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TWELFTH EDITION

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CHAPTER 5

Earthquakes Throughout the United States and Canada

Eventually, everything east of the San Andreas fault will break off and fall into the Atlantic Ocean.

—MICHAEL GRANT, 1982, *SAN DIEGO UNION*

LEARNING OUTCOMES

Earthquakes occur in many places not related to plate tectonics. After studying this chapter you should

- recognize the complexities of fault movements.
- realize the lack of connection between earthquakes and weather.
- know how the dates and magnitudes of prehistoric earthquakes can be determined.
- understand our inability to make short-term predictions of earthquakes.
- know the ways that humans trigger earthquakes.
- realize that earthquakes occur in every state.
- be familiar with the relationship between volcanism and earthquakes.

OUTLINE

- How Faults Work
- Thrust-Fault Earthquakes
- Normal-Fault Earthquakes
- Neotectonics and Paleoseismology
- Earthquake Prediction
- Things to Keep in Mind
- Human-Triggered Earthquakes
- Earthquakes in the United States and Canada
- Western North America: Plate Boundary–Zone Earthquakes
- Intraplate Earthquakes: "Stable" Central United States
- Intraplate Earthquakes: Eastern North America
- Earthquakes and Volcanism in Hawaii

Highway 287 in Montana was destroyed by the Hebgen Lake earthquake on 17 August 1959.

R.B. Colton/U.S. Geological Survey

Ground shook. People were shocked. An earthquake in Virginia was felt by more people in the United States than during any previous seism. It happened at 1:51 p.m. on Tuesday, 23 August 2011, as a 5.8M_w earthquake near the town of Mineral. The earthquake shook eastern North America and rattled the nerves of millions of people. Office workers in the Empire State Building ran down dozens of flights of stairs and poured out into the streets. Air traffic control towers were evacuated at busy eastern U.S. airports, fouling the travel plans of thousands of people. Cell phone service was overwhelmed. The earthquake was felt south to Atlanta; north to Montreal and New Brunswick Province, Canada; and west to Detroit and Chicago. Damages totaled about $300 million and were suffered as far as Washington, D.C., where the Washington Monument and the National Cathedral both cracked, and in Brooklyn, New York. And yet, there were no deaths or serious injuries. Easterners got a taste of what westerners frequently experience.

Because seismic waves move slower than Internet traffic, some Twitter users in New York City and Boston read about the earthquake before they felt it. The citizen-based earthquake intensity website *Did You Feel It?* received more than 100,000 reports within four hours.

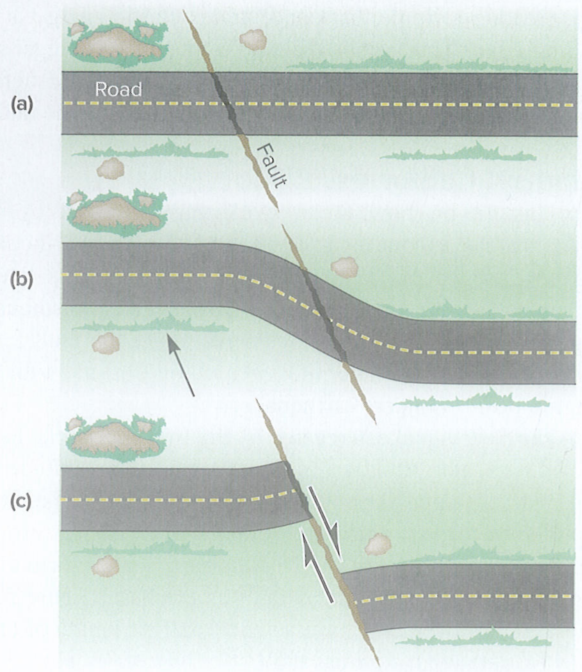


Figure 5.1 Elastic-rebound theory. (a) An active fault with a road as a reference line. (b) Deformation occurs along the fault, but friction of rock masses at the fault retards movement. (c) Finally, the deformation is so great that the fault ruptures, and the two sides race past each other and may actually catch up with and move past the earlier deformation.

How Faults Work

As our instrumentation and field equipment improve, we get better understanding of how faults work.

ELASTIC REBOUND

The popular explanation of how faults move has been the elastic-rebound theory developed after the 1906 San Francisco earthquake. Based on surveyors' measurements of ground along the San Andreas fault, it appears that Earth stresses cause deformation and movement on both sides of a fault (figure 5.1a, b). However, the rocks along the fault itself do not move in response to this stress because they are rough and irregular, resulting in strong interlocking bonds with **friction** that retards movement. But as the landmasses away from the fault continue to move, energy builds up and is stored as elastic strain in the rocks. When the applied stresses become overpowering, the rocks at the fault rupture, and both sides quickly move forward to catch up, and even pass, the rocks away from the fault (figure 5.1c). After a fault movement, all the elastic strain is removed from the area, and the buildup begins anew. The elastic-rebound theory is somewhat analogous to snapping a rubberband or twanging a guitar string; it even accounts for aftershocks. This idea has held sway for more than 100 years and is described in most textbooks. It still works as a first approximation to reality, but a better understanding has emerged in recent years.

NEWER VIEW

Movements along a fault may be better visualized as windows of opportunity. Fault movement begins at a hypocenter and then propagates outward for a certain distance and length of time. How much of the stored energy is released during an earthquake depends on the number of seconds the fault moves. For example, if there were 12 m (40 ft) of unreleased movement along a section of fault and the rupture event, passing by from front to end, lasted long enough for only 6 m (20 ft) of movement, then only half of the strain energy would have been released. An analogous event might be opening a locked gate to a long line of people. If the gate is held open only long enough for half the people to enter and is then closed and locked, the other people will simply have to wait until the next time the gate opens. This is an important modification of elastic-rebound theory. The elastic-rebound theory has said that after a big earthquake, most of the elastic strain is removed from the rocks, and considerable time will be required for it to build again to a high enough level to create another big earthquake. We no longer think this is true.

Another way to visualize how faults move is to imagine rolling out a large carpet to cover an auditorium floor. Suppose that the carpet misses covering the floor to the far wall by a foot. You can't pull the rug the rest of the way to the wall; it won't move because the friction is simply too great. However, if you create a large ripple in the carpet and push the ripple across the auditorium floor, the carpet can be moved. Faults may act the same way. A small portion of a fault may slip, creating a ripple that concentrates elastic energy at its leading edge. The farther the ripple travels, the bigger the earthquake. The moving ripple may encounter different amounts of unreleased energy in different areas of the fault.

Landers, California, 1992

New insight on how faults work was provided by the Landers area earthquakes in 1992 and 1999. This earthquake sequence began on 22 April 1992 with the right-lateral movement of the magnitude 6.1 Joshua Tree earthquake (figure 5.2). Right-lateral movements along the fault trend resumed two months later at 4:58 a.m. on 28 June with the magnitude 7.3 Landers earthquake.

A third earthquake, triggered by the first two, broke loose a few hours later. At 8:04 a.m. on 28 June, the magnitude 6.3 Big Bear earthquake came from a left-lateral movement that ruptured northeast toward the center of the Landers ground rupture. The ruptures of the 28 June earthquakes form a triangle, with the San Andreas fault as the base (figure 5.2). These fault movements have acted to pull a triangle of crust away from the San Andreas fault.

Activity continued along this trend on 16 October 1999 with the right-lateral movement of the Hector Mine earthquake in a magnitude 7.1 event (figure 5.2). Is this sequence of earthquakes finished? Probably not.

Examining the Landers earthquake records to see what happened during the 24 seconds that the faults moved 70 km (43 mi) can teach us a lot about *how faults move:*

1. Fault movements commonly are viewed as being restricted to one fault, with the rupture front stopping at large bends or steps in the fault, thus ending the earthquake. The Landers earthquake was different. It began right-lateral movement on the Johnson Valley fault and traveled northward about 20 km (12 mi) until reaching a right-step, pull-apart zone. The rupture front slowed, but it moved through the step and continued moving northward on successive faults for another 50 km (30 mi) until finally stopping within a straight segment of the Camp Rock fault (figure 5.3).
2. Rupture velocity on the Johnson Valley fault was 3.6 km/sec (8,000 mph), slowing almost to a stop in the right step and then continuing northward at varying speeds.
3. The amount of slip on the faults varied from centimeters to 6.3 m (21 ft) along the fault lengths and below the ground. Figure 5.4 shows the movements calculated by seismologists Dave Wald and Tom Heaton. Look at their cross-section and visualize the fault in movement as the rupture front snaked its way northward, up, down, and not always involving all the fault surface.
4. Notice how the amount of fault movement at the ground surface differs from that at depth (figure 5.4).

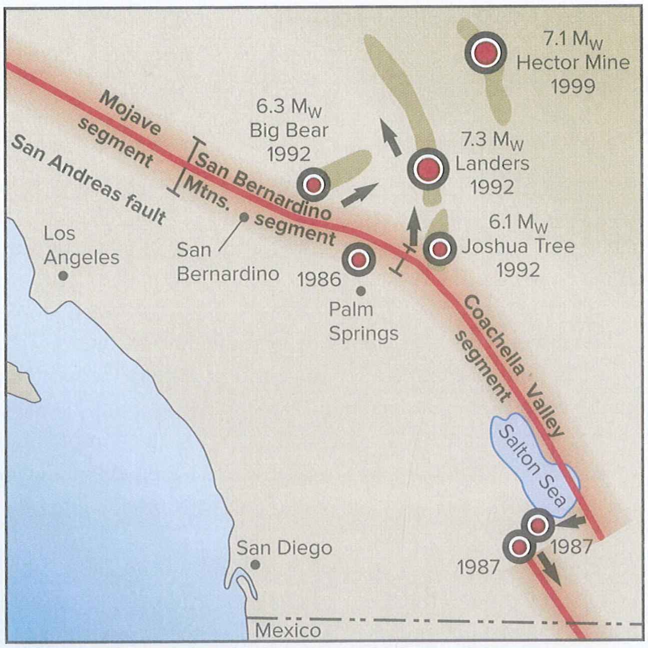


Figure 5.2 Map of major earthquakes near the northern and southern ends of the Coachella Valley segment of the San Andreas fault. The triangular block of crust near the northern end has moved northward.

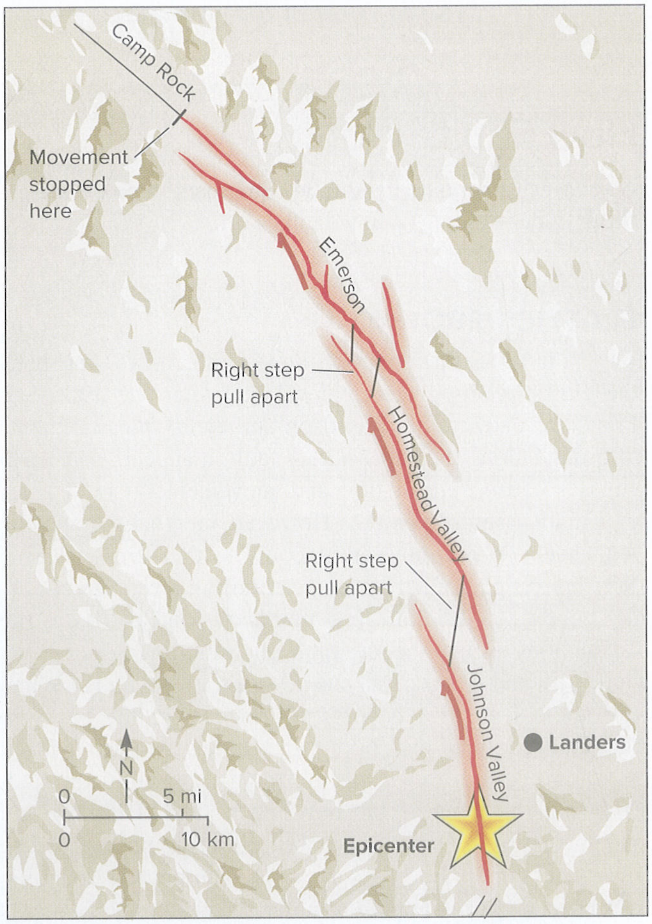


Figure 5.3 Northward-rupturing faults in the 1992 Landers earthquake. The rupture front slowed at right steps, and then moved onto adjacent faults before stopping in the middle of a straight segment.

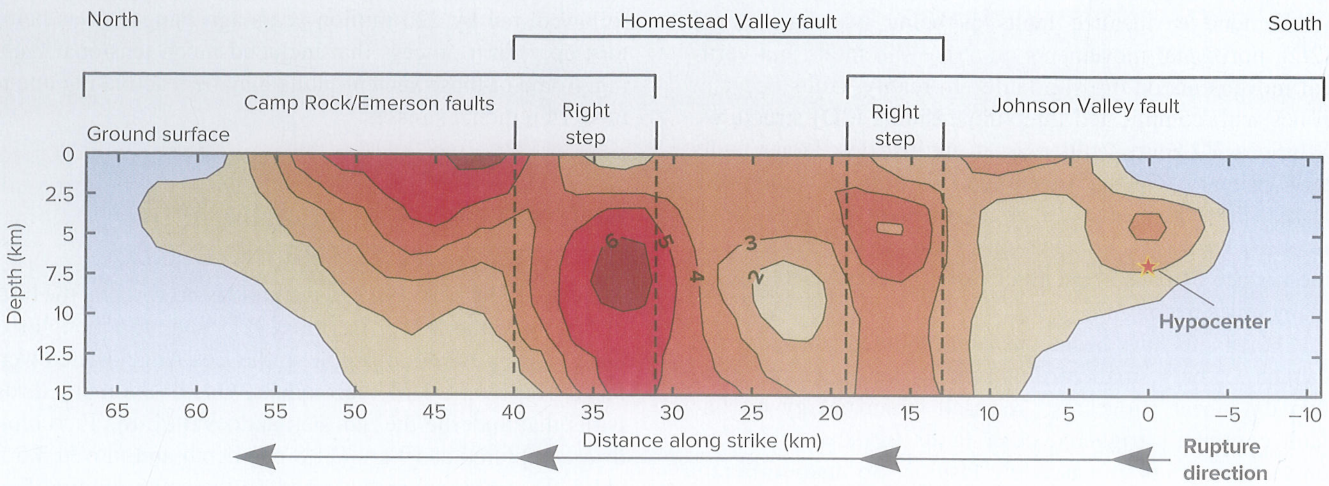


Figure 5.4 Slip on faults varied from centimeters to 6.3 m (21 ft) during movements of the 1992 Landers earthquake. The contour interval of slip areas is 1 m.

Source: Wald and Heaton in *Seismological Society of America Bulletin* 84:668-691, 1994.

5. Fault movement, and shaking, at the hypocenter was modest compared to what came later.
6. As the rupture front moved northward, only a small portion of the fault was slipping at any one time. Fault movement lasted 24 seconds, but the longest any one fault portion moved was less than 4 seconds.
7. Although the rupture front was slowed in a right step, the amount of slip behind the rupture front kept increasing until enough energy built up to cause movement through the step.
8. The earthquake triggered other earthquakes in Nevada, northern California, Utah, and Yellowstone Park, Wyoming. Fortunately for the Los Angeles megalopolis, the northward-moving fault directed its strongest seismic waves to the north into the sparsely inhabited desert. The triggered effects all occurred north of the northward-moving fault. This phenomenon is known as **directivity,** wherein a rupture moving along a fault sends more energy in the direction it is moving.
9. In the 1992 Landers earthquake, the faults moved from south to north; in the 1999 Hector Mine earthquake, it was the opposite, as the fault moved mostly from north to south.
10. Fault patches with little or no movement on figure 5.4 may become the origination points for future earthquakes.

Ridgecrest, California, 2019

Stunning movements occurred in July 2019 along mostly unmapped, short- and medium-length faults that intertwine and crisscross in near-perpendicular surface orientations. At least 24 small faults within a 75 km (45 mi) long by 20 km (13 mi) wide area ruptured in combinations to produce large earthquakes during an interval of 35 hours. On 4 July, three faults at right angles to each other moved in sequence for 12 seconds; this added up to a 6.4 M_w earthquake (figure 5.5, blue lines). On 5 July, about 34 hours later, during a 22-seconds-long interval, at least 20 intersecting faults ruptured, including four larger movements; these energy releases added up to a 7.1 M_w earthquake (figure 5.5, red lines).

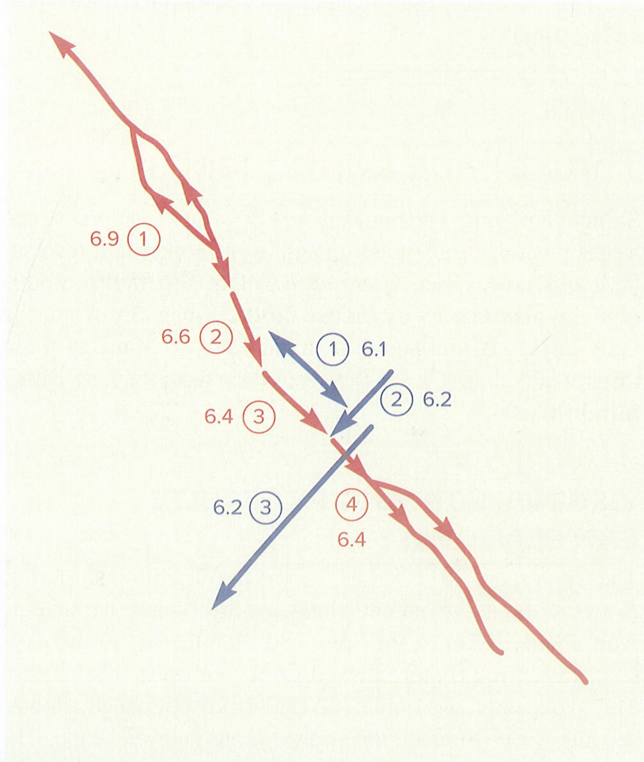


Figure 5.5 A 6.4 Mw foreshock ruptured three main perpendicular faults (blue lines) in numbered order. Aftershocks continued along a northwest trend until four big subevents (red lines) in numbered order quickly added up to a 7.1 M_w mainshock. Arrows show directions of fault rupture. Note that the 6.4 M_w foreshock is the total of energy released by three events: a 6.1 plus a 6.2 plus another 6.2.

We tend to idealize faults as being two-dimensional (2D); horizontal movements on strike-slip faults and vertical movements on dip-slip faults. In reality, faults occur in zones with complicated three-dimensional (3D) structures. Within a 3D zone, faults exist in multiscales; larger faults with primary slip are surrounded by smaller faults with lesser slip, which are, in turn, surrounded by highly fractured rock masses. This complex system of faults seen on the surface extends in irregular patterns down through rock many miles deep.

Short faults have been considered to be independent and capable of only small earthquakes. However, during these two days near Ridgecrest, released strain energy on one fault commonly triggered other faults to move—and then on to other faults, in cascading fashion. So many different faults moving in a 3D pattern during an earthquake episode is a game-changer for seismic-hazard assessments. Forecasting all the possible combinations of faults that could move during a single episode is challenging. There is now a need to reexamine current disaster-preparation plans and consider whether their earthquake potentials have been underestimated.

Thrust-Fault Earthquakes

Some damaging earthquakes result when compressional forces push one rock mass up and over another in a reverse-fault movement (see figure 3.10). Dip-slip faults of this type are also known as **thrust faults,** especially when the fault surface is inclined at a shallow angle. Many of these thrust faults do not reach the ground surface; they are called **blind thrusts.**

VIRGINIA, 2011: ANCIENT FAULTS CAN REACTIVATE

The 23 August 2011 5.8 M_w event in Virginia occurred as a reverse-fault movement along a north-northeast striking fault about 10 km (6 mi) long and dipping 50° to the east-southeast. Fault rupture moved from southwest to northeast. The hypocenter was only 6 km (3.7 mi) deep, which allowed seismic waves to reach the surface largely unweakened. The earthquake shook loose within the Central Virginia Seismic Zone, which has a similar length and width, each about 120 m (75 mi). Small earthquakes are frequent in this zone. Moderate-size events include a 4.5 M_w event on 9 December 2003 and a ~4.8 M in 1875.

We like to explain earthquakes using plate-tectonic processes. But eastern North America does not have active tectonic-plate edges now, but it has a plate-tectonic past. More than 480 million years ago, continent collision, which included much reverse faulting, began building the Appalachian Mountains. This was part of the assembly of the supercontinent Pangaea (see figure 2.24). More collisions followed, but by 220 million years ago Pangaea was being torn apart in a process that included much tensional faulting. Some of these ancient faults may be reactivating due to modern regional stresses.

NORTHRIDGE, CALIFORNIA, 1994: COMPRESSION AT THE BIG BEND

Monday, 17 January 1994, was a holiday celebrating the birth of Martin Luther King, Jr. But at 4:31 a.m., the thoughts of most of the 12 million people in the Los Angeles area were taken over by a 6.7 M_w earthquake. One of the many thrust faults that underlie the San Fernando Valley, the Pico blind thrust, ruptured at 19 km (11.8 mi) depth and moved 3.5 m (11.5 ft) northward as it pushed up the south-dipping fault surface (figure 5.6). Northridge and other cities setting on the upward-moving fault slab (hangingwall) were subjected to some of the most intense ground shaking ever recorded. Ground acceleration was as high as 1.8 g (180% of gravity) horizontally and 1.2 g vertically. (At 1.0 g vertical acceleration, unattached objects on the ground are thrown up into the air.) This intense shaking caused the widespread failure of buildings (figure 5.7), parking garages (see figure 3.33), and bridges that killed 57 people, injured 9,000 more, and caused $40 billion in damages. The damages included the disabling of the world's busiest freeway system, creating months of problems for drivers (see figures 3.30 and 3.36). In terms of deaths, this earthquake can be viewed as a near miss due to its early morning occurrence. Analysis of the failed buildings indicates that an estimated 3,000 people would have died if the seism had occurred during working hours.

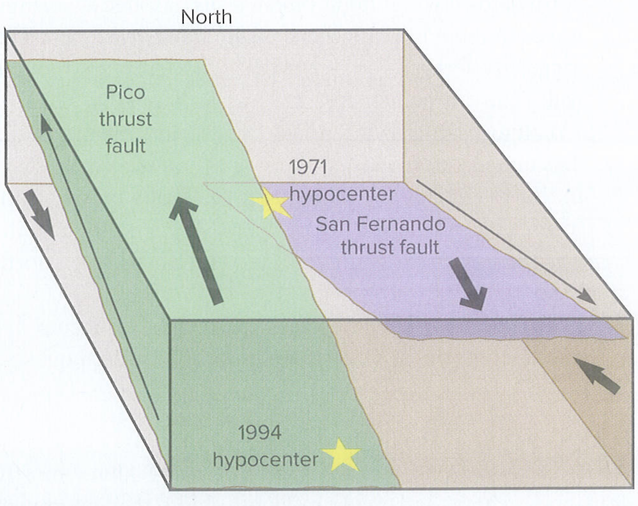


Figure 5.6 Block diagram of thrust-fault movements that created the 1994 Northridge and 1971 San Fernando earthquakes. In 1994, the Pico blind thrust fault moved 3.5 m (11.5 ft) *up to the north* from a 19 km (11.8 mi) deep hypocenter. The cities "riding piggyback" on the upward-moving thrust plate experienced intense ground shaking. In 1971, a block moved *up to the south* on the San Fernando thrust fault from a 15 km (9.3 mi) deep hypocenter.

Figure 5.7 The Kaiser-Permanente Hospital in Granada Hills collapsed during the 17 January 1994 earthquake. It was an older, non-ductile concrete-frame building.
Source: M. Celebi, USGS/NGDC/NOAA

The 1994 Northridge event was similar to the 1971 San Fernando earthquake, which had a magnitude of 6.6 and killed 67 people (see chapter 3). In 1971, the movement was up a north-dipping thrust fault that abuts the blind thrust that moved in 1994 (figure 5.6). In 1971, the energy was directed *toward* the city of Los Angeles, but in 1994, the energy was directed *away* from the city.

Southern California pushes northward against the "Big Bend" of the San Andreas fault, creating thrust faults that are mostly east-west oriented (figure 5.8). Satellite measurements of ground movement using the global positioning system (GPS) tell us that the Los Angeles region is experiencing a compressive shortening of 10 to 15 mm/yr. The measured deformation could generate an earthquake with a magnitude in the mid-6s every six years, plus a seism of magnitude 7 every 10 years.

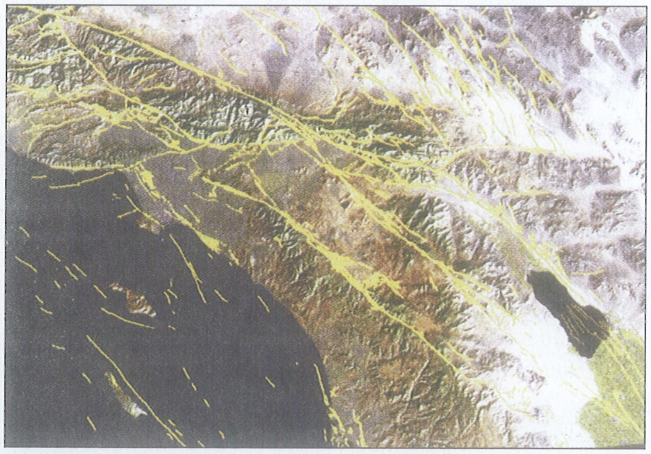


Figure 5.8 Active faults in southern California are shown in yellow. The southern end of the San Andreas fault is on the east side of the Salton Sea (lower right). Follow the San Andreas fault up and to the left where it exits the photo in the upper left corner. The photo shows the San Andreas in its "Big Bend" that southern California pushes against, creating mountains and thrust-fault earthquakes.
Source: Jet Propulsion Laboratory/NASA

The 1971 and 1994 earthquakes may be omens for a more earthquake-active 21st century. The death and destruction from numerous magnitude 6.5 to 7 earthquakes on thrust faults within the city of Los Angeles would exceed the problems caused by a magnitude 8 event on the San Andreas fault some 50 to 100 km away.

SEATTLE, WASHINGTON

The Seattle fault zone is oriented east-west and runs along the south side of Interstate 90 through the city of Seattle (figure 5.9). The fault zone is 4 to 6 km (2.5 to 3.7 mi) wide and has three or more south-dipping reverse faults. A major fault movement occurred there about 1,100 years ago, as indicated by the following evidence: (1) The former shoreline at Restoration Point was uplifted about 7 m (23 ft) above the high-tide line in a single fault movement. This earthquake appears to have had a magnitude of around 7, about the size of the 1989 World Series event in the San Francisco Bay area. (2) Numerous large landslides occurred at this time, including some that carried trees in upright growth position to the bottom of Lake Washington. The age of these trees was determined by carbon-14 dating. (3) Several tsunami deposits have been recognized in the sediment layers of the area. Logs and trunks carried or buried by these large waves date to the same time period. (4) The same date appears in the ages of six major rock **avalanches** in the Olympic Mountains. The avalanches apparently were shaken into action by the earthquake. (5) Coarse sediment layers on the bottom of

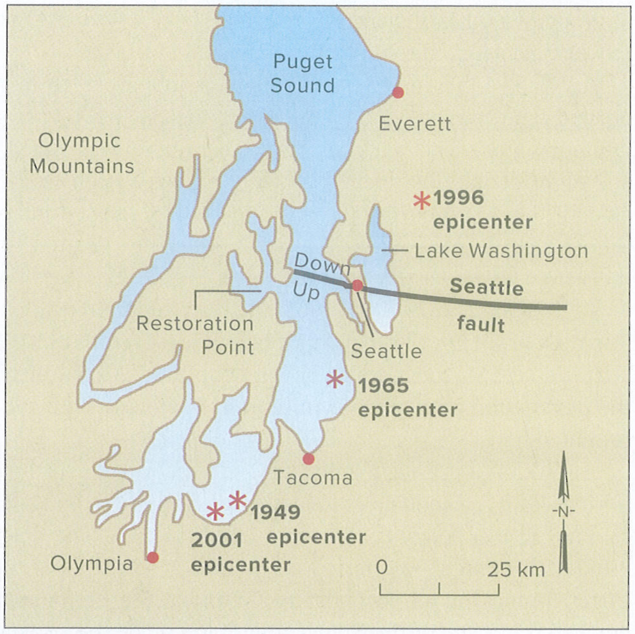


Figure 5.9 Map of the Puget Sound area. *Up* and *down* refer to movements on the Seattle fault.

Lake Washington were formed by downslope movement and redeposition of sediment in deeper waters. These distinctive deposits appear to have been caused by the same earthquake.

Part of Seattle sits on a 10 km (6+ mi) deep basin filled with soft sediments that shake severely during an earthquake. Seattle residents were reminded of this earthquake hazard on 3 May 1996, when a magnitude 5.4 seism struck northeast of the city. Shaking in downtown Seattle's Kingdome was intense enough in the seventh inning of a baseball game between the Seattle Mariners and Cleveland Indians to cause postponement of the game. The owner of the Seattle Mariners then tried to use the earthquake as justification for breaking his lease with the Kingdome. (The team now plays in a new stadium.) When the next major earthquake (greater than magnitude 6.5) occurs on the Seattle fault, it may cause stunning levels of death and destruction. There are about 80 bridges and 1,000 unreinforced masonry (URM) buildings that could suffer damages plus a tsunami 2 m (6.5 ft) high could be created.

Normal-Fault Earthquakes

Some damaging earthquakes result when tensional forces pull one rock mass apart and down from another in normal-fault movements (see figure 3.9).

PUGET SOUND, WASHINGTON, 1949, 1965, 2001: SUBDUCTING PLATES CAN CRACK

In recent decades, normal-fault movements have brought seismic jolts to cities in the Puget Lowlands (figure 5.9). Three of these significant earthquakes were caused by down-to-the-east movements *within* the subducting Juan de Fuca plate.

At 11:55 a.m. on 13 April 1949, a jolt arose from a normal-fault movement 54 km (34 mi) below the Tacoma-Olympia area. The surface wave magnitude was 7.1M_s, and eight people lost their lives. It could have been worse, since it happened during the day and badly damaged many schools, but luckily, it was the week of spring vacation, so the schools were largely vacant.

At 7:28 a.m. on 29 April 1965, the plate ruptured again—this time at 60 km (37 mi) depth below the Tacoma-Seattle area. The 6.5M_s seism killed seven people. In 2014 dollars, the destruction totaled $345 million in 1949 and $115 million in 1965.

At 10:54 a.m. on Wednesday, 28 February 2001, a normal-fault earthquake radiated out from a hypocenter 52 km (32 mi) below the Tacoma-Olympia area. The magnitude 6.8 event shook more than 3 million residents of the Puget Sound for 45 seconds. In Olympia, the earthquake cracked the dome of the State Capitol and made the legislators' offices unusable and the governor's home uninhabitable. In Seattle, 30 people were caught on top of the swaying Space Needle, bricks fell from the Starbucks headquarters building onto parked cars, and Bill Gates's talk at a hotel was interrupted as overhead lights crashed to the floor and frightened people knocked down others in their hurry to get outside. The earthquake killed no one, injured about 400 people, and caused about $2 billion in damages.

In each case, settling of soft sediments and artificial fill during the shaking caused major problems for structures built on them. There was substantial damage to older masonry buildings with inferior mortar and to buildings with inadequate ties between vertical and horizontal elements. Split-level homes suffered more than their share of damage as their different sections vibrated at different frequencies, helping tear them apart.

For all the damage the 2001 earthquake caused, the damage it did *not* do is even more significant. Following the 1965 earthquake, Washington improved its building codes and made many structural changes, such as tying homes to their foundations more securely, removing water-storage tanks from the tops of school buildings, and strengthening more than 300 highway bridges. These investments were more than repaid in damages prevented and lives saved during the 2001 earthquake.

Deep Earthquakes Beneath the Puget Sound

Primary emphasis on earthquake hazards in the Pacific Northwest has been focused on the subducting plates. The hypocenters in the 1949, 1965, and 2001 events were *within* the subducting plate at depth. Earthquakes 30 to 70 km (20 to 45 mi) deep occur beneath the Puget Sound about every 30 years. The subducting Juan de Fuca plate is only 10 to 15 million years old and is warm and buoyant. As the plate is pulled eastward, it reaches greater depths. The increasing temperature and pressure with depth cause the minerals making up the plate to become more dense and shrink. This builds up stresses that cause the plate to rupture, producing earthquakes with magnitudes as large as 7.5.

Neotectonics and Paleoseismology

Geologic history plays out on a longer timescale than human history. An active fault may have a large earthquake only once in several generations. How can the earthquake record be extended back further than the written historic record? Earthquake history can be read in sediments using the techniques of **neotectonics** (*neo* means "young") and **paleoseismology** (*paleo* means "ancient").

Faults slash through the land with compressive bends that cause land to uplift and with pull-apart bends that cause land to drop down (figures 5.10 and 5.11). The down-dropped or fault-dammed areas within the fault zone can become sites of ponds, receiving (1) sand washing in from heavy rains,

Figure 5.10 A close-up of the San Andreas fault at Wallace Creek in the Carrizo Plain. Notice the offset streams and the ponded depressions formed at the fault. Have the movements been right or left lateral?
Pat Abbott

(2) clays slowly settling from suspension in ponded water, and (3) vegetation that lives, dies, and is buried by clay and sand. These processes produce a delicate record of sediment layers that may be disturbed and offset by later fault movements. This is a record we can read.

Older, more deeply buried layers have existed longer (figure 5.12) and have been offset by more earthquake-generating fault movements. The amount of fault offset is proportional to an earthquake's magnitude; the greater the offset of sediment layers, the bigger the earthquake. These principles suggest a method to determine the approximate sizes of prehistoric earthquakes. Simply dig a trench through the sediment infill of a fault-created pond and read the fault offsets recorded in the sediments (figures 5.12 and 5.13). Sediment layers in trench walls can be traced by digging a network of intersecting trenches to gain a three-dimensional view of fault offsets through time (figure 5.14).

Dates of prehistoric earthquakes can be obtained by analyzing amounts of radioactive carbon in organic material (e.g., logs, twigs, leaves, and **coal**) in the sediment layers. All life uses carbon as a fundamental building block. Most carbon occurs in the isotope ^{12}C, but a small percentage is radioactive carbon (^{14}C) produced in the atmosphere by bombardment of nitrogen atoms with subatomic particles emitted from the Sun. Carbon is held in abundance in the atmosphere as carbon dioxide (CO_2). All plants and animals draw in atmospheric CO_2, and their wood, leaves, bones, shells, teeth, etc., are partly built with radioactive carbon. As long as an organism lives, it exchanges carbon dioxide with the atmosphere via **photosynthesis** or breathing. The percentage of radioactive carbon in a plant or animal is the same as that of the atmosphere during the organism's lifetime. However, when an organism dies, it ceases taking in radioactive carbon, and the radiocarbon in its dead tissues decays with a half-life of 5,730 years. The presence of organic material allows us to determine the time of death and hence the age of enclosing sediments. This places actual dates into faulted sedimentary layers. The determination of real dates allows us to estimate the recurrence intervals for earthquakes—that is, how many years pass between earthquakes at a given site.

The half-life of ^{14}C is short, thus restricting its usage to the last 50,000 years or so. This short half-life is useful for determining events in human history.

Figure 5.12 is a schematic representation of a trench-wall exposure of faulted pond sediments, demonstrating how fault-rupture sizes and recurrence intervals may be determined. A real example of a faulted pile of ponded sediments is shown in figure 5.13. Here at Pallett Creek along the San Andreas fault, geologist Kerry Sieh has determined that fault movements with 6 m (20 ft) of horizontal offset recur about every 132 years. However, these 7+ magnitude earthquakes have occurred as close together as 44 years and as far apart as 330 years.

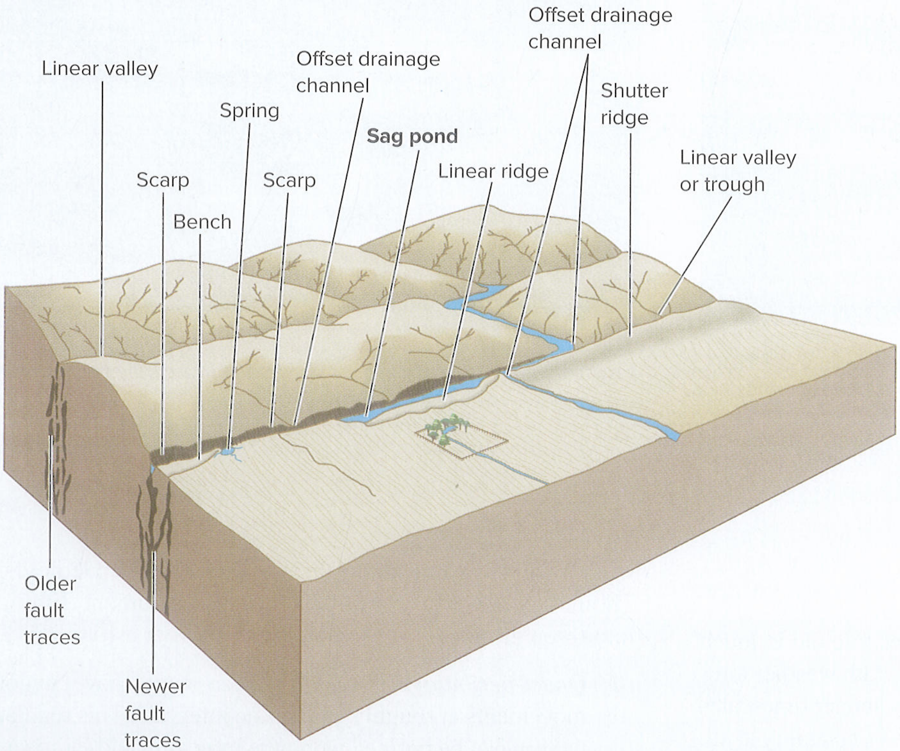


Figure 5.11 Schematic diagram of topography along the San Andreas fault in the Carrizo Plain. Notice the sag pond here and in figure 5.10. Sediments deposited in these depressions allow the prehistoric record of earthquakes to be read.
Source: Misc. Geol. Invest., US Geological Survey.

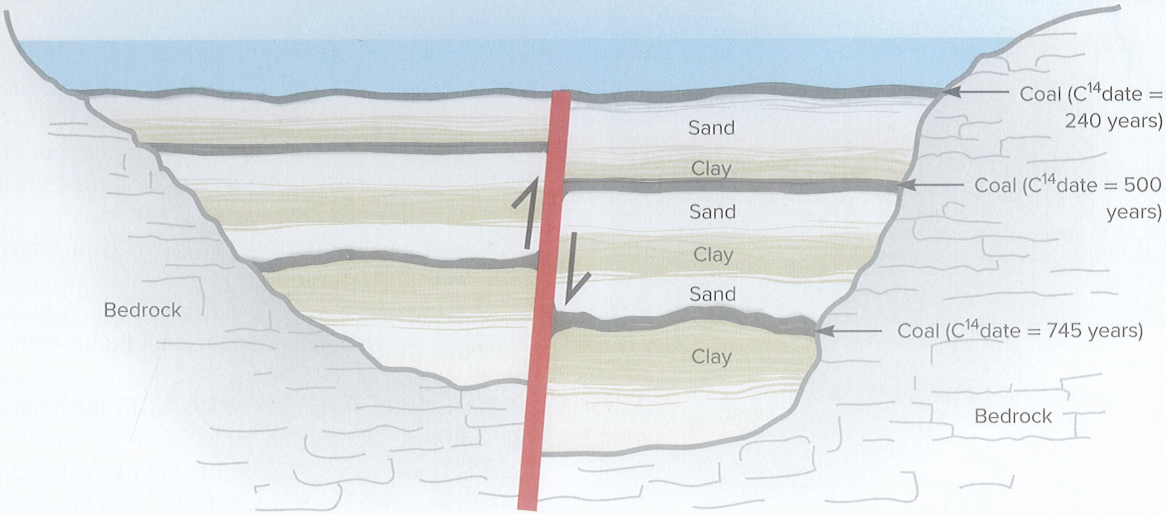


Figure 5.12 Schematic cross-section of trench wall cut through a fault-created pond. The fault offsets the once-continuous sediment layers. Notice that an upper layer of organic material formed 240 years ago is unbroken. At depth, a 500-year-old organic-rich layer has been offset. Deeper still, a 745-year-old organic-rich layer has been offset twice as much, indicating two major fault movements since it formed. What is the approximate recurrence interval between earthquakes at this site? When might the next big earthquake be expected here?

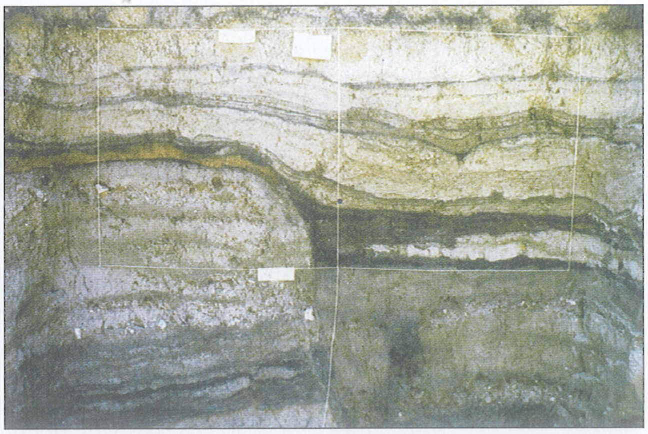


Figure 5.13 A trench wall across the San Andreas fault at Pallett Creek. Sandy layers are whitish, clay-rich layers are grayish, and organic-rich layers are black. The black layer in the center formed about 1500 CE. It has been offset 1.5 m (5 ft) horizontally and 30 cm (1 ft) vertically since 1500 CE.

Pat Abbott

Figure 5.14 Maze of trenches dug to determine the offset of a gravel-filled stream channel by the Rose Canyon fault. The offset here is 10 m (33 ft), and the fault is active.

Pat Abbott

Earthquake Prediction

The public really wants to have earthquakes foretold in much the same style and accuracy as they receive with weather forecasts. Our ability to forecast earthquakes on longer timescales is fairly good, but on short timescales we have *no* ability at all.

LONG-TERM FORECASTS

Can we predict earthquakes on intermediate to long timescales using the paleoseismology approach? It seems to work well for some faults but not for others. Geologist Thomas K. Rockwell classifies fault-movement timing into three groups:

1. *Quasi-periodic movements.* These faults have major movements at roughly equal time intervals. This regular pattern can be defined using the trenching and radiocarbon dating of paleoseismology.
2. *Clustered movements.* Adjacent fault segments move during several decades, and then they cease movement for a century or millennium until the next cluster begins.

Figure 5.15 Working group analyses of expected earthquake magnitudes and their probabilities of occurring before the year 2032. Forecasts are based on historic records and trench-wall offsets of sediments dated by radiocarbon analyses and global positioning system measurements.

A good example of clustered movements is occurring right now on the North Anatolian fault in Turkey (see figure 4.25).

3. *Random movements.* These faults are inherently unpredictable; they have no definable pattern for their major movements. The San Andreas fault seems to be in this category.

In December 1988, using paleoseismologic analysis, a group of geologists forecast earthquake sizes and probabilities for some major faults in California (figure 5.15). They placed a 30% probability on a magnitude 6.5 earthquake occurring on the Loma Prieta segment of the San Andreas fault within 30 years. Ten months later, the magnitude 6.9 World Series earthquake occurred there.

In 2014, the working groups stated that there is a 72% probability of at least one magnitude 6.7 earthquake striking the San Francisco Bay region before 2043 (see figure 4.40). Their 2003 forecast included an 85% probability of a magnitude 7 or higher earthquake in southern California before 2024. On Easter Sunday afternoon, 4 April 2010, a 7.2 M_w event occurred when a fault rupture began in Baja California, with its northward extent moving below ground into Southern California (see Laguna Salada fault in center of figure 4.8).

California Earthquake Scenario

An analysis of probabilities for earthquakes greater than magnitude 6.7 in California shows the event is most likely to occur next on the southern San Andreas fault. A model of this earthquake and its effects was constructed through 13 special studies and 6 expert panels. The scenario earthquake is a magnitude 7.8 event that first ruptures at 7.6 km (4.7 mi) depth next to the Salton Sea and then continues rupturing northward past Palm Springs and through the city of San Bernardino for 300 km (185 mi) (figure 5.16). The modeled earthquake kills 1,800 people, injures another 50,000, and causes $213 billion in damages.

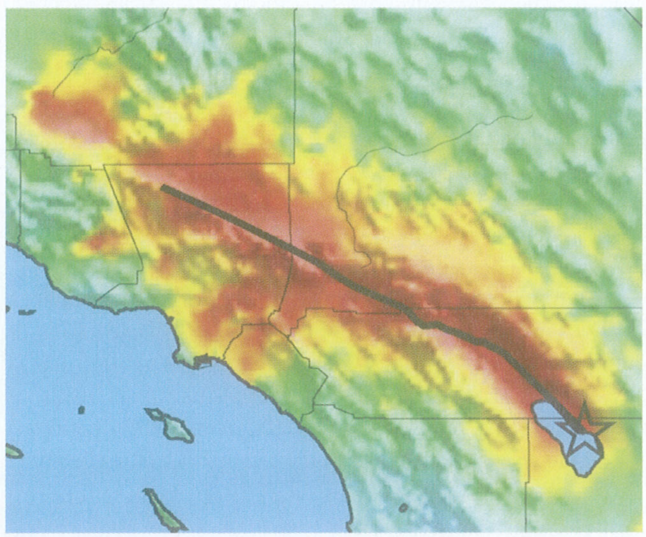


Figure 5.16 The big earthquake most likely to occur next in California is a magnitude 7.8 rupture on the southern San Andreas fault. Here it is assumed that the rupture will begin at the Salton Sea and move northward through Los Angeles. Colors indicate severity of ground shaking.

Source: ShakeOut.org/scenario

Side Note

Perils of Prediction: Scientists on Trial

At 3:32 a.m. Monday, 6 April 2009, the city of L'Aquila, Italy, was hit by a 6.3 M_w earthquake that killed 309 people. L'Aquila is, or was, a charming medieval city with hundreds of old, fragile masonry buildings sitting in a seismically active area in Italy. Twice before, in 1461 and 1703, the city was largely destroyed by earthquakes. The difference this time is that four scientists and three engineers (one a government official) have been charged with felony manslaughter for their roles in reassuring the public that there was no significant earthquake danger. Their trial began before a single judge in late September 2011.

What events led to this unprecedented trial? Beginning in October 2008, dozens of low magnitude seisms hit the city and surrounding region. The first quarter of 2009 brought hundreds more small seisms. On 30 March, a 4.1 M seism shook up residents causing a government official to convene a meeting on 31 March of the Major Risks Committee in L'Aquila featuring the seven experts. After the meeting, the government official tried to calm residents' fears of a big earthquake including saying scientifically false statements such as ". . . it's a favorable situation because of the continuous discharge of energy." Townsfolk are reported to have comforted themselves by telling each other — the more tremors, the less danger. Some residents cancelled their evacuation plans and stayed in their homes — only to have family members die when their houses collapsed during the big earthquake. Residents felt betrayed. They pressed for legal action. The prosecution did not charge the commission members with failing to predict the earthquake, but with presenting a superficial risk assessment with scientifically inaccurate information that gave false reassurances to the public. The prosecution asked for prison terms of four years; on 22 October 2012, the judge gave each defendant a six-year prison term.

BREAKING NEWS

On 10 November 2014, an Italian court overturned the convictions and cleared six scientists and engineers of manslaughter charges. The government official had his sentence reduced to two years. Lawyers for the families of the dead announced that they will challenge this ruling in the Supreme Court of Cassation in Rome. Then on 30 September 2016, Judge Giuseppe Grieco suspended the two-year sentence on the government official and stated that Italy's "period of limitation" time had run out so prosecutors could not further appeal. Thus, 7 years of anguish and trials resulted in no jail time for anyone.

SHORT-TERM FORECASTS

Our knowledge of earthquakes is quite impressive. Plate tectonics tells us *why* and *where* they occur, mostly along plate edges. Neotectonic analysis allows us to know *how big* and *how often* earthquakes have occurred on any fault. However, many people are not satisfied; they want short-term prediction for earthquakes. Unfortunately, we are not even close to having that capability. We don't have a workable hypothesis, and it seems quite possible that the detailed behavior of faults is too unpredictable to ever allow short-term prediction of earthquakes. Hypotheses of earthquake prediction that seem logical have been developed, and they still receive coverage in textbooks, but all of them have been proved false. Science is a demanding thought process. Beautiful ideas may have no substance. Creative hypotheses may have no validity. The truth is elusive.

A public eager for short-term prediction of earthquakes includes many gullible people. In 1977, Charles Richter commented that "journalists and the general public rush to any suggestion of earthquake prediction like hogs toward a full trough . . . [Prediction] provides a happy hunting ground for amateurs, cranks, and outright publicity-seeking fakers."

Earthquake Weather

There are people who believe that earthquakes are related to certain weather conditions, known as **earthquake weather.** The idea that earthquakes are related to weather is flawed. Where is the connection between earthquake energy released by fault movements miles below ground and the weather, which is caused by solar energy received at Earth's surface? Earthquakes are powered by the outflow of Earth's internal energy; this is not affected by whether it is hot or cold, dry or humid, day or night, or any other weather condition.

New Madrid, Missouri

An early 1990s prediction event occurred when a dying economist named Iben Browning filled his final days with personal excitement by predicting a major earthquake in the mid-United States similar to the earthquakes of 1811–1812. Scientists could readily see that his predictions were based on an old failed hypothesis, but an uncritical print and electronic media went on a binge of emotional coverage as a horde of television crews and reporters descended on New Madrid, Missouri, eagerly awaiting the earthquake that never came.

Psychic Predictions

Every so often we hear a psychic predict that a gigantic earthquake will cause California to break off and sink into the Pacific Ocean. Is this possible? No! This gigantic rupture-and-sink process is impossible; it is fantasy. Remember isostasy? Continents are made of less-dense rocks that float on top of denser mantle rocks. In fact, California did break off; it happened 5.5 million years ago as the Gulf of California began forming. California did not sink then and it won't sink in the future. The faulted slice of western California and Baja California will continue moving northwest toward a rendezvous with Alaska. If present trends continue, in a few tens of million years, the Californias will plow into Alaska and become part of its southern margin. Southern California will switch from surfing beaches to ski slopes.

Animal Behavior

Stories of odd behavior of animals before an earthquake go back many centuries. After an earthquake has occurred, we listen to our friends tell us about the strange behavior of their dog or bird before the earthquake; but these tales must be told *before* the earthquake, if they are to have any predictive value.

It may well be that some animals can sense natural phenomena before an earthquake, and that they can react to that information. But to date, no scientific evidence exists to prove any animals can sense an earthquake coming. Remember though, absence of evidence does not provide evidence of absence.

An international effort to track animal movements might, in time, yield some pre-earthquake warnings. The ICARUS (International Cooperation for Animal Research Using Space) initiative based in Germany seeks to track migrating animals using satellite imagery. Tiny solar-powered tracking tags attached to animals, such as elephants, birds, bats, sea turtles, and insects, will provide data on their normal movements. This knowledge will aid in conservation of species, and in following the spread of diseases, and also might allow us to recognize unusual movements that foretell earthquakes. We can't talk to the animals, but learning their movements could teach us something.

Experiment at Parkfield, California

The U.S. Geological Survey forecast a magnitude 6 earthquake on the San Andreas fault in the Parkfield area based on the pattern of historical seismicity. Parkfield experienced magnitude 5.5 to 6 earthquakes six times in the historical period—in 1857, 1881, 1901, 1922, 1934, and 1966. Some people perceived a pattern of an earthquake about every 22 years. U.S. Geological Survey scientists forecast that the next earthquake would occur in 1988, plus or minus five years. Thus, in 1984, the Parkfield Prediction Experiment was launched by deploying an unprecedented array of instruments in the field with a large team of scientists to interpret every detail of the earthquake that would come by January 1993. *Breaking news:* It finally happened! A magnitude 6.0 earthquake occurred on 28 September 2004, 16 years after the forecast date. With more than 22 years of work and tens of millions of taxpayer dollars spent, the earthquake was unpredicted. The Parkfield Earthquake Experiment, the best-staffed and best-funded earthquake prediction experiment ever, was a total failure at short-term earthquake prediction.

What is our current understanding of the possibilities of short-term predictions of fault movements? There is no reason the fault-rupture process must occur with any regularity or predictability. Although it may not be hopeless to look for precursors to earthquakes, there clearly is more to earthquake triggering than can be explained simply by the steady loading of plate-tectonic stress onto faults that then rupture in evenly spaced, characteristic earthquakes. The bottom line for each person is this: short-term prediction of earthquakes is not forthcoming, so plan your life accordingly. Organize your home and office to withstand the biggest earthquake possible in your area, and then don't worry about when that day will come.

Things to Keep in Mind

Numerous responses and actions have been developed to help us live with earthquakes.

EARLY WARNING SYSTEMS

Earthquake early warning systems are becoming increasingly successful. Note: These systems do *not* give predictions; they provide *warning* that a significant earthquake has begun and that seismic waves are already traveling toward you. The systems are based on velocity differences in seismic waves.

1. P waves travel the fastest but they do little damage. S waves and surface waves travel slower but can cause immense damage.
2. Sensors record P wave arrivals and immediately transmit data to an alert center, where the earthquake location is determined and its magnitude is estimated and updated as P waves continue to flow in.
3. Messages from the alert center are immediately transferred to computers and mobile phones stating the expected intensity and arrival time of strong shaking at your location.
4. Length of warning time will depend on your distance from the epicenter. For every 5 miles from the epicenter, you will receive 1 second of warning.
5. There is no warning possible if you are close to the epicenter.

Even a few seconds of warning can prod people to drop, cover, and hold on; allow surgeons and dentists to stop delicate procedures; signal automated systems to place equipment into safe mode; and more.

ShakeAlert

An early warning system called ShakeAlert has been created for the west coast of the United States. The system is still being developed, but it has had successes. For example, during the 6.0 M_w earthquake on 24 August 2014 in Napa, California, the alerts traveled 60 km (37 mi) to San Francisco 8 seconds before damaging seismic waves arrived. The ShakeAlert system can send information to agencies and to individuals (figure 5.17). The warning system will always have a blind zone around the epicentral area where there is little time difference between P and S wave arrivals.

Canada

Ocean Networks Canada has installed accelerometers on the seafloor off British Columbia to monitor the Cascadia subduction zone. The detectors are placed close to potential epicenter/hypocenter areas to increase the warning time they can provide. With a 9.0 M_w earthquake expected, every additional second of warning could be valuable. Advance warnings of 20 seconds to 2 minutes are possible.

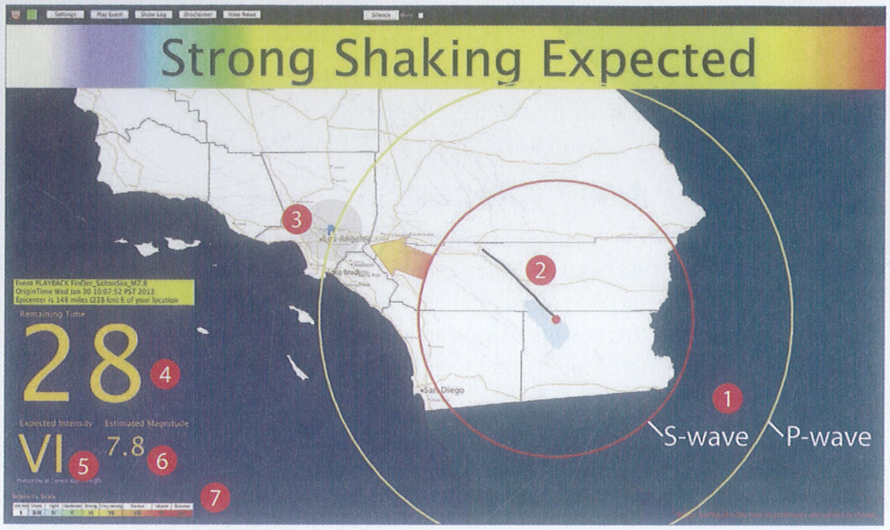


Figure 5.17 ShakeAlert will provide valuable information to you. On this sample screen grab, in the lower left: The large 28 is the number of seconds until dangerous seismic waves hit you. The Roman numeral VI is your expected intensity of shaking. The 7.8 is the estimated magnitude of the earthquake.

Source: Erin R. Burkett, Douglas D. Given, and Lucile M. Jones/USGS

SHAKEMAPS

The intensities of seismic shaking are now recorded by instruments, and the data are fed into computers that generate ShakeMaps (figure 5.18). The ShakeMap for the Northridge earthquake shows the effects of directivity, with most of the intense shaking occurring north of the north-moving fault. The ShakeMap also shows other areas of more intense shaking in land underlain by soft rocks.

The rock and sediment foundations beneath buildings may amplify seismic waves (figure 5.19). Seismic waves travel fast and with less amplitude in hard rocks. When seismic waves pass into soft rock or loose sediment, they slow down, but their amplitudes increase, and thus the shaking increases. Much of Los Angeles is built on soft rocks that amplify seismic shaking. In some areas, the soft rocks are 10 km (6 mi) thick, and seismic shaking may be amplified five times.

DID YOU FEEL IT?

Upon feeling an earthquake, a common response is to turn on the TV, radio, or computer to learn what just happened. Now you can help by sharing your shaking experience via your device or computer. Go through the U.S. Geological Survey (USGS) earthquake website to reach it, or simply google Did You Feel It? Click on Report Unknown Event, enter your ZIP code, and answer the questions about what you felt. In a matter of minutes, a Community Internet Intensity Map will show the intensities of shaking felt in affected ZIP-code areas. You can be an important part of creating these Mercalli intensity maps and can also learn about the earthquake via your own participation.

GREAT SHAKEOUT EVENTS

A valuable way to prepare for earthquakes is to practice your response during a virtual earthquake. The first major virtual event was an effort by scientists and emergency managers to involve the public and schools in the "Great Southern California Shakeout" at 10 a.m. on 13 November 2008; it involved 5.4 million people. The concept has now spread to many U.S. states and countries around the world. The event has grown to become International ShakeOut Day on the third Thursday in October every year.

One of the tips given to participants is that, upon feeling an earthquake, the immediate response that usually works the best is to:

Drop, Cover, and Hold On.

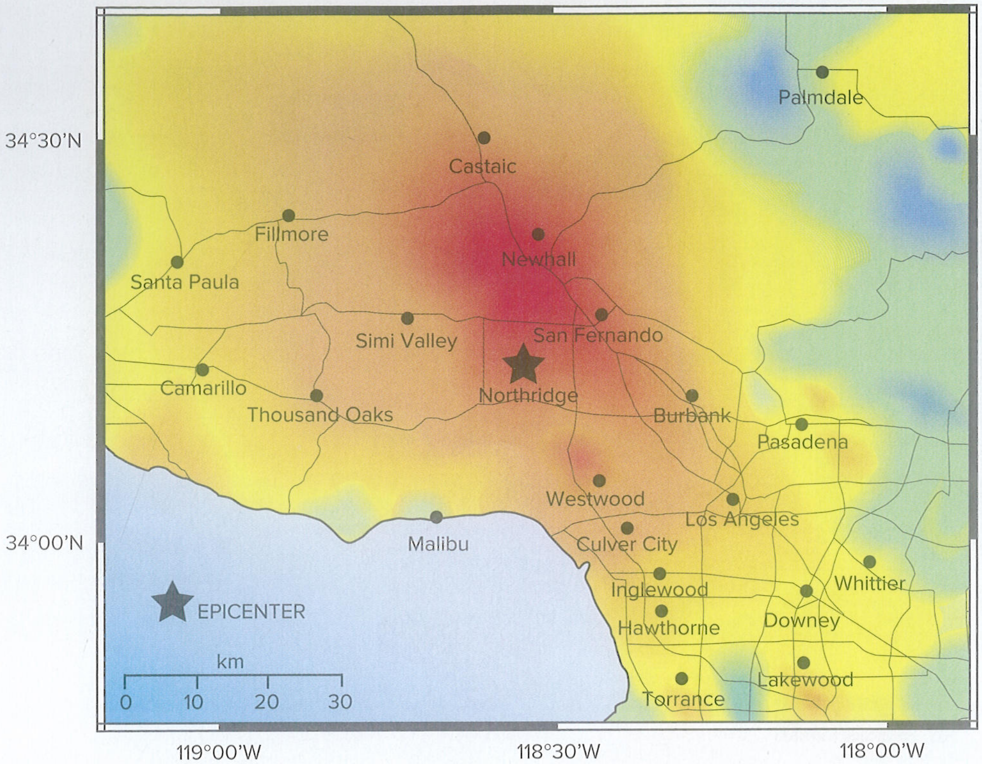
The most common hazard is objects falling on you or flying at you. The best response is to "make like a turtle" and dive under a heavy table or desk to create a protective shell; then hang onto its legs to keep your shell in place until the shaking stops. The best way to remember this strategy is to practice it now so you can react instantly when everything starts shaking. An effective community strategy to mentally prepare for future earthquakes is to have all schoolchildren, in class, practice Drop, Cover, and Hold On once every school year.

EARTHQUAKE LOSSES FOR THE UNITED STATES

Although big earthquakes do not happen every year in the United States, being aware of their potential future costs can help increase risk awareness and policy development. The Federal Emergency Management Agency (FEMA) has created software called HAZUS to analyze data on population, buildings, and ground shaking to estimate earthquake losses. The output from HAZUS in 2017 yielded estimates of \$6.1 billion in annualized earthquake losses for the United States (figure 5.20). Forecast losses are heaviest in the West; 61% of the losses occur in California and another 12% in Oregon and Washington, giving a West Coast total of \$4.5 billion.

Human-Triggered Earthquakes

The Earth exists in a state of delicate balance that is readily adjusted to maintain equilibrium (see Isostasy in chapter 2). Some of our human activities unintentionally upset the equilibrium and trigger earthquakes by adding or removing massive amounts of material at construction sites; by forcing fluids underground under pressure; by extracting large volumes of groundwater; and by setting off underground explosions.



Perceived shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential damage	None	None	None	Very light	Light	Moderate	Moderate/ Heavy	Heavy	Very heavy
Peak ACCEL. (%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
Peak VEL. (cm/s)	>0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 5.18 ShakeMap for the magnitude 6.7 Northridge earthquake in 1994. The fault moved to the north, and the greatest shaking was north of the epicenter. The variations in intensity of shaking are due to distance and variations in rock foundations.

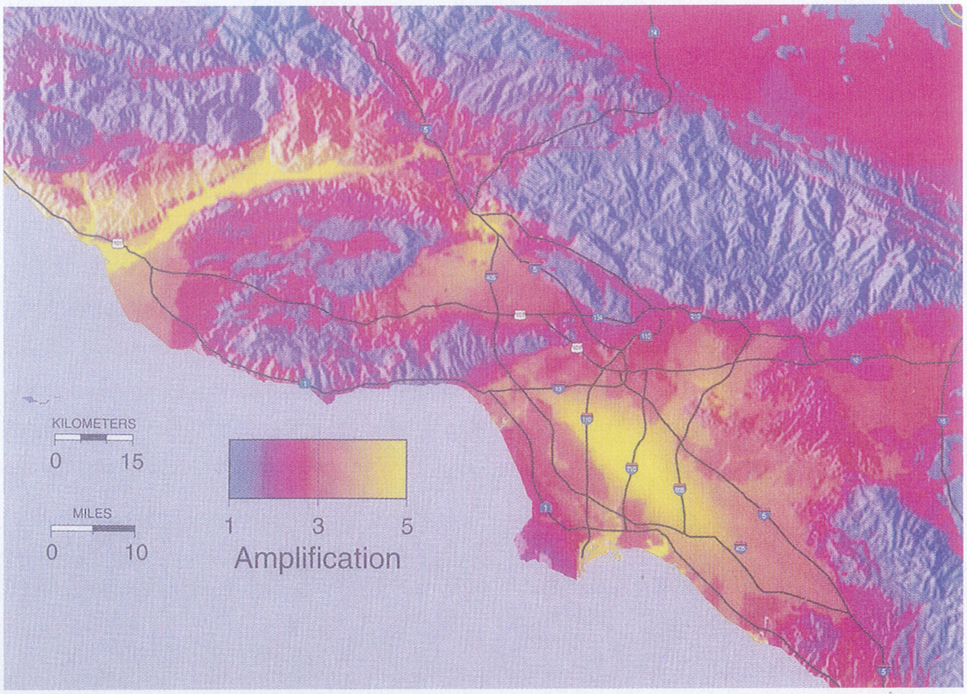


Figure 5.19 Amplification of ground motion during an earthquake in Los Angeles. Amplification is minimal in hard rocks (purple), significant in softer rocks (red), and greatest where the softer rocks are the thickest (yellow).

Source: Ned Field/US Geological Survey

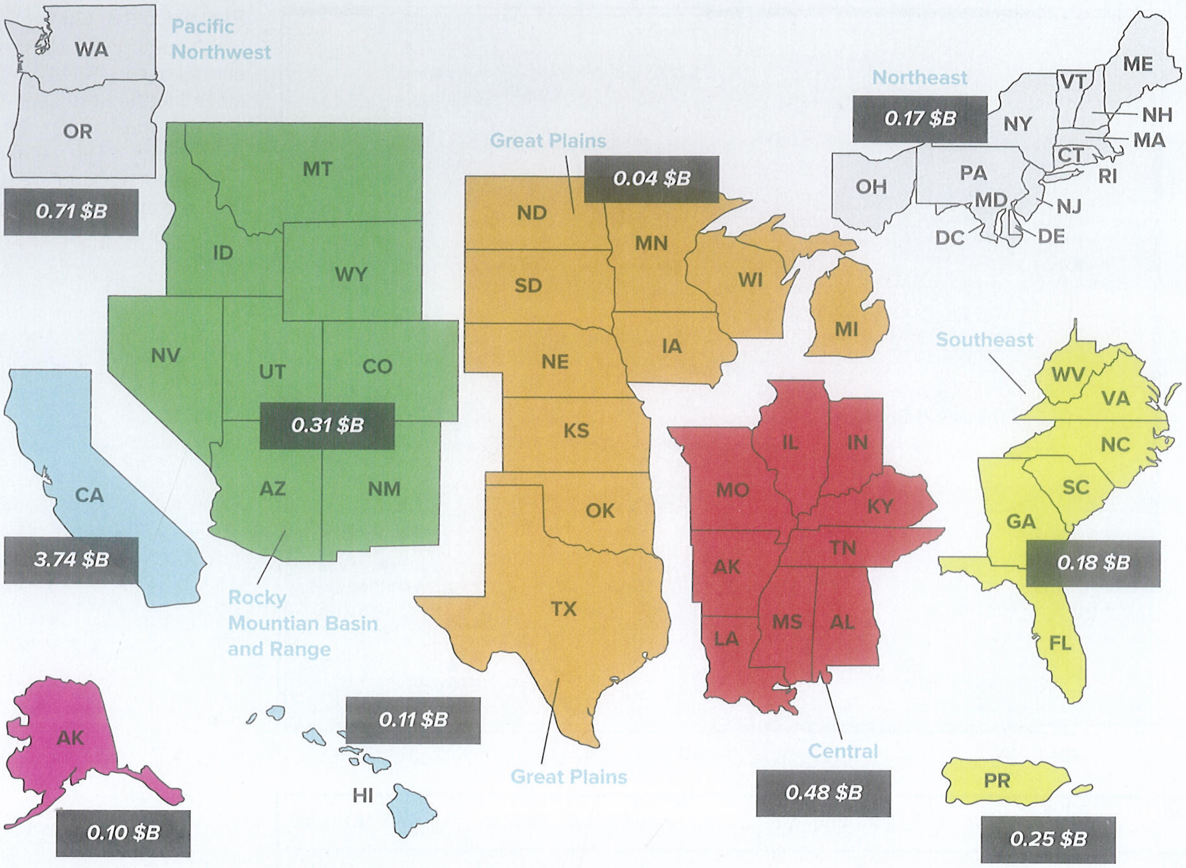


Figure 5.20 Annualized earthquake losses forecast for the United States.
Source: FEMA P-366 (2017)

PUMPING FLUIDS UNDERGROUND

The cause-and-effect relationship between triggered earthquakes and pumping fluids underground under high pressure has long been understood in the petroleum industry. This fact was dramatically proven in the 1960s in the Denver area.

Disposal Wells near Denver, Colorado

In early 1962, in secret, the Rocky Mountain Arsenal began pumping chemical warfare waste under pressure down a well into old rocks 3.7 km (2.3 mi) deep. Earthquakes began one month later and rose to more than 40 per month, causing alarm in Denver. Pumping stopped in September 1963 and earthquakes became minimal in number and magnitude. Pumping resumed in September 1964, again in secret, and so did earthquakes. In 1967, three of the earthquakes exceeded 5M. The suspected cause became public resulting in a hue and cry that forced pumping to stop. And the earthquakes stopped. The relationship is clear. Fluids pumped underground under pressure can be forced into ancient faults if they are present, adding stress and reducing friction and thereby causing the faults to begin moving again. The greater the amount of fluid pumped, the greater the number and magnitude of earthquakes.

Hydraulic Fracturing

We humans have a huge thirst for fossil fuels to power our industries, transportation, and personal lives. This has led to increased use of **hydraulic fracturing,** commonly called **fracking,** wherein liquids are pumped down wells under high pressure in order to fracture and crack open rocks. The fractured rocks yield much greater volumes of natural gas and oil from deep underground. Hydraulic fracturing has been used for many decades and has significantly increased fossil-fuel energy production in the United States. Fracking became even more effective in the 1990s with the advent of horizontal drilling through oil-rich shales. Since then the United States has saved hundreds of billions of dollars in oil-import expenses and has created hundreds of thousands of good-paying jobs in the United States.

On the other side, there are environmental concerns such as triggering earthquakes, the use of enormous volumes of water pumped underground, the potential contamination of aquifers, and more. These worries have led some U.S. states and some countries to ban fracking.

It turns out that the triggered earthquakes are mostly *not* due to hydraulic fracturing of impermeable rocks to release oil and natural gas. The process of pumping oil up to the surface also involves huge volumes of water. Earthquakes are caused by pumping these tremendous volumes of unwanted water back down into the underground rocks under high pressure via wastewater disposal wells.

Dallas–Fort Worth, Texas Hydraulic fracturing and new techniques of horizontal drilling are yielding enormous volumes of natural gas from rocks that previously were too "tight." For example, more than 200 wells drilled into the Barnett Shale (a tight mudstone) in the Dallas–Fort Worth area now yield huge volumes of natural gas. But more than 180 earthquakes up to 3.3M began in 2008 and continued into 2009. The earthquake source was traced to one wastewater disposal well drilled near an ancient fault. Abandonment of this well stopped most of the earthquakes. Natural gas production continues through the many other wells.

Oklahoma Earthquakes increased dramatically in recent years in U.S. midcontinent states such as Texas, Colorado, Arkansas, and Ohio but the biggest increase was in Oklahoma. Earthquakes of magnitude 3+ in Oklahoma averaged 1.6 per year between 1978 and 2008; rose to 39 per year between 2009 and 2012; and kept increasing up to 903 in 2015. This vaulted Oklahoma ahead of California as the earthquake leader in the 48 conterminous states. The Oklahoma earthquake swarms include a 5.7 M_w event west of Prague in 2011 and a state record 5.8 M_w near Pawnee in 2016. The triggers for most of these earthquakes were the increased pore-water pressures in subsurface rocks receiving millions of barrels of water pumped into them under high pressure each month in wastewater-disposal wells.

The large and increasing numbers of earthquakes and their increasing magnitudes led the State of Oklahoma to intervene. The state required more than 50 injection wells to shut down, and placed limits on injection rates and pressures for other wastewater disposal wells. These actions brought dramatic results as earthquakes gradually declined, from 903 in 2015 down to 196 in 2018.

A significant concern is how large future earthquakes might be. Ancient lengthy faults below Oklahoma could be pressured into movements resulting in a magnitude 6 or 7 earthquake (see Central United States Earthquakes later in this chapter).

DAM EARTHQUAKES

The downwarping of the land beneath the filling Lake Mead triggered many small earthquakes beginning in 1935 (see figure 2.7). This is a common occurrence; build a dam and impound a reservoir of water, and then earthquakes follow. First, impounding a reservoir adds a huge weight on the surface, causing the land to sink isostatically. Second, water seeping through the floor of the reservoir flows slowly underground throughout the region pushed by the large body of reservoir water above it. The underground water moves downward and outward as an advancing front of high pressure that may reach a fault and cause it to move. As an analogy, visualize what makes the water flow through the pipes in your house. In most cases, the water comes from a higher-elevation water tank or reservoir that pushes the water down through the pipes to your home.

China, 2008

Monday, 12 May 2008, began peacefully, like so many other days near the Dragon's Gate Mountains in Sichuan, China. The 15 million people of the region were busy at work, their schools were full of children, and the giant pandas were at home in the Wolong Nature Reserve. But at 2:28 p.m., the earth ruptured along the base of the mountains and ripped northeastward along the Longmenshan fault for 250 km (155 mi) for about two minutes. When the shaking stopped, about 87,500 people were dead and 5 million were homeless. This massive 7.9 M_w earthquake was caused by the ongoing collision of India pushing into Asia. This rupture was a mountain-building thrust-fault event; similar movements over millions of years have built the Dragon's Gate Mountains.

Time of day is always a factor in earthquake deaths, and the timing of this seism was terrible. Many of the buildings were made of brittle concrete with little support steel, and at 2:28 p.m. on a Monday, the badly built schools and office buildings were full of people, resulting in a high death toll. The loss of so many children in the collapsed schools was especially tragic for families because of China's one-child policy.

Plate tectonics was the cause of the earthquake, but what was the trigger? A debate is in progress. A 156 m (512 ft) tall dam was built in 2005 to create the Zipingpu Reservoir. In 2008, only 2.5 years later, the reservoir held 900 million tons of water. The dam lies 500 m (1,600 ft) from the Longmenshan fault. The weight of the reservoir water, plus the pore pressure of the water seeping underground, beneath the reservoir, would have caused the land to warp downward. Then water was released in early 2008, removing several hundred million tons of water and causing reservoir land to rise. Were the added stresses of land dropping and then rising the trigger for the fault to move on 12 May 2008 rather than 100 or so years later? Probably.

BOMB BLASTS

Underground nuclear explosions in Nevada have triggered earthquakes. Some of the atomic-bomb blasts released energy equivalent to a magnitude 5 earthquake. The bomb explosions triggered significant increases in earthquakes in their region during the 32 hours after the blast.

Anytime the level of stress or pressure is changed on rocks below the ground, earthquakes are possible. We humans can cause or trigger earthquakes.

Earthquakes in the United States and Canada

Awareness is growing that destructive and death-dealing earthquakes are a widespread problem, not just something that happens in California. Figure 5.21 is a map centered on the United States showing epicenters of significiant earthquakes during a 92-year-long period. Compare the epicenter locations with the earthquake hazards map of the United States (figure 5.22). Figure 5.23 is a map of eight of the

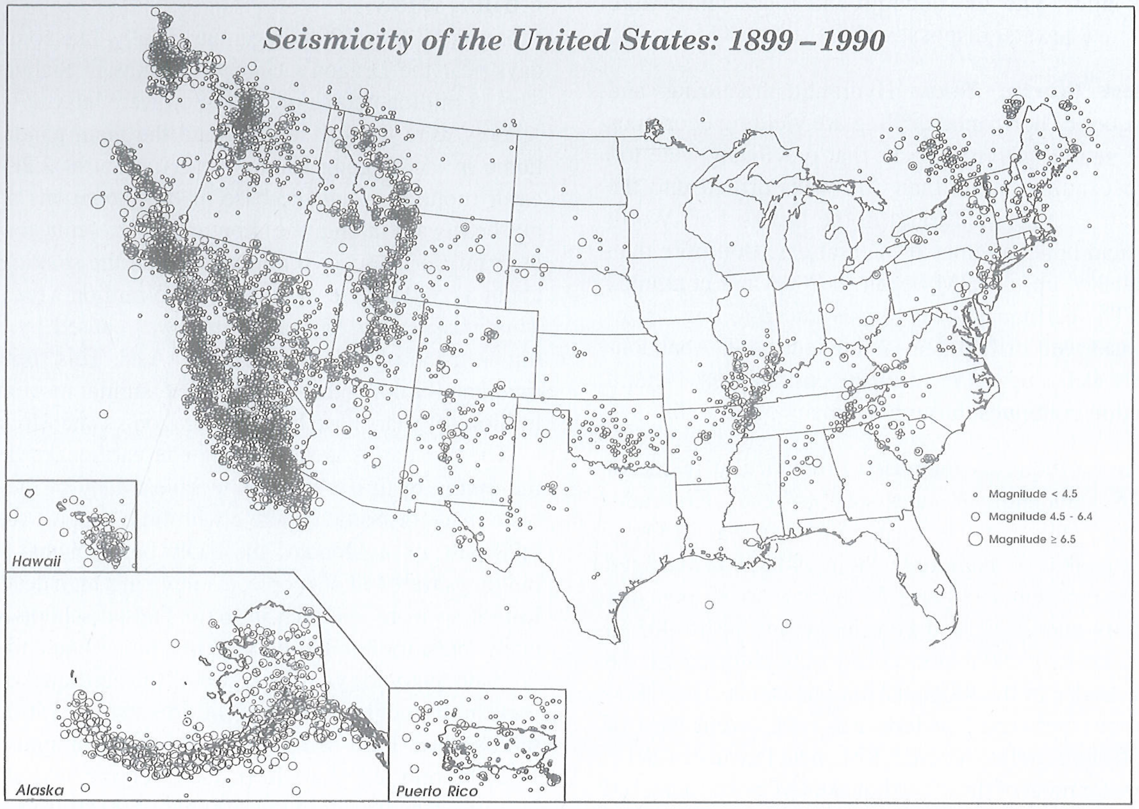


Figure 5.21 Epicenters of earthquakes in the United States, southern Canada, and northern Mexico, 1899–1990.

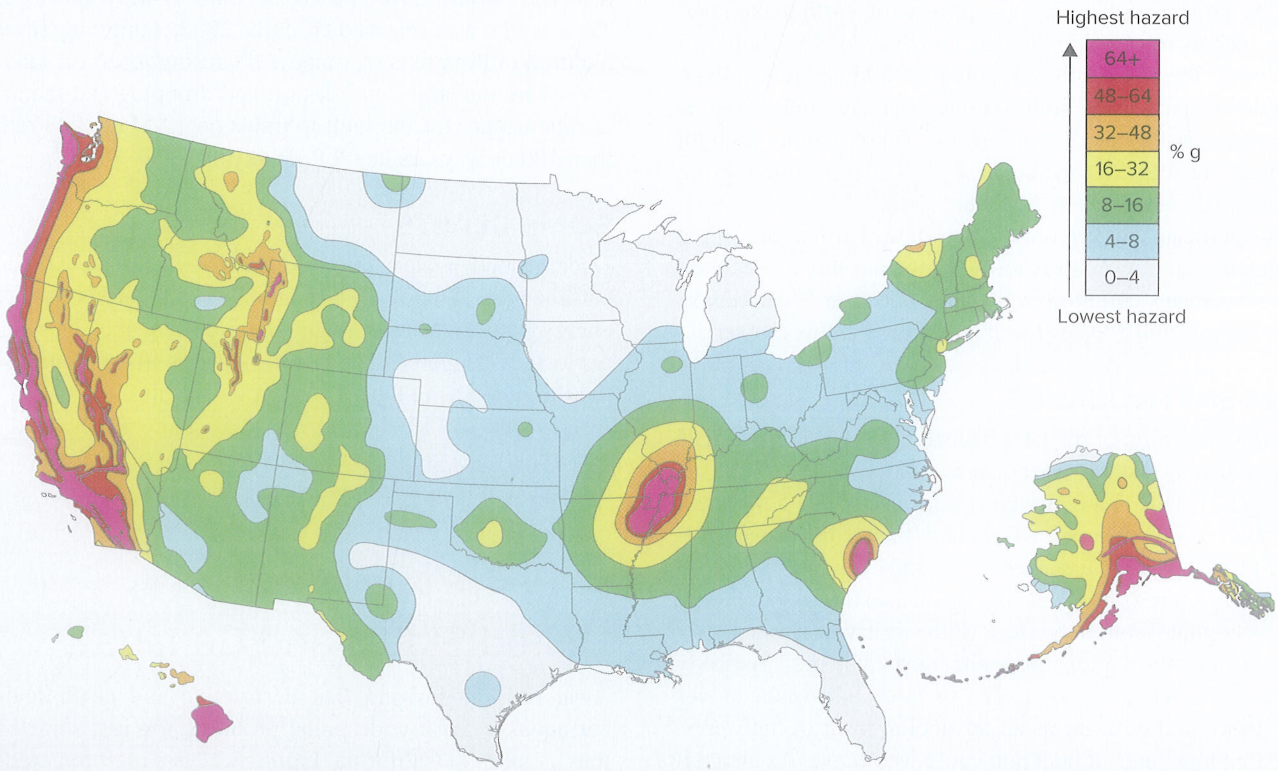


Figure 5.22 Earthquake hazards in the conterminous United States. Colors show horizontal shaking, as a percentage of acceleration of gravity, that have a 2% probability of being exceeded in 50 years.

Source: US Geological Survey, 2008.

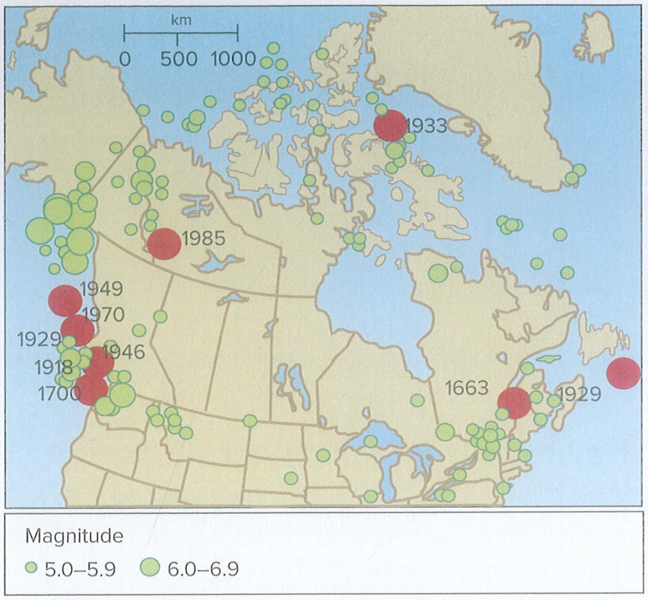


Figure 5.23 Eight of the largest earthquakes in Canadian history, 1660–2011, are shown by red circles. See table 5.2 for more data.

Source: Earthquakes Canada. Reproduced with the permission of Natural Resources Canada, 2015

largest earthquakes in Canadian history. All these figures show that earthquakes cluster in certain areas.

In Alaska and California, earthquakes occur in such large numbers and large sizes that they tend to obscure the earthquake history of the rest of the United States. If Alaska and California are ignored, the list of 10 largest U.S. earthquakes shows that major seisms occur in numerous states—10 major earthquakes, 10 different states (table 5.1).

The history of earthquakes in Canada also shows variety (table 5.2). The list is dominated by events along the tectonically active west coast of British Columbia, yet the list of 11 largest earthquakes involves four provinces.

TABLE 5.1

Ten Largest Earthquakes in the United States (excluding Alaska and California)

Magnitude	Date	Location
9.0	26 Jan 1700	Washington, Oregon—Cascadia subduction
7.9	2 Apr 1868	Hawaii—Ka'u district
7.5	7 Feb 1812	Missouri—New Madrid
7.3	16 Dec 1811	Missouri, Arkansas—New Madrid
7.3	17 Aug 1959	Montana—Hebgen Lake
7.3	31 Aug 1886	South Carolina—Charleston
7.2	16 Dec 1954	Nevada—Dixie Valley
7.0	23 Jan 1812	Illinois—New Madrid zone
7.0	28 Oct 1983	Idaho—Borah Peak
6.8	28 Feb 2001	Washington—Nisqually

TABLE 5.2

Eleven Largest Earthquakes in Canada

Magnitude	Date	Location
9.0	26 Jan 1700	British Columbia—Cascadia subduction
8.1	22 Aug 1949	British Columbia—Queen Charlotte Island
7.7	27 Oct 2012	British Columbia—Queen Charlotte Island
7.4	24 Jun 1970	British Columbia—Queen Charlotte Island
7.3	20 Nov 1933	Northwest Territories—Baffin Bay
7.3	23 Jun 1946	British Columbia—Vancouver Island
7.2	18 Nov 1929	Newfoundland—Grand Banks
7.0	26 May 1929	British Columbia—Queen Charlotte Island
7.0	5 Feb 1663	Quebec—Charlevoix
6.9	23 Dec 1985	Northwest Territories—Nahanni
6.9	6 Dec 1918	British Columbia—Vancouver Island

Source: Earthquakes Canada (2006).

An expanded look at the earthquake history of the United States shows that all 50 states are hit by earthquakes, and many of the states have large earthquakes (table 5.3). At least 17 states have been rocked by magnitude 6 or greater earthquakes; some of the older seisms may have been as big, but scientific records are lacking.

The historic record shows that earthquakes are widespread, but when earthquake frequency is examined, a different picture emerges. The location of all U.S. earthquakes of magnitude 3.5 and higher during a 30-year period shows a marked asymmetry (table 5.4). Alaska has 57% and California 23% of these earthquakes. Add in Hawaii and Nevada, and those four states received 91% of these earthquakes. Eight states had none (Connecticut, Delaware, Florida, Iowa, Maryland, North Dakota, Vermont, and Wisconsin).

A primary goal of the remainder of this chapter is to understand the large earthquakes in the United States and Canada that do not occur on the edge of a tectonic plate. We will examine specific earthquakes and their causes in regional settings: western United States and Canada under the influence of plate tectonics and buoyancy forces; the stable (tectonically "inactive") central and eastern United States and Canada; and finally, the relationship between earthquakes and volcanism in Hawaii.

TABLE 5.3

Largest Earthquakes by State

State	Date	Magnitude or Intensity	State	Date	Magnitude or Intensity
Alabama	18 Oct 1916	5.1	Montana	17 Aug 1959	7.3
Alaska	27 Mar 1964	9.2	Nebraska	28 Mar 1964	5.1
Arizona	21 Jul 1959	5.6	Nevada	16 Dec 1954	7.2
Arkansas	16 Dec 1811	7.0	New Hampshire	24 Dec 1940	5.5
California	9 Jan 1857	7.9	New Jersey	30 Nov 1783	5.3
Colorado	8 Nov 1882	6.6	New Mexico	15 Nov 1906	VII
Connecticut	16 May 1791	VII	New York	5 Sep 1944	6
Delaware	30 Nov 2017	4.1	North Carolina	21 Feb 1916	5.2
Florida	10 Sep 2006	5.8	North Dakota	16 May 1909	5.5
Georgia	5 Mar 1914	4.5	Ohio	9 Mar 1937	5.4
Hawaii	2 Apr 1868	7.9	Oklahoma	3 Sep 2016	5.8
Idaho	28 Oct 1983	7.0	Oregon	5 Aug 1910	6.8
Illinois	23 Jan 1812	7.0	Pennsylvania	25 Sep 1998	5.2
Indiana	27 Sep 1909	5.1	Rhode Island	11 Mar 1976	3.5
Iowa	13 Apr 1905	V	South Carolina	31 Aug 1886	7.3
Kansas	24 Apr 1867	5.1	South Dakota	2 Jun 1911	4.5
Kentucky	27 Jul 1980	5.2	Tennessee	17 Aug 1865	5.0
Louisiana	19 Oct 1930	4.2	Texas	16 Aug 1931	5.8
Maine	21 Mar 1904	5.1	Utah	12 Mar 1934	6.6
Maryland	16 Jul 2010	3.4	Vermont	10 Apr 1962	4.2
Massachusetts	18 Nov 1755	6.3	Virginia	23 Aug 2011	5.8
Michigan	10 Aug 1947	4.6	Washington	26 Jan 1700	9
Minnesota	9 Jul 1975	4.6	West Virginia	20 Nov 1969	4.5
Mississippi	17 Dec 1931	4.6	Wisconsin	6 May 1947	V
Missouri	7 Feb 1812	7.5	Wyoming	17 Aug 1959	6.5

Source: US Geological Survey

Western North America: Plate Boundary–Zone Earthquakes

Much of the earthquake hazard in western North America is due to the ongoing subduction of small plates, as well as the continuing effects of the overridden, but not forgotten, Farallon plate. When considering the size of the Pacific, North American, and Farallon plates, it is easy to appreciate why earthquakes affect the entirety of western North America. Consider that the Pacific plate is more than 13,000 km (8,000 mi) across and that it is grinding past the North American plate, which is more than 10,000 km (6,250 mi) wide. How broad a zone is affected by these passing giants? The affected zone must be large—as big as the entirety of western North America. The scale of these gigantic plates strongly suggests that their interactions are an underlying cause of earthquakes throughout the western United States, Canada, and Mexico.

WESTERN GREAT BASIN: EASTERN CALIFORNIA, WESTERN NEVADA

Owens Valley, California, 1872

The famous naturalist John Muir was in his cabin in Yosemite Valley when:

> *At half past two o'clock of a moon-lit morning in March, I was awakened by a tremendous earthquake, and though I had never before enjoyed a storm of*

TABLE 5.4

Most Active Earthquake States (magnitudes 3.5 and above, 1974–2003)

State	Number of Natural Earthquakes
1. Alaska	12,053
2. California	4,895
3. Hawaii	1,533
4. Nevada	778
5. Washington	424
6. Idaho	404
7. Wyoming	217
8. Montana	186
9. Utah	139
10. Oregon	73
Top 10 states total	20,702
Bottom 40 states total	378

The earthquake totals above are for 30 years of natural seisms. Oklahoma has entered the Top 10 with earthquakes induced by wastewater disposal wells; for example, they had 2,105 earthquakes in just 3 years (2014–2016).

Source: US Geological Survey

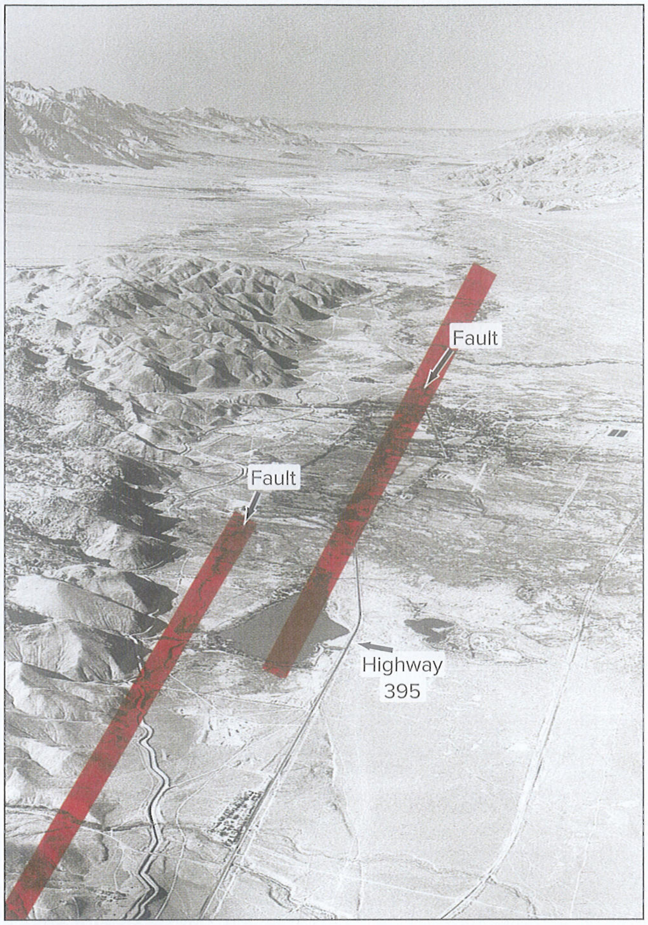


Figure 5.24 View to the north in Owens Valley. Faults are subparallel and to the left of Highway 395; note that the town of Lone Pine (in center of photo) is down-dropped. There is a lake in the right-stepping pull-apart between two fault segments. The Alabama Hills are at left center, and the Sierra Nevada in upper left.

this sort, the strange thrilling motion could not be mistaken, and I ran out of my cabin, both glad and frightened, shouting, "A noble earthquake!" feeling sure I was going to learn something. The shocks were so violent and varied, and succeeded one another so closely, that I had to balance myself carefully in walking as if on the deck of a ship among waves, and it seemed impossible that the high cliffs of the Valley could escape being shattered. In particular, I feared that the sheer-fronted Sentinel Rock, towering above my cabin, would be shaken down, and I took shelter back of a large yellow pine, hoping that it might protect me from at least the smaller outbounding boulders. For a minute or two the shocks became more and more violent—flashing horizontal thrusts mixed with a few twists and battering, explosive, upheaving jolts—as if Nature were wrecking her Yosemite temple, and getting ready to build a still better one.

What happened on 26 March 1872? The fault zone on the western side of the Owens Valley broke loose along a length of 160 km (100 mi). This is the third longest fault rupture in California history after the 1906 San Francisco and 1857 Fort Tejon events (figure 5.24). Today, Highway 395 runs in a north-south direction, right along the faults. The 1872 faulted zone is up to 15 km (10 mi) wide, with vertical drops (normal faulting) of as much as 7 m (23 ft) and horizontal offsets (right lateral) up to 5 m (16 ft). The epicenter was near the town of Lone Pine, where 27 people, about 10% of the residents, were crushed to death in the collapse of their adobe (dried mud blocks) and stone houses. The seism is estimated to have had a magnitude of about 7.4. So, big earthquakes do happen far away from the coastal zone and the San Andreas fault.

Western Great Basin Seismic Trend

This earthquake belt runs through eastern California and western Nevada and has a recognizable line of epicenters (see figure 5.21) and faults (figure 5.25). In historic time, Nevada has averaged one earthquake with a magnitude in the 6s per decade and one with a magnitude in the 7s every 27 years. Why so many earthquakes? In the last 30 million years, the region between the eastern Sierra Nevada in California and the Wasatch Mountain front in central Utah has expanded in an east-west direction, opening up by

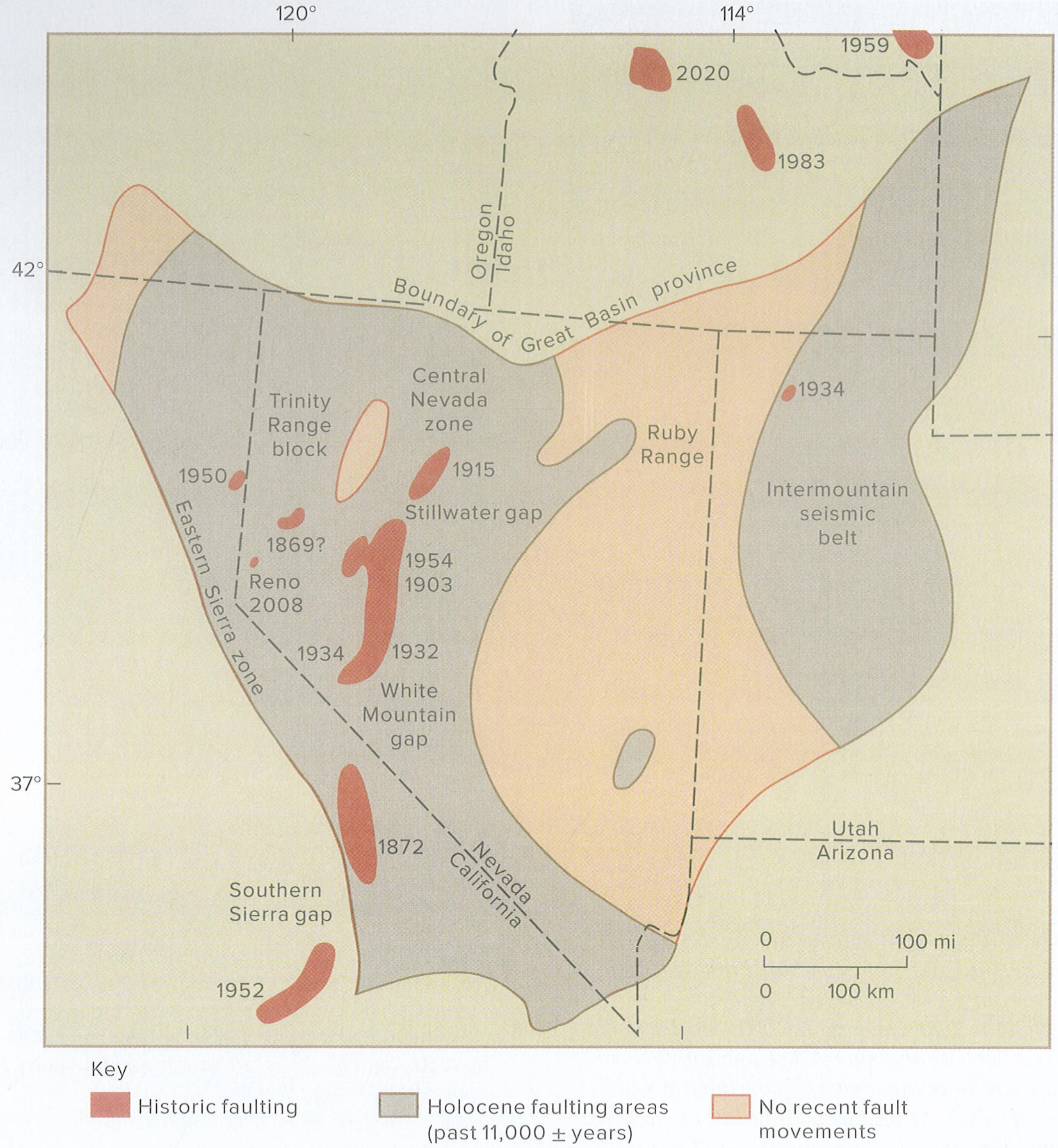


Figure 5.25 Generalized map of historic faulting in the western Great Basin. Areas of ground broken by large earthquakes are in dark orange; notice the seismic gaps in the trend. Areas with numerous smaller seisms are brown.

several hundred kilometers (figures 5.26 and 5.27). This extended area is known as the Great Basin, or the Basin and Range province. Nevada, in the heart of the extended province, has about doubled in width. As much as 20% of the relative motion between the Pacific and North American plates may be accommodated in the Basin and Range province. Extensional, pull-apart tectonics stretch the area, leaving numerous north-south-oriented,

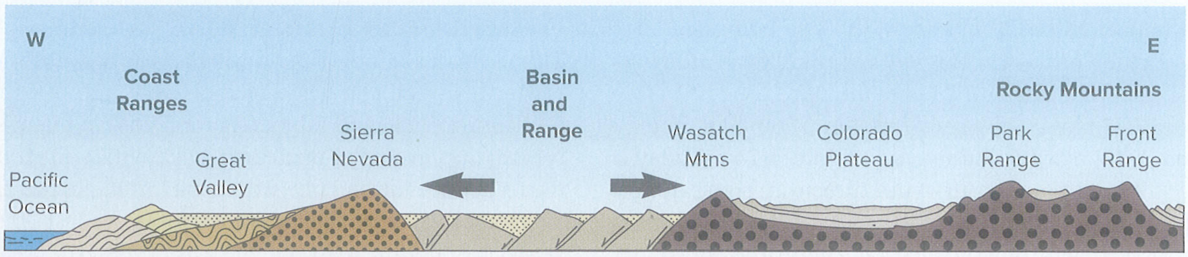


Figure 5.26 Schematic cross-section oriented west-east across the western United States. The Basin and Range province has stretched to double its initial width. This extension has created normal faults that generate earthquakes.

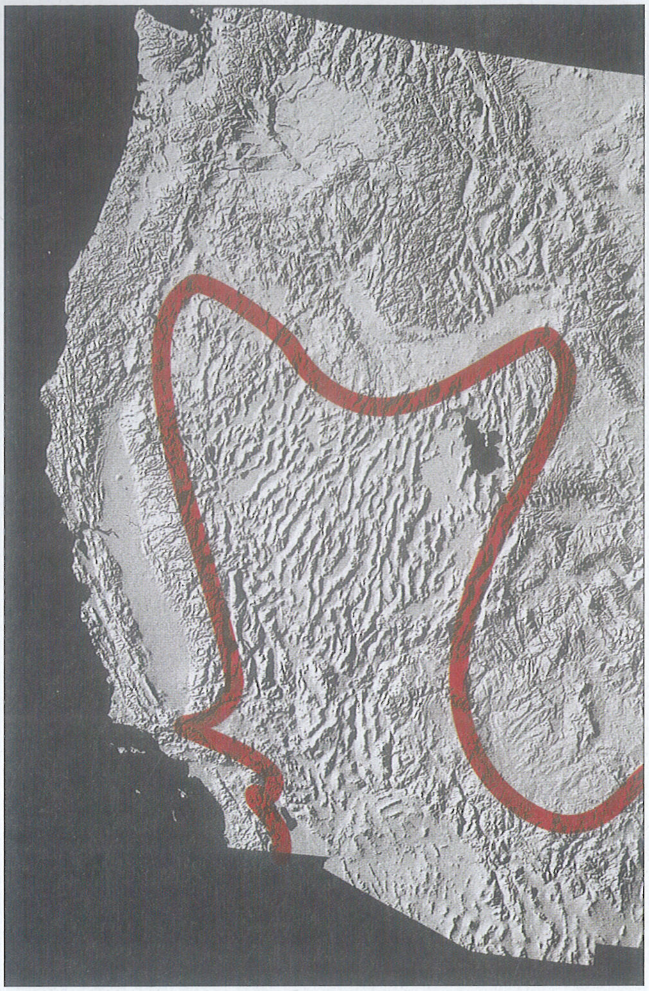


Figure 5.27 Computer-generated image of topography in the western United States. Notice in the center the north-south-oriented mountains separated by linear valleys. Basin and Range topography is outlined by the red line.

Source: USGS

back-tilted mountain ranges separated by down-dropped, sediment-filled basins (see figure 5.26). The extension is accomplished with normal faulting, so vertical separation dominates over horizontal slippage.

Some major earthquakes of historic times have occurred in the western part of the Great Basin province (see figure 5.25). (1) On 2 October 1915, a large earthquake occurred south of Winnemucca in Pleasant Valley, Nevada. This magnitude 7.7 event ruptured the surface for 59 km (37 mi). The slip was dominantly vertical (normal) with displacements up to 5.8 m (19 ft). Some fault strands had right-lateral components of offset up to 2 m (6.5 ft). (2) On 21 December 1932, a magnitude 7.2 event occurred near Cedar Mountain, Nevada, rupturing the ground for 61 km (38 mi). (3) The year 1954 was a big one for earthquakes in Nevada. Events included a magnitude 6.6 on 6 July and a 6.9 on 24 August near Fallon, as well as two shocks of 7.2 and 6.9 that rocked Dixie Valley on 16 December. Figure 5.25 shows several gaps in the trend of historic, long ruptures of faults. Residents in these seismic gaps may be in for some surprises.

Reno, Nevada, 2008

Big earthquakes usually occur as a mainshock followed by numerous aftershocks. But sometimes quakes occur in a *swarm,* a cluster of earthquakes without a mainshock. Between 28 February and 3 June 2008, Reno experienced a swarm of 1,090 quakes of magnitude 2 and greater (see figure 5.25). The peak of the swarm occurred in late April and early May when the numbers of earthquakes increased and magnitudes reached 4.2, 4.7, 4.2, and 3.8. The swarm occurred along a short fault and may well have been an interval of fault growth in response to Nevada being pulled apart by tectonic forces. The good news for Reno residents is that a short, poorly developed fault will not produce a large earthquake. The bad news is that the Reno area has other longer faults with a 65% chance of producing a magnitude 6 earthquake in the next 50 years.

INTERMOUNTAIN SEISMIC BELT: UTAH, IDAHO, WYOMING, MONTANA

The Intermountain seismic belt is a northerly trending zone at least 1,500 km (930 mi) long and about 100 to 200 km (60 to 125 mi) wide (figure 5.28). The belt extends in a curved pattern from southern Nevada and northern Arizona into northwestern Montana (see figure 5.25). In effect, the seismic belt is the eastern boundary of the extending Basin and Range province. The bounding faults on the eastern side of the Great Basin are mostly down-to-the-west, whereas the bounding faults on the western side (in eastern California and western Nevada) are mostly down-to-the-east. The earthquakes reaffirm that this part of the world is being stretched and pulled apart.

Hebgen Lake, Montana, 1959

The Rocky Mountains in the summertime are a beautiful place to be. On the moonlit evening of 17 August 1959, campers were settled into their spots at the Rock Creek Campground at the foot of the high walls of the Madison River Canyon. But at 11:37 p.m., the ground shook, and then an odd wind blew briefly down the canyon at high velocity. The wind was created by the push of an enormous rocky debris flow. The south wall of the canyon dropped 43 million cubic yards of rock, which slid down the steep slope, across the Madison River, and moved about 150 m (500 ft) up the north wall (figure 5.29). It entombed 26 campers. The gigantic landslide buried the canyon to depths of 67 m (220 ft) and created a natural dam that began trapping a large body of water—Earthquake Lake.

What caused this life-ending landslide? At Hebgen Lake, directly west of Yellowstone National Park, two subparallel faults (Hebgen and Red Canyon) moved within 5 seconds of each other with $6.3m_b$ and $7.5\ M_s$ events (figure 5.28). These two normal faults had their southwestern sides drop 7 and

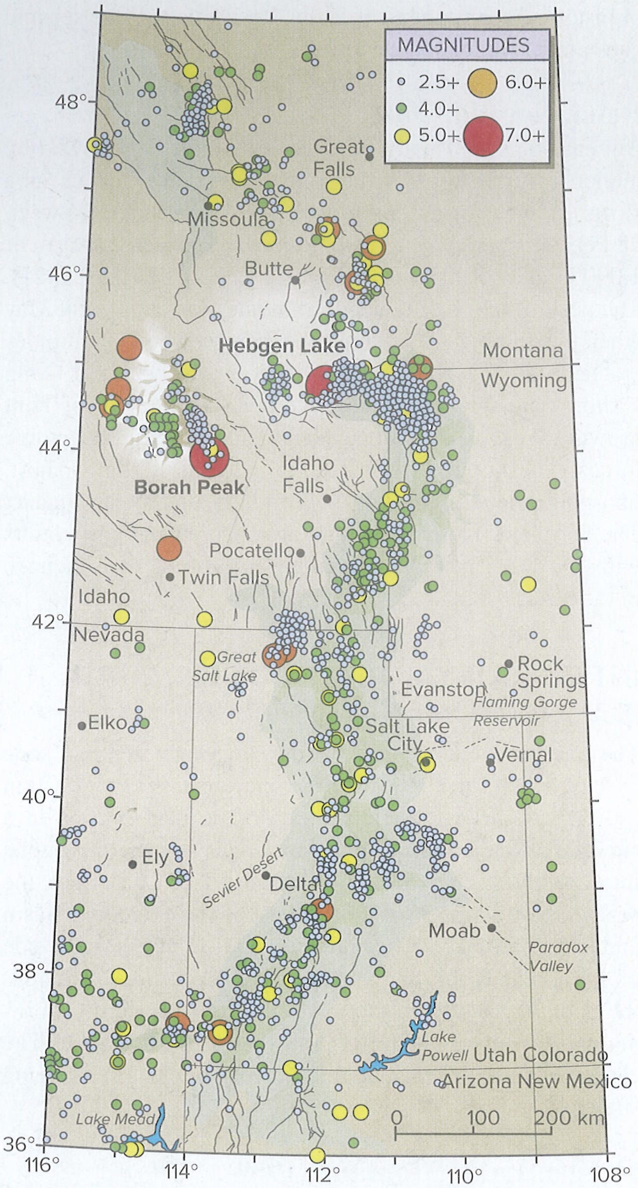


Figure 5.28 Earthquake epicenters in the Intermountain seismic belt, 1900–1985.

7.8 m (23 and 26 ft) down fault surfaces inclined 45° to 50° to the southwest. The fault movements created a huge seiche in Hebgen Lake.

Borah Peak, Idaho, 1983

Just after 7 a.m. on 28 October 1983, the Lost River fault broke free 16 km (10 mi) below the surface and ruptured northwestward 0.45 m (1.5 ft) horizontally and 2.7 m (9 ft) vertically for a 7.3 M_s event (figures 5.28 and 5.30). When the fault finished moving, Borah Peak, Idaho's highest point, was 0.3 m (1 ft) higher, and the floor of Thousand Springs Valley was several feet lower. The ground shaking caused Thousand Springs Valley to live up to its name as underground water, squeezed out by the subterranean pressures, spouted fountains 3 to 6 m (10 to 20 ft) high.

Figure 5.29 Madison Canyon landslide and resulting lake, caused by the earthquake of 17 August 1959.

Figure 5.30 The 28 October 1983 Borah Peak earthquake was a 7.3 M_s event with 2.7 m (9 ft) of vertical offset. Notice that some left-lateral offset also occurred. Mount Borah (in background) was uplifted slightly by this event.

NOAA/NGDC, G. Reagor, U.S. Geological Survey

Wasatch Fault

In historic times, large seisms have occurred in eastern California and western Nevada on the west and in Montana and Idaho on the east, but not on long sections of faults in Utah. Over 80% of Utah's population lives within sight of the **scarps,** or steep slopes, of the 370 km (230 mi) long Wasatch Front, the zone of down-to-the-west normal faults separating the mountains from the Great Basin (figure 5.31). No large earthquakes have been reported along the Wasatch Front faults since the arrival of Brigham Young in 1847, but the sharply defined faults show obvious potential for earthquakes (figure 5.32). In an 1883 article in the *Salt Lake Tribune,* the famous geologist G. K. Gilbert warned the people of Utah of the earthquake threat and the danger for their towns. The fault segments shown in figure 5.31 are each capable of events like those of Hebgen Lake and Borah Peak. In the last 6,000 years, a magnitude 6.5 or stronger earthquake has occurred about once every 350 years on one of the Wasatch system faults. Parts of Salt Lake City, Provo, and Ogden lie on soft lake sediments that will shake violently during a large seism. The fault segment near Brigham City has not moved in the last 2,400 years and is a likely candidate for a major event.

Figure 5.32 Aerial view eastward over Salt Lake City to the Wasatch fault running along the base of the mountains. The Wasatch fault zone is colored red.

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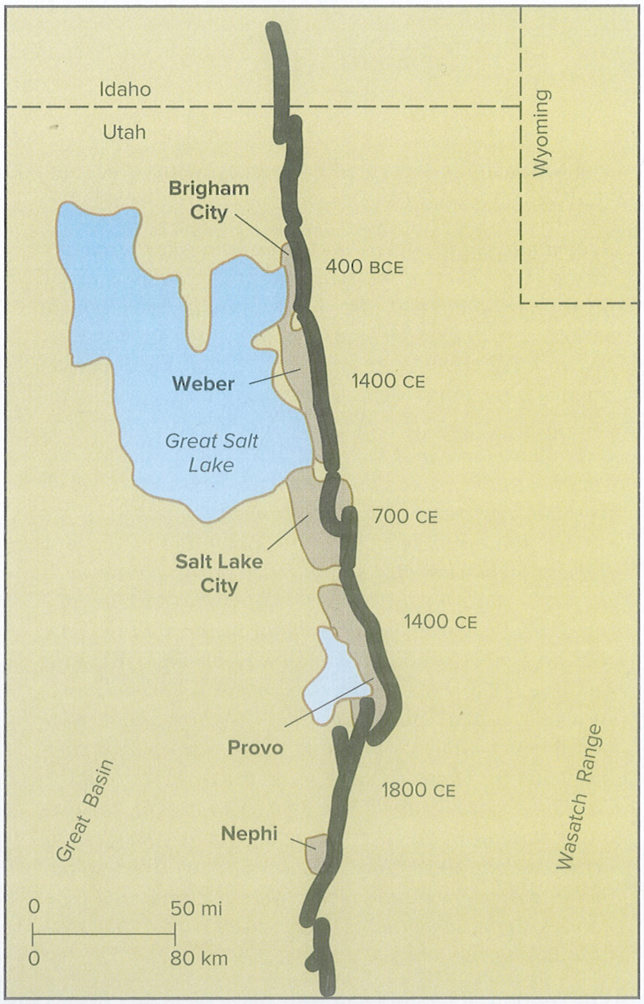

Figure 5.31 Map of faults along the Wasatch Front, Utah. The Wasatch fault has several segments. Dates of the most recent magnitude 6.5 or greater seisms are shown.

A 2019 study by Bagge and others shows that high-stress changes have built up on the Brigham City and Salt Lake City fault segments; both are ready for a 6.9M earthquake on any day.

RIO GRANDE RIFT: NEW MEXICO, COLORADO, WESTERNMOST TEXAS, MEXICO

The Rio Grande rift is one of the major continental rifts in the world. It is a series of interconnected, asymmetrical, fault-block valleys that extend for more than 1,000 km (620 mi) (figure 5.33). Here, it appears that the continental crust is being heated from below and is stretching. The crust responds by thinning and extending with accompanying normal faulting. In the last 26 million years, about 8 km (5 mi) of crustal extension has occurred near Albuquerque, New Mexico, a rate of about 0.3 mm/yr. The dominant motion on the faults is vertical, and the offset totals 9 km (5.5 mi). The rift basin is strikingly deep in places, yet most of the vertical relief created by fault offsets has been lessened by the copious quantities of volcanic materials and sediments that have poured into the rift over millions of years.

The topographic trough of the rift valley has attracted a major river (Rio Grande), which in turn has enticed human settlers in need of water. Today's settlements include Albuquerque, Socorro, and Las Cruces in New Mexico, El Paso in Texas, and Ciudad Juarez in Mexico. Historic earthquakes have had only small to moderate magnitudes, but the continental lithosphere continues to extend, thus presenting a real hazard for large earthquakes.

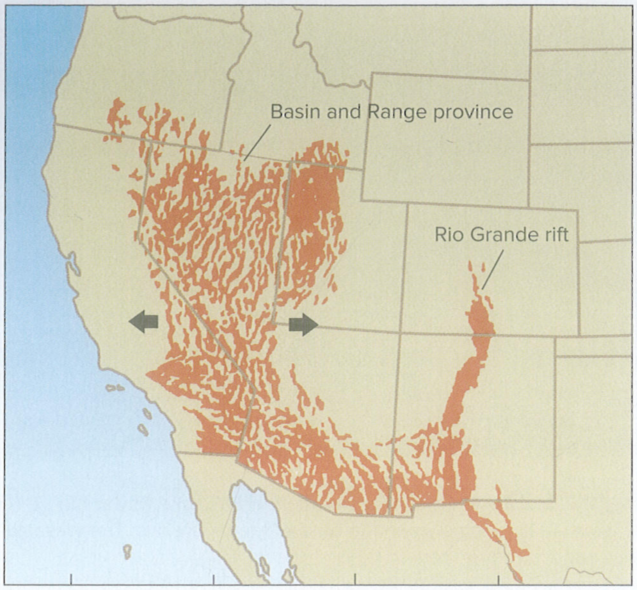

Figure 5.33 An east-west-oriented extension has pulled apart some of western North America to form the topography of Basin and Range province. The Rio Grande rift is a geologically youthful rift valley. The sediment-filled basins are shown in orange.

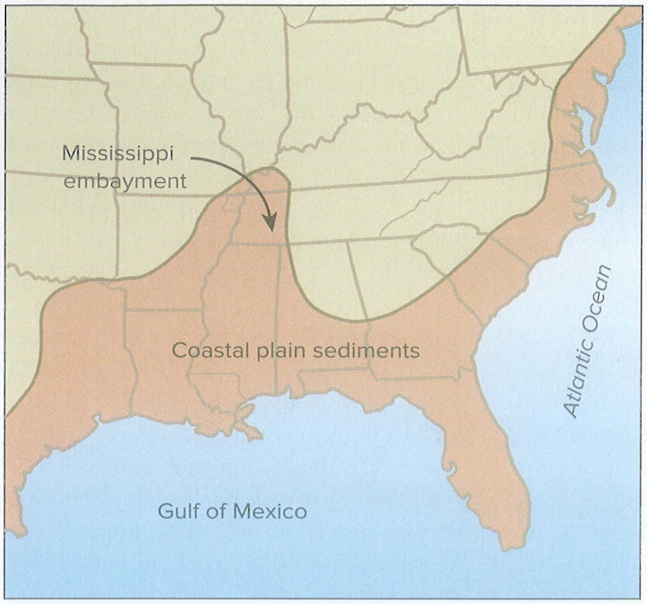

Figure 5.34 Map of coastal-plain sediments deposited by rivers eroding North America. The Mississippi River embayment contains a mass of soft sediments.

Intraplate Earthquakes: "Stable" Central United States

The map of earthquake epicenters in the United States (see figure 5.21) shows that the western third of the country has an elevated level of seismic activity. But there are clusters of epicenters in the "stable" central and eastern United States, the intraplate regions away from the active plate edges. There are not as many epicenters, but some individual earthquakes are big. Seismic hazards are significant (see figure 5.22).

NEW MADRID, MISSOURI, 1811–1812

A succession of earthquakes rocked the sparsely settled central part of the Mississippi River Valley at the time of the War of 1812. Between 16 December 1811 and 15 March 1812, Jared Brooks, an amateur seismologist in Louisville, Kentucky, recorded 1,874 earthquakes. He classified eight of them as violent and another 10 as very severe. The four largest events occurred on 16 December 1811 (two), 23 January 1812, and 7 February 1812. The hypocenters were located below the thick pile of sediments where the Mississippi and Ohio rivers come together, at the upper end of the great Mississippi River **embayment** (figure 5.34). These major seisms are called the New Madrid earthquakes, taking their name from a Missouri town of 1,000 people. Although few people were killed, the destruction of ground and buildings at New Madrid tolled the end of its importance as "the Gateway to the West."

The following is excerpted from an eyewitness account of a New Madrid earthquake:

> *Accompanying the noise, the whole land was moved and waved like waves of the sea, violently enough to throw persons off their feet, the waves attaining a height of several feet, and at the highest point would burst, throwing up large volumes of sand, water, and in some cases a black bituminous shale, these being thrown to a considerable height, the extreme statements being forty feet, and to the top of the trees. With the explosions and bursting of the ground there were flashes, such as result from the explosion of gas, or from the passage of the electric fluid from one cloud to another, but no burning flames; there were also sulphuretted gases, which made the water unfit for use, and darkened the heavens, giving some the impression of its being steam, and so dense that no sunbeam could find its way through. With the bursting of the waves, large fissures were formed, some of which closed again immediately, while others were of various widths, as much as thirty feet, and of various lengths. These fissures were generally parallel to each other, nearly north and south, but not all. In some cases instead of fissures extending for a considerable distance there were circular chasms, from five to thirty feet in diameter, around which were left sand and bituminous shale, which later would burn with a disagreeable sulphorous smell.*

The region is composed of thick deposits of water-saturated, unconsolidated sands and muds dropped by the Mississippi River. These loose materials intensified the shaking of the earthquakes, and the weak sediments flowed

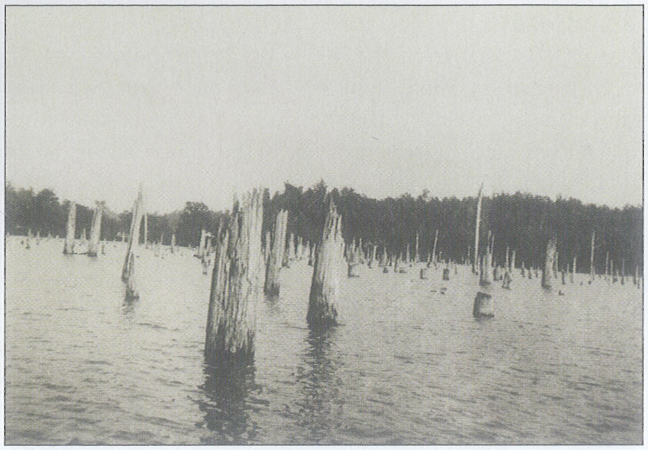

Figure 5.35 Trunks of cypress trees drowned in Reelfoot Lake after water was dammed by the New Madrid earthquakes. (These drowned trees are analogous to those drowned by the January 1700 Pacific Northwest magnitude 9 earthquake; see figure 4.17.)

Guy E. Mitchell/National Geographic Creative

like water, erupted as sand volcanoes, and in places quivered like Jell-O. Several long-lasting effects of the New Madrid earthquakes can still be seen in the topography. A 240 km (150 mi) long area alongside the Mississippi River sank into a broadly depressed area, forming two new lakes: Lake St. Francis, 60 km (37 mi) long and 1 km (0.62 mi) wide; and Reelfoot Lake in Tennessee, 30 km (19 mi) long, 11 km (7 mi) wide, and up to 7 m (23 ft) deep. Reelfoot Lake, now a bird sanctuary, hosts the gray trunks of cypress trees drowned more than 200 years ago; they still stand as silent testimony to the area's earth-wrenching events (figure 5.35). Other topographic features created by the seisms include (1) long, low cliffs across the countryside and streams with new waterfalls up to 2 m (7 ft) high; (2) domes as high as 6 m (20 ft) and as long as 24 km (15 mi); and (3) former swamplands uplifted and transformed into aerated soils.

Felt Area

The New Madrid earthquakes have never been equaled in the history of the United States for the number of closely spaced, large seisms and for the size of the felt area (figure 5.36). The earthquakes were felt from Canada to the Gulf of Mexico and from the Rocky Mountains to the Atlantic seaboard, where clocks stopped, bells rang, and plaster cracked. These big earthquakes were not a freak occurrence. The oral history of the local American Indians tells of earlier dramatic events.

Assessments of the earthquakes based on felt area yield magnitude estimates of 8 to 8.3. But are the sizes of the felt areas in figure 5.36 a good indicator of earthquake magnitude? Were the New Madrid seisms many times bigger than the 1906 San Francisco earthquake? Not necessarily. The size of the felt area is related to the types of rocks being vibrated. The New Madrid seisms shook the rigid basement rocks (more than 1 billion years old) of the continental interior. They rang like a bell, and the seismic energy was transmitted efficiently and far. The San Francisco earthquake took place in younger, tectonically fractured rocks that quickly damped out the seismic energy, thus confining the shaking to a smaller area.

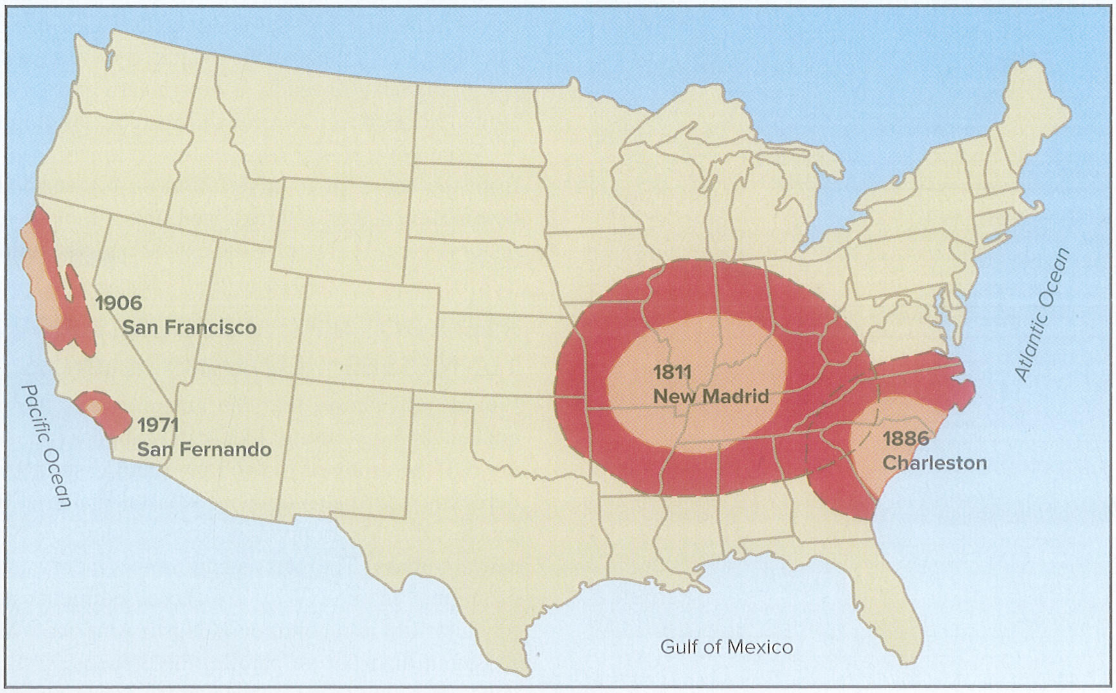

Figure 5.36 Felt areas of some large earthquakes in the United States. Orange areas are Mercalli intensities greater than VII; red areas are intensities of VI to VII.

Magnitudes

The first of four big earthquakes occurred on 16 December 1811 and seems to have occurred on the Cottonwood Grove fault as 13 ft (4 m) of slip along a 37 mi (60 km) rupture length (figure 5.37). This seism is likely to have triggered two ruptures on the Reelfoot blind-thrust fault at New Madrid, Missouri: one also on 16 December 1811 and the largest of the series on 7 February 1812. The large earthquake that occurred on 23 January 1812 has been the most difficult to locate. At present, it seems the earthquake epicenter was about 125 mi (200 km) to the north, around southern Illinois. If this interpretation holds up, the hazards associated with midcontinent earthquakes are more widely distributed than is commonly recognized.

The defined fault-rupture lengths are too short to have generated magnitude 8 earthquakes as suggested from felt-area analysis. When moment magnitudes calculated from fault surface-area estimates are considered with Mercalli intensities, the earthquake magnitudes seem to range from about 7.3 to 7.7. However, remember that the earthquake epicenters sit on top of a thick pile of water-saturated sediment. This loose material amplifies the local shaking several times, leading to high Mercalli intensities. Discounting for amplification of seismic waves leads to earthquake magnitude estimates, in chronologic order, of 7.3, 7.0, 7.0, and 7.5.

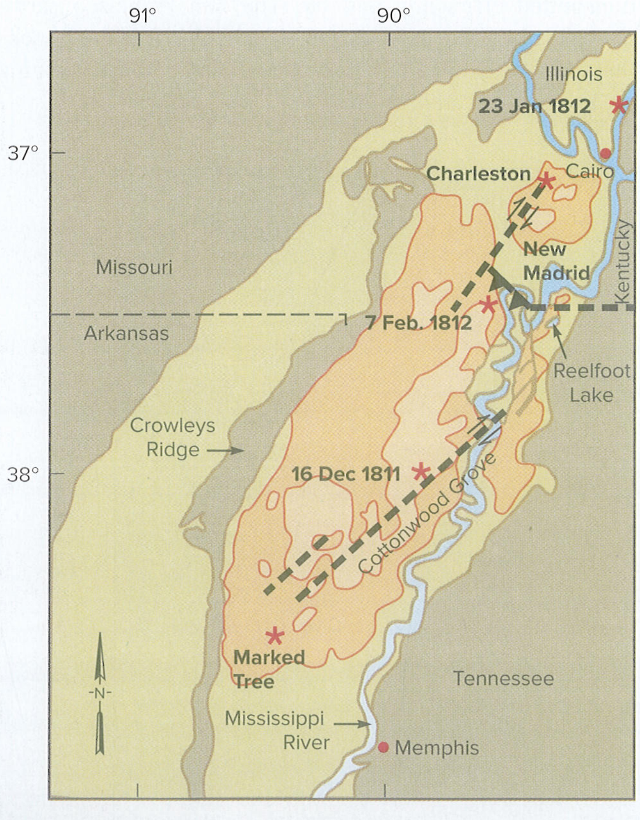

Figure 5.37 Map of the New Madrid region showing epicenters of large earthquakes and faults located using aftershocks. Marked Tree, Arkansas, was the site of a ~6M event in 1843; Charleston, Missouri, had a ~6M seism in 1895. Faults are indicated by dashed lines.

The Future

Can aftershocks from the 1811–1812 earthquakes still be occurring today, more than 200 years later? Yes, but aftershock energy decays with time, and the expected decay rate is not seen here. Seismic activity in the region occurs at too high a level to be only aftershocks. Internal deformation within the tectonic plate appears to be adding strain energy, building toward future earthquakes.

When large earthquakes return again to the upper Mississippi River region, the potential for death and destruction is sobering (figure 5.38). (1) The area has a large population (e.g., Memphis, St. Louis, Nashville); (2) many buildings were not designed to withstand large seisms; (3) the wide extent and great thickness of soft sediments will amplify seismic vibrations (remember the 1985 Mexico City and 1989 World Series events); and (4) a very large area will be subjected to strong shaking. The effects of a magnitude 7.5 earthquake could include deaths in the thousands and damages in the tens of billions of dollars.

How frequent are large earthquakes here? Paleoseismologic analyses of sediment and wood indicate major earthquake clusters occurred around 2350 BCE, 900 CE, 1450 CE, and 1812 CE. A magnitude 7 or greater earthquake could occur here about every 500 years. There is a 7–10% chance of one in the next 50 years. If there is good news, it is the low frequency of occurrence for these large earthquakes. The lessons of history here must be learned, and all new construction in the region should be built to withstand major earthquakes.

The earthquake threat in this region also includes lesser events. In 1843, it was an ~6M event at Marked Tree, Arkansas, and in 1895, it was an ~6M seism at Charleston, Missouri (figure 5.37). Paleoseismologic analyses in trenches cut across faults and folds have led the U.S. Geological Survey to forecast a ~25% chance of a magnitude 6 to 7 earthquake here within the next 50 years. Although earthquakes in the central United States have low probability, they have high impact.

Since New Madrid sits in the continental interior, away from the active plate edges, why do big earthquakes occur here? The answer is unresolved, but a look at the geologic history of the region provides some understanding.

REELFOOT RIFT: MISSOURI, ARKANSAS, TENNESSEE, KENTUCKY, ILLINOIS

Figure 5.37 shows that the epicenters of the large earthquakes line up along the Mississippi River Valley. Figure 5.34 is a map of the southern and eastern United States depicting the distribution of coastal-plain sediments—the sands and muds dropped by rivers eroding the North American landmass. The Mississippi embayment stands out as a prominent feature. Why are these sediments deposited so much farther into continental North America? Why does the sediment distribution parallel the epicenters? Is it a coincidence that this same linear pattern keeps reappearing? No. Is it random chance that the Mississippi River flows along the course that it does? No. Rivers find zones of weakness.

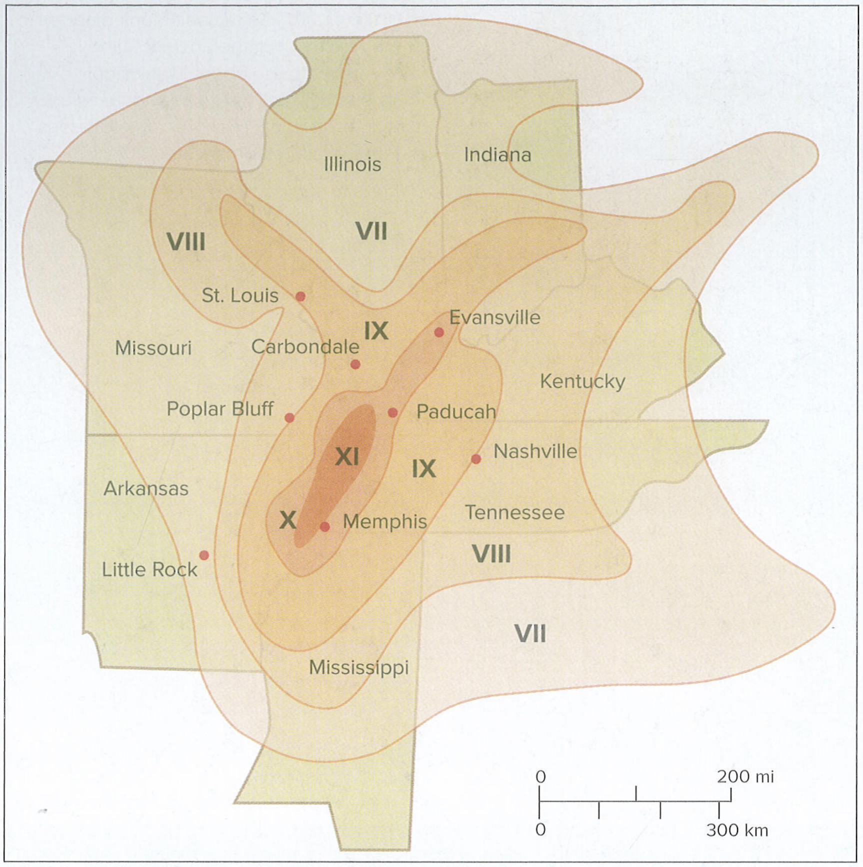

Figure 5.38 Map showing estimated Mercalli intensities expected from a recurrence of an 1811–1812 New Madrid earthquake. Intensity VIII and above indicates heavy structural damage.

Source: Edited by Robert Morrison Hamilton and Arch C. Johnston (1990), "Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake", US Geological Survey Circular 1066.

The results of studies of seismic waves, gravity, and magnetism define a linear structural feature in the basement rocks underlying the New Madrid region (figure 5.39). There is a northeast-trending depression at depth that is more than 300 km (190 mi) long and about 70 km (43 mi) wide. It is linear, has nearly parallel sides, and is about 2 km (1.2 mi) deeper than the surrounding basement rocks. In short, it is an ancient rift valley, known as the Reelfoot rift, formed about 550 million years ago. Similar features that are still forming today and are more apparent at the Earth's surface include the Rio Grande rift in New Mexico (see figure 5.33) and the East African Rift Valley (see figure 4.6). The ancient Reelfoot rift was filled and covered by younger sediments (figure 5.39). Today, the opening Atlantic Ocean basin pushes North America to the west-southwest, and some of the ancient faults of the Reelfoot rift are being reactivated to produce the region's earthquakes.

Isostatic Rebound as an Earthquake Trigger

Although stress from plate-tectonic movements elastically strains the rocks, what triggers the earthquakes? Isostatic rebound may be the trigger for movement of the ancient faults. As the North American ice sheet retreated northward from the United States and Canada between 16,000 to 10,000 years ago, enormous volumes of glacial meltwater poured through the Mississippi and Ohio river systems eroding huge volumes of sediment as they flowed. Examination of existing sediment layers shows that the upper Mississippi River eroded the region and carried away a 12 m (40 ft) thickness of sediments. With removal of this heavy load of sediments, the land rebounded upward, reducing the stresses that held the underlying faults in place. Some faults that were close to failure have failed; other faults will follow.

ANCIENT RIFTS IN THE CENTRAL UNITED STATES

It is the fate of all continents to be ripped apart from below. Continents are rifted and then drifted and reassembled in different patterns. Sometimes the rifting process stops before separating a continent. The Reelfoot rift, now occupied by the Mississippi River, is a prominent **failed rift.** Other failed rifts, from different plate-tectonic histories, also exist beneath the surface in North America (figure 5.40).

Failed rifts remain as zones of weakness that may be reactivated by later plate-tectonic stresses to once again generate earthquakes. Because failed rifts are deeply buried, they are difficult to study. Yet they raise significant questions. What are the frequencies of their major earthquakes? In general, the recurrence intervals for major earthquakes appear to be from a few hundred to more than a thousand years. How great an earthquake might be produced at each rift? The New Madrid earthquake series offers a sobering benchmark.

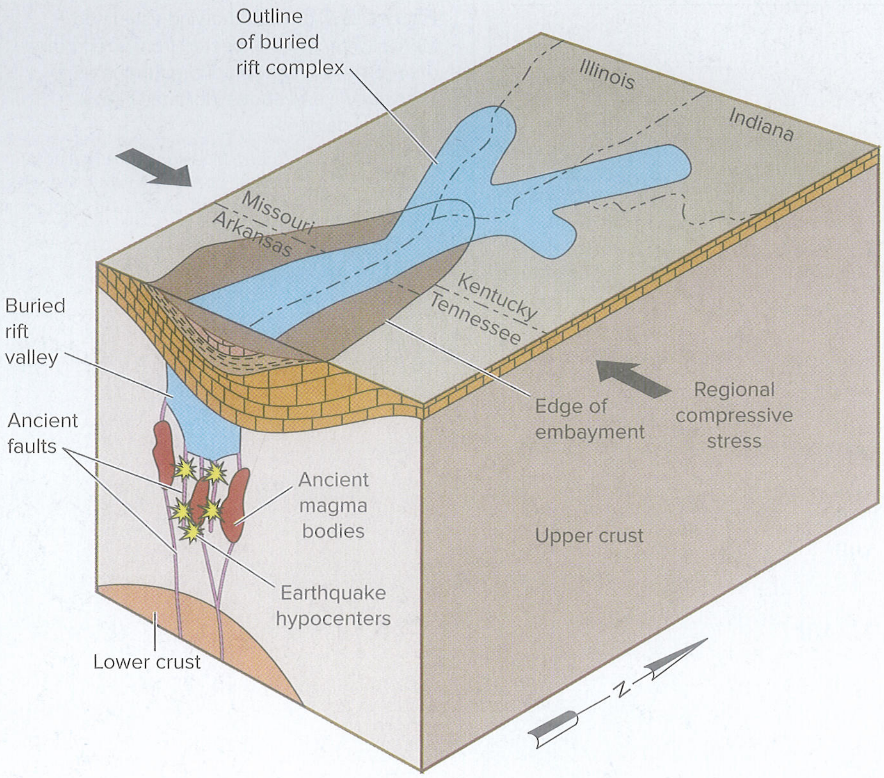

Figure 5.39 Schematic block diagram of the Reelfoot rift, the ancient failed rift valley beneath the upper Mississippi River embayment. Large earthquakes are likely caused by present tectonic stresses triggering failures on ancient faults.

Source: US Geological Survey Professional Paper-1236L.

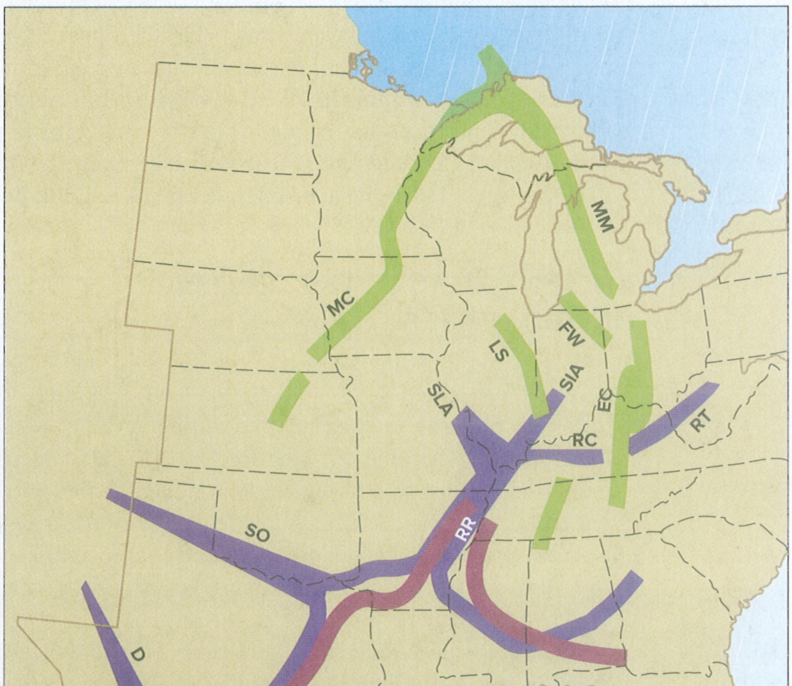

Figure 5.40 Map showing approximate locations of buried, ancient rifts in the central United States. Rifting occurred during three principal times—around 220 to 175 million years ago (red); 600 to 500 million years ago (purple); and 1,100 to 1,000 million years ago (green). Some older rifts were apparently rifted again under later plate-tectonic regimes. Rifts are: D, Delaware; EC, East Continent; FW, Fort Wayne; LS, La Salle; MC, Mid-Continent; MM, Mid-Michigan; RC, Rough Creek; RR, Reelfoot Rift; RT, Rome Trough; SIA, Southern Indiana Arm; SLA, St. Louis Arm; and SO, Southern Oklahoma.

Source: D. W. Gordon, US Geological Survey Professional Paper 1364.

Approximately 83% of the large earthquakes recorded in the central United States are at or near the sites of ancient rifts.

The buried, ancient rifts in figure 5.40 correlate with active fault zones at the surface. There are several examples. (1) The St. Louis arm corresponds to the Ste. Genevieve fault zone. (2) The Rough Creek rift is expressed as the Rough Creek fault zone, appearing to continue eastward as the Kentucky River fault zone. Trenches dug across the Rough Creek fault have exposed the sedimentary records of reverse-fault movements with 1.1 m (more than 3.5 ft) of offset. (3) The southern Oklahoma rift corresponds with the frontal-fault system of the Wichita Mountains. Although this zone does not generate earthquakes at present, the land surface testifies to major earthquakes. The Meers fault is dramatic enough to make any Californian proud, but this fault strikes N 63° W across southwestern Oklahoma. Its fault scarp is 5 m (16 ft) high and 27 km (17 mi) long, and it has left-lateral offset up to 25 m (82 ft). At least two major fault ruptures have occurred there in geologically recent time. (4) The southern Indiana arm is overlain by the Wabash Valley fault zone, which appears to connect with the New Madrid zone. Prehistoric earthquakes read in the sedimentary record suggest seisms with m_b equal to 6.3 to more than 7. Damaging earthquakes occur in the area about once a decade. Examples include a magnitude 5.5 in November 1968, a magnitude 5.2 in June 1987, and a magnitude 5 in southwest Indiana on 18 June 2002.

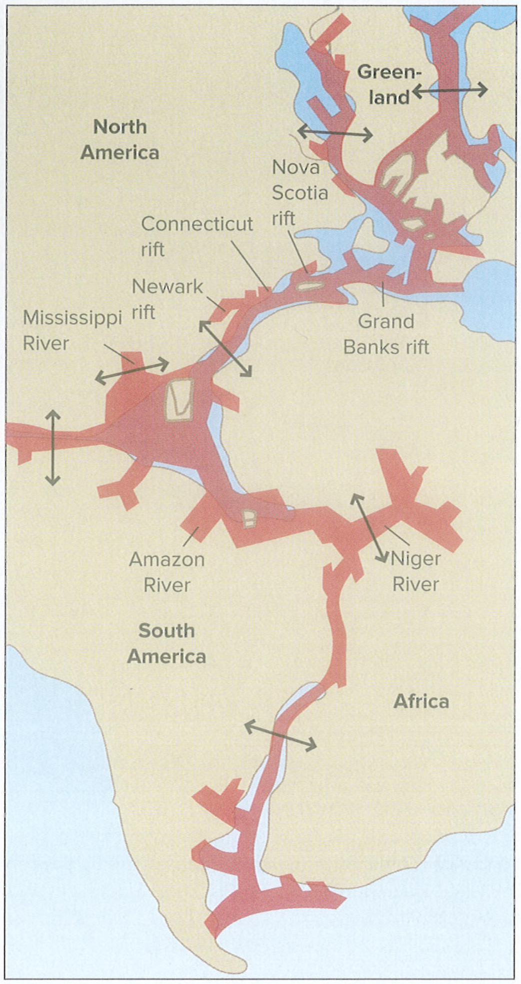

Figure 5.41 Schematic map of rifts that tore at Pangaea about 220 million years ago. Successful rifts combined to open the Atlantic Ocean basin.

Intraplate Earthquakes: Eastern North America

The large earthquakes of eastern North America share characteristics with those of central North America. Most occur at sites of ancient rift valleys. Most lack significant recent faults. The regions have low strain rates. Figure 5.41 shows some rift arms developed 220 to 180 million years ago as Pangaea was torn apart. Some rift arms succeeded, combining to create today's Atlantic Ocean basin. Other rift arms failed and left behind weakened zones within continents.

NEW ENGLAND

New England has a long record of significant earthquakes. On 11 June 1638, just 18 years after the Pilgrims landed in Plymouth, Massachusetts, a sizable earthquake rocked them. It rattled dishes, shook buildings, and in general frightened the Europeans, who were unfamiliar with earthquakes. Due to the limited number of settlements, it is difficult to pinpoint the location of the fault movement that generated this earthquake. However, a suggested epicentral site lies offshore from Cape Ann; estimates of Mercalli intensity range all the way up to IX, and a magnitude estimate based on felt area is 5.5. It has been suggested that this earthquake was merely an aftershock from a magnitude 7 or greater earthquake that occurred offshore at a much earlier date.

On 9 November 1727, an earthquake rattled the East Coast from Maine to Delaware. The epicenter was near Newbury, Massachusetts (figure 5.42), and the shaking caused chimneys and stone walls to fall and cellar walls to collapse. Some uplands were dropped down to become wet lowlands, and some wet lowlands were uplifted and became dry enough to support grasses. **Quicksand** conditions were common during the earthquake.

Shortly before dawn on a frigid 18 November 1755, the entire eastern seaboard from Nova Scotia to South Carolina was shaken with an earthquake that began offshore from Cape Ann, Massachusetts. In Boston, so many chimneys reportedly toppled that some streets were made impassable by the debris. The seism is estimated to have had a magnitude of about 6.3, but the shaking was so severe that residents reported seeing the land rolling with waves like the surface of the sea. This earthquake occurred just 17 days after the epic earthquakes in Lisbon, Portugal, and it fired up the doom-and-gloom preachers who saw the seism as just punishment for the sins of New Englanders.

Many of these earthquakes may be related to the faults that bound former rift valleys (figure 5.41). The ancient faults may be reactivating and failing due to current stresses. Do all the rift-bounding faults have the potential for future

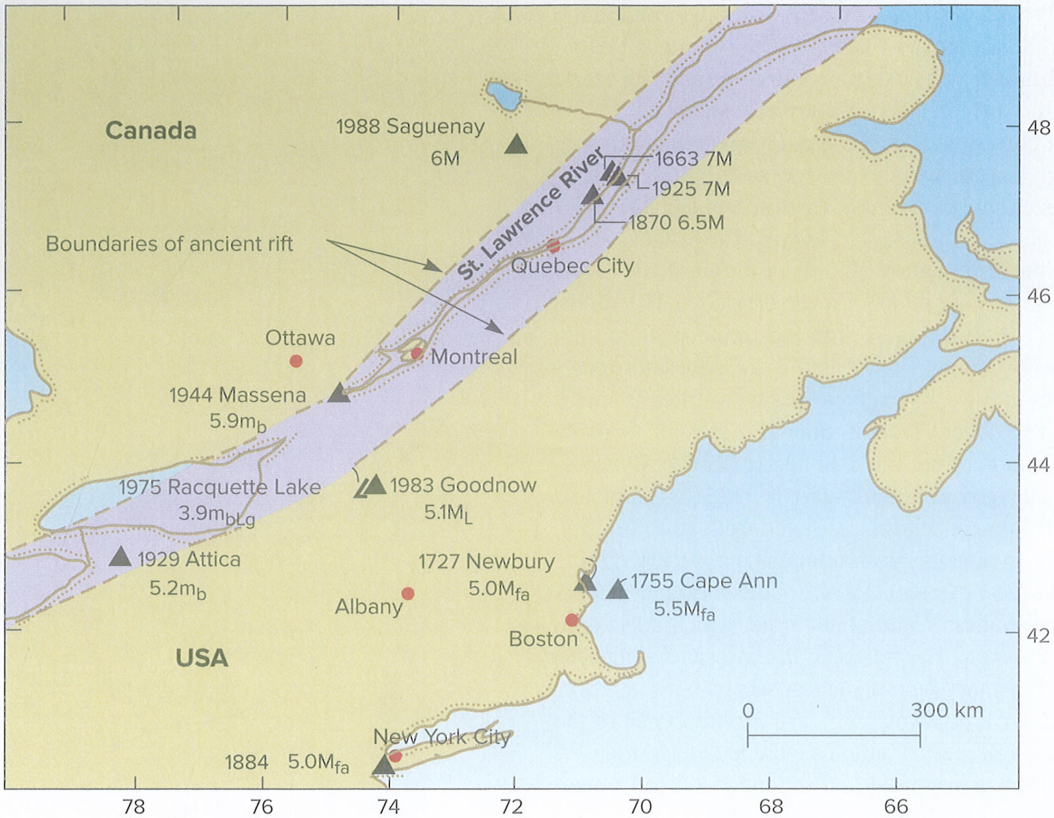

Figure 5.42 Some earthquake locations in the St. Lawrence River valley area. The approximate location of the 600- to 500-million-year-old rift valley is shown in purple. M_{fa} equals magnitude estimated from the felt area. Large earthquakes northeast of Quebec City lie in the circular Charlevoix seismic zone.

seismic activity? The historic record is not long enough to properly answer this question. But if the answer is yes, then virtually the length of the Atlantic Coastal province could receive a significant shake sometime.

When the next magnitude 6 or greater earthquake strikes the eastern United States, the resultant destruction is likely to be proportionately greater than for a similar seism in the western part of the country. In the East, earthquake energy is transmitted more effectively in the older, more solid rocks, so damages may be experienced over a wider area. Also consider (1) the population density of the East, (2) the large number of older buildings not designed to withstand earthquake shaking, and (3) the concentration of industrial and power-generating facilities, including nuclear reactors.

ST. LAWRENCE RIVER VALLEY

The St. Lawrence is another river whose present path results from occupying an ancient tectonic structure. Some 600 to 500 million years ago, a major rift valley extended through the region (figure 5.42). This now-buried rift coincides with most of the significant earthquakes in southeastern Canada. Seisms within the rift valley commonly reach magnitude 7, yet in unrifted continent nearby, the largest earthquakes are usually only in the magnitude 5 range.

The most active area along the St. Lawrence River Valley is an 80 km (50 mi) by 35 km (22 mi) zone near Charlevoix, northeast of Quebec City. Here, earthquakes of magnitudes 6 to 7 occurred in 1534, 1663, 1791, 1860, 1870, and 1925. Why the concentration of large seisms in this one relatively small area? Charlevoix was the site of a meteorite impact some 350 million years ago. The impact caused intensive fracturing of the area, including faults in curving patterns. These impact-caused fractures are perhaps being reactivated today under the stresses generated by the opening Atlantic Ocean basin.

CHARLESTON, SOUTH CAROLINA, 1886

Charleston sits alongside a beautiful bay, a charming city with distinguished buildings, wide boulevards, and inviting gardens. The presence of the port helped the city develop as a wealthy trading center. Yet Charleston has another side. In the mid-1800s, it was a hotbed of secessionist fervor; the first shots of the Civil War were fired over its harbor at Fort Sumter on 12 April 1861. After the war ended four years later, Charleston was

> a city of ruins, of desolation, of vacant houses, of widowed women, of rotting wharves, of deserted warehouses, of acres of pitiful and voiceless barrenness.

Yet by the mid-1880s, Charleston had been restored as a center of wealth, aesthetic buildings, and cultural achievement. Even the damages wrought by an 1885 hurricane were not enough to slow the city. Then came 31 August 1886, a typical sultry summer day. At 9:50 p.m., the quiet, breezeless evening was shattered by the largest earthquake to occur east of the Appalachian Mountains in historic time. Sixty seconds of shaking left 60 people dead, and once again, the remaining citizens had to put their city back together. About 90% of the buildings were damaged or destroyed (figure 5.43).

The earthquake had a magnitude estimated at 7.3. The event produced no surface faulting, so the fault movement may have occurred below 20 km (12 mi) depth. The large magnitude corresponds to a rupture length of about 30 km (19 mi) and a rupture width on the fault surface of about 19 km (12 mi). The seism was felt over a large area, and damages were widespread as well (figure 5.44). The large felt area is typical of the eastern United States and is largely

Figure 5.43 Damage from the 1886 earthquake in Charleston, South Carolina.
Photograph by J.K. Hillers, USGS

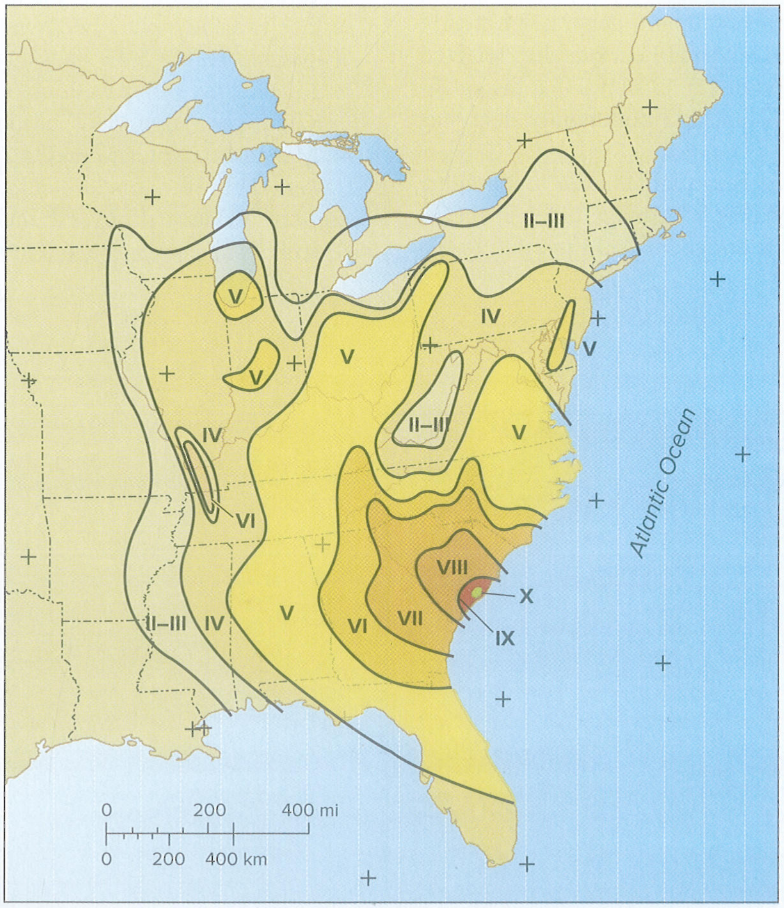

Figure 5.44 Mercalli intensity map for the 31 August 1886 earthquake near Charleston, South Carolina.
Source: G A Bollinger (1977), "Studies Related to the Charleston, South Carolina, Earthquake of 1886-A Preliminary Report ", US Geological Survey Professional Paper 1028.

attributable to the persistence of longer-period seismic waves (e.g., 1 second), which simply do not die down as quickly as they do in the western United States. The continental rocks at depth are geologically old and rigid, causing the region to "ring like a bell" and transmit seismic waves far and wide.

How rare is an earthquake of this size for Charleston? Sediments exposed in trench walls, augmented by radiocarbon dates, tell of at least five other similar-sized earthquakes in the area in the past 3,000 to 3,600 years. Thus, large seisms may be expected about every 600 years.

TABLE 5.5

Some Large Earthquakes in Hawai'i

Date	Location	Intensity	Magnitude
2 Apr 1868	Southeast Hawaii	X	7.9
5 Oct 1929	Holualoa, Hawaii	VII	6.5 M_s
22 Jan 1938	North of Maui	VIII	6.7 M_s
25 Sep 1941	Mauna Loa, Hawaii	VII	6.0 M_s
22 Apr 1951	Kilauea, Hawaii	VII	6.5
21 Aug 1951	Kona, Hawaii	IX	6.9
30 Mar 1954	Kalapana, Hawaii	VII	6.5
26 Apr 1973	Southeast Hawaii	VIII	6.3
29 Nov 1975	Southeast Hawaii	VIII	7.2 M_s
16 Nov 1983	Mauna Loa, Hawaii	VII	6.6 M_s
25 Jun 1989	Kalapana, Hawaii	VIII	6.5
15 Oct 2006	Kalaoa, Hawaii	VIII	6.7 M_w
3 May 2018	Kilauea, Hawaii	IX	6.9 M_w

Earthquakes and Volcanism in Hawaii

When we think about natural hazards in Hawaii, it is volcanism that comes to mind. But the movement of magma can cause earthquakes, including large ones (table 5.5). When rock liquefies, its volume expands, and neighboring brittle rock must fracture and move out of the way. The sudden breaks and slips of brittle rock are fault movements that produce earthquakes. When magma is on the move at shallow depths, it commonly generates a nearly continuous swarm of relatively small earthquakes referred to as **harmonic tremors.** Figure 5.45 shows that the earthquakes below Kilauea Volcano are dominantly near-surface events.

Magma movements also cause larger-scale topographic features and larger earthquakes with magnitudes in the 6s and 7s. The land surface is commonly uplifted due to the injection of magma below the ground surface. But the land surface is also commonly down-dropped due to withdrawal of magma. Figure 5.46 shows some down-dropped valleys on Kilauea; the valley walls are normal faults.

Kilauea is "supported" on the northwest by the gigantic Mauna Loa volcano and the mass of the Big Island of Hawaii. However, on its southeastern side, there is less support; Kilauea drops off into the Pacific Ocean. The effects of subsurface magma movement, both compressive

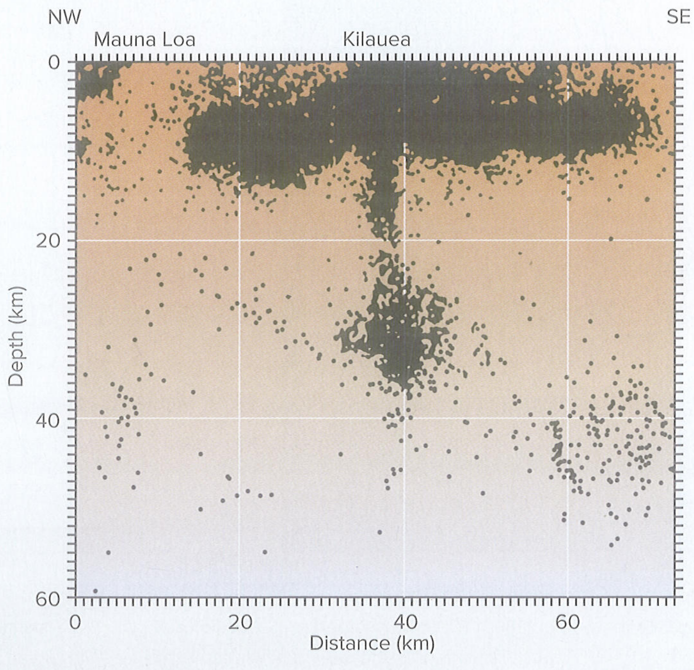

Figure 5.45 Cross-section showing hypocenters beneath Kilauea Volcano on the flank of the larger Mauna Loa Volcano, southeastern Hawaii, 1970–1983.

Source: F W Klein, R Y Koyanagi, "The Seismicity and Tectonics of Hawaii", Geological Society of America, Decade of North American Geology. Vol. N.

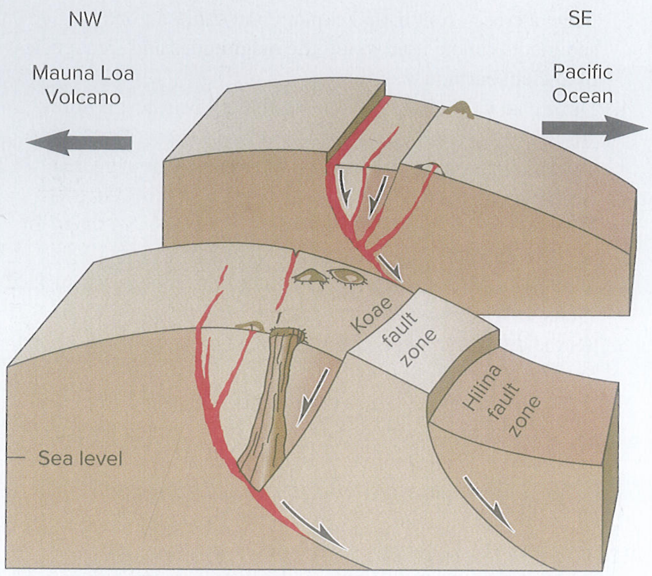

Figure 5.46 Schematic block diagrams of the southeastern flank of Kilauea Volcano. Intruding magma (red) forces brittle rock to break and move, generating earthquakes. Gravity-aided sliding down normal faults causes more earthquakes as rock masses slide southeastward into the ocean and cause rare mega-tsunami.

during injection and extensional during removal, combine with gravitational pull to cause large movements on normal faults.

EARTHQUAKE IN 1975

On 29 November, one of the seaward-inclined normal faults moved suddenly in a 7.2M_s seism. It happened at 4:48 a.m., when a large mass slipped for 14 seconds with a movement of about 6 m (20 ft) seaward and 3.5 m (11.5 ft) downward. The movement of this mass into the sea caused tsunami up to 12 m (40 ft) high. Campers sleeping on the beach were rudely awakened by shaking ground; those who didn't immediately hustle to higher ground were subjected to crashing waves. Two people drowned. This fault movement had an effect on subsurface magma analogous to shaking a bottle of soda pop—gases escaping from magma unleashed an 18-hour eruption featuring magma fountains up to 50 m (165 ft) high.

EARTHQUAKES IN 2006

On 15 October, the Big Island of Hawai'i was rocked by two large earthquakes just 7 minutes apart. The first seism was 6.7 M_w at the hypocentral depth of 40 km (25 mi); the second was 6.0 M_w at 20 km (12 mi) depth. The earthquakes seem to have resulted from the heavy load that the huge island of Hawai'i places on the lithosphere. They occurred where the lithosphere is bent or flexed the most. The initial deeper earthquake resulted from tensional forces pulling rock apart. The following shallower earthquake occurred due to compressional forces pushing rock together.

EARTHQUAKE IN 2018

During 2018, Kilauea Volcano experienced its largest eruption and caldera collapse in about 200 years. Lava flowed out of fissures (giant cracks) and the volcano summit partially drained. All this volcanic activity caused near-daily eruptions and collapses felt as earthquakes up to 4.7 to 5.4 magnitude. At 12:33 p.m. on 4 May, a 6.9 M_w earthquake broke loose. The stack of volcanic rocks more than 5 km (3 mi) thick, sitting on top of older rocks, was thrust 5 m (17 ft) up a plane surface dipping 7° over an area of 700 km^2 (270 mi^2). This huge event was quickly followed by large aftershocks.

Summary

Fault movement is complex; movement lasts only a few seconds at one spot, it speeds up and slows down, it slips different amounts in different sections, and it can trigger other activity in the direction of its movement.

The large left step in the San Andreas fault in the Los Angeles area causes compressive ruptures along east-west-oriented thrust faults, as in the 1971 San Fernando and 1994 Northridge events. More Northridge-type earthquakes are likely.

Prehistoric earthquakes may be interpreted using faulted pond sediments. The amount of offset of sediment layers is proportional to earthquake magnitude. Organic material in sediment layers can be dated by measuring the amount of radioactive carbon present. These techniques were used in 1988 to forecast a 30% probability of a magnitude 6.5 earthquake in the Loma Prieta area by the year 2018. In 1989, a magnitude 6.9 event occurred.

Southern California may have several large earthquakes in the 21st century. The southern segment of the San Andreas fault is the only one not to have a long rupture in historic time. In prehistory, it has ruptured every 250 years on average, but the last big movement was in 1690. The next big earthquake in California quite possibly will be a magnitude 7.8 event rupturing 300 km (185 mi) of the fault.

Humans have triggered earthquakes by pumping water underground under pressure; by building dams and impounding water, which seeps underground under pressure; and by underground explosions of atomic bombs.

Earthquakes occur throughout North America. Most are in the West along the edges of the active plates, but the central and eastern regions also have earthquakes—not as many, but some of them large.

In the Pacific Northwest, earthquakes occur 30 to 70 km (20 to 45 mi) deep within the subducting oceanic plate as minerals change form due to increased temperature and pressure. At the surface, strike-slip faults rupture the ground, as in Seattle.

The Basin and Range province between eastern California and central Utah is an actively extending area. For example, Nevada has about doubled in west-east width in the past 30 million years. Normal faults accommodate most of the extension, unleashing earthquakes up to magnitude 7.3.

In the central United States and eastern North America, ancient rift valleys remain from failed spreading centers. The ancient rifts today are zones of weakness whose faults can be reactivated due to long-distance effects of Atlantic plate spreading and Pacific plate collision. The Reelfoot rift, occupied today by the Mississippi River, had earthquakes in 1811 and 1812 with moment magnitudes (M_w) of 7.3, 7.0, 7.0, and 7.5. Other rift valleys are associated with earthquakes throughout North America.

Charlevoix, Quebec, has frequent earthquakes up to magnitude 7. The region was intensely fractured by the impact of an ancient asteroid, and the fractured rocks apparently move due to stresses within the moving plates.

The underground movement of magma in Hawaii generates earthquakes up to magnitude 7.9 by forcefully rupturing brittle rocks. Land is uplifted as magma is injected and dropped down when magma is removed; these land movements may be sudden, earthquake-generating events, and some create tsunami as well.

Terms to Remember

avalanche 113
blind thrust 112
coal 115
directivity 111
earthquake weather 118
embayment 132
failed rift 135
fracking 122
friction 109
harmonic tremors 140
hydraulic fracturing 122
neotectonics 114
paleoseismology 114
photosynthesis 115
quicksand 137
scarp 131
thrust fault 112

Questions for Review

1. Sketch a map, and explain the elastic-rebound theory of faulting. How has the theory been modified in recent years?
2. Draw a cross-section of a blind-thrust fault, such as the one that affected Northridge in 1994. Why was ground shaking so intense in this earthquake?
3. Draw a cross-section, and explain how faulted pond sediments can be used to tell the magnitudes and frequencies of ancient earthquakes.
4. During an earthquake, you probably will be safest if you _____, _____, and _____.
5. Explain three ways that humans have caused or triggered earthquakes.
6. Earthquakes are most abundant in which two U.S. states? In which Canadian province?
7. What types of evidence indicate major movements on surface faults in Washington?
8. As the depth to a hypocenter increases, how does that affect surface shaking?
9. What tectonic process has affected the Basin and Range province, from eastern California to Utah, during the past 30 million years? How much stretching has occurred across it? What is the orientation of the ranges and basins, and what does this tell us about the direction of stretching?
10. What type of fault movement best characterizes the Basin and Range province? What are the highest magnitude earthquakes generated there in the past century?
11. "Stable" central and eastern North America have earthquakes clustered in distinct areas. What is a likely control on these earthquake locations?
12. When and how did the Reelfoot rift form? Explain its history of earthquakes. What is the name of the strongest historical earthquake swarm that occurred here? What does the future hold?
13. How does intrusion of magma on the flanks of Kilauea volcano on Hawaii generate earthquakes?
14. What are the harmonic tremors experienced in Hawaii? What do they tell us?
15. Why are the western United States and Canada much more seismically active than the central and eastern regions? Does the smaller number of earthquakes in the central and eastern United States and Canada mean that we don't have to worry about a "big one" there?
16. Besides an actual downward subduction movement, how can a subducting plate generate earthquakes, as in Washington?
17. What is hydraulic fracturing? How can it trigger an earthquake?
18. What is meant by directivity of seismic waves? How significant is directivity?
19. Are seismic waves amplified more in hard rocks or in soft sediments? What happens to amplitude of seismic waves when they enter soft sediments? (See discussion under ShakeMaps.)
20. What event, unrelated to plate tectonics, weakened the crust along part of the St. Lawrence River Valley, making it easier to reactivate faults there?

Questions for Further Thought

1. So-called psychics are commonly quoted in the media predicting that California will break off along the San Andreas fault and sink beneath the sea. Is this possible? Why not?
2. Some people suggest that earthquakes usually occur at certain times of day. Does this make sense? Is there a pattern to the times of the earthquakes discussed in this text?

3. Assess the earthquake hazard in Salt Lake City.
4. What controls the course of the Rio Grande in New Mexico? Is there an earthquake threat also?
5. Compare the ability to withstand earthquake shaking of downtown buildings and bridges in West Coast cities to that of structures in the mid-continent or East Coast of the United States.
6. Humans can trigger earthquakes, but should we? Can we set off medium-size earthquakes in a controlled fashion that will prevent a large earthquake in an area? Make a list of pros and cons for earthquake control.
7. Could the Chinese earthquake of 2008 have been triggered by the recent filling of a nearby reservoir?
8. What are possible causes of the 5.8 M_W earthquake in Virginia on 23 August 2011?
9. What are the pros and cons of using hydraulic fracturing to increase recovery of oil and natural gas?