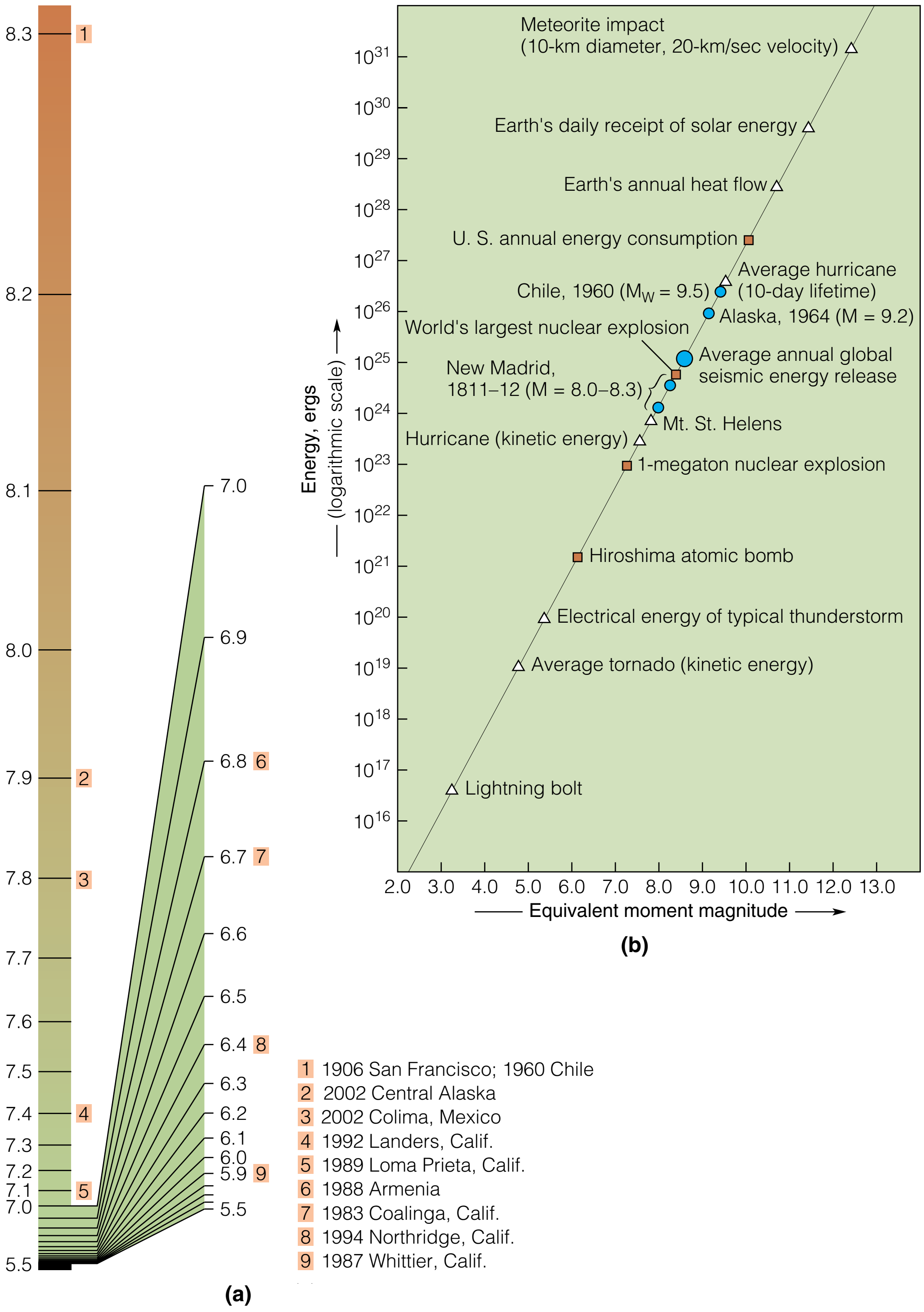
◆ FIGURE 4.10 (a) Isoseismal map of the near-field (close to the epicenter) modified Mercalli scale intensities of the 1994 Northridge, California, earthquake. Intensity-IX values are assigned where there are spectacular partial collapses of modern buildings, destroyed wood-frame buildings, and collapses of elevated freeways (see Appendix 4). (b) Community Internet Intensity Map (CIIM) for the same earthquake. The main difference in appearance is due to the fact that the intensities were not contoured but assigned to ZIP code areas of the respondents. (a) SCEC data (b) USGS

institution that installed the first seismometer in the United States.

## Forensic Use of Seismic Records

Seismic records can be used, in conjunction with other methods, to distinguish between earthquakes and nuclear explosions. The basis for the seismic method is that nuclear explosions are more concentrated in space and time and therefore excite more short-period seismic waves. This method requires extensive analysis of seismograms and is one of the tools that will be used to measure compliance by signers of the Comprehensive Test Ban Treaty. The following are select anomalous seismic events from 1995 to 2003, some of which were believed to be nuclear explosions. Note that the August 12, 2000 event marks the tragic explosion and sinking of the Russian submarine *Kursk*, and the February 1, 2003 event marks the *Columbia* space shuttle disintegration. Although not on this list of special studies compiled by Lynn Sykes of Lamont–Doherty Earth Observatory of Columbia University, the collapse of the Twin Towers on September 11, 2001 was also recorded on seismographs at Lamont–Doherty.

| Location | Date | Type of Event |
|---|---|---|
| Novaya Zemlya | January 13, 1996 | earthquake |
| Kola Peninsula | September 19, 1996 | chemical explosion |
| Germany | September 11, 1996 | mine collapse |
| East Kazakhstan | August 03, 1997 | chemical explosion |
| India | May 13, 1998 | alleged nuclear explosions |
| Novaya Zemlya | September 23, 1999 | alleged nuclear explosion |
| Kursk, Barents | August 12, 2000 | chemical explosion |
| Novaya Zemlya | February 23, 2002 | earthquake |
| U.S. space shuttle *Columbia* | February 01, 2003 | explosion 100 seconds long |



◆ FIGURE 4.11 Earthquake magnitude and energy. (a) Richter magnitudes of nine selected earthquakes, 1906–1994. (b) Equivalent moment magnitudes of energetic human-caused events (*squares*), natural events (*triangles*), and large earthquakes (*circles*). The erg is a unit of energy, or work, in the metric (cgs) system. To lift a one-pound weight one foot requires 1.4 x $10^7$ ergs.

# Seismic Design Considerations

## Ground Shaking

Ground movements, particularly rapid horizontal displacements, are most damaging during an earthquake. Shear and surface waves are the culprits, and the potential for them must be evaluated when establishing design specifications. The design objective for earthquake-resistant buildings is relatively straightforward: structures should be designed to withstand the maximum potential horizontal ground acceleration expected in the particular region. Engineers call this acceleration *base shear,* and it is usually expressed as a percentage of the *acceleration of gravity* ($g$). On earth,

$g$ is the acceleration of a falling object in a vacuum (9.8 m/sec$^2$, or 32 ft/sec$^2$). In your car it is equivalent to accelerating from a dead stop through 100 meters in 4.5 seconds. An acceleration of 1 $g$ downward produces weightlessness, and a fraction of 1 $g$ in the horizontal direction can cause buildings to separate from their foundations or to collapse completely. An analogy is to imagine rapidly pulling a carpet on which a person is standing; most assuredly the person will topple.

The effect of high horizontal acceleration on poorly constructed buildings is twofold. Flexible-frame structures may be deformed from cube-shaped to rhomb-shaped, or they may be knocked off their foundations (◆Figure 4.12). More rigid multistory buildings may suffer "story shift" if floors and walls are not adequately tied together (◆Figure 4.13). The result is a shifting of floor levels and the collapse of one floor upon another like a stack of pancakes. Such structural failures are not survivable by inhabitants, and they clearly illustrate the adage that "earthquakes don't kill people; buildings do."

Damage due to shearing forces can be mitigated by bolting frame houses to their foundations and by *shear walls*. An example of a shear wall is plywood sheeting nailed in place over a wood frame, which makes the structure highly resistant to deformation. Wall framing, usually two-by-fours, should be nailed very securely to a wooden sill that is bolted to the foundation. Diagonal bracing and blocking also provide shear resistance (◆Figure 4.14). L-shaped structures may suffer damage where they join, as each wing of the structure vibrates independently. Such damage can be minimized by designing *seismic joints* between the building wings or between adjacent buildings of different heights. These joints are filled with a compressible substance that will accommodate movement between the structures.

**Wave period** is the time interval between arrivals of successive wave crests, or of equivalent points of waves, and it is expressed as $T$ in seconds. It is an important consideration when assessing a structure's potential for seismic damage, because if a building's natural period of vibration is equal to that of seismic waves, a condition of resonance exists. **Resonance** occurs when a building sways in step with an oscillatory seismic wave. As a structure sways back and forth under resonant conditions, it gets a push in its direction of sway with the passage of each seismic wave. This causes the sway to increase, just as pushing a child's swing at the proper moments makes it go higher with each push. Resonance also may cause a wine glass to shatter when an operatic soprano sings just the right note or frequency.

Low-rise buildings have short natural wave periods (0.05–0.1 seconds), and high-rise buildings have long natural periods (1–2 seconds). Therefore, high-frequency (short-period) waves affect single-family dwellings and low-rise buildings, and long-period (low-frequency) waves affect tall structures. Close to an earthquake epicenter, high-frequency waves dominate, and thus more extensive home and low-rise damage can be expected. With distance from the epicenter, the short-period wave energy is absorbed or dissipated, resulting in the domination of longer-period waves.

**CONSIDER THIS** *Over time, tectonic stresses strain the rocks along a fault and increase the chance of sudden rupture and a potentially damaging earthquake. For this reason, it is generally believed that a region that has had many small earthquakes (magnitude* $<4.0$*) has a low probability for a large earthquake. Question: For a magnitude-7.0 earthquake with a 50-year recurrence interval, how many magnitude-4.0 earthquakes would be required to "balance the energy books"? How many small earthquakes a day is this? Is this belief realistic in a seismically active region based upon your calculations?*

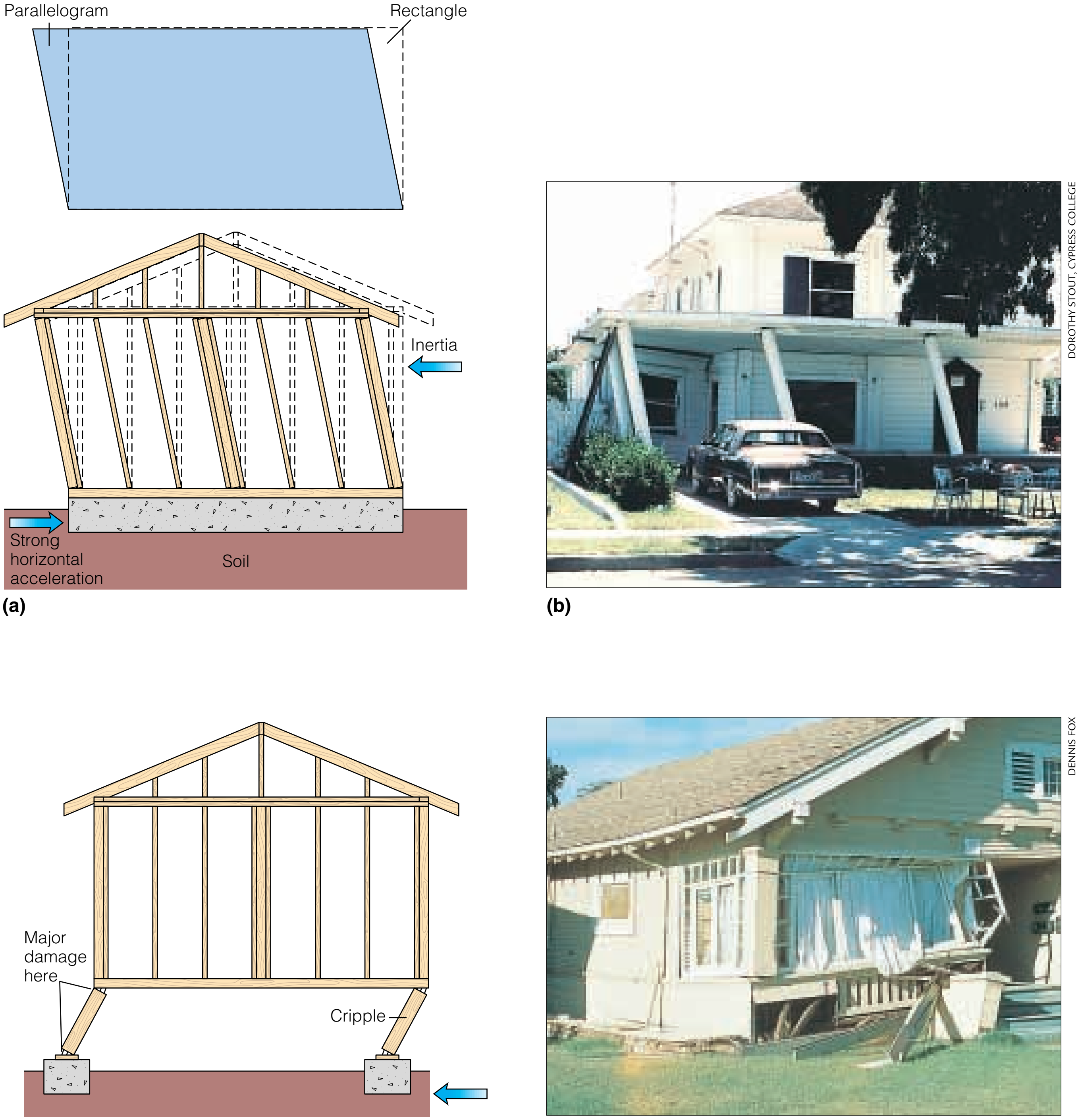
## Landslides

Thousands of landslides are triggered by earthquakes in mountainous or hilly terrain; there were an estimated 17,000 during the Northridge earthquake alone (see ✪ Case Study 4.1 on page 103). The 1989 Loma Prieta earthquake caused landsliding in the Santa Cruz Mountains and adjacent parts of the California Coast Ranges. Such areas are slide prone under the best of conditions, and even a small earthquake will trigger many slope failures. In the greater San Francisco Bay area there was an estimated $10 million damage to homes, utilities, and transportation systems because of landslides and surficial ground failures resulting from the Loma Prieta earthquake.

One of the worst earthquake-triggered tragedies in the United States occurred in August 1959, a short distance from Yellowstone Park. A landslide, in reality a massive rockslide (see Chapter 7), originated on Red Mountain above the Madison River in Montana. The rockslide was triggered by a moderate earthquake that caused the metamorphic rock (schist) composing the mountain to slide down its foliation planes, which were inclined parallel to the hill slopes (◆Figure 4.15). However, the rockslide occurred above a popular campground, and 26 people were killed by the falling rock. The slide generated a terrific shock wave of air that lifted cars, trees, and campers off the ground. In addition, the Madison River was dammed by the slide and a lake formed, later named "Quake Lake."

## Ground or Foundation Failure

**Liquefaction** is the sudden loss of strength of water-saturated, sandy soils resulting from shaking during an earthquake. Sometimes called **spontaneous liquefaction,** it can cause large ground cracks to open, lending support to the ancient myth that the earth opens up to swallow people and animals during earthquakes. Shaking can cause saturated sands to consolidate and thus to occupy a smaller volume. If the water is slow in draining from the consolidated material, the overlying soil comes to be supported only by



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

DOROTHY STOUT, CYPRESS COLLEGE

DENNIS FOX

◆ FIGURE 4.12 (a) Strong horizontal motion may deform a house from a cube to a rhomboid or knock it from its foundation completely. (b) A Coalinga, California, frame house that was deformed by the magnitude-6.3 earthquake in 1983. (c) A cripple-wall consists of short vertical members that connect the floor of the house to the foundation. Cripple-walls are common in older construction. (d) A Watsonville, California, house that was knocked off its cripple-wall base during the Loma Prieta earthquake of 1989. Without exception, cripple-walls bent or folded over to the north relative to their foundations.

JAMES C. ANDERSON, USC

◆ FIGURE 4.13 (Total vertical collapse as a result of "story shift"; Mexico City, 1985. Such structural failures are not survivable.

pore water, which has no resistance to shearing. This may cause buildings to settle, earth dams to fail, and sand below the surface to blow out through openings at the ground surface (◆Figure 4.16a). Liquefaction at shallow depth may result in extensive lateral movement or spreading of the ground, leaving great cracks and openings.

Ground areas most susceptible to liquefaction are those that are underlain at shallow depth—usually less than 30 feet—by layers of water-saturated fine sand. With subsurface geologic data obtained from water wells and foundation borings, liquefaction-susceptibility maps have been prepared for many seismically active areas in the United States.

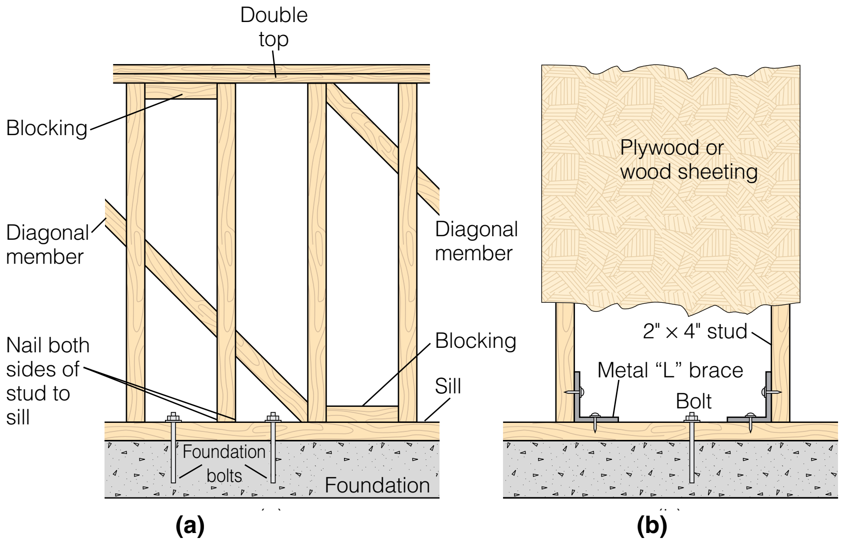
Similar failures occur in certain clays that lose their strength when they are shaken or remolded. Such clays are called *quick clays* and are natural aggregations of fine-grained clays and water. They have the peculiar property of turning from a solid (actually a gel-like state) to a liquid when they are agitated by an earthquake, an explosion, or even vibrations from pile driving. They occur in deposits of glacial-marine or glacial-lake origin and are therefore found mostly in northern latitudes, particularly in Scandinavia, Canada, and the New England states. Failure of quick clays underlying Anchorage, Alaska, produced extensive lateral spreading throughout the city in the 1964 earthquake (◆Figure 4.16b).

The physics of failure in spontaneous liquefaction and in quick clays is similar. When the earth materials are water-saturated and the earth shakes, the loosely packed sand consolidates or the clay collapses like a house of cards. The pore-water pressure pushing the grains apart becomes greater than the grain-to-grain friction, and the material becomes "quick" or "liquifies" (◆Figure 4.17). The potential for such geologic conditions is not easily recognized. In many cases it can be determined only by information gained from bore holes drilled deeper than 30 meters (100 ft). Because of this expense, many site investigations do not include deep drilling, and the condition can be unsuspected until an earthquake occurs.

## Ground Rupture and Changes in Ground Level

Structures that straddle an active fault may be destroyed by actual ground shifting and the formation of a fault scarp (◆Figure 4.18). By excavating trenches across fault zones, geologists can usually locate past rupture surfaces that may reactivate. In 1970 the California legislature enacted the Alquist–Priolo Special Study Zones Act, which was renamed the *Earthquake Fault Zones Act* in 1995. It mandates that all known active faults in the state be accurately mapped and zoned for seismic safety. The act provides funds for state and private geologists to locate the youngest fault ruptures within a zone and requires city and county governments to limit land use adjacent to identified faults within their jurisdic-

◆ FIGURE 4.14 Methods of reinforcing structures against base shear. (a) Diagonal cross-members and blocks resist horizontal earthquake motion (shear). (b) Plywood sheeting forms a competent shear wall, and metal "L" braces and bolts tie the structure to the foundation.




B. PIPKIN

◆ FIGURE 4.15 Pictured is the site of the earthquake-induced rockslide at Red Mountain. The Madison River is just off the picture in the foreground. The rockslide was triggered by an earthquake and took place in schist with foliation planes inclined parallel to the mountain slope (see Chapter 7).

tions. Ironically, the faults responsible for the 1992 Landers earthquake ($M_w = 7.3$) were designated as Earthquake Fault Zones just prior to the June 28 event.

Changes in ground level as a result of faulting may have an impact, particularly in coastal areas that are uplifted or downdropped. For instance, during the 1964 Alaskan event, parts of the Gulf of Alaska thrust upward 11 meters (36 ft), exposing vast tracts of former tidelands on island and mainland coasts.

## Fires

Fires caused by ruptured gas mains or fallen electric power lines can add considerably to the damage caused by an earthquake. In fact, most damage attributed to the San Francisco earthquake of 1906 and much of that in Kobe, Japan, in 1995 was due to the uncontrolled fires that followed the earthquakes. The Kobe quake hit at breakfast time. In neighborhoods crowded with wooden structures, fires erupted when natural-gas lines broke and falling debris tipped over kerosene stoves. Broken water mains made fire-fighting efforts futile. One of the principal "do's" for citizens immediately after a quake is to shut off the gas supply to homes and other buildings in order to prevent gas leaks into the structure. This in itself will save many lives (see Figure 4.41).

## Tsunamis

The most myth-ridden hazard associated with earthquakes (and submarine volcanic eruptions and landslides) is tsunami (pronounced "soo-nah-mee"), or seismic sea waves. **Tsunami** is a Japanese word meaning "great wave in harbor" and it is appropriate because these waves are impulsively generated and most commonly wreak death and destruction inside bays and harbors. They have nothing to do with the tides, even though the term "tidal wave" is commonly used in the English-speaking world. The Japanese written record of tsunamis goes back 200 years and their power is dramatically displayed in the well-known print by Hokusai (◆Figure 4.19). Tsunamis, their causes, and effects are treated in detail in Chapter 10.

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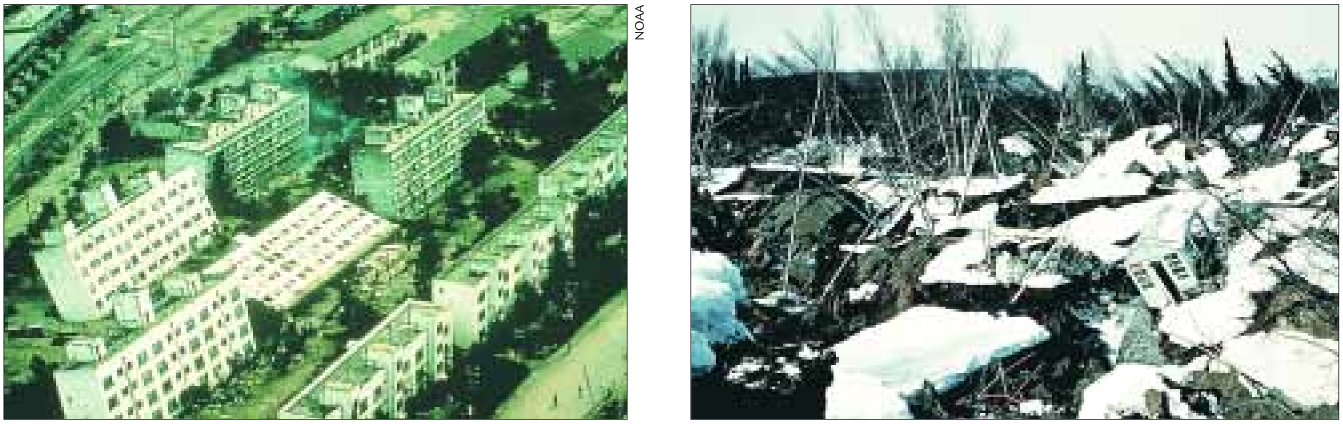
## Four Earthquakes That Make a Point

Each year in the world, on average, there are at least two earthquakes of magnitude 8.0 or greater and 20 earthquakes in the magnitude 7.0 to 7.9 range. Release of seismic energy

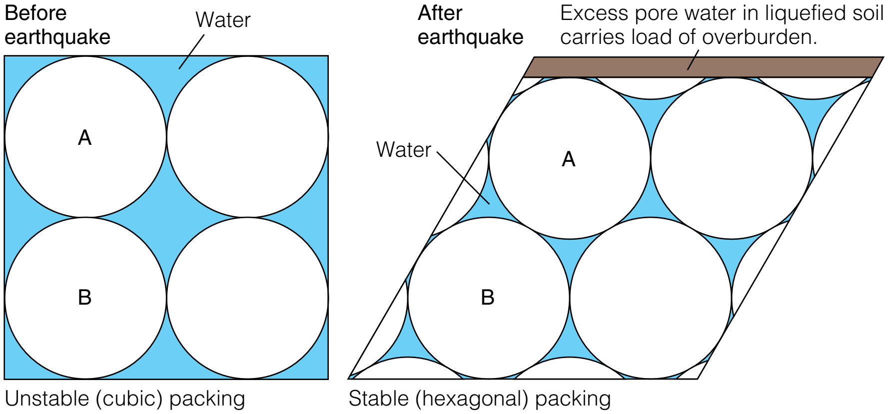

NOAA

NGDC 97

(a)

(b)

◆ FIGURE 4.16 (a) These apartment buildings tilted as a result of soil liquefaction in Niigata, Japan, in 1964. Many residents of the building in the center exited by walking down the side of the structure. (b) "House of cards" collapse of quick clay structure in Turnagain Heights, Anchorage, Alaska in 1964. Total destruction occurred within the slide area, which is now called Earthquake Park.



◆ **FIGURE 4.17** Liquefaction (lateral spreading) due to repacking of spheres (idealized grains of sand) during an earthquake. The earthquake's shaking causes the solids to become packed more efficiently and thus to occupy less volume. A part of the overburden load is supported by water, which has no resistance to lateral motion.

in the form of earthquakes has occurred throughout geologic time, and recorded history contains many references to strong earthquakes. More than 3,000 years of seismicity are documented in China, and Strabo's *Geography* mentions an earthquake in 373 B.C. in Greece. Thus, humans have probably always been subject to earthquakes (✻ Table 4.1).


DAVE JOHNSON

◆ **FIGURE 4.18** The 1992 Landers earthquake ($M_w$ = 7.3) in the Colorado Desert of southern California was felt from Phoenix, Arizona, to Reno, Nevada. Right-lateral offset of 4.27 meters (14 ft) on the Johnson Valley fault created a 2-meter (6.5-ft) vertical scarp due to lateral offset of a ridge. The geologist is 185 cm tall.

This section describes four earthquakes that occurred between 1994 and 2003. All four had very strong magnitudes but had quite different results because of differences in local foundation conditions, building standards, population density, and societal factors. The following is a synopsis of these events.

- A magnitude-7.7 earthquake struck Gujarat, India at 8:46 A.M. on January 26, 2001. It was 60 times more powerful than the Northridge, California, earthquake of 1994 but the death toll was 400 times greater.
- A magnitude-7.9 earthquake struck central Alaska on November 3, 2002. It was on the Denali fault and was one of the largest strike-slip ruptures in Alaska of the past two centuries. One minor injury was reported and the dollar loss was minimal.
- A magnitude-7.8 earthquake struck the state of Colima, Mexico, on January 22, 2003. The destruction was widespread, but the death toll was only 29. The victims were mostly in dwellings that were poorly built and collapsed. Modern high-rise buildings faired well.
- A magnitude-6.7 struck the San Fernando Valley at the community of Northridge on January 17, 1994. It is recognized as the second most costly natural disaster in U.S. history, second only to Hurricane Andrew (see Chapter 10).

## Gujarat, India, 2001

A headline in a well-known American newspaper stated "Bad quake, worse buildings." This just about sums up the impact of this strong event in the state of Gujarat (◆Figure 4.20). It was a reverse-fault earthquake and the closest plate boundary lies many hundreds of kilometers away. It was felt 2000 km away and over an area 16 times that of the $M_w$ = 7.8 San Francisco earthquake of 1906. Field investigation in Gujarat revealed no ground rupture, which is unusual for an earthquake of this magnitude. Liquefaction was widespread because of the high water table and thickness of unconsolidated sediment in the

◆ **FIGURE 4.19** "The Breaking Wave off Kanagawa," wood-block color print by Katsushika Hokusai (1760–1849) from the series "Thirty-six Views of Mount Fuji," 1826–33. Metropolitan Museum of Art, H. O. Havemeyer Collection (JP 1847)

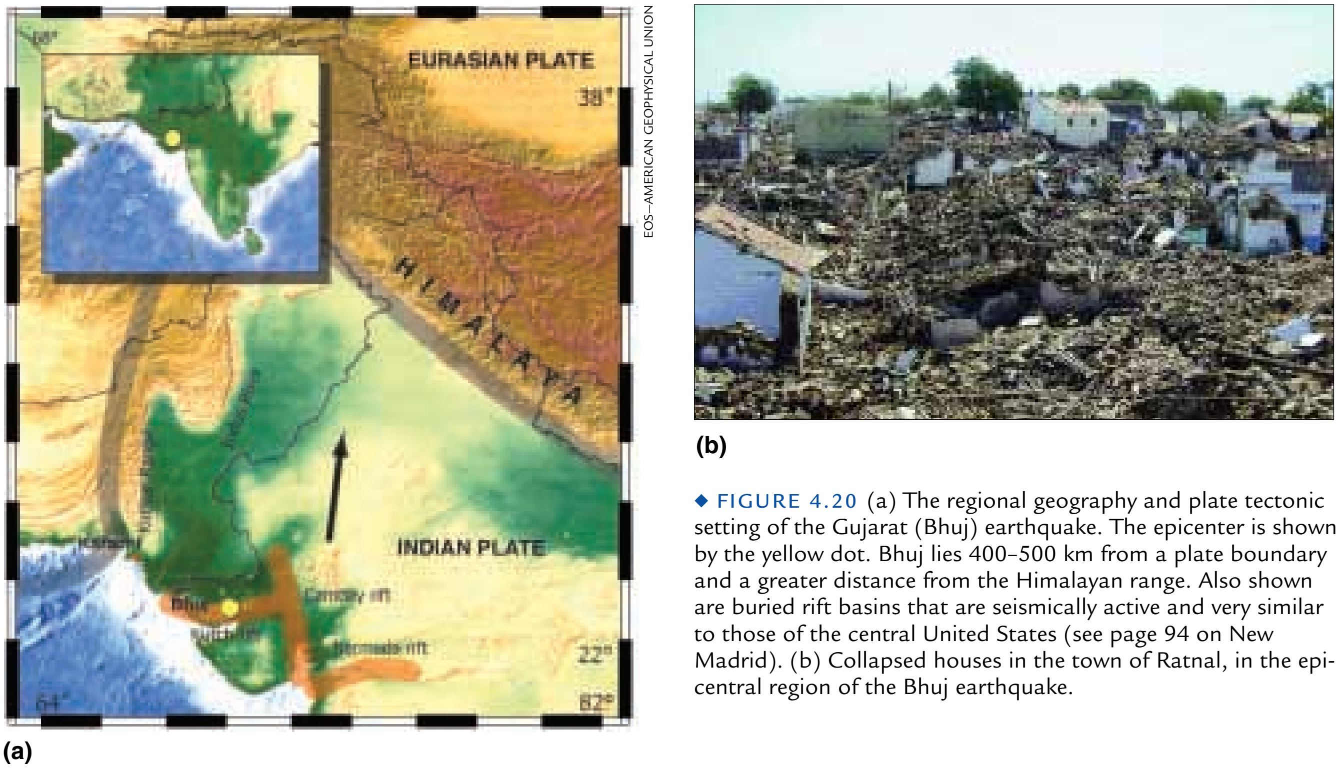
### ∗TABLE 4.1 Selected Significant* World Earthquakes, in Chronological Order

| Location | Year | Richter Magnitude** | Impact |
|---|---|---|---|
| San Francisco | 1906 | 8.3 | 700 killed, $7 million damage, fire |
| Messina (Sicily) | 1908 | 7.5 | 160,000 killed |
| Tokyo, Japan | 1923 | 8.3 | 140,000+ killed, fire |
| Assam, India | 1950 | 8.4 | 30,000 killed |
| Chile | 1960 | $M_w$ 9.5 | 5,700 killed, 58,000 homes destroyed, tsunami |
| Alaska | 1964 | $M_w$ 9.2 | 131 killed, tsunami |
| T'ang-shan, China | 1976 | 7.9 | 330,000 killed |
| Mexico City | 1985 | 8.1 | 10,000+ reported killed |
| Armenia | 1988 | 6.8 | 55,000 killed |
| Loma Prieta (California) | 1989 | $M_w$ 6.9 | 67 killed, $8 billion damage |
| Northridge, California | 1994 | $M_w$ 6.7 | 60 killed, $25 billion damage |
| Kobe, Japan | 1995 | $M_w$ 6.9 | 5,378 killed, $100 billion damage |
| Izmit (Kocaeli), Turkey | 1999 | $M_w$ 7.4 | 15,370 killed, $10–$20 billion damage |
| Chi-Chi, Taiwan | 1999 | $M_w$ 7.6 | 2,300+ killed |
| Gujarat, India | 2001 | $M_w$ 7.7 | Reported 20,000+ |
| Alaska | 2002 | $M_w$ 7.9 | Little impact, no casualties |
| Colima, Mexico | 2003 | $M_w$ 7.8 | Widespread destruction, 27 fatalities |
| Bam, Iran | 2003 | $M_w$ = 6.5 | 30,000 believed killed, 30,00 injured |

*A "significant" earthquake is defined as one that registers a moment magnitude ($M_w$) of at least 6.5 or a lesser one that causes considerable damage or loss of life. The world averages 60 significant earthquakes per year.

**Estimated prior to 1935. $M_w$ = Moment magnitude.

Sources: U.S. Geological Survey: *Earthquakes and Volcanoes;* California Division of Mines and Geology; *Academic American Encyclopedia* (1990, Grolier Electronic Publishing Company).



EOS—AMERICAN GEOPHYSICAL UNION

USGS

◆ FIGURE 4.20 (a) The regional geography and plate tectonic setting of the Gujarat (Bhuj) earthquake. The epicenter is shown by the yellow dot. Bhuj lies 400–500 km from a plate boundary and a greater distance from the Himalayan range. Also shown are buried rift basins that are seismically active and very similar to those of the central United States (see page 94 on New Madrid). (b) Collapsed houses in the town of Ratnal, in the epicentral region of the Bhuj earthquake.

region. The quake occurred in an old rift system, which is a well-known seismic zone that is very similar to parts of the central United States. One doesn't have to be a seismologist to know that an earthquake of this magnitude has real potential to cause devastation. Here, the lack of strict building codes governing construction methods, some of which date back to the British Colonial period, exacerbated the destruction that led to the loss of more than 20,000 lives. Here also, one can become an architect or building contractor without any special education or license. The damage covered an area over 500 km wide from the large city of Ahmedabad in the east to the Arabian Sea in the west. Severe damage was reported within an area 50 km by 70 km in which most high-rises (anything more than 3 stories) and low-rise cobble-stone structures collapsed.

What is surprising to geologists is that this earthquake occurred in an area of relative flat topography without the usual tectonic landforms suggestive of faulting and seismic activity. Strong earthquakes in India usually occur as the Indian plate moves northward against the Himalayas. However, a similar event occurred in 1819 in the Rann of Katchchh, also in the state of Gujarat, just to the southeast of the 2002 earthquake epicenter. This suggests a greater rate of tectonic (earthquake) activity than is indicated by the land forms there.

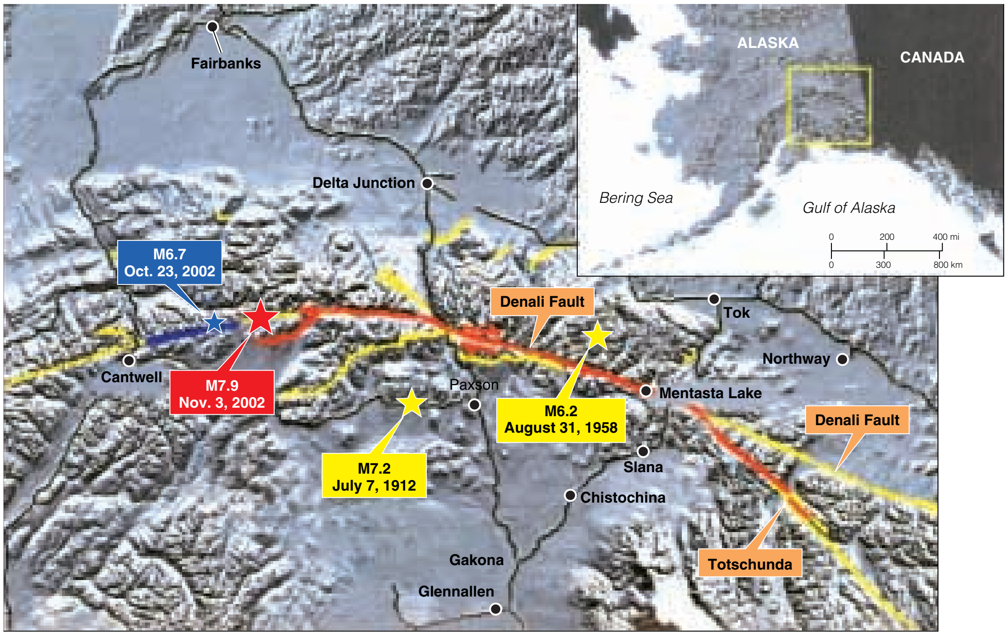
Geologists from the United States are particularly interested in this event because it may serve as an analog for mid-continent earthquakes and the New Madrid, Missouri, seismic zone (Figure 4.30). Major earthquakes are rare in intraplate regions like New Madrid and Gujarat, far from plate edges and the usual seismicity associated with the world's tectonic-plate boundaries. As pointed out, there is little evidence at the ground surface left by these earthquakes. Thus, each intraplate earthquake is an opportunity to study and better understand the hazards posed by these events.

## Alaska, 2002

On November 3 a magnitude-7.9 earthquake occurred some 90 miles south of Fairbanks along the Denali fault (◆Figure 4.21). Denali is the native Tanana word for "high one," and the Denali fault is the most well-known and studied active fault in the state. This earthquake was among the strongest ever recorded in the United States. It shut down the Alaska pipeline, and caused lakes to ripple in Iowa and water to slosh out of swimming pools as far south as Louisiana. The earthquake was shallow and its energy went directly to the surface to produce the distant effects. One resident of Porcupine Creek is quoted as saying "A charging brown bear I can handle. This (the earthquake) scared the heck out of me." Alaska has a history of strong earthquakes, demonstrated in 1964 when the Denali fault ruptured and left 159 dead and many communities in ruins, mostly due to tsunami. This most recent event is a reminder that the fault has a great potential for damage.

## Colima, Mexico, 2003

On January 22 a magnitude-7.8 earthquake struck near the village of Tecoman in the state of Colima (◆Figure 4.22). Twenty-seven people lost their lives in Colima and two more in the adjoining state of Jalisco. In this shallow-focus quake, the epicenter occurred near the junction of three tectonic



(a)

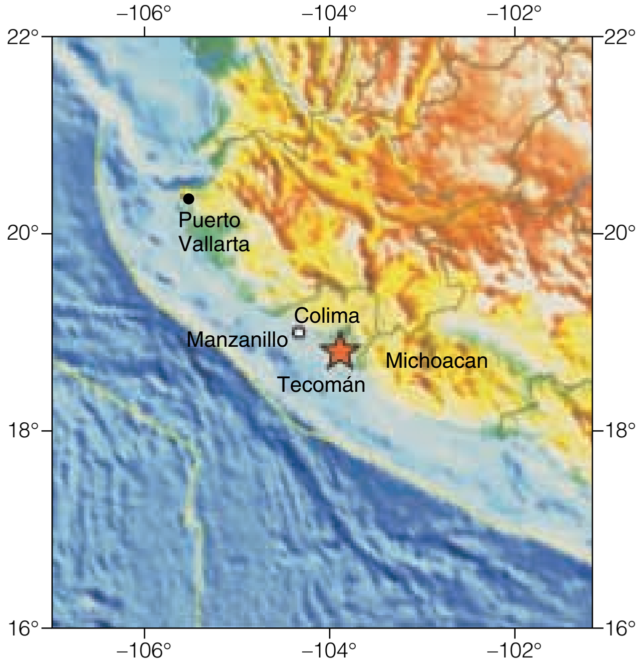
(b)

◆ FIGURE 4.21 (a) The magnitude-7.9 Denali fault earthquake of November 3, 2002, resulted from predominantly right-lateral offset along portions of the Denali and Totschunda fault systems in Alaska. Total length of the surface rupture was about 320 kilometers (200 mi). The western 49 km of the rupture shows mainly low-angle thrust offset as much as 1.5 m, with the northwest side up. Shown here are the epicenters of the November 3 event (red) and the magnitude-6.7 foreshock of October 23, 2002 (blue), as well as two previously recorded large shallow earthquakes (yellow) in the vicinity of the fault. (b) Aerial view of the Trans-Alaska Pipeline System (TAPS) line near the Denali fault, looking west. This is where the pipeline is supported by rails on which it can move freely in the event of fault offset. Here the line has slid toward the west end of the rails. Alyeska Pipeline Service Company reported no breaks to the line and therefore no loss of oil. Out of view to the left (south) is the 2.5 m (ft) right-lateral offset of the highway where it crosses the fault. Photo courtesy of Rod Combellick, Division of Geological and Geophysical Surveys, State of Alaska

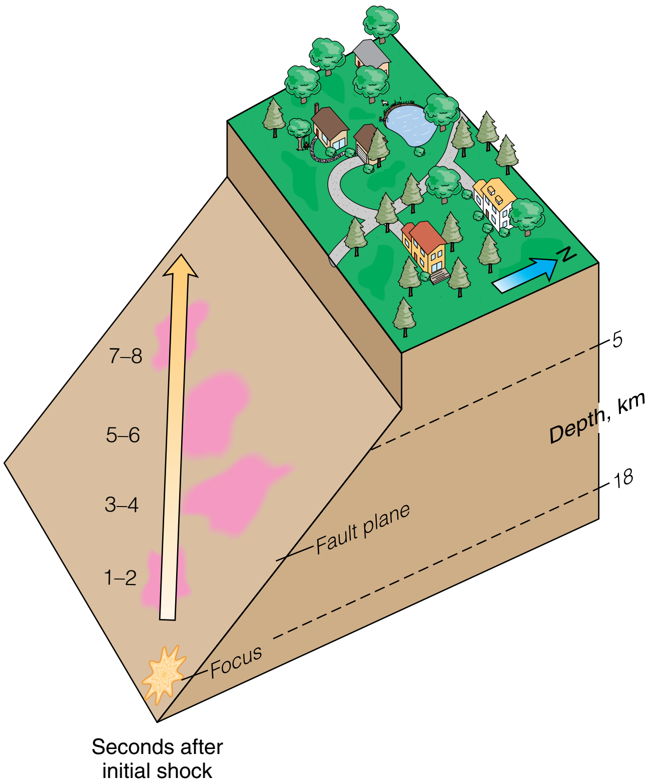
plates: North American plate to the northeast, the Cocos plate to the south, and the Rivera plate to the northwest. Both the smaller plates are being subducted beneath the North American plate, producing significant seismic activity in the region. Twenty of the fatalities occurred in the collapse of adobe-brick houses. Over 150 houses were reported destroyed in the city of 200,000 that dates back to sixteenth-century Spanish colonial times. Mexican structural engineers are very aware of the seismic hazards that exist in this part of the country and are quite good at designing buildings to be earthquake-resistant. As a result, no damage occurred to modern high-rise buildings from this powerful earthquake. However, it was felt strongly and caused some to panic in Mexico City, where an earthquake in 1985 with its epicenter in the same region took over 10,000 lives. Two 20-story buildings in the capital swayed so much that they actually collided, but did little damage.

## Northridge, California, 1994

The largest earthquake in Los Angeles's short history occurred at 4:30 A.M. Monday, January 17, 1994, on a hidden fault below the San Fernando Valley. The $M_w$ = 6.7 earthquake started at a depth of 18 kilometers (11 mi) and propagated upward in a matter of seconds to a depth of 5–8 kilometers (3–5 mi, ◆Figure 4.23). There were thousands of aftershocks, and their clustered pattern indicated the causative fault to be a reverse fault with a shallow dip of 35°



◆ FIGURE 4.22 Magnitude-7.8 earthquake near Tecomán, Colima, Mexico, on January 22, 2003. USGS



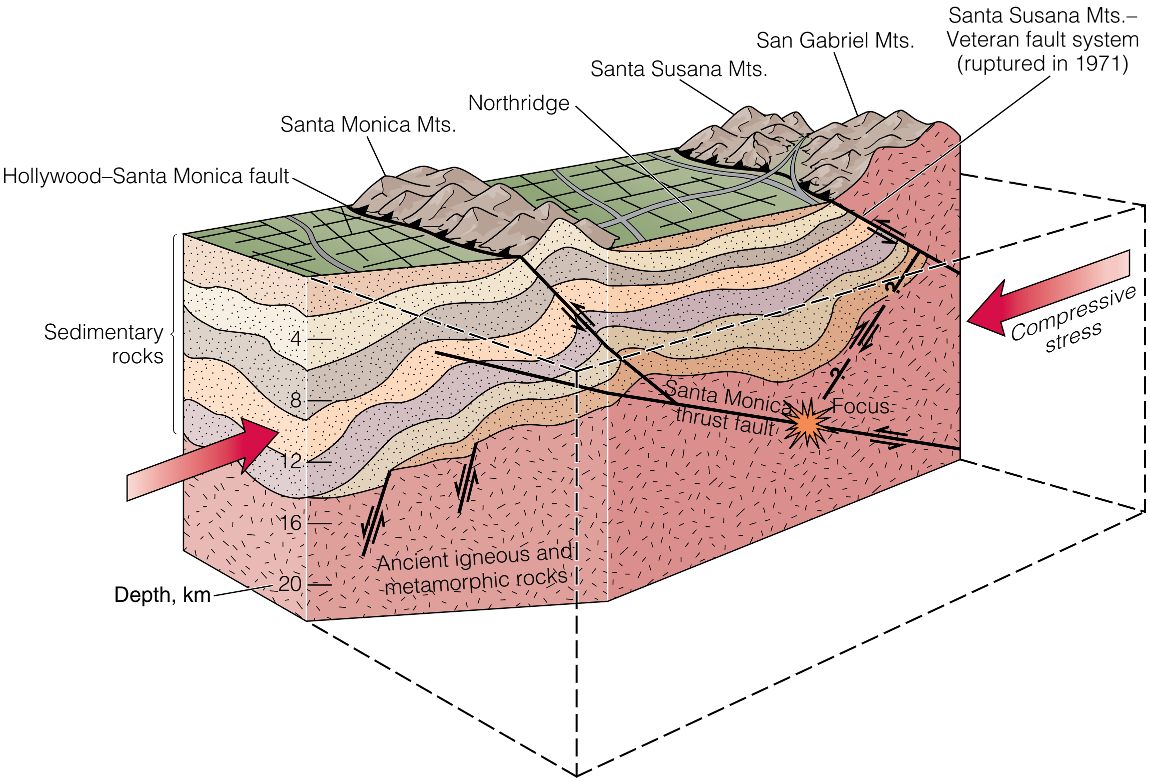
◆ FIGURE 4.23 In the 1994 Northridge earthquake, the fault rupture progressed up the fault plane from the focus at the lower right of the figure to the upper left in 8 seconds. Rather than rupturing smoothly, like a zipper opening, it moved in jerks along the fault plane, as shown by the pink patches. Total displacement was about 4 meters (12 ft).

to the south (Case Study 4.2 and Appendix 3). Such a low-angle reverse fault is called a *thrust fault,* and, because the thrust did not rupture the ground surface, it is described as "blind" (◆Figure 4.24). Blind thrusts were first recognized after the 1987 Whittier earthquake 40 kilometers (25 mi) southwest of Northridge, but they were not fully appreciated until after the Northridge event.

Blind thrust faults were a newly identified seismic hazard, and there is evidence that a belt of them underlies the northern Los Angeles basin. They are especially dangerous because they cannot be detected by traditional techniques such as trenching and field mapping (thus they do not fall within the Earthquake Fault Zones Act as it is written) and yet, as we know now, they can generate significant earthquakes. Just as the residents of earthquake country were beginning to feel confident that geologists knew the location and behavior of most active faults, blind thrusts made their presence known.

Field inspection of the epicentral region was a depressing experience. Thirteen thousand buildings were found to be severely damaged; 21,000 dwelling units had to be ordered evacuated; 240 mobile homes had been destroyed by fire; 11 major freeway overpasses were damaged at 8 locations (✪ Case Study 4.3 on page 104). The reason for the extensive damage was the high horizontal and vertical accelerations generated by the earthquake. Accelerations of more than 0.30 *g* are considered dangerous, and the vertical acceleration of 1.8 *g* measured by an instrument bolted to bedrock in nearby Tarzana probably set a world record. The high ground acceleration explains why many people were literally thrown out of their beds and objects as heavy as television sets were projected several meters from their stands. Although the damage was not as visually spectacular as that at Mexico City in 1985, it was heartbreaking to many residents—brick chimneys, both reinforced with steel bars and unreinforced, came down; houses moved off their foundations; concrete-block walls crumbled; gaps broke open in plaster walls; the number of shattered storefront windows was beyond counting (◆Figure 4.25). The horizontal ground motion was directional; that is, it was strongest in the north–south direction. With few exceptions, block walls oriented east–west tipped over or fell apart, whereas those oriented north–south remained standing. Many two- and three-story apartment buildings built over open first-floor garages collapsed onto the residents' cars. These open parking areas' lack of shear resistance led to failure of the vertical supports, and everything above came down.

California State University at Northridge sustained almost "textbook" earthquake damage. In its library is "Leviathan II," recognized as one of the most advanced automated book-withdrawal systems in the country. On this day it recorded a record withdrawal of about 500,000 books—all of them onto the floor of the library. Bottled chemicals fell



◆ FIGURE 4.24 Interpretation of the fault system in the San Fernando Valley and surrounding area of Southern California. Compressive stresses built up over a long period, causing the subsurface blind thrust fault to rupture. The ensuing Northridge earthquake impacted the entire valley, and extended from the Santa Susana Mountains on the north to the city of Santa Monica on the south. USGS DATA

off their storage shelves (a major concern at any university) and caused a large fire in the Chemistry Building. In addition, one wall of a large open parking structure collapsed inward to produce the stunning art deco architecture seen in ◆Figure 4.25c.

## What We Can Learn

These four earthquakes reinforce the adage that "earthquakes don't kill people, falling buildings kill people." The magnitudes were in the range where destruction is certain if construction methods are not adequate. In Gujarat high-rise structures and stone dwellings alike collapsed due to inadequate design leading to a high death toll. In Alaska, where the population density is about one person per square mile, the strong temblor took no lives and really did minimal damage. On the other hand, the example in Mexico illustrates that even when high population areas are struck by a powerful earthquake, recognition of the importance of seismic design criteria can reduce the loss of life. The Northridge earthquake was an unusual case. There the combination of a blind thrust fault and very high ground accelerations, both vertical and horizontal, combined to cause the extensive damage in Southern California.

It should be noted that other factors beside construction, population density, and kind of fault movement can cause damage. Site effects are extremely important. During the 1989 Loma Prieta (San Francisco) earthquake the ground shaking around the bay area varied considerably. There was liquefaction and widespread destruction in the Marina District, where two-level Interstate 880 was built on bay muds. Near Oakland it shook violently and failed (◆Figure 4.26) causing fatalities, whereas structures in San Francisco built on bedrock suffered much less or no damage. The seismograms shown in ◆Figure 4.27 illustrate this point (also see Case Study 4.3).

Site effects were noted almost 200 years ago when an observer of the New Madrid sequence (next topic) noted "The convulsion was greater along the Mississippi, as well as along the Ohio, than in the uplands. The strata in both valleys are loose. The more tenacious layers of clay and loam spread over the adjoining hills . . . suffered but little derangement" (see Drake, 1815, in For Further Information).

## Does Earthquake Country Include Idaho, Missouri, and New York?

Even though the vast majority of the world's earthquakes occur at plate boundaries, areas hundreds and even thousands

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GREG DAVIS, USC

GREG DAVIS, USC

◆ FIGURE 4.25 (a) Two wings of an apartment building that collapsed toward one another. (b) A staircase that leads to nowhere. In reality, it was the second-floor breezeway that collapsed onto the ground floor. (c) Part of the collapsed parking structure of Fashion Center, Northridge. Such collapses instigated new design criteria for open structures. Note the outside staircase that separated from the main structure.

of kilometers away are not free of seismic activity. In the United States the five most seismically active states between 1980 and 1991 were

|  | Earthquakes 1980–1991 |  |
|---|---|---|
| **State** | **Number Recorded** | **Largest, $M_w$** |
| Alaska | 10,253 | 9.2 |
| California | 6,732 | 7.2 |
| Washington | 615 | 5.5 |
| Idaho | 536 | 7.3 |
| Nevada | 398 | 5.6 |

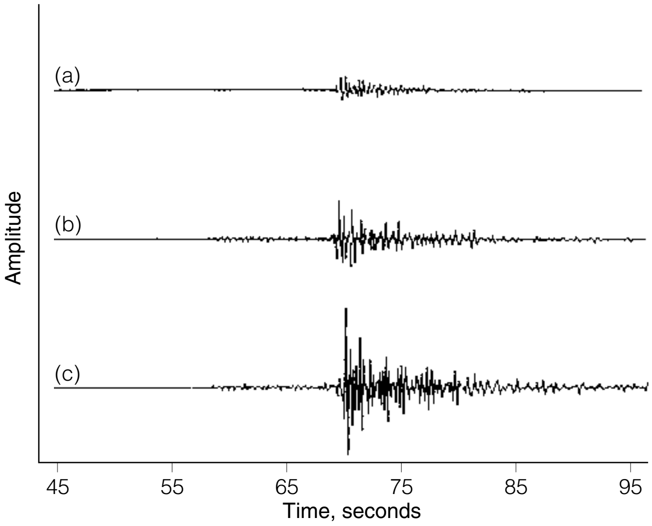
Although Alaska and California continue to lead the United States in the number of shakers, the earthquakes that have been felt over the largest area occurred in Missouri in 1811 and 1812, and significant seismic hazards are recognized in 39 states. No state is earthquake proof, as the seismic-risk map of the United States shows (◆Figure 4.28). It appears that U.S. residents who want to be seismically safe should move to Texas, Florida, or Alabama.

Why do such strong earthquakes occur *intraplate*—that is, far from a plate boundary (✻ Table 4.2)? Intraplate earthquakes have several characteristics in common (see also the Gujarat earthquake, this chapter):

1. The faults causing them are deeply buried and have not broken the ground surface.

DENNIS FOX

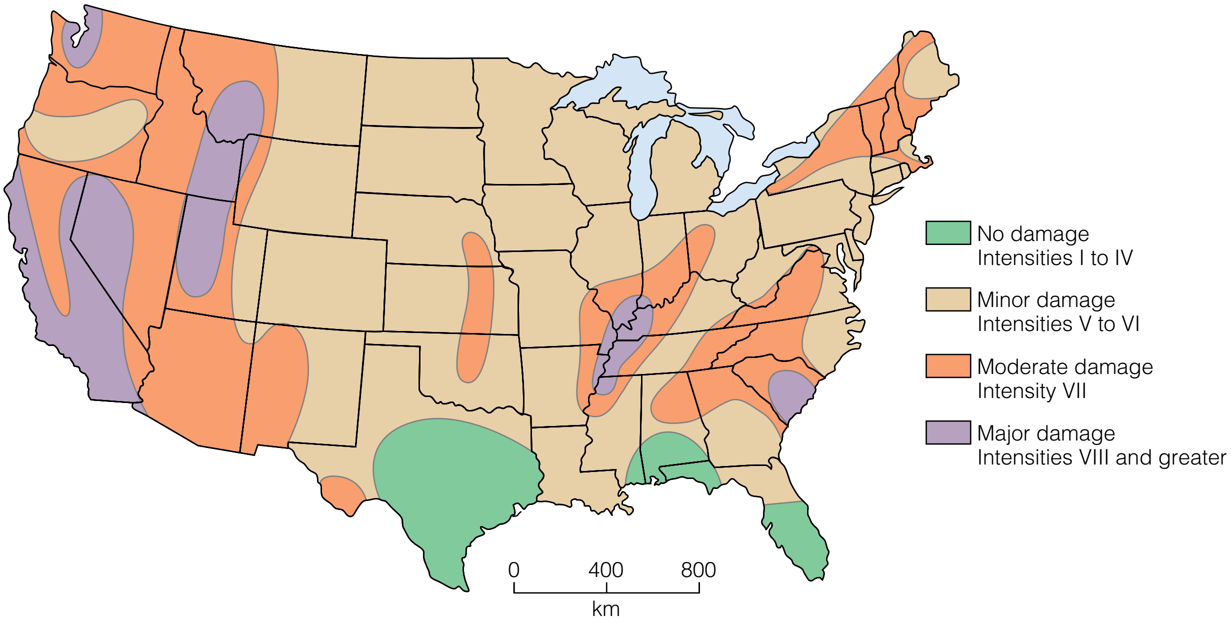
◆ FIGURE 4.26 The I-880 freeway failed because it was built on bay muds that reacted to seismic waves like a bowl of gelatin. Pictured is the Cypress Street viaduct with the upper deck collapsed upon the lower one. There was loss of life here.



◆ FIGURE 4.27 Seismograms for a magnitude-4.1 aftershock as recorded on (a) firm bedrock, (b) alluvium (stream-deposited sediment), and (c) areas of fill and bay muds. This is where the most damage occurred in the San Francisco earthquakes of 1906 and 1989. Data from EOS—American Geophysical Union

2. Because the rocks of the continental interior are stronger than those at plate boundaries, which are laced with faults, they transmit seismic waves better, causing ground motion over a huge area. In the United States this is usually many states (◆Figure 4.29).
3. They do not appear to be random events.

The Charleston, South Carolina, earthquake of 1886 was larger than the 1989 San Francisco shaker. It killed scores of people, ruined the city, and slowed the South's recovery from the Civil War. The New Madrid (pronounced "mad´rid") earthquakes of 1811 and 1812 caused extensive topographic changes, locally reversed the course of the Mississippi River, and may have been felt over a larger area than any other earthquake in recorded history. Ground motion was felt as far away as Washington, D.C., where it caused church bells to ring and scaffoldings on the Capitol to collapse.



◆ FIGURE 4.28 Seismic-risk map of the 48 contiguous states based upon historical records and intensities collected by the U.S. Coast and Geodetic Survey. The Coast and Geodetic Survey gathers intensity data from questionnaires after earthquakes. From M. L. Blair and W. W. Spangle, USGS prof. paper 941-B, 1979

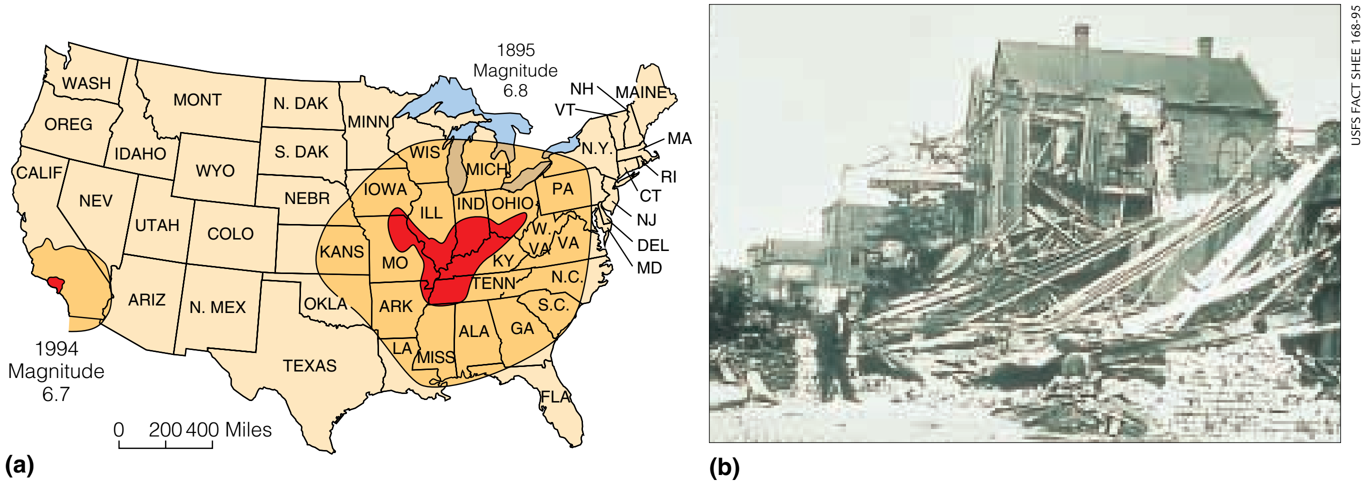
∗TABLE 4.2 Selected North American Intraplate Earthquakes

| Location | Year | Moment Magnitude* | Impact |
|---|---|---|---|
| New Madrid, Missouri | 1811 | 8.2 | Reelfoot Lake formed in NW Tennessee. |
| New Madrid | 1812 | 8.3 | Elevation changes caused Mississippi River to reverse its course locally. |
| New Madrid | 1812 | 8.1 | |
| Charleston, South Carolina | 1886 | 7.6 | Felt from New York to Chicago; 60 killed. |
| Charleston, Missouri | 1895 | 6.8 | Damage in 6 states (see Figure 4.28). |
| Grand Banks, Newfoundland | 1929 | 7.4 | Submarine landslides broke trans-Atlantic cable, disrupting communications. |

*Moment magnitude is used in reconstructing the strength of "preinstrument" earthquakes, because we know something of fault length, rupture length, and area felt.

Recent studies suggest that intraplate earthquakes are concentrated in areas where normally stable crust has been stretched and faulted. Such zones form where continents have been split apart *(rifted),* forming two continents, as occurs at divergent plate boundaries (see Chapter 3). When North America was separated from Africa at the Mid-Atlantic Ridge about 180–200 million years ago, the continental crust being rifted at the ridge was thinned, stretched, and faulted. The North American continent was transported westward with the plate, and the weakened part of the crust along its eastern edge was hidden by a thick cover of younger sedimentary rocks. Buried rifted crust under the Eastern seaboard states forms the intraplate earthquake zone from the Carolinas to Canada.

The Midwest earthquake zone through Arkansas, Missouri, and Illinois is believed to be where an ancient (pre-Pangaea) divergent boundary started to form but "failed" for some reason, leaving behind a significant buried fault zone. Known as the *Reelfoot Rift,* the buried block of crust is downdropped between faults (the hachured lines on the map of ◆Figure 4.30). The rift is 60 kilometers wide and 300 kilometers long (roughly 40 mi × 190 mi) and formed at least 500 million years ago. The linear trend of earthquakes from Marked Tree, Arkansas, northeastward to Caruthersville, Missouri, reveals upwarped sedimentary rocks along the rift axis. Detailed analysis of the geology across the Reelfoot fault scarp by trenching revealed evidence of three large earthquakes within the past 2,000 years, which yields a recurrence-interval estimate of 600–900 years for the fault, but the recurring earthquakes are not necessarily of the same magnitude as the 1811–1812 events. In fact, scientists estimate that a magnitude-6–7 earthquake will occur in the New Madrid seismic zone between 2000 and 2050 with a 90 percent probability.



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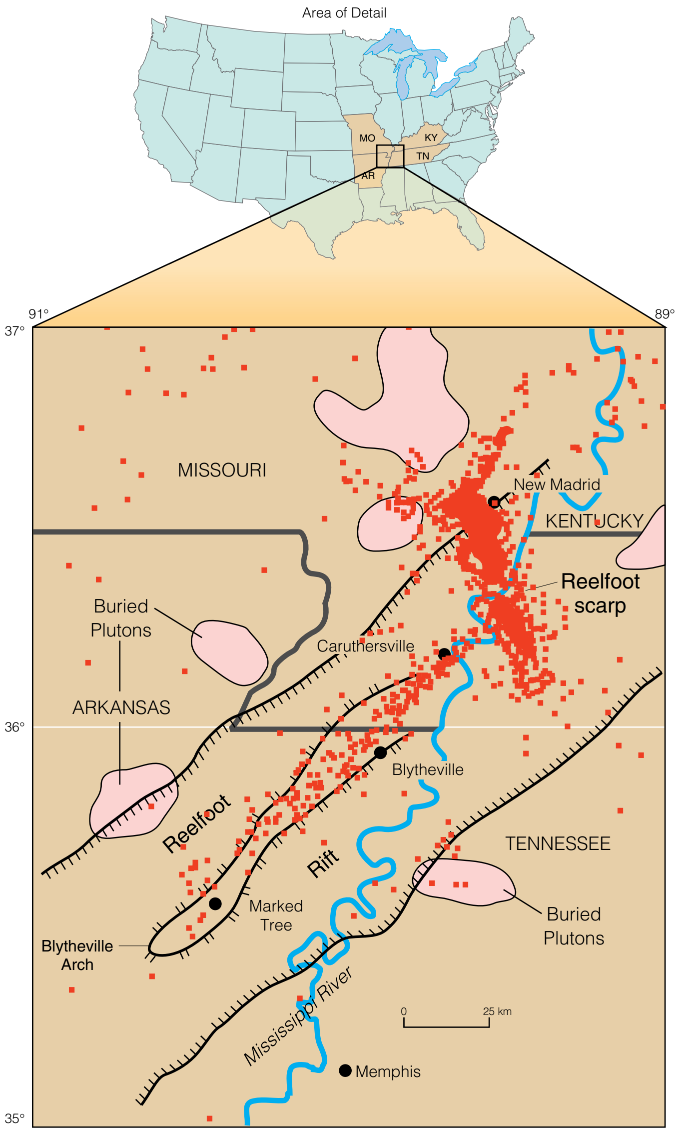
◆ FIGURE 4.29 Mid-continent earthquakes. (a) Comparison of the effects of two earthquakes of similar magnitude. The 1895 Charleston, Missouri, earthquake impacted a relatively huge area in the central United States, whereas the 1994 Northridge earthquake's effects were limited to Southern California. Red indicates areas of minor-to-major damage to buildings and their contents. Yellow indicates areas where shaking was felt but there was little or no damage to objects, such as dishes. (b) Damage from the 1886 earthquake along East Bay Street in Charleston, South Carolina.



◆ FIGURE 4.30 The New Madrid seismic zone covers parts of four states and consists of an ancient, fault-bounded depression (rift) buried below 1.5 kilometers (almost a mile) of sedimentary rocks. An area of major seismic hazard, it is studied intensively. USGS DATA

Nobody knows how many people died in the 1811–1812 earthquakes. An amateur observer in Louisville, Kentucky, recorded almost 2,000 shocks with a homemade pendulum. Liquefaction was widespread along the Mississippi River, and the town of New Madrid, Missouri, was completely destroyed when it settled from 8 meters (25 ft) above sea level to only 4 meters (12 ft). Subsidence caused some swamps to drain and others to become lakes; an example is Reelfoot Lake in northwest Tennessee, which today is more than 50 feet deep. The New Madrid seismic zone is a major geologic hazard in the United States, and efforts are being made to reduce the impact of a future large earthquake there.

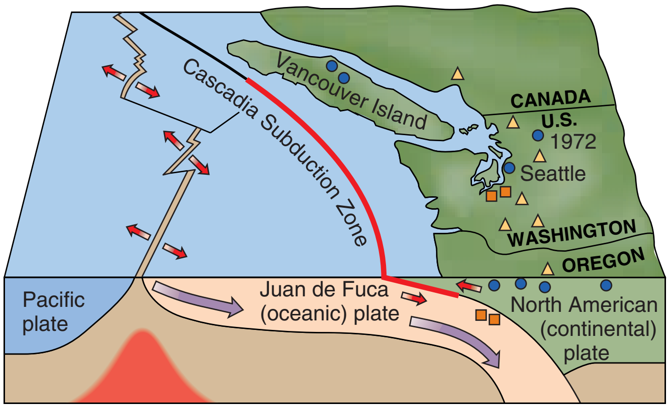
Iben Browning, a scientist with a Ph.D. in physiology but who is best-known for his work on climate, predicted there would be a repeat of the 1811 New Madrid earthquake on December 3, 1990. His prediction was based upon alignment of the planets and consequent gravitational pull, which he believed would be sufficient to trigger an earthquake on that date. Although the prediction was discounted by scientists, it created considerable anxiety in Arkansas, Tennessee, Alabama, and Missouri. Months before "the day," earthquake insurance sales boomed, moving companies were booked up, and bottled-water sales rose dramatically—as did sales of quake-related souvenirs. One church sold "Eternity Preparedness Kits," and "Survival Revivals" were held. On the day of the scientifically discredited prediction nothing earthshaking occurred.

Many earthquakes with epicenters in weakened intraplate continental crust have shaken parts of the Midwest, eastern Canada, New England, New York, and the East Coast of the United States. New York does not have a major fault, but it has many faults. In the 1980s an earthquake in Westchester County ($M = 4.0$) toppled chimneys and caused enough panic for the state to implement new seismic codes that added 2–5 percent to building costs. In April 2002 the state experienced a magnitude-5.1 shaker that centered 15 miles southwest of Plattsburgh near the Canadian border. It rattled dwellings from Maine to Maryland and left cracks in foundations and chimneys. There were no injuries. The point here is that a relatively small intraplate earthquake can be felt over a huge area. By the mid 1990s New York and Massachusetts were the only Northeastern states that had earthquake building codes.

## The Pacific Northwest

In years past, earthquake hazards were considered minor in Oregon and Washington. During the 1980s research changed the perception, however; it revealed geologic evidence that "major" (≥7.0 but <8.0) or "great" (≥8.0 but <9.0) subduction-zone earthquakes have occurred in the past and that they can occur in the future. The Cascadia subduction zone (◆Figure 4.31), extending 1,200 kilometers (740 mi) from northern California to Vancouver Island in Canada, has destructive earthquake potential. Geological evidence, consisting of carbon-dated tsunami deposits and drowned red-cedar forests, suggests that great earthquakes strike the Pacific Northwest roughly every 500 years, the last one in A.D. 1700, approximately 300 years ago. Minor earthquakes occur daily, however, and the cities of Portland, Seattle, and Vancouver, British Columbia, are in earthquake country (◆Figure 4.32). The states now are working to minimize damage should the "big one" occur on the subduction zone or on the Seattle fault, which runs through downtown Seattle.

The year 2000 marked the tricentennial of the last great (equal to or greater than $M = 8.0$) earthquake generated along the Cascadia Subduction Zone. To commemorate this, almost 100 earth scientists and public officials gathered at Seaside, Oregon, to assess the seismic hazard posed by the



■ Deep earthquakes (>65 km or 40 mi deep)* occur when the oceanic plate descends beneath the continental plate. The largest deep earthquakes in recent times were in 1949 ($M = 7.1$) and in 1965 ($M = 6.5$).

● Shallow earthquakes (<17 km or 10 mi deep)* are caused by faults in the North American continent. Magnitude 7+ earthquakes have occurred along the Seattle fault in 1872, 1918, and 1946.

— Subduction earthquakes are huge quakes that occur when the subduction boundary ruptures. The most recent Cascadia Subduction Zone earthquake was 1700 and it sent a tsunami as far as Japan.

*Shallow and deep do not refer to focus of quake; rather, depth is subjective and is related to damage caused by faults in the Seattle area.

◆ FIGURE 4.31 Faults and epicenters in the Seattle, Washington and Vancouver, British Columbia area. USGS

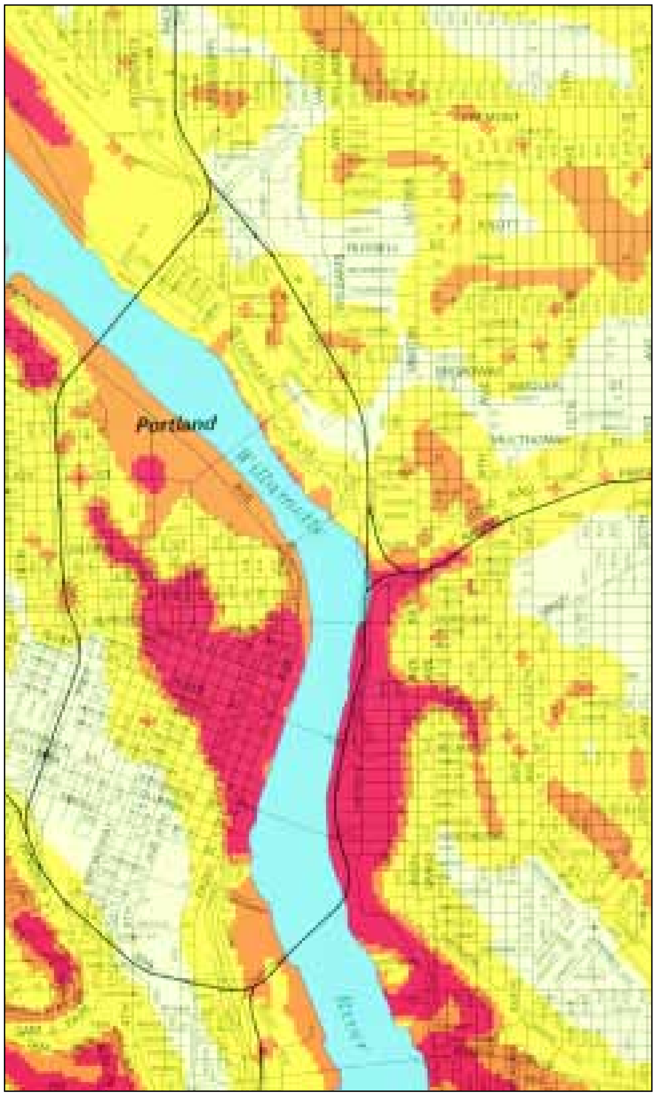
Cascadia Subduction Zone. Besides ways to mitigate great loss of life, selected major points of agreement were:

- Most of the 1100 km of the subduction zone ruptured on January 26, 1700. A correlative tsunami struck Japan and the characteristics of the wave suggest a $M_w$ of 9.0.
- Cascadia earthquakes generate tsunami, the most recent of which was about 10 meters high based on studies of the inundation zone.
- Strong ground shaking from a $M_w$ −9.0 earthquake will last three minutes or more and will be damaging as far inland as Vancouver, Portland, and Seattle.
- The recurrence interval for an event equivalent to the 1700 earthquake is 500–600 years.

Twenty years ago scientists were debating whether great earthquakes occurred at subduction zones. Now there are few doubters, and the 2000 meeting spent a great deal of time and effort in discussing methods of mitigating loss of life and damage. It is ironic that the conference hotel lies within the inundation zone of the 1700 tsunami.

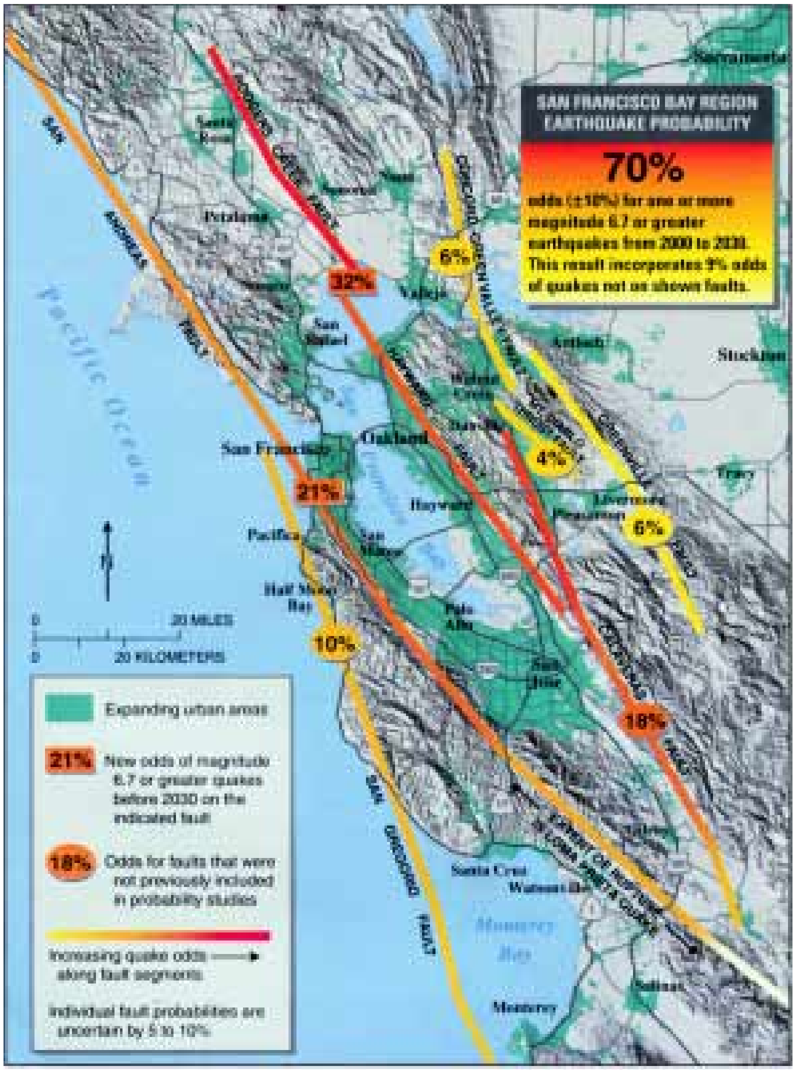
## Prediction

*A guy ought to be careful about making predictions. Particularly about the future.*
Yogi Berra, baseball player



◆ FIGURE 4.32 Seismic-hazard map of downtown Portland, Oregon. The hazard zones are based upon liquefaction potential, landslide potential, and the probable degree of ground shaking. Red denotes greatest hazard; pale yellow, the lowest hazard. Oregon Dept. of Geology and Mineral Industries

Earthquake prediction has the great potential for saving lives and reducing property damage. A good prediction gives the location, time, and magnitude of a future earthquake with acceptable accuracy. Prediction was the hottest area of geophysical and geological research from the 1970s to the early 1990s, based upon the belief that measurable phenomena occurring before large and small earthquakes called **precursors** could be identified. Researchers studied earthquakes and seismograms where presumed precurors were seen. Such things as changes in the ratio of P-wave and S-wave velocities, ground tilt, water-well levels, and emission of noble gases in ground water were measured and piles of data were accumulated. Unfortunately, the hope of finding precursors that would lead to reliable predictions seems to have evapo-



USGS, MODIFIED AND UPDATED

◆ FIGURE 4.33 Probabilities that one or more magnitude-6.7 or greater earthquakes will strike on specific faults in the San Francisco Bay region between 2000 and 2030. The San Andreas, Rogers Creek, and Hayward faults have the highest probabilities. Total probability for the region is computed as 70% (+ or − 10%). These probabilities were developed by scientists with the U.S. Geological Survey, part of the U.S. Department of the Interior, and thus constitute official long-term *forecasts.* The message is that all communities in the Bay region should keep preparing for earthquakes.

rated. In fact, the U.S. Geological Survey is on record as saying that the prospect of earthquake prediction is very dismal. In short, earthquakes cannot be predicted because the mechanics of earthquake generation are, with the present state of our knowledge, too complicated to predict.

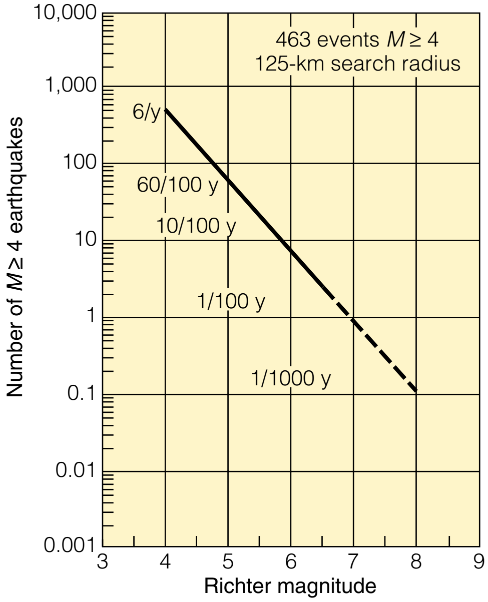
## Forecasts

We are familiar with weather forecasts and are aware that accuracy declines as the time span of the prediction becomes longer. We can usually rely on one-week forecasts, but a year ahead would be asking too much. The same can be said of earthquakes, only in reverse. There is an old saying in geology that "the longer it has been since the last earthquake, the sooner we can expect the next one."

A new approach is to evaluate the probability of a large earthquake occurring on an active fault during a given time period. This falls under the heading of long-term forecasting. An example of this is the U.S. Geological Survey and other scientists' conclusion that there is a 70 percent probability of at least one magnitude-6.7 or greater earthquake striking the San Francisco Bay region between 2000 and 2030. Such an event would be capable of causing widespread damage (◆Figure 4.33). Such forecasts are made on the basis of measured plate tectonic motion and slip on faults. The inexorable movement of the Pacific plate past the North American plate loads strain on the San Andreas network. Periodically this strain is released on one of the faults in the system and an earthquake occurs.

## Statistical Approach

By compiling statistical evidence pertaining to past earthquakes in a region, we acquire basic data for calculating the statistical probability for future events of given magnitudes. These calculations may be done on a worldwide scale or on a local scale, such as the example in ◆Figure 4.34. Analysis of the graph indicates that for the particular area in Southern

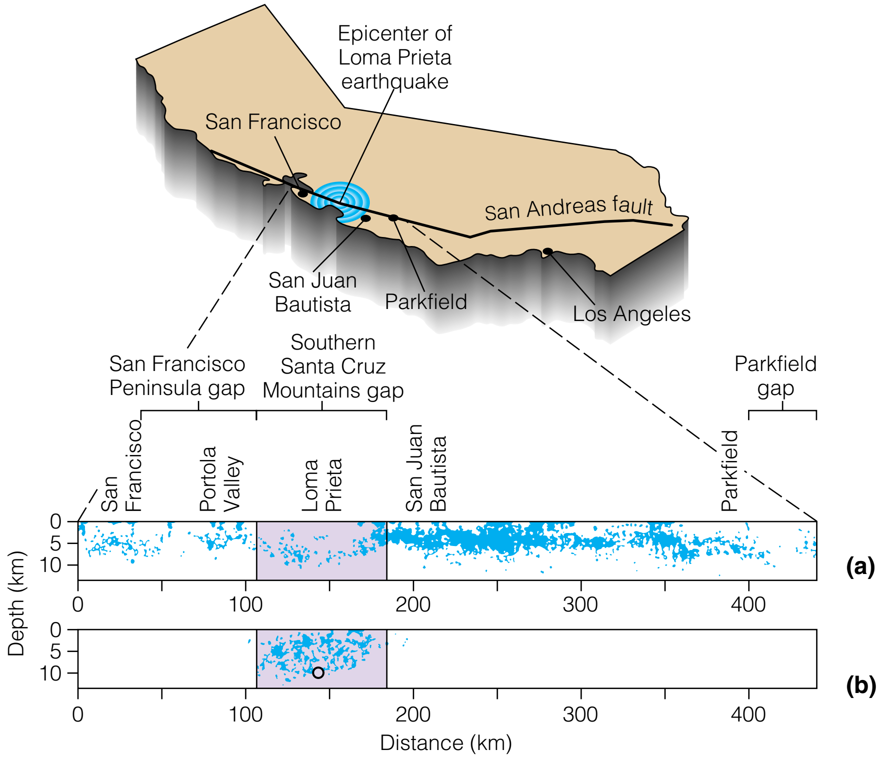


◆ FIGURE 4.34 A graphing of 463 earthquakes of magnitude 4 or greater in a small area near a nuclear reactor in Southern California over a period of 44 years. Statistically, the graph shows that 600 magnitude-4 earthquakes can be expected in 100 years, or 6 per year on average. The probability of a magnitude-8 earthquake in 100 years is 0.1, which would be 1 in 1,000 years. Such plots can be constructed for a region or for the world. The graphs are all similar in shape; only the numbers differ.

California, the statistical **recurrence interval**—that is, the length of time that can be expected between events of a given magnitude—is 1,000 years for a magnitude-8 earthquake (0.1/100 years), about 100 years for a magnitude-7 earthquake (1/100 years), and about 10 years for a magnitude-6 earthquake (almost 10/100 years). The probability of a magnitude-7 occurring in any one year is thus 1 percent, and of a magnitude-6, 10 percent. On an annual basis worldwide, we can expect at least two magnitude-8 earthquakes, 20 magnitude-7 earthquakes, and no less than 100 earthquakes of magnitude 6. Thus for seismically active regions, historical seismicity data can be used to calculate the *probability* of damaging earthquakes. Although these numbers are not really of predictive value as we defined it, they can be used by planners for making zoning recommendations, by architects and engineers for designing earthquake-resistant structures, and by others for formulating other life- and property-saving measures.

**CONSIDER THIS** *Humans have caused earthquakes by injecting fluids, such as oil-field waters and chemical warfare wastes, into deep wells. How does this open the possibility of controlling earthquake activity, and what might be a major deterrent to the effort?*

◆ FIGURE 4.35 (a) Historic seismic activity of about 450 kilometers (275 mi) of the San Andreas fault south of San Francisco before the 1989 Loma Prieta earthquake. The southern Santa Cruz Mountains seismic gap, where Loma Prieta is located, is highlighted. Other seismic gaps apparent in this historical record at the time were one between San Francisco and the Portola Valley and one southeast of Parkfield. (b) Seismicity record of the Southern Santa Cruz Mountains portion of the fault after the 1989 earthquake. The former seismic gap had been "filled" by the earthquake (*open circle*) and its aftershocks.



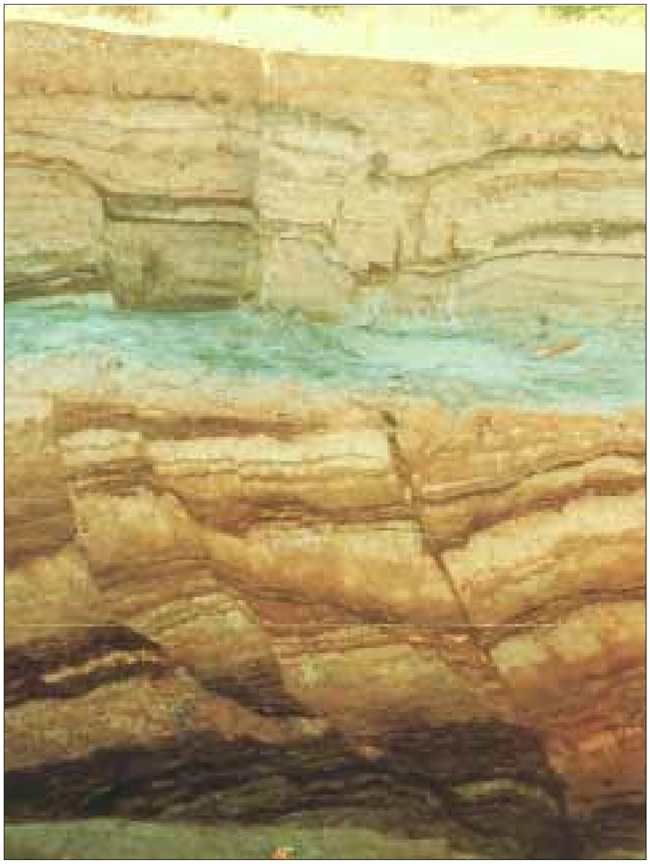
## Geological Methods

Research suggests that active faults and segments of long, active faults tend to have recurring earthquakes of characteristic magnitude, rupture length, and displacement. For example, six earthquakes have occurred along the San Andreas fault at Parkfield since 1857 (Figure 4.35). They had Richter magnitudes of around 5.6, rupture lengths of 13–19 kilometers (8–12 mi), and displacements averaging 0.5 meter. These earthquakes have recurred about every 22 years since the earliest recorded earthquake. A 95 percent probability of an earthquake was predicted for this segment between 1988 and 1993, the first prediction in the United States to be endorsed by scientists and subsequently issued by the federal government. The prediction was a failure.

Geophysical and seismological precursors, as noted previously, have not proved to be reliable predictors of earthquakes. Seismic gaps, however, can indicate stretches of future fault activity. Seismic gaps are stretches along known active fault zones within which no significant earthquakes have been recorded. It is not always clear whether these fault sections are "locked" and thus building up strain energy, or if motion (creep) is taking place there that is relieving strain. Such gaps existed and were "filled" so to speak during the Mexico City (1985), Loma Prieta (1989; Figure 4.35), and Izmit (1999) earthquakes. Seismic gaps serve as alerts or warnings of possible future events and can be used as forecasting tools.

Since recorded history in North America is short, geologists need other means of collecting frequency data of large prehistoric earthquakes. One method is to dig trenches into marsh or river sediments that have been disrupted by faulting in an effort to decipher a region's **paleoseismicity,** its rock record of past earthquake events. Kerry Sieh of the California Institute of Technology has done this across the San Andreas in Southern California (◆Figure 4.36). Sieh found an intriguing history of seismicity recorded in disrupted marsh deposits at Pallett Creek and liquefaction effects extending from the seventh century to a great earthquake in 1857. Ten large events, extending from A.D. 650 to 1857, were dated using $^{14}$C. The average recurrence interval for these ancient earthquakes is 132 years, but they are clustered in four groups. Within each cluster, the recurrence interval is less than 100 years, and the intervals between the clusters are two to three centuries in length. The last big one, also the last one of a cluster, was in 1857. Thus it appears that this section of the San Andreas may remain dormant until late in the twenty-first century or beyond.

Earlier in this chapter we quoted a geologist saying about earthquake prediction that "the longer it's been since the last earthquake, the sooner we expect the next one." Unfortunately, this is about the status of our present predictive ability. We remain uncertain that a quake will follow well-defined percursory phenomena, such as wave velocity changes or anomalous animal behavior (see ✪ Case Study 4.4 on page 106). It seems that no one phenomena is a predictor, and many changes will have to be monitored over a long period of time before our knowledge of fault behavior is refined enough for reliable prediction.


KERRY E. SIEH, SEISMOLOGICAL LABORATORY, CIT

◆ FIGURE 4.36 Disrupted marsh and lake deposits along the San Andreas fault at Pallett Creek near Palmdale, California. Sediments range in age from about A.D. 200 at the lower left to A.D. 1910 at the ground surface. Several large earthquakes are represented here by broken layers and buried fault scarps.

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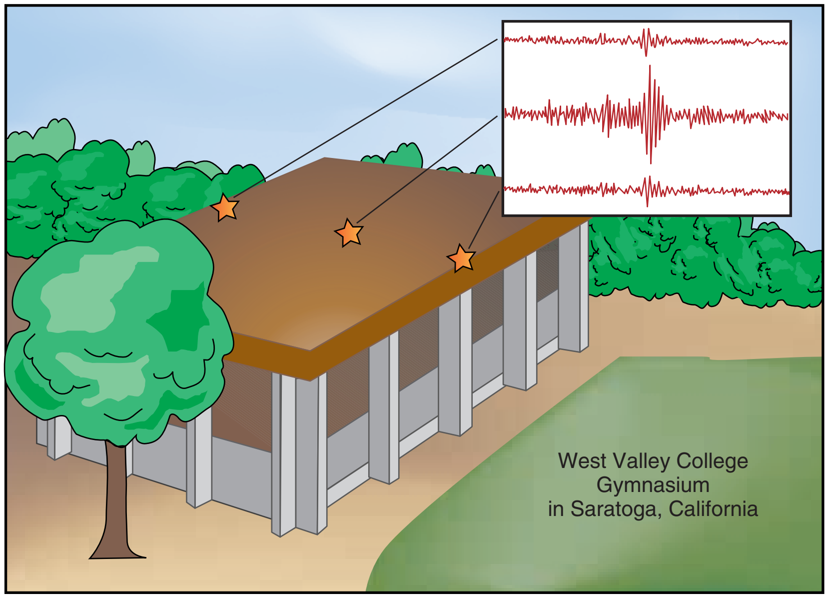
# Mitigation

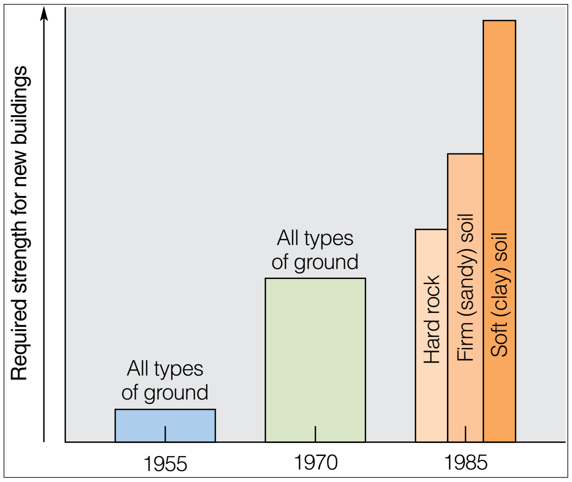
Reducing earthquake risks is an admirable goal of scientists and lawmakers. Building codes provide the first line of defense against earthquake damage and help to ensure the public safety. It has been shown that strict building codes in seismic regions, such as the Pacific Rim, reduce damage and loss of life. Laws passed after the 1933 (Long Beach) and 1971 (Sylmar) California earthquakes have proven the effectiveness of strict earthquake-resistant design. A good example is the magnitude-6.2 Morgan Hill (California) earthquake that

◆ FIGURE 4.37 Seismic records (upper right) obtained during the 1984 Morgan Hill, California, earthquake led to an improvement in the Uniform Building Code (a set of standards used in many states). The center of the gym roof shook sideways three to four times as much as the edges. The code has since been revised to reduce the flexibility of such large-span roof systems and thereby improve their seismic resistance. USGS



shook West Valley College 20 miles from the epicenter. Seismic instruments on the gymnasium showed that the roof was so flexible that in a strong seismic event it could collapse (◆Figure 4.37). Flexible roofs were permitted by the code at that time and many gyms and industrial buildings were built that way. As a result of the experience at West Valley College the Uniform Building Code was revised—this is the code used by hundreds if not thousands of municipalities across the country. The revision requires that the roofs be constructed to be less flexible and thus able to withstand nearby or strong distant earthquakes. Most large cities in strong earthquake zones have their own building codes, patterned after the Uniform Building Code, that require construction to modern seismic standards. For instance, ground response due to differing soil types is now more appreciated as contributing to quake damage. ◆Figure 4.38 shows how the code has evolved from 1955 as we obtained more information. For example, soft clays react more violently with earthquake waves than do, say, granites, and this difference in response is now taken into consideration.

The primary consideration in earthquake design is to incorporate resistance to horizontal ground acceleration, or "base shear." Strong horizontal motion tends to topple poorly built structures and to deform more flexible ones. In California, high-rise structures are built to withstand about 40 percent of the acceleration of gravity in the horizontal



◆ FIGURE 4.38 Earthquake requirements in building codes have increased over time as scientists and engineers have obtained new information. Note that recent codes specify separate criteria for different ground types. USGS data


D. D. TRENT

◆ FIGURE 4.39 Salt Lake City and County Building, Utah. Constructed in 1890, largely of brick, it is now seismically retrofitted to meet the modern building code.

◆ FIGURE 4.40 Basement of the Salt Lake City and County Building. The building has been seismically retrofitted by cutting the massive structure from its foundation pillars (one shown on the far left, another in the center of the photograph), and lifting the building onto 440 large rubber isolators (one left of center, another at the extreme right of the photograph).

direction (0.4 *g*), and single-family dwellings are built to withstand about 15 percent (0.15 *g*). *Base isolation* is now a popular design option. The structure, low- or high-rise, is placed upon Teflon plates, rubber blocks, seismic-energy dissipators that are similar to auto shock absorbers, or even springs, which allows the ground to move but minimizes building vibration and sway.

The ultimate earthquake resistance for large buildings is provided by "base isolation." The century-old Salt Lake City and County Building (◆Figure 4.39), scheduled at the time for demolition, was cut from its foundation and retrofitted with 440 rubber base isolators. These permit the structure to move as a single unit during an earthquake while the ground shakes in all directions (◆Figure 4.40). About seventy-five percent of Utah's population live near the Wasatch Range and the fault responsible for the uplift. The retrofit of older public buildings is an example of the awareness of earthquake hazards by government officials and the public. In this case it saved an architectural treasure for future generations.

## Survival Tips

Knowing what to do before, during, and after an earthquake is of utmost importance to you and your family.

### Before an Earthquake:

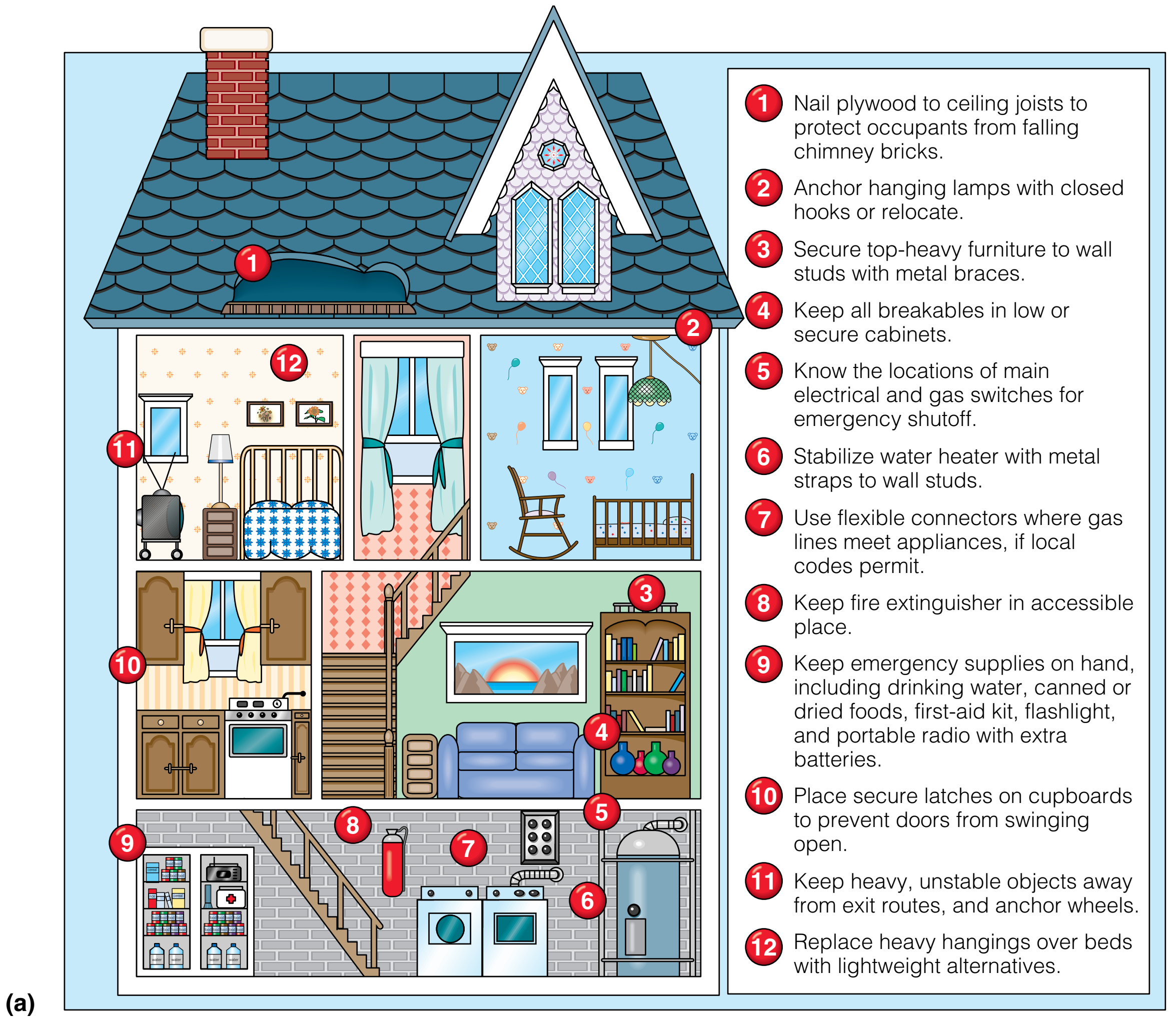
◆Figure 4.41 provides the Federal Emergency Management Agency's (FEMA) suggestions for minimizing the possibility of damage, fire, and injuries in the home.

### During an Earthquake:

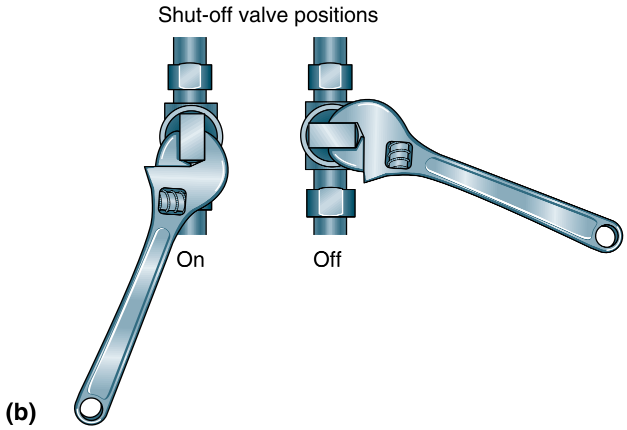
- Remain calm and consider the consequences of your actions.
- If you are indoors, stay indoors and get under a desk, bed, or a strong doorway.
- If you are outside, stay away from buildings, walls, power poles, and other objects that could fall. If driving, stop your car in an open area.
- Do not use elevators, and if you are in a crowded area, do not rush for a door.

### After an Earthquake:

- Turn off the gas at the meter.
- Use portable radios for information.
- Check water supplies, remembering that there is water in water heaters, melted ice, and toilet tanks. Do not drink waterbed or pool water.
- Check your home for damage.
- Do not drive.



1. Nail plywood to ceiling joists to protect occupants from falling chimney bricks.
2. Anchor hanging lamps with closed hooks or relocate.
3. Secure top-heavy furniture to wall studs with metal braces.
4. Keep all breakables in low or secure cabinets.
5. Know the locations of main electrical and gas switches for emergency shutoff.
6. Stabilize water heater with metal straps to wall studs.
7. Use flexible connectors where gas lines meet appliances, if local codes permit.
8. Keep fire extinguisher in accessible place.
9. Keep emergency supplies on hand, including drinking water, canned or dried foods, first-aid kit, flashlight, and portable radio with extra batteries.
10. Place secure latches on cupboards to prevent doors from swinging open.
11. Keep heavy, unstable objects away from exit routes, and anchor wheels.
12. Replace heavy hangings over beds with lightweight alternatives.



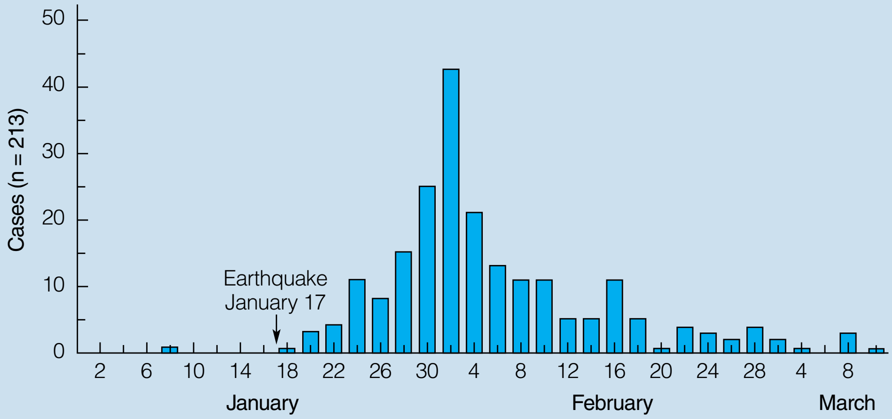
◆ FIGURE 4.41 (a) How to minimize earthquake damage in the home in advance. (b) Keep a small crescent wrench at the gas meter. Turn off the gas by turning the valve end 90°. FEMA

## CASE STUDY 4.1

# Earthquakes, Landslides, and Disease

Dynamically induced landslides are not particularly newsworthy, even though the 1994 Northridge earthquake caused 17,000 of them. However, the soil dislodged during sliding caused an outbreak of *coccidioidomycosis* (CM), commonly known as "valley fever." Endemic to the Southwest, the disease causes persistent flu-like symptoms and in extreme cases can be fatal. The victims breathe in airborne *Coccidioides immitis* spores that are released from the solid during sliding. From January 24 to March 15, 166 people were diagnosed with valley fever symptoms in Ventura County, up from only 53 cases in all of 1993. Most of the cases were reported from the Simi Valley, an area in which only 14 percent of the county's population resides (◆Figure 1).

Large clouds of dust hung over the Santa Susana Mountains for several days after the earthquake, promoted by the lack of winter rains preceding the quake. During this period, pressure-gradient winds known locally as "Santa Ana" winds of 10–15 knots (11–17 mph) blew into the Simi Valley, carrying in spore-laden dust from the Santa Susana Mountains to the northeast. Researchers believe that the more "coherent" metamorphic rocks of the San Gabriel Mountains northeast of the San Fernando Valley probably account for the lack of cases reported in the epicentral region. This is the first report of an earthquake-associated outbreak of valley fever, even though many earthquakes have occurred in CM endemic areas.



◆ FIGURE 1 Histogram of the almost-epidemic outbreak of coccidioidomycosis (valley fever) in Ventura County in early 1994 following the Northridge earthquake.

## CASE STUDY 4.2

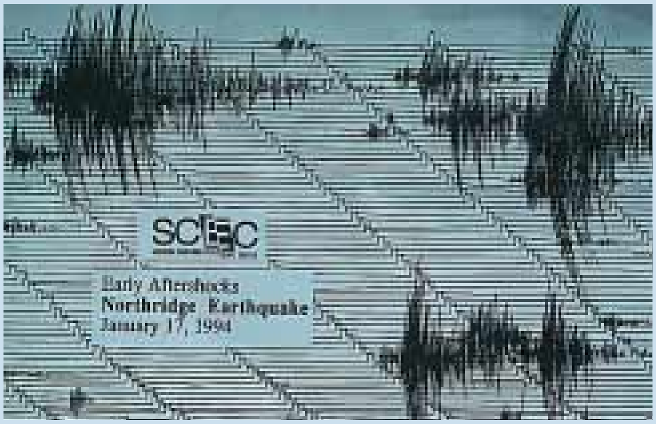
# Predictable "Future Shocks"

A large earthquake is normally followed by thousands of smaller-magnitude earthquakes known as aftershocks (◆ Figure 1). If the main shock is small—say in the magnitude-4.0–5.0 range—aftershocks are small and nonintimidating. Following Northridge-size and bigger earthquakes, however, the strongest aftershocks (*M* = 5.0–6.0 at Northridge) can cause buildings damaged by the main earthquake to collapse and, even worse, can greatly increase anxiety in the already damaged psyche of the local citizenry. Aftershocks are caused by small adjustments (slips) on the causative fault or on other faults close to the causative one. For example, try this: push the eraser on the end of a lead pencil across a desktop. You'll find that it does not slide smoothly; it moves in jerky jumps and starts. This is called "stick–slip" and it is what happens along faults that are adjusting after a big earthquake.

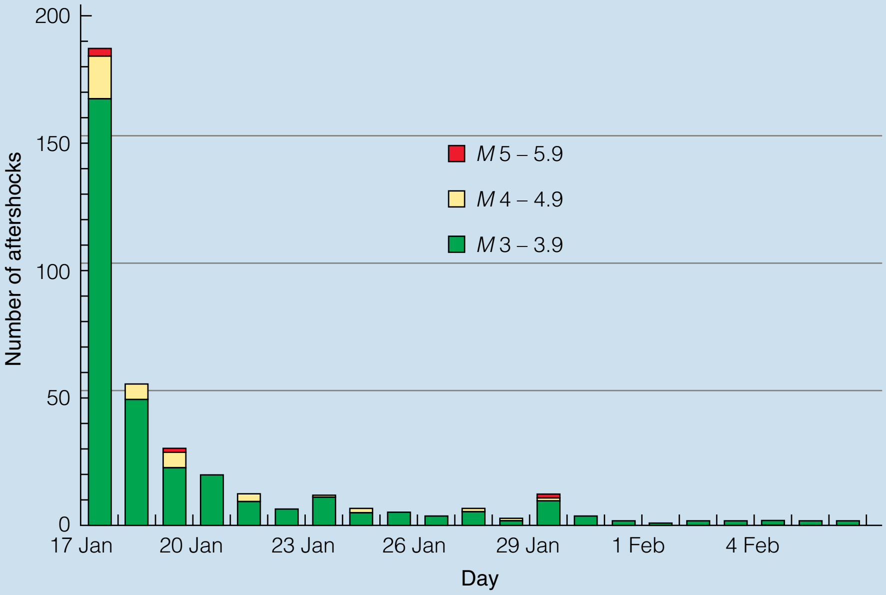
Los Angeles experienced 2,500 aftershocks in the week following the

CONTINUED

Northridge earthquake. Three strong ones, magnitude 5 or greater, occurred the first day. The largest (*M* = 5.6) occurred eleven hours after the main shock, causing concern among rescuers digging for victims beneath the rubble and the already traumatized citizens. Aftershocks follow statistically predictable patterns, as exemplified by the Northridge sequence. On the first day there were 188 aftershocks of magnitude 3 or greater, and on the second day only 56 were recorded (◆Figure 2). By fitting an equation to the distribution of aftershocks during the first few weeks, seismologists were able to estimate the number of shocks to be expected in the future. Statistically, there was a 25 percent chance of another magnitude-5 or greater aftershock occurring within the following year, but it did not happen.



◆ FIGURE 1 Seismogram of early aftershocks following the Northridge earthquake, one of them a magnitude-5.6. Southern California Earthquake Center (SCEC)



◆ FIGURE 2 Daily record of aftershocks of magnitude 3.0 to 5.9 during the three weeks following the main shock at Northridge. Note the sharp drop in aftershock frequency in the first four days. Redrawn from F. Harp and R. Jibson, USGS

## CASE STUDY 4.3

## Rx for Failed Freeways

Extensive damage to freeway bridges and overpasses typically accompanies earthquakes in large urban areas. Such damage has occurred in Alaska, California, and Japan. Overpass damage commonly is due to failure of the shorter columns, which lack the flexibility of longer ones. During an earthquake the tall columns supporting a bridge or overpass system bend and sway with the horizontal forces of the quake. Because the parts of the overpass system are tied together, the stresses are transferred through the structure to the short columns, which are designed to bend only a few centimeters (◆Figure 1). Failure causes the short columns to bulge just

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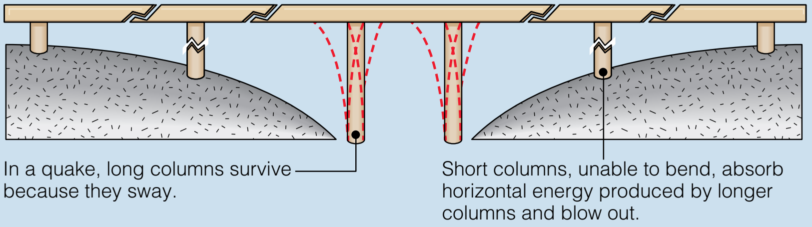
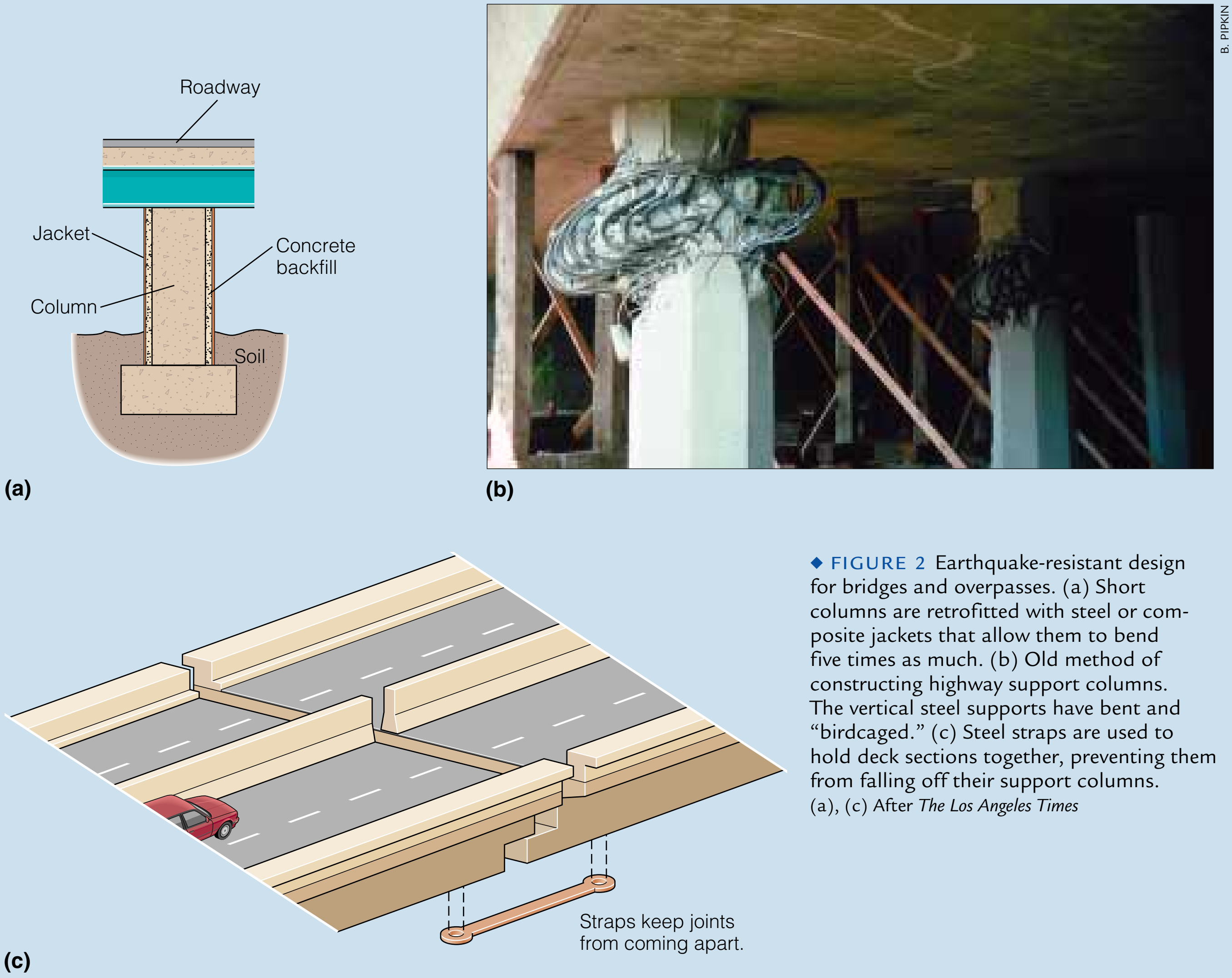
◆ FIGURE 1 The difference in long and short columns' flexibility results in failure of the short ones.



above ground level, which breaks and pops off the exterior concrete, exposing the warped, "birdcaged" steel in the interior. In addition, high vertical accelerations can cause some columns to actually punch holes through the platform deck. With excessive horizontal motion some deck spans may slip off their column caps at one end and fall to the ground like tipped dominoes.

The California Department of Transportation in 1971 decided to retrofit 122 overpasses to alleviate these problems. One aspect of the retrofitting was jacketing the short columns with steel or a composite substance and filling the space between the jacket and the original column with concrete (◆Figure 2a). This allows the columns to bend 12.5 centimeters (5 in), instead of 2.5 centimeters (1 in), without shattering. Another solution is to increase columns' horizontal strength by wrapping heavy steel rods around their vertical support bars, particularly on short columns. This allows the columns to bend but prevents "birdcaging" or permanent bending (◆Figure 2b). To prevent the decks from slipping off their supports and dropping to the ground, steel straps or cables are installed at the joints (◆Figure 2c). Of the 122 overpasses that CalTrans retrofitted, not one collapsed in the 1994 Northridge earthquake. Ten of the eleven that collapsed were slated for future retrofitting.



◆ FIGURE 2 Earthquake-resistant design for bridges and overpasses. (a) Short columns are retrofitted with steel or composite jackets that allow them to bend five times as much. (b) Old method of constructing highway support columns. The vertical steel supports have bent and "birdcaged." (c) Steel straps are used to hold deck sections together, preventing them from falling off their support columns.

(a), (c) After *The Los Angeles Times*

CASE STUDY 4.4

## Depressed Tigers, Restless Turtles, and Earthquakes!

Anomalous animal behavior preceding earthquakes is well documented. Domesticated animals such as barnyard fowl, horses, cats, and dogs have been known to behave so peculiarly before big events that they attracted the notice of people not knowledgeable in what is normal or abnormal animal behavior (◆ Figure 1). Remember that although anomalous animal behavior precedes many earthquakes, it does not appear to precede every earthquake, and abnormal animal behavior is not always followed by an earthquake. Other natural phenomena, such as atmospheric disturbances, also can cause animals to behave strangely. Here are some reported incidents of unusual animal behavior noted before earthquakes:

- Tientsin Zoo, China, 1969: 2 hours before the magnitude-7.4 earthquake the tiger appeared depressed, pandas screamed, turtles were restless, and the yak would not eat.
- Haicheng, China, 1975: 1½ months before the magnitude-7.3 earthquake, snakes came out of hibernation; 1–2 days before, pigs would not eat and they climbed walls; 20 minutes before, turtles jumped out of the water and cried.
- Tokyo, Japan, 1855: 1 day before the magnitude-6.9 earthquake wild cats cried, and rats disappeared.
- Concepción, Chile, 1835: 1 hour and 40 minutes before the earthquake, flocks of sea birds flew inland, and dogs left the city.
- San Francisco, 1906: dogs barked all night before the magnitude-8.3 earthquake.
- Friuli, Italy, 1976: 2–3 hours before the magnitude-6.7 earthquake, cats left their houses and the village, mice and rats left their hiding places, and fowl refused to roost.

B. PIPKIN

◆ FIGURE 1 Anomalous animal behavior. An earthquake may be in the offing if your dog dons a hard hat.

# Earthquakes Are Hard on Cars

The sight of cars buried beneath a pile of bricks and rubble after an earthquake seem to be standard fare for the press. We captured a few of these scenes just by coming upon them and hope you feel, as we do, that there is a light side to most bad natural disasters. The other photos were just too unusual or amusing to pass up.

B. PIPKIN

◆ FIGURE 1 This luxury car seems to be pursuing the garage in which it is normally kept. The house and garage slid down the hillside, but the car was parked with its rear wheels on the driveway, which was on stable ground. Nobody was hurt; Northridge, 1994

FREDERICK LARSON, *SAN FRANCISCO CHRONICLE*

◆ FIGURE 2 A row of cars in need of body-and-fender work because their owners were asleep in the apartment building at the time of the earthquake; Northridge, 1994

B. PIPKIN

◆ FIGURE 3 Earthquakes have no respect for “No Parking” signs; State University–Los Angeles, California, 1971

YI-BEN TSAI, NATIONAL CENTRAL UNIV., TAIWAN

◆ **FIGURE 4** One hundred yard . . . dash? The September 21, 1999 earthquake ($M_w$ = 7.8) in Taiwan was caused by movement on the Chelungpu fault. This running track at Kuang Fu High School was built across the fault that here had a vertical offset of 2.5 meters (8.1 ft). It is obvious that no 100-meter-dash records will be broken here.

◆ **FIGURE 5** The Hector Mine earthquake of October 16, 1999 was a real bomb! The magnitude-7.0 event occurred in California's remote Mojave Desert. The fault scarp, shown here, forms a gash across the desert for 40 kilometers (25 mi), but the earthquake did little damage. This area happens to be a U.S. Marine Corps bombing range, as you can see, which made geologists' field work interesting.

TED REEVES, CHAFFEY HIGH SCHOOL, UPLAND, CALIF.

# Summary

## Earthquakes

### Cause

Movements on fractures in the crust known as *faults* that result in three types of wave motion: P- and S-waves, which are generated at the focus of the earthquake and travel through the earth, and surface waves.

### Distribution

Most (but not all) large earthquakes occur near plate boundaries, such as the San Andreas fault, and represent the release of stored elastic strain energy as plates slip past, over, or under each other. Intraplate earthquakes can occur at locations far from plate boundaries where deep crust has been faulted, probably at "failed" continental margins.

### Measurement Scales

Some of the scales used to measure earthquakes are the modified Mercalli intensity scale (based on damage), the Richter magnitude scale (based on energy released as measured by maximum wave amplitude on a seismograph), and the moment magnitude (based on the total seismic energy released as measured by the rigidity of the faulted rock, the area of rupture on the fault plane, and displacement).

## Earthquake-Related Hazards and Mitigation

### Ground Shaking

Damaging motion caused by shear and surface waves.

*Ways to reduce effects*—seismic zoning; building codes; construction techniques such as shear walls, seismic joints, and bolting frames to foundations.

### Landslides

Hundreds of landslides may be triggered by an earthquake in a slide-prone area.

*Ways to reduce effects*—proper zoning in high-risk areas.

### Ground Failure (Spontaneous Liquefaction)

Horizontal (lateral) movements caused by loss of strength of water-saturated sandy soils during shaking and by liquefaction of quick clays.

*Ways to reduce effects*—building codes that require deep-drilling to locate liquefiable soils or layers.

### Ground Rupture/Changes in Ground Level

Fault rupture and uplift or subsidence of land as a result of fault displacement.

*Ways to reduce effects*—geologic mapping to locate fault zones, trenching across fault zones, implementation of effective seismic zonation like the Earthquake Fault Zones Act in California.

### Fire

In some large earthquakes fire has been the biggest source of damage.

*Ways to reduce effects*—public education on what to do after a quake, such as shutting off gas and other utilities.

### Tsunamis

Multidirectional sea waves generated by disruption of the underlying sea floor (see Chapter 10).

### Earthquake Prediction

It is not feasible at this time to predict within useful limits the time, magnitude, and location of an earthquake. However, seismologists continue to search for clues to accurate prediction, which is what scientists do and what, we might add, science is.

*Upside/downside*—no proven large earthquakes predicted. Inaccuracies in short-term prediction have made the public wary.

### Earthquake Forecasts

Based on plate movement and known fault movement there is a 70 percent chance there will be a magnitude-6.7 earthquake in the San Francisco Bay area between 2000 and 2030. This kind of forecast is the research thrust today and forecasts will vary for each seismic region.

*Upside/downside*—good for planning purposes but not for short-term warnings.

### Statistical Methods

Tell us that worldwide there will be two $M = 8.0+$ and at least 20 $M = 7.0+$ earthquakes each year. Statistics can be applied for a smaller area in earthquake country.

*Upside/downside*—good for planning purposes but not for short-term warnings.

### Geological Methods

Active faults are studied to determine the characteristic earthquake magnitudes and recurrence intervals of particular fault segments; sediments exposed in trenches may disclose historic large fault displacements (earthquakes) and, if they contain datable C-14 material, their recurrence intervals.

*Upside/downside*—useful for long-range forecasting along fault segments and for identifying seismic gaps; not useful for short-term warnings.

## Key Terms

base isolation
body wave
elastic rebound theory
epicenter
fault
fault creep
focus (pl. *foci*)
forecasts
intensity scale
isoseismal
liquefaction
longitudinal wave

magnitude
modified Mercalli scale (*MM*)
moment magnitude ($M_w$ or $M$)
paleoseismicity
precursor
P-wave
recurrence interval
resonance
Richter magnitude scale
seismogram
seismograph
spontaneous liquefaction
strain
stress
S-wave
transverse (shear) wave
tsunami (pl. *tsunamis*)
wave period ($T$)

## Study Questions

1. What is "elastic rebound," and how does it relate to earthquake motion?
2. Distinguish among earthquake intensity, Richter magnitude, and moment magnitude. Which magnitude scale is most favored by seismologists today? Why?
3. Why should one be more concerned about the likelihood of an earthquake in Alaska than of one in Texas?
4. In light of plate tectonic theory, explain why devastating shallow-focus earthquakes occur in some areas and only moderate shallow-focus activity takes place in other areas.
5. What should people who live in earthquake country do before, during, and after an earthquake (the minimum)?
6. Describe the motion of the three types of earthquake waves discussed in the chapter and their effects on structures.
7. Why do wood-frame structures suffer less damage than unreinforced brick buildings in an earthquake?

## For Further Information

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*Fact sheets are one- or two-page condensations of a geological problem and are free of charge. Some are found on the Web at http://quake.usgs.gov. Hard copies may be obtained from the U.S. Geological Survey, Mail Stop 977, 345 Middlefield Road, Menlo Park, CA 94025.

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