Earthquakes and Earth’s Interior

Earthquakes are among Earth’s deadliest natural phenomena. Ground shaking during an earthquake can topple buildings, liquefy normally solid ground, and unleash massive ocean waves that wipe out coastal cities. A single earthquake can kill more than 100,000 people. What causes earthquakes, and how do we study them? In this chapter, we explore important aspects about earthquakes and Earth’s interior.

The world’s strongest earthquake in 40 years struck Indonesia on December 26, 2004. The magnitude 9 earthquake occurred west of Sumatra and was caused by movement on a fault, shown by the red line on this map. The fault is part of a plate boundary where the Indian-Australian plate is being subducted to the northeastward beneath the Eurasian plate. The red line shows the length of the fault that ruptured during the earthquake. Yellow dots nearby show the locations of smaller, related earthquakes.

What causes earthquakes and where are they most likely to strike?

The earthquake occurred beneath the ocean, where the Eurasian plate was thrust over the Indian-Australian plate. Movement on the fault abruptly uplifted the overriding plate, pushing up a large region of seafloor and displacing overlying seawater. This caused a massive wave, called a tsunami, that spread out across the Indian Ocean as a low wave, traveling at speeds approaching 800 kilometers/hour (500 miles/hour). The curved gray lines show a model of the wave’s position by hour.

What happens when an earthquake occurs under the sea, rather than on land?

The tsunami increased in height as it crashed into the coasts of Indonesia, Thailand, Sri Lanka, India, east Africa, and various islands. Low coastal areas were inundated by as much as 20 to 30 meters of water (65 to 100 feet) in Indonesia and 12 meters (40 feet) in Sri Lanka. Cities and villages were completely demolished along hundreds of kilometers of coastline, leaving more than 250,000 people dead or missing. The numbers below show casualties by location.

How does a tsunami form, how does it move through the sea, and what determines how destructive it is?
The 2004 Sumatran Earthquake and Indian Ocean Tsunami

The 2004 Sumatran earthquake struck on the morning of December 26, violently shaking the region and triggering the massive Indian Ocean tsunami. It ranks as one of the two or three largest earthquakes ever recorded. The magnitude of the earthquake is variably estimated at 9.0 to 9.3, depending on how the calculations are done. Large aftershocks followed the main quake, including one with a surprisingly large magnitude of 8.7. From the seismic records of the main quake and aftershocks, it is estimated that a fault surface 1,220 (700 miles) kilometers in length slipped by as much as 10 meters during the earthquake. The earthquake lasted over 8 minutes, an unusually long duration.

The earthquake started at a depth of 30 kilometers (19 miles) and ruptured all the way up to the seafloor. It lifted a large section of seafloor several meters in height, displacing tens of cubic kilometers of seawater, which spread out in all directions. The tsunami rose to heights of more than 30 meters (100 feet) when it came ashore, and in many places it washed inland for more than a kilometer.

As a result of the earthquake, parts of the Andaman Islands, northwest of Sumatra, were changed forever. Coral reefs, which had been undersea, were lifted above sea level. A lighthouse that was originally on land is now surrounded by seawater one meter deep. The changes to the land seem insignificant compared to the massive loss of life in this event, one of the deadliest disasters in world history.
What Is an Earthquake?

An earthquake occurs when energy stored in rocks is suddenly released. Most earthquakes are produced when stress builds up along a fault and causes the fault to slip. Similar kinds of energy are released by volcanic eruptions, explosions, and even meteorite impacts.

How Do We Describe an Earthquake?

When an earthquake occurs, mechanical energy is released, some of which is transmitted through rocks as vibrations called seismic waves. These waves spread out from the site of the disturbance, travel through the interior or along the surface of Earth, and can be recorded by scientific instruments at seismic stations.

1. The place where the earthquake is generated is the hypocenter or focus. For most earthquakes, this is at some depth within Earth. Most earthquakes occur at depths of less than 100 kilometers (60 miles) and are as shallow as several kilometers. Those that occur in subduction zones may be as deep as 700 kilometers (430 miles).

2. The epicenter is the point on Earth's surface directly above where the earthquake occurs (directly above the hypocenter). If the seismic event happens on the surface, such as during a surface explosion, then the epicenter and hypocenter are the same.

3. Seismic waves, once generated, move out in all directions, as shown by the curved bands radiating out from the hypocenter. They can be measured by seismic stations (locations 1 and 2). Seismic stations closer to the hypocenter, such as station 1, will detect the waves sooner than those farther away, such as station 2.

What Causes Most Earthquakes?

Most earthquakes are generated by movement along faults. When rocks on opposite sides of a fault slip past one another abruptly, the movement generates seismic waves as materials near the fault are pushed, pulled, and sheared. Slip along any type of fault can generate an earthquake.

Normal Faults

Reverse and Thrust Faults

Strike-Slip Faults

In a normal fault, the rocks above the fault (the hanging wall) move down with respect to rocks below the fault (the footwall). The crust is stretched horizontally, so earthquakes related to normal faults are most common along divergent plate boundaries, such as oceanic spreading centers, and in continental rifts.

Many large earthquakes are generated along reverse faults, especially the gently dipping variety called thrust faults. In thrust and reverse faults, the hanging wall moves up with respect to the footwall. Such faults are formed by compressional forces, such as those associated with subduction zones and continental collisions.

In strike-slip faults, the two sides of the fault slip horizontally past each other. This can generate large earthquakes. The largest strike-slip faults are transform plate boundaries, like the San Andreas fault in California and parts of the seismically dangerous Alpine fault, which cuts diagonally across the South Island of New Zealand.
C How Do Volcanoes and Magma Cause Earthquakes?

Volcanoes generate seismic waves and cause the ground to shake through several processes. An explosive volcanic eruption causes compression, transmitting energy through seismic waves (shown here with yellow lines).

Volcanoes add tremendous weight to the crust. This loading can lead to faulting and earthquakes. The fault shown here, which caused an earthquake at depth, has dropped the volcano relative to its surroundings.

D What Are Some Other Causes of Seismic Waves?

Landslides

Catastrophic landslides, whether on land or beneath water, cause ground shaking. Lava flows forming new crust on the Big Island of Hawaii can become unstable and suddenly collapse into the ocean. Seismometers at the nearby Hawaii Volcanoes National Park often record seismic waves caused by such landslides.

Meteoroid Impacts

Ground shaking accompanies the impact of meteoroids on Earth’s surface. The 100 kilometer-wide Manicouagan ring lake in Canada is one of Earth’s largest meteoroid impact sites. The impact occurred about 200 million years ago, and would have resulted in an earthquake much larger than any recorded in history.

Explosions

Mine blasts and nuclear explosions compress Earth’s surface, producing seismic waves measurable by distant seismic instruments. Monitoring compliance with nuclear test-ban treaties is done in part using a worldwide array of seismic instruments. These instruments recorded a nuclear bomb exploded by India in 1998. Seismic waves generated by a blast are more abrupt than those caused by a natural earthquake.

Earthquakes Caused by Humans

Humans can cause earthquakes in several ways. Reservoirs built to store water fill rapidly and load the crust, which responds by flexing and faulting. After Lake Mead behind Hoover Dam in Nevada and Arizona was filled, hundreds of moderate earthquakes occurred under the reservoir between 1934 and 1944. Similarly, very shallow (less than 3 kilometers deep) earthquakes occur near Monticello Reservoir in South Carolina. In China, there were fears that the filling of the Three Gorges Dam, the world’s largest hydroelectric project, would trigger earthquakes in this seismically active area.

Humans have also caused earthquakes by injecting waste water underground into a deep well at the Rocky Mountain Arsenal northwest of Denver. This caused more than a thousand small earthquakes and two magnitude 5 earthquakes, which caused minor damage nearby. When the waste injection stopped and some waste was pumped back out of the ground, the number of earthquakes decreased.

Before You Leave This Page Be Able To

- Explain what a hypocenter and epicenter each represent.
- Sketch and describe the types of faults that cause earthquakes.
- Describe some other ways earthquakes or seismic waves are formed, including volcanoes and ways that humans cause earthquakes.
How Does Faulting Cause Earthquakes?

Most earthquakes occur because of movement along faults. Faults slip because the stresses applied to them exceed the ability of the rock to withstand the stress. Rocks respond to the stress in one of two ways—they either flex and bend, or they break. Breaking causes earthquakes.

What Processes Precede and Follow Faulting?

Before faulting, rocks change shape (i.e., they strain) slightly as they are squeezed, pulled, and sheared. Once stress builds up to a certain level, slippage along a fault generally happens in a sudden, discrete jump. Faulting reduces the stress on the rocks, allowing some of the strained rocks to return back to their original shapes. This type of response, where rocks return to their original shape after being strained, is called elastic behavior.

Pre-Slip

1. An active strike-slip fault has been offsetting a stream bed for hundreds of thousands of years, causing the stream to bend. The last earthquake occurred before people settled in the area. The straight section of the stream seemed a perfect place to put a bridge to provide a crossing for a road.

Stress Increase and Elastic Strain

3. Tectonic stress continues to act upon the rocks along the fault. The rocks strain and flex, as shown by a slight warp in the right side of the block, but the stresses are not great enough to make the rocks break. The cement bridge, however, develops a few cracks.

Slip and Earthquake

5. Finally the stress along the fault becomes so great that the fault slips and the rocks on opposite sides of the fault move past each other. A large earthquake occurs, generating seismic waves (not shown) radiating outward from the fault. Movement along the fault severs the bridge and offsets the road.

Post-Slip

7. After the earthquake, stress again begins to slowly build up along the fault. A new bridge is installed over the stream and the road is realigned. The abandoned part of the bridge, like the straight part of the stream, is a clue that something happened here.

2. The strike-slip fault is present at depth, but is not obvious at the surface because it is beneath the stream or covered with loose rocks, sand, and soil. The fault has some expression on the landscape, such as a very straight segment of the stream.

4. As stress builds in the rocks along the fault, the rocks deform elastically, changing shape slightly without breaking. If the rocks are strong enough and there is sufficient friction along the fault surface, the rocks and fault hold the added stress.

6. With the stress partially relieved, the rocks next to the fault relax by elastic processes, many returning to their original, unstrained shape. The movement that has occurred along the fault, however, is permanent. It is not elastic.

8. During this sequence, rock strains elastically before the earthquake, ruptures during the earthquake, and mostly returns to its original shape afterwards. This sequence is called stick-slip behavior because the fault sticks (does not move) and then slips.
**How Do Earthquake Ruptures Grow?**

Most earthquakes occur by slip on a preexisting fault, but the entire fault does not begin to slip at once. Instead, the earthquake rupture starts in a small area (the hypocenter) and expands over time.

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A rupture starts on a small patch below Earth's surface and begins to expand along the preexisting fault plane. Some rock breaks adjacent to the fault, but most slip occurs on the actual fault surface.

As the edge of the rupture migrates outward, it may eventually reach Earth's surface, causing a break called a fault scarp. Seen from above, the rupture migrates in both directions, but may expand more in one direction than in the other.

The rupture continues to grow along the fault plane and the fault scarp lengthens. The faulting releases some of the stress, and rupturing will stop when the remaining stress can no longer overcome friction along the fault surface.

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**Build Up and Release of Stress**

When a fault slips, it relieves some of the stress on the fault, causing the stress levels to suddenly drop. Gradually, the stress rebuilds until it exceeds the strength of the rock or the ability of friction to keep the fault from slipping. A conceptual model of how the amount of stress changes over time is shown below.

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On this plot, the magnitude of the stress imposed on the fault builds up gradually. When the amount of stress equals the strength of the fault, the fault slips, and the stress immediately decreases to the original level. In this manner, the amount of stress on a fault forms a zigzag pattern on the graph. It increases gradually (sloping line), and then decreases abruptly (vertical line) when an earthquake occurs. This process is called the earthquake cycle, and is one explanation for why some faults apparently produce earthquakes of a similar size. The time between repeating earthquakes is called the recurrence interval.

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**Before You Leave This Page Be Able To**

- Describe or sketch how the buildup of stress can flex rocks, leading to an earthquake.
- Describe or sketch how a rupture begins in a small area and grows over time and ruptures Earth's surface.
- Describe some characteristics of fault scarps and ruptures.
- Describe how stress changes through time along a fault according to the earthquake-cycle model.
Where Do Most Earthquakes Occur?

Most earthquakes occur along plate boundaries or in regions near plate boundaries, but some also strike in the middle of plates. Different tectonic settings generate different sizes and depths of earthquakes, with some types of plate boundaries being much more dangerous than others.

A Where Do Earthquakes Occur?

This map shows the world distribution of earthquake epicenters, colored according to depth. Yellow dots represent shallow earthquakes (0 to 70 km), green dots mark earthquakes with intermediate-depths (70 to 300 km), and red dots indicate earthquakes deeper than 300 km. Examine this map and note how earthquakes are distributed. Note how this distribution compares to other features, such as edges of continents, mid-ocean ridges, subduction zones, and continental collisions.

B How Are Earthquakes Related to Mid-Ocean Ridges?

In mid-ocean ridges, seafloor spreading forms new oceanic lithosphere, which is very hot and thin. Stress levels increase downward in Earth, but the rocks in the lithosphere get too hot to fracture (they flow instead). As a result, earthquakes along mid-ocean ridges are relatively small and shallow, with hypocenters less than about 20 kilometers (12 miles) deep.

Many earthquakes occur along the axis of a mid-ocean ridge, where spreading and slip along normal faults downdrop blocks along the narrow rift. Numerous small earthquakes occur due to intrusion of magma into dikes.

Deep- and intermediate-depth earthquakes occur only near subduction zones. There is a consistent pattern of shallow earthquakes close to the trench and progressively deeper earthquakes farther away. This pattern follows, and helps define, the position of the subducted slab, which is inclined from the shallow to the deep earthquakes.

As the newly created plate moves away from the ridge, it bends and cools. The stress caused by the bending forms steep faults, which are associated with relatively small earthquakes.

Strike-slip earthquakes occur along transform faults that link adjacent segments of the spreading center. The typically thin lithosphere keeps earthquakes along these oceanic transform faults small.
How Are Earthquakes Related to Subduction Zones?

A subduction zone, where an oceanic plate is underthrust beneath another plate, undergoes compression and shearing along the plate boundary. It can produce very large earthquakes.

1. As the oceanic plate moves toward the trench, it is bent and stressed, causing earthquakes in front of the trench.
2. Larger earthquakes occur in thrust faults formed in the accretionary prism as material is scraped off the downgoing plate.
3. Large earthquakes occur along the entire contact between the subducting plate and the overriding plate. The plate boundary is a huge thrust fault called a megathrust.
4. The downgoing oceanic plate continues to produce earthquakes from shearing along the boundary and from downward-pulling forces on the sinking slab. Subduction zones are typically the only place in the world producing deep earthquakes, as deep as 700 kilometers (430 miles). Below 700 kilometers, the plate is too hot to behave brittlely and fault.
5. Earthquakes can also be due to movement of magmas, volcanic eruptions, and thrust faulting behind the magmatic arc.
6. A deep trench marks a subduction zone on the west side of South America.
7. In a side view, subduction-related earthquakes, shown as dots, are shallower to the west (near the trench) and deeper to the east, recording the descent of the oceanic plate.

How Are Earthquakes Related to Continental Collisions?

During continental collisions, one continental plate is underthrust beneath another. Large thrust faults form in both the overriding and underthrust plates near the plate boundary, causing large but shallow earthquakes.

Large, deadly earthquakes are produced along the plate boundary, or megathrust.

Thrust faults also form within both continental plates, causing moderately large earthquakes. The immense stresses associated with a collision can reactivate older faults within the interior of either continent. Strike-slip and normal faults may be generated as entire regions are stressed by the collision zone.

Any oceanic plate material that was subducted prior to the collision is detached, so subduction stops and deep earthquakes cease.

How Are Earthquakes Generated Within Continents?

1. A transform fault, like the San Andreas fault, can cut through a continent, moving one piece of crust past another. The strike-slip motion causes earthquakes that are mostly shallower than 20–30 kilometers (10–20 miles), but that can be quite large.
2. Continental rifts generally cause normal-fault earthquakes, whether the rift is a plate boundary or is within a continental plate. Such earthquakes are typically moderate in size.
3. Intrusion of magma (shown here in red) within a plate can cause small earthquakes as the magma moves and creates openings in the rock.
4. Preexisting faults in the crust can readjust and move as the continental plate ages and is subjected to new stresses. These structures can produce large earthquakes, such as those in Missouri in 1811.

Before You Leave This Page
Be Able To

- Explain why subduction zones have earthquakes at various depths, whereas mid-ocean ridges have only shallow earthquakes.
- Summarize how subduction and continental collisions cause earthquakes, identifying differences between these two settings.
- Describe how an earthquake can occur within a continental plate.
How Do Earthquake Waves Travel Through Earth?

Earthquakes generate vibrations that travel through rocks as physically distinguishable waves, called seismic waves. Geophysicists digitally record and process seismic waves in order to understand where and how the earthquake occurred. The word seismic comes from the Greek word for earthquake.

What Kinds of Seismic Waves Do Earthquakes Generate?

Earthquakes generate different types of seismic waves. Those that travel inside Earth are called body waves and those that travel on the surface of Earth are surface waves. Scientists who study earthquakes are seismologists.

1. To describe seismic waves, we begin by defining waves in general. Most waves are a series of repeating crests and troughs.

2. Waves, whether moving through the ocean or through rocks, can travel, or propagate, for long distances. However, the material within the wave barely moves. Sound waves travel through the air and thin apartment walls, but the wall does not move much. Think of a wave as a pulse of energy moving through a nearly stationary material.

3. An earthquake, as depicted by the red dot in the tan and gray block below, generates seismic waves. Most earthquakes occur at depth, so they first produce waves that travel through the Earth as body waves.

4. When body waves reach Earth's surface, some energy is transformed into new waves that only travel on the surface (surface waves). It is easier to visualize processes on the surface of Earth than within it, so we begin by discussing surface waves, of which there are two kinds.

Primary Body Wave

7. Body waves travel through Earth, and come in two main varieties. The primary or P-wave compresses the rock in the same direction it propagates. It is like a sound wave, which compresses the air through which it travels.

8. P-waves can travel through solids and liquids because these materials can be compressed and then released. The P-wave is the fastest seismic wave, and it travels through rocks at 6 to 14 kilometers/second depending on the properties of the rock.

Secondary Body Wave

9. The secondary, or S-wave, shears the rock side to side or up and down. This movement is perpendicular to the direction of travel. The wave shown below propagates to the right, but the material shifts up and down. It could also shift side to side, but the motion would still be perpendicular to the propagation direction of the wave.

10. S-waves cannot travel through liquids because liquids are not rigid (they cannot be sheared). If an area of the Earth's interior does not allow S-waves to pass, then it may be molten. S-waves are also slower than P-waves, travelling through rocks at about 3.6 kilometers/second.
How Are Seismic Waves Recorded?

Sensitive digital instruments called seismometers are able to precisely detect a wide range of earthquakes. The recorded seismic data are uploaded to computers that process signals from hundreds of instruments registering the same earthquake. These computers calculate the hypocenter and magnitude, and produce digital maps showing the magnitude of ground shaking.

1. A seismometer detects and records the ground motion during earthquakes.
2. A large mass is suspended from a wire. It resists motion during earthquakes.
3. The mass hangs from a frame that in turn is attached to the ground. When the ground shakes, the frame shakes too, but the suspended mass resists moving because of inertia. As the ground and frame move under the mass, a pen attached to the mass marks a roll of recording paper that slowly rotates. As a result, the pen draws a line that records the ground movement over time.
4. This device only records ground movement parallel to the red arrows, so it only records a single direction or component of motion.
5. Modern seismic detectors contain 3 seismometers oriented 90° from each other to record three components of motion (N-S, E-W, and up-down). From these three components, seismologists can better determine the direction and magnitude of the seismic signal.
6. Seismologists place seismometers away from human noise and bury them to reduce wind noise. Waves (in yellow) can come from any direction.

How Are Seismic Records Viewed?

1. Until the early 1990s, seismic waveforms were mostly represented as curves on a paper seismogram, which is a graphic plot of the waves. Seismologists developed this plot to better visualize the ground shaking caused by earthquakes. Today, most seismic data are displayed on computer screens, rather than on paper.

Amplitude and Period

Seismic waves are characterized by how much the ground moves (wave amplitude) and the time it takes for a complete wave to pass by (period). Period is related to the wavelength and velocity of the wave. Both amplitude and wavelength can be measured from a seismogram. Amplitude is critical when estimating the magnitude and damage potential of an earthquake. The period can also be a critical component in assessing potential damage, because buildings vibrate when shaken by earthquakes. Every building has a natural period that can match, or resonate with, the earthquake wave. Resonance can cause intensified shaking and increased damage.

Before You Leave This Page
Be Able To

- Describe or sketch the characteristics of P-waves, S-waves, and surface waves, including the way motion occurs compared to the propagation of the wave.
- Sketch or describe how seismic waves are recorded, and the order in which they arrive at a seismometer.
How Do We Determine the Location and Size of an Earthquake?

Earthquakes occur daily around the world, and a network of seismic instruments records these events. Using the combined seismic data from several instruments, seismologists calculate where an earthquake started and how large it was. The principal measurement of size is called magnitude.

A How Do We Locate Earthquakes?

Seismologists maintain thousands of seismic stations that actively sense and record ground motions. When an earthquake occurs, parts of this network can detect it. Large earthquakes generate seismic waves that can be detected around the world. Smaller earthquakes are detected only locally.

1. Seismometer Network Senses a Quake

Seismometers in the U.S. National Seismic Network (shown below) represent a fraction of all seismometers.

On October 1, 2005, a moderate earthquake was felt in Colorado. Three stations (DUG, WUAZ, and ISCO) recorded wave arrivals and are chosen to locate the epicenter. Each station is given an abbreviation that reflects its location.

2. Select Earthquake Records

Records from at least three stations are normally compared when calculating an earthquake location.

P-waves travel faster than, and arrive before, S-waves, and the time interval between arrival of the P-wave and S-wave is called the P-S interval. The farther a station is from the earthquake, the longer the P-S interval will be. Picking the arrival of the P-wave and S-wave on these graphs is not always easy, but can be done by seismologists or by computer.

The three seismograms show differences in the P-S interval. Based on the P-S intervals, ISCO is the closest station, followed by DUG and WUAZ.

3. Estimate Station Distance from Epicenter

The P-S interval is mathematically related to the distance from the epicenter to the seismic station, factoring in the type of materials through which the waves pass. This relationship is shown on a graph as a time-travel curve.

P-S intervals are measured from the seismograms shown in part 2 and then plotted on the graph. This gives the distance for each station.

The distance from each station to the epicenter is now known, but not the direction.

4. Triangulate the Epicenter

The distance from each station to the earthquake can be compared graphically to find the epicenter.

A circle is drawn around each station, with a radius equal to the distance calculated from the P-S interval.

The intersection of the three (or more) circles is the epicenter of the earthquake.

We calculate the depth of the earthquake's hypocenter in a similar way, using the interval between the P-wave and another compressional wave that forms when the P-wave reflects off Earth's surface near the epicenter. Again, we use multiple stations.
B How Do We Measure the Size of an Earthquake?

The magnitude of an earthquake is a measure of the released energy and is used to compare the sizes of earthquakes. There are several ways to calculate magnitude, depending on the earthquake's depth. The most commonly used scale, called the "Richter" or "Local" magnitude (ML), is illustrated here.

Measuring Amplitude

The maximum height (amplitude) of the S-wave is measured on the seismogram. It is proportional to the earthquake energy. This measure is used for shallow earthquakes.

Seismographs are calibrated so that the measurements made by two different instruments are comparable.

C What Can the Intensity of Ground Shaking Tell Us About an Earthquake?

Some of the most damaging earthquakes occurred before seismometers were in place. Reports of damage and shaking intensity are another way to classify earthquakes.

The Modified Mercalli Intensity Scale, abbreviated as MMI, describes the effects of shaking in everyday terms. A value of "I" reflects a barely felt earthquake. A value of "XII" indicates complete destruction of buildings, with visible surface waves throwing objects into the air!

A series of very large earthquakes in 1811 and 1812 shook Missouri, Arkansas, and the surrounding areas. Shaking was felt over a wide region. The magnitudes on this map, numbered from III to XI, indicate what you would feel and see if the earthquake happened today.

III. Felt strongly by persons indoors, especially on upper floors of buildings.

IV. Felt by nearly everyone; many awakened. Some dishes and windows broken. Unstable objects overturned.

V. Felt by all. Many frightened. Some heavy furniture moved. Some plaster cracks and falls. Damage slight.

VI. Felt by all, many frightened. Some heavy furniture moved. Some plaster cracks and falls. Damage slight.

X and XI. Some well-built wooden structures destroyed. Most masonry and frame structures destroyed, along with foundations. Bridges destroyed. Rails bent. Damage extensive.

Energy of Earthquakes

Richter or local magnitude measures the amount of ground motion, but the scale is logarithmic so the ground motion increases by a factor of 10 from a magnitude 4 to a 5, from a 5 to a 6, and so on. The amount of energy released increases more than 30 times for each increase in magnitude, so a magnitude 8 releases more than 30 times more energy than a magnitude 7.

Another common measure of earthquake energy is moment magnitude or \( M_w \), which is calculated from the amount of slip (displacement) on the fault and the size of fault area that slipped. Moment magnitude is useful for both large and small earthquakes. How do earthquakes compare to other energy releases with which we are familiar? An average lightning strike (\( M_w \approx -2 \)) is miniscule compared to a small earthquake. However, an average hurricane is larger than the energy released by the largest historic earthquake (Chile, 1960).
How Do Earthquakes Cause Damage?

MANY GEOLOGISTS SAY that "earthquakes don't kill people, buildings do." This is because most deaths from earthquakes are caused by the collapse of buildings or other human structures. Destruction can occur during the earthquake or later from fires, floods, and large ocean waves caused by the earthquake.

A What Destruction Can Arise from Shaking Due to Seismic Waves?

Direct damage from an earthquake results from ground shaking during the passage of seismic waves, especially surface waves near the epicenter of the earthquake. Damage can also be due to secondary effects, such as fires and flooding, that are triggered by the earthquake. The area below received mostly direct damage.

1. Mountainous regions that undergo ground shaking may experience landslides, rock falls, and other earth movements.

2. The ground can rupture along parts of the fault that slip during an earthquake or from shaking of unconsolidated materials. The cracks can destroy buildings and roads.

3. Damage to structures from shaking depends on the type of construction. Concrete and masonry structures are rigid and do not flex easily. Thus, they are more susceptible to damage than wood or steel structures, which are more flexible. In this area, a flexible, metal bridge in the center of the city survived the earthquake.

4. A concrete bridge farther downstream was too rigid and collapsed. Furthermore, it was built upon delta sediments that did not provide a firm foundation against shaking. In general, loose, unconsolidated sediment is subject to more intense shaking than solid bedrock.

5. A tsunami is a giant wave that can rapidly travel across the ocean. An earthquake that occurs undersea or along coastal areas can generate a tsunami, which can cause damage along shorelines thousands of kilometers away.

6. Aftershocks are smaller earthquakes that occur after the main earthquake, but in the same area. Aftershocks occur because the main earthquake changes the stress around the epicenter, and the crust adjusts to this change with more faulting. Aftershocks are very dangerous because they can collapse structures already damaged by the main shock. Aftershocks after a tsunami can cause widespread panic.

8. Historically, most deaths from earthquakes are due to collapse of poorly constructed houses and buildings, such as those with mud, loosely connected blocks, and earthen walls. Even modern reinforced concrete can fail (v). [Oakland, California, 1989]
What Destruction Can Happen Following an Earthquake?

Some earthquake damage occurs from secondary effects that are triggered by the earthquake. Fire is one of the main causes of destruction after an earthquake. Natural gas lines may rupture, causing explosions and fires. The problem is compounded if water lines also break during the earthquake, limiting the amount of water available to extinguish fires. (Northridge, California)

Earthquakes may cause both uplift and subsidence of the land surface by more than 10 meters (30 feet). Subsidence, such as occurred during the 2004 Sumatra earthquake, can cause areas that had been dry land before the earthquake to become inundated by seawater. (Sumatra)

Flooding may occur due to failure of dams as a result of ground rupturing, subsidence, or liquefaction. Near Los Angeles in 1971, 80,000 people were evacuated because of damage to nearby dams during the 1971 San Fernando earthquake (Mw 6.7).

How Can We Limit Risks from Earthquakes?

The probability that you will be affected by an earthquake depends on where you live and whether or not that area experiences tectonic activity. The risk of earthquake damage depends on the number of people living in the region, how well the buildings are constructed, and individual and civic preparedness.

1. Earthquake hazard maps show zones of potential earthquake damage. Near Salt Lake City, Utah, the risk is greatest (red) near active normal faults along the Wasatch Front, the mountain front east of the city.

2. Some utilities and hospitals have computerized warning systems that are notified of impending earthquakes by seismic equipment. The system will automatically shut down gas systems (to avoid fire) and turn on back-up generators to prevent loss of electrical power.

What to Do and Not Do During an Earthquake

There are actions you can take during an earthquake to reduce your chances of being hurt. If an earthquake strikes, you can seek cover under a heavy desk or table, and protect your head. You can also stand under door frames or next to inner walls, as these are the least likely to collapse. If possible, stand clear of buildings, especially those made of bricks and masonry.

During the shaking, stay away from glass and heavy objects that could fall, such as bricks or other loose debris. Always keep a battery-operated flashlight handy. Avoid using candles, matches, or lighters, since there may be gas leaks. Earthquakes may interrupt electrical and water service. Keeping 72 hours worth of food and water in an easily-carried backpack is a prudent plan for any natural disaster.
What Were Some Major North American Earthquakes?

LARGE AND DAMAGING EARTHQUAKES have struck North America since written and oral records have been kept. We discuss seven important earthquakes here.

This map of the conterminous United States has yellow dots showing earthquakes that occurred in the last 15 years and that were larger than magnitude 4. The red lines on the map are faults that are interpreted to have slipped during the last 2 million years. Compare the distribution of earthquakes and recently active faults. Most active faults are in the western states, and most large earthquakes are in these same areas. Earthquakes have occurred elsewhere in the country, but most of these were too small to break the surface and form a fault scarp.

Alaska, 1964

A magnitude (Mw) 9.2 earthquake, one of the two or three largest earthquakes ever recorded, struck southern Alaska in 1964. It killed 125 people and triggered landslides, and collapsed neighborhoods and the downtown of a nearby city. This event was caused by thrusting along the subduction zone. Most deaths and much damage were from a tsunami generated when a huge area of the sea floor was uplifted. This earthquake is not shown on the map.

San Francisco, 1906

A huge earthquake occurred when 470 kilometers (290 miles) of the San Andreas fault ruptured near San Francisco. The earthquake was likely a magnitude (Mw) ~8. It ruptured the surface, leaving behind a series of cracks and open fissures. Within San Francisco, ground shaking destroyed most of the brick and mortar buildings. More than 300 people were killed and much of the city was devastated by fires that broke out after the earthquake.

Northridge, Los Angeles Area, 1994

This magnitude (Mw) 6.7 earthquake was generated by a thrust fault northwest of Los Angeles. The earthquake killed 57 people and caused $20 billion in damage. A section of freeway buckled, crushing the steel-reinforced concrete slabs. The thrust is not exposed on the surface, but when it ruptured it lifted up a large section of land. Geologists are concerned about a similar fault causing a similar earthquake right below downtown Los Angeles.

Mexico City, 1985

A magnitude (Mw) 8.0 earthquake occurred on a subduction zone along the southwestern coast of Mexico, well west of Mexico City (not shown on this map). It damaged or destroyed many buildings in Mexico City and killed at least 9,500 people. Destruction was so extensive partly because Mexico City is built on lake sediments deposited in a bowl-shaped basin, which amplified the seismic waves. This geologic setting caused intensified and highly destructive ground shaking. Surface waves, which caused the most damage, traveled 200 kilometers (120 miles) from their source!
Hebgen Lake, Yellowstone Area, 1959

This magnitude (MI) 7.5 event was generated by slip along a normal fault northwest of Yellowstone National Park. Ground shaking set loose the massive Madison Canyon slide, which buried 26 campers and formed a new lake, aptly named Earthquake Lake.

New Madrid, 1811–1812

New Madrid, Missouri experienced a series of large (MI ~8) earthquakes generated over an ancient fault zone in the crust. The 1811–1812 earthquake death toll was probably low because of the sparse population at the time. The New Madrid zone has a high earthquake risk and, as shown on this earthquake-hazard map, is one of two areas in the eastern United States that are predicted to experience strong earthquakes in the future. Memphis lies in this zone, yet most of its buildings are not constructed to survive large earthquakes.

Charleston, 1886

This earthquake occurred at the other high-risk area along the East Coast, near Charleston, South Carolina. It had an estimated magnitude of MI 7.3, the largest ever recorded in the Southeast. Buildings incurred some damage (>), and 125 people died. The tectonic cause for this earthquake is still debated among geologists.

Earthquakes in the Interiors of Continents

Why do large earthquakes occur in the middle of continents, such as New Madrid, Missouri? Although the interior of North America is not near a plate boundary, the region is subjected to stress generated along far-off plate boundaries. Such stress includes compression from the Mid-Atlantic Ridge, called ridge push. These stresses can reactivate ancient faults that lie buried beneath the cover of sediment. In the case of New Madrid, there is seismic and other geophysical evidence to suggest that the area is underlain by an ancient rift basin that formed about 750 million years ago during the breakup of the supercontinent of Rodinia. Modern-day stress related to the current plate configuration is interacting with the ancient faults, occasionally causing them to slip and trigger earthquakes.

Before You Leave This Page
Be Able To

- Describe some large North American earthquakes and how they were generated.
- Summarize the various ways these earthquakes caused damage.
- Describe why the eastern United States has earthquake risks.
What Were Some Major World Earthquakes?

THE WORLD HAS ENDURED a number of large and tragic earthquakes. These earthquakes have struck a collection of geographically and culturally diverse places, causing many deaths and extensive damage. Most large earthquakes occur along or near plate boundaries, especially along subduction zones.

Nicaragua, 1972
On December 23, 1972, a magnitude (Mw) 6.2 earthquake killed about 6,000 people in central America. In the capital city of Managua, wood and adobe structures were leveled and fractures opened in the street (<i>). The earthquake was caused by strike-slip along a boundary of the Caribbean plate.

Chile, 1960
This huge, magnitude (Mw) 9.5 earthquake occurred offshore along a megathrust and triggered a destructive, Pacific-wide tsunami. At least 3,000 people died and $550 million of damage was done to infrastructure and buildings, such as in this city in Chile. ▼

Lisbon, 1755
On November 1 (All Saints Day) in 1755, a large earthquake, estimated at magnitude (Mw) 8.5, shook Lisbon, Portugal. The earthquake demolished the city and triggered tsunamis, which sank ships in Lisbon's famous harbor. Photography was not yet invented, but the destruction was portrayed by artists (<i>). The event caused an upheaval in religious and scientific thought, as people began to think that such catastrophes must be due to natural causes, since this one struck on such a holy day.

Turkey, 1999
In 1999, a large quake (Mw 7.4) generated along a transform fault zone killed more than 17,000 people and severely impacted the economy. The earthquake destroyed many buildings, including these multi-story apartment complexes. ▼
Before You Leave This Page
Be Able To

- Briefly describe some of the world’s most significant earthquakes and the tectonic settings in which these deadly earthquakes occurred.
- Summarize some ways that these earthquakes caused deaths.

Deadly Earthquakes

Mortality due to earthquakes averages about 10,000 per year. Most earthquake-related deaths are due to collapse of poorly built structures in cities and villages. Earthquake-generated tsunamis also account for a large part of the yearly average. The table to the right shows some deadly earthquake events. The highest death tolls are due to a deadly combination of high population densities, substandard construction practices, and being situated along subduction zones or other high-risk areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Mw</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shandong, China</td>
<td>1556</td>
<td>8</td>
<td>813,000</td>
</tr>
<tr>
<td>Naples, Italy</td>
<td>1857</td>
<td>6.9</td>
<td>11,000</td>
</tr>
<tr>
<td>Messina, Italy</td>
<td>1908</td>
<td>7</td>
<td>70,000</td>
</tr>
<tr>
<td>Ninixia, China</td>
<td>1920</td>
<td>8.6</td>
<td>200,000</td>
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<tr>
<td>Kanto, Japan</td>
<td>1923</td>
<td>7.9</td>
<td>143,000</td>
</tr>
<tr>
<td>Tsinghai, China</td>
<td>1927</td>
<td>7.9</td>
<td>200,000</td>
</tr>
<tr>
<td>Erzincan, Turkey</td>
<td>1939</td>
<td>7.9</td>
<td>32,700</td>
</tr>
<tr>
<td>Colombia</td>
<td>1970</td>
<td>7.9</td>
<td>66,000</td>
</tr>
<tr>
<td>Guatemala</td>
<td>1976</td>
<td>7.5</td>
<td>23,000</td>
</tr>
<tr>
<td>Tangshan, China</td>
<td>1976</td>
<td>7.8</td>
<td>242,000</td>
</tr>
<tr>
<td>Burn, Iran</td>
<td>2003</td>
<td>6.6</td>
<td>31,000</td>
</tr>
</tbody>
</table>
How Does a Tsunami Form and Cause Destruction?

AN EARTHQUAKE BENEATH THE OCEAN can cause a large wave called a tsunami, which can wreak havoc on coastal communities. Most of Earth is covered by oceans, so many earthquakes, landslides, and volcanic eruptions occur beneath the sea. Each of these can generate a tsunami.

How Are Tsunamis Generated?

Tsunamis are waves that affect an entire body of water from top to bottom. They are generated by abrupt changes in water level in one area relative to another. This occurs when a mass is dropped into the water, such as a landslide, or when the ocean floor is unevenly uplifted or downdropped by an earthquake.

1. A tsunami forms when a sudden change in sea level accompanies fault movement. The most common way this occurs is when a fault beneath the sea uplifts or downdrops an area of the seafloor.

2. A tsunami is a wave, or series of waves, that radiates away from the disturbance. It travels at speeds between 600-800 kilometers per hour (370-500 miles per hour) away from the source. In deep water, the wave energy is distributed over the entire water depth, forming a wave only a meter or so high but more than 700 kilometers across. It is so low relative to its width that it may be barely noticeable; it is much smaller in height out at sea than can be shown here.

3. As the wave approaches the shore, its energy is distributed over a smaller depth. The velocity of the front of the wave decreases to 30-40 km/hour, causing following water to pile up in a higher wave. Near shore, the tsunami becomes a massive, thick wave, like the front wall of a plateau of water. It may be a series of such waves.

Tsunamis Triggered by Landslides

A large mass of rock entering the water can catastrophically displace the water, generating a tsunami that radiates outward.

This has occurred off the west side of Hawaii, where huge landslide-debris deposits (shown in green) sit on the ocean floor. The tsunami generated by one of these slides moved debris 6 kilometers (3.7 miles) inland. The volume of water displaced during these events probably produced a tsunami that struck coastlines around the Pacific about 120,000 years ago.

Tsunamis Caused by Eruptions

The 1883 eruption of Krakatau in Indonesia, and the collapse of its immense caldera, generated a series of huge tsunamis that killed 36,000 people. A single catastrophic volcanic explosion produced the loudest sound ever heard, and most of Krakatau Island was demolished. The tsunami was as high as 40 meters (more than 130 feet), and some effects of the tsunami were recorded 7,000 kilometers away.
What Kind of Destruction Can a Tsunami Cause?

Tsunamis cause death and destruction along coastlines where human populations are concentrated. On May 22, 1960, the largest earthquake ever recorded on a seismograph (Mw 9.5) occurred in the subduction zone (megathrust) offshore of southern Chile. The tsunamis that followed flattened coastal settlements in Chile, and traveled across the Pacific to devastate coastlines in Hawaii and Japan.

Chile, May 22, 1960

During this earthquake, tsunamis were generated parallel to the coast. One headed in toward the shoreline, quickly striking Chile and Peru. Another set of tsunamis swept out across the Pacific Ocean at 670 kilometers (420 miles) per hour! Each stripe equals two hours of travel time.

Hawaii, May 23, 1960

In 1960, a magnitude 7.8 earthquake occurred off the coast of Hokkaido and within five minutes a tsunami struck the coastline. The tsunami killed at least 100 people and caused $60 million in property loss. It swept these boats inland across a concrete barrier built along the shoreline.

Papua New Guinea, 1998

In 1998, a magnitude 7.1 earthquake and associated underwater landslides generated three tsunami waves that destroyed villages along the country's north coast, killing 2,200 people. A 10-meter-high wave destroyed a row of heavily populated houses along the coast shown here.

Tsunami Warning System

In an international effort to save lives, the United States National Oceanic and Atmospheric Administration (NOAA) maintains two tsunami warning centers for the Pacific Ocean. Twenty-six nations participate in this effort. Informed by worldwide seismic networks, these centers broadcast warnings based on an earthquake's potential for generating a tsunami. Since the huge loss of life after the Sumatran earthquake and accompanying tsunami in 2004, the United Nations has begun implementing a warning system in the Indian Ocean. Scientists are deploying warning buoys, like the one shown below, which can relay tsunami data by satellite. These buoys detect small changes in sea level as a tsunami passes underneath.

Before You Leave This Page

Be Able To

- Describe the different mechanisms by which tsunamis are generated.
- Summarize the kinds of damage tsunamis have caused.
- Briefly describe how tsunamis are monitored to provide an early-warning system.
How Do We Study Earthquakes in the Field?

GEOLOGISTS USE A VARIETY of tools and techniques to study evidence left behind by recent and ancient earthquakes. They examine and measure faults in natural exposures and in trenches dug across faults. Satellites and other tools allow faults to be studied in new and exciting ways.

A How Do We Study Recent Earthquakes in the Field?

Where a fault is visible at Earth's surface, it can be scrutinized in order to understand how it moves during an earthquake. Geologists investigate numerous features, some of which are shown below.

1. Faulting during an earthquake commonly is accompanied by smaller structures such as cracks and smaller faults. The geometry of these and other features can indicate the direction of fault movement.

2. When a fault moves, it can offset natural and human-made features. Streams and gullies, as well as roads, fences, and telephone lines, provide pre-earthquake reference points. Geologists can measure how much and in what direction the fault has offset these features.

3. When a fault ruptures the surface, geologists carefully measure its location, dimensions, and orientation. Detailed drawings and photographs are essential for documenting features along the fault.

4. Faulting is commonly accompanied by changes in the topography of the land surface. Faulting can uplift linear ridges or form new hills. It can create ponds and other low areas by downdropping areas along the fault.

5. Rocks and soils, both in natural exposures and in trenches dug to study a fault, preserve a history of motion. They give clues to the magnitudes and recurrence of past earthquakes.

B How Do We Study Faults with Satellites and Geology-Based Models?

Ground Displacement

Damage from earthquakes can be compared to underlying geology. This helps geologists understand the patterns of damage and help plan for future earthquakes. This geologic map of San Francisco shows weak sediments as gray and light yellow.

Geologic Control of Damage

The map below shows a geology-based model estimating the acceleration of the ground during the 1906 San Francisco earthquake. Dark reds indicate the most intense ground movement. Notice that many areas underlain by weak sediments experienced high accelerations.
How Do We Study Faults Associated with Prehistoric Earthquakes?

Features on the Surface and in the Subsurface

Shallow trenches dug across the fault expose what is just below the surface. Most trenches are several meters deep, allowing geologists to examine the fault zone for clues about its earthquake history. In the trench above, a recent rupture of the San Andreas fault offsets layers of carbon-rich peat, which were used to date the layers and therefore date the history of earthquakes.

Geologists also evaluate the amount of movement on a fault by looking for distinctive rock units that have been cut and displaced by the fault.

Earthquake Studies Along the North Anatolian Fault, Turkey

1. In 1999, a magnitude (Mw) 7.4 earthquake ruptured over 100 kilometers (60 miles) of the North Anatolian fault in Turkey. Soon after the earthquake, geologists conducted field studies to determine how much and how often the fault moved in the past. They used surveying equipment to precisely measure the heights of the fault scarps (>) to determine how much the fault moved. During this earthquake, one side of the fault moved up by 1.6 meters (5 feet), but much movement was horizontal.

2. Several trenches dug along the fault revealed a wealth of information about its prior history. The geologists meticulously examined the walls of the trenches and carefully mapped how the fault offset layers of sediment and soil. They documented that older layers were offset by several distinct earthquake events. The colors on this figure indicate different ages of sediment.>

3. Samples of charcoal were dated by the Carbon-14 method (in years AD), providing a timeline for interpreting when the fault moved.

4. From these studies, the geologists determined that a major earthquake occurs along this fault about every 200–300 years, and that previous events were about the same size as the 1999 event. Such earthquakes are characteristic of this fault.

San Andreas Experiment

Geologists in California are engaged in a novel experiment. The San Andreas Fault Observatory at Depth sunk a deep drill hole through part of the San Andreas fault. The drill hole is equipped with a wide array of geophysical instruments that are providing data on this active fault system. The scientists hope to catch an earthquake as it happens. In this figure, a drill hole crosses the fault at 3.2 kilometers (2 miles) depth.

Before You Leave This Page

Be Able To

- Summarize the kinds of field and remote measurements geologists use to investigate recent earthquakes.
- Summarize the methods of investigating prehistoric earthquakes on faults, including observations within trenches dug across a fault.
Can Earthquakes Be Predicted?

EARTHQUAKES CAN BE DEVASTATING to places and people. For this reason, we have a great interest in finding ways to predict when and where earthquakes will occur. Although much is known about where earthquakes occur, there is no reliable way to predict exactly when one will strike.

A Can We Anticipate Which Areas Are Most Likely to Have Earthquakes?

We try to predict which areas will have earthquakes by understanding the (1) frequencies and sizes of historic earthquakes, (2) geologic record of prehistoric earthquakes, and (3) tectonic settings of different regions.

World Earthquake Hazard

This seismic-hazard map shows the intensity of shaking expected on land. Red areas have the highest hazard, gray areas have the lowest hazard, and yellow areas are considered to have a moderate seismic hazard.

Australia experiences few earthquakes, mostly because it is not along a plate boundary. Islands to the north (New Guinea) and southeast (New Zealand) straddle active plate boundaries and have higher hazards.

The Middle East is highly susceptible to earthquakes, largely because collision of the Arabian plate is causing thrust faults and strike-slip faults across the region.

For the United States, the risk for earthquakes is greatest in the most tectonically active areas, especially near the plate margin in the western United States. The San Andreas fault forms the boundary between the Pacific plate and the North American plate. It is responsible for about one magnitude 8 or greater earthquake per century.

Historically, large earthquakes have occurred in New Madrid, Missouri, marked by the red area along the Mississippi River. Earthquakes have also struck in Charleston, South Carolina, and along the St. Lawrence River near New York, so these areas have at least a moderate hazard.

United States Earthquake Hazard

This map shows the most seismically active areas of the United States, including Hawaii and Alaska. Which regions experience little damage from earthquakes, and which regions experience the most damage? Do some areas surprise you?
How Do We Approach Long-Range Earthquake Forecasting?

Long-term forecasting is based mainly on the knowledge of when and where earthquakes occurred in the past. Thus, geologists study present tectonic settings, geologic evidence of events, and historical records. These studies aim to determine the locations and recurrence of past earthquakes.

1. One approach to long-range forecasting is to measure patterns of seismic activity along a fault. These two cross sections show seismicity along the San Andreas fault in northern California. The top shows earthquakes that occurred along the fault prior to October 17, 1989; the second shows seismicity after the Loma Prieta earthquake on October 17, 1989.

2. In the top section, three segments of the fault have fewer earthquakes than other sections. These segments, called seismic gaps, are "locked" (not moving), and are accumulating stress. The three seismic gaps were at San Francisco, Loma Prieta, and Parkfield.

3. In 1989, a magnitude 7 earthquake struck the Loma Prieta gap. This earthquake and its aftershocks, shown in the lower section, filled in the gap. The Parkfield gap was filled by an earthquake in 2004. When will an earthquake fill the San Francisco gap?

How Successful Are Short-Term Predictions?

Short-term prediction involves monitoring the activity along an earthquake-prone fault. There are often precursor events, which can be gauged using sophisticated scientific equipment. The complexity inherent in fault systems means that prediction techniques are still developing, but they hold promise.

1. Seismologists shine lasers across a fault to monitor small-scale movements that might be precursors to a larger earthquake. They can even record movement during a larger earthquake.

2. Measurements taken near active faults sometimes show that prior to an earthquake, the ground is uplifted or tilted as rocks swell under the strain building on the fault. The buildup in stress may also cause numerous small cracks. These can slip and produce foreshocks, small earthquakes that may advertise an upcoming main earthquake.

3. Prior to 2004, the Parkfield segment of the San Andreas Fault, southeast of San Francisco, had six magnitude (Mw) ~6 quakes since 1857. These occurred approximately every 22 years and had similar characteristics. This situation provided an opportunity to study the short-term precursors of the next earthquake. Seismologists set up a detailed array of seismic instruments to record the region's many earthquakes, shown here as red, black, and yellow symbols.

4. From various data, the USGS assigned probabilities of a magnitude 6.7 earthquake on faults of the area before 2032. The combined probability is over 60%.

5. The next big earthquake was predicted to occur between 1988 and 1993. The earthquake finally happened in 2004, 11 years later than expected.
What Is the Potential for Earthquakes Along the San Andreas Fault?

THE SAN ANDREAS FAULT is the world's best-known and most extensively studied fault. It runs across California from the Mexican border to north of San Francisco, and inflicts the region with destructive earthquakes. What has happened along the fault in the recent past, and what does this history say about the fault's current behavior and its likelihood of causing large earthquakes in the future?

Recent Earthquake History of Different Segments of the San Andreas Fault and Related Faults

1. The San Andreas fault has distinct segments that behave differently, as expressed by the size and inferred frequency of earthquakes along each segment. As a result, the earthquake hazard varies along the fault. This map shows some of the major faults that have caused earthquakes in California. These faults account for the largest quakes, but there are many recently active faults (shown in black). Some of these have caused damaging, moderate-sized earthquakes.

2. The northern San Andreas fault was responsible for the famous 1906 earthquake that destroyed much of San Francisco. The earthquake had a magnitude of 7.7 and ruptured 430 kilometers (270 miles) of the fault, from south of the city all the way to the north end of the fault (the part that ruptured is shown in red). Damage (<3) was caused by ground shaking, fires, and liquefaction of water-saturated soils in areas that had originally been part of San Francisco Bay.

3. The southern part of this segment ruptured in 1989 in the magnitude 7.1 Loma Prieta earthquake, which was centered south of San Francisco. This earthquake is famous for disrupting a World Series baseball game. Ground shaking and liquefaction collapsed buildings (<5) and parts of bridges and freeways.

4. The next segment to the south, shown in blue, is the central creeping segment. The two sides of the fault creep past one another somewhat continuously and slowly, rather than storing up energy for a large earthquake. Creep continues to the north along the Hayward fault, also colored blue, through Oakland. The Hayward fault was the site of a ruinous magnitude 7 earthquake in 1868.

5. South of the creeping segment is the Parkfield segment, a short segment included here as part of a larger orange-colored segment discussed below. It produces moderate-sized earthquakes that occur, on the average, every couple of decades. The Parkfield segment receives special scrutiny from geologists and seismologists because the frequent earthquakes provide an opportunity to study the behavior of a fault before, during, and after an earthquake.

6. The San Andreas continues to the southeast through a segment (shown in orange) that last ruptured during the great Fort Tejon earthquake of 1857. This earthquake ruptured 300 kilometers (190 miles) of the fault, from Parkfield all the way to east of Los Angeles. The earthquake was approximately magnitude 8, but damage was limited because the area was much less populated than it is now. This earthquake is considered by many geologists to be the model for the "big one" along the San Andreas. This part of the San Andreas commonly is called the locked segment because it has not ruptured since 1857.
Features Along the San Andreas Fault

The San Andreas fault generally has a clear expression in the landscape. It is marked by a number of features that are common along active faults. Some of these features also can form in ways unrelated to active faulting.

7. North and east of the San Andreas is a series of faults, called the East California Shear Zone. This zone caused several >7 magnitude earthquakes in the 1900s and the large 1872 Owen Valley earthquake on the eastern side of the Sierra Nevada. The zone continues from the eastern side of the Sierra Nevada southward through the Mojave Desert, where it unleashed the 1992 Landers earthquake (Mw 7.3) and the 1999 Hector Mine earthquake (Mw 7.1).

8. On the map, note that the San Andreas fault has a distinct curve or bend in the middle of the southern locked (orange) segment. The bend causes regional compression and thrust faults, some of which are not exposed at the surface. These thrust faults caused the 1994 magnitude (Mw) 6.7 Northridge earthquake in metropolitan Los Angeles, and have uplifted the large mountains north and northeast of the city.

9. East of Los Angeles, the San Andreas branches southward into several faults. Some of these experienced several moderate-sized earthquakes in the 1900s, including some near important agricultural areas. The fault scarp for these events are colored pink and red on this map.

Before You Leave This Page
Be Able To

- Briefly summarize the main segments of the San Andreas fault and whether they have had major earthquakes.
- Summarize features that might help you recognize the fault from the air.
How Do We Explore What Is Below Earth's Surface?

OUR VIEW OF GEOLOGY is typically limited to those rocks and structures that are exposed at the surface. In deep canyons we can glimpse subsurface rocks and structures. How else do we determine what lies beneath the surface?

1. The region shown here has a few hills of granite and a dark lava flow, but is otherwise covered by soil and vegetation. There are few clues as to what types of rocks and structures lie below the surficial cover. There are two general approaches for investigating subsurface geology: obtaining samples of rocks at depth, and performing geophysical surveys that measure the subsurface magnetic, seismic, gravity, and electrical properties.

3. We can gain a sense of what is below the surface by examining rocks and geologic structures that have been uplifted and are exposed at the surface. Geologists study rocks under the microscope to constrain the temperature and pressure conditions under which the rocks formed and to infer the geologic processes that created the rocks.

5. The geometry of rock units and geologic structures can be explored by sending seismic energy (sound waves) into the ground and measuring how the waves are reflected back to the surface off boundaries between rock types. This commonly is accomplished by using large trucks that shake the ground in a controlled manner, as shown here. The sound waves bounce off rock layers, faults, and other boundaries. They are then recorded using seismic receivers, called geophones, which are buried or stuck into the ground (such as the red-topped geophones shown on the next page).

6. Seismic-reflection data are processed using sophisticated computer programs and allow geologists to draw interpretive line drawings that show the geometry of the rock units, along with any faults and folds.

8. Geologists and engineers drill holes to search for petroleum, minerals, groundwater, and scientific knowledge. Most drill holes are less than several hundred meters deep, but some reach depths of 5 kilometers (3 miles) or more. Cylinder-shaped samples of rock, called drill cores, can be retrieved during the drilling process to provide samples of rocks from depth.

2. As magma rises to the surface, it incorporates pieces of the rock through which it passes. Geologists study such pieces, called inclusions, to determine the types of rocks that lie beneath volcanoes.
9. Instruments that measure the intensity of the Earth's magnetic field can be used to determine the subsurface distributions of magnetic rocks. The equipment can be carried on foot or towed behind a plane. Earth scientists who measure and interpret magnetic, seismic, gravity, and other types of physical data are geophysicists. Such data is called a geophysical survey. Many geology graduates are involved with geophysical surveys at some point in their careers.

10. Magnetic data are generally portrayed as a map, with warmer colors (reds) representing more magnetic rocks and cooler colors (blues) representing areas with lower magnetism.

11. The red and orange areas mark the dark lava flow and hills of gray granite, which are more magnetic than the sediments that cover the rest of the area.

12. A curving magnetic low, represented by the darker blue colors, coincides with a buried stream channel. In the figure below, the channel forms a band of gray soil where the two teams of geophysicists are standing.

13. The strength of gravity varies slightly from one place to another on Earth's surface. This is because some rocks, such as basalt, are more dense and cause a stronger pull than less dense materials, such as sediment. The variations in gravity can be measured using sensitive gravity meters.

14. In this area, the team of geophysicists measured gravity across the buried stream channel and plotted the data on a profile relative to the average value of gravity for the area. The plot shows a gravity minimum caused by low-density sediment within the buried channel.

15. From the gravity profile, computer programs can model possible density configurations that are consistent with the data.

16. Some rocks, such as clays, conduct electrical currents better than other rocks. Rocks containing groundwater conduct an electrical current better than dry rocks. Geologists and geophysicists use these principles to explore for mineral deposits and groundwater. An electrical transmitter runs current into the ground, and one or more electrical receivers some distance away measure how much current reaches the surface.

17. The results of an electrical survey across the buried stream channel are plotted in cross section and contoured, with warmer colors for rocks with higher conductivity, such as those with more water. Geologists compare all the various types of data to infer the subsurface geology.

Before You Leave This Page Be Able To

- Summarize how volcanic inclusions, exposed geology, drill holes, and mines provide observations of the subsurface.
- Briefly summarize what is measured by the various types of geophysical surveys (seismic, magnetic, gravity, and electrical).
What Do Seismic Waves Indicate About Earth's Interior?

EARTHQUAKES, EXPLOSIONS, AND OTHER SEISMIC EVENTS generate seismic waves that can be used to interpret Earth's internal structure. The way seismic waves travel through Earth enables us to identify distinct layers and boundaries within the interior, including the crust, mantle, and core.

A How Do Seismic Waves Travel Through Materials?

1. An earthquake or other source of seismic energy generates seismic waves, which radiate out from the source in all directions.
2. The path that any part of the wave travels is a seismic ray. If the physical properties of the material do not change from place to place, then a seismic ray travels in a straight line. In this case, a family of straight rays diverges outward from the source.

Most seismic waves encounter boundaries between materials with different physical properties, causing the waves to reflect, speed up, or slow down. Some of the energy is reflected off the interface as a reflected wave.

How Seismic Waves Refract Through Different Materials

1. If a seismic wave passes into a material that causes it to slow down, it will be refracted away from the interface at a steeper angle.
2. If a descending seismic ray passes from a slow material to a faster one, it will be refracted to a shallower angle.
3. If a rising seismic ray passes from a fast material to slower one, it will be refracted upward toward the surface.

B How Do Seismic Waves Travel Through Earth's Crust and Mantle?

1. Refraction causes seismic waves to take curved paths through the Earth. Steeply descending rays will first be refracted to shallower angles as they encounter faster and faster material at depth. The waves will then be bent back toward the surface as they pass back through slower material.
2. In the figures below, an earthquake sends seismic waves into the crust and mantle. Both waves are refracted back toward the surface. Waves in the mantle travel faster than those in the crust, resulting in an interesting and useful phenomenon.
3. Close to the earthquake, waves that travel through the crust arrive sooner than those from the mantle because the crustal waves travel a shorter distance.
4. Farther from the earthquake, waves that travel through the mantle arrive at the surface first because the faster velocity lets them overtake the crustal waves.
5. Seismologists observe at what distance from the hypocenter the mantle waves begin to arrive first. They then use simple computer models of velocities, crustal thicknesses, and ray paths to calculate the depth to the crust-mantle boundary.
How Are Seismic Waves Used to Examine Earth's Deep Interior?

Seismologists recognize distinct boundaries within Earth, largely based on changes in seismic velocities. Such changes reflect the physical and chemical properties of the rock layers through which the seismic waves pass. Not all seismic waves make it through every part of Earth. Observing where particular kinds of waves are blocked helps determine which parts of Earth are molten.

1. As P-waves travel through Earth, they speed up and slow down as they pass through different kinds of material. Their velocity depends upon three factors: (1) how easily the rocks are compressed; (2) how rigid the material is; and (3) the density of the material. Based on these factors, seismologists conclude that faster velocities indicate denser rocks.

2. This graph plots P-wave velocity as a function of depth. Overall, P-wave velocity increases with depth in the mantle and in the core because the rocks in each part become more rigid and dense downward.

3. As P-waves and S-waves travel through Earth, many follow curved paths that return them to the surface.

4. Along the core-mantle boundary, some P-waves are refracted inward because the outer core has a slower velocity than the adjacent mantle. These P-waves pass through the core and out toward the other side of Earth.

5. There is a zone, called the P-wave shadow zone, that receives no direct P-waves. This is because the P-waves are either refracted upward before they reach this area, or are refracted inward through the core. Some weak P-waves reach the surface in this zone, but they took indirect routes by reflecting and refracting around Earth's core.

6. On the opposite side of Earth from the seismic source, there is also an S-wave shadow zone, that receives no direct S-waves. This implies that S-waves cannot pass through the core. From this and other observations, seismologists conclude that the outer part of the core is molten and blocks S-waves.

7. From the sizes and locations of the P-wave and S-wave shadows, we can determine the diameter and depth of Earth's core. Seismologists also learn about Earth's interior by studying indirect waves. These are waves that have reflected off boundaries or have changed wave type as they crossed a boundary (e.g., mantle to core).

The Moho

The boundary between the crust and mantle is named the Mohorovičić Discontinuity after the last name of the Croatian seismologist who discovered it. Most geologists simply call it the Moho.

Much effort is expended trying to determine the depth to the Moho because this tells us how thick the crust is. Geophysicists investigate this problem using various approaches. Some observe the arrivals of seismic waves from naturally occurring earthquakes, whereas others use mine blasts as the seismic source. The depth to the Moho can sometimes be identified as reflections on seismic-reflection profiles. Since seismic waves travel through the crust at ~6 km per second, it takes 10 seconds for a wave to travel 30 km down to the Moho, bounce off, and travel 30 km (19 miles) back up. It takes less time if the crust is thin and more time if it is thick.
How Do We Investigate Deep Processes?

ROCK PROPERTIES, SUCH AS DENSITY, temperature, pressure, and composition, change through Earth. Seismologists use observations of seismic-wave velocities to determine how rock properties change with depth and how material moves in Earth's mantle and at the core-mantle boundary.

A How Do We Investigate Deep Conditions?

Much of what we know about Earth's interior comes from our knowledge of seismic-wave velocities and how they vary within Earth's interior.

One way to constrain the conditions deep within Earth is to examine rocks that have resided at great depths. Some metamorphic rocks in Norway and China contain high-pressure minerals, which indicate that they were buried at ultra-high pressures and depths of 60 to 100 kilometers. Documenting the minerals and structures that formed under these conditions provides insight into what processes and conditions occur at depth.

In the laboratory, rocks can be subjected to high temperatures and pressures in order to determine the conditions under which they melt, solidify, or flow in the solid state. Many minerals change into another mineral at high temperatures, high pressures, or both. The conditions under which these changes occur are then inferred for equivalent depths and temperatures within Earth's interior.

B How Does Seismic Tomography Help Us Explore the Earth?

Seismologists examine Earth using earthquakes in much the same way that medical doctors examine the internal parts of the body with CT scans and other types of imaging technologies. The technique seismologists use is called seismic tomography, where "tomography" means an image of what is inside.

1. In seismic tomography, one examines a number of earthquake waves that have passed through the same subsurface region, but from different directions. In this diagram, the directions along which the seismic waves passed through the region are shown as a series of lines called ray paths.

2. Ray paths coming from points A and B are recorded on a number of seismometers, shown as triangles.

3. If part of the crust or mantle has a higher seismic velocity than other areas, then waves passing through that area will arrive sooner than expected. Those that travel through slow regions will arrive later than expected.

4. This figure models the velocities in the same region using seismic tomography. Areas that are slower than expected are shaded red and may represent areas that might be hotter than normal.

5. Some areas, such as the granite block, will be faster than expected and so are shaded blue. Fast areas might be abnormally cool or composed of stiff, dense rocks. Earthquakes do not come from every direction, so many details cannot be resolved and remain a little fuzzy.
**What Processes Are Occurring in the Mantle?**

Seismic wave velocities increase abruptly at the Moho, passing from the crust down into the mantle. They vary within the mantle due to major changes in mineralogy and density with depth, and because of upward and downward flow of mostly solid mantle material.

### Seismic Velocities of the Lowermost Mantle

1. This globe shows computed velocities of seismic shear waves in the lowermost mantle, as modeled using seismic tomography. Red areas represent seismically slow materials, and blues represent materials that are seismically faster than average. The outlines of the continents (centered on North and South America) are shown on the surface for reference.

2. The red areas in the model are interpreted to represent rising masses of hot, mostly solid mantle material. Many, but not all, seismologists regard these rising masses as the source areas for mantle plumes and hot spots.

### A Model of Flow Within Earth

1. Seismologists and other geologists strive to develop models for the flow of materials throughout Earth. This figure, from seismologist Ed Garnero, presents one view of the inner workings of Earth. There are many other views.

2. In this model, cold, dense material from subducted slabs sinks deep into the mantle. These slabs correspond to the blue, fast velocities in Ed's seismic tomography figure above.

3. Some cold slabs are interpreted to travel all the way down to the base of the mantle, where they pile up to form the D" layer. This figure greatly exaggerates the thickness of this layer.

4. Spirals in the outer core are aligned parallel to Earth's spin axis and represent the flow of material and electrical current to generate Earth's magnetic field.

5. This model shows large-scale upwelling of material from the core-mantle boundary, corresponding to the red areas in the tomography figure above. Material rising from the tops and edges of these upwellings may provide material for mantle plumes and hot spots.

6. Mid-ocean ridges do not show prominently on this figure because they are not believed to represent large-scale convection currents in the mantle or upwelling from the lower mantle. Instead, when two oceanic plates spread apart, the space is filled by local flow from the shallow part of the asthenosphere. There may be some exceptions, such as where a mid-ocean ridge coincides with a hot spot, like at Iceland.

### Before You Leave This Page

Before you leave this page, be able to:

- Describe four ways we can investigate or model Earth's interior.
- Summarize how seismic tomography identifies different regions within Earth.
- Describe some ideas about flow in the mantle and core-mantle boundary that have arisen from seismic tomography.
What Happened During the Great Alaskan Earthquake of 1964?

THE SOUTHERN COAST OF ALASKA experienced one of the world’s largest earthquakes in 1964. The magnitude (Mw) 9.2 earthquake, which is the strongest to have ever struck North America, destroyed buildings, triggered massive landslides, and unleashed a tsunami that caused damage and deaths from Alaska to California. This event provides an example of the causes and manifestations of an earthquake.

A What Types of Damage Did the Earthquake Cause?

The earthquake occurred along the southern coast, but was felt throughout Alaska, except for the north coast. These yellow circles show distances from the epicenter in kilometers.

△ Severe damage occurred in the Turnagain Heights area of Anchorage, where a layer of weak clay liquefied carrying away shattered houses.

▼ Ground shaking destroyed buildings and generated huge landslides of rock and soil. This dark, rocky landslide covered parts of the white Sherman Glacier.

△ Parts of downtown Anchorage were completely demolished when shaking caused the underlying land to slip and collapse. Some buildings sunk so much that their second stories were level with the ground.

The epicenter of the earthquake was along the southern coast of Alaska, between the cities of Anchorage and Valdez. The earthquake began at depths of 20 to 30 kilometers. Based on the wide distribution of about 600 aftershocks, seismologists estimate that the earthquake ruptured a fault surface that was over 900 kilometers (560 miles) long and 250 kilometers (160 miles) wide. The earthquake occurred on a thrust fault that dips from the Aleutian trench gently northwestward beneath Alaska.
**What Happened in the Sea During the Earthquake?**

Because it occurred along the coast, the earthquake also caused (1) faulting and uplift of the seafloor, (2) huge waves from landslides, and (3) a tsunami that struck the coasts of Alaska, British Columbia, Washington, Oregon, California, Hawaii, and Japan.

> The main fault that caused the earthquake did not break the land surface, but two subsidiary faults did. One fault cut a notch into a mountain and uplifted the seafloor 4 to 5 meters (15 feet). The white material on the uplifted (left) side of the fault consists of calcareous marine organisms that were below sea level before the earthquake. The maximum observed uplift was 11.5 meters (38 feet)! Other areas subsided as much as 6 meters (20 feet) during the earthquake, flooding docks, oil tanks, and buildings along the coast.

> Faulting uplifted a large area of seafloor off the southern coast of Alaska, sending a large tsunami out across the sea and up the many bays and inlets along the coast. The highest tsunami recorded was 67 meters (220 feet), in a bay near Valdez. The photo above shows damage done to Kodiak by a wave 6 meters (20 feet) high. The tsunami killed 106 people in Alaska and 17 more in Oregon and California.

**How Did Geologists Study the Aftermath of the Earthquake?**

Immediately after the earthquake, the U.S. Geologic Survey (USGS) dispatched a team of geologists to (1) survey the damage; (2) document the faults, landslides, and other features of the earthquake; (3) understand what happened; and (4) identify high-risk areas and devise plans to minimize loss from future earthquakes.

> 1. The USGS team investigated the coastline, measuring uplift and subsidence in hundreds of sites. They plotted and contoured the measurements (in feet) on a detailed map. Numbers are positive for uplift and negative for subsidence. Dashed lines mark extrapolated values.

> 2. The map was used to identify broad zones of subsidence and uplift, which affected an area of over 250,000 square kilometers (100,000 square miles). The large affected area reflects the huge size of the ruptured fault surface.

> 3. This huge earthquake occurred along a megathrust, where oceanic crust is subducting beneath the continent. USGS geologist George Pflafer constructed a cross section showing how the uplift was explained by southward thrusting of the continent over the oceanic crust. His 1964 paper predated the idea of plate tectonics and was a key step that led to development of the theory.
INVESTIGATION

Where Did This Earthquake Occur, and What Damage Might It Cause?

THE REGION BELOW CONTAINS TWO FAULTS, an active volcano, and a steep-sided mountain prone to landslides. Any of these features could cause ground shaking. You will use seismic records from a recent earthquake to determine which feature caused the observed shaking. From this information, you will decide what hazards this earthquake poses to each of the small towns in the area.

Goals of This Exercise:
- Examine the large illustration and read the text boxes describing the types of features that are present.
- Use the seismograms to determine which feature is likely to have caused the earthquake.
- Consider potential earthquake hazards to determine what dangers each small town would face from the earthquake.
- Decide which town you think is the safest from earthquake-related hazards and justify your decision with supporting evidence.

Procedures

The area has several small towns and three seismometers, each named after the town which it is near. Seismograms recorded at each seismic station during a recent earthquake are shown at the top of the next page. Use the available information to complete the following steps and enter your answers in the appropriate places on the worksheet.

1. Observe the features shown on the three-dimensional perspective. Read the text associated with each location and think about what each statement implies about earthquake hazards.

2. Inspect the seismograms for the three seismic stations to determine where the earthquake probably occurred. You can get an idea from simply comparing the time intervals between the arrivals of P-waves and S-waves for each station.

3. Your instructor may have you use the graph next to the seismograms to determine the distance from each station to the epicenter. This will allow you to more precisely locate the epicenter. Detailed instructions for this procedure are listed in Topic 12.5 earlier in this chapter.

4. From the general location of the earthquake, infer which geologic feature is likely to have caused the earthquake.

5. Use the information about the topographic and geologic features of the landscape to interpret what types of hazards the recent earthquake posed for each town. From these considerations, decide which three towns are the least safe and which two are the safest for this type of earthquake. There is not necessarily one right answer, so explain and justify your logic on the worksheet.

1. There is a deep ocean trench along the edge of the continent. Ocean drilling encountered fault-bounded slices of oceanic sediment.

2. Along one part of the coastline, there is a thin steep beach, called Roundstone Beach, that rises upward to some nearby small hills. The seafloor offshore is also fairly steep as it drops off toward the trench.

3. The town of Sandpoint is built upon land that was reclaimed from the sea by piling up loose rocks and beach sand until the area was above sea level.

12. Offshore is a coral reef that blocks larger waves, creating a quiet lagoon between the reef and the shore.
4. A picturesque town, called Hillside, lies inland of some small mountains. The town is build on a flat, open area flanked by hills with fairly gentle slopes. The Hillside Seismic Station, shown by a triangle symbol, lies just to the east of the town.

5. In the northern part of the area, there is a flat-topped mountain, known as Red Mesa, surrounded by steep cliffs. A new landslide lies along the southern flank of the mountain.

6. A small town and a seismic station, both called Mesaview, lie between the mesa and a high volcano.

7. A volcano called Lava Mountain rises above the region. It has steep slopes and is surrounded by layers of volcanic ash that appear to have erupted quite recently. Every so often, the volcano releases steam and makes rumbling noises. The shaking triggers landslides down the hillsides. The small town of Ashton is on the flanks of the volcano and has a picturesque setting with huge, colorful blocks of volcanic rocks near the town.

8. The Gray Cliffs form a nearly vertical step in the landscape. Streams pour over the cliffs in pleasant waterfalls, each taking a jog to the left after crossing the cliffs. The small settlement of Cascade Village is located next to one of the waterfalls. Rocks along the cliffs are fractured and shattered.

9. The small village of Cliffside lies next to a gray cliff. It was built on a marshy area that was underlain by soft, unconsolidated sediments. Several streams drain into the area, but no streams are able to leave because the area is lower than the surrounding landscape. As a result, the soil is commonly very soft and people sink in as they walk.

10. Riverton, a picturesque town, is built near a river at the head of a sandy bay. The seafloor slopes out to the bay at a gentle angle. Muddy waters from the river prevent reefs from growing offshore in front of the bay.