Chapter 20

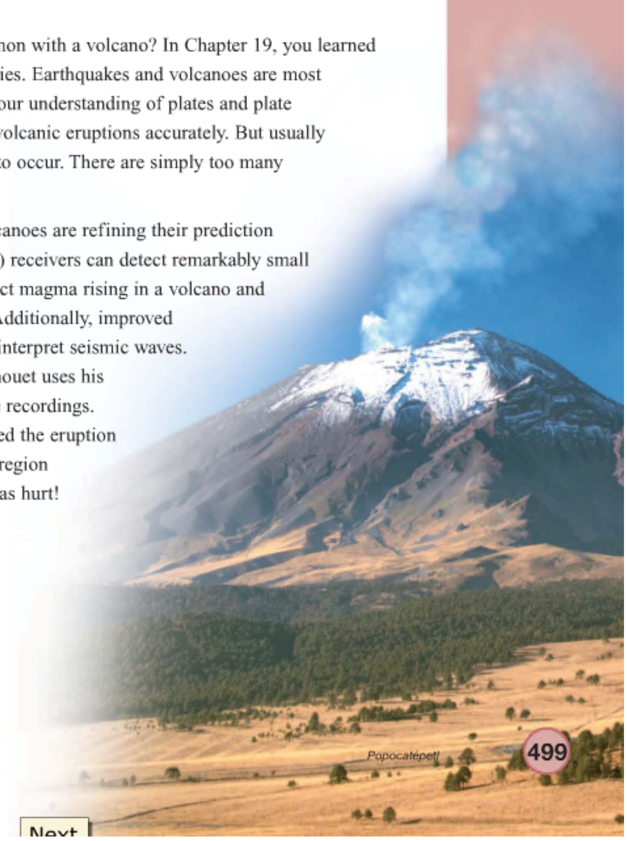
Earthquakes and Volcanoes

What does an earthquake have in common with a volcano? In Chapter 19, you learned about plate tectonics and plate boundaries. Earthquakes and volcanoes are most common along plate boundaries. It would seem that, with our understanding of plates and plate boundaries, we should be able to predict earthquakes and volcanic eruptions accurately. But usually we can only estimate whether they are more or less likely to occur. There are simply too many variables involved for precise predictions.

However, scientists who specialize in earthquakes and volcanoes are refining their prediction capabilities. Sophisticated global positioning system (GPS) receivers can detect remarkably small changes in position. These instruments can be used to detect magma rising in a volcano and stress building along a fault that precedes an earthquake. Additionally, improved instruments and methods are refining scientists' ability to interpret seismic waves. United States Geological Survey volcanologist Bernard Chouet uses his knowledge of musical harmonics to interpret seismic wave recordings. Using Chouet's research, volcanologists in Mexico predicted the eruption of Popocatépetl in 2000 and initiated an evacuation of the region 48 hours before the volcano erupted. As a result, no one was hurt!

Key Questions

- ✔ Can one earthquake cause another?
- ✔ Why are some volcanic eruptions explosive and some gentle?
- ✔ Does the appearance of an igneous rock provide clues about magma and eruptions?



Popocatépetl

Next

20.1 Earthquakes

In Chapter 19, you read about the San Andreas Fault, which lies along the California coast (Figure 20.1). This fault passes right through San Francisco and part of Los Angeles. As you might know, earthquakes occur in California and future earthquakes are expected. This is because California is on the boundary between the North American Plate on the east and the Pacific Plate on the west. This section explains the relationship between earthquakes and lithospheric plates.

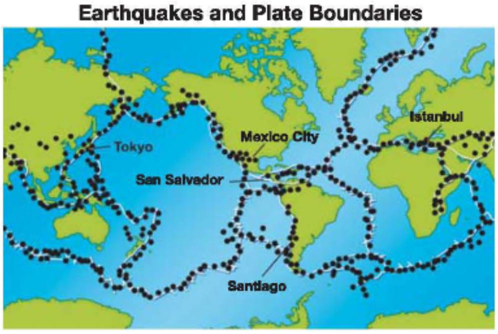
Figure 20.1: *The San Andreas Fault lies along the California coast.*

Earthquakes and plate boundaries

Where do you find earthquakes? When earthquake locations are plotted for many years, a map like the one below can be created. From the map we can see that earthquakes commonly occur at the boundaries of lithospheric plates. Earthquakes occur less commonly at faults that are inside plate boundaries.

Earthquake zones Figure 20.2 illustrates that Japan, a country that experiences earthquakes, is near converging plate boundaries. Subduction of one plate under another is causing seismic activity. Notice that the locations of earthquakes do not exactly follow the boundaries. At all plate boundaries including transform fault boundaries where the fault often branches, seismic activity occurs in zones called *earthquake zones*.

Earthquakes and Plate Boundaries



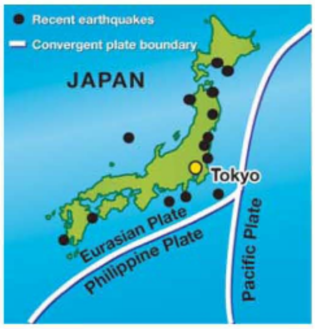
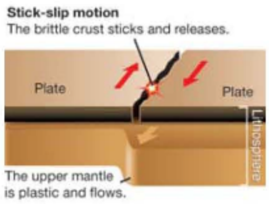


Figure 20.2: *Earthquakes along converging plate boundaries do not occur in neat lines but in zones of seismic activity.*

When an earthquake occurs

What is an earthquake? You now know that earthquakes are likely to occur at plate boundaries, but you might not know why this is the case. By definition, an **earthquake** is the sudden movement of Earth's crust due to the release of built-up potential energy (stored energy) along a fault. A **fault** is a region on Earth's surface that is broken and where movement takes place.

Plates stick together, then break Lithospheric plates slide past one another. As this happens, the plates might stick together due to friction. Often the brittle crust will stick near the surface as the plastic upper mantle continues to flow underneath. *Plastic* here means "able to change shape without breaking," like modeling clay. With the crust stuck above and the upper mantle moving below, the rocks at plate boundaries stretch or compress. As a result, potential energy builds in the plate. When potential energy exceeds the strength of the rock and friction—CRACK!—the rock breaks and slips as potential energy converts to kinetic energy. This motion is called *stick-slip motion*.



Stick-slip motion Three conditions are necessary for stick-slip motion to occur. These are: (1) two objects are in contact and at least one of the objects can move, (2) a force (or forces) causes the movement, and (3) friction is strong enough to temporarily prevent movement from starting so that potential energy builds.

Stress relief for plates The sudden release of potential energy when plates "slip" causes earthquakes. In this sense, an earthquake is a stress reliever for lithospheric plates. However, the relief is only temporary. Potential energy starts building up again as soon as the quake ends.

Earthquake terms The **focus** of an earthquake is the point below the surface where the rock breaks. After the break occurs, plates move along the fault. The energy of this movement is spread by seismic waves. These waves are strongest at or near the **epicenter** of an earthquake, the point on Earth's surface above the focus (Figure 20.3).

VOCABULARY

earthquake - the movement of Earth's crust resulting from the release of built-up potential energy along a fault.

fault - a region on Earth's surface that is broken and where movement may take place.

focus - the point below Earth's surface where a rock breaks or slips and causes an earthquake.

epicenter - a point on Earth's surface right above the focus of an earthquake.

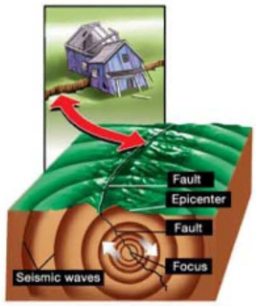


Figure 20.3: *The focus, epicenter, and seismic waves of an earthquake at an active fault.*

Lithospheric plates have many sections

Sections of plate boundaries Although a lithospheric plate moves as a single unit, its boundary acts as though it were made of many sections. A line of grocery carts is a good analogy of lithospheric plate movement (Figure 20.4). A line of grocery carts moves as a single unit, but there are small movements between each cart. When a person pushes the back end of a line, the carts at the front end remain still for a moment. It takes some time for the first cart to push the second, the second to push the next, and so on, until eventually, the front cart starts to move.

The San Andreas Fault A lithospheric plate boundary might be thousands of kilometers long. Therefore, it takes a long time for movement on one end of the boundary to affect a section farther away. Like each cart in a line of carts, each section of a plate boundary can move before or after other sections. The San Andreas Fault is a well-known example of a transform plate boundary. Although most sections remain stuck together, other sections might move at any time. An earthquake happens each time a fault section moves, but only in the section that moved (Figure 20.5).

Frequency and strength Imagine two sections along the same fault. The first section has earthquakes a few times a year. The earthquakes are mild because relatively little energy is released during each quake. These frequent earthquakes release potential energy before it can build up to a high level. Now, let's say that earthquakes take place only once every 20 years in the second section. The long time period between earthquakes allows a great deal of potential energy to build up. Earthquakes in this section are likely to be devastating.

One earthquake might trigger others It is common for an earthquake in one section of a fault to cause an earthquake in a neighboring section. Imagine two neighboring plate sections. One section is ahead of the other along the fault in the direction of plate movement. Both sections have built up a lot of potential energy. Then, an earthquake occurs in the front section, reducing its potential energy. Now there is an energy difference between the first and second sections. This difference may trigger a new earthquake in the second section. It is common for one earthquake to have a ripple effect among sections along a fault.

Figure 20.4: *A moving line of grocery carts is like a moving lithospheric plate.*

Figure 20.5: *This graphic shows that activity along the San Andreas Fault occurs in sections.*

Seismic waves

Recording seismic waves An earthquake involves the conversion of potential energy into kinetic energy as movement along a fault. The fault movement generates seismic waves that radiate from the fault. The point on the fault that moves first is the earthquake focus. A **seismograph** records the arrival time and strength of the various seismic waves. Seismographs are located around the world at seismic stations on land and in the oceans. The picture above shows how older seismic stations recorded *seismograms* (records of seismic waves) on paper on a large drum. Today, most seismic data are recorded by computers.

Photo courtesy of U.S. Geological Survey.

Body waves Seismic waves that travel through Earth are called **body waves**. The two main types of body waves are P-waves and S-waves, also called primary and secondary waves. P-waves are faster and arrive first at a seismic station (Figure 20.6). As P-waves move through rock, it is pushed and pulled in the same direction as the waves move. Like sound waves, P-waves are longitudinal waves and can travel through any medium including solid and fluid rock. S-waves only move through solids, so they cannot travel through Earth's liquid outer core. S-waves move side to side and cause rock to shear or break at right angles to the direction that the wave is moving. As seismic waves travel through Earth, their speed changes as the strength of the material that they are traveling through changes. Seismic waves travel faster in cool materials because these materials are stronger. The waves travel slower in hot materials because heat weakens a material. In addition, seismic waves bend or reflect as they pass through the different materials and layers of Earth.

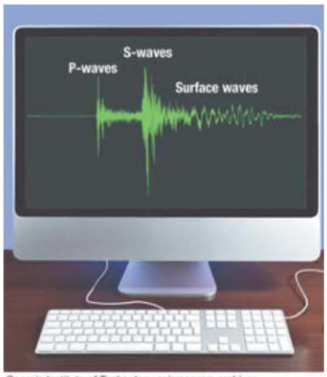
Surface waves Seismic waves that can only move along the surface of Earth are called **surface waves**. Surface waves are slower than body waves. Often larger than body waves, surface waves can cause more damage to structures such as buildings. One kind of surface wave moves up and down as it moves back and forth causing a circular motion. Another type of surface wave moves from side to side. The side-to-side motion rather than the vertical motion of surface waves most often causes buildings to collapse.

VOCABULARY

seismograph - an instrument that records seismic waves.

body waves - seismic waves that travel through the interior of Earth.

surface waves - seismic waves that can travel only along Earth's surface.



Georgia Institute of Technology seismogram archives, courtesy of Tim Long.
Seismograms may also be viewed at www.IRIS.edu.

Figure 20.6: *After an earthquake occurs, the fastest waves, the P waves, are recorded first. The slower S-waves are recorded next, and are followed by the surface waves.*

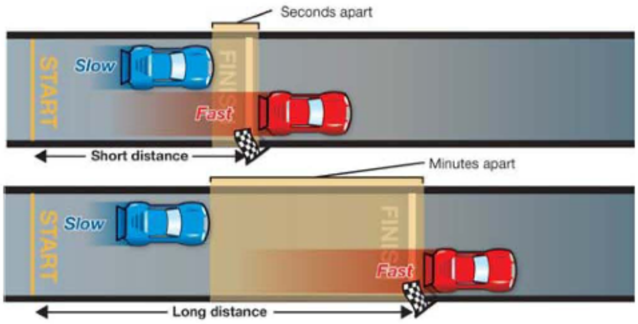
Locating the epicenter of an earthquake

A seismic waves "race"

The difference in the arrival times of P- and S-waves at a seismic station can be used to locate an earthquake's epicenter. This analogy explains how it's done. In a car race, all cars start together. In time, the fastest car gets ahead of the slowest car. The longer the race, the farther ahead the faster car gets. Like fast and slow cars, P- and S-waves have different speeds. The difference in the arrival time between P- and S-waves can be used to determine the distance to the epicenter from the seismic station. The larger the difference in arrival time, the farther the epicenter is from the seismic station.

Remember...

$$speed = \frac{distance}{time}$$



Three seismic stations are needed

At least three seismic stations are needed to locate the epicenter of an earthquake (Figure 20.7). First, each station determines the distance to the epicenter based on the P- and S-wave arrival times. Then each station draws a circle around its location on a map. The radius of the circle is based on the calculated distance to the epicenter. The edge of each station's circle represents all of the possible locations of the earthquake from that station. When all three circles are drawn on the same map, they will cross at a single point—the epicenter.

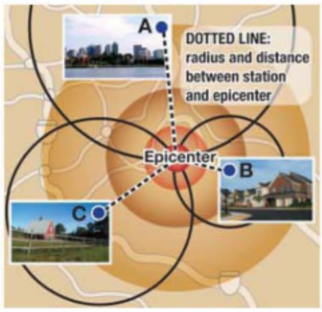
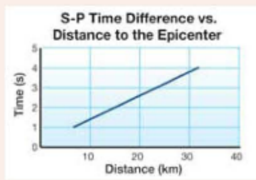


Figure 20.7: *An epicenter is located using data from at least three seismic stations labeled A, B, and C in this diagram.*

SOLVE IT!

How Far Away Is the Epicenter?

A time-distance graph is used to determine the distance to an epicenter. If the arrival time between P- and S-waves is 2.5 seconds, what is the approximate distance to the epicenter?



Measuring earthquakes

The Richter scale The **Richter scale** ranks earthquakes according to the magnitude of their seismic waves recorded on a seismograph. Seismic wave amplitude increases ten times for each Richter magnitude change. For example, a magnitude 6.3 earthquake has a wave amplitude that is ten times greater than a magnitude 5.3 earthquake. The largest recorded earthquake occurred in Chile in 1960 (Figure 20.8). It was off the Richter scale. Seismologists estimated this quake to have been a magnitude 9.5.

The Richter Scale

Level	Magnitude	Effects* (*These descriptions are not part of the scale.)
Micro	Less than 2.0	Barely felt but recorded by seismographs
Very minor	2.0–2.9	Recorded but not felt by most people
Minor	3.0–3.9	Little damage but felt by people
Light	4.0–4.9	No serious damage; objects shake
Moderate	5.0–5.9	Major damage to poorly designed buildings
Strong	6.0–6.9	Serious damage over a 100-km area or less
Major	7.0–7.9	Serious damage over a larger area
Great	8.0–8.9	Serious damage over several hundred kilometers
Rare great	9.0 or greater	Serious damage over several thousand kilometers

The Moment Magnitude scale The **Moment Magnitude scale** rates the total energy released by an earthquake. The numbers on this scale combine energy ratings and descriptions of rock movements. This scale can be used at locations that are close to and far away from an epicenter. The Richter and Moment Magnitude scales are similar up to magnitude 5. However, seismologists tend to use the more descriptive Moment Magnitude scale for larger earthquakes.

VOCABULARY

Richter scale - a scale that ranks earthquakes according to the magnitude of the seismic waves.

Moment Magnitude scale - a scale that rates the total energy released by earthquakes.

Damage Caused by the 1960 Chile Earthquake

Photo courtesy of the National Geophysical Data Center

Figure 20.8: *The 1960 Chile earthquake, which caused devastating damage, was estimated to be a 9.5 magnitude on the Richter scale!*

Energy and the Richter Scale

Each higher value on the Richter scale represents a ten times increase in wave amplitude. However, in terms of energy, each higher number represents the release of about 31 times more energy!

Measuring earthquake damage

The **Modified Mercalli scale** has 12 descriptive categories. Each category is a rating of how an earthquake is experienced by people and the damage caused to structures. Because earthquake damage can be different from place to place, a single earthquake will have different Mercalli numbers in different locations depending on the distance from the epicenter (Figure 20.9).

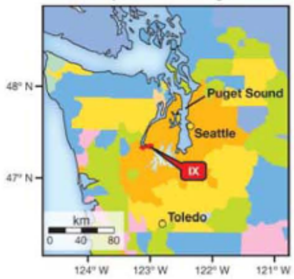
VOCABULARY

Modified Mercalli scale - a scale that rates how an earthquake is experienced by people and the damage caused to buildings.

The Modified Mercalli Scale

Category	Effects	Richter scale (approximate)
I. Instrumental	Not felt	1–2
II. Just perceptible	Felt by only a few people, especially on upper floors of tall buildings	3
III. Slight	Felt by people lying down, seated on a hard surface, or in the upper stories of tall buildings	3.5
IV. Perceptible	Felt indoors by many, by few outside; dishes and windows rattle	4
V. Rather strong	Generally felt by everyone; sleeping people might be awakened	4.5
VI. Strong	Trees sway, chandeliers swing, bells ring, some damage from falling objects	5
VII. Very strong	General alarm; walls and plaster crack	5.5
VIII. Destructive	Felt in moving vehicles; chimneys collapse; poorly constructed buildings seriously damaged	6
IX. Ruinous	Some houses collapse; pipes break	6.5
X. Disastrous	Obvious ground cracks; railroad tracks bent; some landslides on steep hillsides	7
XI. Very disastrous	Few buildings survive; bridges damaged or destroyed; all services interrupted (electrical, water, sewage, railroad); severe landslides	7.5
XII. Catastrophic	Total destruction; objects thrown into the air; river courses and topography altered	8

Sample Modified Mercalli Map for an Earthquake in Washington State



Intensity	Shaking	Damage
I	Not felt	None
II-III	Weak	None
IV	Light	None
V	Moderate	Very light
VI	Strong	Light
VII	Very strong	Moderate
VIII	Severe	Moderate/Heavy
IX	Violent	Heavy
X+	Extreme	Very Heavy

Figure 20.9: *From the map, you can see that the earthquake was a category IX on the Modified Mercalli scale in a very small area. Most of the surrounding areas experienced less shaking and damage.*

Section 20.1 Review

1. The largest earthquake ever recorded occurred in Chile, which is on the west coast of South America. Why does Chile experience violent earthquakes? Explain your answer.
2. What is the difference between the focus and the epicenter of an earthquake?
3. What three conditions are needed for stick-slip motion? Describe how all three conditions are met at the boundary between two lithospheric plates.
4. How is a lithospheric plate like a line of moving grocery carts?
5. Can one earthquake cause another earthquake? Explain your answer.
6. In terms of the release of potential energy, which situation might cause more damage to a city—many small earthquakes or one big earthquake? Explain your answer.
7. What is the difference between body waves and surface waves?
8. List what can happen to a seismic wave as it moves from one material to another.
9. How is the location of an earthquake epicenter determined?
10. At least how many seismic stations are needed to find the epicenter of an earthquake? Why?
11. How does a 3.0 magnitude earthquake compare to a 2.0 magnitude earthquake on the Richter scale in terms of seismic wave amplitude and energy released?
12. What is the Moment Magnitude scale based upon? How is this different from the Richter scale?
13. A friend tells you that he witnessed books and other objects falling off a bookcase during an earthquake. What might have been the intensity of this earthquake on the Modified Mercalli scale? Give the Richter scale magnitude that approximates this intensity value.
14. Why is it possible for a single earthquake to have different Modified Mercalli scale ratings in different locations?

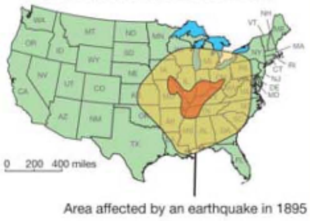
SCIENCE FACT

Earthquakes in the Middle of Plates

Throughout Earth's history, lithospheric plates have been torn apart, added to, and joined with other plates. As a result of this reshaping, there are old plate boundaries that are now faults inside of the plates we see today. The New Madrid Fault, for example, is a fault zone within the North American Plate. This zone is an "old" plate boundary that can break when the North American crust flexes as a result of plate tectonic activity. This can result in a major earthquake, such as the New Madrid events in 1811 and 1812.

Find out more about this fault zone. What are the chances of a large earthquake happening here again?

The New Madrid Seismic Zone



Little damage, but shaking felt

Minor to major damage