NATURAL DISASTERS

Ninth Edition

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Plate Tectonics and Earthquakes

CHAPTER

4

During the Northridge earthquake, the ground moved rapidly to the north and pulled out from under this elevated apartment building, causing it to fall back onto its parking lot in Canoga Park, California, 17 January 1994.

Photo by Peter W. Weigand.

LEARNING OUTCOMES

Movements along tectonic-plate edges are responsible for many large earthquakes. After studying this chapter, you should:

- be able to describe the types of movements along tectonic-plate edges and the resultant earthquake magnitudes.
- be able to explain why subduction-zone earthquakes have the greatest magnitudes.
- understand the seismic-gap method of forecasting earthquakes.
- recognize the relationship between buildings and earthquake fatalities.

OUTLINE

- Tectonic-Plate Edges and Earthquakes
- Spreading-Center Earthquakes
- Convergent Zones and Earthquakes
- Subduction-Zone Earthquakes
- Continent-Continent Collision Earthquakes
- The Arabian Plate
- Transform-Fault Earthquakes

A bad earthquake at once destroys our oldest associations: the earth, the very emblem of solidity, has moved beneath our feet like a thin crust over a fluid;—one second of time has created in the mind a strange idea of insecurity, which hours of reflection would not have produced.

—*Charles Darwin, 1835, notes for* The Voyage of the Beagle

TABLE 4.1

Mega-Killer Earthquakes, 2003–2011

Year	Place	Magnitude	Deaths	Tectonic Setting
2011	Japan	9.0	~22,000	subduction
2010	Haiti	7.0	~230,000	transform fault
2008	China	7.9	87,500	continent collision
2005	Pakistan	7.6	88,000	continent collision
2004	Indonesia	9.1	~245,000	subduction
2003	Iran	6.6	31,000	continent collision

The past decade brought a staggering number of mega-killer earthquakes (table 4.1). The causes of these earthquakes are best understood using their plate-tectonic settings.

Tectonic-Plate Edges and Earthquakes

Most earthquakes are explainable based on plate-tectonics theory. The lithosphere is broken into rigid plates that move away from, past, and into other rigid plates. These global-scale processes are seen on the ground as individual **faults** where Earth ruptures and the two sides move past each other in earthquake-generating events.

Figure 4.1 shows an idealized tectonic plate and assesses the varying earthquake hazards that are concentrated at plate edges:

1. The divergent or pull-apart motion at spreading centers causes rocks to fail in tension. Rocks rupture relatively easily when subjected to tension. Also, much of the rock here is at a high temperature, causing early failures. Thus, the spreading process yields mainly smaller earthquakes that do not pose an especially great threat to humans.
2. The slide-past motion occurs as the rigid plates fracture and move around the curved Earth. The plates shear and slide past each other in the dominantly horizontal movements of transform faults. This process creates large earthquakes as the irregular plate boundaries retard movement because of irregularities along the faults. It takes a lot of stored energy to overcome the rough surfaces, nonslippery rocks, and bends in faults. When these impediments are finally overcome, a large amount of seismic energy is released.
3. The convergent or push-together motions at subduction zones and in continent-continent collisions cause rocks to fail in compression. These settings store immense amounts of energy that are released in Earth's largest tectonic earthquakes. The very processes of pulling a 70 to 100 km (45 to 60 mi) thick oceanic plate back into the mantle via a subduction zone or of pushing continents together—such as India slamming into Asia to uplift the Himalayas—involve incredible amounts of energy. This results in Earth's greatest earthquakes.

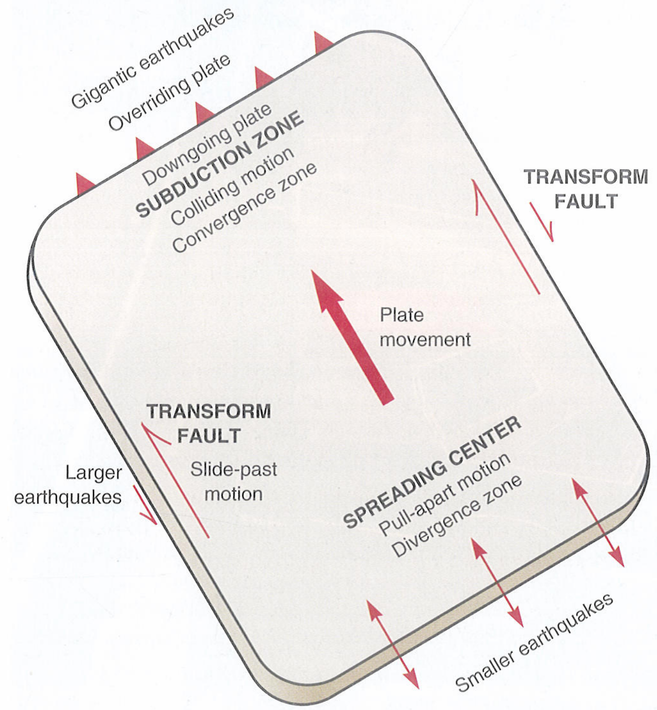


FIGURE 4.1 Map view of an idealized plate and the earthquake potential along its edges.

Moving from an idealized plate, let's examine an actual plate—the Pacific plate. Figure 4.2 shows the same type of plate-edge processes and expected earthquakes. The Pacific plate is created at the spreading centers along its eastern and southern edges. The action there produces smaller earthquakes that also happen to be located away from major human populations.

The slide-past motions of long transform faults occur: (1) in the northeastern Pacific as the Queen Charlotte fault, located near a sparsely populated region of Canada; (2) along the San Andreas fault in California with its famous earthquakes; and (3) at the southwestern edge of the Pacific Ocean where the Alpine fault cuts across the South Island of New Zealand (see figures 3.5 and 3.6).

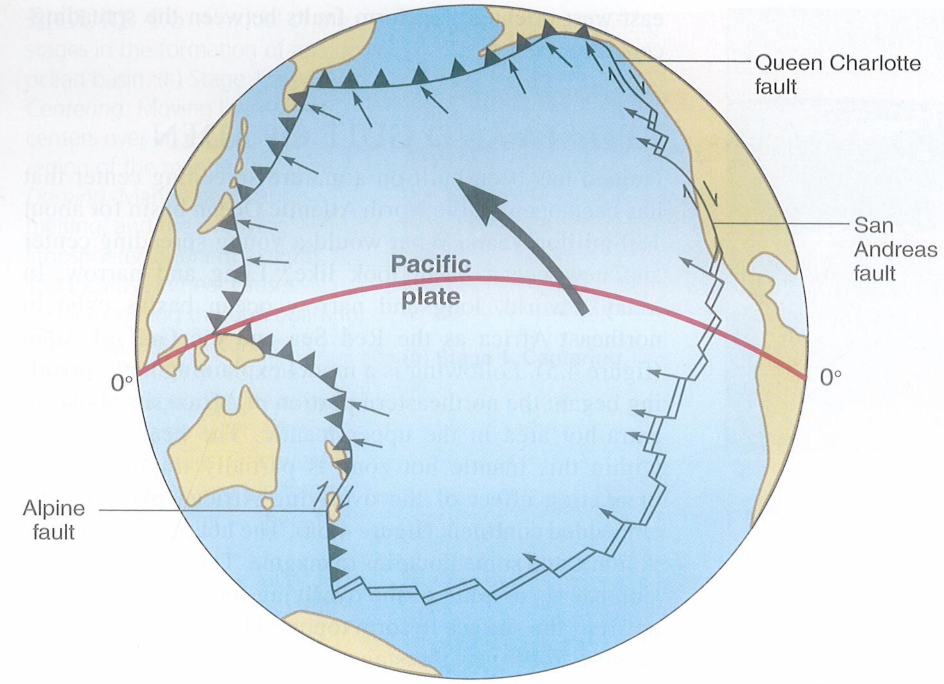


FIGURE 4.2 The Pacific plate is the largest in the world; it underlies part of the Pacific Ocean. Its eastern and southern edges are mostly spreading centers characterized by small- to intermediate-size earthquakes. Three long transform faults exist along its sides in Canada (Queen Charlotte), California (San Andreas), and New Zealand (Alpine); all are characterized by large earthquakes. Subduction zones (shown by black triangles) lie along the northern and western edges, from Alaska to Russia to Japan to the Philippines to Indonesia to New Zealand; all are characterized by gigantic earthquakes.

The Pacific plate subducts along its northern and western edges and creates enormous earthquakes, such as the 2011 Japan seism, the 1964 Alaska event, and the 1931 Napier quake on the North Island of New Zealand.

Our main emphasis here is to understand plate-edge effects as a means of forecasting where earthquakes are likely to occur and what their relative sizes may be.

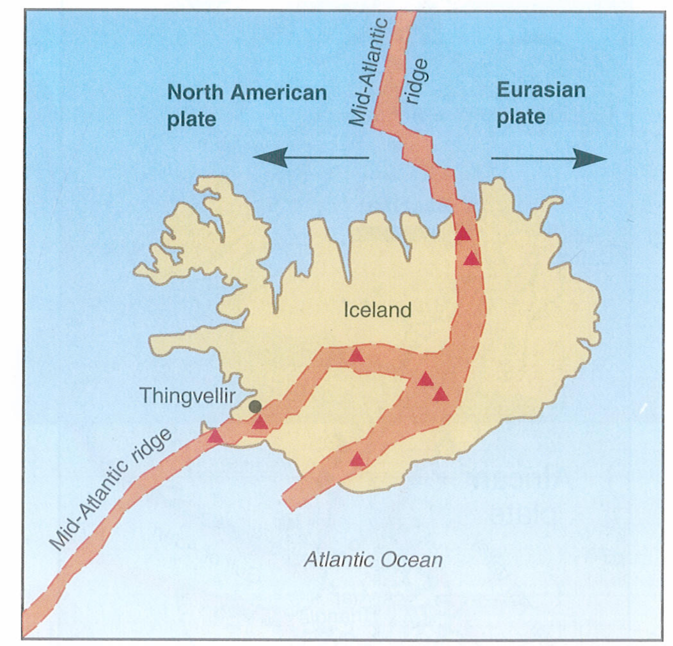


FIGURE 4.3 Iceland sits on top of a hot spot and is being pulled apart by the spreading center in the Atlantic Ocean. Triangles mark sites of some active volcanoes.

Spreading-Center Earthquakes

A look at earthquake epicenter locations around the world (see figure 2.20) reveals that earthquakes are not as common in the vicinity of spreading centers or divergence zones as they are at transform faults and at subduction/collision zones. The expanded volumes of warm rock in the oceanic ridge systems have a higher heat content and a resultant decrease in rigidity. These heat-weakened rocks do not build up and store the huge stresses necessary to create great earthquakes.

Iceland

The style of spreading-center earthquakes can be appreciated by looking at the earthquake history of Iceland, a nation that exists solely on a hot-spot–fed volcanic island portion of the mid-Atlantic ridge spreading center (figures 4.3 and 4.4). The Icelandic geologist R. Stefansson reported on catastrophic earthquakes in Iceland and stated that in the portions of the country underlain by north-south-oriented spreading centers, stresses build up to cause earthquakes too small to destroy buildings or kill people. These moderate-size earthquakes tend to occur in swarms, as is typical of volcanic areas where magma is on the move. Iceland does have large earthquakes, but they are associated with

FIGURE 4.4 Looking south along the fissure at Thingvellir, Iceland. This is the rift valley being pulled apart in an east-west direction by the continuing spreading of the Atlantic Ocean basin. Photo by John S. Shelton.

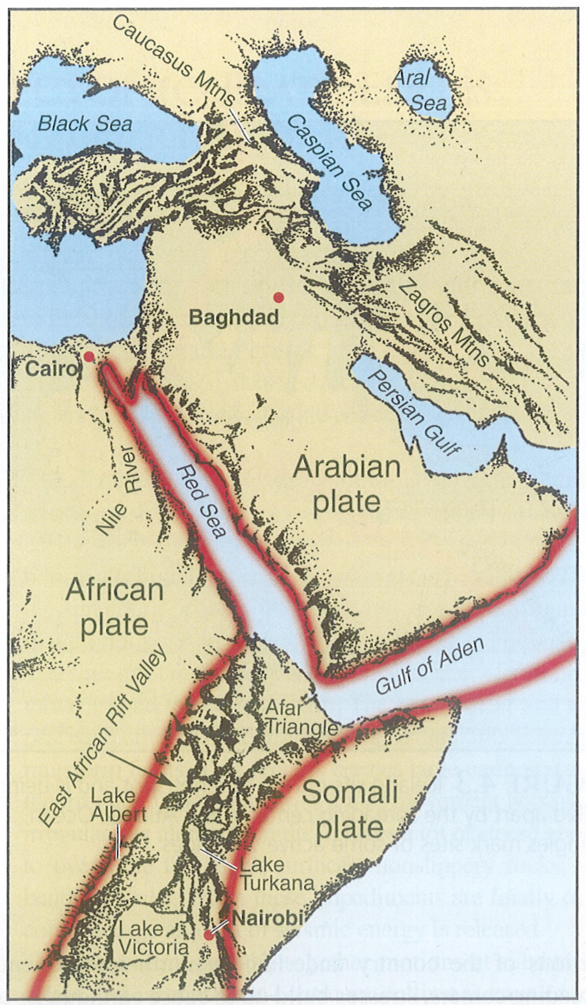


FIGURE 4.5 Topography in northeastern Africa and Arabia. Northeastern Africa is being torn apart by three spreading centers: Red Sea, Gulf of Aden, and East African Rift Valley. The spreading centers meet at the triple junction in the Afar Triangle.

east-west-oriented transform faults between the spreading-center segments.

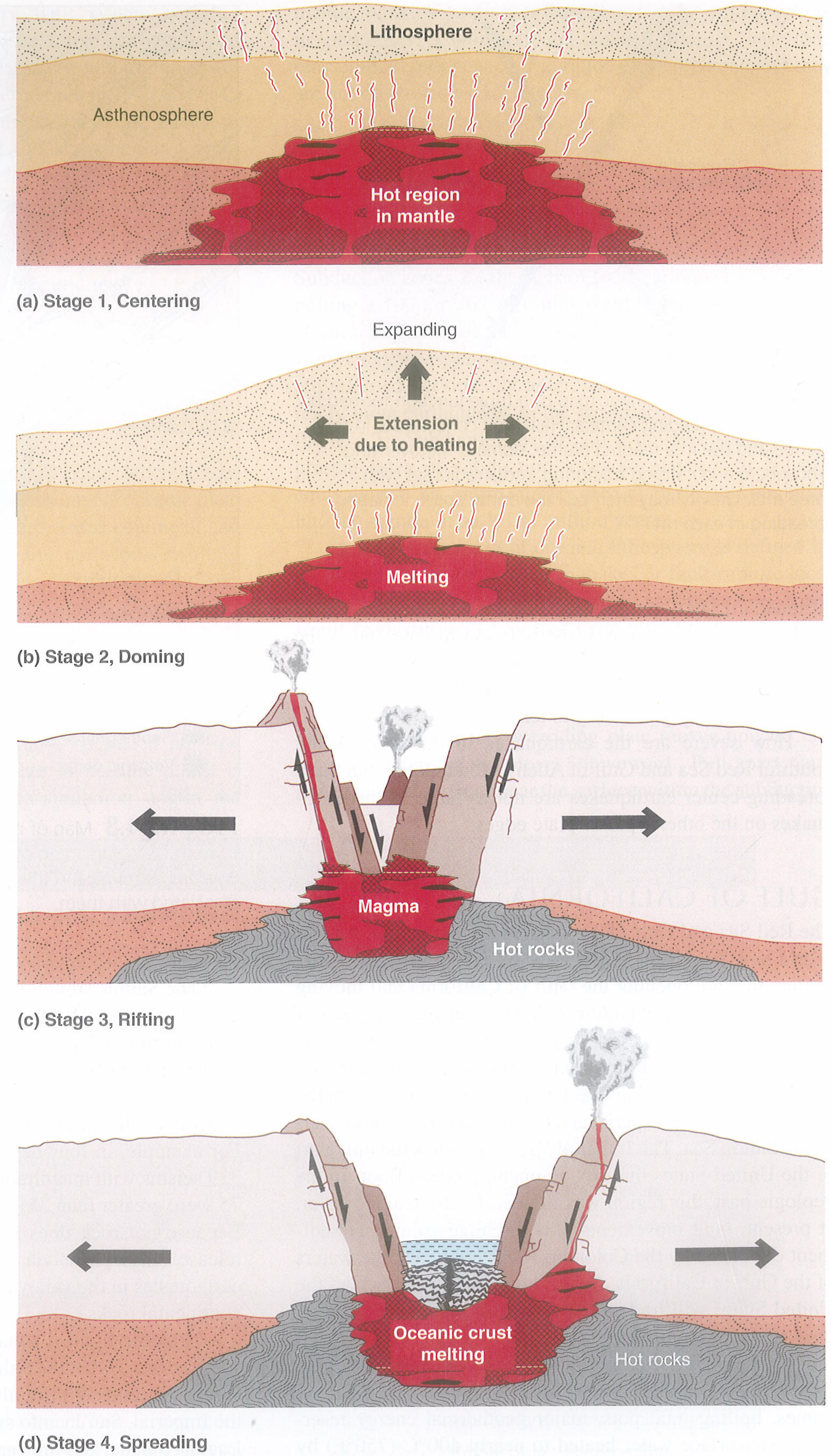
RED SEA AND GULF OF ADEN

Iceland has been built on a mature spreading center that has been opening the North Atlantic Ocean basin for about 180 million years. What would a young spreading center and new ocean basin look like? Long and narrow. In today's world, long and narrow ocean basins exist in northeast Africa as the Red Sea and the Gulf of Aden (figure 4.5). Following is a model explaining how spreading began: the northeastern portion of Africa sits above an extra-hot area in the upper mantle. The heat contained within this mantle hot zone is partially trapped by the blanketing effect of the overlying African plate and its embedded continent (figure 4.6a). The hot rock expands in volume, and some liquefies to magma. This volume expansion causes doming of the overlying rocks, with resultant uplift of the surface to form topography (figure 4.6b). The doming uplift sets the stage for gravity to pull the raised landmasses downward and apart, thus creating pull-apart faults with centrally located, down-dropped **rift** valleys, also described as pull-apart basins (figure 4.6c). As the fracturing/faulting progresses, magma rises up through the cracks to build volcanoes. As rifting and volcanism continue, seafloor spreading processes take over, the down-dropped linear rift valley becomes filled by the ocean, and a new sea is born (figure 4.6d).

Figure 4.5 reveals another interesting geometric feature. Three linear pull-apart basins meet at the south end of the Red Sea; this point where three plate edges touch is called a **triple junction.** Three rifts joining at a point may concentrate mantle heat, or a concentration of heat in the upper mantle may begin the process of creating this triple junction. Earth's surface may bulge upward into a dome, causing the elevated rocks to fracture into a radial pattern (figure 4.7). Gravity can then pull the dome apart, allowing magma to well up and fill three major fracture zones, and the spreading process is initiated.

The triple junction in northeast Africa is geologically young, having begun about 25 million years ago. To date, spreading in the Red Sea and Gulf of Aden has been enough to split off northeast Africa and create an Arabian plate and to allow seawater to flood between them. But the East African Rift Valley has not yet been pulled far enough apart for the sea to fill it (see figure 4.5). The East African Rift Valley is a truly impressive physiographic feature. It is 5,600 km (3,500 mi) long and has steep escarpments and dramatic valleys. Beginning at the Afar triangle at its northern end and moving southwest are the domed and stretched highlands of Ethiopia, beyond which the Rift Valley divides into two major branches. The western rift is markedly curved and has many deep lakes, including the world's second deepest lake, Lake Tanganyika. The eastern rift is straighter and holds shallow, alkaline lakes and volcanic peaks, such as Mount

FIGURE 4.6 A model of the stages in the formation of an ocean basin. (a) Stage 1, *Centering:* Moving lithosphere centers over an especially hot region of the mantle. (b) Stage 2, *Doming:* Mantle heat causes melting, and the overlying lithosphere/continent extends. The increase in heat causes surface doming through uplifting, stretching, and fracturing. (c) Stage 3, *Rifting:* Volume expansion causes gravity to pull the uplifted area apart; fractures fail and form faults. Fractures/faults provide escape for magma; volcanism is common. Then, the dome's central area sags downward, forming a valley such as the present East African Rift Valley. (d) Stage 4, *Spreading:* Pulling apart has advanced, forming a new seafloor. Most magmatic activity is seafloor spreading, as in the Red Sea and the Gulf of Aden.



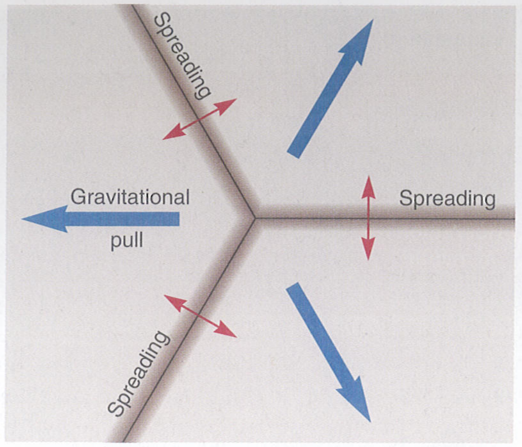


FIGURE 4.7 Schematic map of a triple junction formed by three young spreading centers. Heat may concentrate in the mantle and rise in a magma plume, doming the overlying lithosphere and causing fracturing into a radial set with three rifts. Gravity may then pull the dome apart, initiating spreading in each rift.

Kilimanjaro, Africa's highest mountain. The Rift Valley holds the oldest humanoid fossils found to date and is the probable homeland of the first human beings. Will the spreading continue far enough to split a Somali plate from Africa? It is simply too early to tell.

How severe are the earthquakes in the geologically youthful Red Sea and Gulf of Aden? Moderately—but these spreading-center earthquakes are not as large as the earthquakes on the other types of plate edges.

GULF OF CALIFORNIA

The Red Sea and Gulf of Aden spreading centers of the Old World have analogues in the New World with the spreading centers that are opening the Gulf of California and moving the San Andreas fault (figure 4.8). Geologically, the Gulf of California basin does not stop where the sea does at the northern shoreline within Mexico. The opening ocean basin continues northward into the United States and includes the Salton Sea and the Imperial and Coachella valleys at the ends of the Salton Sea. The Imperial Valley region is the only part of the United States that sits on opening ocean floor. In the geologic past, this region was flooded by the sea. However, at present, fault movements plus the huge volume of sediment deposited by the Colorado River hold back the waters of the Gulf of California. If the natural dam is breached, the United States will trade one of its most productive agricultural areas for a new inland sea.

The spreading-center segment at the southern end of the Salton Sea is marked by high heat flow, glassy volcanic domes, boiling mud pots, major geothermal energy reservoirs (subsurface water heated to nearly 400°C (750°F) by the magma below the surface), and swarms of earthquakes associated with moving magma (figure 4.8).

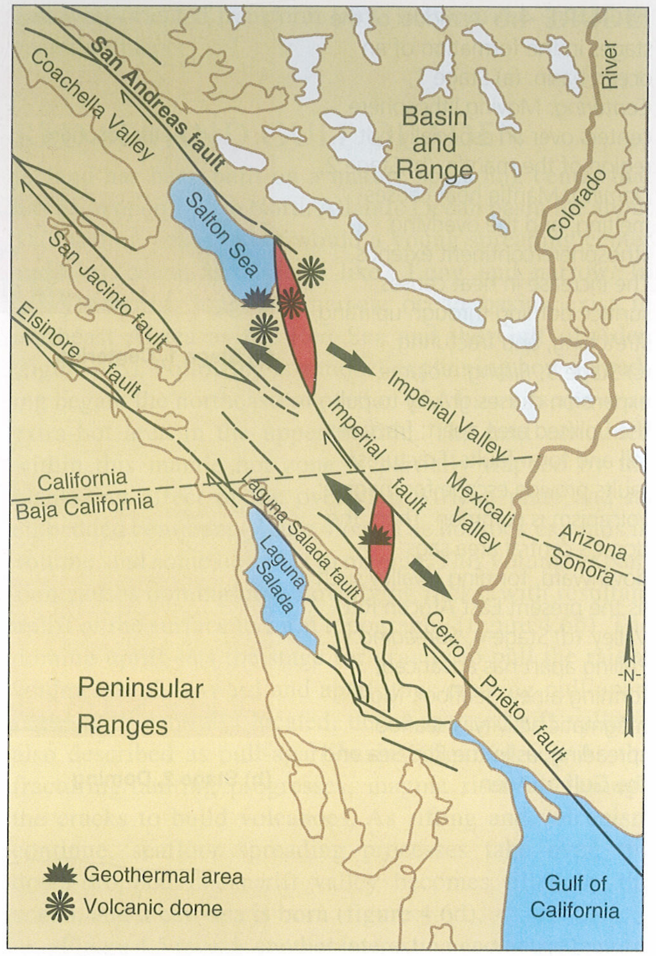


FIGURE 4.8 Map of northernmost Gulf of California. Note the two spreading centers (shown in red and by large, diverging arrows) and the right-lateral (transform) faults associated with them.

The Salton Trough is one of the most earthquake-active areas in the United States. There are seisms caused by the splitting and rifting of continental rock and swarms of earthquakes caused by forcefully moving magma. The Brawley seismic zone at the southern end of the Salton Sea commonly experiences hundreds of earthquakes in a several-day period. For example, in four days in January 1975, there occurred 339 seisms with magnitudes (M_L) greater than 1.5; of these, 75 were greater than $3M_L$, with the largest tremor at $4.7M_L$. Because hot rock does not store stress effectively, energy release takes place via many smaller quakes. The larger earthquakes in the valley are generated by ruptures in brittle continental rocks.

Notice in figure 4.8 that the San Andreas fault ends at the southeastern end of the Salton Sea at the northern limit of the spreading center. Notice also that other major faults, such as the Imperial, San Jacinto system, Cerro Prieto, Elsinore, and Laguna Salada, also appear to be transform faults that line up with spreading-center segments. From a broad perspective, all these subparallel, right-lateral, transform faults are part of the San Andreas plate boundary fault system carrying peninsular California to the northwest. Large earthquakes on these faults in recent years in the area covered by figure 4.8 include a $6.9M_w$ quake on the Imperial fault in 1940, a $6.6M_w$ event in the San Jacinto system in 1942, a $6.4M_w$ quake on the Imperial fault in 1979, a $6.6M_w$ quake in the San Jacinto system in 1987, and a $7.25M_w$ seism in the Laguna Salada fault system in 2010. These are large earthquakes, but deaths and damages for each event typically were not high because the region is sparsely inhabited, most buildings are low, and the frequent shakes weed out inferior buildings.

CONVERGENT ZONES AND EARTHQUAKES

The greatest earthquakes in the world occur where plates collide. Three basic classes of collisions are (1) oceanic plate versus oceanic plate, (2) oceanic plate versus continent, and (3) continent versus continent. These collisions result in either subduction or continental upheaval. If oceanic plates are involved, subduction occurs. The younger, warmer, less-dense plate edge overrides the older, colder, denser plate, which then bends downward and is pulled back into the mantle. If a continent is involved, it cannot subduct because its huge volume of low-density, high-buoyancy rocks simply cannot sink to great depth and cannot be pulled into the denser mantle rocks below. The fate of oceanic plates is destruction via subduction and reassimilation within the mantle, whereas continents float about on the asthenosphere in perpetuity. Continents are ripped asunder and then reassembled into new configurations via collisions, but they are not destroyed by subduction.

SUBDUCTION-ZONE EARTHQUAKES

Subduction zones are the sites of great earthquakes. Imagine pulling a 100 km (62 mi) thick rigid plate into the weaker, deformable rocks of the mantle that resist the plate's intrusion. This process creates tremendous stores of energy, which are released periodically as great earthquakes. Most of the really large earthquakes in the world are due to subduction (table 4.2). Subduction occurs on a massive scale. At the present rates of subduction, oceanic plates with an area equivalent to the entire surface area of Earth will be pulled into the mantle in only 180 million years.

A descending slab of oceanic lithosphere is defined by an inclined plane of deep earthquakes or fault-rupture locations (see figure 2.21). Earthquakes at subduction zones result from different types of fault movements in shallow versus deeper realms. At shallow depths (less than 100 km, or 62 mi), the two rigid lithospheric plates are pushing against each other. Earthquakes result from compressive movements where the overriding plate moves upward and the subducting plate moves downward. Pull-apart fault movements also occur near the surface within the subducting

TABLE 4.2

Earth's Largest Earthquakes, 1904–2011

Rank	Location	Year	M_w	Cause
1.	Chile	1960	9.5	Subduction—Nazca plate
2.	Alaska	1964	9.2	Subduction—Pacific plate
3.	Indonesia	2004	9.1	Subduction—Indian plate
4.	Japan	2011	9.0	Subduction—Pacific plate
5.	Kamchatka	1952	9.0	Subduction—Pacific plate
6.	Chile	2010	8.8	Subduction—Nazca plate
7.	Ecuador	1906	8.8	Subduction—Nazca plate
8.	Alaska	1965	8.7	Subduction—Pacific plate
9.	Indonesia	2005	8.6	Subduction—Indian plate
10.	Assam	1950	8.6	Collision—India into Asia
11.	Alaska	1957	8.6	Subduction—Pacific plate
12.	Indonesia	2007	8.5	Subduction—Indian plate
13.	Kuril Islands	1963	8.5	Subduction—Pacific plate
14.	Banda Sea	1938	8.5	Subduction—Pacific/Indian plate
15.	Russia	1923	8.5	Subduction—Pacific plate
16.	Chile	1922	8.5	Subduction—Nazca plate

plate as it is bent downward and snaps in tensional failure and as the overriding plate is lifted up from below. Notice in figure 2.21 that the shallow earthquakes occur (1) in the upper portion of the down-going plate, (2) at the bend in the subducting plate, and (3) in the overriding plate.

Compare the locations of the shallow earthquake sites to those of intermediate and deep earthquakes (see figure 2.20). At depths below 100 km, earthquakes occur almost exclusively in the interior of the colder oceanic lithosphere, the heart of the subducting slab. The high temperatures of rock in the upper mantle cause it to yield more readily to stresses and thus not build up the stored energy necessary for gigantic earthquakes. At depth, the upper and lower surfaces of the subducting slabs are too warm to generate large earthquakes. Thus, the earthquakes occur in the cooler interior area of rigid rock, where stress is stored as gravity pulls against the mantle resistance to slab penetration. In the areas of most rapid subduction, the down-going slab may remain rigid enough to spawn large earthquakes to depths in excess of 700 km (435 mi). A great earthquake that occurs deep below the surface has much of its seismic energy dissipated while traveling to the surface. Thus, the biggest disasters are from the great earthquakes that occur at shallow depths and concentrate their energy on the surface.

Most of the subduction-zone earthquakes of today occur around the rim of the Pacific Ocean or the northeastern Indian Ocean. This is shown by the presence of most of the deep-ocean trenches (see figure 2.14) and by the dense concentrations of earthquake epicenters (see figure 2.20).

When will the next large earthquake occur in the northwestern Pacific Ocean region? A popular way of forecasting the locations of future earthquakes is the **seismic-gap method.** If segments of one fault have moved recently, then it seems reasonable to expect that the unmoved portions will move next and thus fill the gaps. Looking at figure 4.9, where would you forecast large earthquakes to occur? It is easy to see the gaps in earthquake locations, and although seismic-gap analysis is logical, it yields only expectations, not guarantees. One segment of a fault can move two or more times before an adjoining segment moves once. In 2011, a seismic gap was filled in Japan by a 9.0M_W earthquake (figure 4.9).

JAPAN, 2011: STUCK SEGMENTS OF SUBDUCTING PLATE

At first glance, the plate tectonics of eastern Japan seem fairly simple. The Pacific plate moves northwest 8.3 cm (3.3 in) per year and dives under Japan (figure 4.9). The subducting plate is slowed by friction and stress builds until there is enough to rupture individual segments of the fault, resulting in earthquakes of 7 to 8 M. This has been the pattern of the past several centuries. But on 11 March 2011, five adjacent segments of the fault ruptured together over an area with length more than 600 km (375 mi). Two central segments had enormous movements or **slips** up to 50 m (165 ft), which helped produce the 9.0M_w seism.

The 9.0M_w mainshock was preceded two days earlier by a 7.2M_w event 40 km (25 mi) away and three other seisms greater than 6M. But we don't know how to recognize that an earthquake is a foreshock until after the mainshock occurs; thus, no warnings were given. The maximum acceleration offshore is calculated as 3g, that is, three times stronger than the pull of gravity. Acceleration of 2.7g was measured onshore in Miyagi Prefecture.

Before the earthquake, 15 years of **global positioning system (GPS)** data showed that the eastern edge of Japan was being dragged downward. Apparently the down-going Pacific plate was stuck to the overlying continental plate and was warping it downward. The strain of this movement accumulated during many centuries. When the stuck zone ruptured as the Pacific plate moved downward, the overlying plate carrying Japan sprang upward and released elastic strain.

The Japanese have kept the best historic records of earthquakes and tsunami in the world. A look farther back in their records shows that a similar-size earthquake and tsunami hit the same area of northeast Japan on 13 July 869 CE. The 2011 event surprised many experts who had disregarded the older historic record. But 1,142 years is a short time in geologic history.

A concern now is that the March 2011 earthquake transferred stress southward, closer to Tokyo, which was hit hard in 1923. In November 2011, an official Japan earthquake assessment committee forecast a 30% chance of a 9M event

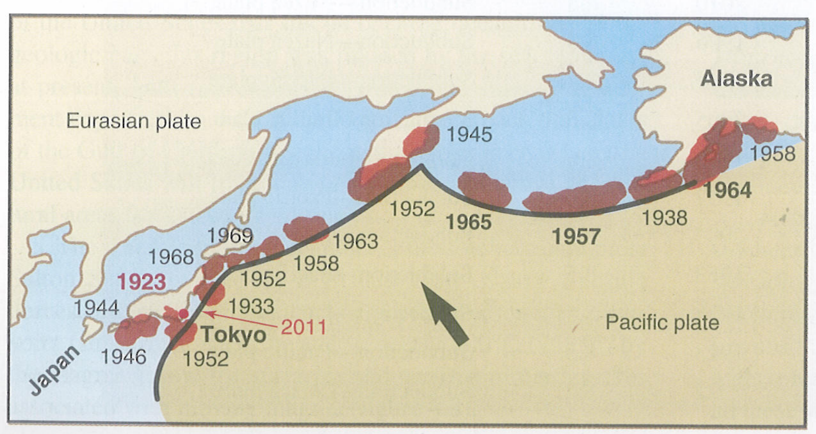


FIGURE 4.9 Brown patterns show severely shaken areas, with dates, from recent earthquakes caused by Pacific plate subduction. The 1957, 1964, and 1965 Alaska earthquakes are three of the largest in the 20th century. They were part of an earthquake cluster. Using the seismic-gap method, where are the next earthquakes most likely to occur? See the seismic gap filled in 2011.

A CLASSIC DISASTER

THE TOKYO EARTHQUAKE OF 1923

Early on Saturday morning, 1 September 1923, the cities of Tokyo and Yokohama were shattered by a deadly series of earthquakes. The principal shock occurred as the floor of Sagami Bay dropped markedly and sent 11 m (36 ft) high seismic sea waves (tsunami) crashing against the shore. The waves washed away hundreds of homes. Yet fishermen spending their day at sea were unaware of the monster waves. At day's end, as they sailed toward home through Sagami Bay, they were sickened to find the floating wreckage of their houses and the bodies of their families. Devastation on land was great; houses were destroyed, bridges fell, tunnels collapsed, and landslides destroyed hills. The shaking caused the collapse of flammable house materials onto cooking fires, and the flames, once liberated, quickly raced out of control. Little could be done to stop their spread because the earthquake had broken the water mains. Shifting winds pushed the fires for two and a half days, destroying 71% of Tokyo and 100% of Yokohama.

Possibly the most tragic event in this disaster occurred when 40,000 people, clutching their personal belongings, attempted to escape the flames by crowding into a 250-acre garden on the edge of the Sumida River. People packed themselves into this open space so densely that they were barely able to move. At about 4 p.m., several hours after the earthquake, the roaring fires approached on all three landward sides of the crowd. Suddenly the fire-heated winds spawned a tornado that carried flames onto the huddled masses and their combustible belongings. After the flames had died, 38,000 people lay dead, either burned or asphyxiated. The usual instinct to seek open ground during a disaster was shockingly wrong this time.

The combined forces of earthquakes, tsunami, and fires killed 99,331 people and left another 43,476 missing and presumed dead. Yet, despite this immense catastrophe, the morale of the Japanese people remained high. They learned from the disaster. They have rebuilt their cities with wider streets, more open space, and less use of combustible construction materials.

The historic record of earthquakes in the region is thought provoking. The region 80 km (50 mi) southwest of Tokyo has been rocked by five very strong earthquakes in the last 400 years. The seisms have occurred roughly every 73 years, the most recent in 1923.

closer to Tokyo in the next 30 years. The fault there is closer to shore, meaning more intense shaking for buildings and less time before tsunami come ashore.

The death and destruction caused by the 2011 earthquake are not known because many of its effects were erased by the tsunami that followed. We will pick up this story again in Chapter 8 on tsunami.

INDONESIA, 2004: ONE EARTHQUAKE TRIGGERS OTHERS

The Indian-Australian plate moves obliquely toward western Indonesia at 5.3 to 5.9 cm/yr (2 to 2.3 in/yr). The enormous, ongoing collision results in subduction-caused earthquakes that are frequent and huge (figure 4.10). Many of these earthquakes send off tsunami. On 26 December 2004, a 1,500 km (930 mi) long fault rupture began as a 100 km (62 mi) long portion of the plate-tectonic boundary ruptured and slipped during 1 minute. The rupture then moved northward at 3 km/sec (6,700 mph) for 4 minutes, then slowed to 2.5 km/sec (5,600 mph) during the next 6 minutes in a 9.1M_w event. At the northern end of the rupture, the fault movement slowed drastically and only traveled tens of meters during the next half hour.

On 28 March 2005, the subduction zone broke again and this time ruptured 400 km (250 mi) southward from the southern end of the 2004 rupture in an 8.6M_w event (figure 4.10).

Was this second rupture event, just 92 days later, a continuation of the earlier earthquake? It appears that a bend or scissors-like tear in the subducting plate may have delayed the full rupture in December 2004. The history of the region suggested there were more big earthquakes to come.

And come they did. An **earthquake cluster** is under way. On 12 September 2007, there were two earthquakes, an 8.4M_w followed 12 hours later by a 7.9M_w; on 20 February 2008 there was a 7.4M_w; on 30 September 2009 there was a 7.6M_w; and in 2010 there was a 7.8 M_W on 6 April and a 7.7 M_W on 25 October (figure 4.10). And there are more seismic gaps to fill.

Another earthquake cluster consisting of a 9.2M_w and several magnitude 8s occurred in the mid-20th century at the Pacific plate subduction zone along Alaska, Russia, and northern Japan (see figure 4.9 and table 4.2).

MEXICO CITY, 1985: LONG-DISTANCE DESTRUCTION

On Thursday morning, 19 September 1985, most of the 18 million residents of Mexico City were at home, having their morning meals. At 7:17 a.m., a monstrous earthquake broke loose some 350 km (220 mi) away. Seismic waves traveled far to deal destructive blows to many of the 6- to 16-story buildings that are heavily occupied during the working day (figure 4.11). Building collapses killed more than 9,000 people.

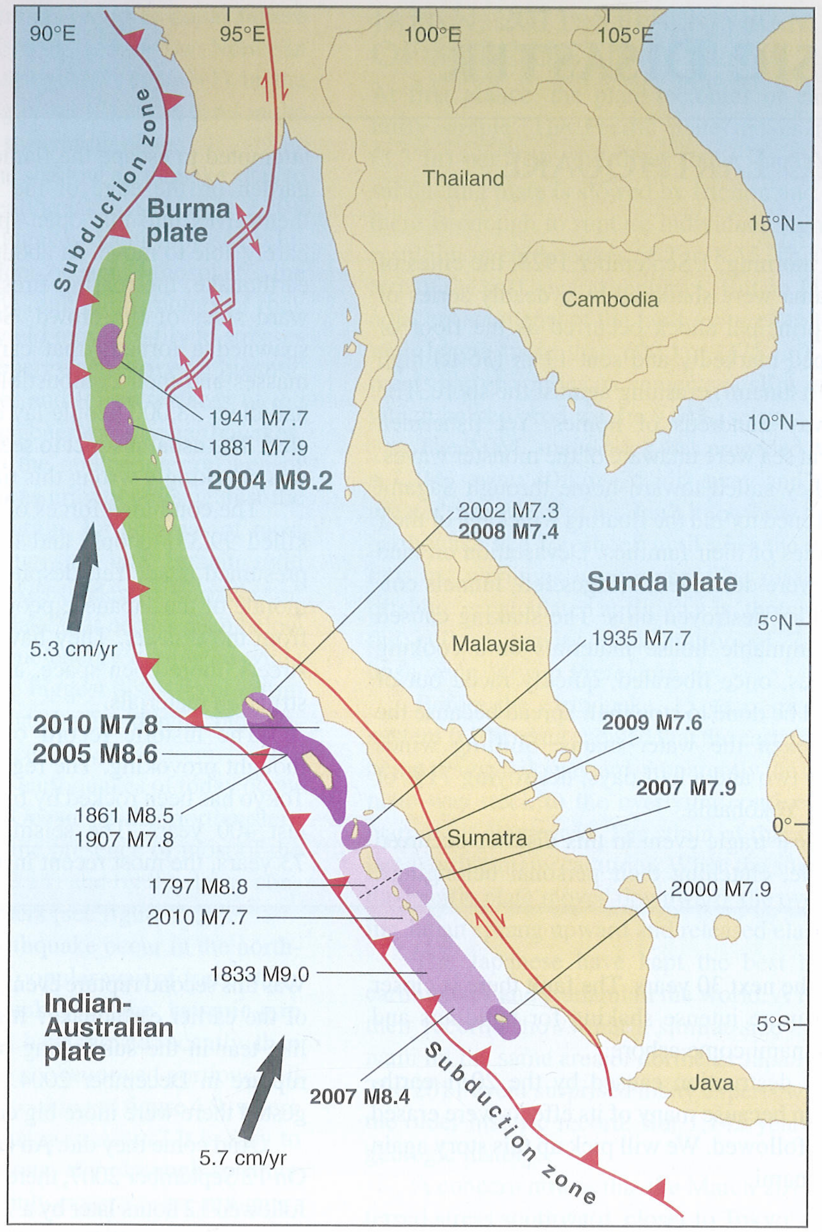


FIGURE 4.10 Subduction of the Indian-Australian plate beneath Indonesia was the cause of the huge earthquakes in 2004, 2005, 2007, 2008, 2009 and 2010. The region has a long history of large earthquakes, and more will occur.

What caused this earthquake? The Cocos plate made one of its all-too-frequent movements. This time, a 200 km (125 mi) long front, inclined 18° east, thrust downward and eastward about 2.3 m (7.5 ft) in two distinct jerks about 26 seconds apart (figure 4.12). The mainshock had a surface wave magnitude (M_s) of 8.1. It was followed on 21 September by a 7.5M_s aftershock and by another on 25 October of 7.3M_s. The earthquakes were not a surprise to seismologists. Before these seisms occurred, the area was called the Michoacan seismic gap, and many instruments had been deployed in the region to measure the expected big event.

As figure 4.12 shows, another large seismic gap waits to be filled by a major movement of the Cocos plate. The Guerrero seismic gap lies near Acapulco and is closer to Mexico City than the Michoacan epicenter.

Resonance Matters

Many of the coastal towns near the epicenter received relatively small amounts of damage. Yet in Mexico City, more than 5,700 buildings were severely damaged, with 15% of them collapsing catastrophically. Why did so many buildings collapse and kill so many people when Mexico City lies 350 km (220 mi) from the epicenter? It was largely due to resonance between seismic waves, soft lake-sediment foundations, and improperly designed buildings. The duration of shaking was increased due to seismic energy trapped within the soft sediments.

Mexico City is built atop the former Aztec capital of Tenochtitlan. The Aztecs built where they saw the favorable omen—an eagle sitting on a cactus and holding a writhing snake in its mouth. The site was Lake Texcoco, a broad lake surrounded by hard volcanic rock. Over time, the lake basin was partially filled with soft, water-saturated clays. Portions of Lake Texcoco have been drained, and large buildings have been constructed on the weak lake-floor sediments.

Building damages were the greatest and the number of deaths the highest where three factors combined and created resonance: (1) the earthquakes sent a tremendous amount of energy in seismic waves in the 1- to 2-second frequency band; (2) the areas underlain by thick, soft muds (clays) vibrating at 1- to 2-second frequencies amplified the seismic waves (figure 4.13); and (3) buildings of 6 to 16 stories vibrated in the 1- to 2-second frequency band. Where all three factors were in phase, disaster struck.

There were design flaws in the failed buildings (figure 4.14), including soft first stories, poorly joined building wings, odd-shaped buildings prone to twist on their foundations, and buildings of different heights and vibration frequencies that sat close together and bumped into each other during the earthquake (figures 4.14c and 4.15).

CHILE, 1960: THE BIGGEST ONE

Earth's biggest measured earthquake is a 9.5M_w event that sprang forth on Sunday afternoon, 22 May 1960, in southern Chile. Here the Nazca plate converges with the South American plate at 8 m/century (see figure 2.14). In 1960, the

FIGURE 4.11 This 15-story building collapsed during the 1985 Mexico City earthquake, crushing all its occupants as its concrete floors pancaked.
Photo by M. Celebi, *US Geological Survey.*

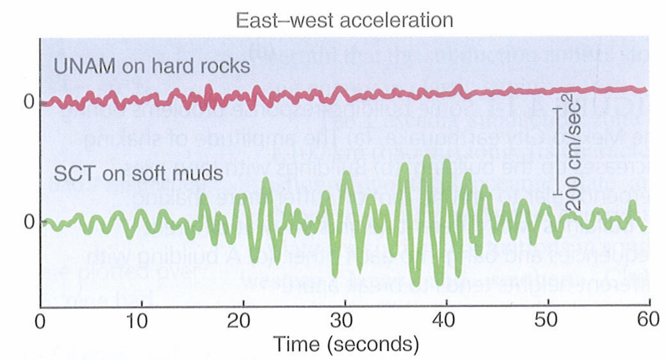


FIGURE 4.13 Some east–west accelerations recorded in Mexico City in 1985. The Universidad Nacional Autonoma de Mexico (UNAM) sits on a hard-rock hill and received small accelerations. The Secretaria de Comunicaciones y Transportes site (SCT) sits on soft lake sediments that amplified the seismic waves.

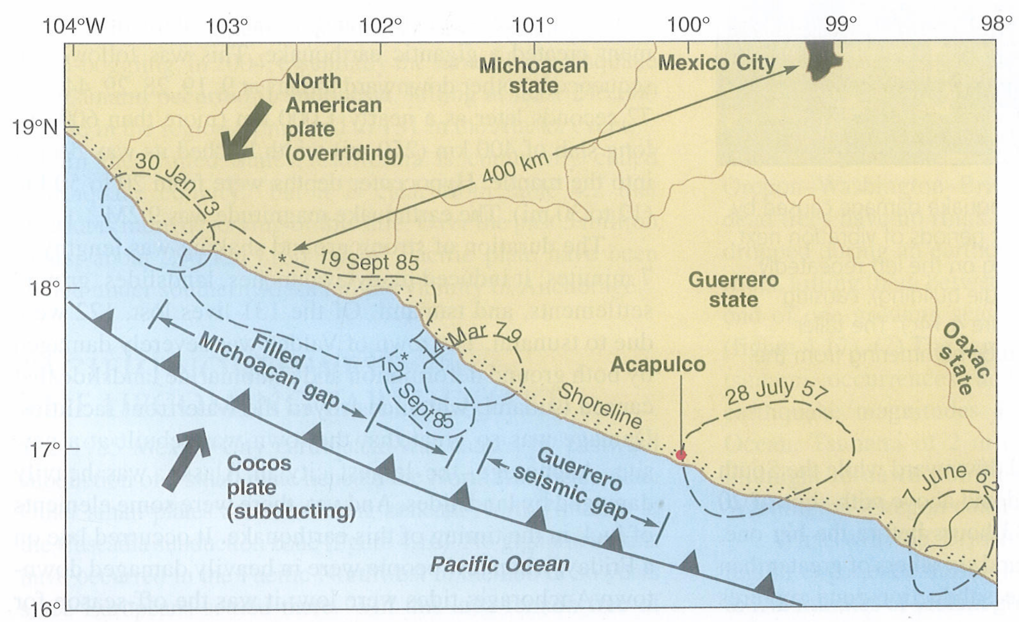


FIGURE 4.12 Map of coastal Mexico showing dates of earthquakes and fault areas moved (dashed lines) during Cocos plate subduction events. The Michoacan seismic gap was filled by the 1985 seisms. The Guerrero seismic gap is overdue for a major movement.

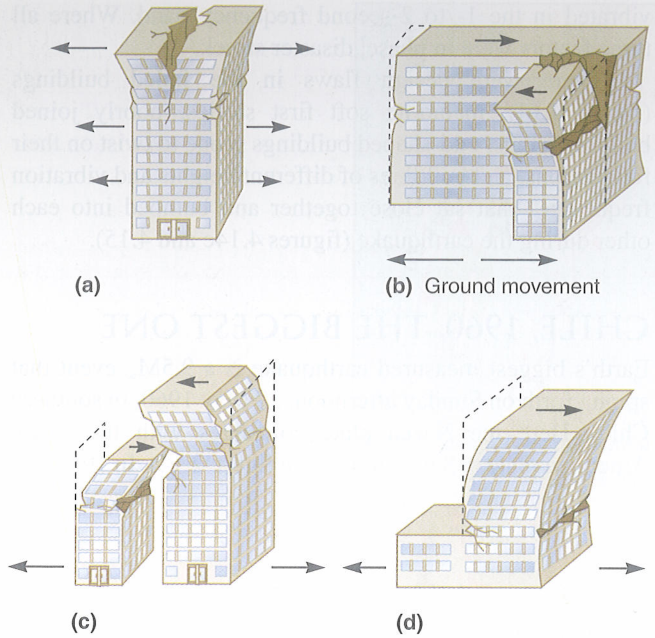


FIGURE 4.14 Some building-response problems during the Mexico City earthquake. (a) The amplitude of shaking increases up the building. (b) Buildings with long axes perpendicular to ground motion suffer more shaking. (c) Buildings with different heights sway at different frequencies and bang into each other. (d) A building with different heights tends to break apart.

FIGURE 4.15 Mexico City earthquake damage caused by constructing buildings with different periods of vibration next to each other. The four-story building on the left repeatedly struck the taller Hotel de Carlo (middle building), causing collapse of its middle floors (see figure 4.14c). The taller building on the right was damaged by hammering from the Hotel de Carlo.
Photo from NOAA.

Nazca plate moved eastward and downward while the South American plate moved westward and above with slips of 20 to 30 m (65 to 100 ft). In the 33 hours before the big one, there were foreshocks of 8.1M_w and six others of greater than 6M. Over a period of days, the subduction-zone ruptures involved a 1,000 km (620 mi) length and a 300 km (185 mi) width.

Chile, 1835 and 2010: Emptying, Filling, and Emptying Elastic Strain in a Seismic Gap

Giant earthquakes are common phenomena in Chile. During his epic voyage on the HMS *Beagle,* Charles Darwin was resting on his back in the woods near Valdivia, Chile, on 20 February 1835 when a huge earthquake struck. His well-written description of large areas of land being uplifted, giant sea waves crossing the shoreline, and two volcanoes being shaken into eruptions are instructive even today. The modern estimate is that the elastic strain released in Darwin's earthquake yielded an 8.5M_w event.

During the 175 years following the 1835 seism, tectonic-plate convergence in the region was about 14 m (46 ft), but few earthquakes were being recorded. A seismic gap was recognized and the region was heavily instrumented. GPS measurements showed that the area was not moving; it was locked. Frictional resistance was causing elastic strain to accumulate in the rocks; the seismic gap was filling with strain. A big earthquake was expected, and on 27 February 2010, it happened: the 8.8M_w event is the 6th biggest earthquake ever measured. A 500 km (310 mi) long subduction-zone interface ruptured with bilateral movement at 3.1 km/sec (6,930 mph). Some areas of fault surface moved up to 15 m (50 ft), whereas other areas had low to no slip. The elastic-strain buildup in the seismic gap was largely emptied. South America, from Chile to the Argentina coast, had all moved westward.

ALASKA, 1964: SECOND BIGGEST ONE

Saint Matthew's account of the first Good Friday included: "And, behold . . . the earth did quake, and the rocks rent." His words applied again, more than 1,900 years later, on Good Friday, 27 March 1964. At 5:36 p.m., in the wilderness at the head of Prince William Sound, a major subduction movement created a gigantic earthquake. This was followed in sequence by other downward thrusts at 9, 19, 28, 29, 44, and 72 seconds later as a nearly 1,000 km (more than 600 mi) long slab of 400 km (250 mi) width lurched its way deeper into the mantle. Hypocenter depths were from 20 to 50 km (12 to 30 mi). The earthquake magnitude was 9.2M_w.

The duration of strong ground shaking was lengthy—7 minutes; it induced many avalanches, landslides, ground settlements, and tsunami. Of the 131 lives lost, 122 were due to tsunami. The town of Valdez was severely damaged by both ground deformation and a submarine landslide that caused tsunami, which destroyed the waterfront facilities. Damage was so great that the town was rebuilt at a new site. Anchorage, the largest city in Alaska, was heavily damaged by landslides. And yet, there were some elements of luck in the timing of this earthquake. It occurred late on a Friday, when few people were in heavily damaged downtown Anchorage; tides were low; it was the off-season for

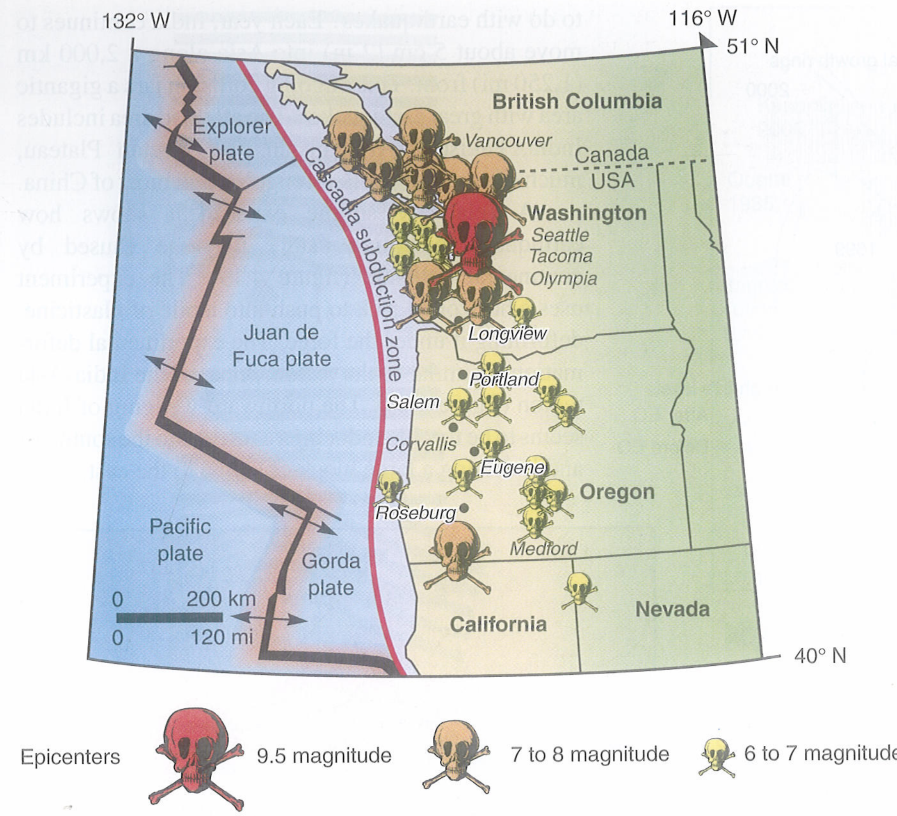


FIGURE 4.16 Epicenters for the 1960 Chile earthquake sequence are plotted over the Cascadia subduction zone. One earthquake had a magnitude of 9.5; nine had magnitudes of 7 to 8; and 28 had magnitudes of 6 to 7.

fishing, so few people were on the docks or in the canneries; and the weather in the ensuing days was seasonally warm, thus sparing people from death-dealing cold while their homes and heating systems were out of order.

If Alaska had been a densely inhabited area, the dimensions of the human catastrophe would have been mind-boggling. In 2004, essentially the same-size earthquake and tsunami occurred in Indonesia, killing at least 245,000 people in the region, compared to 131 in the Alaska event.

In the United States, California is commonly called "earthquake country," but it is clear from table 4.2 that Alaska is more deserving of this title. Over the past 5 million years, about 290 km (180 mi) of Pacific plate have been pulled under southern Alaska in the vicinity of Anchorage.

PACIFIC NORTHWEST: THE UPCOMING EARTHQUAKE

The 1985 Mexico City earthquake was caused by eastward subduction of a small plate beneath the North American plate. Other small plates are subducting beneath North America at the Cascadia subduction zone (figure 4.16). No gigantic seisms have occurred in the Pacific Northwest in the 200 or so years since Europeans settled there. Will this area remain free of giant earthquakes? Could the Cascadia subduction zone be plugged up like a clogged drain, meaning that subduction has stopped? No. The active volcanoes above the subducting plates testify that subduction is still occurring. Could the subduction be taking place smoothly and thus eliminating the need for giant earthquakes? Probably not. The oceanic lithosphere being subducted is young, only about 10 million years old. Young lithosphere is more buoyant and is best subducted when overridden by continental lithosphere. The North American continent is moving southwest at 2.5 cm/yr (1 in/yr) and colliding with the oceanic plate, which is subducting along a N 68° E path at 3.5 cm/yr (1.4 in/yr). Thus, it seems certain that the subduction zone is storing energy in elastic strain.

The Cascadia subduction zone is 1,100 km (680 mi) long. Its characteristics of youthful oceanic plate and strong coupling with the overriding plate are similar to situations in southwestern Japan and southern Chile. Events of Chilean magnitude could unlock the entire Cascadia subduction zone. Figure 4.16 is a plot of the epicenters of the 1960 Chile mainshock, foreshocks, and aftershocks over a map of the Pacific Northwest to give an idea of what could happen in British Columbia, Washington, and Oregon. Could the Pacific Northwest experience a magnitude 9 earthquake? Yes—in fact, it already has.

Earthquake in 1700: The Trees Tell the Story

Recent work by Brian Atwater has shown that the last major earthquake in the Pacific Northwest occurred about 9 p.m. on 26 January 1700 and was about magnitude 9. This is indicated by two converging lines of evidence: (1) Counting the annual growth rings in trees of drowned forests along the Oregon–Washington–British Columbia coast shows that the dead trees have no rings after 1699. Apparently the ground dropped during an earthquake, and seawater got to the tree roots, killing them between August 1699 and May 1700, the end of one growing season and the beginning of the next (figure 4.17). (2) The Japanese maintain detailed records of tsunami occurrences and sizes that they correlate to earthquake magnitudes and locations around the Pacific Ocean. Tsunami of 2 m (7 ft) height that hit Japan from midnight to dawn point to a 9 p.m. earthquake along the Washington–Oregon coast on 26 January 1700.

What will the British Columbia–Washington–Oregon region experience during a magnitude 9 earthquake? Three to five minutes of violent ground shaking will be followed by

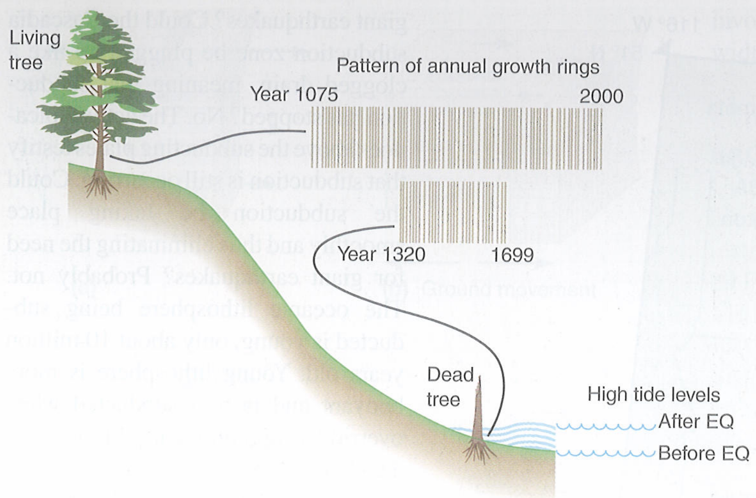


FIGURE 4.17 Annual growth rings in drowned trees along the Oregon–Washington–British Columbia coast tell of their deaths after the 1699 growing season. Seawater flooding occurred as land dropped during a magnitude 9 earthquake (EQ).

tsunami 10 m (33 ft) high surging onshore 15 to 40 minutes after the earthquake. Energy will be concentrated in long-period seismic waves, presenting challenges for tall buildings and long bridges.

What will the next magnitude 9 earthquake, along with its major aftershocks, do to cities such as Portland, Tacoma, Seattle, Vancouver, and Victoria? When will the next magnitude 9 earthquake occur in the Pacific Northwest?

Continent-Continent Collision Earthquakes

The grandest continental pushing match in the modern world is the ongoing ramming of Asia by India. When Gondwanaland began its breakup, India moved northward toward Asia. The 5,000 km (3,000 mi) of seafloor (oceanic plate) that lay in front of India's northward path had all subducted beneath Asia by about 40 million years ago. Then, with no seafloor left to separate them, India punched into the exposed underbelly of Asia (figure 4.18). Since the initial contact, the assault has remained continuous. India has moved another 2,000 km (1,250 mi) farther north, causing complex accommodations within the two plates as they shove into, under, and through each other accompanied by folding, overriding, and stacking of the two continents into the huge mass of the Himalayas and the Tibetan Plateau. The precollision crusts of India and Asia were each about 35 km (22 mi) thick. Now, after the collision, the combined crust has been thickened to 70 km (44 mi) to create the highest-standing continental area on Earth. The Tibetan Plateau dwarfs all other high landmasses. In an area the size of France, the average elevation exceeds 5,000 m (16,400 ft). But what does all of this have to do with earthquakes? Each year, India continues to move about 5 cm (2 in) into Asia along a 2,000 km (1,250 mi) front. This ongoing collision jars a gigantic area with great earthquakes. The affected area includes India, Pakistan, Afghanistan, the Tibetan Plateau, much of eastern Russia, Mongolia, and most of China.

A relatively simple experiment shows how earthquake-generating faults may be caused by continental collision (figure 4.19). The experiment uses a horizontal jack to push into a pile of plasticine, deforming it under the force. The experimental deformation is similar to the tectonic map of the India-Asia region (figure 4.20). The northward wedging of India seems to be forcing Indochina to escape to the southeast and is driving a large block of China to the east.

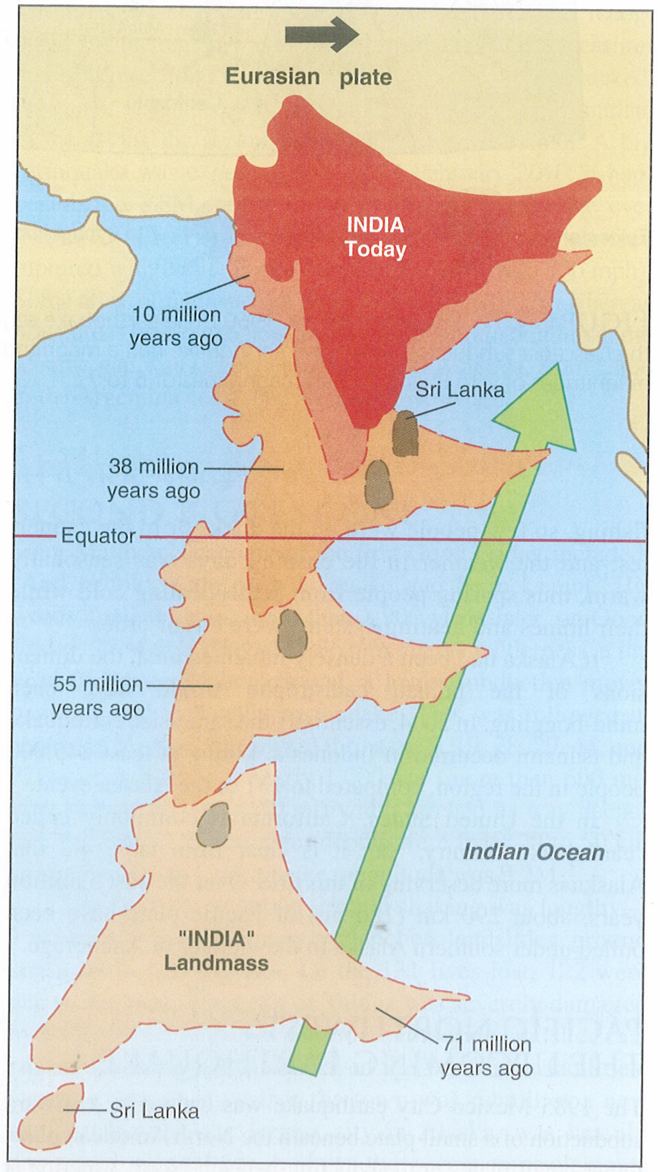


FIGURE 4.18 Map showing the movement of India during the past 71 million years. India continues to shove into Eurasia, creating great earthquakes all the way through China.

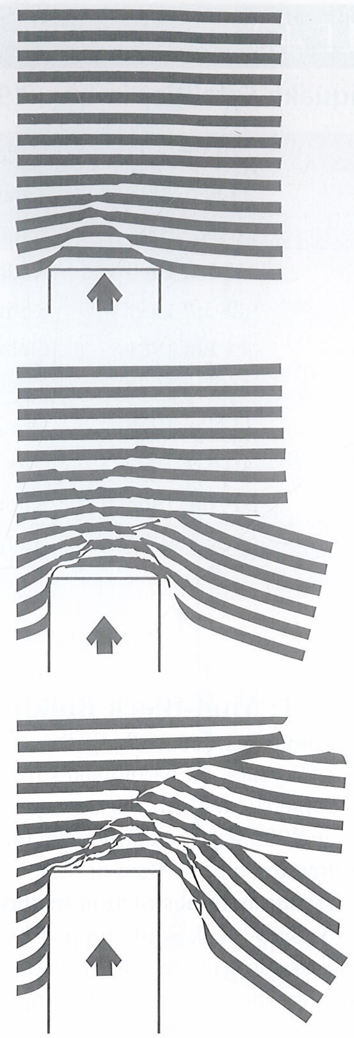


FIGURE 4.19 Simulated collision of India into Asia. A wedge is slowly jacked into layered plasticine confined on its left side but free to move to the right. From top to bottom of figure, notice the major faults that form and the masses that are compelled to move to the right. Compare this pattern to the tectonic map of India and Asia in figure 4.20.
After P. Tapponier, et al. (1982). *Geology*, 10, 611–16.

China, Pakistan, and India, 2008, 2005, and 2001: Continent Collision Kills

India's continuing push into Asia has caused three deadly earthquakes in the 21st century (figure 4.20). The May 2008 Sichuan, China, event killed about 87,500 people; the October 2005 Kashmir, Pakistan, earthquake killed about 88,000 people; and the January 2001 Gujarat, India, event killed more than 20,000. These earthquakes were close together in space and time. Is this just a coincidence, or will they be part of a cluster of ongoing killer events? We don't know. But there are seismic gaps waiting to be filled in this region, and some are large, including a 600 km (375 mi) long section in the central Himalaya front that has not moved since 1505. The rapid population growth in these countries has resulted in the construction of millions of new buildings. Many buildings were and are being built without seismic-safety inspections to guide their construction. Even where codes exist, poor construction practices have led to catastrophic failures of many buildings during shaking.

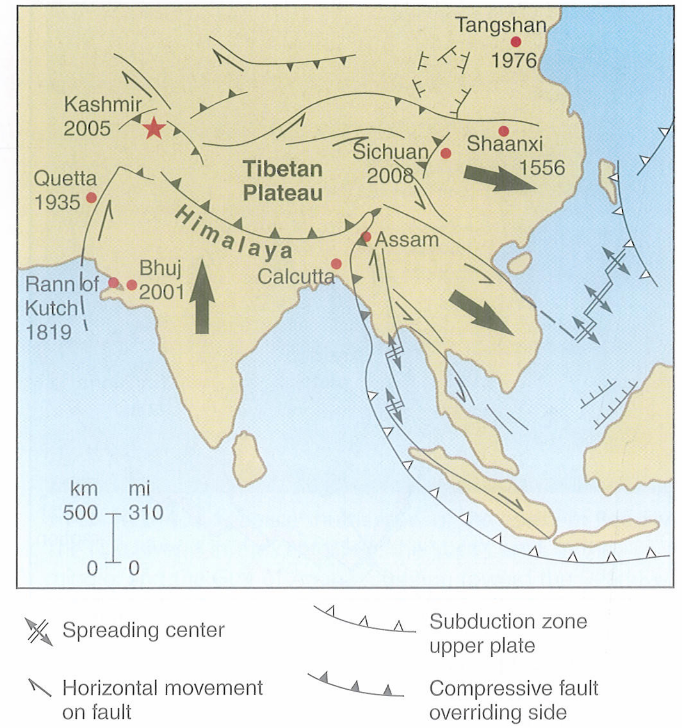


FIGURE 4.20 Tectonic map showing India pushing into Asia. The ongoing collision causes devastating earthquakes, each killing tens or hundreds of thousands of people. The list includes two in the Indian state of Gujarat (in 1819 at Rann of Kutch and in 2001 near Bhuj), three in China (in 1556 at Shaanxi, in 1976 at Tangshan, and in 2008 at Sichuan), and two in Pakistan (in Quetta in 1935 and in Kashmir in 2005).

The earthquakes of recent years have been deadly, but none of them have been a direct hit on the mega-cities of the region. Some Indian plate–caused earthquakes in China show how disheartening the death totals can be.

China, 1556: The Deadliest Earthquake

In Shaanxi Province, the deadliest earthquake in history occurred in 1556 when about 830,000 Chinese were killed in and near Xi'an on the banks of the mighty Huang River (once known as the Yellow River). The region has numerous hills composed of deposits of windblown silt and fine sand that have very little **cohesion** (ability to stick together). Because of the ease of digging in these loose sediments, a tremendous number of the homes in the region were caves dug by the

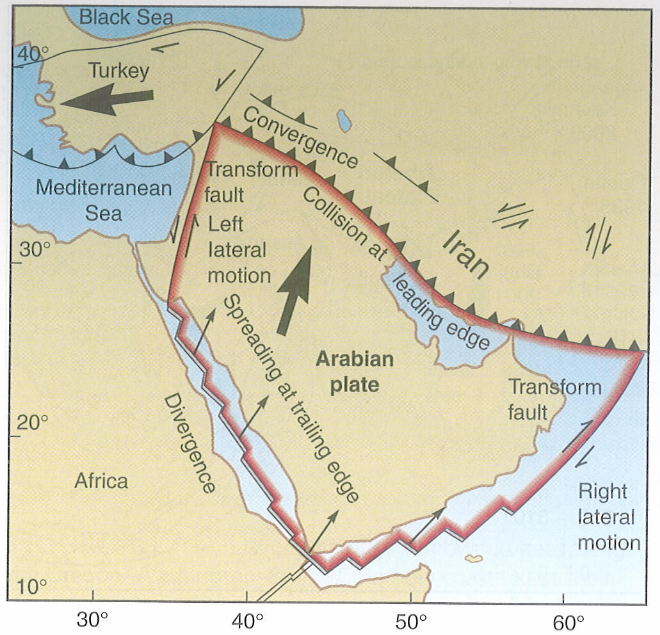


FIGURE 4.21 The Arabian plate pulls away from Africa, pushes into Eurasia, slices through the Holy Land with a transform fault, and squeezes Turkey westward.

inhabitants. Most of the residents were in their cave homes at 5 a.m. on the wintry morning of 23 January, when the seismic waves rolled in from the great earthquake. The severe shaking caused many of the soft silt and sand sediments of the region to vibrate apart and literally behave like fluids. Most of the cave-home dwellers were entombed when the once-solid walls of their homes liquefied and collapsed.

THE ARABIAN PLATE

The emergence of the geologically young spreading centers in the Red Sea and Gulf of Aden has cut off the northeast tip of the African continent (figure 4.21; see figure 4.5) and created the Arabian plate. Analysis of the movement of the Arabian plate gives us good insight into different earthquake types.

CONTINENT-CONTINENT COLLISION EARTHQUAKES

The Red Sea and Gulf of Aden areas may not have many large earthquakes, but their spreading centers are responsible for shoving the Arabian plate into Eurasia, causing numerous devastating earthquakes there. The rigid continental rocks of the Arabian plate are driven like a wedge into the stiff underbelly of Eurasia. The force of this collision uplifts mountain ranges (e.g., Caucasus and Zagros in figure 4.5) and moves many faults that create the killer earthquakes typical of this part of the world.

TABLE 4.3

Earthquake Fatalities in Iran, 1962–2011

Fatalities	Date	Location
612	22 Feb 2005	Zarand
41,000	26 Dec 2003	Bam
50,000	21 Jun 1990	Rudbar-Tarom
3,000	28 Jul 1981	Kerman
3,000	11 Jun 1981	Golbas
25,000	16 Sep 1978	Tabas-e-Golshan
5,000	24 Nov 1976	Northwest
5,044	10 Apr 1972	Fars
12,000	31 Aug 1968	Khorasan
12,225	1 Sep 1962	Buyin-Zara
156,881 Total deaths		

Iran, 1962–2011: Mud-Block Buildings Kill

Catastrophic earthquakes occur along the entire length of Iran. In the past 50 years, 10 earthquakes have killed more than 150,000 people (table 4.3). For example, the deadliest natural disaster in 2003 was the earthquake that shook loose 8 km (5 mi) below the city of Bam at 5:27 a.m. on Friday, 26 December. Traditional construction methods there consist of sun-dried, mud-block walls topped by heavy roofs. When the earthquake shaking began, the walls crumbled and the heavy roofs crashed down. Collapsing homes killed 41,000 people.

TRANSFORM-FAULT EARTHQUAKES

The Arabian plate is moving away from Africa and is pushing into Eurasia, but what is happening along the sides of the Arabian plate? The slide-past movements of transform faults. On the eastern side, the plate-boundary fault occurs beneath the Indian Ocean and has scant effect on humans. But look where the slide-past fault movements occur along the western side of the Arabian plate (figures 4.21, 4.22, and 4.23).

Dead Sea Fault Zone: Holy Land Disasters

The Dead Sea fault zone is an Eastern Hemisphere analogue of the San Andreas fault in California. It not only runs right through the Holy Land but has also created much of the area's well-known topography. Notice in figure 4.22 that there are four prominent overlaps or steps in the Dead Sea fault zone. Fault movements on both sides of these steps have created pull-apart basins that are filled by historically famous water bodies, such as the Dead Sea and the Sea of Galilee. The Dead Sea fault zone has been operating for as

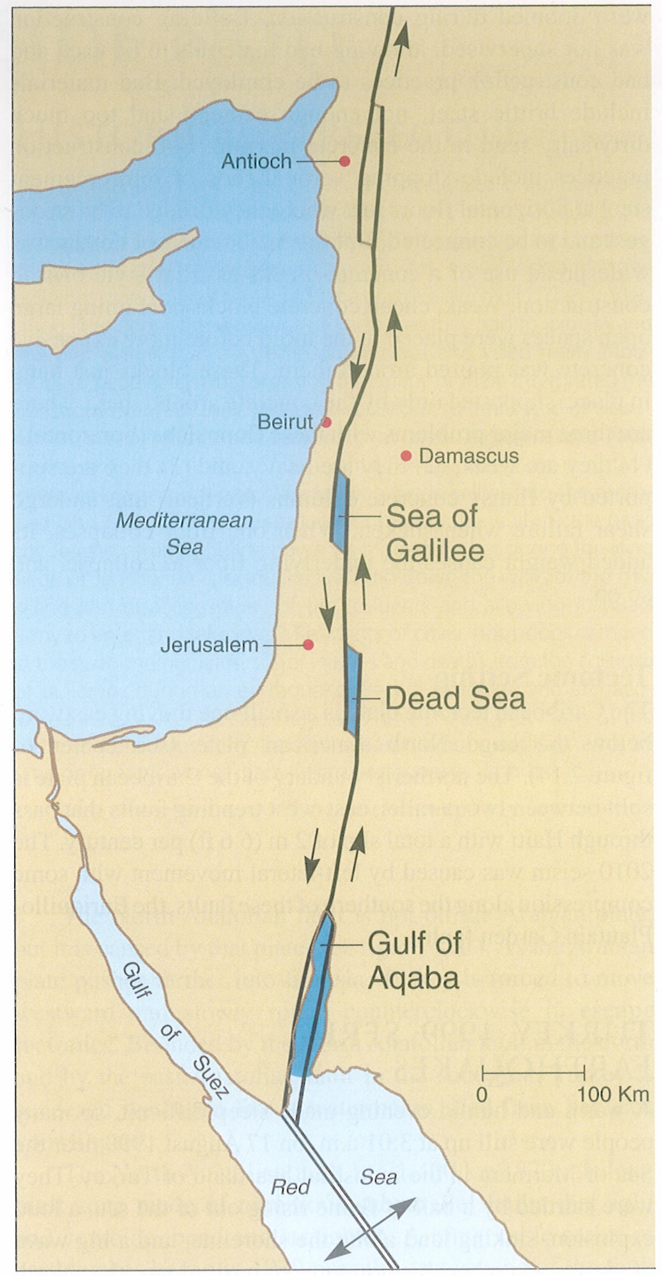


FIGURE 4.22 Map of the Dead Sea fault zone. Notice that the subparallel faults have pull-apart basins in the steps between faults. The Dead Sea basin is deep; it has a 7 km (greater than 4 mi) thick infill of sediments below its water. On 21 November 1995, a magnitude 7.2 earthquake in the Gulf of Aqaba killed people as far away as Cairo, Egypt.

long as the Red Sea has been opening. During that time, there has been 105 km (65 mi) of offset, and 40 km (25 mi) of this movement has happened in the past 4.5 million years. This computes to an average slip (movement) rate of more than 5 mm/yr over the longer time frame or 9 mm/yr over the more recent time span. However, the rough, frictionally resistant faults do not easily glide along at several millimeters

FIGURE 4.23 Space shuttle view of the northern Red Sea. The Nile River is in the center left; the Suez Canal, in the middle; and the Gulf of Aqaba, pointing toward the Dead Sea in the upper right.
Photo from NASA.

TABLE 4.4

Some Earthquakes in the Holy Land

Year	Magnitude	Year	Magnitude
1927	6.5	1068	6.6
1834	6.6	1033	7.0
1759	6.5	749	6.7
1546	6.7	658	6.2
1293	6.4	363	7.0
1202	7.2	31 BCE	6.3
		759 BCE	7.3

Source: "When the Walls Came Tumbling Down" (1991). [Video] Amos Nur, Stanford University.

each year. The rocks along the fault tend to store stress until they can't hold any more, and then they rupture in an earthquake-producing fault movement. How often do these earthquakes occur? Table 4.4 is a partial list from Amos Nur of Stanford University.

TRANSFORM-FAULT EARTHQUAKES

The transform faults forming the sides of some tectonic plates have dominantly horizontal movements that cause major earthquakes. Examples include the Alpine fault of New Zealand, the San Andreas fault in California, the North Anatolian fault in Turkey, and the Enriquillo-Plantain Garden fault in Haiti.

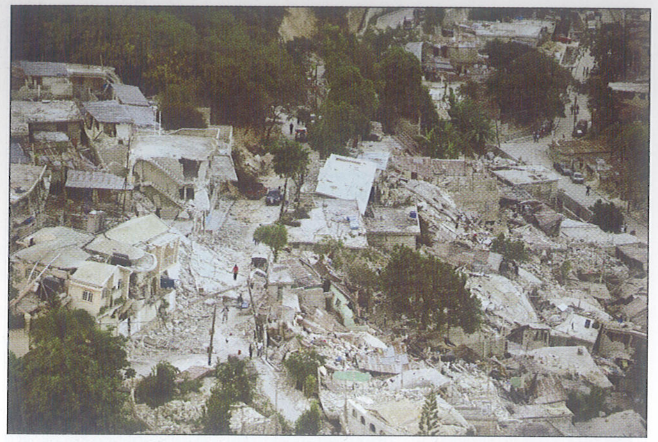


FIGURE 4.24 Houses collapsed as poorly made concrete floors, support beams, and walls all failed; Port-au-Prince, Haiti, January 2010.
Photo by James L. Harper, Jr., U.S. Air Force.

HAITI, 2010: EARTHQUAKES DON'T KILL, BUILDINGS DO

Year 2010 began with a horrifying event. The earth shook in a $7.0M_w$ event in the Republic of Haiti and much of its capital city of Port-au-Prince collapsed, killing an estimated 230,000 people, seriously injuring another 300,000, and displacing 1.1 million more people. What lies behind this tragedy?

In 1751, most of the buildings in Port-au-Prince were destroyed in an earthquake. In 1770, another earthquake demolished most of the reconstructed city. In response to this double destruction, the French authorities required that buildings be constructed with wood, and they banned the use of construction relying on concrete (masonry).

Haiti gained independence from France in 1804. During its two centuries of independence, the Haitian population grew to 9.35 million people, most of whom suffer poverty, low rates of literacy, and life in poorly constructed, concrete buildings. The lessons of their past about building construction were forgotten.

In 2008, four tropical storms hit Haiti, killing 800 people, displacing 10% of the population, and reducing economic output by 15%. But for every bad, there is a worse—and life became much worse at 4:53 pm on Tuesday, 12 January 2010, when the powerful earthquake occurred. About 250,000 houses collapsed and another 30,000 commercial buildings fell (figure 4.24). The buildings that collapsed were great and small, rich and poor. Destruction ranged from shacks in shantytowns to the National Palace, the National Assembly building, the United Nations headquarters, the main Catholic cathedral, the upscale Hotel Montana, the Citibank building, schools, hospitals, both fire stations, the main prison, and more.

The death total from this earthquake is more than double that from any previous 7M earthquake anywhere in the world. The deaths were due to bad buildings, all of which were doomed during construction. Building construction was not supervised, allowing bad materials to be used and bad construction practices to be employed. Bad materials include brittle steel; not enough cement; and too much dirty/salty sand in the concrete mixture. Bad construction practices include stopping vertical rods of reinforcement steel at horizontal floors just where they needed to be strongest and to be connected. But the major cause of deaths was widespread use of a concrete-blocks-as-filler style of slab construction. Weak, cheap concrete blocks containing large open spaces were placed in the mold before more expensive concrete was poured around them. These blocks just hang in place, supported only by the concrete around them. There are three major problems with these floor slabs (horizontal): (1) they are weak, (2) they are heavy, and (3) they are supported by flimsy concrete columns (vertical) that undergo shear failure when shaken. When one floor collapses, its added weight causes the underlying floor to collapse, and so on.

Tectonic Setting

The Caribbean tectonic plate is a small one moving eastward below the huge North American plate (see center of figure 2.14). The northern boundary of the Caribbean plate is split between two parallel, east-west trending faults that pass through Haiti with a total slip of 2 m (6.6 ft) per century. The 2010 seism was caused by left-lateral movement with some compression along the southern of these faults, the Enriquillo-Plantain Garden fault.

TURKEY, 1999: SERIAL EARTHQUAKES

A warm and humid evening made sleep difficult, so many people were still up at 3:01 a.m. on 17 August 1999 near the Sea of Marmara in the industrial heartland of Turkey. They were startled by a ball of flame rising out of the sea, a loud explosion, sinking land along the shoreline, and a big wave of water. Another big rupture moved along the North Anatolian fault as a magnitude 7.4 earthquake. This time the fault ruptured the ground surface for 120 km (75 mi), with the south side of the fault moving westward up to 5 m (16.5 ft) (figure 4.26). Several weeks later, after evening prayers for Muslims, another segment of the North Anatolian fault ruptured in a 7.1 magnitude earthquake. The two devastating events combined to kill more than 19,000 people and cause an estimated $20 billion in damages.

Why were so many people killed? Bad buildings collapsed. Industrial growth in the region attracted hordes of new residents who, in turn, caused a boom in housing construction. Unfortunately, many residential buildings were built on top of soft, shaky ground, and some building contractors cut costs by increasing the percentage of sand in their concrete, causing it to crumble as the ground shook.

SIDE NOTE

HISTORICAL PERSPECTIVE

It is interesting to ponder the effects of earthquakes in the Holy Land on the thinking of the religious leaders in this region, which is the birthplace of Judaism and Christianity and an important area to Islam. Imagine the great early leaders living in stiff, mud-block and stone buildings along one of the world's major strike-slip faults. They understood little about the workings of Earth, yet they had to explain and interpret events that destroyed entire cities and killed many thousands of people. It is not surprising that many of them interpreted the disastrous events of their times as directly due to "the hand of God."

Let's use today's understanding of plate tectonics and fault movements to think about past events. For example, how might we interpret the account of Joshua leading the Israelites into the promised land, specifically the famous event when the walls of the oasis city Jericho came tumbling down? Is it possible that during the long siege of Jericho, an earthquake knocked down the walls of the city, killing and disabling many of the residents and allowing Joshua's army to enter and take over? Residents of cities, not troops camped in the surrounding fields, suffer injuries and deaths from the collapse of buildings during an earthquake. Recent historical and archaeological investigations in the Holy Land have shown that many of the destroyed buildings and cities of the past did not meet their ends by time or humans alone; many fell to earthquakes (figure 4.25).

FIGURE 4.25 Building damage in Beit She'an, Israel, caused by the earthquake in 749 CE (**common era**).
Photo by Thomas K. Rockwell.

The North Anatolian fault is not on the Arabian plate, but it is caused by that plate (see figure 4.21). As the Arabian plate pushes farther into Eurasia, Turkey is forced to move westward and slowly rotate counterclockwise in **escape tectonics.** Bounded by the North Anatolian fault in the north and by the east Anatolian fault in the southeast, Turkey is squeezed westward like a watermelon seed from between your fingers.

The North Anatolian fault is a 1,400 km (870 mi) long fault zone made of numerous subparallel faults that split and combine, bend and straighten. A remarkable series of earthquakes began in 1939 near the eastern end of the fault with the magnitude 7.9 Erzincan earthquake, which killed 30,000 people. Since 1939, 11 earthquakes with magnitudes greater than 6.7 have occurred as the fault ruptures westward in a semiregular pattern that is unique in the world (figure 4.26). At intervals ranging from 3 months to 32 years, more than 1,000 km (620 mi) of the fault has moved in big jumps.

What is likely to happen next? There is every reason to expect the fault rupture to keep moving to the west, ever closer to Istanbul. The Sea of Marmara fills a basin partly created by movements along subparallel strands of the North Anatolian fault. The region had big earthquakes in 1063, 1509, and 1766. The next big earthquake will likely occur near Istanbul, a city of 13 million people and growing rapidly. In the last 15 centuries, Istanbul has been heavily damaged by 12 earthquakes. Calculations indicate that the next big earthquake affecting Istanbul has a 62(+/–15)% probability of occurring within the next 30 years.

SAN ANDREAS FAULT TECTONICS AND EARTHQUAKES

The plate-tectonic history of western North America explains why earthquakes occur. As the Atlantic Ocean basin widens further, both North and South America move westward into the Pacific Ocean basin, helping reduce its size (see figures 2.14 and 4.2). At 30 million years ago, most of the northern portion of the Farallon plate had subducted eastward beneath North America (figure 4.27). At about 28 million years ago, the first segment of the Pacific spreading center collided with North America at about the site of Los Angeles today. The spreading centers to the north and south still operated as before. What connected the northern and southern spreading centers? A transform fault, specifically the ancestor of the San Andreas fault.

In the last 5.5 million years, the Gulf of California has opened about 300 km (190 mi). This rifting action has torn Baja California and California west of the San Andreas fault (including San Diego, Los Angeles, and Santa Cruz) from the North American plate and piggybacked them onto the Pacific plate (figure 4.27). The Gulf of California continues to open and is carrying the western Californias on a Pacific plate ride at about 56 mm/yr (2.2 in/yr).

The San Andreas fault is part of a complex system of sub-parallel faults (figure 4.28). The San Andreas fault

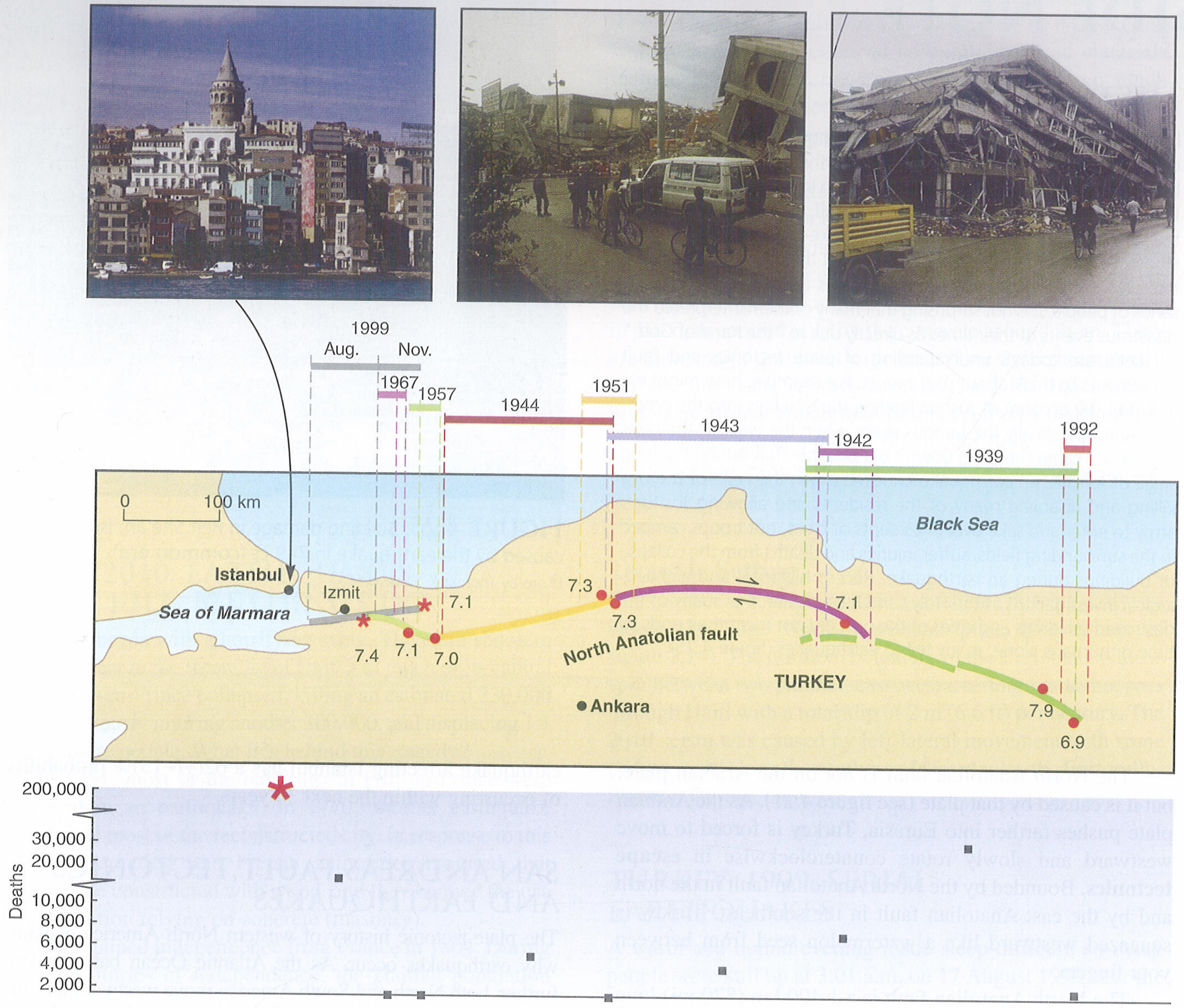


FIGURE 4.26 The North Anatolian fault accommodates the movement of Turkey westward into the Mediterranean basin. Note the time sequence of the fault ruptures from east to west. What does the near future hold for Istanbul?
Photo (left) © John A. Rizzo/Getty Images RF and photo (center and right) by Roger Bilham/NOAA.

proper is a 1,200 km (750 mi) long, right-lateral fault. In 1906, the northernmost section of the fault broke loose just offshore of the city of San Francisco, rupturing northward and southward simultaneously (figure 4.29). When it stopped shifting, the ground between Cape Mendocino and San Juan Bautista had been ruptured; this is a distance of 400 km (250 mi). The earthquake had a moment magnitude estimated at 7.8 resulting from 110 seconds of fault movement. When movement stopped, the western side had shifted northward a maximum of 6 m (20 ft) horizontally. In the peninsula south of San Francisco, fault movements have formed elongate topographic low areas now filled by lakes, and some of the land offset by the 1906 movements was smoothed out and built upon (figure 4.30). In the vertical plane, the fault movement completely ruptured the 15 to 20 km thick brittle layer in the region. The amount of fault movement in 1906 died out to zero at the northern and southern ends of the rupture.

Today, the San Francisco section of the San Andreas fault has a deficit of earthquakes. Apparently this is a "locked" section of the fault (see figure 4.28). Virtually all the stress from plate tectonics is stored as elastic strain for many decades until the fault finally can take no more and ruptures in a big event that releases much of its stored energy in a catastrophic movement.

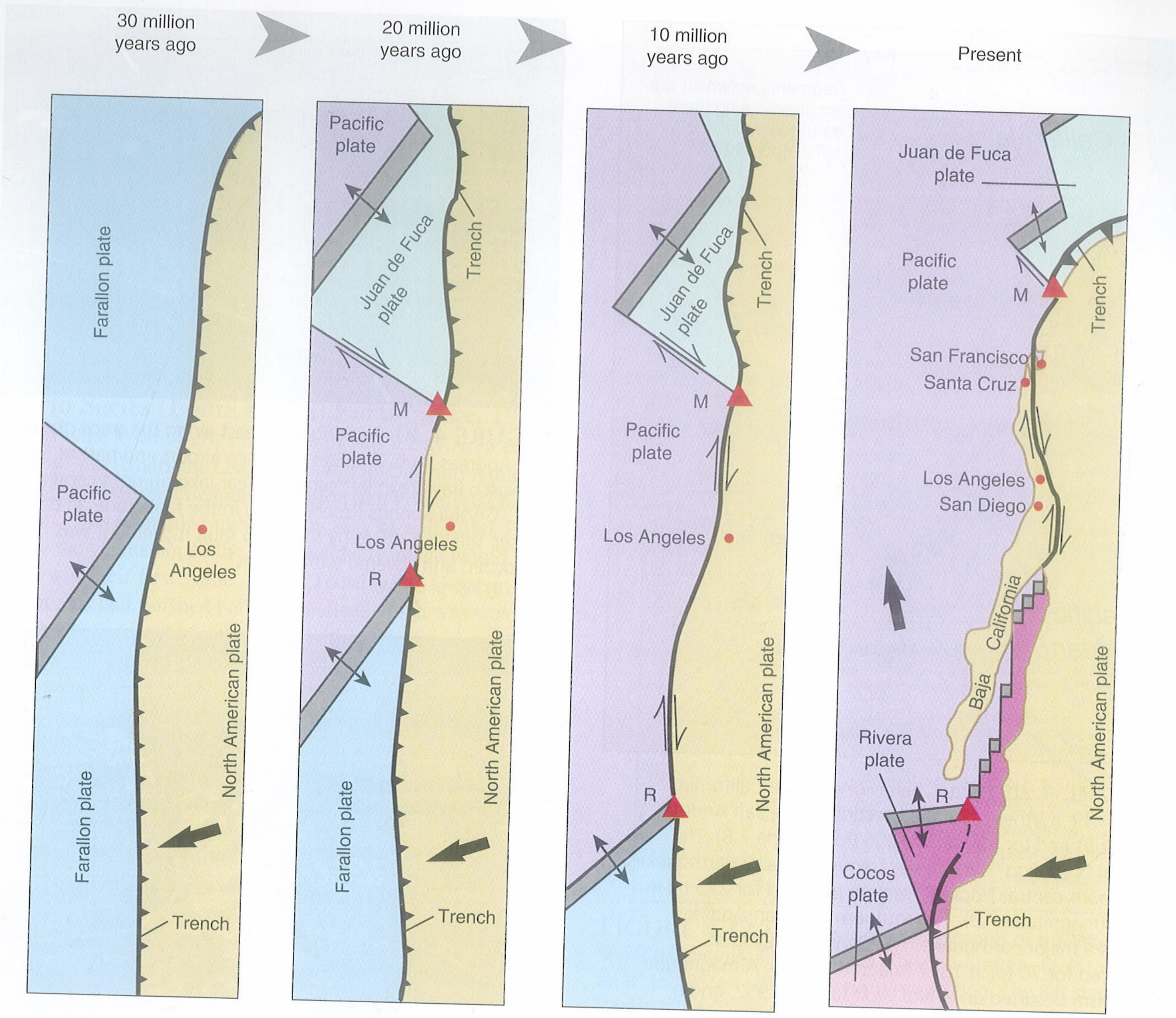


FIGURE 4.27 Collision of the Pacific Ocean basin spreading center with the North American plate: (a) 30 million years ago, the first spreading-center segment nears Southern California; (b) 20 million years ago, a growing transform fault connects the remaining spreading centers; (c) 10 million years ago, the Mendocino (M) and Rivera (R) triple junctions continue to migrate north and south respectively; (d) at present, the long transform fault is known as the San Andreas fault. (Interpretations based on the work of Tanya Atwater.)
Source: Kious, W. J., and Tilling, R. I., *This Dynamic Earth. US Geological Survey*, p. 77.

The San Andreas fault has different behaviors along its length. The section to the south of San Francisco (figure 4.28) has frequent small-to moderate-size earthquakes. This is a "creeping" section of the fault where numerous earthquakes accommodate the plate-tectonic forces before they build to high levels. The creeping movements of the fault are shown by the millimeters per year of ongoing offset of sidewalks, fences, buildings, and other features. Earthquakes in this fault segment do not seem to exceed magnitude 6. These are still significant seisms, but they are small compared to events on adjoining sections of the fault.

The San Andreas fault segment north of Los Angeles is another locked zone that is deficient in earthquake activity (figure 4.28). However, on 9 January 1857, this segment of the fault broke loose at its northwestern end, and the rupture propagated southeastward in the great Fort Tejon earthquake with a magnitude of about 7.9. Due to the one-way advance of the rupture front, the fault movement lasted almost 3 minutes. The ground surface was broken for at least 360 km (225 mi), and the maximum offsets in the Carrizo Plain (figure 4.31) were a staggering 9.5 m (31 ft). One of the offset features was a circular corral for livestock that was split and shifted to an

FIGURE 4.28 Historic behavior of some California faults. The northern "locked" section of the San Andreas fault ruptured for 250 mi in 1906 (magnitude 7.8). The central "creeping" section has frequent smaller earthquakes. The south-central "locked" section ruptured for 225 mi in 1857 (magnitude 7.9). The southernmost San Andreas awaits a major earthquake. The Owens Valley fault ruptured for 70 mi in 1872 (magnitude 7.3). A magnitude 7.5 seism occurred on White Wolf fault in 1952, and a magnitude 7.3 seism happened in the Mojave Desert in 1992.
Source: "The San Andreas Fault," *US Geological Survey*.

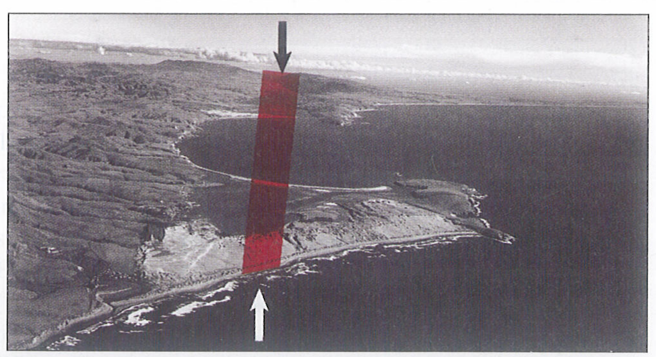


FIGURE 4.29 Looking south-southeast down the San Andreas fault. View is over Bodega Head and Tomales Bay toward the epicenter of the 1906 San Francisco earthquake.
Photo by John S. Shelton.

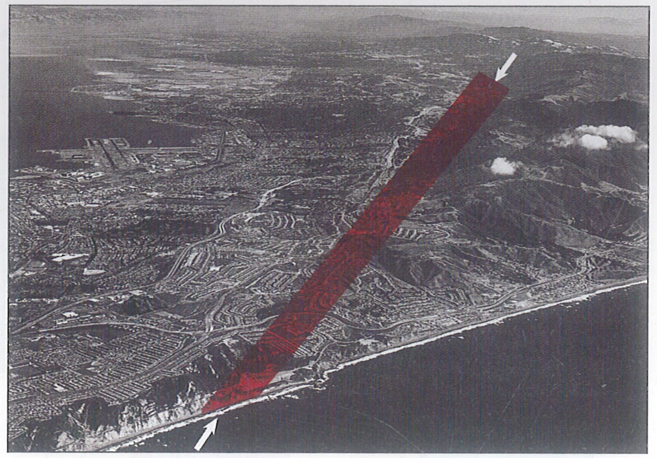


FIGURE 4.30 Looking southeast along the trace of the San Andreas fault. The San Francisco airport and part of San Francisco Bay are in left center. Linear lakes in right center (e.g., Crystal Springs Reservoir) are in the fault zone. In bottom center, the land offset by the 1906 fault movement was bulldozed and covered with houses!
Photo by John S. Shelton.

FIGURE 4.31 The San Andreas fault slashes across the Carrizo Plain. Notice the ridges and basins caused by local squeezing and pulling apart.
Photo courtesy of Pat Abbott.

S-shape by the fault movement. In 1857, the region was sparsely settled, so the death and damage totals were small. The next time a great earthquake occurs here, the effects may be disastrous.

The southernmost segment of the San Andreas fault, from San Bernardino to its southern end at the Salton Sea, has not generated a truly large earthquake in California's recorded history. But we can extend our knowledge of earthquakes into the prehistoric past by measuring offsets in sedimentary rock layers. For example, we've learned that the last truly big earthquake on the southern San Andreas fault occurred about the year 1690. These techniques will be discussed in chapter 5.

World Series (Loma Prieta) Earthquake, 1989

In 1989, the World Series of baseball was a Bay Area affair. It pitted the American League champion Oakland Athletics against the National League champion San Francisco Giants. Game 3 was scheduled in San Francisco's Candlestick Park, where the Giants hoped the home field advantage would help them win their first game. It was Tuesday, 17 October, and both teams had finished batting practice, which was watched by 60,000 fans at the park, along with a television crowd of another 60 million fans in the United States and millions more around the world. At 5:04 p.m., 21 minutes before the game was scheduled to start, a distant rumble was heard, and a soft thunder rolled in from the southwest, shaking up the fans and stopping the game from being played. San Francisco was experiencing another big earthquake, and this time, it shared it with television viewers. After the earthquake, the San Franciscans at Candlestick Park broke into a cheer, while many out-of-staters were seen heading for home.

What caused this earthquake? An 83-year-long pushing match between the Pacific and North American plates resulted in a 42 km (26 mi) long rupture within the San Andreas fault system. The southernmost section of the fault zone that moved in 1906 had broken free and moved again. There were several different aspects to the 1989 earthquake: (1) The fault rupture took place at depth; (2) the fault movement did not offset the ground surface; (3) there was significant vertical movement; and (4) the fault rupturing lasted only 7 seconds, an unusually short time for a magnitude 6.9 event.

Movement occurred in a gently left-stepping constraining bend of the San Andreas fault zone (figure 4.32). Long-term compressive pressures along this left step have uplifted the Santa Cruz Mountains. This step in the San Andreas fault is near where the Calaveras and Hayward faults split off and run up the east side of San Francisco Bay. The epicenter of the 1989 seism was near Loma Prieta, the highest peak in the Santa Cruz Mountains. Loma Prieta is the official name of this earthquake; it follows the rule of taking the name from the most prominent geographic feature near the epicenter. Nonetheless, this event remains known to many people as the World Series earthquake.

It is difficult for a fault to move around a left-stepping bend. Constraining bends commonly "lock up"; thus, movements at a

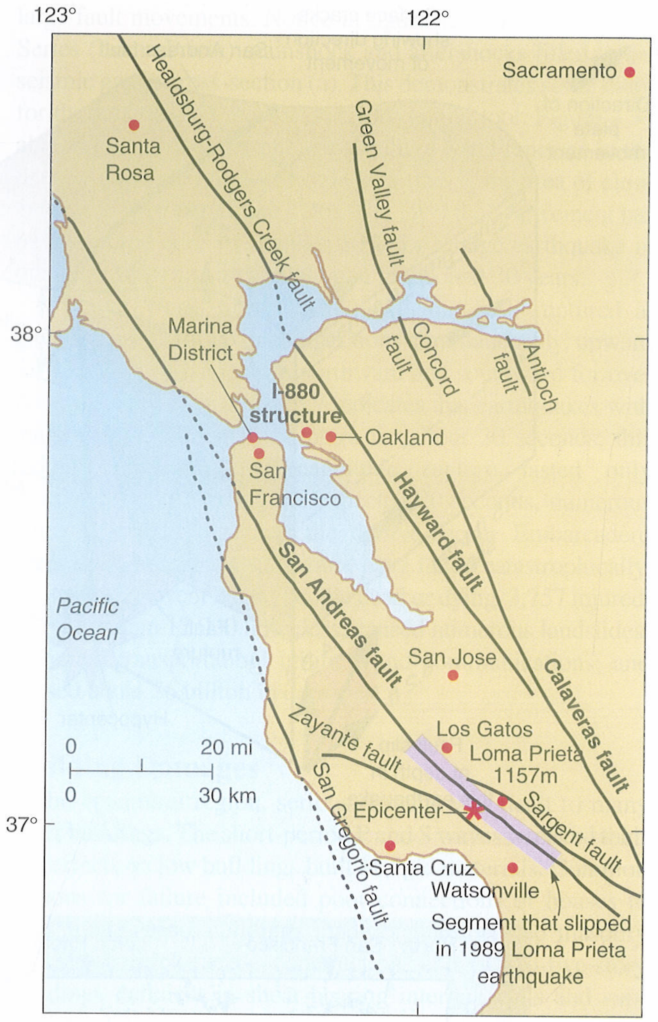


FIGURE 4.32 Map showing the epicenter of the World Series (Loma Prieta) earthquake. The San Andreas fault takes an 8° to 10° left step in the ruptured section. The left step also is where the Calaveras and Hayward faults split off from the main San Andreas trend.
Source: "Lessons Learned from the Loma Prieta Earthquake of October 17, 1989" in *US Geological Survey Circular 1045*, 1989.

bend tend to be infrequent and large. This left step in the San Andreas zone also causes the fault plane to be inclined 70° to the southwest (figure 4.33). The fault movement began at 18.5 km (11.5 mi) depth and slipped for 2.3 m (7.5 ft). The motion can be resolved into 1.9 m (6.2 ft) of horizontal movement (strike slip) and 1.3 m (4.3 ft) of vertical movement (reverse slip). Stated differently, the western or Pacific plate side moved 6.2 ft to the northwest, and a portion of the Santa Cruz Mountains was uplifted 36 cm (14 in). Although the fault did not rupture the surface, the uplifted area was 5 km (3 mi) wide and had numerous fractures in the uplifted and stretched zone. Many of the cracked areas became the sites of landslides.

The mainshock had a surface-wave magnitude (M_s) of 7.1 and a moment magnitude (M_w) of 6.9; numerous aftershocks followed, as is typical for large earthquakes. The Loma Prieta

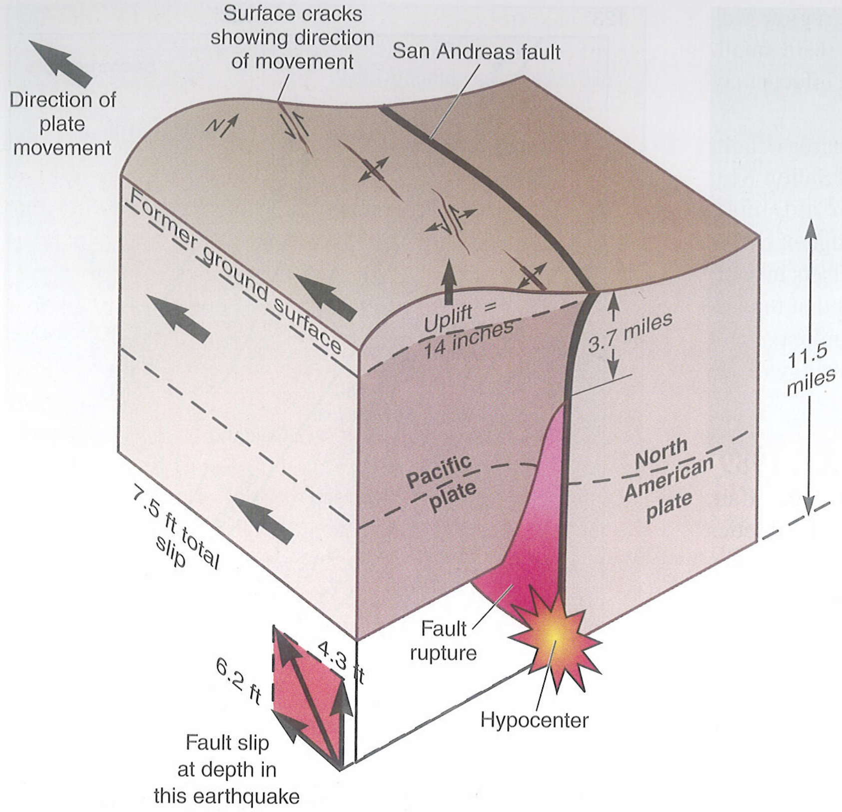


FIGURE 4.33 Schematic diagram of fault movement within the San Andreas zone in the World Series earthquake. The San Andreas fault dips 70° southwest because of the left-step bend. Fault movement began at 18 km (11.5 mi) depth and moved 1.9 m (6.2 ft) horizontally and 1.3 m (4.3 ft) vertically. Fault movement died out upward and did not rupture the ground, although the surface bulged upward 36 cm (14 in). Think three-dimensionally here: because of the dipping fault plane, will the epicenter plot on the ground-surface trace of the San Andreas fault? No.
Source: "Lessons Learned from the Loma Prieta Earthquake of October 17, 1989" in *US Geological Survey Circular 1045*, 1989.

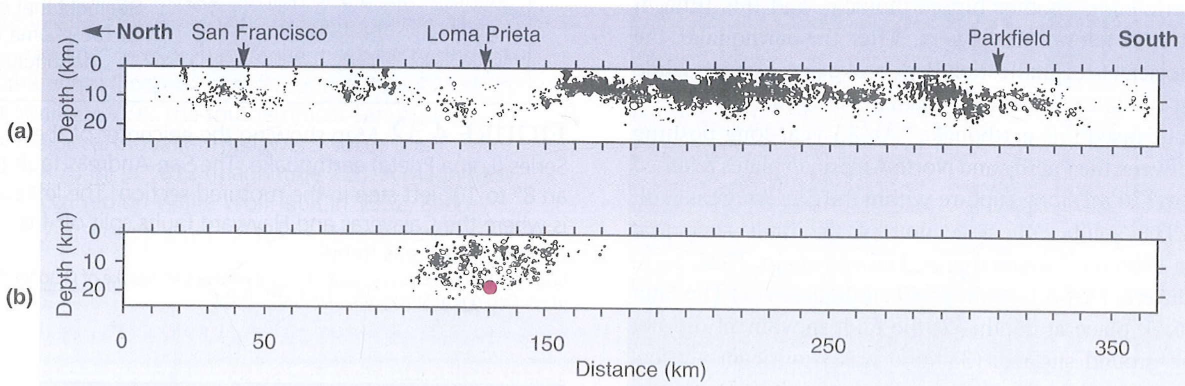
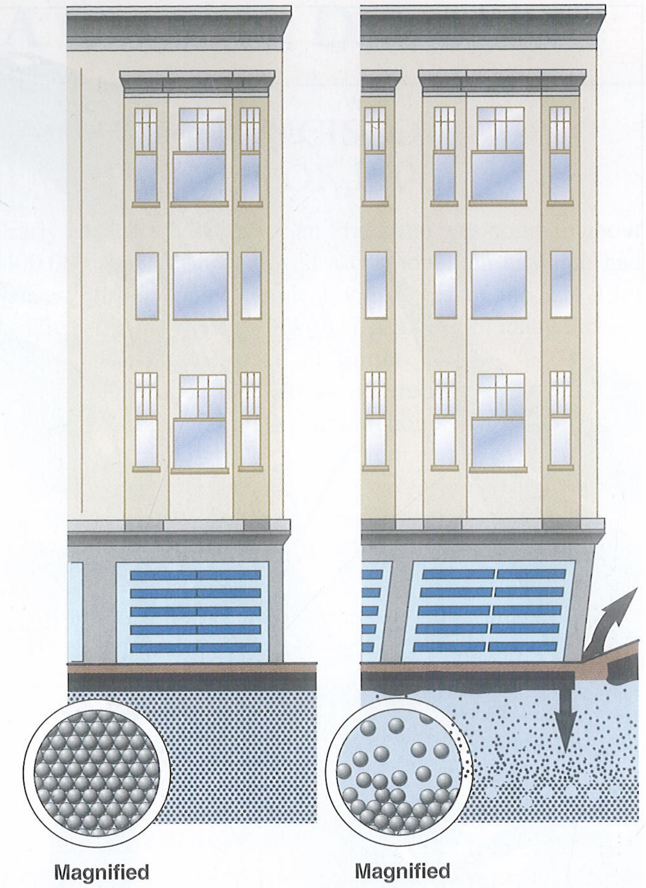


FIGURE 4.34 Cross-sections of seismicity along the San Andreas fault, 1969 to early 1989. (a) Notice the dense concentrations of hypocenters in the central creeping section of the fault from south of Loma Prieta to Parkfield, as well as the "seismic gap" in the Loma Prieta area. (b) Notice the deep hypocenter (in red) of the 1989 mainshock plus the numerous aftershocks. Putting the two cross-sections together fills the seismic gap. Are there other seismic gaps in cross-section (a)? Yes, south of San Francisco in the Crystal Springs Reservoir area (see figure 4.30), just west of the densely populated midpeninsula area. When will this seismic gap be filled?
Source: "Lessons Learned from the Loma Prieta Earthquake of October 17, 1989" in *US Geological Survey Circular 1045*, 1989.

area had been a relatively quiet zone for earthquakes since the 1906 fault movement (figure 4.34); before 1989, the Loma Prieta region had been a *seismic gap*. As the numerous epicenters in figure 4.34a show, the San Andreas fault section to the south moves frequently, generating numerous small earthquakes. But the same plate-tectonic stresses affecting the creep zone also affect the locked or seismic-gap zone. How does a locked zone catch up with a creep zone? By infrequent but



(a)

(b)

FIGURE 4.35 (a) Water-saturated sediment usually rests quietly (left). However, when seismic waves shake, sand grains and water can form a slurry and flow as a liquid (right). When earth materials liquefy, building foundations may split and buildings may fail. (b) A typical Marina District building collapse. Three residential stories sat above a soft first story used for car parking; now, the four-story building is three stories tall.
Photo from Dames and Moore.

large fault movements. Notice in figure 4.34b how the World Series (Loma Prieta) mainshock and aftershocks filled in the seismic gap in cross-section (a). This demonstrates some merit for the seismic-gap method as a forecasting tool. Figure 4.34 also shows another seismic gap, south of San Francisco in the heavily populated midpeninsula area (this is the area of elongate lakes shown in figure 4.30). The 1989 fault movement has increased the odds by another 10% for a large earthquake in the Crystal Springs Reservoir area in the next 30 years.

In the World Series earthquake, the fault ruptured at greater than 2 km/sec in all directions simultaneously, upward for 13 km (8 mi), and both northward and southward for over 20 km (13 mi) each. Table 3.7 indicates that earthquakes with magnitudes of 7 usually rupture for about 20 seconds; this radially spreading, 6.9-magnitude rupture lasted only 7 seconds. Had it lasted the expected 20 seconds, numerous other large buildings and the double-decker Embarcadero Freeway in San Francisco would have failed catastrophically. As it was, the event left 67 people dead or dying, 3,757 injured, and more than 12,000 homeless; caused numerous landslides; disrupted transportation, utilities, and communications; and caused about $6 billion in damages.

Building Damages

In the epicentral region, serious damage was dealt to many older buildings. The short-period P and S waves wreaked their full effects on low buildings built of rigid materials. Common reasons for failure included poor connections of houses to their foundations, buildings made of unreinforced masonry (URM) or brick-facade construction, and two-to-five-story buildings deficient in shear-bearing internal walls and supports. In Santa Cruz, four people died, and the Pacific Garden Mall, the old city center of historic brick and stone buildings that had been preserved and transformed into a tourist mecca, was virtually destroyed.

From the epicentral region, the seismic waves raced outward at more than 3 mi/sec. Some longer-period shear waves remained potent even after traveling 100 km (more than 60 mi). Upon reaching the soft muds and artificial-fill foundations around San Francisco Bay, these seismic waves had their vibrations amplified. Ground motion at some of these soft-sediment foundation sites was 10 times stronger than at nearby sites on rock.

Marina District

The Marina District is one of the most beautiful areas in San Francisco. It sits on the northern shore of the city next to parks, the Golden Gate Bridge, and the bay itself. In this desirable and expensive district, five residents died, building collapses were extensive, and numerous building-eating fires broke out due to: (1) amplified shaking, (2) deformation and liquefaction of artificial-fill foundations, and (3) soft first-story construction, which led to building collapses (figure 4.35).

Much of the Marina District is built on artificial fill dumped onto the wetlands of the bay to create more land

FIGURE 4.36 The Cypress double-decker section of Interstate 880 in Oakland was completed in 1957. It failed in the 1989 seism and dropped 1.25 mi of upper roadbed onto the lower roadbed, crushing many vehicles and people.
Photo from Dames and Moore.

FIGURE 4.38 The support columns of the Interstate 880 structure failed at the joints. There were 20 #18 bars of steel in each column, but they were discontinuous at the joints and failed there.
Photo from Dames and Moore.

for development. Ironically, much of the artificial fill was the debris from the San Francisco buildings ruined by the 1906 earthquake. Seismic waves in 1989 were amplified in this artificial fill. Some fill underwent permanent deformation and settling, and some formed **slurries** as underground water and loose sediment flowed as fluids in the process of **liquefaction** (figure 4.35a). Liquefaction in the Marina District in 1989 brought to the surface pieces of glass, tar paper, redwood, and other debris from 1906 San Francisco.

The central cause of building failure was flawed design. Because the Marina District is home to many affluent people, they need places to park their cars. But where? The streets are already overcrowded, and basement parking garages would be below sea level and thus flooded. A common solution has been to clear obstructions from the first stories of buildings to make space for car parking. That means removing the internal walls, lateral supports, and bracing needed to support the upper one to four stories. This creates a "soft" first story, so that in an earthquake, buildings simply pancake and become one story shorter (figure 4.35b). It is estimated that there are 2,800 blocks of soft first-story residences in San Francisco today and another 1,500 blocks in Oakland.

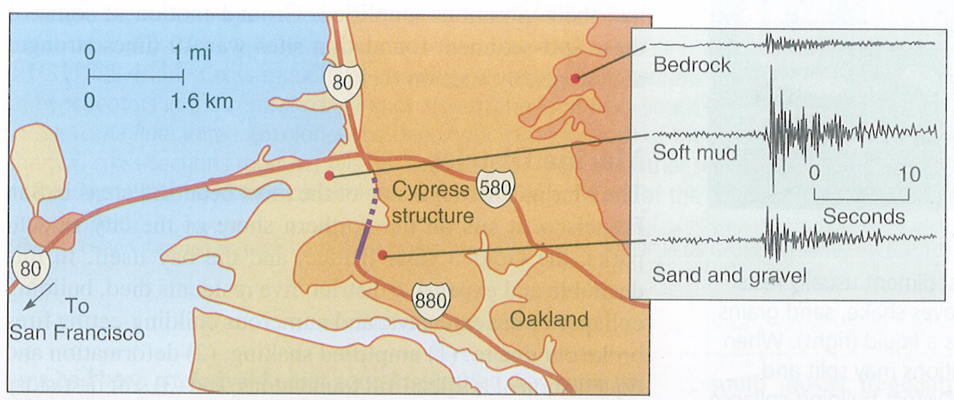


FIGURE 4.37 The portion of Interstate 880 elevated roadway built on top of soft bay mud collapsed (dashed purple line), while the portion resting on sand and gravel still stood (solid purple line). Notice how the shaking was amplified in the soft mud.

Interstate 880

The most stunning tragedy associated with the World Series earthquake was the crushing of 42 people during the collapse of a double-decker portion of Interstate 880 in Oakland (figure 4.36). The elevated roadway was designed in 1951 and completed in 1957. A 2 km (1.25 mi) long section collapsed: 44 slabs of concrete roadbed, each weighing 600 tons, fell onto the lower roadbed and crushed some vehicles to less than 30 cm (1 ft) high. The section that collapsed was built on young, soft San Francisco Bay mud. The elevated freeway structure had a natural resonance of two to four cycles per second; the bay-mud foundation produced a five to eight-fold amplification of shaking in that range. The seismic waves excited the mud (figure 4.37), causing the heavy structure to sway sharply. The portion of I-880 elevated roadway built on firmer sand and gravel stood intact; the portion standing on soft mud collapsed catastrophically.

The weak foundation was compounded by a flawed structural design. The joints where roadbeds were connected to concrete support columns were not reinforced properly. Cracks initiated at the joints caused failure of supporting columns, which slid off the crushed areas of the joints and dropped the upper roadbed onto the lower level (figure 4.38). Was this bridge failure a surprise? Not really. The lessons had been learned 18 years earlier in the 1971 San Fernando earthquake, but no one had corrected this disaster-in-waiting.

An ironic and deadly footnote to this disaster lay in the mode of failure. There was a delay between the initial shock

A Classic Disaster

The San Francisco Earthquake of 1906

Early in the 20th century, San Francisco was home to about 400,000 people who enjoyed a cosmopolitan city that had grown during the economic boom times of the late 19th century. During the evening of 17 April 1906, many thrilled to the special appearance of Enrico Caruso, the world's greatest tenor, singing with the Metropolitan Opera Company in Bizet's *Carmen*. But several hours later, at 5:12 a.m., the initial shock waves of a mammoth earthquake arrived to begin the destruction of the city. One early riser told of seeing the earthquake approach as the street before him literally rose and fell like a series of ocean swells moving toward shore.

During a noisy minute, the violently pitching Earth emitted dull booming sounds joined by the crash of human-made structures. When the ground finally quieted, people went outside and gazed through a great cloud of dust to view the destruction. Unreinforced masonry buildings lay collapsed in heaps, but steel-frame buildings and wooden structures fared much better. Another factor in the building failures was the nature of the ground they were built on. Destruction was immense in those parts of the city that were built on artificial fill that had been dumped onto former bay wetlands or into stream-carved ravines.

As repeated aftershocks startled and frightened the survivors, another great danger began to grow. Smoke arose from many sites as fires fed on the wood-filled rubble. Unfortunately, the same earthquake waves that wracked the buildings also broke most of the water lines, thus hindering attempts to stop the growing fires. From the business district and near the waterfront, fires began their relentless intrusion into the rest of the city. Desperate people tried dynamiting buildings to stop the fire's spread, but they only provided more rubble to feed the flames or even blew flaming debris as far as a block away, where it started more fires.

The fires did about 10 times as much damage as the earthquake itself; fire destroyed buildings covering 490 city blocks. More than half the population lost their homes. Death and destruction were concentrated in San Francisco, where 315 people died, but the affected area was much larger. About 700 deaths occurred in a 430 km (265 mi) long belt of land running near the San Andreas fault. Towns within the high-intensity zone, such as San Jose and Santa Rosa, were heavily damaged, yet other cities to the east of the narrow zone, such as Berkeley and Sacramento, were spared significant damage. Problems continued in the months that followed as epidemics of filth-borne diseases sickened Californians; more than 150 cases of bubonic plague were reported. When all the fatalities from earthquake injuries and disease are included, the death total from the earthquake may have been as high as 5,000.

Total financial losses in the event were almost 2% of the US gross national product in 1906; for comparison, Hurricane Katrina economic losses were much less than 1%. Politicians and the press in their desire to restore the city called the disaster a fire-related event and listed the death total at about 10% of actual life loss. In their desire to rebuild, the emphasis was on quickness, not on increasing safety. This problem haunts us today because much of the early rebuilding was done badly and is likely to fail in the next big earthquake.

One of the intriguing aspects of disasters is their energizing effects on many survivors. Hard times shared with others bring out the best in many people. Shortly after this earthquake, the resilient San Franciscans were planning the Panama-Pacific International Exposition that was to impress the world and leave behind many of the beautiful buildings that tourists flock to see today. You can't keep a good city down.

and the final collapse, which allowed some people a brief time to plan. Some maneuvered their vehicles under beams next to support columns, and others got out of their cars and walked under the same supports, thinking that these were the strongest parts of the structure; but the steel bars in the support columns were discontinuous. Tragically, these were the weak spots, where failure was most catastrophic, and no one survived there.

BAY AREA EARTHQUAKES—PAST AND FUTURE

The historic record of California earthquakes is accurate only back to about 1850, and thus is shorter than the recurrence times for major movements on most faults. Nonetheless, the San Francisco Bay Area has enough information contained in newspaper accounts, diaries, personal letters, and similar sources to piece together a fairly accurate history of 19th-century earthquakes, and it is quite different from the 20th-century record. During the 19th century, earthquakes with magnitudes greater than 6 were much more common (figure 4.39). There were seven destructive seisms in the 70 years before the 1906 San Francisco earthquake, averaging a large earthquake every decade. Then came the monstrous movement of the San Andreas fault in 1906. This 250-mile-long rupture removed so much of the plate-tectonic stress stored in the rocks that several decades of the 20th century were effectively free of large earthquakes (figure 4.40). But large earthquakes returned to the southern part of the Bay Area beginning in the 1970s (figure 4.39). We can identify three patterns in these data.

Pattern 1

Common Large Earthquakes versus Rare Giant Shakes

The movement of the Pacific plate past the North American plate in the Bay Area seems to be satisfied by either a magnitude

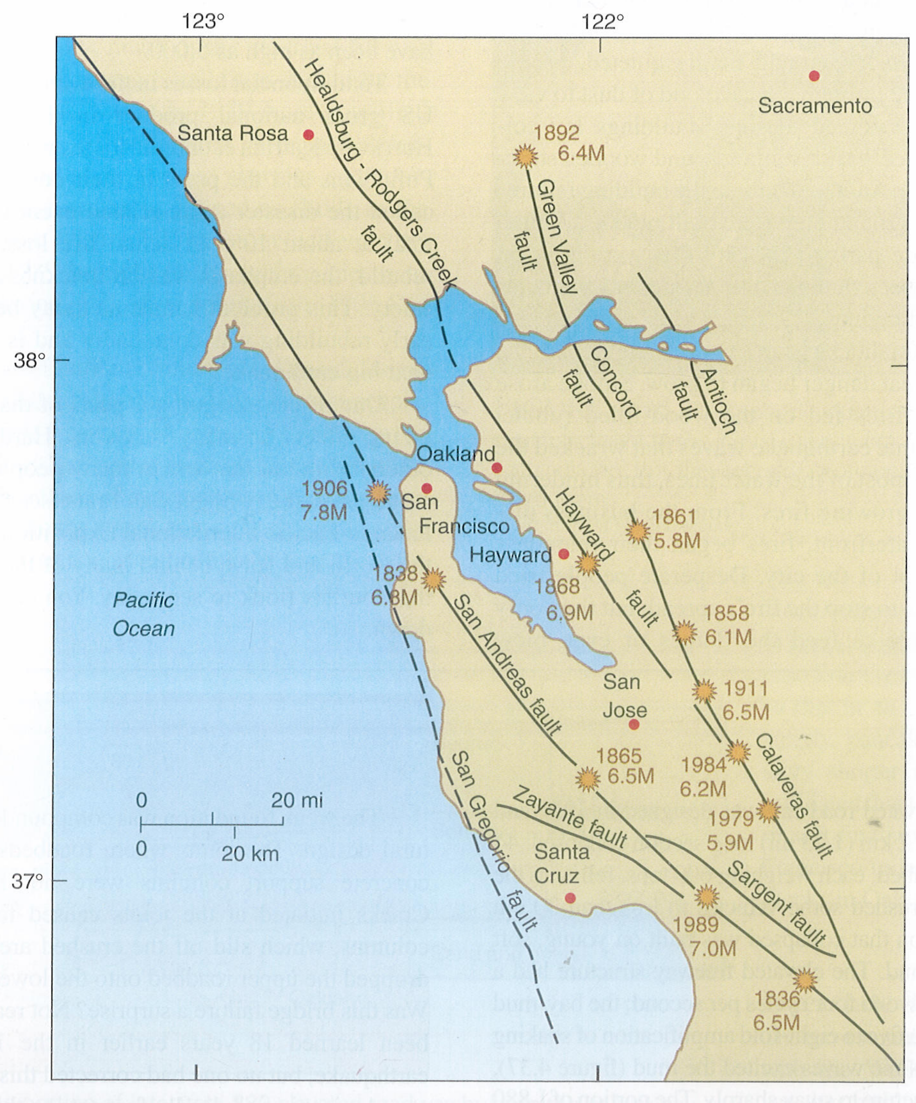


FIGURE 4.39 Locations and approximate sizes of some larger Bay Area earthquakes.
Source: *US Geological Survey.*

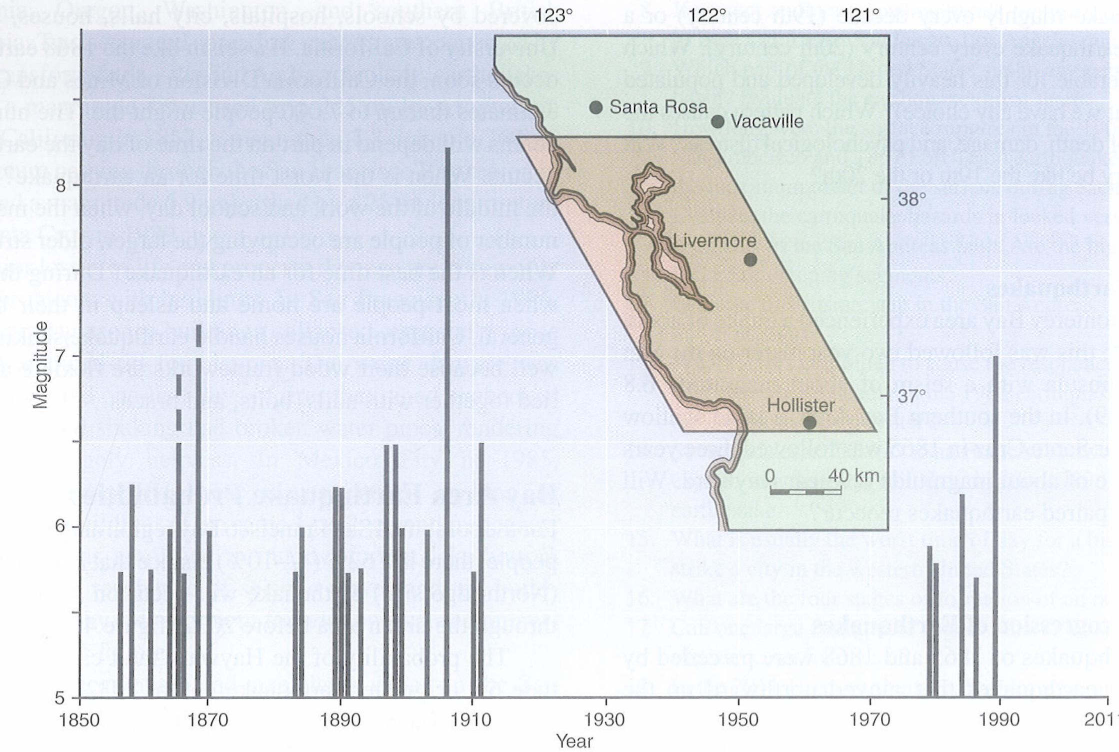


FIGURE 4.40 Distribution of earthquakes with magnitudes greater than 5.5 near San Francisco Bay, 1849–2011. The index map shows the area of earthquake epicenters.

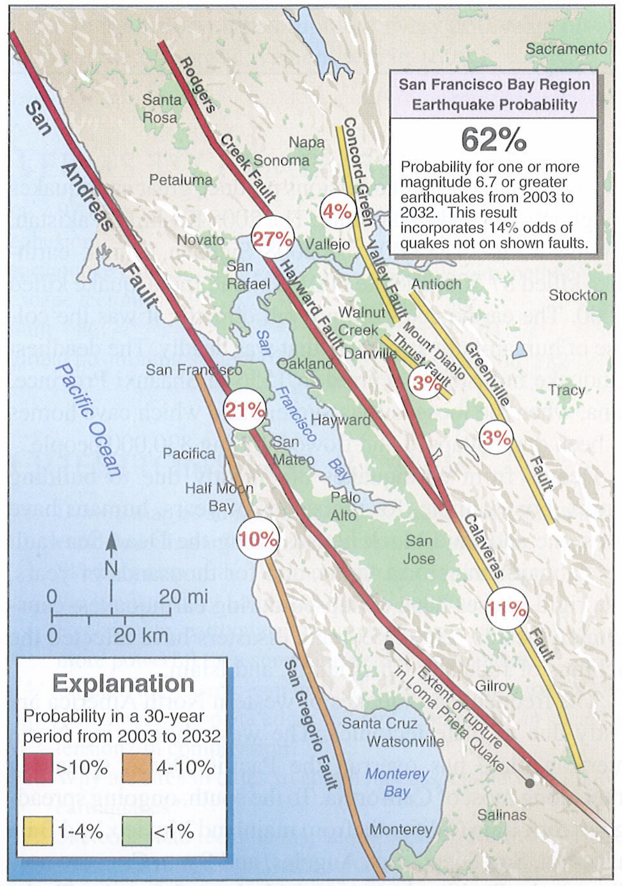


FIGURE 4.41 Probabilities of one or more magnitude 6.7 or larger earthquakes in the San Francisco Bay region, 2003–2032.
Source: Redrawn from Working Group on California Earthquake Probabilities, 2003.

6 to 7 earthquake roughly every decade (19th century) or a magnitude 8 earthquake every century (20th century). Which pattern is preferable for this heavily developed and populated region (not that we have any choice)? Which pattern causes the least amount of death, damage, and psychological distress? Will the 21st century be like the 19th or the 20th?

Pattern 2

Pairings of Earthquakes

In 1836, the Monterey Bay area experienced a quake of about magnitude 6.5; this was followed two years later on the San Francisco Peninsula with a seism of about magnitude 6.8 (see figure 4.39). In the southern Bay Area, a large shallow earthquake near Santa Cruz in 1865 was followed three years later by a shake of about magnitude 6.9 near Hayward. Will this pattern of paired earthquakes reoccur?

Pattern 3

Northward Progression of Earthquakes

The large earthquakes of 1865 and 1868 were preceded by five moderate earthquakes that moved northward up the Calaveras fault. Figure 4.39 shows moderate to large earthquakes that have moved from south to north up the Calaveras fault. Does this repeat pattern suggest an upcoming large seism on the Hayward fault? This region today is populated by more than 2 million people in 10 cities. The fault is covered by schools, hospitals, city halls, houses, and the University of California. If a seism like the 1868 earthquake occurs soon, the California Division of Mines and Geology estimates that up to 7,000 people might die. The number of deaths will depend in part on the time of day the earthquake occurs. When is the worst time for an earthquake? During the middle of the work and school day, when the maximum number of people are occupying the larger, older structures. When is the best time for an earthquake? During the night, when most people are home and asleep in their beds. In general, California houses handle earthquake shaking quite well because their wood frameworks are flexible and well tied together with nails, bolts, and braces.

Bay Area Earth quake Probabilities

For the combined San Francisco Bay region and its 6.8 million people, there is a 62% (+/–10%) chance that a 6.7 magnitude (Northridge-size) earthquake will occur on a fault crossing through the urban area before 2032 (figure 4.41).

The probability of the Hayward fault causing a magnitude 6.7 or greater earthquake before 2032 is estimated at 27%. The Hayward fault is expected to rupture for about 22 seconds with about 2 m (6 ft) of slip extending down about 13 km (8 mi). The next movement of the Hayward fault will cause tens of billions of dollars in property losses, and deaths may total in the thousands.

Summary

Most earthquakes are caused by fault movements associated with tectonic plates. Plates have three types of moving edges: (1) divergent at spreading centers, (2) slide-past at transform faults, and (3) convergent at collision zones. The tensional (pull-apart) movements at spreading centers do not produce very large earthquakes. The dominantly horizontal (slide-past) movements at transform faults produce large earthquakes. The compressional movements at subduction zones and continent-continent collisions generate the largest tectonic earthquakes, and they affect the widest areas.

Subduction zones produce the largest number of great earthquakes. In 1923, a subduction movement of the Pacific plate destroyed nearly all of Tokyo and Yokohama; much of the devastation was caused by fires unleashed during building collapses. The largest earthquakes along western North America are due to subduction beneath the continent. The magnitude 9.2 Alaska earthquake in 1964 and Japan earthquake in 2011 were due to subduction of the Pacific plate, and the magnitude 8.1 Mexico City event in 1985 was caused by subduction of the Cocos plate. The plates subducting beneath Oregon, Washington, and British Columbia generated a magnitude 9 earthquake on 26 January 1700 and will do so again in the future. In 2004, the Sumatra, Indonesia, earthquake and tsunami killed more than 245,000 people.

Continent-continent collisions produce great earthquakes throughout Asia and Asia Minor. The 2005 Kashmir, Pakistan, earthquake killed 88,000; the 2008 Sichuan, China, earthquake killed 87,500; and the 2001 Gujarat, India, quake killed 20,000. The earthquakes did not kill directly; it was the collapse of human-built structures that was deadly. The deadliest earthquake in history occurred in 1556 in Shaanxi Province, China, when the loose, silty sediment into which cave homes had been dug collapsed and flowed, killing 830,000 people.

Deaths from earthquakes are mostly due to building failures. For example, for thousands of years, humans have built stone and mud-block houses along the Dead Sea fault zone (a major transform fault), and for thousands of years, these rigid houses have collapsed during earthquakes, causing many deaths. These geologic disasters have affected the teachings of Judaism, Christianity, and Islam.

The frequent earthquakes of western North America are mostly due to plate tectonics. The westerly moving North American plate has overrun the Pacific Ocean spreading center along most of California. To the south, ongoing spreading has torn Baja California from mainland Mexico, and Baja California, San Diego, Los Angeles, and Santa Cruz are now riding on the Pacific plate toward Alaska at 5.6 cm/yr. To the north, spreading still occurs offshore from northernmost California, Oregon, Washington, and southern British Columbia. Two separated spreading centers are connected by a long transform fault—the San Andreas fault. Its earthquakes include a magnitude 7.9 caused by a 225 mi long rupture in central California in 1857, a magnitude 7.8 due to a 260 mi long rupture passing through the San Francisco Bay region in 1906, and a magnitude 6.9 unleashed by a 25 mi long rupture near Santa Cruz in 1989.

Major losses of life and property damage are commonly due to problems with buildings. In San Francisco in 1906, unreinforced-masonry buildings collapsed, especially those built on artificial-fill foundations. The worst damage was done by two and one-half days of fires that raged unchecked because ground shaking had broken water pipes, rendering firefighters largely helpless. In Mexico City in 1985, 1- to 2-second-period shear waves caused shaking of 6- to 16-story buildings at the same 1- to 2-second frequency, and shaking was amplified in muddy, former lake-bottom sediments. The resonance of seismic waves and tall buildings, amplified by soft sediment foundations, caused numerous catastrophic failures.

Earthquake numbers and sizes have varied in the San Francisco Bay region. In the 19th century, magnitude 6.5 to 7 events occurred at an average of one per decade; the 20th century was dominated by the magnitude 7.8 event in 1906.

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.

Terms to Remember

CE 97
cohesion 93
earthquake cluster 87
escape tectonics 97
fault 80
global positioning system (GPS) 86
liquefaction 104
rift 82
seismic-gap method 86
slip 86
slurry 104
triple junction 82

Questions for Review

1. Draw a map of an idealized tectonic plate and explain the earthquake hazards along each type of plate edge.
2. Sketch a map of the Arabian plate and explain the origin of the Iranian, Holy Land, and Turkey earthquakes.
3. Explain why earthquakes at subduction zones are many times more powerful than spreading-center earthquakes.
4. Explain the seismic-gap method of forecasting earthquakes.
5. Which tectonic-plate edges fail most commonly in shear? In tension? In compression?
6. Why are fires in cities so commonly associated with major earthquakes?
7. Sketch a plate-tectonic map along western North America from Alaska through Mexico. Label the spreading centers, subduction zones, and transform faults. Label the maximum earthquakes expected along the coastal zones.
8. If present seafloor spreading trends continue, what will happen to Baja California, San Diego, Los Angeles, and Santa Cruz?
9. Which part of the United States sits in an opening ocean basin? Evaluate the earthquake threat there.
10. How long were the surface ruptures in the 1906 San Francisco and 1857 Fort Tejon earthquakes? What was the maximum offset of the surface during each quake?
11. Evaluate the earthquake hazards in locked versus creeping segments of the San Andreas fault. Are the biggest cities in locked or creeping segments?
12. Evaluate the seismic gap in the San Andreas fault south of San Francisco.
13. What factors combined to cause the resonance in Mexico City that was so deadly in the 1985 earthquake? How far was the city from the epicenter?
14. Sketch a Marina District (San Francisco) dwelling and explain why so many failed during the 1989 Loma Prieta earthquake.
15. What is usually the worst time of day for a big earthquake to strike a city in the western United States?
16. What are the four stages of formation of an ocean basin?
17. Can one large earthquake trigger others? What is the recent experience in Indonesia?
18. In the 2011 Japan earthquake, how large an area of plate moved? What was the maximum slip? What was the earthquake magnitude? When did the last earthquake of this size occur in the same area?
19. What is the largest earthquake measured (see Chile)?
20. Why do so many mega-killer earthquakes occur in the China, India, Pakistan region?
21. The 2010 Haiti and 1989 Loma Prieta (World Series) earthquakes were both 7M events. Why were 3,000 times more people killed in the Haiti earthquake?
22. Can we recognize that an earthquake is a foreshock before the mainshock occurs?
23. Sketch a sequence of cross-sections that shows how a continent is split, then separated to form an ocean basin.

Questions for Further Thought

1. How might people with no geologic knowledge, living in stone houses next to a major fault, explain a disastrous earthquake?
2. How might you use food to create a plate-tectonics model in your kitchen?
3. Which U.S. states are on the Pacific plate?
4. Which would be the better of two bad choices for an urban area: a magnitude 6.5 to 7 earthquake every 15 years or a magnitude 8 every century?
5. Why is the zone of active faults so much wider in southern than in northern California?
6. If a magnitude 9 earthquake occurred in the Cascadia subduction zone offshore from the Pacific Northwest, what might happen in Vancouver, Seattle, Portland, and other onshore sites?
7. On 19 September 1985, Mexico City was rocked by a magnitude 8.1 earthquake. Two days later, the city was shaken by a magnitude 7.5 earthquake. Would you consider this a mainshock and an aftershock or twin earthquakes?
8. Is East Africa likely to pull away from the rest of Africa to form a Somali plate?