LEARNING OBJECTIVES

After reading this chapter, you will be able to:

1. Explain the frequency, location, and worldwide distribution of earthquakes.
2. Explain how earthquakes are measured.
3. Describe the damage from some historic earthquakes.

4 Earthquakes and Seismology

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AT A GLANCE

Introduction

4.1 Distribution of Earthquakes

- 4.1.1 How Earthquakes Occur
- 4.1.2 Determining Earthquake Location
- 4.1.3 Earthquake Depths
- 4.1.4 Plate Boundary Earthquakes
- 4.1.5 Intraplate Earthquakes

4.2 Measuring Earthquakes

- 4.2.1 Intensity
- 4.2.2 Magnitude

4.3 Earthquake Damage

- 4.3.1 Examples of Significant Earthquakes
- 4.3.2 Factors Contributing to Earthquake Destruction
- 4.3.3 Earthquake Damage Prevention

4.4 Earthquake Prediction

- 4.4.1 Worldwide Seismic Network
- 4.4.2 Paleoseismology
- 4.4.3 Long- and Short-Term Earthquake Prediction

SUMMARY

KEY TERMS

ANSWERS TO CONCEPT CHECKS

REVIEW EXERCISES

INTRODUCTION

At 5:12 A.M. on April 18, 1906, a geological event of historic proportions occurred in San Francisco, California. One eyewitness described it like this:

"All of a sudden we had found ourselves staggering and reeling. It was as if the earth was slipping gently from under our feet. Then came the sickening swaying of the earth that threw us flat upon our faces. We struggled in the street. We could not get on our feet. Then it seemed as though my head were split with the roar that crashed into my ears. Big buildings were crumbling as one might crush a biscuit in one's hand."

The shaking that occurred in the 1906 San Francisco earthquake was strong enough to be felt as far north as Oregon, as far east as central Nevada, and as far south as Los Angeles. When shaking stopped, broken gas mains caught fire, adding an inferno to the disaster. By the time all was over, 80 percent of the city lay in ruins, destroyed by toppling or burning (Figure 4.1).

FIGURE 4.1 The shaking and subsequent fires of the 1906 earthquake destroyed 80 percent of San Francisco. Photo: NARA.

The 1906 San Francisco earthquake was not the strongest one ever to take place in North America, and it certainly was not the last one to happen on this continent. It was, however, one of the most important for several reasons. Because it took place in a populated area, its effects were well documented, allowing seismologists to reconstruct what had happened in an effort to learn more about earthquakes and how they occur. In addition, the devastation caused by this earthquake led to the adoption of safety measures that have reduced both casualties and property damage in subsequent earthquakes.

In this chapter, we will take a closer look at earthquakes: how they occur, where they occur, how we measure their strength, the damage they cause, and the steps being taken to develop models that may one day predict their occurrence.

4.1 DISTRIBUTION OF EARTHQUAKES

4.1.1 How Earthquakes Occur

One of the outcomes of the 1906 San Francisco earthquake was the development of the **elastic rebound theory**, an explanation for how earthquakes occur. As discussed in Chapter 3, when brittle rocks are subjected to stress, the rocks undergo elastic deformation during which they store the energy of the stress (see Figure 4.2). As is the case with all materials, there is a limit as to how much energy the rocks can store during this elastic phase, called the elastic limit of the material. Once the stress exceeds the elastic limit, the stored energy is released. If the stress is along a fault, some of the released energy causes the rocks to slip along the fault plane, rupturing the fault. If there is no fault, the released energy will fracture the rocks to create one. The remaining energy is released as seismic waves: an earthquake.

ELASTIC REBOUND THEORY
The theory that rocks along a fault deform elastically until their internal strength is exceeded, then suddenly release the stored energy as seismic waves to resume their former shape.

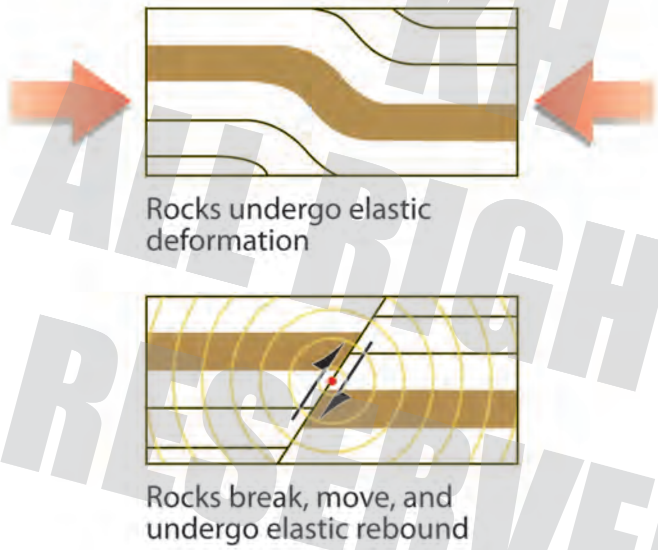


FIGURE 4.2 Rocks under stress may deform (top), but if they are brittle, they can only deform until they've reached their elastic limit. Once the elastic limit is exceeded (bottom), the rocks will fracture (if they have not done so already) and slip into a new position, releasing seismic energy as they do. Illustration by Don Vierstra.

The ruptures may be localized or travel along a long segment of a fault. The rupture along the San Andreas Fault during the 1906 earthquake was some 296 miles. Energy was released along the entire segment.

As described in Chapter 1, energy released as seismic waves travels at high velocities. The Love and Rayleigh waves move along Earth's surface to shake buildings and people. Meanwhile, the P and S waves travel through the interior of the earth to other points on the surface, where they are detected by the seismographs at various seismic stations. The difference in the time of arrival between the P and S waves reveals the distance from the seismic station to the epicenter of the earthquake using the time-travel chart introduced in Chapter 1 (Figure 4.3). Seismologists have used this information to infer Earth's composition.

4.1.2 Determining Earthquake Location

Further use of the time-travel chart pinpoints the focus and the epicenter of the earthquake through a process called **triangulation**. After calculating the distance from the seismic station to the epicenter, the next step is to draw a sphere with a radius that is the distance from the

TRIANGULATION
The method of locating the focus and epicenter of an earthquake by drawing three spheres, each centered at a seismic station with a radius of the calculated distance from the station to the quake. The intersection of the three spheres indicates the focus; the point on the surface above the focus is the epicenter.

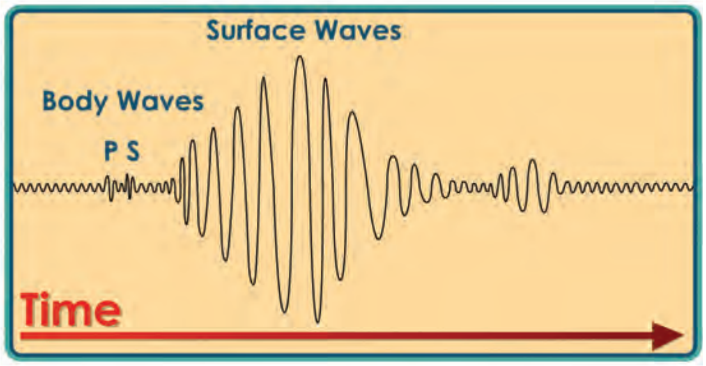
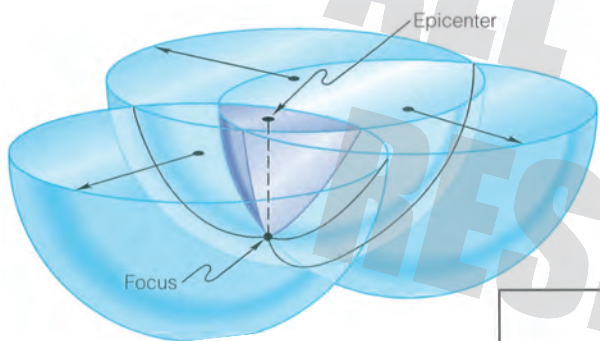


FIGURE 4.3 When waves generated by an earthquake arrive at a seismograph, two sets of waves are recorded: body waves and surface waves. The body waves travel quickly through the interior of the earth and arrive first as P and S waves. The surface waves travel on the surface more slowly and arrive second. Illustration by John J. Renton.

seismic station (see Figure 4.4). The surface of this sphere (below ground) locates all of the possible sites of the focus relative to the recording station. Drawing a second sphere narrows down the possible locations, as the focus must be at one of the points where the spheres overlap. Drawing a third sphere further narrows down the possible locations; the spheres will overlap at only one location, which is the earthquake's focus (Figure 4.4). The epicenter is the point on the surface directly above the focus. Determining just the epicenter can be done by drawing circles on a map each with the radius of the distance between the seismic station and the earthquake.



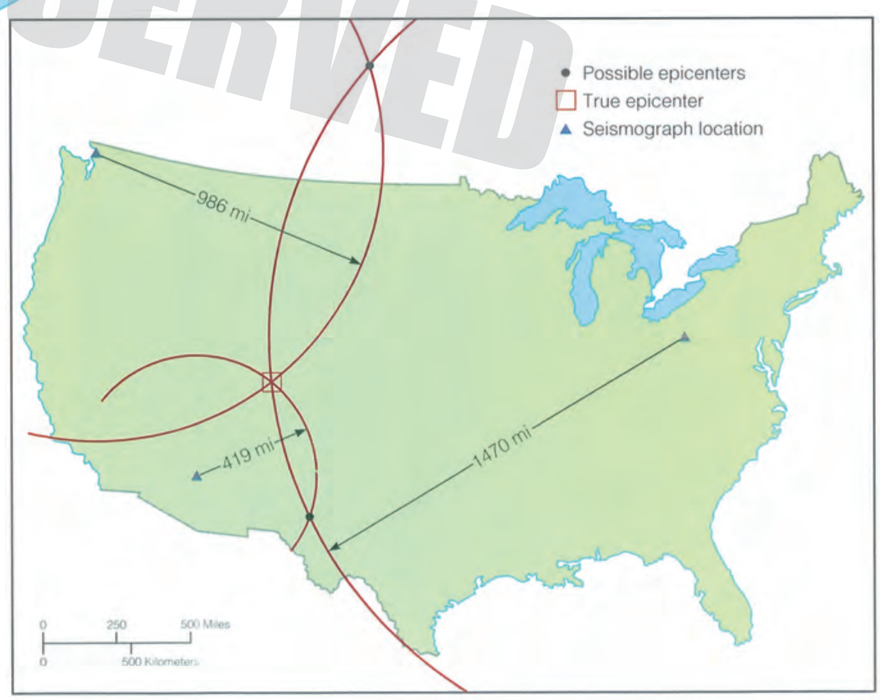


FIGURE 4.4 The focus of an earthquake can be pinpointed by drawing spheres from at least three seismic stations. The radius of each sphere is the distance from the seismic station to the focus, as calculated from the arrival times of P and S waves. The circles in the bottom image represent the intersection of the spheres with the earth's surface. Illustration by John J. Renton.

In actuality, seismologists no longer draw spheres or circles on maps, as computers handle these calculations. However, the computer data is at least partly based on this method and the information contained in a time-travel chart.

The ability to determine the focus and epicenter of an earthquake has made it possible to map both locations for any earthquake recorded by seismographs. Over time, the mapping has revealed two facts: (1) most earthquakes occur at plate boundaries, and (2) most earthquakes occur less than 65 kilometers (40 miles) beneath the surface, with the deepest earthquakes occurring at about 640 kilometers (400 miles) beneath the surface.

SHALLOW-FOCUS EARTHQUAKE
An earthquake with a focus less than 65 km (40 miles) beneath the earth's surface.

INTERMEDIATE-FOCUS EARTHQUAKE
An earthquake with a focus between 65 and 300 km (40–220 miles) beneath the earth's surface.

DEEP-FOCUS EARTHQUAKE
An earthquake with a focus deeper than 300 km (220 miles) beneath the earth's surface.

4.1.3 Earthquake Depths

About 75 percent of all earthquakes occur between the earth's surface and a depth of approximately 65 km (40 miles). These are known as **shallow-focus earthquakes**. Another 20 percent of all earthquakes, referred to as **intermediate-focus earthquakes**, occur at depths from about 65 to 300 km (40–185 miles). The remaining five percent of earthquakes, called **deep-focus earthquakes,** take place between 300 km to about 640 km (185–400 miles) (Figure 4.5).

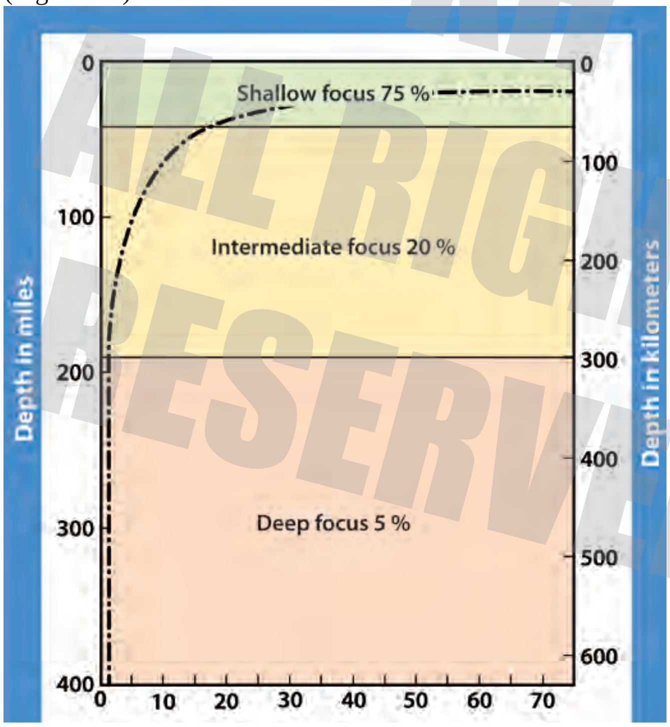


FIGURE 4.5 The increase in the number of earthquakes above depths of 200 miles (300 km)—and especially the rapid increase above a depth of about 40 miles (65 km)—is due to the increasingly brittle nature of the rocks approaching the earth's surface. Illustration by John J. Renton.

This rather uneven distribution of earthquakes is easily explained by the fact that an earthquake can only occur where rocks are brittle. Rocks that are a high enough temperature or under enough pressure to become ductile do not break; rather, they undergo plastic deformation, as described in Chapter 3. However, the depth at which this change from brittle to ductile takes place varies with location. Rocks are ductile at shallower depths where magma is upwelling—divergent boundaries. In fact, divergent boundaries feature mostly shallow-focus earthquakes. On the other hand, the sinking lithosphere in subduction zones is where rocks are coolest, and therefore brittle, at the greatest depths. Thus, most of the intermediate- and all of the deep-focus earthquakes occur at convergent boundaries featuring subduction zones.

This distribution was first noted during the 1940s, when the seismologists *Hugo Benioff* and *Kiyoo Wadati* were studying intermediate- and deep-focus earthquakes. Both researchers had observed that deep-focus earthquakes were located within a plane that dipped below the ocean floor where the edges of ocean basins approached chains of volcanoes and continental margins (Figure 4.6). Their calculations indicated that the earthquake zone terminated at depths of about 640 km (400 miles).

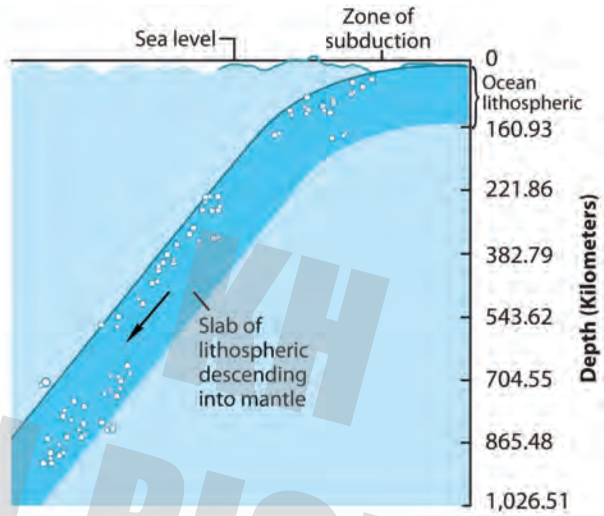


FIGURE 4.6 Below the zones of subduction and dipping toward the continents at an angle of about 45° is a plane called the Wadati-Benioff zone along which abundant earthquake foci are located. Illustration by John J. Renton.

Once the concept of plate tectonics began to evolve, and the significance of the deep-sea trenches became understood, the importance of their finding was realized. The plane of earthquakes, now called the **Wadati-Benioff zone**, represents the contact between the upper surface of a subducting oceanic plate and the rocks of the overlying asthenosphere. The point at which deep-focus earthquakes stop occurring is the depth at which the rocks of the oceanic lithosphere are completely assimilated into the plastic asthenosphere. Thus, the identification of the Wadati-Benioff zone not only was explained by plate tectonics but also provided additional evidence in support of it.

WADATI-BENIOFF ZONE
The 45° plane along subducting plates where intermediate and deep focus earthquakes occur.

4.1.4 Plate Boundary Earthquakes

The map in Figure 4.7 gives a clear picture of the proportion of earthquakes that occur along plate margins; in fact, the earthquake epicenters trace the boundaries of the plates. About 90 percent of earthquakes occur at plate margins; only ten percent of earthquakes occur elsewhere. The pattern of epicenter locations outlines the plates, acting as additional evidence in support of plate tectonic theory.

The earthquakes that occur at divergent plate boundaries do so as the result of tensional stresses; consequently, the faults along which the earthquakes occur are normal faults. On the other hand, earthquakes that occur at convergent plate boundaries are the result of compression, so the faults are reverse or thrust faults. A subduction zone is actually an extensive thrust fault.

Earthquakes associated with divergent and convergent plate margins also differ in the amount of energy released. Rocks are generally weaker under tension, which limits the amount of energy that can be stored during the elastic phase of deformation. Consequently, there is less energy released during earthquakes at divergent plate margins. In contrast, rocks become stronger under compression and can store relatively higher levels of elastic energy. Because of

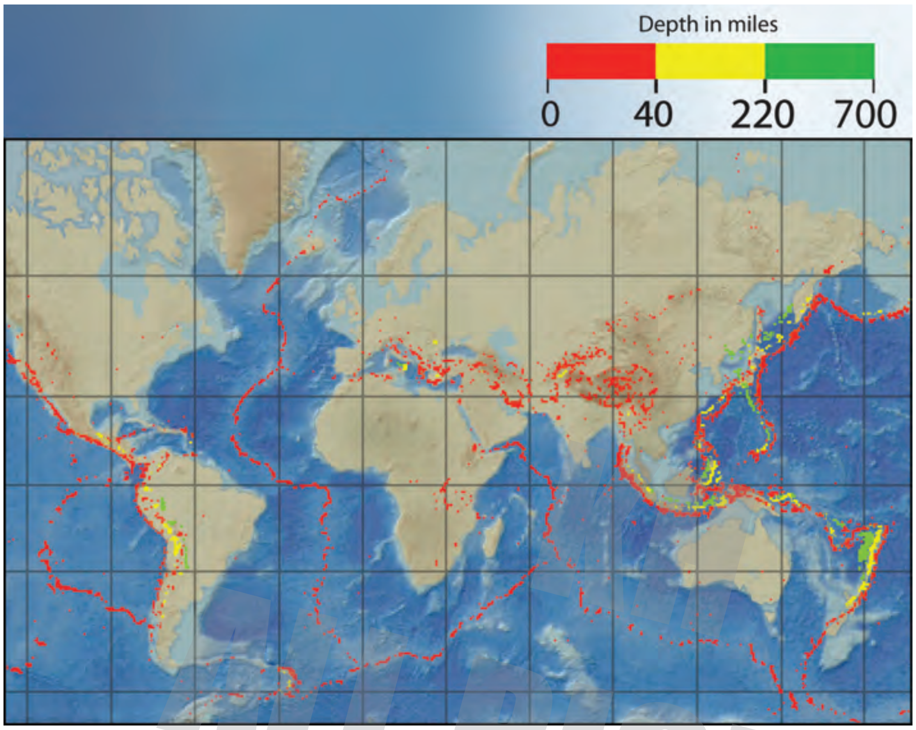


FIGURE 4.7 A map of the worldwide distribution of earthquakes shows not only that most earthquakes occur along plate boundaries but also that the intermediate- and deep-focus earthquakes are characteristic of subduction zones. Illustration by Don Vierstra.

this, earthquakes generated at convergent margins release large amounts of energy and have the potential to cause extreme damage. The largest recorded earthquakes have all taken place in subduction zones.

4.1.5 Intraplate Earthquakes

Only ten percent of earthquakes occur within plates far from any plate margin. Some of these earthquakes are associated with hot spot volcanoes, such as those that are often felt on the Big Island of Hawaii and in Wyoming's Yellowstone National Park, where volcanic activity is ongoing. Others, called **intraplate earthquakes**, are caused by the same types of stresses and faulting as the plate boundary earthquakes. Two major zones of intraplate earthquakes exist in the United States: the New Madrid, Missouri (see Figure 4.8 on page 158), and Charleston, South Carolina, seismic zones.

INTRAPLATE EARTHQUAKE An earthquake whose focus and epicenter are in the interior of a tectonic plate.

Most earthquakes associated with intraplate seismic zones are not very strong; a notable exception is a trio of earthquakes that occurred during the winter of 1811–1812, when three earthquakes with magnitudes in excess of 8.0 occurred within the New Madrid Fault Zone. Likewise, in 1886, Charleston, South Carolina, suffered an unrelated earthquake estimated to have a magnitude of 7.6 (see Figure 4.9 on page 158)

Several ideas have been presented to explain such intense seismic activity, but none has gained universal acceptance. It is generally thought that the New Madrid area and Charleston were probably the sites of ancient tectonic activity. The New Madrid seismic zone is located above a failed rift zone, called the Reelfoot Rift, which formed about 550 million years ago. Failed rifts like this one tend to remain zones of weakness. Likewise, Charleston is underlain by a failed rift zone that developed about 180 million years ago, shortly after the Atlantic Ocean began to open. It is possible that the westward movement of the North American plate has stressed these two former fracture zones; when the stress exceeds the elastic limit of the rocks, the faults rupture, causing intraplate earthquakes.

SEE IT SIDEBAR

DENALI NATIONAL PARK AND PRESERVE

A convergent plate boundary, with subducting oceanic crust, is the source of deep-focus earthquakes. The friction caused by a slab of oceanic lithosphere colliding with the opposing plate can create the earth's largest earthquakes. *The San Andreas* is a right lateral strike-slip fault, which means that it is a vertical fault that has the plates sliding past each other. The Pacific plate is moving toward the northwest and the North American plate is moving to the southwest.

The Native American Athabascan name for *Mount McKinley* is *Denali*, "the High One." This magnificent mountain peak rises to summit at 20,320 feet, has the greatest vertical relief of any mountain in the world, and can be seen by ships out in the *Gulf of Alaska*. The *Denali National Park and Preserve* in south central Alaska surrounds the original *McKinley National Park* on three sides and ensures the protection of the entire area, its glaciers, and its ecosystem.

The Denali National Park and Preserve, as is the case for most of Alaska, has a long history of collision tectonics and accretionary terrane accumulation, which has resulted in continuous orogeny and varying conditions of alteration (metamorphism) to nearly all rocks. In general, rock units have been folded, faulted, and altered in places (rocks of low temperature, low pressure metamorphism), often resulting in homogenous lithologies, as well as effectively blending faults and other contacts into oblivion.

In this view of the North/South Summits of Mount McKinley, the high point on the left side of the picture is the true summit at 20,320 feet, while the north peak caps out at 19,470 feet. Although the bulk of Mount McKinley is made up of 56 million-year-old granite rock, the upper 1,000 feet of the north peak is a cap (roof pendant) of 100 million-year-old flysch (shallow marine rock) sequence. Photo: Shutterstock 37766683, credit Michael Papasidero; Map: Shutterstock 15180868, credit Map Resources.

Additionally, *Denali National Park and Preserve* geology is only mapped at a basic level. Because of Alaska's vast size, detailed mapping, often driven by mineral or oil resource concerns, is limited in national parks, where economic mineral or energy exploration is not encouraged.

In recent time, attempts have been made to determine active seismic movement on the *Denali Fault*. A trilateration network (high precision survey) established across the *McKinley Strand*, east-west for 30 miles near Cantwell by the U.S. Geologic Survey in 1975, found no significant movement in the 14-year period of measurement. In a current, ongoing effort (a six-year study period for stations north and south of the fault—*McKinley Strand*), survey grade global positioning system (GPS) surface stations have taken measurements along the highway between Fairbanks and Talkeetna. The study has shown a 0.24 to 0.36 inch per year westerly migration rate. The rates of westerly migration of GPS stations are slightly greater just south of the fault.

Some 600 seismic events occur within the *Denali National Park and Preserve* each year. While linear seismic patterns on the *Denali* have been surprisingly minimal, an earthquake at magnitude 6.7 occurred on or near the *Denali Fault* on October 23, 2002. This was followed by a main shock at magnitude 7.9 eleven days later. It was the largest earthquake at the time to occur in North America and the largest to hit interior Alaska in its recorded history. The fault movement history at many locations of this wild ***See It*** location remains poorly understood. It is undeniable that *Denali National Park and Preserve* exemplifies a landscape carved out, thrust up, and shifted beneath by powerful geologic forces.

An aerial view of a river running through Denali National Park and Preserve. Mapping seismic patterns and activity within the immense landscape of Denali requires the use of data gathered via satellites. GPS surface stations record precise measurements of earth movements near the Denali Fault, the fastest moving and most active fault in the Alaskan interior, that provide insight into the tectonic forces that caused the 2002 Denali Fault earthquake. Photo: Shutterstock 15791044, credit Ulrich Mueller.

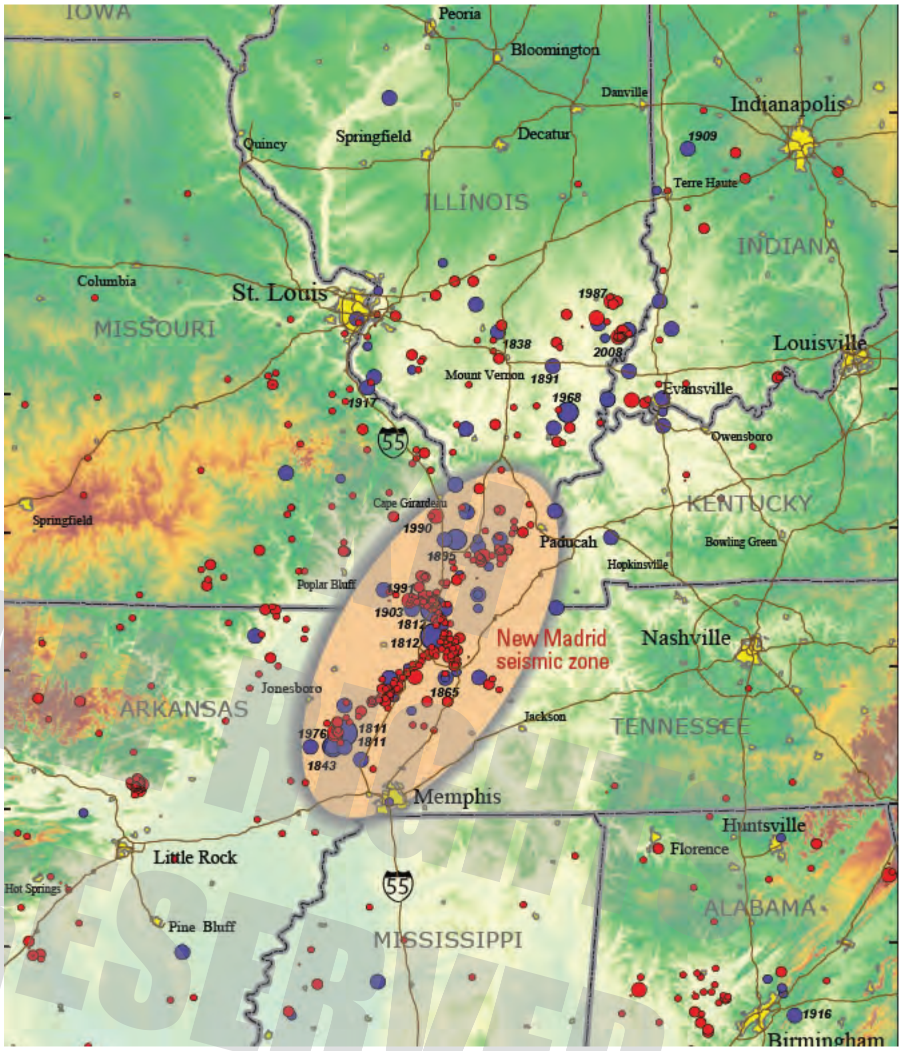


FIGURE 4.8 A map of earthquakes that have occurred in the New Madrid Seismic Zone. Red circles are earthquakes that have occurred since 1972; blue circles are those that occurred before 1972. This seismic zone is an area far from any plate boundary; therefore, earthquakes occurring in this zone are intraplate earthquakes. Image: USGS.

FIGURE 4.9 This photograph shows some of the worst wreckage from the 1886 Charleston, South Carolina, earthquake. Far from any plate boundary, this earthquake had an estimated magnitude of 7.6. Photo: Courtesy of J. K. Hillers/ USGS.

Concept Check

1. Can the earthquake focus and epicenter ever start from the same location?
2. How deep are the majority of earthquakes?
3. Is there a plate tectonic cause for most earthquakes?
4. What is the Wadati-Benioff zone?
5. What are intraplate earthquakes?

4.2 MEASURING EARTHQUAKES

Whenever an earthquake occurs, there are two questions on everyone's mind: "Where was it and how big was it?" The size of an earthquake is a reference to its strength. There are two methods scientists use to describe earthquake strength: (1) intensity, and (2) magnitude.

4.2.1 Intensity

The **intensity** of an earthquake describes the impact of its shaking on both humans and objects. The effort to quantify earthquake intensity began in Italy after a particularly destructive earthquake in 1857. The Italian seismologist Giuseppe Mercalli developed a ten-point scale called the **Mercalli Intensity Scale** that described the intensity of shaking based on its impact to human beings and property. The scale was later modified to twelve steps and is called the **Modified Mercalli Scale**. Table 4.1 shows the range of effects contained in the scale. The lowest levels describe the effects felt by people; the highest levels focus on destruction to property.

The Mercalli scale has usefulness exceeding simple description. Reports from those who experience earthquakes are consolidated to generate **shakemaps** that illustrate the range of shaking over an area (see Figure 4.10 on page 161). In a shakemap, the darkest red areas are those that experienced the most violent shaking with light blue representing the mildest shaking reported. The shakemaps are used by emergency agencies to determine the areas in which services are most likely to be needed after major earthquakes, and to predict the likely impact of future earthquakes during the development of emergency planning. They can also be compared with actual damage to assess the efficacy of building codes in developing structures able to withstand the stress of earthquakes. Finally, the shakemaps show the distributions of various levels of shaking, which provide information about the impact the underlying rock, or **bedrock**, and the soil have on the transmission of seismic waves.

4.2.2 Magnitude

The **magnitude** of an earthquake is the number most often referred to in news reports regarding the size of an earthquake. Magnitude refers to the amount of energy released based on ground movement detected by seismographs, and is expressed as a value on

INTENSITY
The impact of an earthquake on people and property.

MERCALLI INTENSITY SCALE
A scale rating an earthquake's intensity on a scale from I to XII.

MODIFIED MERCALLI SCALE
A refinement of the original Mercalli intensity scale currently used to describe earthquake intensity.

SHAKEMAP
A map in which shadings correspond to Mercalli values, providing a visual image of the relative amount of shaking in areas affected by an earthquake.

BEDROCK
Solid rock.

MAGNITUDE
The amount of energy released by the quake as evidenced by ground movement recorded on seismograms.

TABLE 4.1 The Modified Mercalli scale describes a range of shaking from that which was not felt to total destruction.

Modified Mercalli Intensity Scale of 1931 (Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings.

III. Felt quite noticeably indoors, especially on upper floors, but many people do not recognize it as an earthquake. Vibration like a passing truck.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some furniture moved; a few instances of damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage *negligible* in buildings of good construction; *slight* to moderate in well-built ordinary structures; *considerable* in poorly built or badly designed structures.

VIII. Damage slight in specially design structures; *considerable* in ordinary substantial buildings; *great* in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls.

IX. Damage *considerable* in specially designed structures; well-designed frame structures thrown out of plumb; *great* in substantial buildings, with partial collapse. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed; ground badly cracked. Considerable landslides from riverbanks and steep slopes.

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in the ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground.

XII. Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward into the air.

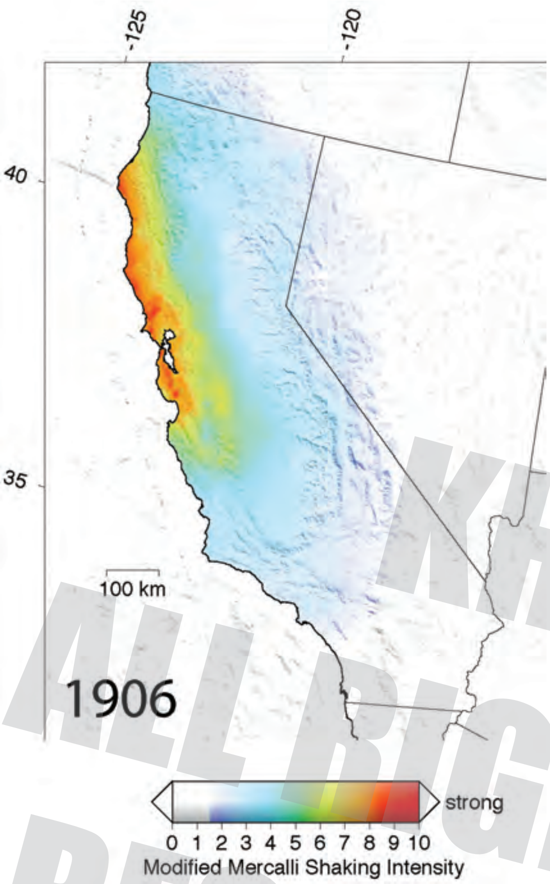


FIGURE 4.10 The shakemap of the 1906 San Francisco earthquake shows violent shaking along the San Andreas Fault and decreasing intensity as distance from the fault increases. Image: Matt D'alessio/USGS.

the **local magnitude scale**. This scale is commonly referred to the Richter scale because it was devised by seismologist Charles Richter in 1935. The greater the energy release as evidenced by ground movement, the higher the magnitude.

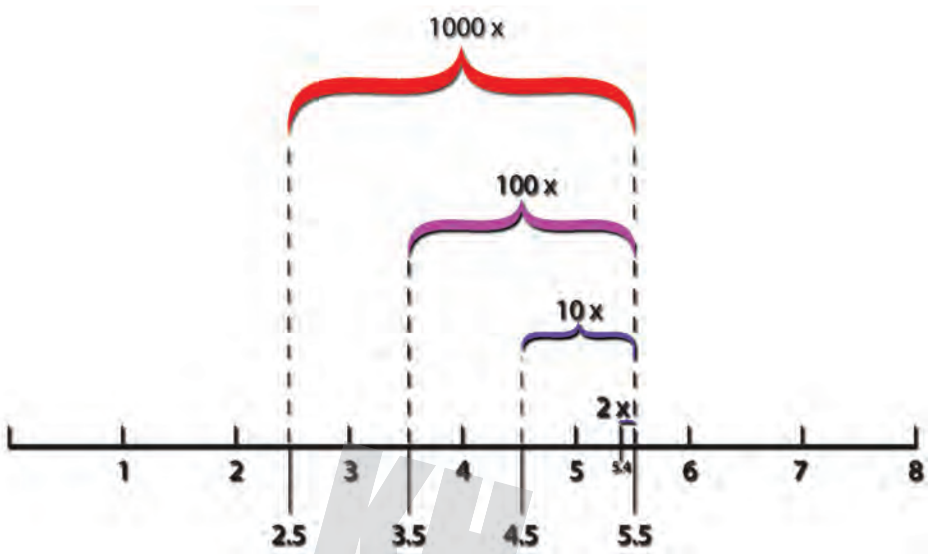
Magnitude covers a wide range of energy release, from earthquakes that cannot be felt to those in which the energy release is so great it moves through the ground in visible waves. A linear scale capturing this range would be impossibly large, so the local magnitude scale is logarithmic. Each whole number represents a ten-fold increase in ground motion. Thus a 5.5 magnitude earthquake has ten times the ground motion of a 4.5 earthquake, 100 times the ground motion of a 3.5 quake, and 1,000 times the ground motions of a 2.5 earthquake (see Figure 4.11 on page 162). At the same time, the local magnitude scale also describes how much energy was released with each whole number increment representing almost 32 times as much energy release as the one before it. Figure 4.12 on page 162 provides some energy equivalents for local magnitude scale values.

Calculating local magnitude is based on the fact that the amount of ground movement produced by an earthquake generally decreases with distance from the epicenter, a phenomenon clearly seen on shakemaps. Seismographs record the seismic vibration at the station. The amplitude of the recorded waves is an indication of the amount of ground movement at that station. The amplitude information combined with the distance information reveals the amount of energy released during the fault rupture—the earthquake's magnitude. While computers rapidly make these calculations today, they are based on the **nomograph**, a diagram that arranges two scales, such as amplitude and distance, in a way that allows one to determine a value on the third scale, in this case, the earthquake's magnitude (see Figure 4.13 on page 163).

LOCAL MAGNITUDE SCALE
A logarithmic scale expressing the magnitude of an earthquake, also known as the *Richter scale*. Each whole number increment represents a tenfold difference in earth movement.

NOMOGRAPH
A diagram arranging different scales so that values on two can determine the value of a third. A nomograph is used to determine an earthquake's magnitude from known distance and wave amplitude values.

FIGURE 4.11 The local magnitude scale is logarithmic. Each tenth of a point on the scale represents double the shaking of the previous tenth of a point. A full point on the scale represents a tenfold increase in shaking; two points represents 100 times the shaking, and three points represents a 1,000 times increase in shaking. Illustration by Marie Hulett.



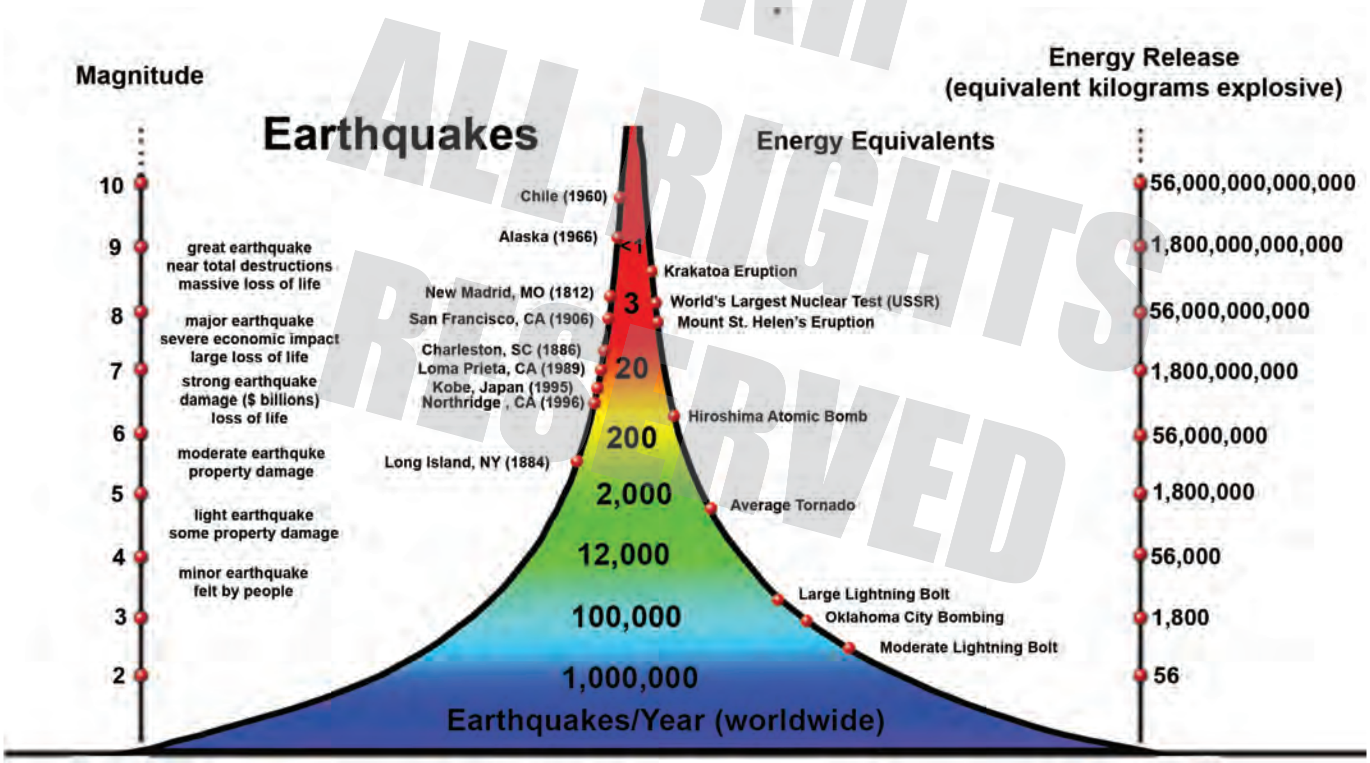


FIGURE 4.12 This graph shows the energy equivalents of the local magnitude scale. Illustration by Marie Hulett.

MOMENT MAGNITUDE SCALE
A refinement of the local magnitude scale that more accurately expresses large magnitudes.

Originally designed to study small- and medium-sized earthquakes, the original Richter scale did not work well for earthquakes with magnitudes in excess of 7.0. The shortcomings of the Richter scale were taken into account in 1979 by Thomas Hanks and Hiroo Kanamori of Harvard University with their introduction of the **moment magnitude scale**. The adjustment yields different magnitudes for large quakes than does the local magnitude scale. For instance, the original local magnitude calculated for the 1906 San Francisco earthquake was 8.3 but its moment magnitude has been calculated as 7.7. Today, the moment magnitude scale is used exclusively for earthquakes with magnitudes of 8 or greater, and the local magnitude scale values are cited for moderate and smaller earthquakes.

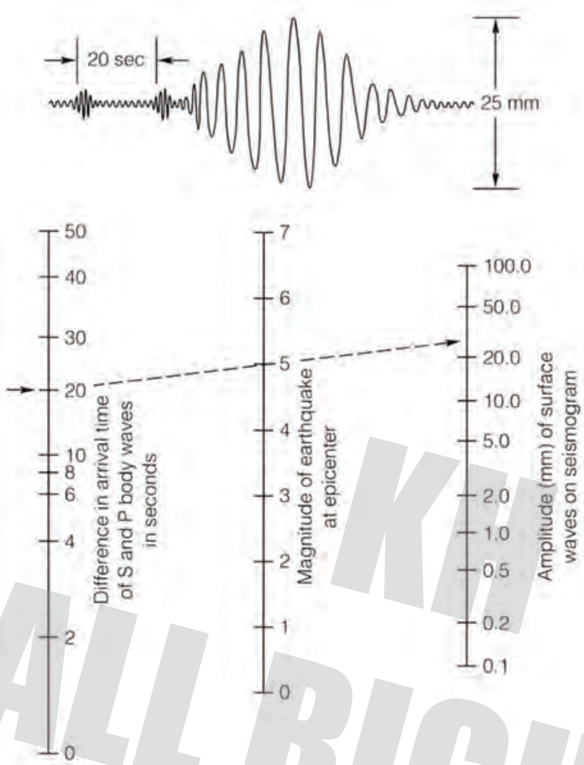


FIGURE 4.13 A nomograph allows magnitude information to be determined from a single seismogram. A line is drawn from the distance value on the left-hand scale to the amplitude value on the right-hand scale. The magnitude is the intersection of the line with the center scale. Illustration by John J. Renton.

Concept Check

1. What does the Modified Mercalli Intensity Scale actually measure?
2. What does a shakemap illustrate?
3. The local magnitude scale is not an earthquake intensity scale. What is it measuring?
4. What kind of earthquakes does the local magnitude scale fail to accurately measure?

4.3 EARTHQUAKE DAMAGE

Only a small proportion of earthquakes that occur annually around the world are headline grabbers. In most cases, that is because of their impact on life and property. In fact, most earthquakes are either too small to be of concern or occur in relatively uninhabited areas. Table 4.2 on page 164 reveals the numbers of earthquakes of each magnitude that occur around the world in an average year.

As noted earlier, earthquakes are concentrated near plate boundaries; when a plate boundary is in a populated area, the earthquake is more likely to be a damaging one. There are three such areas in North America: the San Andreas Fault, which is a transform boundary in California; the Washington and Oregon area, which lie above the subduction zone where the Juan de

TABLE 4.2

Frequency data from *Earth* by F. Press and R. Seiver. Copyright © 1986 by W.H. Freeman and Company.

NOTE: For every unit increase in Richter magnitude, ground displacement increases by a factor of ten, while energy release increases by a factor of thirty. Therefore, most of the energy released by earthquakes each year is released not by the hundreds of thousands of small tremors, but by the handful of earthquakes of magnitude 7 or larger, the so-called major or great earthquakes.

TABLE 4.2

FREQUENCY AND ENERGY RELEASE OF EARTHQUAKES OF VARIOUS MAGNITUDES

Richter Magnitude	Number per Year
Over 8.0	1 to 2
7.0–7.9	18
6.0–6.9	120
5.0–5.9	800
4.0–4.9	6,200
3.0–3.9	49,000
2.0–2.9	300,000

Fuca plate is sliding under the North American plate; and Alaska, where the Pacific plate is subducting under the North American plate.

4.3.1 Examples of Significant Earthquakes

1906 San Francisco Earthquake

The 1906 earthquake began at 5:12 A.M. on April 18, 1906, when a 477 km (296 mile) segment of the San Andreas Fault ruptured, displacing the earth as much as 6 meters (20 feet) in some locations. Originally, it was thought that the epicenter of the earthquake was located in the Point Reyes area of Marin County, about 40 km (25 miles) north of San Francisco. However, more recent analyses have placed the epicenter along the coast near Mussel Rock just south of San Francisco. Although neither the Richter nor the Moment Magnitude scales existed at the time, estimates indicate the earthquake to have had a magnitude of about 7.8. The damage suffered by San Francisco included a death toll that exceeded 3,000, with property damage estimated to be more than $400 million. The combined insurance company claims submitted following the earthquake would be equivalent to nearly $6 billion in 2008 dollars (Figure 4.14).

Most of the property damage was the result of fires that occurred when kerosene lamps were toppled by the quaking and burst, setting the largely wooden homes and buildings on fire (Figure 4.15). Natural gas lines were severed and burst into flames. Fallen building facades blocked the streets, keeping firefighters from quickly responding to the fires. Even when they could reach the flames, they found that the water mains were also severed. Without water to put out the fires, the fires burned for four days. By the time it was over, more than 80 percent of the city was destroyed, and 16,000 people were without homes. Nearby towns also suffered major damage, including the downtown areas of San Jose and Santa Rosa, which were almost totally destroyed. In fact, a look at the shakemap in Figure 4.10 on page 161 shows that severe shaking occurred all along the entire ruptured segment of the San Andreas, with similar destructive impacts.

1964 Prince William Sound, Alaska

The largest recorded earthquake on the North American continent—and the second largest earthquake ever recorded—occurred at 5:36 P.M. on March 27, 1964. The epicenter was in Prince William Sound, the body of water off Anchorage, Alaska. In this area, the Pacific plate

FIGURE 4.14 Many buildings in 1906 San Francisco could not withstand the shaking of a magnitude 7.8 earthquake and crumbled into rubble. Photo: NARA; Map: Shutterstock 15180868, credit Map Resources.

FIGURE 4.15 Buildings that survived the shaking succumbed to the fires that ravaged San Francisco after the 1906 earthquake. Photo: Arthur Genthe Collection, Library of Congress.

is subducting beneath the North American plate at a average rate of 6–8 cm (2.7–3.2 inches) per year. As it moves, compression builds up on the North American plate causing the rocks to substantially deform. They reached their elastic limit on 5:36 P.M., March 27, 1964, snapping back over the course of four minutes to their original positions. During this time, the Latouche Island area moved about 18 meters (59 feet) to the southeast. In some areas, the adjustment meant uplifting by as much as 4 to 9 meters; other areas dropped as much as 3 meters. The Pacific plate slipped an average of 9 meters under the North American plate. The local magnitude of the earthquake was 8.4 to 8.6, with an estimated moment magnitude of 9.2.

FIGURE 4.16 The largest recorded earthquake in North America occurred in 1964 in Alaska's Prince William Sound. The quake, which had an estimated moment magnitude of 9.2, destroyed downtown Anchorage. This photograph shows a graben that subsided 11 feet in response to 14 feet of horizontal movement. Photo: USGS; Map: Shutterstock 15180868, credit Map Resources.

FIGURE 4.17 Much of the damage from the Prince William Sound earthquake was from waves generated not only by the earthquake but also by landslides triggered during the shaking. Photo: USGS.

The shaking damaged or destroyed about 30 blocks of dwellings and commercial buildings in downtown Anchorage, including many schools and government buildings. An area of about 130 acres in an residential area called Turnagain Heights broke into blocks that collapsed and tilted (Figure 4.16). The earthquake disrupted water mains and gas, sewer, telephone, and electrical systems.

As devastating as the damage was from the shaking, 90 percent of the lives lost were as a result of the tsunamis that followed (Figure 4.17). A tsunami is a deep ocean wave that travels fast and can build to great heights upon reaching shore. Tsunamis generated by this quake damaged and destroyed seacoast villages and took 115 lives, some of which were in Oregon and California. Tsunamis, their causes and their behavior will be discussed in more detail in Chapter 12.

The 1556 Earthquake in Shensi, China

The deadliest earthquake occurred not in North America but in China. The estimated Modified Mercalli Scale intensity of the 1556 Shensi Earthquake was XI and the local magnitude of the earthquake is estimated at more than 8. The epicenter of the earthquake was located about 89 km (50 miles) east-northeast of the city of Xi'an and about 900 km (560 miles) southwest of Beijing. This earthquake was so destructive that in Xi'an, only 10 percent of the homes were left standing and around a third of the inhabitants were killed. Additional damage from the earthquake was recorded as far as 430 km (270 miles) from the epicenter, and the tremors were felt more than 800 km (500 miles) away.

This single earthquake had the highest death toll in the history of civilization. It has been estimated that some 830,000 identified soldiers and civilians died as a result of the earthquake in addition to uncounted unidentified victims. Many of the deaths resulted when homes carved into loess (fine windblown silt) cliffs collapsed. Northern China is covered with a blanket of loess up to several hundred feet thick consisting of dust that has been blown out of the Gobi Desert for millions of years. The loess particles interlock and are able to maintain vertical cliff faces many tens of feet high while at the same time being soft enough to be dug out by shovel. While loess homes provide shelter from the elements, they do not have the structural integrity to withstand earthquakes (Figure 4.18). Even so, throughout northern China, hundreds of thousands of people still live in homes carved into the loess cliffs.

FIGURE 4.18 Loess homes like this one were no match for the intensity of the 1556 Shensi earthquake, which had an estimated magnitude more than 8 and a Modified Mercalli value of XI. Some 830,000 people died when homes, walls, and temples made of loess collapsed. Photo: Shutterstock 35857027, credit ellakay.

1989 Loma Prieta Earthquake

One other North American earthquake deserves attention both because it was a major quake and because it provides a contrast with the 1906 San Francisco earthquake. During the warm-up for the third game of the World Series on October 17, 1989, a movement occurred along the San Andreas Fault that produced a magnitude 7 earthquake, the largest earthquake recorded along the San Andreas Fault since the 1906 event. The epicenter for the earthquake was located in an unpopulated portion of the Santa Cruz Mountains about 16 km (10 miles) northeast of Santa Cruz and about 89 km (55 miles) south of San Francisco; it was named for Loma Prieta Peak about 8 km (5 miles) to the northeast of the epicenter.

Throughout Northern California, the earthquake killed 63 people, injured 3,757 people, and left nearly 12,000 people homeless. Property damage was estimated to be as much as $13 billion, most of which was in the San Francisco area. The worst damage occurred on the eastern side of San Francisco Bay, where the Cypress Street Viaduct section of the Interstate Highway (I-880) in West Oakland collapsed, crushing 41 people in their cars as the upper deck fell onto the lower deck (Figure 4.19).

FIGURE 4.19 Most of the lives that were lost in the 1989 Loma Prieta earthquake were the result of the collapse of the I-880 Freeway. Although experts still do not agree on the exact cause of the structural failure experienced by the overpass, the fact that portions of the freeway that collapsed were located on unconsolidated bay sediments may have contributed to its failure. Photo: Courtesy of H. G. Wilshire/USGS.

The Loma Prieta quake also caused natural gas lines and water mains to be severed, re-creating the identical conditions experienced during the 1906 earthquake, although not on the same scale. Water was again pumped from the San Francisco Bay and the fires were eventually extinguished. It is interesting to note that the crew of the Goodyear blimp that was in the air over San Francisco at the time of the earthquake reported the blimp being bounced around. This was the first evidence ever recorded indicating that the air column above an earthquake is affected by the movement of Earth's surface.

The quake left behind badly damaged areas, but unlike the 1906 earthquake, the city was basically intact (Figure 4.20). Some of the damage that did occur during the Loma Prieta earthquake was a direct result of decisions made during the rebuilding of San Francisco after the 1906 earthquake. To understand how the first contributed to the second, it is first necessary to take a look at some of the factors that contribute to earthquake damage.

FIGURE 4.20 Although there were badly damaged areas after the 1989 Loma Prieta earthquake, the city of San Francisco fared far better during this quake than it had 83 years earlier during the 1906 event. The first story of this house collapsed as a result of liquefaction, causing the second story to collapse as well. What is seen here is the third story of the home. Photo: Courtesy of G. Plafker/USGS.

4.3.2 Factors Contributing to Earthquake Destruction

One of the changes that occurs during the rock cycle discussed in the Introductory chapter is the weathering of rock into sediment that is then carried away to accumulate elsewhere. Deposits of such accumulated sediment cover much of the North American continent, sometimes quite deeply. Sometimes this sediment is loosely packed, and referred to as **unconsolidated sediment** (Figure 4.21). In other areas, the sediment has been packed together enough over time to become almost rock-like. This is called **consolidated sediment**. There are other areas in which underlying bedrock is exposed at the surface.

UNCONSOLIDATED SEDIMENT
Loose or poorly packed soil.

CONSOLIDATED SEDIMENT
Well-packed sediment.

Bedrock and consolidated sediments transmit seismic waves quickly and efficiently, with little of the waves' energy being dissipated through the material. Consequently, these materials

FIGURE 4.21 Unconsolidated sediment is a loose mixture of rocks and soil that amplifies an earthquake's shaking. Photo: Courtesy of Susan Wilcox.

minimize the shaking that accompanies earthquakes; the energy of the wave goes into travel rather than shaking. The shaking from the magnitude 8.0 New Madrid earthquakes in Missouri, described earlier in this chapter, was felt as far away as Boston and Ontario because the seismic waves traveled through bedrock.

Unconsolidated sediments are another story. Loosely packed sediments transmit seismic waves inefficiently and exaggerate shaking. One example often cited is that unconsolidated sediments are like Jell-O in a bowl; if one moves the bowl a lot, the Jell-O jiggles a lot. Given this example, it is easy to see how building structures on unconsolidated sediments could lead to disaster, something confirmed by data after the 1906 earthquake. Data showed that areas located in sediment-filled valleys sustained stronger shaking than areas located on bedrock; in addition, the areas experiencing the maximum amount of quaking were located built on landfills.

Unconsolidated sediments are almost certainly a contributing factor to the failure of the I-880 Freeway in the Loma Prieta earthquake. The supports for the double-deck freeway were anchored in marshland that amplified ground movement. The combination of out-dated building standards and an unstable foundation resulted in the twisting of the freeway to the point where support columns failed. The upper deck fell onto the lower deck crushing the unfortunate drivers and their passengers.

Liquefaction

LIQUEFACTION
The transformation of water-soaked, unconsolidated soil into a fluid state.

Water adds an additional dimension to the instability of unconsolidated sediments that may otherwise seem solid, unlike the marshland involved with the I-880 Freeway collapse. When the particles in water-saturated sediment are dry, they rest on each other and hold each other in place. But if those particles are saturated with water, the water can act as a lubricant. When the ground starts shaking, the sediment loses its cohesion altogether and turns to quicksand in a process called **liquefaction**. The conversion from seemingly solid ground to quicksand is so sudden and complete that water is often seen spurting on to the surface during an earthquake, sometimes creating holes in the ground called sand boils, or sand volcanoes (Figure 4.22).

FIGURE 4.22 During liquefaction, water may spurt out of the ground, creating sand boils, or sand volcanoes, such as this one that was created during the 1989 Loma Prieta earthquake. Photo: Courtesy of Dr. Jonathan Bray/ USGS.

FIGURE 4.23 In general, structures anchored in bedrock have the best chance at surviving an earthquake, while those built on unconsolidated materials generally suffer the most damage. A case in point is the effect of the 1989 earthquake in Loma Prieta, California, on the city of San Francisco. In the downtown area, where the foundations of the buildings are in bedrock, there was little damage. Most of the damage occurred in the Marina District, where the structures were built on land formed by dumping the unconsolidated debris of the 1906 San Francisco earthquake along the edge of the bay. Photos: (left) Courtesy of J. K. Nakata/USGS; (right) Courtesy of C. E. Meyer/USGS.

Liquefaction played a significant role in the damage caused in the 1989 Loma Prieta earthquake. Townhouses in the Marina District along San Francisco's waterfront were constructed on landfill subject to liquefaction. Landfill is an extreme example of unconsolidated material that greatly magnifies shaking. In addition, the landfill was saturated with water. As the shock waves passed through the water-saturated debris, liquefaction ensued and the solid ground beneath the buildings turned to quicksand. The buildings sank and slumped (Figure 4.23), killing four people, collapsing seven buildings, and rendering another 63 buildings too dangerously damaged to live in.

Ironically, the landfill used to create the Marina District was debris from the 1906 earthquake. During the clean up of the city in the quake's aftermath, the debris was hauled down to the edge of the bay and dumped, eventually becoming part of the Marina District, where it contributed to the greatest damage during the 1989 event.

4.3.3 Earthquake Damage Prevention

Construction Standards

The 1906 San Francisco earthquake also contributed to the development of standards for building codes designed to resist earthquake damage. As a result of what was learned, California became one of the leaders in the design of earthquake-resistant structures as well as legislation meant to protect both people and property against future earthquakes.

One change that has become standard for new houses along the West Coast is the requirement to bolt the structure to its foundation. A common aftermath of earthquakes involves buildings that have "fallen off their foundations" (see Figure 4.24). In reality, the horizontal movement of the Love waves pulled the foundation out from under the building. Bolting the foundation to the structure keeps this from happening.

Another practice is to reinforce crawl space between the floor and the ground with solid plywood. Material that bends rather than breaks is favored for construction; for instance, wood over brick. If a brick building is desired, then heavy concrete supports reinforced with steel rebar is added to allow the building to flex during earthquakes. There must be enough rebar to keep the concrete supports from breaking or collapsing.

FIGURE 4.24 Love waves can literally move the foundation from beneath homes, as they did to this home during the 1989 Loma Prieta earthquake. Current building codes require that this type of structure be bolted to its foundation. Photo: USGS.

Base isolation is used for larger buildings. In this case, the building is constructed on a foundation containing springs or rubber that would absorb the shock and ground movement of even large earthquakes, isolating the energy of the earthquake from the structure.

Most of these steps are requirements for new structures. In addition, existing structures can be retrofitted to meet these standards. Thousands of homes in seismically active areas of the western United States have been modified to be more earthquake resistant.

With fire being the major cause of property damage in most earthquakes, California also requires utilities such as hot water heaters to be securely fixed to a wall rather than left freestanding. Storage facilities for materials such as flammable gases and liquids or caustic chemical are prohibited from sites considered to have the highest potential for large earth movements.

SEISMIC RETROFITTING Modification of structures to better withstand earthquake stresses.

Meanwhile, roadway construction has been commonplace as thousands of bridges have undergone **seismic retrofitting**, or modification to better withstand earthquake stresses. The effort to complete the retrofitting accelerated after the 1994 Northridge earthquake in Los Angeles, a magnitude 6.7 event that collapsed two freeways (Figure 4.25). Seismic retrofitting of freeway overpasses and parking garages (among other structures) involves such measures as wrapping metal sleeves around concrete columns to keep the columns from collapsing.

Such building standards and retrofitting are not the norm in all parts of the country, however—something of concern to many seismologists. While most North American earthquakes occur in the seismically active regions at the plate boundaries along the West Coast, many other areas of the continent have the occasional earthquake. The New Madrid Seismic Zone area continues to generate quakes and a large one is likely to happen again in that area. The largest earthquake on the East Coast of the continent was the 1886 magnitude 7.6 Charleston earthquake mentioned earlier. Damages during the New Madrid and Charleston events were limited by low population densities at the time; however, that is no longer the case. Memphis, Tennessee, is fairly close to the New Madrid zone, and the region around Charleston is also densely populated.

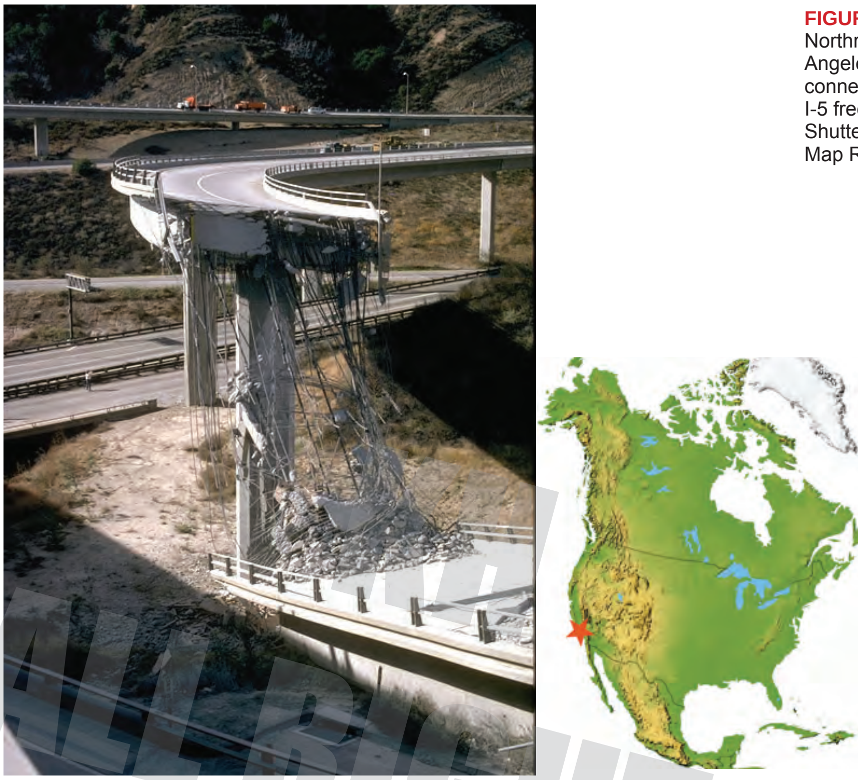


FIGURE 4.25 The 1994 Northridge earthquake in Los Angeles collapsed an overpass connecting the I-14 freeway to the I-5 freeway. Photo: USGS; Map: Shutterstock 15180868, credit Map Resources.

In spite of their seismic history, however, building codes in east of the Mississippi do not necessarily reflect the risk of earthquakes. To add to the seismic hazard, many of the homes in these areas are historic, built well before earthquake awareness became widespread. A repeat performance of the New Madrid or Charleston quakes is likely to cause greater damage and casualties than would be seen in a West Coast quake of the same magnitude, simply because the preparation has not been done.

Liquefaction Mapping

In addition to building better structures and reinforcing old ones, seismologists and geologists are actively mapping areas to better predict the impact of earthquakes in those areas. Of particular interest are liquefaction hazards, which are now part of the geological analysis that takes place before new projects are approved. In addition, the United States Geological Survey publishes maps of liquefaction zones in California and other many seismically active areas (see Figure 4.26 on page 174). Knowing whether an area is subject to liquefaction can help residents in their home buying decisions and in the development of their emergency plans. It also provides data for disaster teams in determining where the most assistance is likely to be needed.

Liquefaction mapping is also useful in land use planning. Because it has been long known that buildings with foundations anchored into bedrock have the best chance of surviving an earthquake while those built on fill, especially water-logged fill, have the highest levels of damage, the construction of new commercial or residential developments on such sites is either discouraged or prohibited.

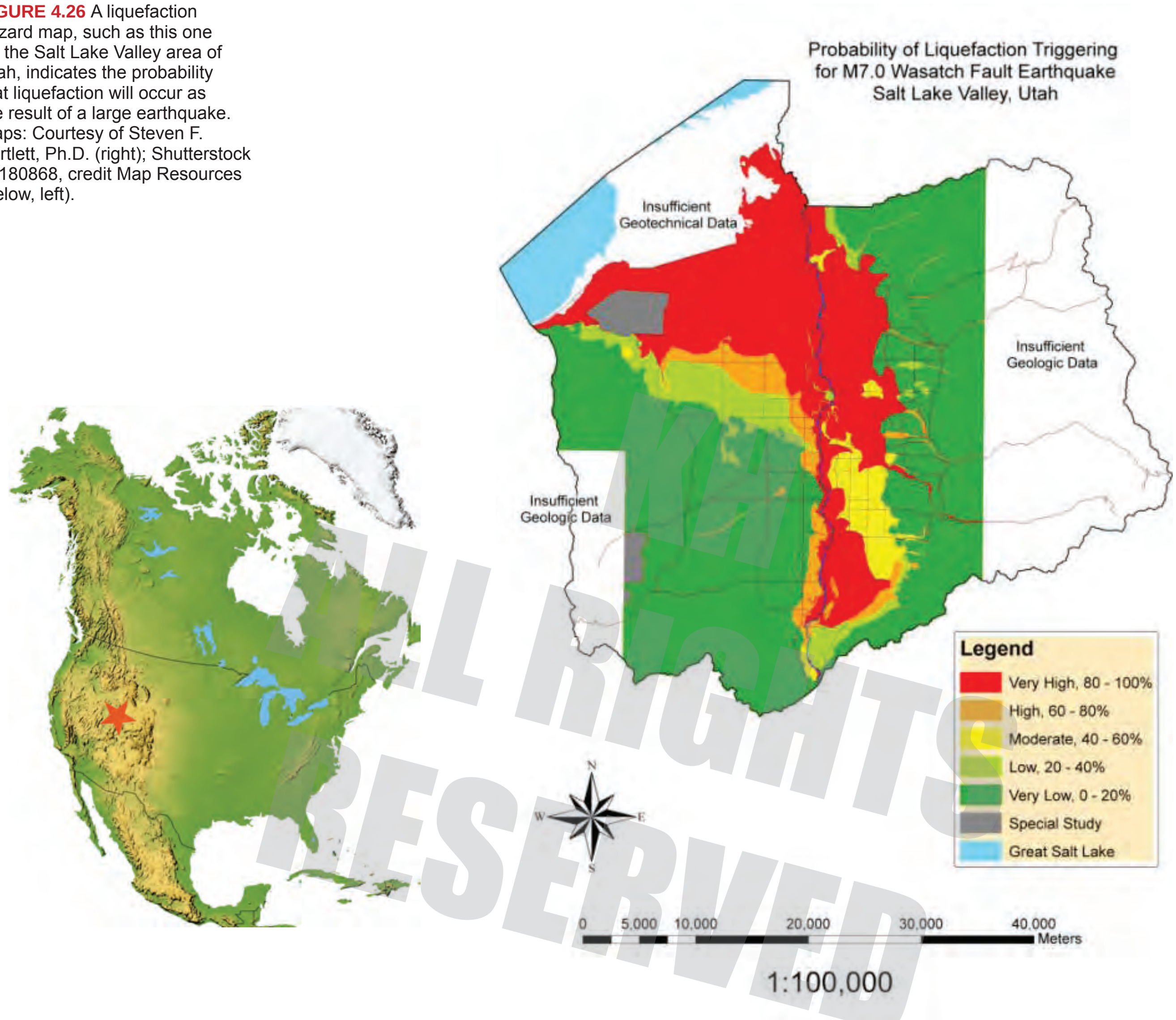


FIGURE 4.26 A liquefaction hazard map, such as this one for the Salt Lake Valley area of Utah, indicates the probability that liquefaction will occur as the result of a large earthquake. Maps: Courtesy of Steven F. Bartlett, Ph.D. (right); Shutterstock 15180868, credit Map Resources (below, left).

Concept Check

1. How was most of the damage in the 1906 San Francisco earthquake caused?
2. How did the recovery from the 1906 earthquake contribute to damage in the 1989 Loma Prieta earthquake?
3. Describe why unconsolidated sediment and liquefaction produce greater amounts of damage to an area struck by an earthquake.

4.4 EARTHQUAKE PREDICTION

Hundreds of millions of people who live in the world's seismically active area would be delighted and relieved to receive an accurate prediction of when and where the next large earthquake will strike. So far, seismologists have not been able to accommodate them. They are, however, conducting the research that may one day lead to the ability to better predict earthquakes. Such research depends first on the accurate collection of data.

4.4.1 Worldwide Seismic Network

Prediction of future earthquakes begins with the accurate accumulation of data about past earthquakes. Analysis of such data may allow scientists to discover patterns that can be used in making predictions. To provide a database of such data, the U.S. Department of the Interior established the National Earthquake Information Center (NEIC) at Golden, Colorado. This network includes more than 3,000 seismic stations located in 120 countries worldwide, including the United States, that constantly send their data to the NEIC (Figure 4.27).

Agencies use this data to quickly estimate the magnitudes, foci and epicenters of earthquakes occurring worldwide. The data is used not only for analysis but also to alert global relief agencies when there is a major earthquake so that they can provide emergency assistance to the area.

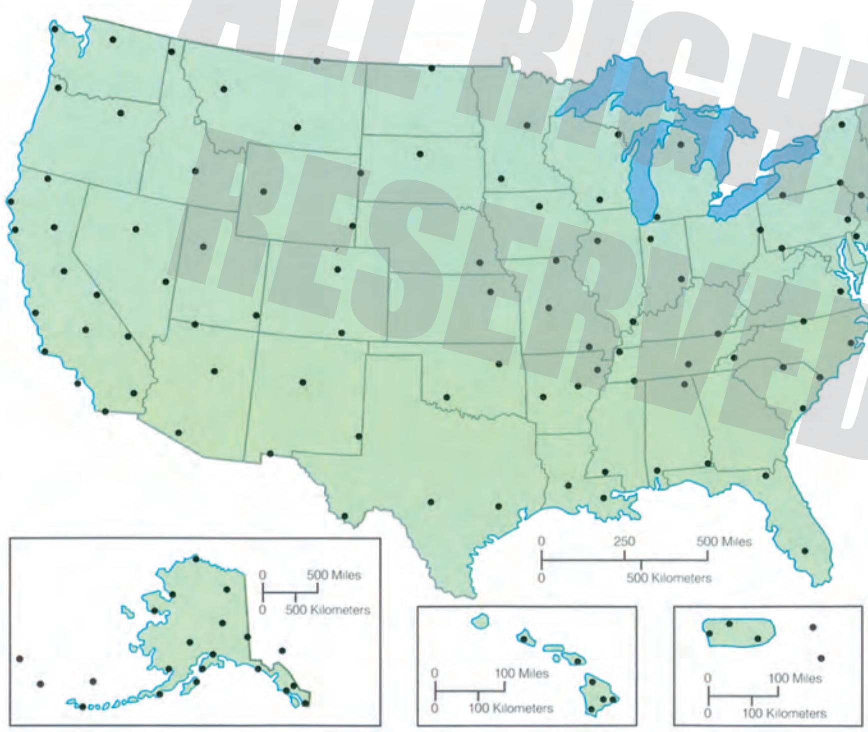


FIGURE 4.27 The U.S. National Seismograph Network (USNSN) consists of 120 cooperating seismic stations that provide seismic data to the National Earthquake Information Center (NEIC) at Golden, Colorado, where they are combined with data from more than 3,300 stations worldwide. The center not only conducts research to improve our ability to detect and locate earthquakes worldwide, but also is closely associated with organizations whose mission is to provide disaster relief to areas struck by major earthquakes anywhere in the world. Illustration by John J. Renton.

4.4.2 Paleoseismology

The data gathered by the NEIC network only provides information on earthquakes occurring since its establishment. To detect patterns in earthquake activity, it is also necessary to have information about earthquakes that have occurred in the past. One source of information is historical records, which often provide enough facts for geologists to estimate both a magnitude and an epicenter. The epicenter, in turn, reveals information about faults that exist in the area.

FIGURE 4.28 Paleoseismologists look for evidence of ancient earthquakes by digging trenches in fault zones. This trench has been dug to study a fault in Nevada's Basin and Range Province. The main fault zone is exposed in the area above the head of the person in the bottom of the trench. Photo: USGS.

Another source of data comes from the field of **paleoseismology**, which involves studying Earth's layers for signs of ancient earthquakes. Paleoseismologists make trenches along known faults and enter them to look for clues to previous earthquakes that may have appeared in the last ten thousand years or so (Figure 4.28). If there are any organic materials mixed into the layers, they are also able to use techniques (described in Chapter 9) to determine when those layers were first deposited. In this way, they can calculate the age of any evidence of ruptures in the fault zone and then calculate the intervals between earthquakes in the past, which would indicate an average recurrence time. Historical data plus an average recurrence time can indicate about when the next earthquake along that segment of a fault zone is likely to happen, if the pattern holds.

PALEOSEISMOLOGY
The geological study of prehistoric earthquakes.

SEISMIC GAP
A segment of a fault whose rupture is overdue.

Seismic Gaps

One outcome of such analysis is the identification of **seismic gaps**, segments along a fault zone that haven't had an earthquake within the average recurrence time. Seismic gaps occur because movement along fault zones is not necessarily the same along the entire fault. A perfect example is the San Andreas Fault, a long fault with a well-known history. Some areas of the San Andreas move constantly, millimeters at a time. Because stresses do not build up, these areas are less prone to earthquakes. In other areas, however, friction keeps the plates from sliding past each other; instead, stress builds up and then releases on a fairly regular basis. A seismic gap is an area where that release is overdue.

A successful test of this approach to predicting earthquakes occurred in 2004. Seismologists had identified a segment of the San Andreas in Parkfield, California, as a seismic gap. Based on its history and inactivity, seismologists predicted a 90 percent chance of a rupture along this section of the fault by 2018. They launched a massive study that monitored fault movement so that they could collect data about conditions leading up to a rupture. In 2004, the Parkfield segment did fail, generating a magnitude 6.0 earthquake. It was the most thoroughly recorded earthquake in history, and it validated the process used to make the prediction.

4.4.3 Long- and Short-Term Earthquake Prediction

The prediction made for Parkfield is an example of a **long-term earthquake prediction,** one that is made in terms of probability of an earthquake happening over a number of years or decades. Such long-term prediction techniques have become commonplace. In fact, the USGS generates seismic hazard maps for many areas of the United States expressing the likelihood of earthquakes in terms of probability over the long term (Figure 4.29).

LONG-TERM EARTHQUAKE PREDICTION
An estimate of the probable occurrence of earthquakes years or decades into the future.

For instance, significant seismic gap currently exists where the San Andreas Fault bends in Southern California. The bend inhibits the movement of the Pacific Plate, building stresses that must eventually release. In 2007, seismologists estimated a 59 percent chance that a 6.7 magnitude—or higher—earthquake would occur within 30 years along this section, a densely populated area bordering the Los Angeles Basin. The magnitude could be as high as 7.8 and rupture a 200-mile segment of the fault. This is the earthquake Southern Californians refer to as "The Big One." It is important to note that Northern California, Portland, and Seattle have their own versions of "The Big One" based on earthquake patterns in their areas.

It would be a mistake to consider seismic hazards to be limited to the West Coast, however. Recall that four of North America's largest earthquakes occurred east of the Mississippi River: the three 8.0 quakes in the New Madrid Fault Zone and the 7.6 Charleston earthquake. Smaller earthquakes occur almost everywhere on the North American continent; in fact, in the twenty years from 1975 to 1995, only four states failed to have a single earthquake (Florida, Iowa, North Dakota, and Wisconsin). Some areas are located on faults capable of generating significant earthquakes. New York City, for example, lies above a network of faults that have generated several magnitude 5.0 quakes over the past 350 years. The faults are believed to be capable of producing a 6.0 or even a 7.0 earthquake—about the same size as predicted for Los Angeles.

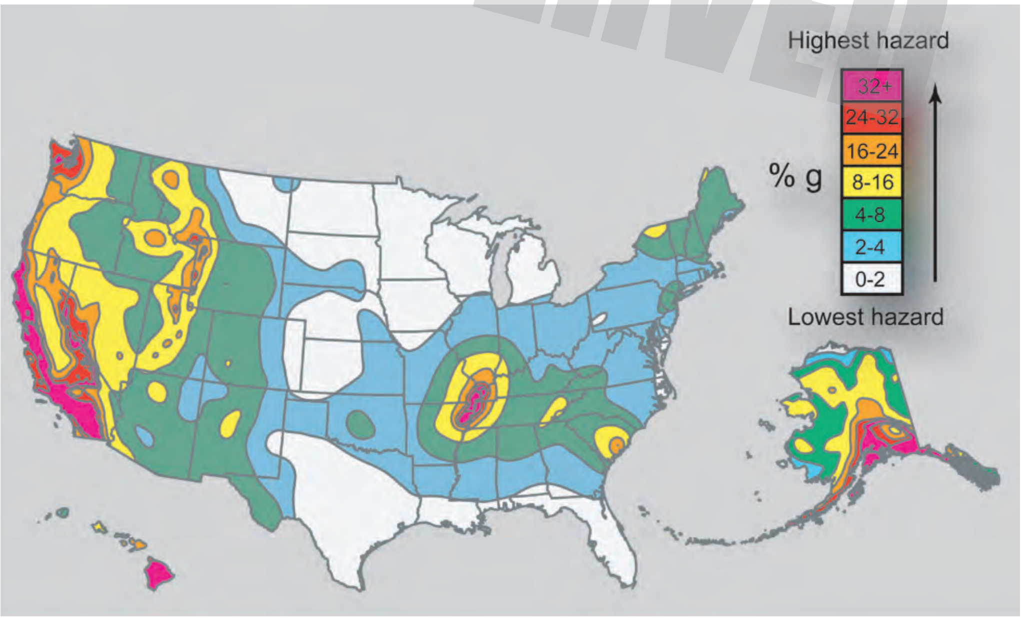


FIGURE 4.29 A simplified seismic hazard map of the United States showing probable ground movement of an earthquake calculated to be the maximum size likely for the area. The contours, from low to high hazard, are based on the acceleration due to the force of gravity ("percent g") during ground shaking. Image: USGS.

SHORT-TERM EARTHQUAKE PREDICTION
A prediction that a fault will rupture within days or weeks.

The usefulness of seismic hazard maps is primarily to planning agencies, whose staff must be prepared to respond when the inevitable happens. For individuals, long-term earthquake prediction suffers the same shortcomings as predictions of other natural events, such as volcanic eruptions and landslides: the precision of the prediction is not such that people will take notice on a day-to-day basis.

What both scientists and the general public want are **short-term earthquake predictions** that will accurately predict an earthquake event within a few days, or even hours, of its occurrence. This would allow time for the area to be evacuated, or for people to take precautions. However, earthquakes are complicated and data is still being gathered and analyzed, so the ability to make such short-term earthquake predictions is still a long way off.

Concept Check

1. How does paleoseismology contribute to earthquake prediction?
2. What information does a seismic hazard map give?
3. What is the difference between a long-term prediction and a short-term prediction?

SUMMARY

Earthquakes are a common occurrence in North America, particularly along the West Coast from California through Alaska. Earthquakes occur when rocks release stress, according to the elastic rebound theory, which states that pressures due to plate tectonics are stored in rocks, which respond elastically. When the elastic limit is exceeded, the rocks slip along a fault or break to create one, releasing energy in the form of seismic waves.

The focus and epicenter of an earthquake are located through triangulation using the time-travel chart from Chapter 1. Drawing spheres around three seismic stations, each with a radius of the distance between that station and the focus, creates one point of overlap that is the focus; the epicenter is the point on the surface directly above it.

Calculations of the foci of many thousands of earthquakes have revealed that most earthquakes occur at plate boundaries, although there are areas where intraplate earthquakes occur, including hot spots. Some 75 percent of earthquakes are shallow-focus earthquakes, less than 65 km deep. Intermediate-focus (65–300 km) and deep-focus (greater than 300 km) earthquakes occur only in subduction zones. These data provide evidence in support of plate tectonics theory.

Earthquakes are measured in terms of intensity and energy release. Intensity is expressed on the Modified Mercalli scale in terms of the impact of shaking on people and property, using values from I, where shaking is not felt, to XII, total devastation. Mercalli values are plotted on a shakemap that illustrates the extent and intensity of an earthquake's shaking. Energy release is measured in terms of ground movement, and is expressed by the local magnitude scale, often called the Richter scale, a logarithmic scale in which each point represents ten times the energy release of the point below it. Another scale, the moment magnitude scale, has been developed that is more accurate for earthquakes higher than about magnitude 8.

Most earthquakes are small and cause no damage. Significant earthquakes include the 1906 magnitude 7.8 earthquake that devastated San Francisco. After the earthquake crumbled many of the buildings, fire from broken gas mains swept through the city; the combination of shaking and fire destroyed 80 percent of the city. The largest recorded earthquake in North America occurred in 1964 in Alaska's Prince William Sound. With a moment magnitude of 9.2, it caused part of the crust to uplift several meters and other parts to subside several meters, generating ocean-wide and local tsunamis that wiped out several villages. The most deadly earthquake was China's 1556 Shensi earthquake that killed some 836,000 people, a toll that was largely the result of the practice of using loess to construct buildings, walls and temples. The loess could not hold up against the shaking of the earthquake, whose local magnitude exceeded 8, and collapsed. The 1989 Loma Prieta earthquake was a local magnitude 7 earthquake in the San Francisco area. The city fared better in this earthquake with the damage limited to buildings and the I-880 freeway.

Construction on unconsolidated materials, including those subject to liquefaction, were major contributing factors to the damage in the Loma Prieta earthquake. Unconsolidated materials are loose soil and rock and amplify the shaking of an earthquake, which brought down the freeway. Liquefaction occurs when water is added to the mix, and the shaking turns the soil/water mixture into quicksand, a process that collapsed many homes in San Francisco's Marina District. Earthquake damage protection involves the development of building codes that contain provisions that strengthen new structures against earthquake shaking, including bolting them to foundations. Existing buildings and freeway overpasses and bridges are undergoing seismic retrofitting in the seismically active states along the West Coast, strengthening them for future earthquakes. In addition, the mapping of liquefaction zones provides information for future construction projects as well as an indication as to where future earthquakes might do the most damage to existing buildings.

Earthquake forecasting is limited to long-term predictions expressed in terms of probability over a number of years. The worldwide seismic network provides data that allows seismologists to identify the strength and locations of earthquakes around the world, providing data that can then be analyzed for patterns. The field of paleoseismology, the study of ancient earthquakes, looks for patterns of past events in order to identify areas of seismic gaps, segments along faults that are overdue for an earthquake and along which pressure is highly likely to be building. Short-term predictions, those that would forecast an earthquake due in a few hours, days, or weeks, are not yet possible.

KEY TERMS

bedrock (p. 159)
consolidated sediment (p. 169)
deep-focus earthquake (p. 153)
elastic rebound theory (p. 151)
intensity (p. 159)
intermediate-focus earthquake (p. 153)
intraplate earthquake (p. 155)
liquefaction (p. 170)
local magnitude scale (p. 161)
long-term earthquake prediction (p. 177)
magnitude (p. 159)
Mercalli intensity scale (p. 159)
modified Mercalli Scale (p. 159)
moment magnitude scale (p. 162)
nomograph (p. 161)
paleoseismology (p. 176)
seismic gap (p. 176)
seismic retrofitting (p. 172)
shakemap (p. 159)
shallow-focus earthquake (p. 153)
short-term earthquake prediction (p. 178)
triangulation (p. 151)
unconsolidated sediment (p. 169)
Wadati-Benioff zone (p. 154)

ANSWERS TO CONCEPT CHECKS

4.1 DISTRIBUTION OF EARTHQUAKES

1. Can the earthquake focus and epicenter ever be at the same location?

   Yes, the focus of an earthquake, which is the location of the fault rupture and the surface location of the earthquake epicenter can be the same point if it is on the earth's surface.

2. How deep are the majority of earthquakes?

   Most earthquakes are shallow because rocks become plastic at greater depth and earthquakes take place when rocks store energy elastically and then suddenly break.

3. Is there a plate tectonic cause for most earthquakes?

   Yes, plate boundary interactions appear to be the cause of most earthquakes. Earthquakes also result from the movement of magma in volcanic areas, but the movement of the crust along active or inactive plate boundaries is the best explanation for the majority of earthquakes.

4. What is the Wadati-Benioff?

   The 45° plane which is the source of intermediate- and deep-focus earthquakes in a subduction zone.

5. What are intraplate earthquakes?

   Earthquakes that occur in the interior of a tectonic plate, far from any plate boundary.

4.2 MEASURING EARTHQUAKES

1. What does the Modified Mercalli Intensity Scale actually measure?

   The Modified Mercalli Scale is an intensity scale that measures the seismic motion felt by people as well as the damage that building and other structures experienced.

2. What does a shakemap illustrate?

   A shakemap uses color and shading to illustrate the intensity of an earthquake in areas surrounding the epicenter.

3. The local magnitude scale is not an earthquake intensity scale. What is it measuring?

   The local magnitude scale measures the amount of energy released by an earthquake by taking into account the movement experienced by recording stations. The amplitude of the pen motion on the seismogram and the distance from the epicenter shows how much energy is moving through the earth.

4. What kind of earthquakes does the local magnitude scale fail to accurately measure?

   Extremely large earthquakes cannot be accurately measured with the local magnitude scale. These enormous earthquakes have so much energy that a new system called the moment magnitude scale is used for these huge quakes.

4.3 EARTHQUAKE DAMAGE

1. How was most of the damage in the 1906 San Francisco earthquake caused?

    The shaking of the magnitude 7.8 quake devastated many buildings and broke gas mains that then caught on fire. What was not destroyed by the shaking was burned in the fire. Ultimately 80 percent of the city was destroyed.

2. How did the recovery from the 1906 earthquake contribute to damage in the 1989 Loma Prieta earthquake?

    Some of the debris from cleaning up the city after the 1906 earthquake was used as landfill to create the Marina District near the ocean. This was waterlogged, unconsolidated material that was subject to liquefaction during the 1989 earthquake. Much of the structural damage in the Loma Prieta earthquake occurred in the Marina District.

3. Describe why unconsolidated sediment and liquefaction produce greater amounts of damage to an area struck by an earthquake.

    Unconsolidated sediment amplifies the shaking of an earthquake; greater shaking means greater intensity. Soils subject to liquefaction turn to quicksand during an earthquake, eliminating ground support for structures that sag and collapse.

4.4 EARTHQUAKE PREDICTION

1. How does paleoseismology contribute to earthquake prediction?

    Paleoseismology is the study of ancient earthquakes. Paleoseismologists look for evidence of past earthquakes in order to establish patterns; the patterns can be used to determine if a segment of a fault is a seismic gap, overdue for an earthquake.

2. What information does a seismic hazard map give?

    A seismic hazard map shows the possible ground movement if an earthquake of the maximum predicted intensity occurs in a region.

3. What is the difference between a long-term prediction and a short-term prediction?

    Long-term predictions are those stated in terms of the probability of an earthquake over a period of decades. Short-term predictions, which are not feasibly made for earthquakes, would provide warning within hours, days, or weeks of an event.

REVIEW EXERCISES

1. How does elastic rebound theory explain the occurrence of earthquakes?

2. Describe how to find the focus and epicenter of an earthquake using a time-travel chart. What is this process called?

3. Which is the most common type of earthquake: shallow, intermediate, or deep focus?

4. What type of plate boundary generates deep-focus earthquakes?

5. Name two ways the distribution of earthquakes provides evidence for plate tectonics theory.

6. What caused the huge New Madrid earthquakes in 1811 and 1812?

7. How does the Modified Mercalli Scale measure earthquake intensity?

8. What does the local magnitude scale measure in an earthquake?

9. What is the moment magnitude scale, and why was it developed?

10. What did the 1906 San Francisco earthquake teach seismologists and governments?

11. When earthquake waves pass through water-saturated soil, liquefaction sometimes occurs. What is liquefaction?

12. The deadliest earthquake in history took place in China in 1556. Why was it so deadly?

13. What are some construction standards that help to prevent earthquake destruction and where are they in effect?

14. What are seismic gaps, and why do they interest seismologists?

15. Explain the value of short-term earthquake predictions.