CHAPTER 5

Earth Science Concepts

IN THIS CHAPTER

Summary: Land mass movements and environmental impacts of natural events have occurred over geological time.

Keywords

KEY IDEA

✪ Geological time, principle of uniformitarianism, plate tectonics, subduction, convection, earthquakes, P and S waves, volcanism

Investigating Our Environment

The Earth's limitless beauty and complexity provide broad areas for scientific study. Researchers from many different fields focus their skills on the mechanisms and interactions of hundreds of environmental factors. These natural and industrial factors affect the environment in ways that are known or suspected, as well as those that are totally unidentified. Some changes have been taking place for millions of years; others appear to be accelerating. Today, environmental scientists are sorting through tons of data to understand impacts of modern processes on the environment.

Geological Time

The concept of geological time describes time over millions of years. However, for scientists to be sure they are talking about the same time increment, they divide geological time into different amounts. These amounts are known as eons, eras, periods, and epochs. Table 5.1 shows the different time divisions.

Table 5.1 Geological time is divided into eons, eras, periods, and epochs.

EON	ERA	PERIOD	EPOCH	YEARS (MILLIONS)
Phanerozoic	Cenozoic	Quaternary	Holocene	0.1
			Pleistocene	2
		Tertiary	Pliocene	5
			Miocene	25
			Oligocene	37
			Eocene	58
			Paleocene	66
	Mesozoic	Cretaceous		140
		Jurassic		208
		Triassic		245
	Paleozoic	Permian		286
		Carboniferous		320
		Devonian		365
		Silurian		440
		Ordovician		500
		Cambrian		545

KEY IDEA

Time that spans millions of years is known as **geological time**. The entire history of the Earth is measured in geological time.

Geological time includes the history of the Earth from the first hints of its formation until today. It is measured mathematically, chemically, and through observation. Figure 5.1 shows a geological time clock with one second roughly equal to one million years.

In 1785, Scottish scientist James Hutton, often called the father of modern geology, tried to figure out the Earth's age. He studied and tested local rock layers in an attempt to calculate time with respect to erosion, weathering, and sedimentation.

Hutton knew that over a few years, only a light dusting of sediments are deposited in an undisturbed area. He figured out that sedimentary rock must have been compressed, tighter and tighter, from the weight of upper rock layers over many ages. He also thought that changes in a sedimentary rock layer, through uplifting and fracturing of weathering and erosion, could only have taken place over a very long period of time. Hutton was one of the first scientists to suggest that the Earth is extremely ancient compared to the few thousand years that earlier theories suggested. He thought the formation of different rock layers, the building of towering mountains, and the widening of the oceans must have taken place over millions of years.

Hutton wrote the *principle of uniformitarianism* suggesting that changes in the Earth's surface happened slowly instead of all at once. His early work paved the way for other geologists to realize the Earth was not in its final form, but still changing. Gradual shifting and compression changes occurred across different continental land forms.

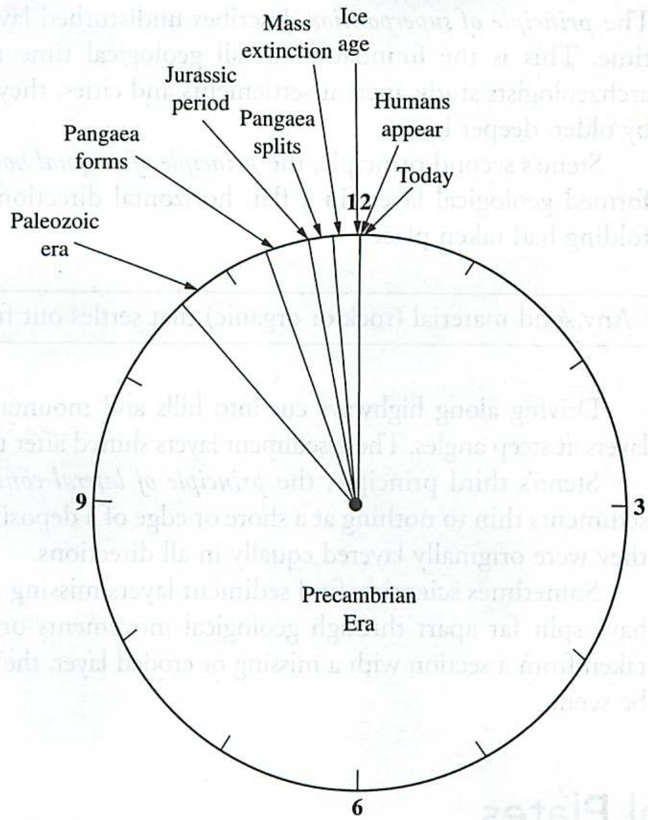


Figure 5.1 Compared to ancient eras, our modern time period is very small.

Time Measurements

Until the 17th century, people believed the Earth was approximately 6,000 years old. This estimate, based on humankind's history, was handed down through stories and written accounts. Except for theory, there were no "scientific" ways to check its accuracy. However, in the 1800s, following the early work of geological pioneers like Nicolaus Steno and Hutton, scientists began to test rock samples for their age. It was during this time that scientists began to use dating methods which suggested that the Earth was millions or even billions of years old.

Relative Time

Relationships between earth layers and soil samples are described by *relative time measurements,* which reveal age. With relative time measurements, the age of rock and soil layers is found by comparing them to neighboring layers above and below.

KEY IDEA

Dating an unknown sample to a certain time period when compared to samples of known ages is called *relative dating.*

In 1669, Nicolaus Steno came up with three ways to order samples in geological time:

1. Principle of superposition
2. Principle of original horizontality
3. Principle of lateral continuity

The *principle of superposition* describes undisturbed layers piled on top of each other over time. This is the foundation of all geological time measurements. For example, when archaeologists study ancient settlements and cities, they record the top layers first, followed by older, deeper layers.

Steno's second principle, the *principle of original horizontality,* described how sediments formed geological layers in a flat, horizontal direction even after base layer bending and folding had taken place.

KEY IDEA

Any solid material (rock or organic) that settles out from a liquid is known as *sediment.*

Driving along highways cut into hills and mountainsides, you will see horizontal rock layers at steep angles. These sediment layers shifted after the original sedimentation took place.

Steno's third principle, the *principle of lateral continuity,* describes how water-layered sediments thin to nothing at a shore or edge of a deposition area. This happens even though they were originally layered equally in all directions.

Sometimes scientists find sediment layers missing from different sections. These layers have split far apart through geological movements or by timeless erosion. If a sample is taken from a section with a missing or eroded layer, the true sedimentation picture wouldn't be seen.

Continental Plates

Geologists know that the original supercontinent, Pangaea, broke up into huge land masses (North America, Africa, etc.) called *continental plates.* There are 15 to 20 major plates of different sizes that make up the Earth's crust.

KEY IDEA

A geological *plate* is a layer of rock that drifts slowly over the supporting, upper mantle layer.

Continental and ocean plates range in size from 500,000 to about 97 million kilometers (km) in area. Plates can be as much as 200 miles (mi) thick under the continents and beneath ocean basins. Plates as much as 100 km thick fit loosely together in a mosaic of constantly pushing and shoving land forms. At active continental plate margins, land plates ram against other continental plates causing rock to push up into towering mountains.

The border between the Eurasian and Indian–Australian plates is a good example of plate conflict. Along this plate margin lies the Himalayan range with the world's tallest mountain (Mount Everest). Where the Nazca ocean plate and South American continental plate collide, the Andes Mountains formed. Similarly, where two ocean plates collide, one dives beneath the other and deep ocean trenches are formed.

Plate Tectonics

The outer crust, or *lithosphere,* is a puzzle of movable parts that mold to each other according to different applied pressures. Originally, scientists studied mountains, valleys, volcanoes, islands, earthquakes, and other geological happenings independently. Each study was considered unique and unrelated to other geological sites until widespread travel and communication began.

Geophysicist J. Tuzo Wilson put it all together. Knowing the movement and folding of the Earth's outer layers were ongoing, he devised the concept of *plate tectonics.* Continental drift made sense to Wilson when combined with the idea of large-plate movement and pressures.

KEY IDEA

Plate tectonics (*tektonikos* is Greek for "builder") describes the formation and movement of ocean and continental plates.

Plate tectonics is an umbrella theory, which explains the Earth's activity and the creation, movement, contact, and flattening of the lithosphere's solid rock plates.

Plate Movement

After Wilson's description of plate tectonics, geologists began comparing plate measurements and found that most plates aren't even close to their original positions! Fossils of tropical plants, once at the equator, were found in Antarctica. Deep rock in the Sahara desert, sliced by glacier travel, was frosty long before arriving at its current hot and dry retreat.

Most importantly, plates slide along at rates of up to 8 inches per year in some areas. The Pacific and Nazca plates are separating as fast as 16 centimeters (cm) per year, while the Australian continental plate is moving northward at a rate of nearly 11 cm per year. In the Atlantic, plates crawl along at only 1 to 2 cm per year.

When enough new material from within the Earth is deposited, plates slant, slide, collide, and push over, under, and alongside their neighbors. Continental and ocean plates ride over or dive under each other, forcing movement down into the mantle and liquid core.

KEY IDEA

A *subduction zone* is an area where two crustal plates collide and one plate is forced under the other into the mantle.

Figure 5.2 illustrates the subduction zone between plates. The lithospheric plate causes volcanism on the overriding plate, while the crustal plate is forced deep into the mantle.

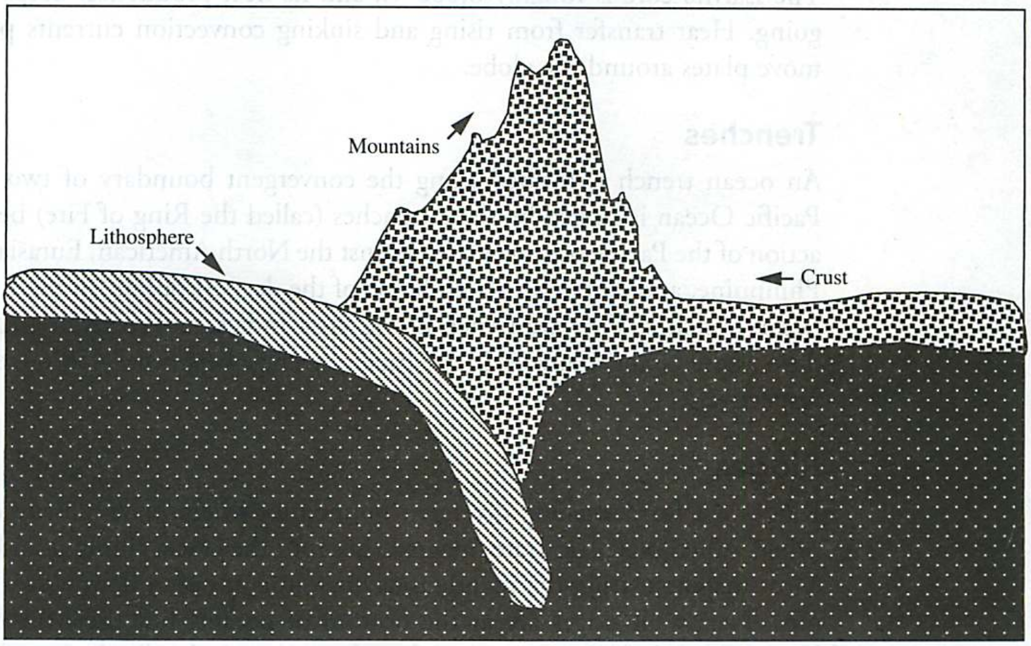


Figure 5.2 Mountain building occurs at subduction zones between plate margins.

Convection

Material circulation caused by heat is called *convection*. In the Earth's system, convection is affected by gravitational forces within the planet, as well as heat and radioactive recycling of elements in the molten core.

KEY IDEA

> *Convection* is the process of heat transfer that causes hot, less dense matter to rise and cool matter to sink.

All tectonic processes within the Earth involve movement of solid or malleable matter. Mantle convection, driven by the thermal gradient between the core and crust, takes place by the extremely slow deformation (creep) of the rocks and minerals in the upper and lower mantle and the transition zone. Flaws in mineral crystalline structures provide gaps. The application of extreme pressure causes atoms in the structure to creep, one atom at a time, into a new position.

Magma movement depends on temperature and density differences within large "pockets" of molten matter. Depending on conditions, magma rises in hotter pockets and sinks in cooler pockets. The Earth's molten core keeps thermal activity and tectonic processes going.

Plate Boundaries

TIP

There are three main types of plate boundaries that form when convection drives plates together and apart. These boundaries include

- *Convergent boundaries.* Plates clash, and one is forced below the other, pulling older lithosphere into the depths of the mantle. (See the Trenches section that follows.)
- *Divergent boundaries.* Plates pull apart and move in opposite directions making room for new lithosphere to form from outpouring magma. (See the Ridges section that follows.)
- *Transform fault boundaries.* Plates slide past each other parallel to their shared boundaries.

The Earth's core is roughly 6,000°C, and its heat production keeps the convection cycle going. Heat transfer from rising and sinking convection currents provides the power to move plates around the globe.

Trenches

An ocean trench is formed along the convergent boundary of two colliding plates. The Pacific Ocean is ringed by these trenches (called the Ring of Fire) because of the constant action of the Pacific oceanic plates against the North American, Eurasian, Indian–Australian, Philippine, and Antarctic plates. Some of the deepest points on the Earth are found within ocean trenches. The Java trench in the West Indies, and the Mariana Trench (five times as deep as the Grand Canyon) in the Pacific, average between 7,450 meters (m) and 11,200 m, respectively.

Ridges

Ridges are formed along divergent boundaries where plates slowly edge apart from each other. When plates separate, magma rises into the crack, filling it and hardening into rock. Most magma exiting the mantle today is found at ocean floor ridges and along plate margins. Nearly all ridges are at the bottom of oceans, but the Mid-Atlantic Ridge, which bisects the Atlantic, emerges in a few places (e.g., Iceland) where geologists can measure its growth and movement.

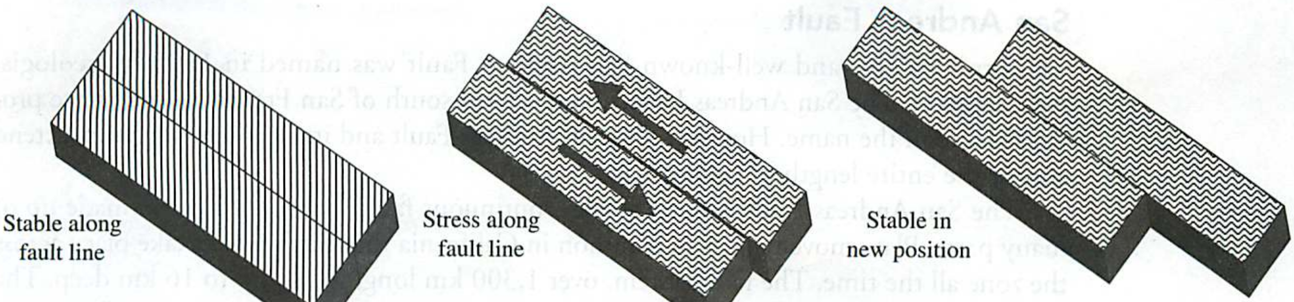


Figure 5.3 Stress builds along a fault until a plate suddenly snaps into a new position.

Transform Fault Boundaries

A *fault* is a crack between two tectonic plates caused by building pressures, which eventually causes surrounding rock to split.

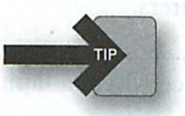
Some plates slide past each other horizontally as in a *transform fault.* The rock on either side moves in opposite directions as the buildup of pressure between the plates provides energy. The well-known San Andreas Fault in California where the North American and Pacific plates meet is a transform fault boundary. Along this fault, the Pacific Ocean plate is sliding north while the continental plate is moving southward. Since these two plates have been at it for millions of years, the rock facing each other on either side of the fault is of different types and ages.

As with most plate collisions, transform faults do not slide along at a constant rate, but in fits and starts. Extreme friction is caused by the buildup of pressure between two grinding plates. This pressure is usually released by earthquakes and a sideways slip between the transform fault fractures. The 1906 and 1989 earthquakes near San Francisco were caused by side-slip transform fault movement.

Following a slip, pressure builds up for many years until it again reaches a critical point. Figure 5.3 shows stress buildup and fault displacement in a transform fault. One day, when the "last straw" is added by pressure buildup, everything shifts violently again. This sudden movement causes millions of dollars in damages to populated areas by breaking roads, building foundations, bridges, and gas lines.

Faults

Rocks, under enough pressure, reach a breaking point. As stress overwhelms rock binding forces something gives and an earthquake is triggered. A *fault plane* is used to represent an actual fault or a section of a fault. Faults are generally not perfectly flat, smooth planes, but fault planes give geologists a rough idea of a fault's direction and orientation. The intersection of a fault plane with the Earth's surface along a crack is called the *fault line* or *surface trace.* Faults lines are not always obvious on the surface.



A fault *trend* is the direction it takes across the Earth's surface. A *fault strike* is the line formed by the intersection of the fault plane with a horizontal plane. The direction of the strike is at an angle off due north. So, when discussing the direction of a certain strike, geologists might call it a northwest-striking fault.

San Andreas Fault

California's active and well-known San Andreas Fault was named in *1895* by geologist A.C. Lawson. The San Andreas Lake, about 32 km south of San Francisco, may have provided Lawson the name. However, the San Andreas Fault and its neighboring faults extend almost the entire length of California.

The San Andreas Fault is not a single, continuous fault, but a *fault system* made up of many parts. Plate movement is so common in California that earthquakes take place across the zone all the time. The fault system, over 1,300 km long, is also up to 16 km deep. The average rate of motion along the San Andreas Fault Zone during the past 3 million years has been 56 mm per year. At this rate, geologists speculate that Los Angeles and San Francisco will be side-by-side in about 15 million years.

Fault Size and Orientation

Active faults have a high potential for causing earthquakes. *Inactive faults* slipped at some point in time (causing earthquakes) but are now stuck solid. However, if local tectonic processes change, it is possible for inactive faults to reactivate.

Faults can measure from less than a meter to over a thousand kilometers in length with corresponding widths. Large fault depths are limited by the thickness of the Earth's crust.

KEY IDEA

$\uparrow$ fault slip area $\Rightarrow$ $\uparrow$ earthquake produced

It is important to remember that the size of a fault rupture is directly proportional to the size of the earthquake produced by the slip. When a set of fractures is large and developed, it is known as a *fault zone.*

Earthquakes

An *earthquake* describes the sudden slip of a fault between two plates. The associated ground shaking and vibrations are known as *seismic waves.* Volcanic activity and other geological processes may also cause stress changes that may result in an earthquake.

KEY IDEA

Seismic waves are caused by vibrations in the Earth from cracks or shifts in the underlying rock.

Earthquakes occur globally, but some regions are more earthquake prone than others. Earthquakes happen in all types of weather, climate zones, seasons, and at any time of day, making it impossible to predict exactly when one will occur. *Seismologists* examine historical earthquake activity and calculate the probability of an earthquake happening again.

Not all fault movement results in seismic waves strong enough for a person to feel. Minor shifts aren't even picked up by sensitive instruments. However, every shift results in some crustal movement along a fault surface.

Hypocenters and Epicenters

Since earthquakes are usually caused by tectonic activity, hypocenters are always located at some depth underground. Figure 5.4 illustrates hypocenters versus epicenters.

KEY IDEA

The *hypocenter* of an earthquake is the location beneath the Earth's surface where a fault rupture begins.

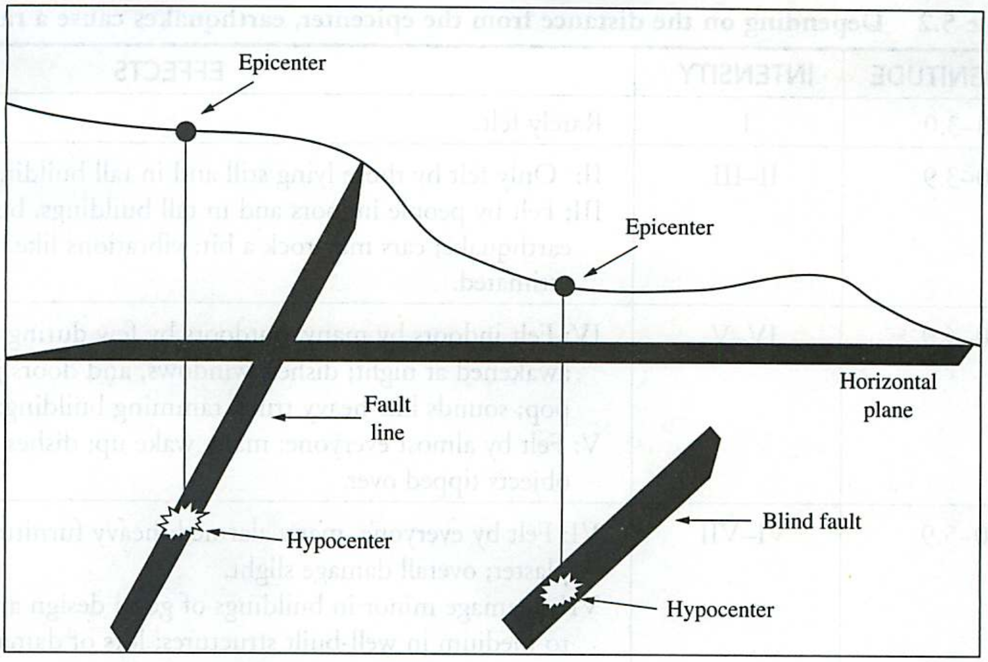


Figure 5.4 The epicenter is the surface point above the earthquake's hypocenter.

During TV earthquake coverage, the *epicenter* is often identified. This point is often named after local geography or a town closest to the epicenter (e.g., the San Francisco earthquake).

KEY IDEA

The *epicenter* of an earthquake is the location directly above the hypocenter on Earth's surface.

The hypocenter and epicenter may be far apart. The epicenter is found by comparing the distance from different measuring stations in a network. A deep hypocenter oriented at an angle away from vertical would not be found along the fault line, but at some distance away.

Earthquake Intensity

Seismology is based on the measurement and observation of ground motion. A pendulum *seismograph* was developed in 1751, but it wasn't until 1855 that geologists realized fault slips caused earthquakes.

KEY IDEA

A *seismograph* is an instrument that records seismic waves (vibrations) onto a tracing called a *seismogram.*

Richter Magnitude Scale

Seismographs record a zigzag trace of the changing amplitude of ground movement beneath the instrument. Sensitive seismographs greatly magnify these vibrations and can detect earthquakes all over the world recording time, location, and earthquake magnitude.

Table 5.2 Depending on the distance from the epicenter, earthquakes cause a range of damage.

MAGNITUDE	INTENSITY	EFFECTS
1.0–3.0	I	Rarely felt.
3.0–3.9	II–III	II: Only felt by those lying still and in tall buildings. III: Felt by people indoors and in tall buildings, but not recognized as an earthquake; cars may rock a bit; vibrations like truck going by; time estimated.
4.0–4.9	IV–V	IV: Felt indoors by many, outdoors by few during the day; some awakened at night; dishes, windows, and doors jarred; walls crack and pop; sounds like heavy truck ramming building; cars rocked a lot. V: Felt by almost everyone; many wake up; dishes and windows broken; objects tipped over.
5.0–5.9	VI–VII	VI: Felt by everyone, many alarmed; heavy furniture moved; some fallen plaster; overall damage slight. VII: Damage minor in buildings of good design and construction; slight to medium in well-built structures; lots of damage in poorly built or designed structures; some chimneys broken.
6.0–6.9	VIII–IX	VIII: Damage minor in specially designed structures; lots of damage and some collapse in common buildings; huge damage in poorly built structures; chimneys, factory stacks, columns, monuments, and walls fall; heavy furniture flipped. IX: Damage great in specially designed structures; well-designed frame structures jerked sideways; great damage in substantial buildings, with partial collapse; buildings moved off foundations.
7.0 and higher	X and higher	X: Some well-built wooden buildings destroyed; most masonry, frame and foundation destroyed; rails bent. XI: Few masonry structures left standing; bridges destroyed; rails bent completely. XII: Damage complete; lines of sight and level are distorted; objects airborne.

The *Richter Magnitude Scale* was developed in 1935 by Charles F. Richter of the California Institute of Technology to compare earthquakes. Using high-frequency data from nearby seismograph stations, Richter could measure an earthquake's magnitude (size). Each logarithmic magnitude rise in the Richter scale represents a tenfold increase in energy. Table 5.2 lists increasing earthquake magnitudes and effects.

Earthquakes with a magnitude of 2.0 or less are often called *microearthquakes.* Most people don't feel them and only nearby seismographs record their movement. Earthquakes of 4.5 or greater magnitudes (thousands each year) are recorded by sensitive seismographs worldwide. On average, one large earthquake of >8.0 occurs somewhere in the world yearly. In 2011, 19,000 lives were lost with $574 billion in structural damages, including those to a nuclear power plant, when Japan was hit by an offshore 9.0 magnitude earthquake.

Seismic Waves

Today's digital monitoring instruments use waveforms to record and analyze seismic data. In 2011, 19,000 lives were lost with $574 billion in structural damages, including those to a nuclear power plant, when Japan was hit by an offshore 9.0 magnitude earthquake.

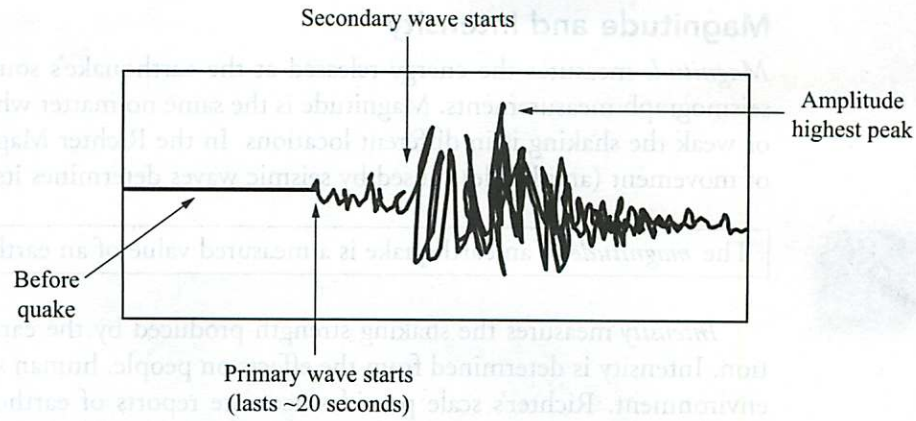


Figure 5.5 Seismographs record earthquake primary waves, secondary waves, and wave amplitude.

Resulting from a 1,200 km long section of the Indian Ocean floor sliding under the Southeast Asian Continental Plate, the seismic waves rattled the Earth for days. Over 300,000 people from 40 nations were reported dead or missing from the resulting tsunamis that hit Indonesia, India, and western Africa. Millions were homeless.

Body Waves

There are two types of seismic waves, *body waves* and *surface waves.* Body waves travel through the Earth's interior, while surface waves travel the top surface layers. Most earthquakes take place at depths of less than 80 km below the Earth's surface. Body waves are further divided into *P waves* and *S waves.* Figure 5.5 shows a typical earthquake tracing.

- *Primary waves.* Primary (P) waves, which bunch together and move apart like an inchworm, are the fastest seismic waves, moving 5 km/s (14 times faster than sound waves move through air) to arrive at a monitoring station. P waves are *longitudinal compression waves.* Like sound waves, they travel through rock or buildings, causing squeezing and expanding parallel to the direction of transmission. The speed of a P wave depends on the types of matter through which it moves. Generally, the denser the matter, the faster the P wave travels.
- *Secondary waves.* Secondary (S) waves travel around 60% of the speed of P waves and arrive at monitoring stations later. S waves are *transverse shear waves.* They cause a shearing, side-to-side motion perpendicular to their travel direction. Because of this, they can only travel through material (e.g., rock) with shear strength. Liquids and gases have no shear strength, so S waves can't travel through water, air, or molten rock.

TIP

Since a seismogram indicator jumps wildly with P wave action, it can be tricky to spot lower frequency and longer wavelength S wave arrival. A sudden wavelength increase and amplitude jump indicates an S wave. However, when a large earthquake occurs, this isn't obvious, because P wave action hasn't slowed to the point where S waves overwhelm it.

Surface Waves

Surface waves are further divided into *Love waves* and *Rayleigh waves.* These waves travel along the Earth's surface and produce distinct types of motion. Love waves produce motion at a 90 degree angle to the wave's direction. This causes the horizontal shearing that wipes out building foundations.

Rayleigh waves produce a lazy rolling motion, causing buildings to experience a bobbing motion transverse to or parallel to a wave's direction of travel. This rolling, elliptical action is extremely hard for non-earthquake-proof buildings to withstand.

Magnitude and Intensity

Magnitude measures the energy released at the earthquake's source and is determined by seismograph measurements. Magnitude is the same no matter where you are or how strong or weak the shaking is in different locations. In the Richter Magnitude Scale, the amount of movement (amplitude) caused by seismic waves determines its magnitude.

KEY IDEA

> The *magnitude* of an earthquake is a measured value of an earthquake's size.

Intensity measures the shaking strength produced by the earthquake at a certain location. Intensity is determined from the effects on people, human structures, and the natural environment. Richter's scale provides accurate reports of earthquake intensity. Table 5.2 gives intensities that are often seen near the epicenter of different earthquake magnitudes.

Types of Earthquakes

Oregon, Washington, and California sit on the North American Plate. The Juan de Fuca Plate is west of the Pacific Northwest coastline in the Pacific Ocean. The shared margin of these two plates is called the Cascadia Subduction Zone and is located 80 km offshore. When the Juan de Fuca Plate clashes with the North American Plate, it subducts into the Earth's mantle producing earthquakes.

Subduction Zone Earthquakes

When an oceanic plate is shoved beneath a continental plate, it may stick instead of sliding. This sticking causes pressure to build up until it is released suddenly as a major earthquake.

TIP

No large earthquakes have been recorded in the Cascadia Subduction Zone since records began in 1790, but the Cascadia had magnitude 8 to 9 earthquakes in the past. If an earthquake took place in this subduction zone, it would probably be centered off the coast of Washington or Oregon where the plates converge. The 1980 eruption of Mt. St. Helens may signal growing tectonic activity in the area.

Volcanoes

Magma movement is called *igneous* activity (from the Latin *ignis* meaning "fire"). Magma erupting from a volcano is called *lava,* which cools to volcanic rock.

KEY IDEA

> A *volcano* is a mound, hill, or mountain formed from hot magma exiting the crust and piling up on the land or beneath the seas.

When referring to volcanic materials ejected during an eruption, most volcanologists talk about volcanic dust, ash, cinders, lapilli, scoria, pumice, bombs, and blocks. These are mostly sorted by size and composition and collectively called pyroclastic fallout.

KEY IDEA

> *Tephra* describes all the different types of matter sent blasting from a volcano compared to slow flowing lava.

Mount St. Helens

Mount St. Helens was once considered one of the most beautiful mountains in the Pacific Northwest's Cascade mountain range. Then, in March of 1980, a series of increasingly stronger earthquakes (over 170) occurred before the mountain top was blown off in a tremendous explosion sending a column of volcanic ash and steam into the sky.

KEY IDEA

Volcanic ash ejected during a volcanic eruption is made up of rock particles less than 4 mm in diameter. Coarse ash is sized from $\frac{1}{4}$ to 4 mm, with fine ash (dust) measuring $<\frac{1}{4}$ mm in grain size.

Then, after two months of nearly constant tremors, a large bulge appeared on the mountain's side. On the morning of May 18, 1980, a huge earthquake a mile underground lowered the internal magma pressure within the volcano and caused the bulge to collapse, followed by a huge landslide moving nearly 250 km/h. The pressurized magma below exploded with a violence calculated at over 500 times the force of the Hiroshima bomb and sent ash 19 km into the air. Over 540 million tons of ash was spewed from Mount St. Helens over a 35,410 km^2 area, with most of it dropping on Oregon, Washington, and Idaho. As much as 3 inches of ash coated the countryside.

Hot Spots

Volcanoes, formed away from plate boundaries, are often a result of geological *hot spots*. A hot spot on the earth's surface is commonly found over a chamber of high-pressure and high-temperature magma. For example, the temperature of the basalt lava of the Kilauea volcano in Hawaii reaches 1,160°C.

TIP

Volcanoes form when vents rise to the surface from a magma chamber. As a plate experiences magma upwelling from deep, ocean rifts, the volcano above slowly slides past the hot spot. The hot spot then begins forming a new volcano. Figure 5.6 shows how this process works. Repeated eruptions form a hot spot creating a string of closely spaced volcanoes. Island chains like the Hawaiian Islands were formed over a hot spot in the mantle.

Currently, a new island called *Loihi* is being formed at the end of the Hawaiian Island chain over the hot spot. Its peak is 1,000 meters below the water's surface and will break the surface in the next 10,000 to 100,000 years.

Craters

A bowl-shaped crater is found at the summit of most volcanoes and is centered over the vent. During an eruption, lava blasts or flows from the vent until the pressure below is released. The lava at the tail end of the eruption cools, sinks back onto the vent, and hardens. The crater fills with debris and sometimes its sides collapse. When this happens repeatedly,

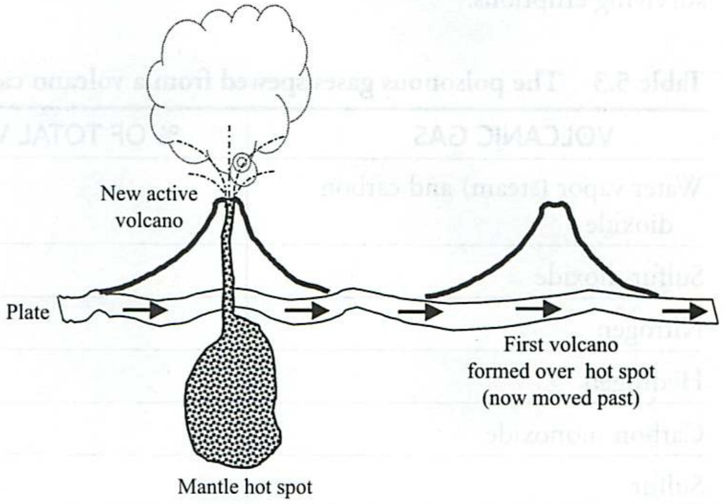


Figure 5.6 As the crust moves over a hot spot, a volcano is formed and eventually forms an island.

the crater grows to many times the size of the base vent and hundreds of meters deep. The crater on Mount Etna in Sicily is more than 300 m across and over 850 m deep.

Calderas

After a massive volcanic eruption spews huge volumes of lava from a magma chamber located a few kilometers below the vent, the empty chamber might not be able to support the weight of its roof. When this happens, the rock above the chamber caves in and a steep-walled basin, larger than the original crater is formed. Known as a *caldera,* these basins can be huge, ranging from 4 to 5 kms to more than 50 km across.

Crater Lake, Oregon, in the northwestern United States is formed from a caldera that is 8 km in diameter. Geologists think the original eruption, which caused the formation of the caldera, happened about 6,600 years ago.

Volcanic Gases

Since Earth's formation, elemental gases have played a part in its makeup and matter. Volcanologists collect eruption gases and sample lava flows at great risk to study their composition. Most eruption gases are made of water vapor from groundwater, seawater, or the atmosphere. Other gases such as sulfur dioxide, nitrogen, hydrogen, and carbon monoxide are from chemical changes in magma and rock during melting and release to the surface. Table 5.3 lists these gases.

TIP

Since most of these gases are poisonous in large quantities, people are often not killed by pyroclastic fallout and lava during an eruption, but by the searing hot, poisonous gases, that make breathing impossible. Archaeologists determined that when Mount Vesuvius erupted, most people were killed by the foul volcanic gases released.

Volcanic Activity

Volcanoes are classed into three types: active, dormant, or extinct. A volcano is *active* if it has erupted within recent recorded history. A *dormant* volcano has little erosion and may become active at any time. However, if a volcano has not erupted within recorded time and is greatly eroded, it is thought to be *extinct* and very unlikely to erupt again.

An average volcano erupts once every 220 years, but 20% of all volcanoes erupt only once every 1000 years and 2% erupt less than once every 10,000 years. There are nearly 600 active volcanoes on the planet today, with 50% of those erupting yearly. Luckily, volcanologists' use of modern technology has greatly improved the odds of predicting and surviving eruptions.

Table 5.3 The poisonous gases spewed from a volcano can be as dangerous as the lava.

VOLCANIC GAS	% OF TOTAL VOLCANIC GAS (AVERAGE)
Water vapor (steam) and carbon dioxide	90–95%
Sulfur dioxide	<1%
Nitrogen	<1%
Hydrogen	<1%
Carbon monoxide	<1%
Sulfur	<0.5%
Chlorine	<0.2%

❯ Review Questions

Multiple-Choice Questions

1. Archaeologists record the top layers first, followed by older, deeper layers to study ancient settlements and cities following the
   (A) principle of original horizontality
   (B) principle of uniformitarianism
   (C) principle of superposition
   (D) principle of uniformity
   (E) principle of lateral continuity

2. Because he figured out that sedimentary rock must have been compacted and compressed, over many ages, ______ is known as the father of modern geology.
   (A) Richard Palmer
   (B) James Hutton
   (C) W. Clayton Scott
   (D) Nicolaus Steno
   (E) Aubrey Hough

3. Relationships between earth layers and soil samples are described by
   (A) tectonic time measurements
   (B) Jurassic time measurements
   (C) chronostatic time measurements
   (D) continental drift
   (E) subjective time measurements

4. When Mount Vesuvius erupted in 79 A.D., most people were killed by
   (A) lava
   (B) pyroclastic flow
   (C) volcanic rock
   (D) poisonous volcanic gases
   (E) the hysterical crowd running toward the sea

5. The umbrella theory explaining the Earth's movement, contact, and flattening of large land plates is known as
   (A) the Coriolis effect
   (B) plate tectonics
   (C) hot spots
   (D) the Richter Magnitude Scale
   (E) the subduction zone

6. Water-layered sediments that thin to nothing at a shore or the area where first deposited are the subject of the
   (A) principle of uniformity
   (B) principle of original horizontality
   (C) second law of thermodynamics
   (D) principle of superposition
   (E) principle of lateral continuity

7. A volcano with little erosion and that may erupt at any time is classified as
   (A) active
   (B) dormant
   (C) high risk
   (D) sedimentary
   (E) extinct

8. Vibrations in the Earth caused by cracks or shifts in the underlying rock are called
   (A) caldera
   (B) sedimentation
   (C) igneous activity
   (D) faults
   (E) seismic waves

9. Where two crustal plates collide and one plate is forced under the other into the mantle, it is called a
   (A) hot spot
   (B) pressure zone
   (C) surface trace
   (D) subduction zone
   (E) sedimentary layer

10. The principle of uniformitarianism includes the idea that
   (A) continental shifting and compression are possible across different regions
   (B) energy can neither be created nor destroyed
   (C) volcanoes can erupt even when quiet for 200 years
   (D) population growth is slow and the birth rate drops to around the death rate
   (E) primary consumers (i.e., herbivores) consume plants and algae

11. A huge layer of rock that drifts slowly over the supporting upper mantle layer is a

(A) caldera
(B) hot spot
(C) geological plate
(D) tropical oasis
(E) transform fault

12. Any solid material (rock or organic) that settles out from a liquid is known as

(A) sediment
(B) ash
(C) a biofuel
(D) granite
(E) cinders

13. Love waves are a type of

(A) primary seismic wave
(B) surface wave
(C) pyroclastic flow
(D) folded rock
(E) lapilli

14. The following are all time units of the geological time scale except

(A) eons
(B) eras
(C) ages
(D) periods
(E) epochs

15. Gravitational forces within the Earth, as well as heat and radioactive element recycling in the molten core, take place through

(A) subduction
(B) deflection
(C) transformation
(D) convection
(E) divergent boundaries

16. An ocean trench is formed along the

(A) transform fault boundary of two colliding plates
(B) Mid-Atlantic Ridge
(C) distant edge boundary of two colliding plates
(D) divergent boundary of two colliding plates
(E) convergent boundary of two colliding plates

17. Primary waves, which bunch together and then move apart like an inchworm, are

(A) the slowest seismic waves
(B) the fastest seismic waves
(C) known as Rayleigh waves
(D) a type of surface wave
(E) the only wave to move through air

18. The location directly above an earthquake's hypocenter on the earth's surface is the

(A) epicenter
(B) trench
(C) hypercenter
(D) surface trace
(E) ridge

19. A large earthquake occurs, on average, somewhere in the world each year of greater than

(A) 1.5 magnitude
(B) 2.0 magnitude
(C) 4.0 magnitude
(D) 5.2 magnitude
(E) 8.0 magnitude

› Answers and Explanations

1. C—The principle states that younger strata are deposited on top of older layers during normal deposition.
2. B
3. C—Chronostatic time measurements are sequential.
4. D—During an eruption, searing hot and poisonous gases make breathing impossible.
5. B—Contact, grinding, and flattening of large land plates is known as tectonics.
6. E—Originally layered equally in all directions, the Grand Canyon's walls show this.
7. B—A dormant volcano hasn't erupted lately but may become active at any time.
8. E
9. D—Subduction zones can cause earthquakes and volcanism.
10. A—Hutton thought surface changes happened slowly and the land was still changing.
11. C
12. A
13. B—The motion is at a 90° angle to wave direction and causes horizontal shearing.
14. C—*Ages* is more a literary term for time than scientific.
15. D—Convection is affected by gravitational forces, as well as heat and radioactive recycling of elements in the molten core.
16. E—The clashing edges also cause volcano formation.
17. B—The speed of P waves depends on the types of matter they move through (i.e., the denser the matter, the faster a P wave moves).
18. A—An epicenter is found by comparing the distance from various measuring stations.
19. E

Free-Response Questions

1. On February 4, 1975, the Chinese government issued an immediate earthquake warning to the area of the city of Haicheng and began a huge evacuation. Nine hours later, Haicheng experienced an earthquake of magnitude 7.3. Luckily, most of the population was outside when 90% of the city's buildings were severely damaged or destroyed. Injuries were few.

   Although there have been other prediction successes in this region of China, the misses are frequent. On July 28, 1976, a 7.8 magnitude earthquake hit Tangshan, 150 km east of Beijing, and home to over one million people. The hypocenter was located directly under the city, at a depth of 11 kilometers. About 93% of all buildings were destroyed and 240,000 people killed. Though the area was monitored, Chinese seismologists were caught off guard. In 2008, an 8.0 magnitude earthquake took place in China that was the second deadliest since Tangshan. It was centered in the Sichuan province and killed an estimated 70,000 people, leaving over 5 million people homeless.

   (a) How are earthquakes caused?
   (b) What is the difference between P waves and S waves?
   (c) Should people be allowed to build in earthquake-prone areas?

2. Currently, a new island called Loihi is being formed at the end of the Hawaiian Island chain. Its peak is 1,000 meters below the water's surface and will break the surface in the next 10,000 to 100,000 years.

(a) What is this process commonly called?
(b) What causes this process?
(c) Does this process affect the size of previously formed islands?
(d) How does this process affect magma pressure deep in the Earth?

Free-Response Answers and Explanations

1.

a. Continental plates are in constant motion. In areas where two plates come in contact the motion isn't smooth. As with most plate collisions, transform faults do not slide along at a constant rate, but in fits and starts. Extreme friction is caused by the buildup of pressure between the two grinding plates. This pressure is usually released by earthquakes and a sideways slip between the transform fault fractures.
b. Though both types of body waves, P and S waves can be distinguished by their speed and seismic motion. P, or primary, waves, move quickly through the Earth's interior. They are longitudinal compression waves, moving like an inchworm parallel to the direction of transmission. S, or secondary, waves move more slowly and are transverse shear waves causing side-to-side motion within the Earth's interior.
c. Policy is divided on this. In poor areas, people build where they own or lease land despite the potential danger. In many earthquake-prone cities, there are building code regulations in place to protect inhabitants during an earthquake.

2.

a. Volcanoes, formed away from plate boundaries, are often a result of geological hot spots.
b. Volcanoes form when vents rise to the surface from a magma chamber. As a plate experiences magma upwelling from deep, ocean rifts, the volcano above slowly slides past the hot spot. The hot spot then begins forming a new volcano.
c. No. The other islands in the chain are finished forming.
d. A hot spot on the Earth's surface is commonly found over a chamber of high-pressure and high-temperature magma. Magma pressure is released as the volcano flows up and out.

› Rapid Review

- Any solid material (rock or organic) that settles out from a liquid is known as sediment.
- Magma movement is called igneous activity (from the Latin *ignis* meaning "fire").
- The original supercontinent, Pangaea, broke up into huge land masses called continental plates.
- A fault is a crack between two rock plates caused by extreme, built-up pressure.
- An earthquake's hypocenter is the location beneath the Earth's surface where a fault rupture begins.
- The epicenter is the location on the surface that is directly above the hypocenter.
- The hypocenter and epicenter may be far apart.
- Tephra describes the matter blasted from a volcano compared to slow-flowing lava.

- When plates clash along convergent boundaries, one is forced below the other, pulling older lithosphere (crust) to deep mantle depths.
- A subduction zone is an area where two crustal plates collide and one plate is forced under the other into the mantle.
- An ocean trench is formed along the convergent boundary of two plates colliding with one another.
- Along divergent boundaries, plates pull apart and move in opposite directions making room for new lithosphere to form at the lip from outpouring magma.
- Ridges are formed along divergent boundaries where plates slowly edge apart.
- Plates slide past each other, parallel to their shared edges, along transform fault boundaries.
- P waves or longitudinal compression waves travel through rock or buildings, causing squeezing and expanding parallel to the direction of transmission.
- Love waves produce motion perpendicular to the direction of wave travel in a horizontal orientation *only* causing horizontal shearing, which wipes out building foundations.
- Rayleigh waves produce a lazy rolling motion, which causes buildings to experience a bobbing motion transverse to or parallel to the wave's direction of travel.
- Magnitude measures the size of an earthquake, while intensity measures the shaking strength created by the earthquake at a certain location.
- The intersection of a fault plane with the Earth's surface, along which a crack occurs, is called the fault line or surface trace.
- Each logarithmic magnitude rise in the Richter scale represents a tenfold increase in energy.