TOPIC 5

The Dynamic Earth

Earth's crust and rigid, upper mantle are broken into enormous slabs of rock (tectonic plates) that move slowly over Earth's surface, much like icebergs drift through polar oceans. Some of these slabs of rock drift toward one another and eventually collide. Some slabs move apart. Other slabs move horizontally past one another. In this topic, you will learn that interactions among these slabs of rock make many volcanoes erupt and form mountain ranges. The slabs' motions also cause many of the earthquakes that shake our planet. The movement of and interactions among these slabs show that Earth is a dynamic system.

SUBTOPIC A
PLATE TECTONICS

Covers National Science Content Standards UCP.1, UCP.2, UCP.3, UCP.4, UCP.5; A.1, A.2; D.1, D.2, D.3; G.1, G.2, G.3

Unifying Concepts and Processes

UCP.1	Systems, order, and organization
UCP.2	Evidence, models, and explanation
UCP.3	Change, constancy, and measurement
UCP.4	Evolution and equilibrium
UCP.5	Form and function

Science as Inquiry

A.1	Abilities necessary to do scientific inquiry
A.2	Understandings about scientific inquiry

Earth and Space Science

D.1	Energy in the Earth system
D.2	Geochemical cycles
D.3	Origin and evolution of the Earth system

History and Nature of Science

G.1	Science as a human endeavor
G.2	Nature of scientific knowledge
G.3	Historical perspectives

VOCABULARY

Pangaea
continental drift
magnetometer
paleomagnetism
magnetic reversal
isochron
seafloor spreading
theory of plate tectonics
mantle
lithosphere
asthenosphere
outer core
inner core
divergent boundary
rift valley
convergent boundary
subduction
transform boundary
ridge push
slab pull

Earth's continents were once joined in a supercontinent called **Pangaea.** It began to break up about 200 million years ago, with **continental drift** moving enormous pieces of land across Earth's surface as shown in Figure 5-1. Continental drift is the idea that Earth's continents were once joined as a single landmass that broke apart and allowed the continents to move to their present positions.

Evidence of Continental Drift

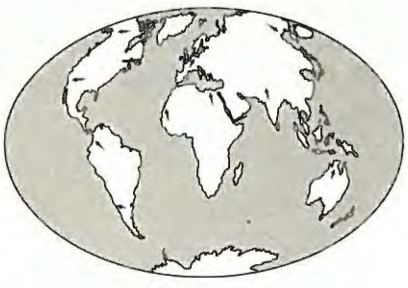
The matching shapes of coastlines on either side of the Atlantic Ocean provide some evidence for continental movement. The east coast of South America fits into the west coast of Africa much like pieces of a jigsaw puzzle.

200 million years ago

180 million years ago

135 million years ago

65 million years ago



Present

Figure 5-1 Pangaea was a supercontinent made of all of Earth's landmasses. It began to break apart about 200 million years ago, sending continents slowly drifting over Earth's surface.

Another nearly perfect match is the coastlines of northern Europe and parts of North America.

Some rock formations on different continents are nearly the same age and share similar structures. Some highly folded rocks in southern Africa, for example, are nearly identical to rocks just south of Buenos Aires, Argentina. Parts of mountain chains in northern Europe are similar to parts of the Appalachians of North America. These rock formations were parts of large structures that fractured when Pangaea broke apart. Figure 5-2 shows some of these matching rock formations.

Fossils of very similar land-dwelling animals have been found on different continents. According to the theory of evolution, organisms evolve from a common ancestor. It is unlikely that these land-dwelling animals evolved from similar ancestors on widely separated continents or swam vast distances to get to a new continent. These animals are evidence of continental drift, as are fossils of a seed fern called *Glossopteris*, which has been discovered on continents that today have very different climates. The fern, which grew in temperate climates, indicates that some of Earth's continents were closer to the equator in the geologic past than they are today. The distribution of *Glossopteris* and several land dwelling animals is shown in Figure 5-2.

Coal is a sedimentary rock that forms in warm, humid swamps, and coal beds have been discovered in Antarctica. These beds formed in a rainy, temperate environment—quite unlike the cold, dry climate of Antarctica today—evidence that this continent had been closer to the equator than it is today. Conversely, glacial deposits found on the southern continents suggest that these landmasses were once closer to the South Pole than they are today. Nearly 300 million years old, the deposits predated the breakup of Pangaea.

Seafloor Spreading

Just like its continental counterpart, the ocean crust rises thousands of meters above the seafloor to form the highest and longest mountain chains on Earth. Some of the deepest valleys on Earth are oceanic trenches. One of these trenches is nearly six times as deep as the Grand Canyon. In the early 1960s, military technology provided some information about these highs and lows of Earth's seafloors.

Technology and the Seafloor

To better understand the crust that covers much of Earth, scientists collected samples of seafloor crust as well as the sediments that accumulated on it. Detailed analysis of these samples showed that the seafloor and sediments are youngest near ocean ridges and become progressively older with increasing distance from the ridge. The seafloor crust is much younger than its continental counterparts, and sedimentation rates on the seafloor are much lower than expected. These data were integrated with information

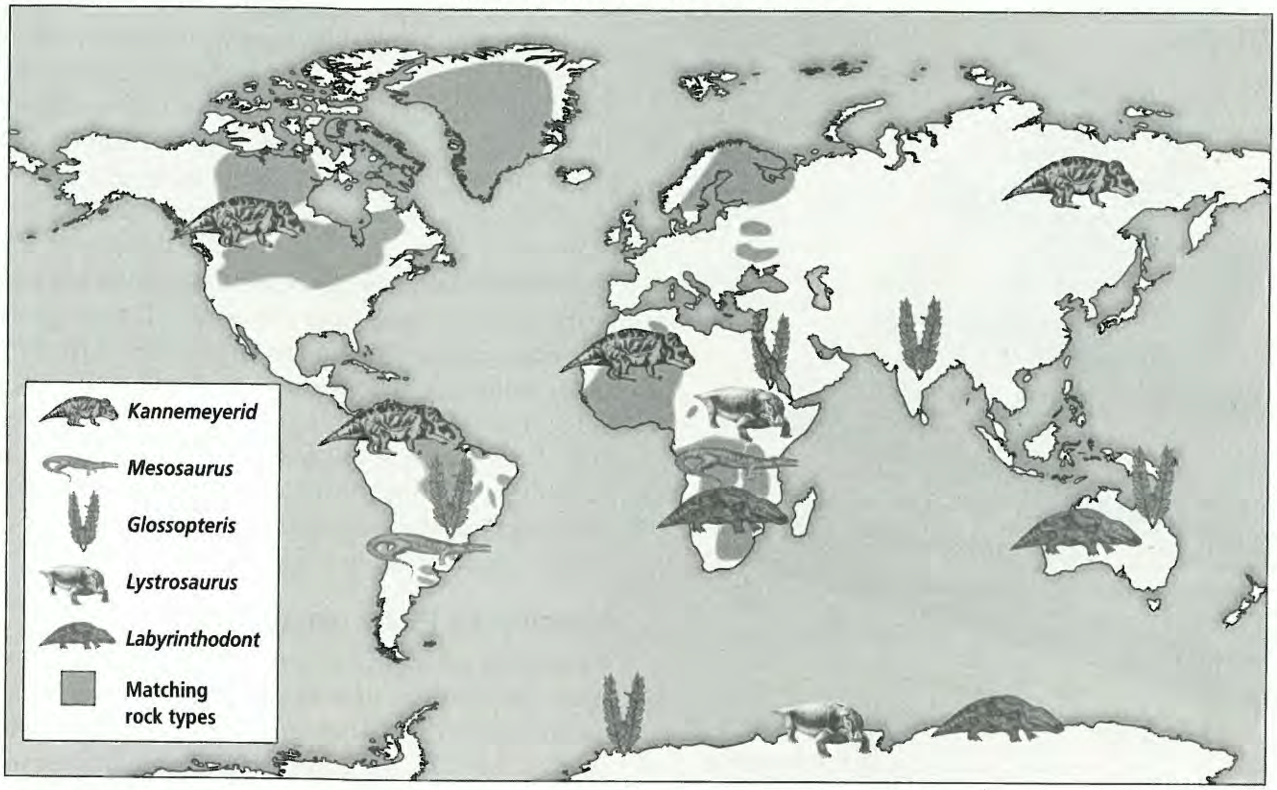


Figure 5-2 Various fossils and the similarity of rock formations on opposite sides of the Atlantic Ocean provide evidence that Earth's continents were once joined.

gathered with other technologies, such as sonar. Sonar, as shown in Figure 5-3, is an echo-sounding technique that was originally developed to detect enemy submarines prowling the seas. Sonar devices use sound waves to measure water depth at a particular point. A device on the ship sends out sound waves, which reflect from the seafloor. The time it takes the waves to travel from the device on the ship to the bottom of the seafloor and back is used to calculate the ocean depth at that point.

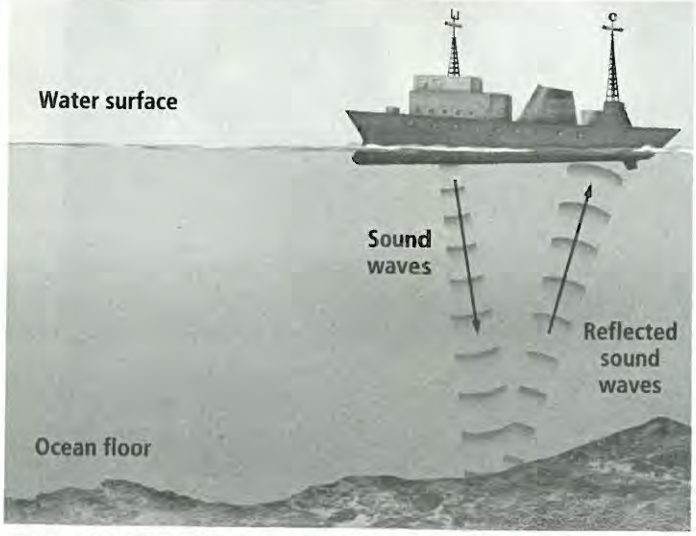


Figure 5-3 Sonar has been used to map ocean-floor topography. The travel times of the sound waves can be used to calculate the distance to the ocean floor.

A **magnetometer,** which is a tool that measures changes in magnetic fields, is another important technology that was used in early studies of the seafloor. The basalts that make up oceanic crust are rich in iron-bearing minerals. These minerals act like compasses and provide a record of Earth's magnetic field, both past and present. The study of the record of Earth's magnetic field is called **paleomagnetism.** When a magnetometer is towed behind a ship, small changes in the magnetic field strength of seafloor rocks are recorded. A stronger-than-normal reading indicates a magnetic field with normal polarity. A weaker-than-normal reading indicates a field with reversed polarity.

Magnetic data from basalts that make up the seafloors and the continents indicate that Earth's magnetic field has changed polarity many times over the course of geologic time. These changes in the magnetic field are called **magnetic reversals.** Figure 5-4 shows some of the most recent magnetic reversals on a portion of the seafloor.

The seafloor maps that were generated from magnetic data show an interesting pattern. The magnetic pattern on one side of an ocean ridge is a mirror image of the pattern on the other side of the same ridge. Using these patterns, scientists can make isochron maps of the seafloor, such as the map shown in Figure 5-5 on the next page. An **isochron** is a line on a map that connects points that have the same age. An isochron is a specific type of isoline that represents age data. Note that the youngest oceanic crust is closest to ocean ridges. Older oceanic crust is found along deep-sea trenches.

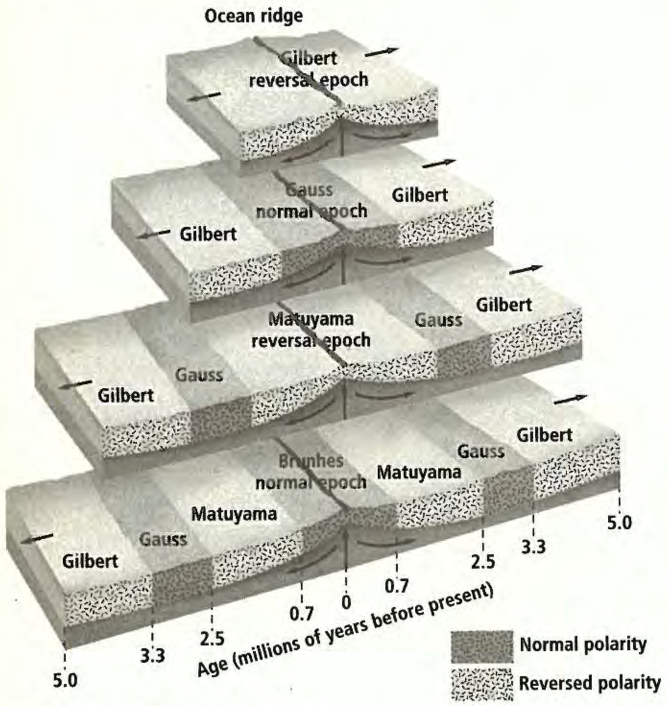


Figure 5-4 Changes in Earth's magnetic field are recorded in igneous rocks that contain iron, including the basalts that make up oceanic crust. Similar strips of oceanic crust on both sides of an ocean ridge have the same polarity.

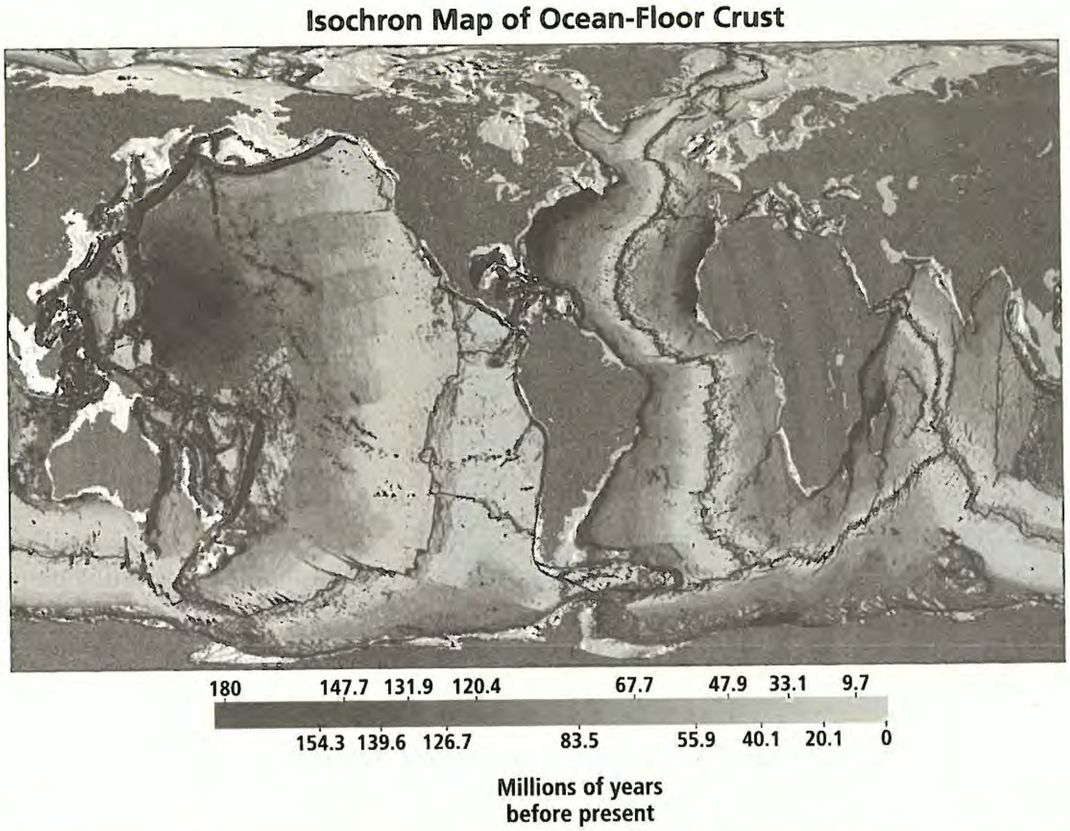
Theory of Seafloor Spreading

The theory of **seafloor spreading** states that new oceanic crust forms at ocean ridges and is destroyed (subducted) at deep-sea trenches. During seafloor spreading, magma from deep within the mantle is forced upward toward the crust along an ocean ridge. The lava that flows from the ocean ridge hardens to fill the fractures that run along the ridge axis. Iron-bearing minerals in the lava are magnetized in the direction of Earth's magnetic field at the time the lava hardens. Over time, the newly formed seafloor moves away from the center of the ridge. Half of this new oceanic crust moves to one side of the ridge. The other half of the new crust moves to the other side of the ridge. The ridge fractures are then filled with new material, which hardens, splits, and slowly moves away from the ridge axis. This continuous formation of new oceanic crust explains the symmetrical magnetic bands of crust on either side of an ocean ridge.

Theory of Plate Tectonics

Eventually, geologists proposed a theory that explained most observations of seafloor crust and its continental counterpart. The **theory of plate tectonics** states that Earth's crust and rigid upper mantle are broken into a dozen or so major slabs of rock called tectonic, or lithospheric, plates. The movements of these plates over Earth's surface create most volcanoes and major mountain ranges. These movements also cause most earthquakes.

Figure 5-5 This isochron map of Earth's ocean floors shows that crust on either side of an ocean ridge gets progressively older with distance from the ridge axis. Some of the oldest oceanic crust is found near deep-sea trenches.



Earth's Structure

To understand plate tectonics, you must understand Earth's structure. Earth has three major parts: the crust, the mantle, and the core, as shown in Figure 5-6 and in *Inferred Properties of Earth's Interior* in the *Earth Science Tables and Charts.* There are two kinds of crust: continental and oceanic. The Mohorovicic Discontinuity, or Moho, discovered through the analysis of seismic waves, separates the crust from the next layer of Earth, which is called the **mantle.** The uppermost part of the mantle is rigid and solid. This rigid part of the upper mantle, together with Earth's crust, makes up the **lithosphere.**

Below the lithosphere, the mantle is partly molten. Although this part of the mantle is solid, it flows like a soft plastic under pressure. This partly molten part of the mantle is the **asthenosphere.** The portion of the mantle below the asthenosphere is solid and is probably composed of simple oxides.

Beneath the mantle is Earth's core. The core has two parts: a liquid **outer core** and a solid **inner core.** Earth's core is extremely dense. Laboratory experiments and studies of earthquake waves and meteorites indicate that Earth's core is probably mostly iron and nickel.

Various properties also vary throughout Earth's interior, as shown in Figure 5-6. Density increases from 2.7 g/cm^3 in the continental crust to 13.0 g/cm^3 in the inner core. Pressure also shows a general increase towards the center of Earth. However, pressure increases slowly in the lithosphere and asthenosphere, increases rapidly throughout the stiff mantle and outer core, and begins to level off in the inner core. Temperature also increases with depth inside Earth. The solid line in the bottom graph in Figure 5-6 shows that temperature increases with depth most rapidly in the lithosphere and asthenosphere. Also shown in this graph are the melting points with depth for the various layers inside Earth (shown as lines with small dashes). Note that some of these melting points, such as those in the stiffer mantle, are quite uncertain. These uncertain values are indicated by question marks on the graph.

Inferred Properties of Earth's Interior

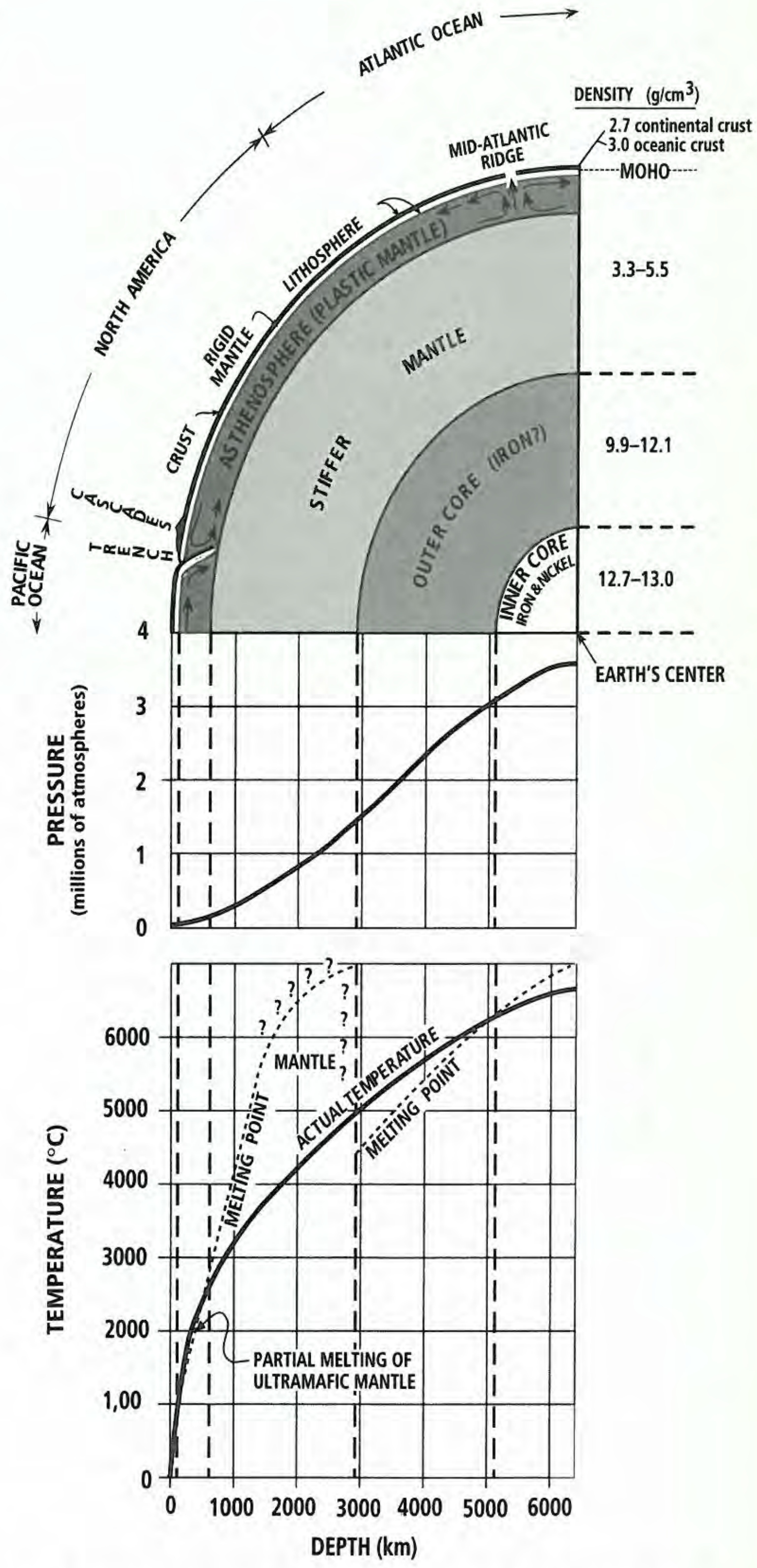


Figure 5-6 Earth's crust and the uppermost part of the mantle form the rigid lithosphere. Beneath the lithosphere is the asthenosphere, the partially molten part of the mantle. Beneath the asthenosphere, a zone of stiffer mantle can be found. Beneath the mantle are the outer core and the inner core, which are composed of mostly iron. The properties of density, pressure, and temperature vary throughout Earth's layers.

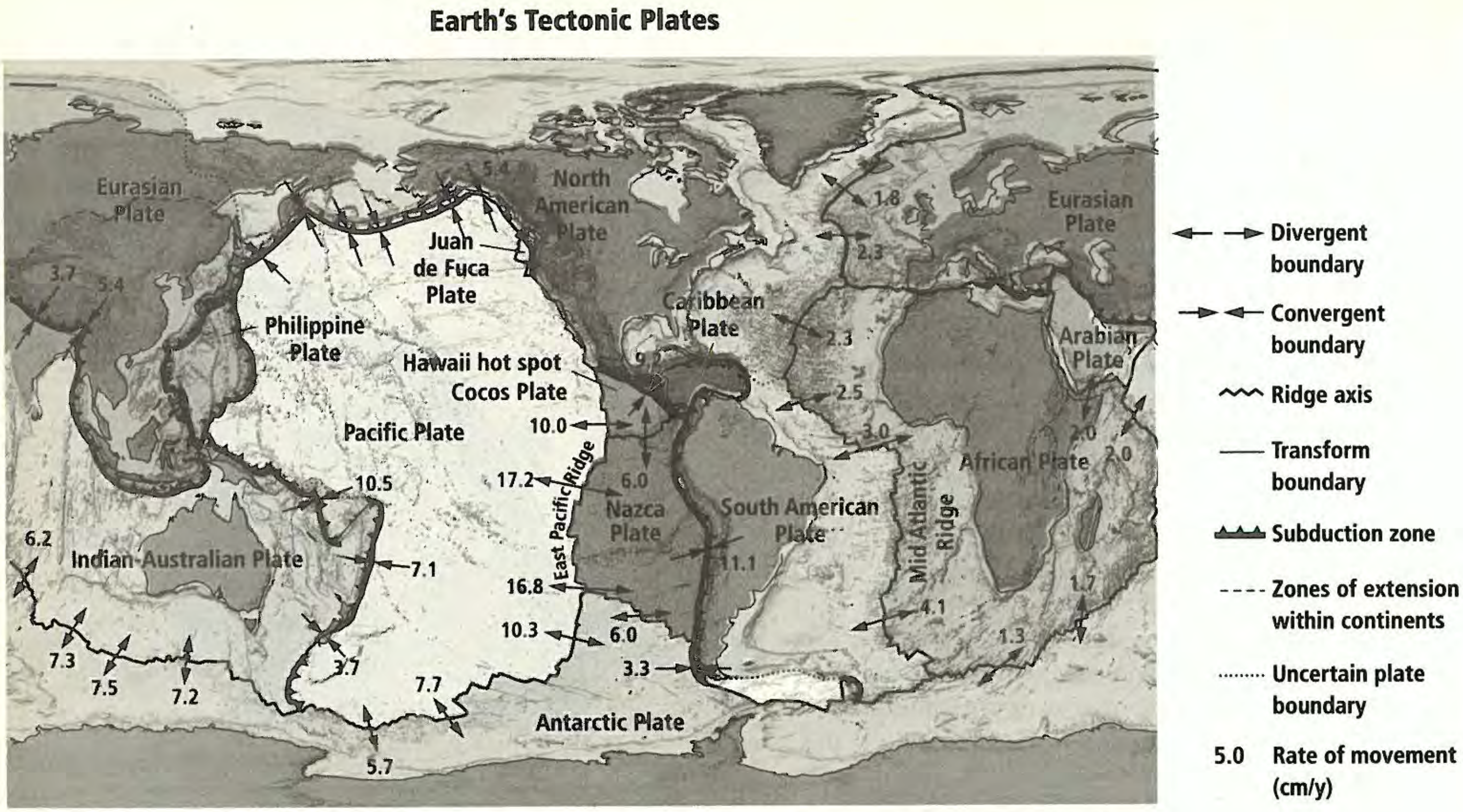

Earth's Tectonic Plates

Figure 5-7 Earth's lithosphere is broken into enormous slabs called plates. These plates move slowly over Earth's surface. At divergent boundaries, plates move apart; at convergent boundaries, plates move toward each other; and at transform boundaries, plates move horizontally past each other.

Plate Boundaries

Earth's lithosphere is broken into a number of major tectonic plates, as shown in Figure 5-7 and in *Tectonic Plates* in the *Earth Science Tables and Charts.* Tectonic Plates interact at places called plate boundaries, or margins. There are three types of plate boundaries: divergent boundaries, convergent boundaries, and transform boundaries. Each plate boundary has different processes and geologic features associated with it.

At **divergent boundaries,** lithospheric plates move away from one another, as shown in Figure 5-8. Most divergent boundaries are on the seafloor, where they form ocean ridges. The actual plate boundary is located in a rift, which is a long, narrow, fault-bounded valley. The process of seafloor spreading begins in this central rift and accounts for the high heat flow associated with divergent boundaries. These plate boundaries are also the sites of many shallow-focus earthquakes and normal faults.

Divergent boundaries can also form on continents. Divergence stretches continental crust to form a long, narrow depression called a **rift valley.** As with divergence on the ocean floor, continental divergence is characterized by high heat flow and shallow-focus earthquakes.

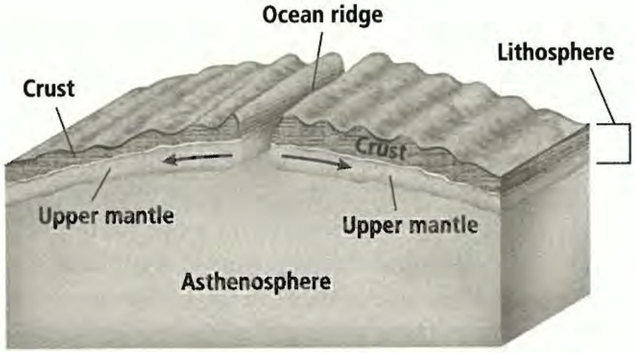
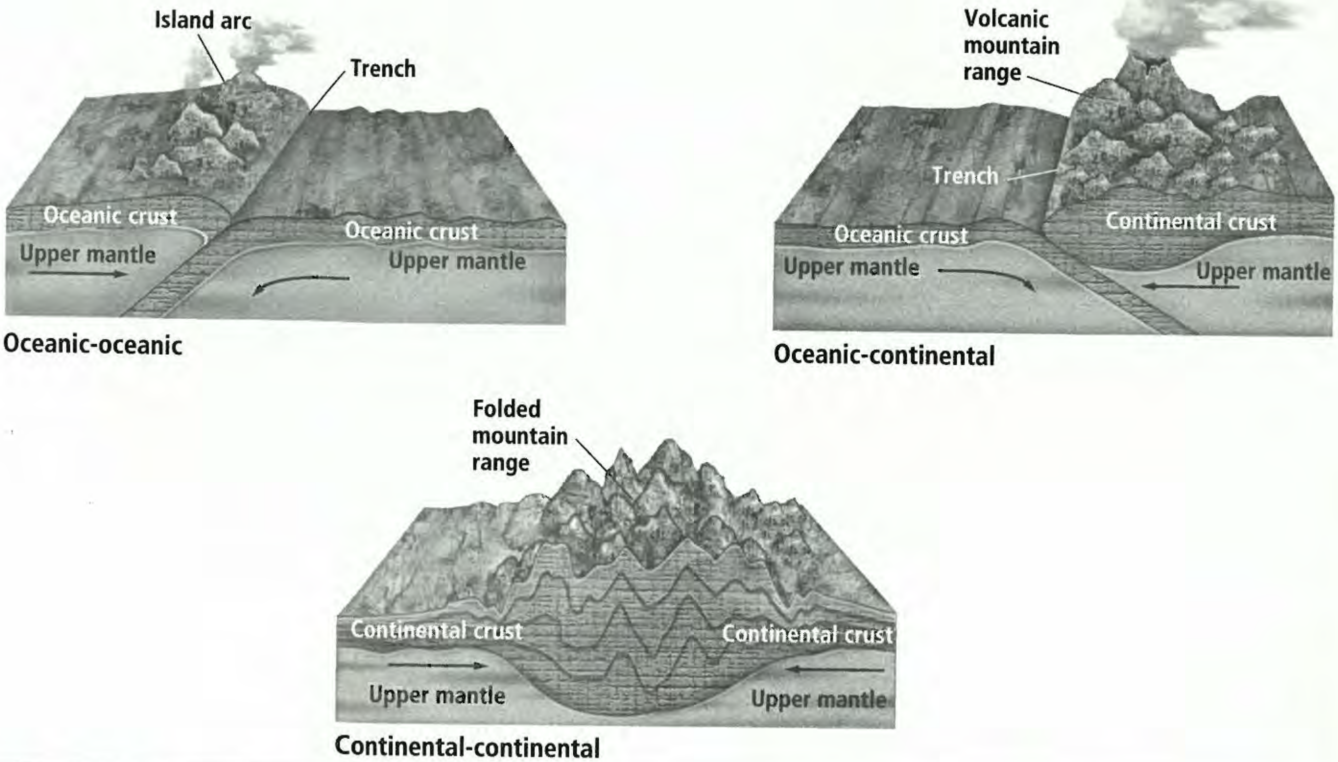


Figure 5-8 Lithospheric plates separate at divergent boundaries. Most divergent boundaries are at the sites of seafloor spreading, where they form ocean ridges.

At **convergent boundaries,** tectonic plates come together, or converge, as shown in Figure 5-9. Convergent boundaries are classified by the type of crust involved. At an oceanic-oceanic boundary, two oceanic plates converge. One plate descends beneath the other to form a deep-sea trench in a process known as **subduction.** During subduction, the descending plate partially melts. The magma that forms is forced toward the surface, where it fuels a series of volcanoes that are parallel to the deep-sea trench. Where the volcanoes rise above sea level, they form island arcs. Convergence

Figure 5-9 Lithospheric plates come together at convergent boundaries.

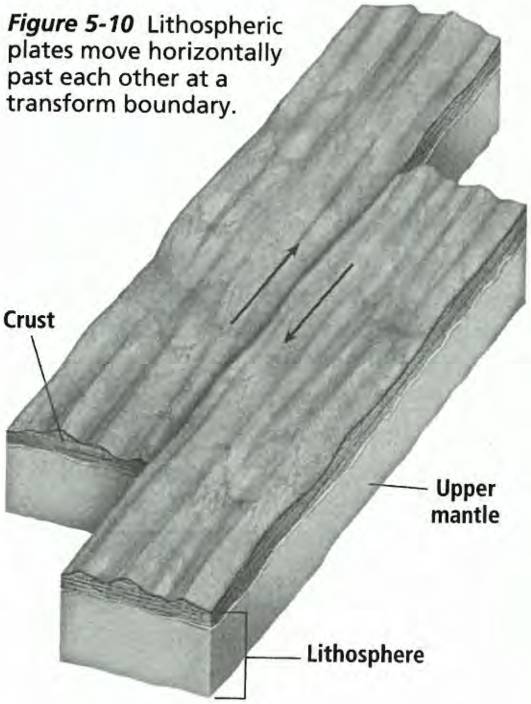


between an oceanic plate and a continental plate causes the oceanic plate, because it is denser, to subduct into the mantle. One result is magma that fuels a series of volcanoes along the edge of the continental plate.

At a continental-continental boundary, neither plate is subducted. One plate overrides the other to form an enormous wedge of continental crust. The forces of convergence deform and fold the crustal wedge to produce some of Earth's highest mountain ranges.

At **transform boundaries,** two plates slide horizontally past each other, as shown in Figure 5-10. Most transform boundaries are on the ocean floor, where they offset segments of divergent boundaries found along ocean ridge systems. Long faults, sometimes hundreds of kilometers long, and shallow-focus earthquakes characterize transform boundaries found along ocean ridge systems. An example of a transform boundary is the San Andreas fault located in California.

Figure 5-10 Lithospheric plates move horizontally past each other at a transform boundary.



Causes of Plate Motions

There are several hypotheses as to what moves lithospheric plates. Each hypothesis is related to Earth's internal heat. The two sources of internal heat for our planet are remnant heat from Earth's formation and the heat generated by the decay of certain radioactive elements. The outward transfer of this heat is thought to generate convection currents in the mantle. These currents, in turn, are related to the motions of lithospheric plates.

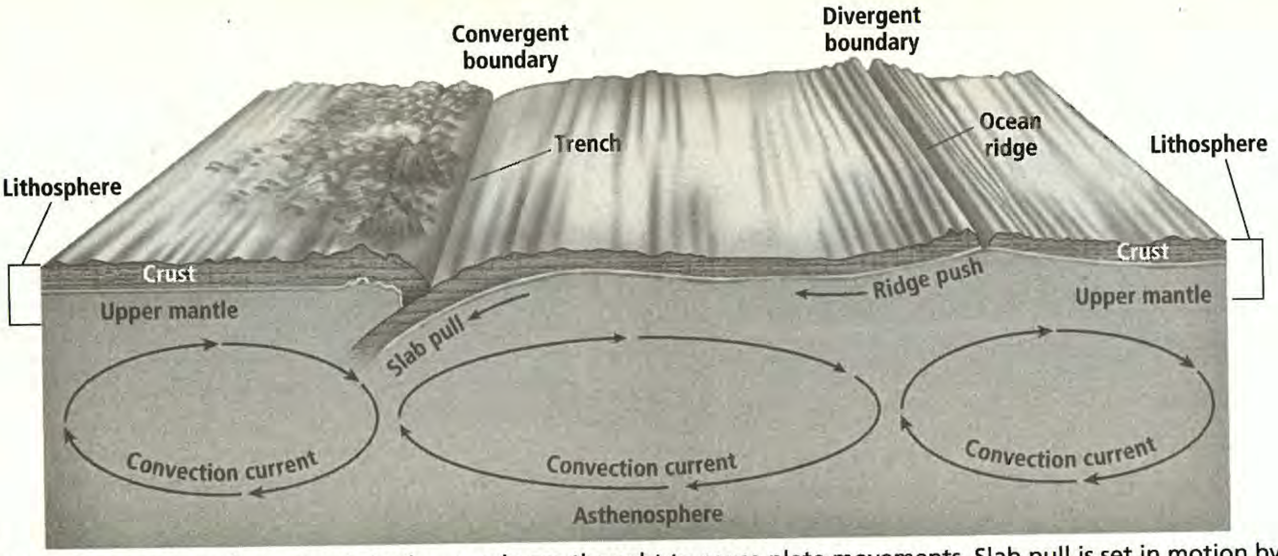


Figure 5-11 Convection currents in the mantle are thought to cause plate movements. Slab pull is set in motion by the downward leg of a convection current. Ridge push is set in motion by the upward leg of a convection current. Slab pull occurs at convergent plate boundaries, and ridge push is associated with divergent plate boundaries.

Mantle Convection

The transfer of thermal energy by the movement of heated matter is known as convection. Convection in the mantle occurs when hot mantle material is forced upward because it is less dense than the surrounding material. As the material is forced upward, it cools, becomes denser, and slowly flows back into the mantle. The convection currents that form may be thousands of kilometers wide and perhaps just as deep.

Push and Pull

One possible explanation of the forces behind plate motions is related to the plates themselves. At a divergent boundary, the rising part of a convection current causes upward and lateral forces. These forces lift the lithosphere and split it to form an ocean ridge. The weight of an uplifted ocean ridge may push an oceanic plate toward a subduction zone in a process called **ridge push,** which is illustrated in Figure 5-11.

Likewise, the descending part of a convection current may cause a sinking force that pulls a tectonic plate downward at a convergent boundary. The weight of a subducting plate helps pull trailing lithosphere into a subduction zone in a process called **slab pull,** also illustrated in Figure 5-11.

Another hypothesis is that the plates move as a result of convection currents in the underlying asthenosphere. Legs of the convection currents exert drag on the bottoms of lithospheric plates, as hot material rises and sinks in the mantle. Yet another explanation is related to plumes of hot mantle material. These plumes seem to rise from deep within the planet and spread laterally as they cool. This lateral motion could cause the overlying plates to move.

SUBTOPIC B
VOLCANIC ACTIVITY

Covers National Science Content Standards UCP.1, UCP.2, UCP.3, UCP.4, UCP.5; A.1, A.2; D.1, D.2, D.3; F.5; G.1, G.2, G.3

Unifying Concepts and Processes

UCP.1	Systems, order, and organization
UCP.2	Evidence, models, and explanation
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UCP.5	Form and function

Science as Inquiry

A.1	Abilities necessary to do scientific inquiry
A.2	Understandings about scientific inquiry

Earth and Space Science

D.1	Energy in the Earth system
D.2	Geochemical cycles
D.3	Origin and evolution of the Earth system

Science in Personal and Social Perspectives

F.5	Natural and human-induced hazards

History and Nature of Science

G.1	Science as a human endeavor
G.2	Nature of scientific knowledge
G.3	Historical perspectives

VOCABULARY

viscosity
pluton
sill
dike
vent
crater
caldera
shield volcano
cinder-cone volcano
composite volcano
hot spot

Most of Earth's igneous activity occurs deep below the surface. There magma cools and solidifies to form massive igneous rock bodies of various shapes and sizes. A more obvious type of igneous activity, however, is volcanoes. Sometimes the lava flows from these openings in the crust are spectacular geologic events that spew tons of volcanic rock and lava into the atmosphere.

Magma

All igneous activity is ultimately due to the formation and movement of magma. The formation of magma depends on three factors: the temperature and pressure to which a rock is subjected, the presence of water, and the composition of the rock that melts. Most rocks melt at temperatures between about 800°C and 1200°C. Such temperatures exist at the base of the lithosphere and the top of the asthenosphere. Pressure, like temperature, increases with depth. As pressure increases, the temperature at which a rock melts also increases. Water plays an important role in whether a rock will melt to form magma. At any given pressure, a wet rock melts at a lower temperature than the same rock under dry conditions. The type of magma that forms depends on the composition of the melting rock.

Types of Magma

The three basic types of magma are basaltic magma, andesitic magma, and rhyolitic magma, as shown in Table 5-1. Basaltic magma forms when rocks in the upper mantle melt. This type of magma contains small amounts of silica and dissolved gases. Basaltic magma fuels the volcanoes of the Hawaiian Islands and Iceland.

Table 5-1 Magma Characteristics

	Basaltic magma	Andesitic magma	Rhyolitic magma
Source material	Upper mantle	Oceanic crust and ocean sediments	Continental crust
Viscosity	Low	Intermediate	High
Gas content	1–2%	3–4%	4–6%
Silica content	About 50%	About 60%	About 70%
Explosiveness	Low	Intermediate	High
Location of magma	Oceanic and continental crust	Continental margins at subduction zones	Continental crust

The source materials for andesitic magma include oceanic crust and oceanic sediments. This type of magma is common along continental margins associated with subduction zones. Its intermediate amounts of silica and gas make the volcanoes fueled by this type of magma rather explosive. Mount St. Helens in Washington State, Mount Mayon in the Philippines, and Mount Fuji in Japan are volcanoes fueled by andesitic magma.

Rhyolitic magma has the same composition as granite, an intrusive igneous rock. This magma forms when molten material mixes with overlying continental crust. The high silica content and the large amount of dissolved gases make the volcanoes fueled by this type of magma very explosive. The dormant, or inactive, volcanoes near Yellowstone National Park in the United States were fueled by rhyolitic magma.

Viscosity

Viscosity is internal resistance to flow. Motor oil and molasses have high viscosity. Water and vinegar, on the other hand, have low viscosity. The viscosity of magma and lava depends on temperature and composition. Hotter magma or lava is less viscous than cooler magma or lava. In other words, as the temperature of magma or lava increases, viscosity decreases.

The amount of silica in magma or lava also affects viscosity. Magma and lava high in silica are more viscous than molten materials low in silica. Rhyolitic magma and lava are extremely viscous because they contain large amounts of silica. Basaltic magma and lava are at the other extreme; they are low in silica and therefore are not very viscous.

Plutons

Magma is less dense than surrounding rock and thus is forced slowly upward toward Earth's crust. When magma intrudes into the crust, it makes space for itself in various ways. First, magma can fracture overlying rocks. It then enters the fractures. Second, magma can break off large blocks of overlying rock. These blocks of rock sink into the magma chamber, where they melt into the magma. The spaces that once held the blocks are then filled by the ascending magma. Third, magma makes space for itself by melting the rocks into which it intrudes. Once again, the voids are filled by the rising magma.

As magma rises toward the crust, it cools and often solidifies to form intrusive igneous rock bodies called **plutons.** Plutons are classified based on their size, shape, and relationship to the rocks into which they intrude, as shown in Figure 5-12. Some plutons are parallel to the rocks they intrude; others cut across preexisting rocks.

Batholiths and Stocks

Batholiths, which cover areas of at least 100 km^2, are the largest plutons. Batholiths are irregular intrusions composed of coarse-grained, intrusive igneous rocks. Most batholiths have thick, fingerlike lobes that extend from a funnel-shaped central region. Batholiths are found in the cores of tectonically deformed mountain belts.

Scientists hypothesize that most batholiths form as the result of mountain building associated with tectonic plate boundaries. Some batholiths may form when continental-continental convergence forces crust into the upper mantle. There the crust melts, intrudes into the overlying rocks, and eventually cools to form batholiths.

Batholiths also form as a result of oceanic-continental convergence and oceanic-oceanic convergence. As a subducted plate descends into the mantle, parts of it melt to form magma. As this magma moves toward the crust, it cools and solidifies to form enormous intrusive rock bodies. The Sierra Nevada Batholith formed as the result of at least five episodes of igneous activity beneath what is now California.

A stock is another type of irregular pluton. Stocks are similar to batholiths, but are much smaller. Batholiths and stocks cut across the rocks into which they intrude, and generally form at depths between 10 km and 30 km.

Laccoliths

Laccoliths are mushroom-shaped plutons that form when magma intrudes into parallel rocks relatively close to the surface, as shown in Figure 5-12. As the magma intrudes, the overlying rocks bow upward. Compared to batholiths and stocks, laccoliths are small intrusive bodies probably not much more than a few kilometers wide. The Henry Mountains in southeastern Utah and the Black Hills of South Dakota include several laccoliths.

Sills and Dikes

A **sill** is a relatively small pluton that is parallel to the rocks into which it intrudes, as shown in Figure 5-12. Sills range from a few centimeters to hundreds of meters thick. They cause low-grade metamorphism in the rocks above and below them. The Palisades Sill, which is exposed along the western shore of the Hudson River in New York and New Jersey, is one of the largest sills in the world and is about 300 m thick.

As shown in Figure 5-12, a **dike** is a pluton that cuts across the rocks into which it intrudes. Dikes can form when magma enters existing cracks in surrounding rock bodies. Dikes also form when the force of the intruding magma cracks and enters surrounding rocks. Unlike sills, dikes rarely occur alone. Hundreds or thousands of dikes are common in areas deformed by large igneous intrusions. Like sills, dikes vary in thickness from a few centimeters to many meters.

Volcanoes

Magma chambers (pockets of molten rock) deep within Earth fuel the volcanoes that erupt on the surface. When magma reaches Earth's surface, it is called lava. Lava erupts through an opening in the crust called a **vent.** Successive eruptions can lead to the accumulation of volcanic material that forms a volcano. At the top of a volcano is a steep-walled depression called a **crater.** Volcanic craters greater than about 1 km in diameter are known as **calderas.** Calderas form when the top or sides of a volcano collapse into the magma chamber that fuels the volcano.

Types of Volcanoes

Volcanoes can be classified according to their shape and their eruptive patterns. Using these criteria, volcanologists recognize three types of volcanoes: shield volcanoes, cinder-cone volcanoes, and composite volcanoes.

Shield volcanoes form from successive eruptions of fluid, basaltic lava. A shield volcano has broad, gently sloping flanks (sides) and a nearly circular base, as shown in Figure 5-13. Shield volcanoes are thought to form in stages. Early in a shield volcano's formation, basaltic lava flows quite frequently. As the volcano grows, eruptions occur from the central vent and the flanks of the volcano. The summit (top) collapses after each eruptive phase. As the volcano gets older, it erupts less frequently, and the lava changes composition, becoming more viscous.

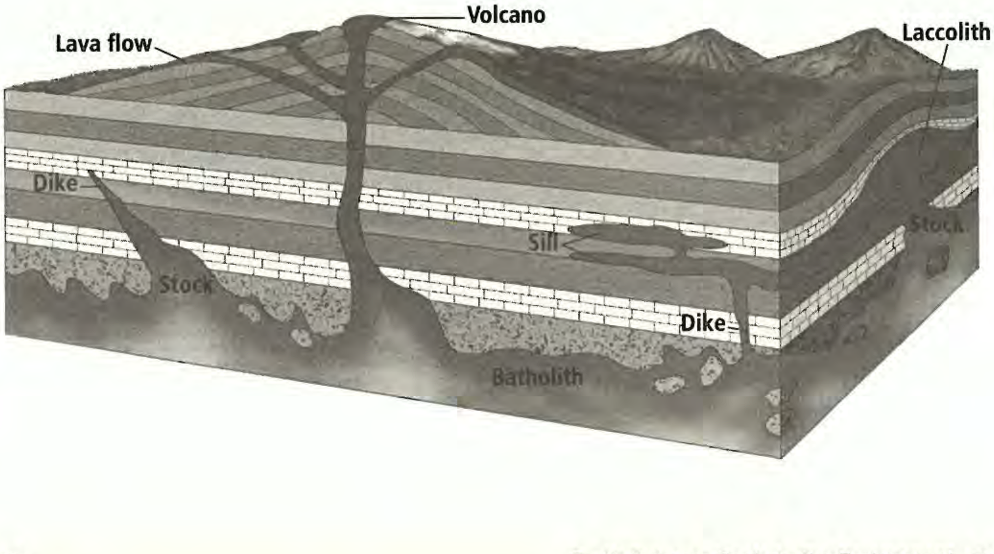


Figure 5-12 Intrusive igneous activity forms bodies of rock called plutons. It also fuels the volcanoes that form on Earth's surface.

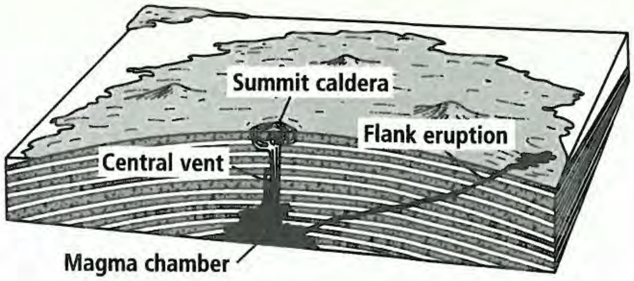


Figure 5-13 A shield volcano is a mountain with broad, gently sloping sides and a nearly circular base. Shield volcanoes form as basaltic lava flows over Earth's surface and accumulates to form a cone.

Probably the best known shield volcanoes are in the Hawaiian Islands. Mauna Loa, for example, is one of the five shield volcanoes that make up the island of Hawaii. This volcano is probably the largest on Earth. Its base rests over 5000 m below sea level on the Pacific Ocean floor, while its summit towers about 4170 m above sea level. Mauna Loa formed as the result of numerous volcanic eruptions over the past 1 million years.

Cinder-cone volcanoes form as expanding gases throw volcanic material high into the air. This material accumulates around the vent to form a small, steep-sided volcano with concave slopes, as shown in Figure 5-14. Cinder-cone volcanoes are much smaller than shield volcanoes; most are less than 500 m high. The magma that fuels cinder cones is more viscous than the basaltic magma that fuels shield volcanoes. Therefore, cinder-cone volcanoes are much more explosive than shield volcanoes. Cinder-cone volcanoes often occur on or near much larger volcanoes.

One well-known cinder-cone volcano is Paricutín, which formed literally overnight in a cornfield a few hundred kilometers west of Mexico City in the early 1940s. Within a day, the volcano reached a height of 40 m. By the fifth day, it was over 100 m high. The last eruption of Paricutín formed a crater at the top of the volcano. Molten material then quietly poured out of the cone and moved down the volcano's flanks as lava. This cycle of volcanic activity—numerous eruptions, formation of a volcanic cone and a crater, and subsequent lava flows—is typical for cinder-cone volcanoes

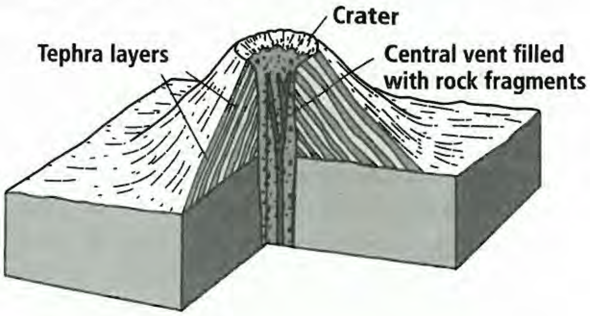


Figure 5-14 Cinder volcanoes are small, steep-sided volcanoes that form as tephra (volcanic debris) accumulate around a volcanic vent.

Composite volcanoes are made of alternating layers of lava and volcanic fragments, as shown in Figure 5-15. The andesitic magma that fuels composite volcanoes is very viscous as a result of its high silica content. Andesitic magma also has a high water and gas content. Therefore, composite volcanoes are the most explosive type of volcano.

Mount Vesuvius in Italy is a composite volcano that completely destroyed the city of Pompeii in 79 A.D. The volcano, which had been dormant for centuries, erupted for several days. It killed nearly 2000 people, many of whom were preserved for centuries by the blanket of hot ash that covered the city.

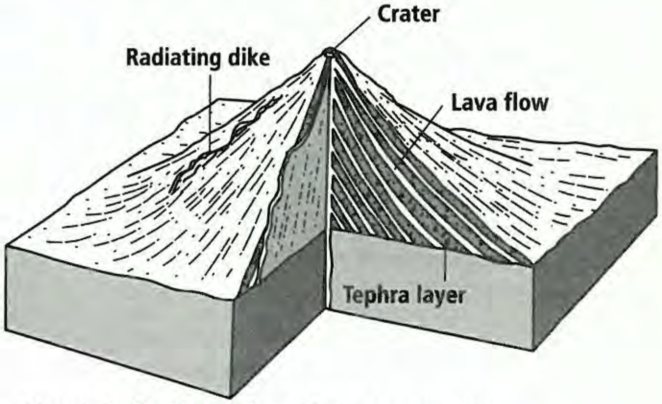


Figure 5-15 Composite volcanoes are very explosive volcanoes composed of alternating layers of tephra and lava.

Volcanic Materials

Rock fragments thrown into the air by an erupting volcano are called tephra, or pyroclastic materials. Tephra can be newly hardened lava fragments, minerals that started to form before the eruption, or pieces of the volcano itself. Tephra range in size from very fine dust to debris as large as houses, as shown in Table 5-2.

Table 5-2 Descriptions and Sizes of Tephra

Tephra	Description
Volcanic dust	< 0.25 mm in diameter
Ash	> 0.25 mm but < 2 mm in diameter
Lapilli	> 2 mm but < 64 mm in diameter
Volcanic blocks	large, angular fragments
Volcanic bombs	are ejected as lava and cool to form large, rounded, streamlined pieces of rock

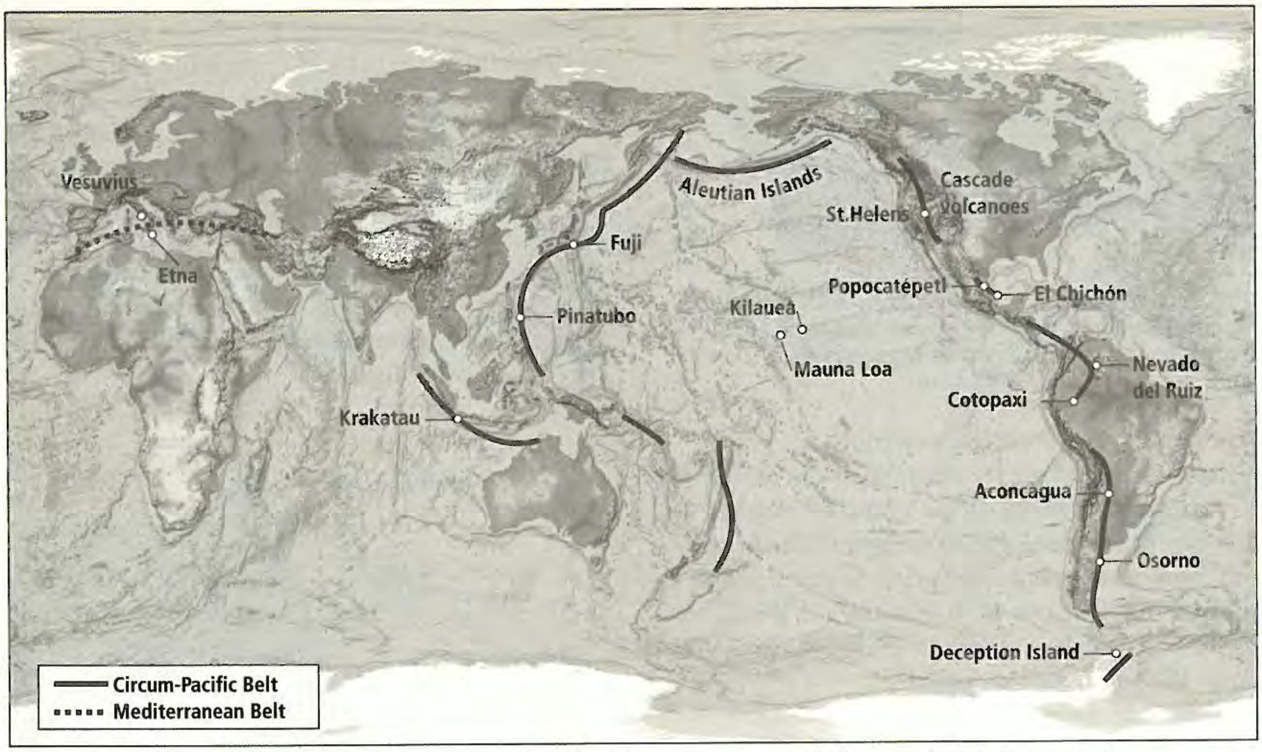


Figure 5-16 Most volcanism on Earth is associated with convergent and divergent plate boundaries. Only about 5 percent of Earth's volcanoes form far from plate boundaries.

Hazards Associated with Volcanoes

Although tephra can cause considerable damage as they fall back to Earth, pyroclastic flows are much more dangerous and devastating. A pyroclastic flow is an extremely hot cloud of gas, ash, and other tephra that thunders down the slopes of a volcano at speeds of up to 200 km/h. One of the most devastating pyroclastic flows in recorded history occurred in 1902 on the Caribbean island of Martinique. The flow had an internal temperature of more than 700°C. It exploded from the side of Mount Pelée and raced down the volcano at 160 km/h. In less than a minute, 29 000 people died, and the flow destroyed everything in its path.

Lava contains many dissolved gases that are released into the air when a continental volcano erupts. These gases can rise tens of kilometers into the air and linger there for years. Gases that pose the greatest potential hazard to people, animals, property, and agriculture are sulfur dioxide, carbon dioxide, and hydrogen fluoride. Sulfur dioxide can result in acid precipitation and air pollution; promote ozone depletion; lower Earth's surface temperature; and irritate the skin, eyes, nose, and throat. Carbon dioxide can accumulate in low-lying areas and soil where it can be lethal to all types of organisms. Fluorine compounds accumulate on fine-grained ash particles, which can kill organisms that ingest them.

Communication and preparedness can prevent injuries and save lives during major volcanic eruptions. Many countries monitor active volcanoes and have warning systems in place. Emergency-response exercises are carried out in most volcanically active parts of the world, and many community projects and activities are aimed at increasing people's awareness of volcanic hazards. However, in the cases of some volcanic eruptions, such as the eruption of Mount Pelée, no warning is possible. In such cases, death and destruction often will result.

Where do volcanoes form?

Most of Earth's volcanoes are associated with tectonic plate boundaries. About 80 percent of all volcanoes are located on convergent boundaries. Another 15 percent are located on divergent boundaries. Only about 5 percent of Earth's volcanoes erupt far from plate boundaries.

Convergent Volcanism

At a convergent boundary that involves an oceanic plate, subduction occurs. The oceanic plate descends into the mantle. Because pressure and temperature increase with depth, parts of the oceanic plate melt to produce magma. The magma is less dense than surrounding mantle material, and so it is forced upward toward the crust. When the magma breaks through the crust, volcanoes erupt. When two oceanic plates converge, an island arc complex forms. When an oceanic plate converges with a continental plate, a chain of volcanic intrusive mountains forms.

The volcanoes associated with convergent plate boundaries form two distinct volcanic belts, as shown in Figure 5-16. The larger one is the Circum-Pacific Belt. It runs parallel to the west coasts of the Americas, across the Aleutian Islands, and down the east coast of Asia. Many well-known volcanoes are found in the Circum-Pacific Belt, including Mount St. Helens in Washington, Mount Fuji in Japan, and Mount Pinatubo in the Philippines. Trenches are also associated with some convergent plate boundaries, as shown in Figure 5-9 on page 103.

The second prominent volcanic belt is the Mediterranean Belt, which runs from the northern tip of Africa through southern Europe. It is much smaller than the Circum-Pacific Belt. Two well-known volcanoes in the Mediterranean Belt are Mount Etna and Mount Vesuvius, both of which are located in Italy.

Divergent Volcanism

At a divergent boundary, two tectonic plates move apart. Magma is forced upward to fill the rift that is created. Most of Earth's rift volcanism occurs along ocean ridges. When the magma cools, new oceanic crust forms. As the plates continue to move apart, the newly formed oceanic crust moves slowly away from the ridge. Volcanoes that result from divergence include Surtsey, Eldfell, and the other volcanoes that dot the island of Iceland, which is a part of the Mid-Atlantic Ridge.

Hot Spots

Some volcanoes form over **hot spots,** unusually hot regions of Earth's mantle where high-temperature plumes of molten material rise toward Earth's surface. The intense heat from these plumes melts surrounding rocks to form magma. This magma is forced up and breaks through the crust to fuel volcanoes. As a tectonic plate moves over a hot spot, a chain of volcanoes forms.

The Hawaiian Islands are the classic example of hot-spot volcanism. New islands continue to form as the Pacific Plate moves over a mantle hot spot. Volcanoes on the oldest Hawaiian Island of Kauai are inactive because the island no longer sits over the hot spot. Earth's most active volcano, Kilauea, is currently located over the hot spot. Another volcano, Loihi, is forming on the ocean floor and may form a new island in the future.

Another product of hot spots are flood basalts. These deposits erupt from fissures, or long fractures in Earth's crust, to produce extensive plains or plateaus of igneous rock. The Columbia River Basalts in the northwest United States are flood basalts that contain an estimated 170 000 km^3 of basalt.

SUBTOPIC C
EARTHQUAKES

Covers National Science Content Standards UCP.1, UCP.2, UCP.3, UCP.4, UCP.5; A.1, A.2; B.4; D.1; F.5; G.1, G.2, G.3

Unifying Concepts and Processes

UCP.1	Systems, order, and organization
UCP.2	Evidence, models, and explanation
UCP.3	Change, constancy, and measurement
UCP.4	Evolution and equilibrium
UCP.5	Form and function

Science as Inquiry

A.1	Abilities necessary to do scientific inquiry
A.2	Understandings about scientific inquiry

Physical Science

B.4	Motions and forces

Earth and Space Science

D.1	Energy in the Earth system

Science in Personal and Social Perspectives

F.5	Natural and human-induced hazards

History and Nature of Science

G.1	Science as a human endeavor
G.2	Nature of scientific knowledge
G.3	Historical perspectives

VOCABULARY

stress
strain
fault
primary wave (*P*-wave)
secondary wave (*S*-wave)
focus
epicenter
seismometer
seismogram
shadow zone
magnitude
Richter scale
modified Mercalli scale
tsunami
seismic gap

Earthquakes are vibrations of the ground that happen when bodies of rock suddenly break. These intense vibrations travel outward from the initial point of rupture and can be very destructive. By studying these vibrations, scientists have been able to infer Earth's internal structure and composition. Earthquake studies have also enabled scientists to determine the earthquake history of an area and to use this information to try to predict these destructive

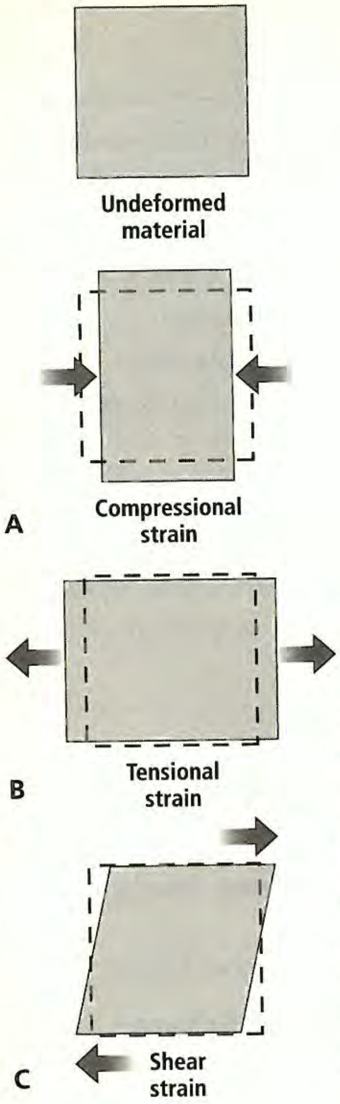


Figure 5-17
Stresses are the forces that act on a material. Strain is the deformation of a material in response to stress. Compressional forces make a material shorter (A). Tensional forces make a material longer (B). Shear forces distort a material (C).

events. Finally, earthquakes are yet another indicator of the dynamic nature of the Earth system.

Forces and Faults

Most earthquakes occur when rocks fracture deep within Earth. Rocks fracture when they are subjected to **stress,** a force acting on the rocks. Fractures form when the stress exceeds the strength of the rocks. Deformation of rocks in response to stress is **strain.**

Three kinds of stress can be exerted on Earth's rocks: compression, tension, and shear. Compression pushes on rocks from directly opposite sides. It makes material shorter, as shown in Figure 5-17A. Tension pulls on rocks from directly opposite sides. It makes material longer, as shown in Figure 5-17B. Shear makes material twist. It distorts material, as shown in Figure 5-17C.

Low stresses result in deformation known as elastic strain. Elastic strain bends or stretches a material. When the stress becomes zero, however, the strain disappears. High stresses result in strain known as ductile deformation. This type of strain produces permanent deformation even when the stress becomes zero. When stress exceeds the strength of a material, the material fails or breaks.

Faults

Fractures in rocks along which movement has occurred are called **faults.** Fault movement takes place on a surface called the fault plane, which can be vertical, horizontal, or at an angle. In diagrams, small arrows show the direction of movement of the rocks.

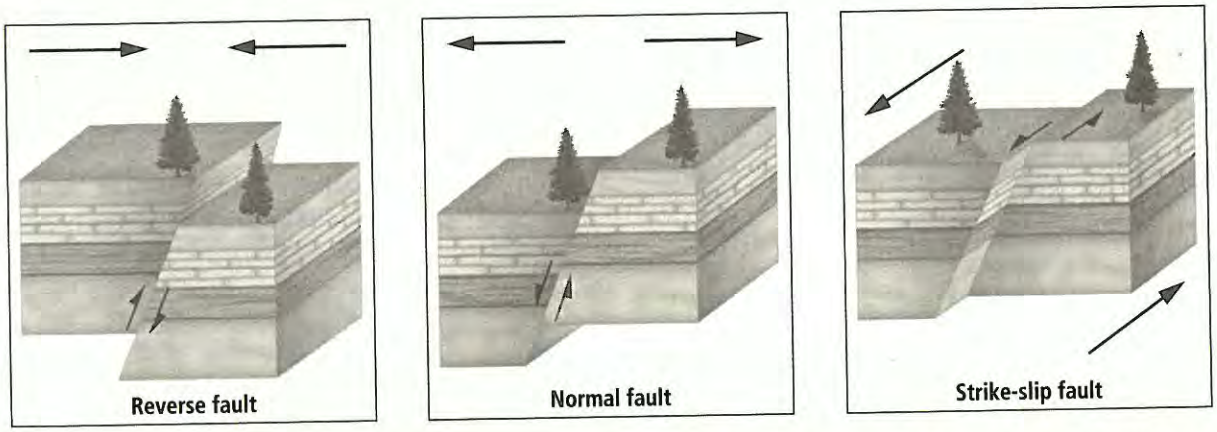
The three basic types of faults are shown in Figure 5-18. Reverse faults are fractures that form with horizontal compression. Compression makes the crust shorter. Very low-angle reverse faults are called thrust faults. Normal faults are fractures that form with horizontal tension. Tension makes the crust longer. Strike-slip faults are fractures that form with horizontal shear. Shear distorts the crust.

Seismic Waves

Earthquakes are natural vibrations of the ground caused by movements along faults. Irregularities in the rocks involved make the rocks snag and lock so that stress builds up. When the rocks reach their elastic limit, they break and produce an earthquake.

The vibrations of the ground during an earthquake are called seismic waves. **Primary waves,** which are also called ***P*-waves** or compressional waves, compress and dilate rocks in the same direction as the waves are traveling, as shown in Figure 5-19A. *P*-waves travel through crustal rocks at about 6 to 7 km/s. They travel through mantle rocks at about 8 km/s. **Secondary waves,** which are also called ***S*-waves** or

Figure 5-18
A fault is a fracture in Earth's rocks along which movement takes place. Reverse faults result from compression. Normal faults result from tension. Strike-slip faults result from shear.



shear waves, oscillate rocks at right angles to the direction of wave movement, as illustrated in Figure 5-19B. *S*-waves travel at about half the velocity of *P*-waves.

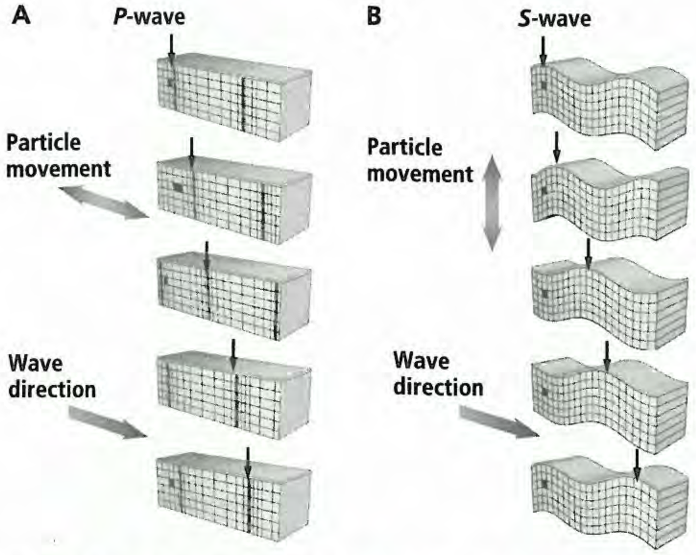


Figure 5-19 Seismic waves are generated by earthquakes. *P*-waves are seismic waves that compress and dilate rock particles as they pass. Particle movement is in the same direction as the seismic wave movement. *S*-waves move rock particles at right angles to the direction of wave movement.

Because they travel through Earth's interior, *P*-waves and *S*-waves are sometimes called body waves. Body waves travel outward from the initial point of failure of deep rocks. This point of failure, where an earthquake originates, is the **focus** of the earthquake, as shown in Figure 5-20. The point at Earth's surface that is directly above the focus is the **epicenter** of the earthquake, also shown in Figure 5-20.

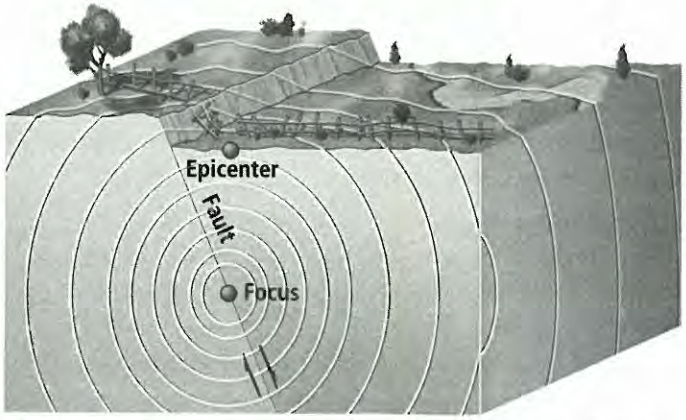


Figure 5-20 The focus of an earthquake is the point of initial fault rupture. The surface point directly above the focus is called the epicenter.

Earthquake Classification

Earthquakes can be classified by the depth of their focus. Shallow earthquakes have foci between the surface and a depth of about 60 km. Earthquakes associated with ocean ridges are always shallow. Intermediate earthquakes originate between about 60 km and 300 km below Earth's surface. Deep earthquakes have foci greater than 300 km below the surface. Almost all deep earthquakes occur in the Circum-Pacific Belt. Most of these deep-foci seismic events occur landward of deep-ocean trenches.

Seismic Waves and Earth's Interior

Every earthquake generates both *P*-waves and *S*-waves. Instruments called seismographs, or **seismometers,** detect and record these waves. A seismometer has a frame anchored to the ground. A spring or a wire suspends a mass from the frame. When the ground vibrates, the frame of the seismometer vibrates, but the suspended mass remains stationary. The movement of the mass relative to the frame is recorded on paper or on a computer disk. An example of a seismometer is shown in Figure 5-21. The record produced by a seismometer during an earthquake is called a **seismogram,** shown in Figure 5-22. Note that *P*-waves, because they travel more rapidly than *S*-waves, are the first seismic waves to arrive at a seismic station.

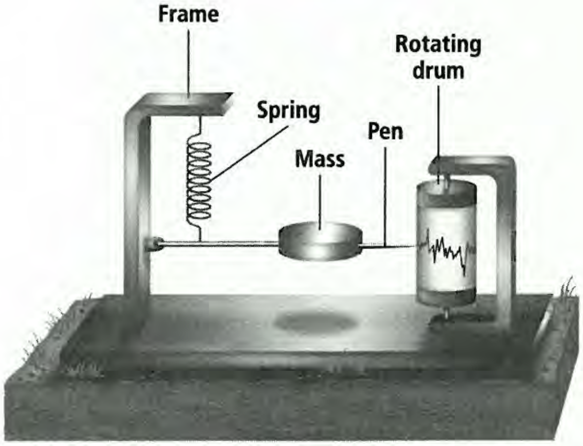
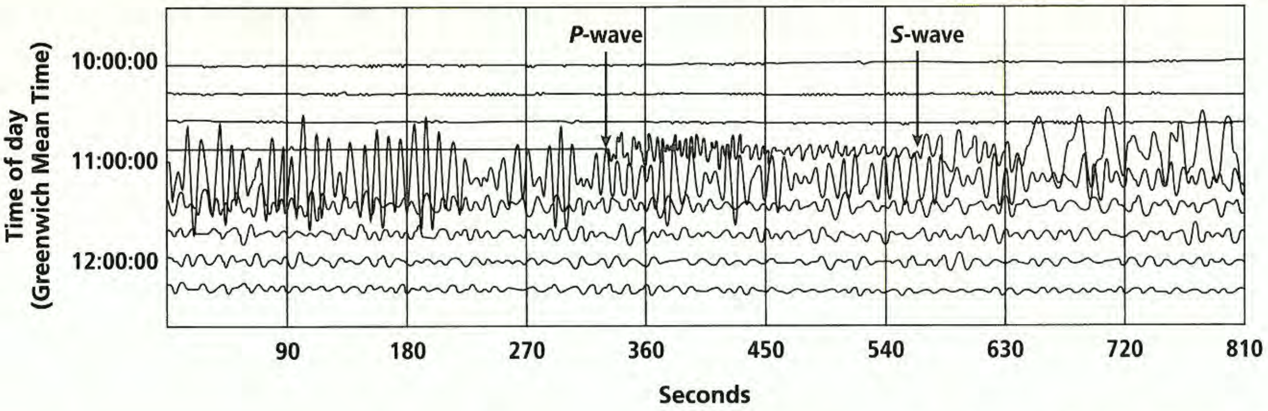


Figure 5-21 A seismometer consists of a frame, a spring, a mass, a pen, and a rotating drum.

Travel-Time Curves

Data from countless earthquakes have been used to construct travel-time curves like the ones shown in Figure 5-23 and in *Earthquake* P*-wave and* S*-wave Travel Time* in *Earth Science Tables and Charts.* Travel-time curves show the time it takes for *P*-waves and *S*-waves to travel from an earthquake's epicenter to seismic stations around the globe. The farther a seismic station is from an epicenter, the greater the time between the arrival of *P*-waves and *S*-waves. Figure 5-24 on page 113 demonstrates how to use travel-time curves to find the distance to an earthquake's epicenter and the time when the earthquake occurred.

Figure 5-22 A seismogram is a record of the seismic waves generated by an earthquake.



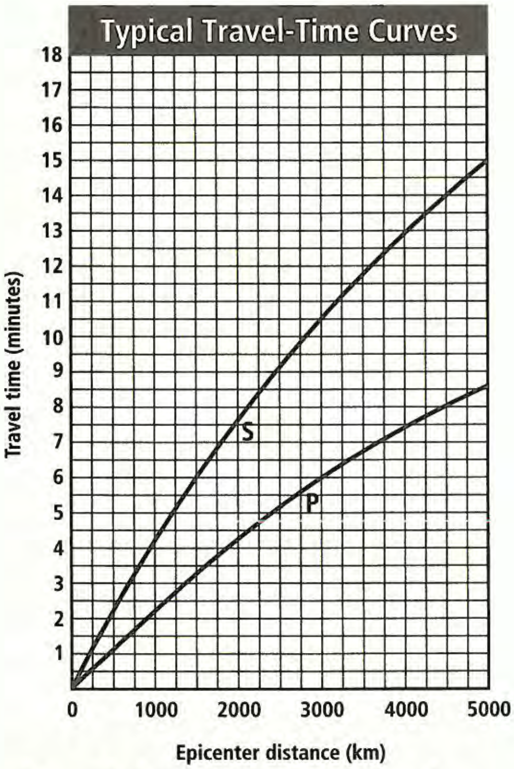


Figure 5-23 Travel-time curves show how fast seismic waves travel. The distance between the epicenter and a seismic station is the epicentral distance for that station.

Clues to Earth's Internal Structure

Seismic waves provide information not only about the distance to an earthquake's epicenter but also about Earth's internal structure. When *P*-waves and *S*-waves encounter a different medium, they are reflected, transmitted, and refracted, as shown in Figure 5-25. Note that *P*-waves and *S*-waves travel along fairly direct paths through the crust and mantle. When *P*-waves strike the core, however, they are refracted so that they disappear beyond a distance of about 11 000 km from the earthquake's focus. The refracted *P*-waves reappear at a distance of about 16 000 km from the focus. The region that doesn't receive any direct *P*-waves is called the *P*-wave **shadow zone.** *S*-waves are shear waves and can't travel through liquids. Thus, *S*-waves can't enter the core, and they do not reappear beyond the *P*-wave shadow zone.

Earth's Composition

The travel times of *P*-waves and *S*-waves indicate that Earth's lithosphere (its crust and rigid upper mantle) is made primarily of three types of igneous rock: granite, basalt, and peridotite. Granite and basalt make up the bulk of continental and oceanic crust, respectively. Peridotite makes up the bulk of the mantle. Earth's lower mantle is most likely composed of simple oxides containing iron, silicon, and magnesium. Earth's core is extremely dense and is probably made of iron and nickel.

Information on Earth's composition provided by seismic waves is supported by studies of meteorites. Meteorites are pieces of asteroids, solid rock bodies that orbit the Sun. Asteroids are believed to have formed at about the same time and in much the same way as the planets in the solar system. Most meteorites are composed of iron, nickel, and pieces of rock similar to peridotite, in roughly the same proportions as the rocks thought to make up Earth's core and mantle.

Measuring Earthquakes

Approximately a million or so earthquakes shake Earth each year. Most earthquakes are barely felt and are registered only by sensitive seismometers.

Richter Magnitude

The **magnitude** of an earthquake describes the amount of energy the earthquake releases. The **Richter scale** is a measure of earthquake magnitude based on the amount of ground movement caused by the earthquake's seismic waves. Each successive value on the Richter scale represents a tenfold increase in wave amplitude. For example, the seismic waves of a magnitude-3 earthquake on the Richter scale are ten times larger than the seismic waves generated during a magnitude-2 earthquake, and 100 times larger than the seismic waves generated by a magnitude-1 earthquake. Each successive value on the Richter scale also corresponds to about a 32-fold increase in energy.

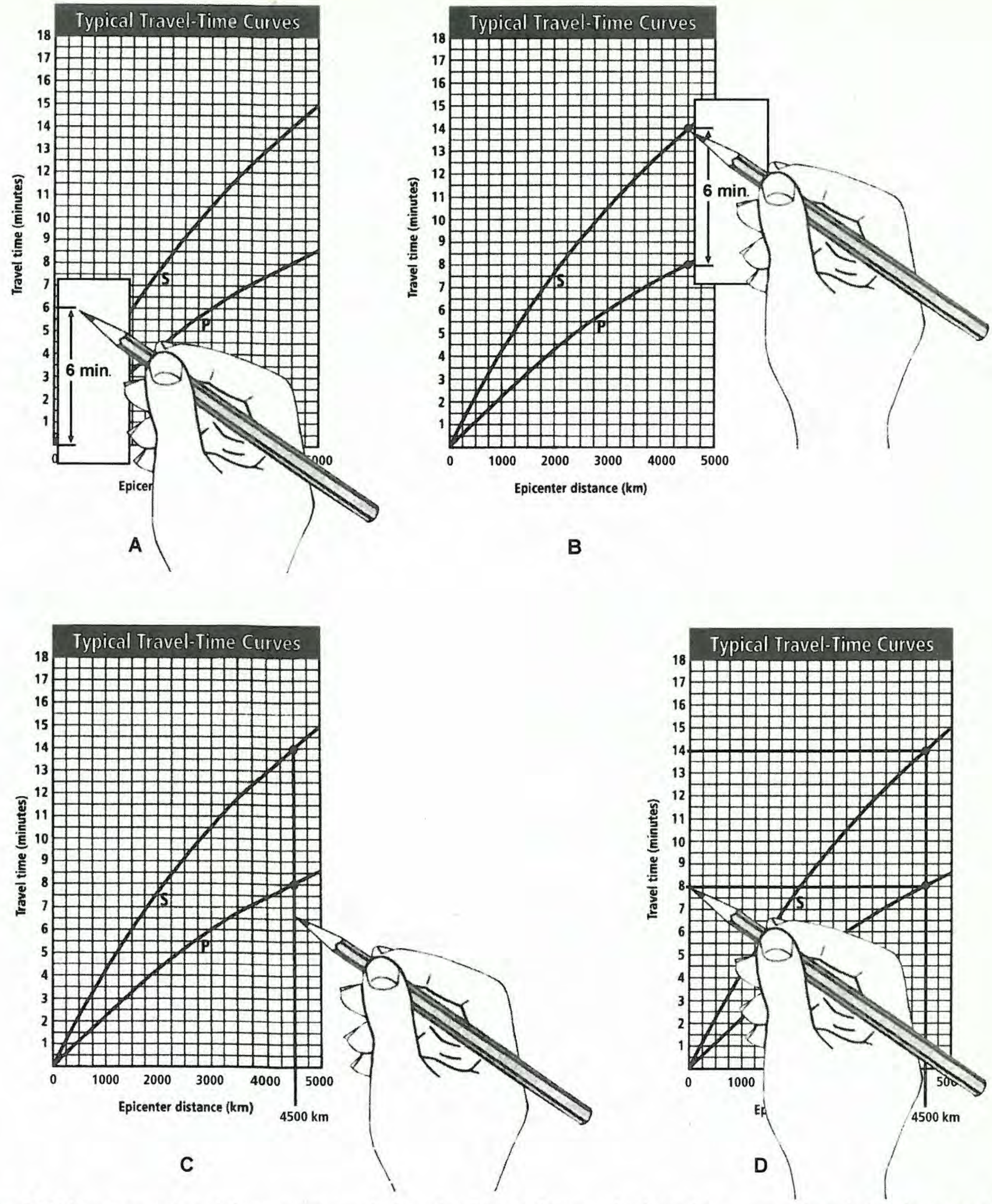


Figure 5-24 You can use travel-time curves to calculate the distance from a seismic station to an earthquake's epicenter and to determine when the earthquake occurred. Suppose *P*-waves arrive at a seismic station 6 minutes before *S*-waves arrive. Place a strip of paper along the lower part of the vertical axis in Figure 5-23 or in *Earthquake* P*-wave and* S*-wave Travel Time* in *Earth Science Tables and Charts.* Mark the distance that corresponds to 6 minutes on the strip of paper (A). Keeping the strip of paper vertical, move it to the right along the curves until the top mark intersects the S curve and the bottom mark intersects the P Curve; draw a dot at each intersection (B). Connect the dots with a vertical line and extend the line to the bottom of the graph (C). The point where the line crosses the horizontal axis is the distance to the epicenter (4500 km in this example). Now draw a horizontal line from either dot to the left edge of the graph (D). The point where that line crosses the vertical axis indicates when the earthquake occurred. In this example, the earthquake occurred 8 minutes before the *P*-wave and 14 minutes before the *S*-wave reached the seismic station.

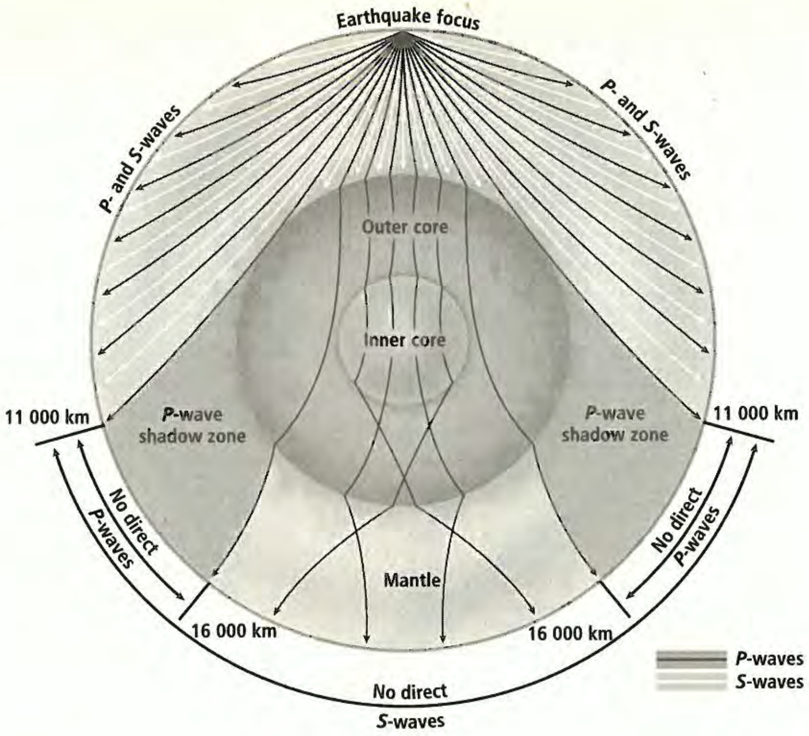


Figure 5-25 *P*-waves and *S*-waves travel through Earth's interior. They are reflected, refracted, and absorbed by the different materials that make up the interior. *P*-waves can travel through solids, liquids, and gases. *S*-waves can travel through solids. The shadow zone receives no direct seismic waves.

Moment Magnitude

A more exact measure of an earthquake's magnitude can be made using the moment magnitude scale. The moment magnitude scale uses the size of the fault rupture, the area of the fault break, and the stiffness of the rocks to rate an earthquake. The moment magnitude value is closely related to the amount of energy released by the quake. Therefore, Richter values are often very close to moment magnitude values.

Earthquake Intensity

Earthquakes can also be rated on their intensity, based on the damage they do to structures. The **modified Mercalli scale,** shown in Table 5-3, rates the types of damage and other effects of an earthquake as noted by observers during and after the quake. This scale ranges from I to XII. Like the Richter scale, the modified Mercalli intensity scale uses wave amplitude to rate an earthquake. Intensity decreases with distance from the focus of an earthquake because seismic waves gradually decrease in amplitude with distance. Maximum intensity values are generally observed very near the epicenter.

Table 5-3 Modified Mercalli Intensity Scale

I	Not felt except under unusual conditions.
II	Felt by only a few persons. Suspended objects may swing.
III	Quite noticeable indoors. Vibrations are like those caused by a passing truck.
IV	Felt indoors by many, outdoors by few. Dishes and windows rattle. Standing cars rock noticeably.
V	Felt by nearly everyone. Some dishes and windows break and some plaster cracks.
VI	Felt by all. Furniture moves. Some plaster falls and some chimneys are damaged.
VII	Everybody runs outdoors. Some chimneys break. Damage is slight in well-built structures but considerable in weak structures.
VIII	Chimneys, smokestacks, and walls fall. Heavy furniture is overturned. Partial collapse of ordinary buildings occurs.
IX	Great general damage occurs. Buildings shift off foundations. Ground cracks. Underground pipes break.
X	Most ordinary structures are destroyed. Rails are bent. Landslides are common.
XI	Few structures remain standing. Bridges are destroyed. Railroad ties are greatly bent. Broad fissures form in the ground.
XII	Damage is total. Objects are thrown upward into the air.

Locating an Earthquake's Epicenter

The distance between an epicenter and a single seismic station is not enough information to pinpoint the epicenter. The epicenter can be anywhere on a circle centered on the seismic station and having a radius equal to the epicenter distance. The exact location of the epicenter is determined by drawing circles around at least three seismic stations that recorded the earthquake. The point where the circles intersect is the earthquake's epicenter, as shown in Figure 5-26.

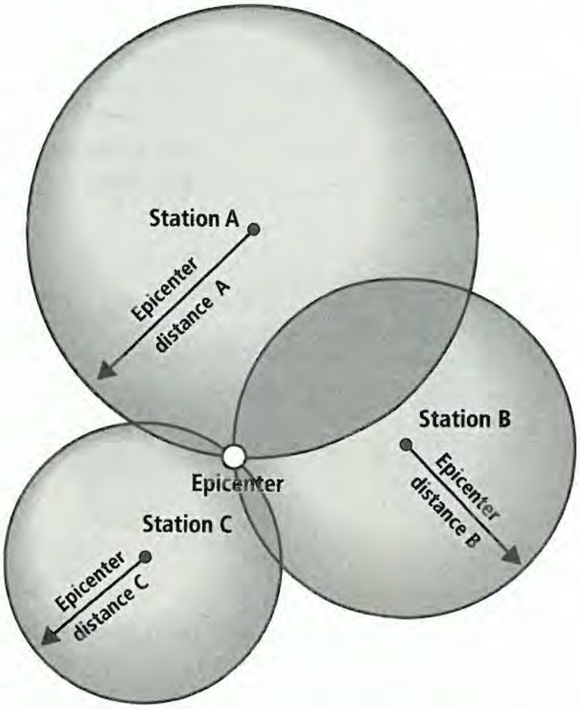


Figure 5-26 To determine an earthquake's epicenter, the locations of at least three seismic stations are plotted on a map. Circles with radii equal to the epicenter distance from each station are drawn around the corresponding station. The point of intersection of the three circles is the epicenter.

The locations of earthquake epicenters are not random; most of Earth's seismic activity occurs in areas called seismic belts, as shown in Figure 5-27. These seismic belts correspond closely to lithospheric plate boundaries, as you can see by comparing Figure 5-27 with Figure 5-7. About 80 percent of all earthquakes occur in the Circum-Pacific Belt, and about 15 percent occur in the Mediterranean Belt. Most of the remaining earthquakes have epicenters associated with divergent plate boundaries, which include ocean ridges and continental rift zones.

Earthquakes and Society

There are many hazards associated with a powerful earthquake. Seismic waves can damage or destroy buildings, bridges, and highways. Violent ground movements can rupture gas lines and down power lines, causing fires. Earthquakes may cause failure of land and soil and the formation of fault scarps, which are steep cliffs produced by faulting. Coastal areas may be flooded by large waves generated by earthquakes.

Structural Damage Done by Earthquakes

The degree of structural damage done by an earthquake depends on several factors, including the subsurface on which the structures are built and the strength and quality of the structures. Earthquake waves are amplified as they travel through soft sediments and are muted as they travel through bedrock. Thus, structures built on soft, unconsolidated sediments suffer extensive damage during an earthquake. Unreinforced buildings made of brittle materials such as stone or concrete suffer much more damage than buildings constructed of wood. Many high-rise buildings with supporting steel frameworks also sustain relatively little damage during an earthquake.

Seismic waves can destroy buildings via a process described as pancaking. In some buildings, the supporting walls of the ground floor fail. The upper floors then fall

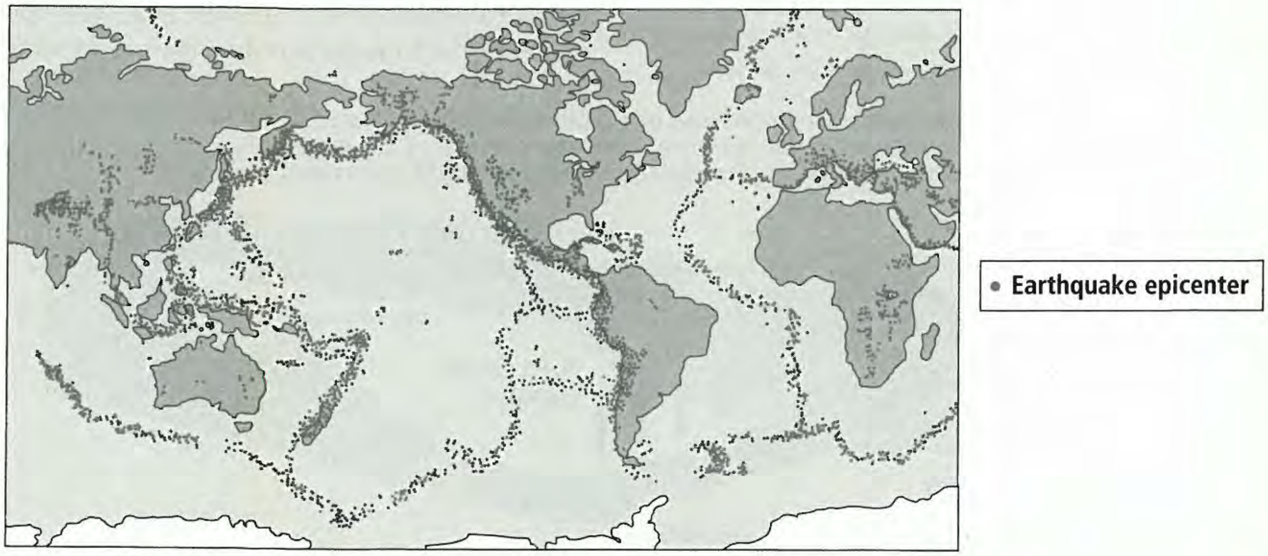


Figure 5-27 Most earthquakes are associated with tectonic plate boundaries.

and collapse onto the ground floor, producing wreckage that resembles a stack of pancakes. Pancaking was responsible for much of the destruction caused by the earthquakes that occurred in Taiwan in 1999.

Land and Soil Failure

Ground movements during an earthquake can set loose materials in motion. In sloping areas, earthquakes can trigger landslides, rock falls, mudslides, avalanches, and other types of mass movements. The countless deaths from the 1970 Peruvian earthquake and the 1949 earthquake that struck the former Soviet Union were the result of avalanches.

Where the substrate is saturated with water, seismic waves can cause subsurface materials to liquefy (or become more fluidlike) and behave like quicksand. Soil liquefaction can produce mass movements in areas of low relief and can make buildings and other structures sink into the ground. It can also cause underground pipes and tanks to rise to the surface. Soil liquefaction destroyed parts of Anchorage, Alaska, during the 1964 Good Friday earthquake.

Tsunamis

Another earthquake hazard are **tsunamis,** which are enormous ocean waves generated by vertical motions of the seafloor during an earthquake or a volcanic eruption. The motions displace the entire overlying column of water, as shown in Figure 5-28. The disturbance becomes an ocean wave that travels at speeds of up to 800 km/h. In the open ocean, the wave height of a tsunami is generally less than a meter. When the wave reaches shallow water, however, it can form a wall of water more than 20 m high. The wave height can be even further amplified if a tsunami occurs in conjunction with a high tide.

Tsunamis threaten coastal areas, even those far from an earthquake's epicenter. The magnitude-9.5 earthquake that struck Chile in 1960 generated a tsunami that destroyed many villages along the South American coastline. The tsunami also crossed the Pacific Ocean and killed several hundred people in Japan nearly a day later. Because of a tsunami's potential for extensive damage and fatalities, many countries have initiated tsunami-warning programs.

Seismic Risk

The probability of future earthquakes is much greater in seismic belts than in other places on Earth. The past seismic activity of an area is also a reliable indicator of seismic risk. The map in Figure 5-29 is a seismic-risk map of the United States. Areas of high seismic risk include Alaska, Hawaii, parts of some other western states, a region in the south-central United States, and parts of some New England states. Some high-risk areas are close to lithospheric boundaries, while others are sites of past seismic activity.

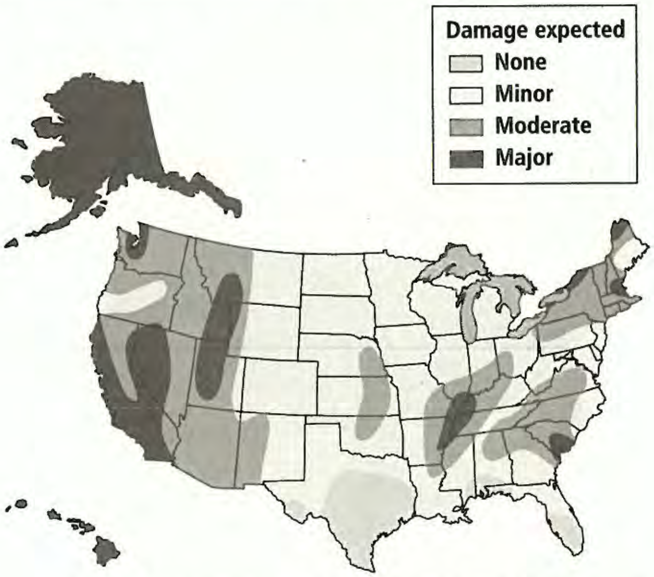
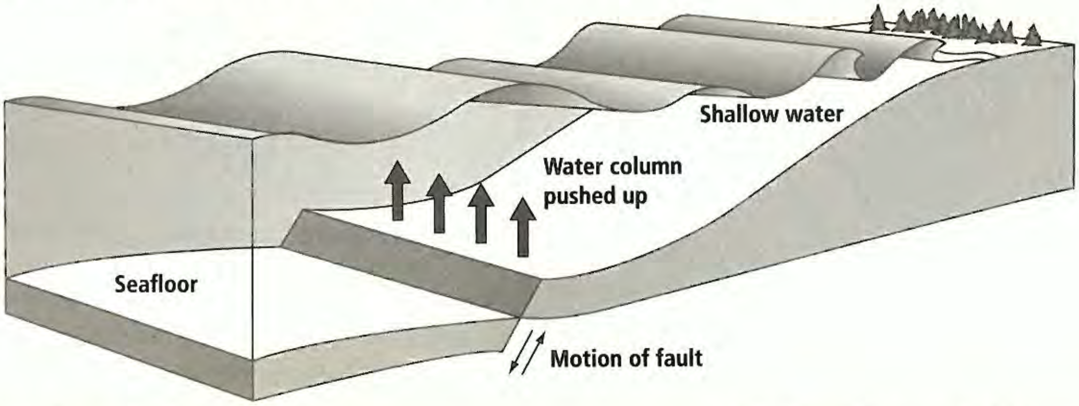


Figure 5-29 Alaska, Hawaii, and parts of other states are areas of high seismic risk.

Before, During, and After an Earthquake

Earthquake preparedness can often decrease the damage done by an earthquake and reduce the number of casualties, even in areas of high seismic risk. An earthquake-emergency kit should include at least a few bottles of water, a battery-operated radio, a flashlight, plenty of fresh batteries, a wrench, a first-aid kit, canned food, a handheld can opener, and a blanket or two. Everyone in the home should know where the kit is and should participate in earthquake drills.

Figure 5-28 A tsunami is an ocean wave generated by an earthquake or a volcanic eruption on the seafloor. In the open ocean, the wave height of a tsunami is less than a meter. Once the wave reaches shore, however, its height can exceed 20 m.



Another way to prepare for an earthquake is to move heavy objects to low places. For example, heavy books should be placed on the bottom shelves of bookcases. Heavy pieces of furniture and heavy appliances, such as stoves, refrigerators, and water heaters, should be anchored to the floor, walls, or both. Every responsible person in a household should know how to turn off the gas and water mains in the building.

If you are indoors during an earthquake, stay inside and away from anything that might fall. Crawl under a desk or another piece of sturdy furniture. This procedure is sometimes referred to as the duck-and-cover method. Stay away from windows and outside doors. Don't use any open flames, as ruptured gas lines are common during an earthquake. If you are in a car, stop the car away from overpasses and bridges. Stay in the car until the shaking has stopped. If you are outdoors, stay in the open away from electric wires or anything that might fall, such as trees, telephone poles, playground equipment, chimneys, and other parts of buildings.

After an earthquake, help anyone who needs first aid. Listen to the radio for emergency instructions and follow them. Check your home for damage to water, gas, and electric lines. If these lines are damaged, turn off the main valves or circuit breaker. If you smell a gas leak, do not use any open flames. Instead, open all the windows, evacuate the building, and contact authorities immediately.

Expect aftershocks, which shake the ground after an earthquake and can cause additional damage. Also stay away from beaches. A tsunami is possible long after the initial earthquake.

Earthquake Prediction

Predicting earthquakes is largely based on probability studies. The two major factors in determining the probability of an earthquake are the seismic history of an area and the rate at which strain builds up in the rocks in the area. Recurrent earthquakes can indicate that a fault ruptures repeatedly. Probability forecasts are also based on studies of seismic gaps. A **seismic gap** is a section of an active fault that hasn't experienced significant seismic activity in a long time.

To predict whether an earthquake will occur along a section of a fault, scientists consider three factors. The first is how much strain has accumulated along the fault. The second is how much strain was released during the most recent earthquake. The third is how much time has passed since the last earthquake struck that part of the fault.

Other possible indicators of earthquakes include rapid tilting of the ground or some other surface deformation; an unusual, slow, smooth movement along an active fault; stretching of the crust across a fault; changes in rock properties in the vicinity of a fault; an increase in seismic activity in an area; and abrupt changes in well water levels.

SUBTOPIC D
MOUNTAIN BUILDING

Covers National Science Content Standards UCP.1, UCP.2, UCP.3, UCP.4, UCP.5; A.1, A.2; D.1, D.2, D.3; G.1, G.2, G.3

Unifying Concepts and Processes

UCP.1	Systems, order, and organization
UCP.2	Evidence, models, and explanation
UCP.3	Change, constancy, and measurement
UCP.4	Evolution and equilibrium
UCP.5	Form and function

Science as Inquiry

A.1	Abilities necessary to do scientific inquiry
A.2	Understandings about scientific inquiry

Earth and Space Science

D.1	Energy in the Earth system
D.2	Geochemical cycles
D.3	Origin and evolution of the Earth system

History and Nature of Science

G.1	Science as a human endeavor
G.2	Nature of scientific knowledge
G.3	Historical perspectives

VOCABULARY

isostasy
isostatic rebound
orogeny
uplifted mountain

Many mountains dot Earth's landscape. Some of these towering landforms are solitary peaks. Others are parts of ranges that stretch for kilometers over the landscape. Mountains form as the result of complex relationships among Earth's outer layers, the crust, and mantle.

Crust-Mantle Relationships

The change in elevation of Earth's surface is called topography. Most of Earth's elevations cluster around two modes: 0–1 km above sea level and 4–5 km below sea level, as shown in Figure 5-30. These modes reflect the basic differences between the two types of crust and the crust's relationship to the mantle.

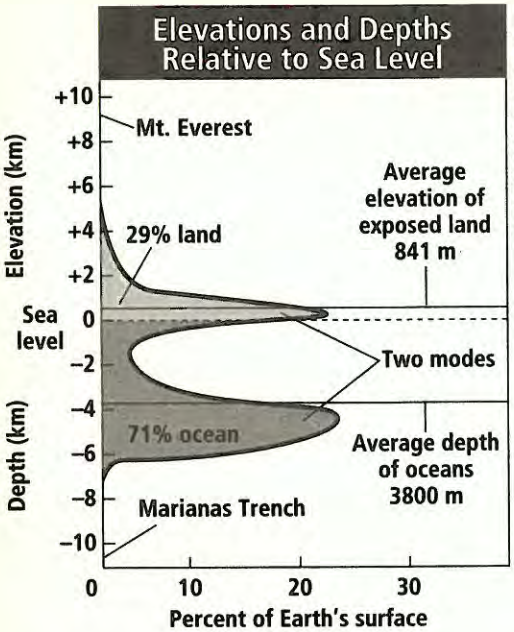
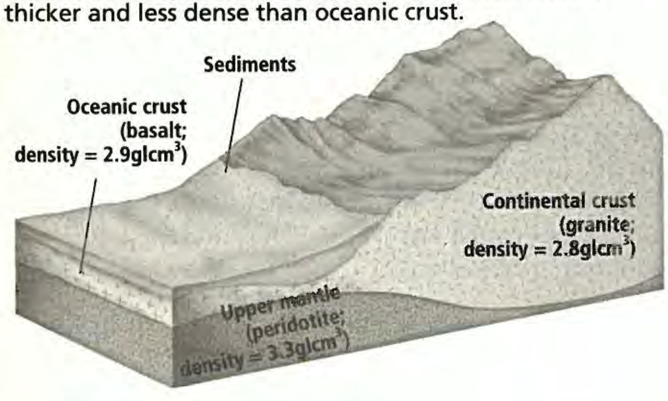


Figure 5-30 Earth's elevations cluster around two modes: 0–1 km above sea level and 4–5 km below sea level.

Continental crust makes up Earth's continents; it averages between 30 and 40 km thick and covers about 30 percent of the planet. Most continental crust is made of granite, which has a density of about 2.8 g/cm^3. Oceanic crust makes up Earth's ocean basins. This type of crust averages about 5 km thick and is primarily composed of basalt, which has a density of about 2.9 g/cm^3. Oceanic crust covers about 70 percent of the planet.

The crust overlies Earth's mantle. This 2885-km-thick layer of Earth is primarily made of peridotite, which has a density of about 3.3 g/cm^3. The crust is less dense than the mantle. Therefore, the crust rides atop and partially displaces the mantle, as shown in Figure 5-31. The slightly higher density of oceanic crust compared to continental crust causes oceanic crust to displace more of the mantle than the same thickness of continental crust. Because it is thicker, however, continental crust extends farther into the mantle and rises higher above Earth's surface than oceanic crust.

Figure 5-31 There are two kinds of crust: continental crust, which is composed mostly of granite, and oceanic crust, which is made primarily of basalt. Continental crust is thicker and less dense than oceanic crust.



Isostasy

The crust and mantle are in an equilibrium in which the downward force of gravity on the mass of the crust is balanced by the upward force of buoyancy. This equilibrium is called **isostasy.** It is similar to people getting into and out of a small boat. When people board the boat, it sinks lower in the water because it displaces a volume of water equal to the mass of the boat plus the mass of the people aboard. When people leave the boat, it rises in the water because, as the mass decreases, the boat displaces less water.

According to the principle of isostasy, parts of the crust rise or subside until these parts are buoyantly supported by so-called roots. For example, as mountains rise, they displace more and more of the mantle to form roots. These roots develop until they can support the mass of the mountains above Earth's surface. A mountain's roots are much thicker than the mountain is tall. For example, the tallest mountains on Earth are the Himalayas in Asia. The tallest peak in this range is Mount Everest, which towers nearly 9 km above sea level. Gravity and seismic surveys have shown that parts of the Himalayas are underlain by roots nearly 80 km thick.

As a mountain erodes, its roots become smaller, and the crust beneath the mountain slowly rises in a process called **isostatic rebound.** This process is diagrammed in Figure 5-32. Erosion is just one cause of isostatic rebound. Another cause is the melting of continental glaciers. Thousands of years ago, continental glaciers covered large parts of North America, adding substantial mass to the crust. When these 3-km-thick masses of ice melted, the crust rebounded as much as 330 m.

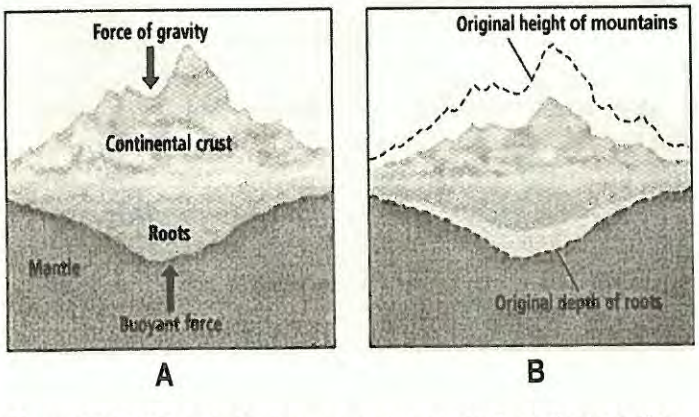


Figure 5-32 Mountains have massive roots that displace the underlying mantle. According to the principle of isostasy, the crust and mantle are in equilibrium: the downward force of gravity on the crust is balanced by the upward force of buoyancy provided by the mantle (A). As a mountain erodes, mass is removed and the crust beneath the mountain rises in isostatic rebound (B).

Orogeny at Convergent Boundaries

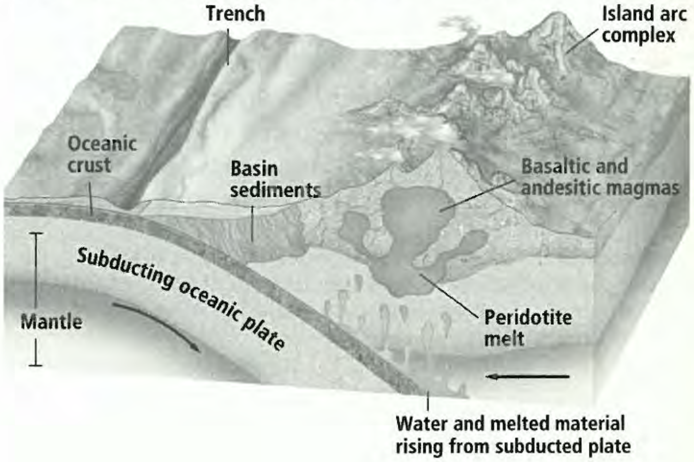
Orogeny, or orogenesis (also known as mountain building), includes all the processes involved in mountain building: folding, faulting, metamorphism, magma production and emplacement, and down-warping. Orogeny forms broad, linear belts of deformation. Most orogenic belts, which are shown in Figure 5-33, formed as the result of interactions between Earth's lithospheric plates.

Orogeny at Oceanic-Oceanic Convergent Boundaries

When an oceanic plate converges with another oceanic plate, one plate is subducted into the mantle, as shown in Figure 5-34. As the subducted plate sinks, part of it melts to form magma. Because it is less dense than the surrounding rock, the magma is forced upward toward the crust and metamorphoses the rocks that it touches. When the magma reaches the crust, it fuels a series of volcanoes called an island arc complex. The island arc complex grows over time as a result of numerous episodes of volcanism and intrusive igneous activity.

Sediments eroded from the island arc complex collect in a forearc basin, which is located between the complex and the trench that forms at the subduction zone. Sediments scraped off the descending plate, as well as pieces of the plate itself, accumulate between the trench and the forearc basin. These accumulating sediments form an accretionary wedge.

Figure 5-34 Orogeny that involves two oceanic plates forms an oceanic trench, an island arc complex, and a forearc basin that fills with sediments eroded from the islands.



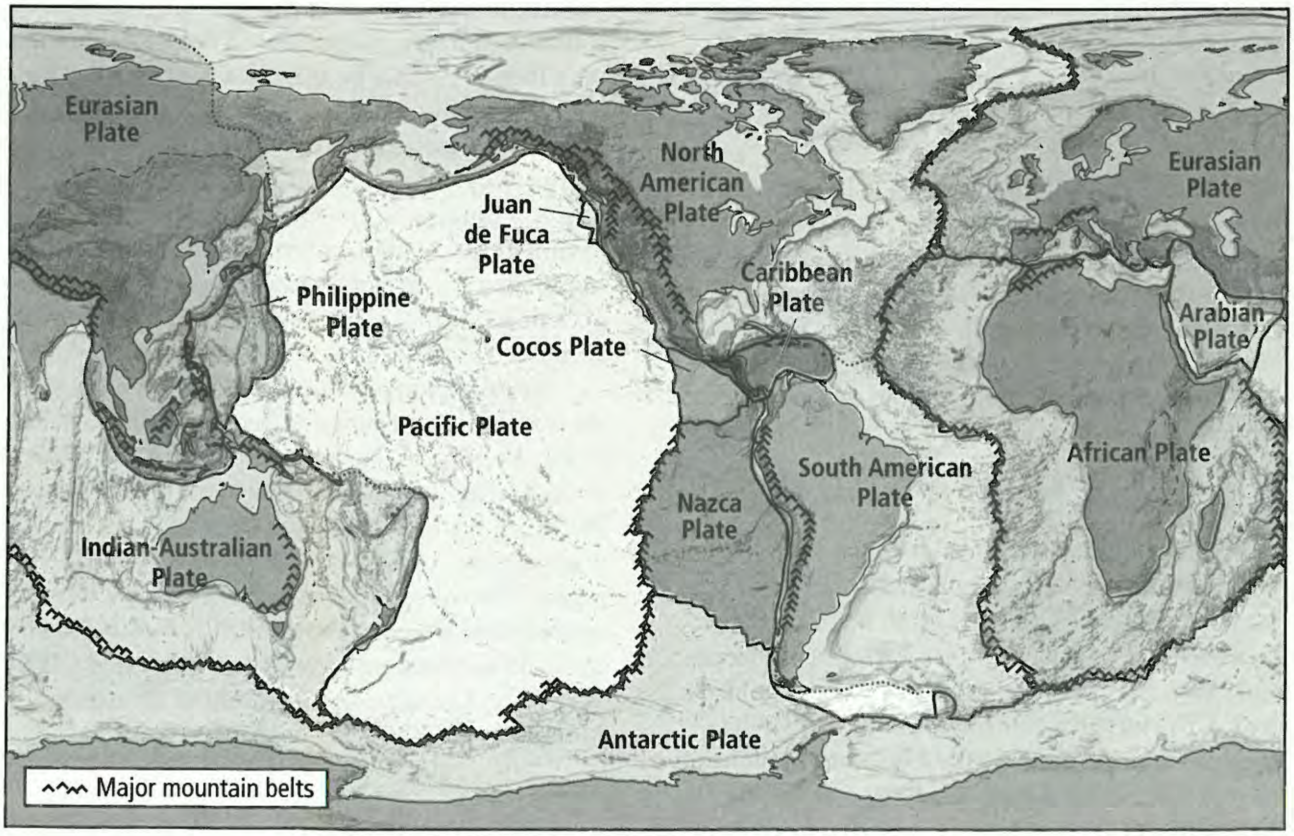
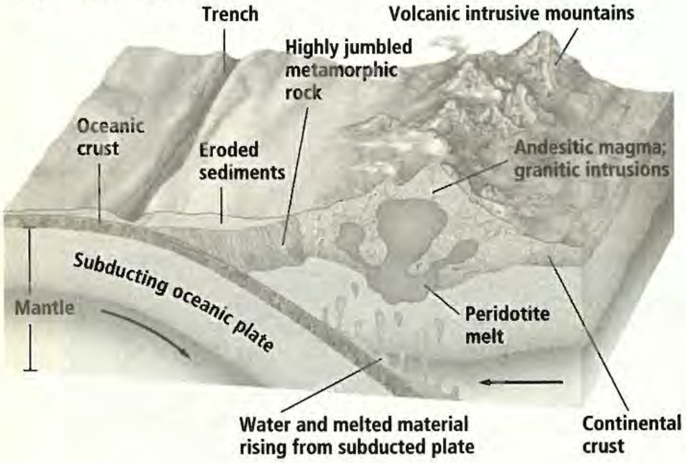


Figure 5-33 Most of Earth's major mountain belts formed as the result of interactions between lithospheric plates.

Orogeny at Oceanic-Continental Convergent Boundaries

When an oceanic plate converges with a continental plate, the denser oceanic plate is subducted into the mantle, as illustrated in Figure 5-35. The subducted plate forces the leading edge of the continental plate upward, and the compressional forces associated with convergence fold and thicken the continental crust into mountain ranges. As is the case in oceanic-oceanic convergence, the subducted plate partially melts to form magma. The magma is forced upward, interacts with continental crust, and becomes rich in silica as a result of fractional crystallization (the process in which different minerals crystallize from molten rock at different temperatures, removing elements from the molten rock). This silica-rich magma gives rise to granitic intrusions below the developing mountain range. The volcanic peaks in the range are fueled by andesitic magma.

Figure 5-35 Orogeny that involves an oceanic plate and a continental plate forms an oceanic trench, chaotic mixtures of various kinds of rocks, and intrusive mountains with volcanic peaks.



As the mountains continue to rise, sediments from land as well as those scraped off the descending plate accumulate landward of the trench that forms. The compressional forces involved in convergence intricately fold and fault these materials. Some of the sediments metamorphose as well.

Orogeny at Continental-Continental Convergent Boundaries

The features of orogeny as the result of convergence between two continental plates are illustrated in Figure 5-36. Continental lithosphere is too buoyant to be subducted. The immense energy associated with convergence and collision transfers to the crust, which becomes highly folded and faulted. This extensive deformation can double the thickness of the crust, producing the highest mountains on Earth. Magma that forms during this type of orogeny cools and hardens beneath the surface to form extensive granitic batholiths.

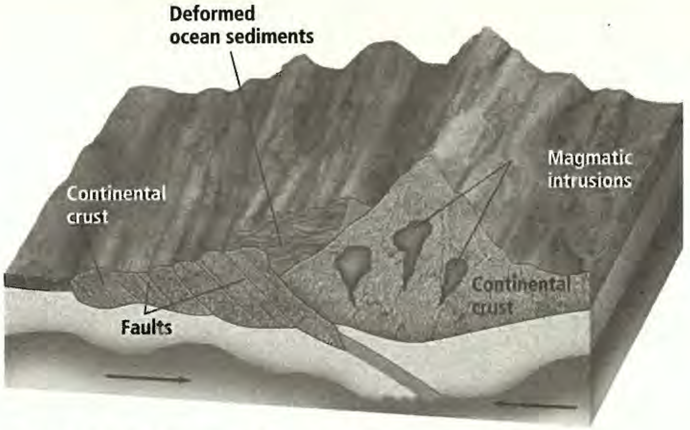


Figure 5-36 Orogeny that involves two continental plates forms very tall mountain ranges that often contain deformed ocean sediments.

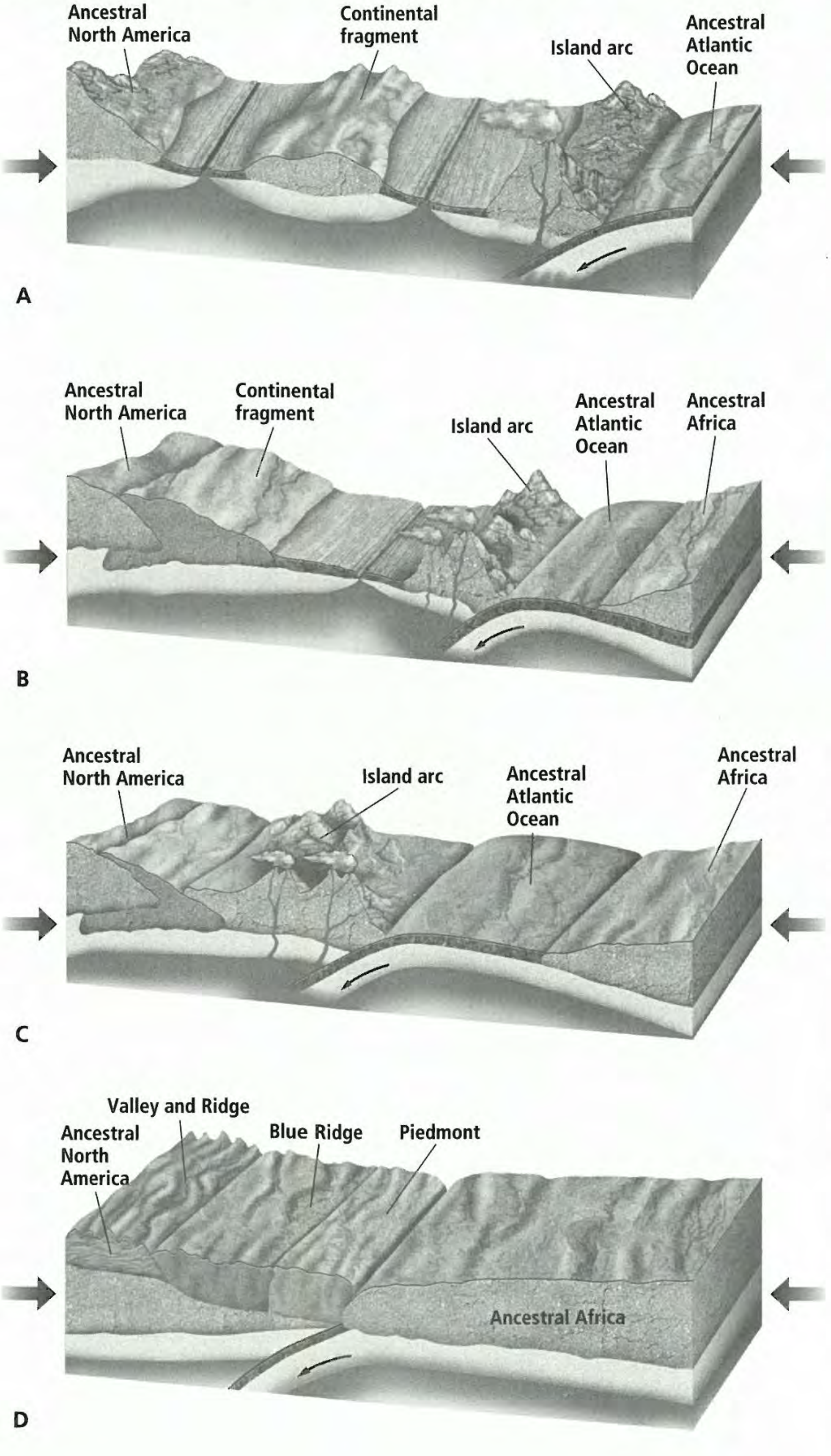
Orogeny of the Appalachian Mountains

The Appalachian Mountains extend along the eastern side of North America from Newfoundland to Alabama. These mountains began to form about 800 to 700 million years ago, when ancestral North America separated from ancestral Africa to form the proto-Atlantic Ocean, or the Iapetus Ocean, off the west coast of ancestral Africa. About 700 to 600 million years ago, plate motions reversed, and the Iapetus Ocean began to close. Convergence formed a subduction zone and a volcanic island arc between the two protocontinents, as shown in Figure 5-37A.

Approximately 500 to 400 million years ago, the continental fragment that would eventually become the Blue Ridge Province became attached to ancestral North America, as illustrated in Figure 5-37B. Erosion of the highlands associated with this Taconic Orogeny deposited a large wedge of sediment called the Queenston Delta. The largest remnants of the Taconic Orogeny are the Taconic Mountains located in eastern New York State. These mountains are primarily composed of metamorphosed oceanic rocks that were thrust westward over the sedimentary deposits that accumulated on the continental shelf.

Between about 400 and 300 million years ago, the island arc was thrust westward and became attached to ancestral North America, as illustrated in Figure 5-37C. This volcanic-rock complex would eventually become the Appalachian Piedmont Province. Between about 375 and 335 million years ago, the Acadian Orogeny occurred in the Appalachian region. The convergence associated with the orogeny continued to close the proto-Atlantic Ocean. Deformation of the rocks is evident as far west as the Adirondacks in New York State. The subsequent erosion of the Acadian Mountains produced the Catskill Delta.

Figure 5-37 The formation of the Appalachian Mountains involved three periods of orogeny: the Taconic Orogeny between 500 and 400 million years ago; the Acadian Orogeny between about 375 and 335 million years ago; and the Alleghenian Orogeny between 300 and 250 million years ago.



700–600 M.Y.B.P.*
Convergence begins to close the ancestral Atlantic Ocean. An island arc develops east of ancestral North America.

500–400 M.Y.B.P.*
The continental fragment, which eventually becomes the Blue Ridge Province, becomes attached to ancestral North America.

400–300 M.Y.B.P.*
The island arc becomes attached to ancestral North America, and the continental fragment thrusts farther onto ancestral North America. The arc becomes the Piedmont Province.

300–250 M.Y.B.P.*
Ancestral Africa collides with ancestral North America to close the ancestral Atlantic Ocean. Compression forces the Blue Ridge and Piedmont rocks farther west, and the folded Valley and Ridge Province forms.

*Million Years Before Present

Between about 300 and 250 million years ago, the Alleghenian Orogeny took place. Convergence between ancestral Africa and ancestral North America completely closed the proto-Atlantic Ocean to form the supercontinent Pangaea. Convergence also pushed the rocks of the Blue Ridge and Piedmont Provinces farther west, as illustrated in Figure 5-37D. The compression folded the rocks now known as the Valley and Ridge Province.

Orogeny at Divergent Boundaries

Ocean ridges are divergent boundaries on the ocean floors. These volcanic submarine mountain ranges form as a result of mantle convection. Convection currents force molten material upward, where it warms the overlying lithospheric plate. As a result of this warming, the lithospheric plate along a divergent boundary bulges upward and stands higher than the surrounding oceanic crust, forming a gently sloping mountain range, as shown in Figure 5-38.

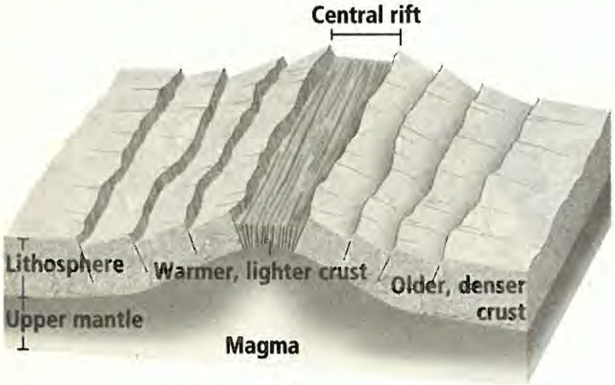


Figure 5-38 Orogeny at a divergent boundary on the ocean floor forms a gently sloping mountain range known as an ocean ridge.

Ocean ridges are made of igneous rocks that form as the magma from the main rift of the ridge cools and solidifies. Some magma cools and hardens just above the magma chamber to form the intrusive igneous rock gabbro. Other magma intrudes into the overlying rock to form sheeted dikes, which resemble a deck of playing cards on edge. Still other magma pushes through the dikes. When it comes into contact with cold seawater, it forms pillow-shaped rocks called pillow basalts, which resemble a stack of sandbags. The inside of pillow basalt is crystalline because it cools more slowly than the outside, which is glassy (lacking a crystalline structure).

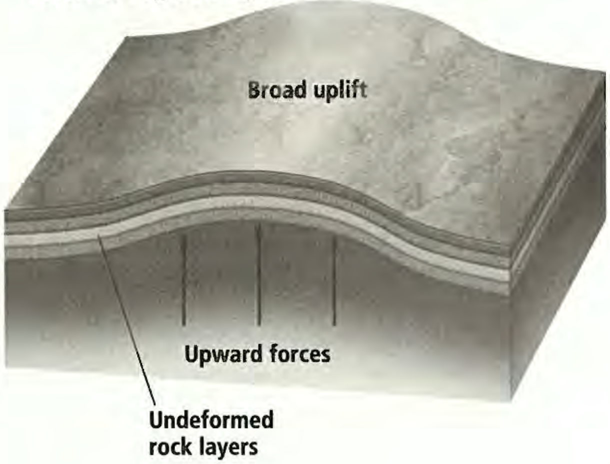
Orogeny Far from Plate Boundaries

Some mountain ranges and peaks form far from tectonic plate boundaries. The three types of nonboundary mountains are uplifted mountains, fault-block mountains, and some volcanoes.

Uplifted Mountains

Uplifted mountains form when large regions of Earth are slowly forced upward as a unit, as illustrated in Figure 5-39. In general, the rocks that form uplifted mountains undergo much less deformation than the rocks associated with plate boundary orogeny. The mechanisms that form uplifted mountains are not well understood. One hypothesis is that warmer regions of the mantle heat the overlying lithosphere. The increase in temperature makes the crust less dense, causing the crust to rebound in response to isostasy. Another hypothesis is that hot mantle plumes rise toward the crust and cause uplift without much deformation. Examples of uplifted mountains include the Black Hills in western South Dakota, portions of the southern Rocky Mountains, and the Adirondack Mountains in upstate New York.

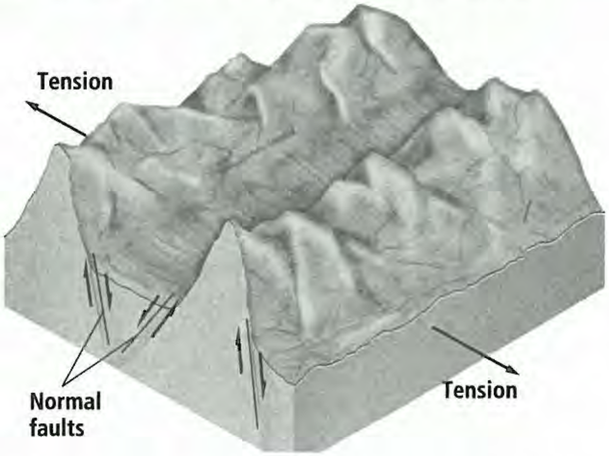
Figure 5-39 Uplifted mountains form as the result of regional uplift.



Fault-Block Mountains

Fault-block mountains form when large pieces of Earth's crust are tilted, uplifted, or dropped downward between high-angle normal faults, as depicted in Figure 5-40. The Basin and Range Province, which encompasses all of Nevada and parts of Utah, New Mexico, Arizona, and California, is an example of fault-block mountains. There the crust has broken into hundreds of pieces as the result of the tension associated with normal faulting.

Figure 5-40 Fault-block mountains form when large pieces of crust are tilted, uplifted, or dropped downward between high-angle normal faults.



Other examples of fault-block mountains are the Tetons in Wyoming and the Sierra Nevada in California. Both of these mountain ranges are faulted along their eastern flanks. Uplift caused these highly faulted blocks to tilt downward to the west to form mountains.

Volcanic Peaks

Volcanoes that form over mantle hot spots are often isolated peaks. As a lithospheric plate moves over a hot spot in the mantle, plumes of material move upward and force their way through the crust to form volcanoes. As the plate continues to move, a chain of successively younger volcanoes forms. The shield volcanoes that make up the Hawaiian Islands formed as the Pacific Plate moved slowly over a hot spot in the mantle.

QUESTIONS FOR SUBTOPIC A

Type A

Some questions may require the use of the *Earth Science Tables and Charts.*

1. The theory of plate tectonics suggests that

- **a.** the continents move due to changes in Earth's orbital velocity.
- **b.** the continents' movements are caused by Earth's rotation.
- **c.** the present-day continents of South America and Africa are moving toward each other.
- **d.** the present-day continents of South America and Africa once fit together like puzzle parts.

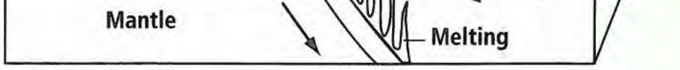
2. Contact zones between tectonic plates may produce trenches. One of these trenches is at the boundary between which plates?

- **a.** Indian-Australian and Pacific
- **b.** South American and African
- **c.** Indian-Australian and Antarctic
- **d.** North American and Eurasian

3. The Taconic Mountains of New York, Connecticut, Massachusetts, and Vermont are largely composed of metamorphic rocks that were pushed westward by reverse or thrust faults. What was most likely responsible for the formation of these mountains?

- **a.** a transform boundary
- **b.** regional uplift
- **c.** a convergent boundary
- **d.** a divergent boundary

4. The diagram below shows the convergence between an oceanic plate and a continental plate.

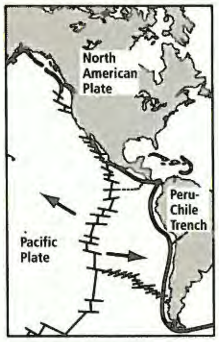


Collisions between these two types of plates are thought to be driven by

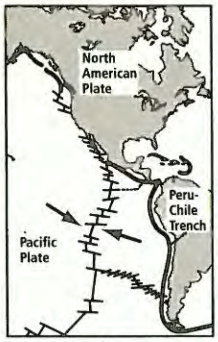
- **a.** hot liquid magma in the inner core.
- **b.** convection currents in the mantle.
- **c.** volcanic eruptions along coastlines.
- **d.** meteor impacts in the ocean basins.

Type B

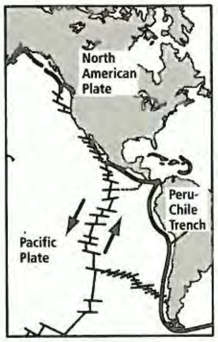
5. Which map below best shows the direction of movement of the oceanic lithospheric plates in the vicinity of the East Pacific Rise?



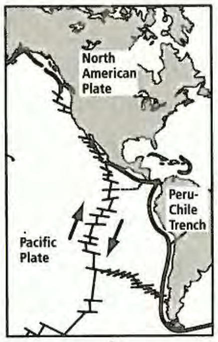
a.



b.

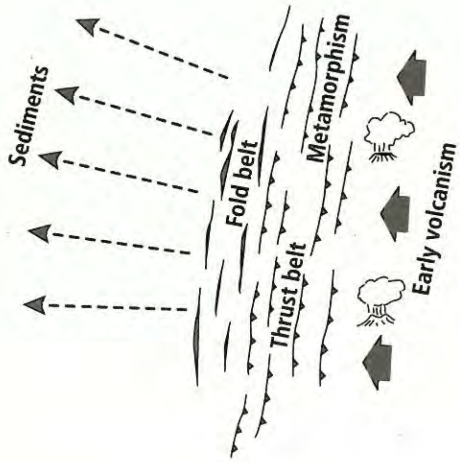


c.



d.

Base your answers to questions 6–8 on the diagram below, which shows some tectonic processes at work on an area of Earth's surface.



6. What type of tectonic boundary is in this area?

a. convergent boundary
b. divergent boundary
c. transform boundary
d. three-point juncture

7. The volcanic rocks of this geologic time period resulted from

a. subduction.
b. convection.
c. erosion.
d. deposition.

8. What was the source of the sediments that formed during the processes shown in the diagram?

a. seas to the north
b. glaciers in the south
c. the mountains to the east
d. the mountains to the west

Type C

Questions 9–11 may require the use of the *Earth Science Tables and Charts.*

9. On which tectonic plate is the Canary Islands hot spot located?

10. In which direction is North America moving in relation to the Mid-Atlantic Ridge?

11. Which continent has rocks that are probably very similar in age and structure to some rocks along the eastern coast of the United States?

QUESTIONS FOR SUBTOPIC B

Type A

12. What does not affect the formation of molten rock?

a. temperature
b. pressure
c. water
d. viscosity

13. Volcanoes fueled by rhyolitic magma are very explosive because rhyolitic magma has a

a. high silica content and a high dissolved-gas content.
b. high silica content and a low dissolved-gas content.
c. low silica content and a high dissolved-gas content.
d. low silica content and a low dissolved-gas content.

14. Which statement about molten basaltic rock is false?

a. It forms when rocks in the upper mantle melt.
b. It contains relatively small amounts of silica.
c. It has high viscosity.
d. It forms on oceanic and continental crust.

15. The Palisades Sill in New York can be best described as

a. a multitude of parallel plutons.
b. a mushroom-shaped intrusive igneous body.
c. a pluton that formed parallel to the layers of rocks into which it intruded.
d. an intrusive igneous rock body that cut across the rocks into which it intruded.

16. What happens as a tectonic plate moves over a hot spot?

a. The plate descends into the mantle.
b. A chain of volcanoes forms.
c. The pressure of the plate keeps magma below Earth's surface.
d. The hot spot is pushed to the edge of the plate.

17. What is most likely to harm people living near a volcano?

a. pyroclastic flows
b. vent formation
c. ash fallout
d. a mantle hot spot

Type B

Some questions may require the use of the *Earth Science Tables and Charts.*

18. Where does most of Earth's convergent volcanism occur?

a. along the Mid-Atlantic Ridge
b. in the Hawaiian Islands
c. in the Mediterranean Belt
d. in the Circum-Pacific Belt

19. Deposits of granite in the northeastern United States probably formed as the result of

a. intrusive igneous activity.
b. a pyroclastic flow.
c. hot-spot activity.
d. igneous activity associated with shield volcanoes.

20. What effect might the Palisades Sill have had on the sedimentary rocks that it intruded?

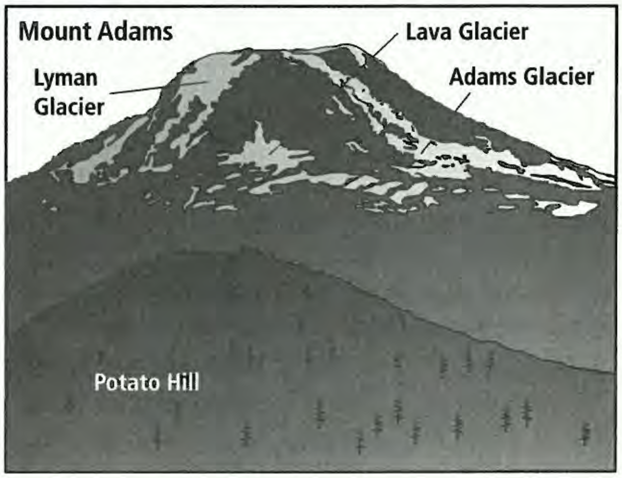
a. The rocks became graded and sorted.
b. The sill caused contact metamorphism.
c. A volcanic vent formed.
d. Extensive batholiths formed.

Type C

Questions 21 and 22 may require the use of the *Earth Science Tables and Charts.*

21. Describe one threat to human life or property that is posed by gases released into the air when a continental volcano erupts.

22. The sketch below shows a landscape in the Pacific Northwest.



Describe the type of mountains in the sketch and their tectonic origin.

QUESTIONS FOR SUBTOPIC C

Type A

Some questions may require the use of the *Earth Science Tables and Charts.*

23. What is the average velocity of an earthquake's *S*-wave in its first 4 minutes of travel?

a. 1 km/min
b. 4 km/min
c. 250 km/min
d. 500 km/min

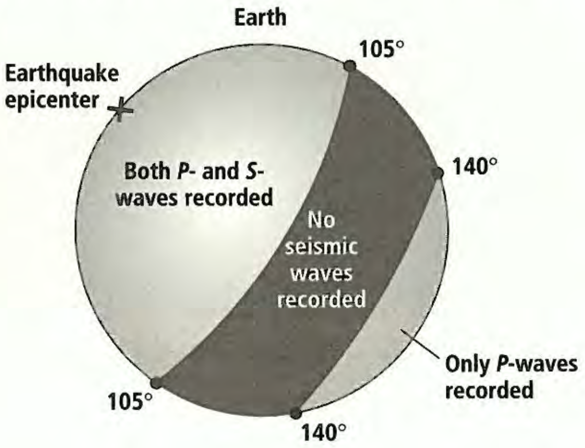
24. Which statement best describes the relationship between the travel times of seismic waves from an earthquake's focus to a seismic station?

a. *P*-waves travel more slowly than *S*-waves and take less time to reach the station.
b. *P*-waves travel more quickly than *S*-waves and take less time to reach the station.
c. *S*-waves travel more slowly than *P*-waves and take less time to reach the station.
d. *S*-waves travel more quickly than *P*-waves and take less time to reach the station.

25. When the seafloor moves in an underwater earthquake, a tsunami develops. What will most likely occur?

- **a.** Deep-ocean sediments will travel great distances.
- **b.** No destruction will occur near the origin of the earthquake.
- **c.** The magnitude of the earthquake will determine the direction of the tsunami.
- **d.** Severe destruction may occur in some coastal areas.

26. An earthquake recorded by seismic stations around the world created the pattern of seismic waves in the recordings below.



Which statement best explains this pattern?

- **a.** Some seismic waves cannot travel through oceans to reach every location on Earth.
- **b.** *S*-waves are too weak to travel very far from the earthquake focus.
- **c.** Mountain ranges and plate boundaries absorb or refract seismic waves.
- **d.** Layers of Earth with different properties absorb or refract seismic waves differently.

27. *P*-waves can travel through

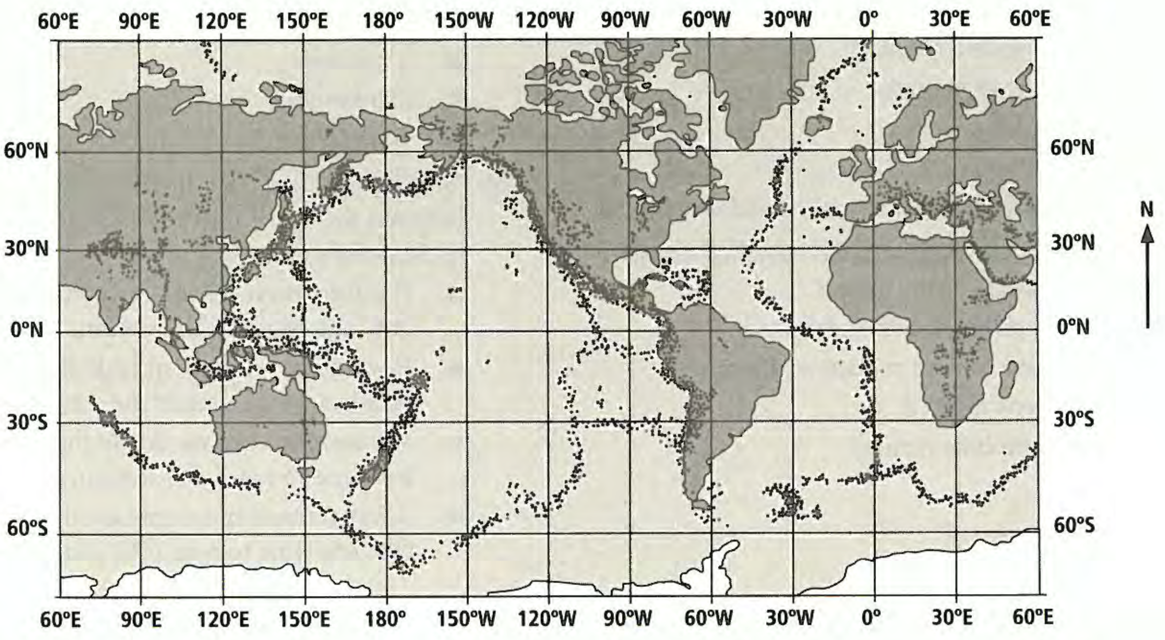
- **a.** solid rock only.
- **b.** magma and water only.
- **c.** magma, water, and gas only.
- **d.** solid rock, magma, water, and gas.

Type B

Some questions may require the use of the *Earth Science Tables and Charts.*

28. The world map below shows the distribution of major earthquake epicenters. Each epicenter is represented by a dot. Which conclusion can best be inferred from the data shown on this map?

- **a.** Earthquakes generally are evenly distributed over the surface of Earth.
- **b.** Most earthquakes occur west of the prime meridian and north of the equator.
- **c.** Most earthquakes are concentrated in zones along plate boundaries.
- **d.** Most earthquakes occur on continents.



Base your answers to questions 29–33 on the maps and seismograms below. The map on the left shows seismic stations in Chicago, Oklahoma City, and Tampa. The seismograms below this map show, in Greenwich Mean Time, the arrival times of earthquake waves at the three stations.

29. Which location on the map on the right is closest to the epicenter of this earthquake?

a. W **c.** Y
b. X **d.** Z

30. Which seismogram was recorded at Tampa?

a. seismogram A **c.** seismogram B
b. seismogram C **d.** none of the above

31. What was the origin time of this earthquake?

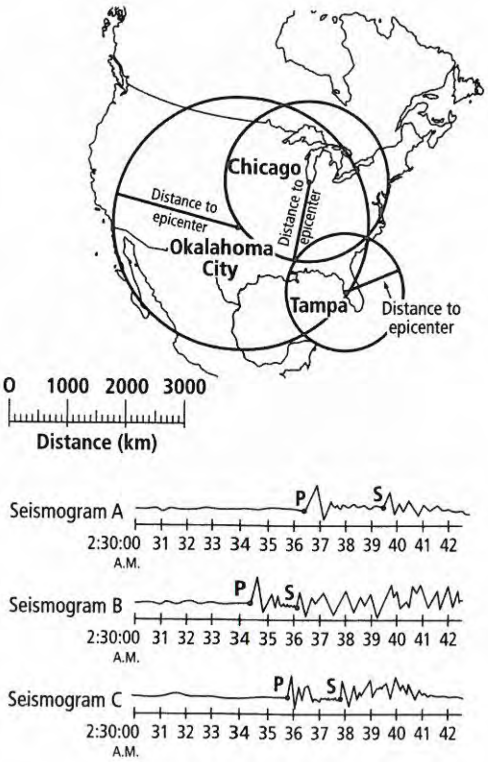
a. 2:32:10 A.M. **c.** 2:35:40 A.M.
b. 2:34:40 A.M. **d.** 2:37:40 A.M.

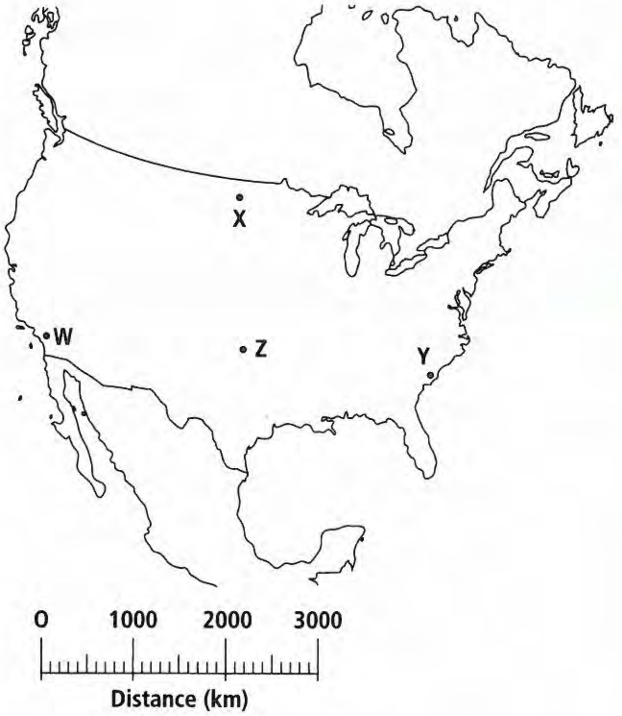
32. The *P*-waves generated by this earthquake took 3 min 40 s to reach one of the seismic stations. Approximately how long did the *S*-waves take to reach this same seismic station?

a. 1 min 20 s
b. 2 min 40 s
c. 3 min 30 s
d. 6 min 40 s

33. What is the minimum number of seismic stations needed to locate an earthquake epicenter?

a. one **c.** three
b. two **d.** four



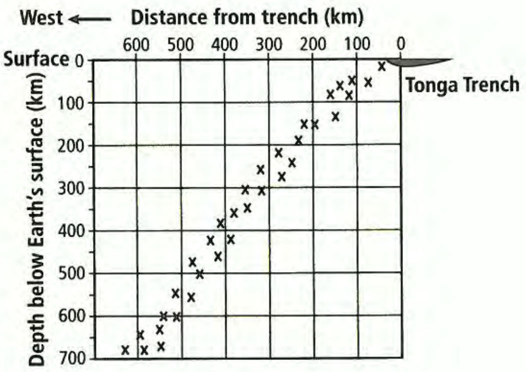


Type C

Some questions may require the use of the *Earth Science Tables and Charts.*

34. The distance from an earthquake's epicenter to Los Angeles is 3000 km. What is the approximate travel time for *P*-waves from the epicenter to the city?

Base your answers to questions 35–37 on the cross section below of a portion of Earth's interior and your knowledge of Earth science. Each X in the cross section represents the focus of an earthquake.



35. State the relationship between the depth of an earthquake's focus and the earthquake's distance from the Tonga Trench.

36. The Tonga Trench is the surface boundary between two tectonic plates. Name these two plates.

37. The focal-depth pattern shown in the cross section represents the location of the subsurface boundary between two tectonic plates. Describe the relative motion of the plates along this boundary.

QUESTIONS FOR SUBTOPIC D

Type A

Some questions may require the use of the *Earth Science Tables and Charts.*

38. Which statement best describes Earth's crust and mantle?

a. The crust is thicker and less dense than the mantle.

b. The crust is thicker and more dense than the mantle.

c. The crust is thinner and less dense than the mantle.

d. The crust is thinner and more dense than the mantle.

39. Where is Earth's crust the thickest?

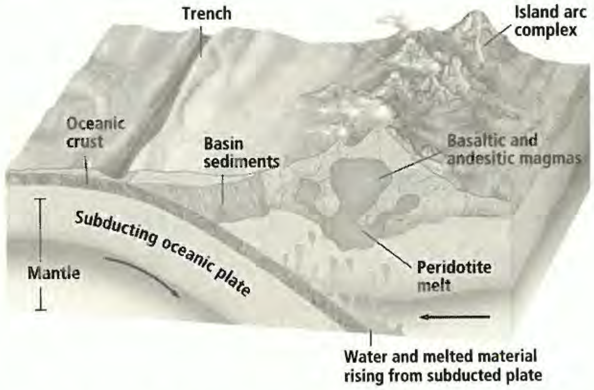
a. along ocean ridges

b. at transform faults

c. under continental mountain ranges

d. under volcanic islands

Base your answers to questions 40–42 on the diagram below.



40. What type of orogeny (mountain building) is shown?

a. oceanic-oceanic convergence

b. oceanic-continental convergence

c. continental-continental convergence

d. divergence

41. What is the source of the magma that fuels the island arc complex?

a. continental crust

b. the subducted plate

c. the overriding plate

d. the volcanoes that make up the complex

42. What is the origin of the peridotite melt?

a. the crust

b. the mantle

c. the inner core

d. the volcanoes themselves

Type B

Some questions may require the use of the *Earth Science Tables and Charts.*

43. Which of the following is likely to cause the continental crust to sink over a given area?

- **a.** the erosion of mountains in that area
- **b.** the formation of a continental glacier over that area
- **c.** the melting of a continental glacier over that area
- **d.** the development of hot mantle plumes beneath the crust in that area

44. How are the Black Hills in South Dakota similar to the mountains of the Hawaiian Islands?

- **a.** Both were formed through tectonic convergence.
- **b.** Both are examples of uplifted mountains.
- **c.** Both occur at divergent boundaries.
- **d.** Both occur far from plate boundaries.

45. What type of mountains are the Tetons? Briefly discuss how the Tetons were formed.

Type C

Some questions may require the use of the *Earth Science Tables and Charts.*

Base your answers to questions 46–48 on the diagrams below. The diagrams are an aerial view and a cross section of the major physiographic regions of the Appalachians.

46. How does the degree of deformation change among provinces?

47. What kinds of rocks would you expect to find in New York City?

48. During which orogeny did the rocks of the Piedmont Province form?