

HS Plate Tectonics

Dana Desonie

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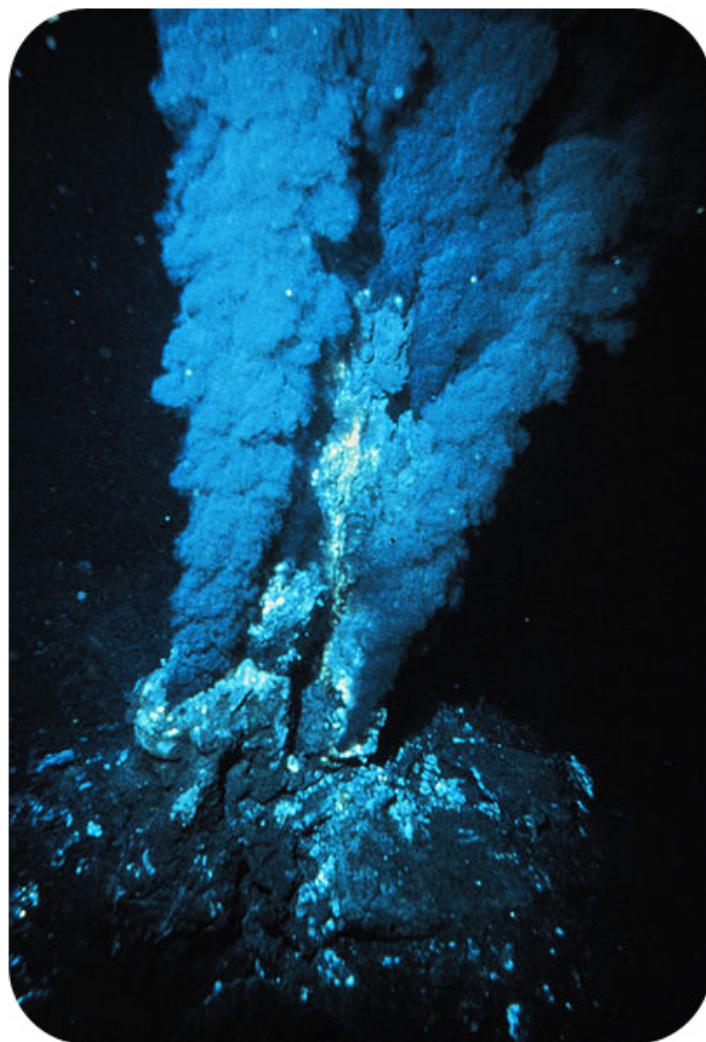
CHAPTER

1

HS Plate Tectonics

CHAPTER OUTLINE

- 1.1 Inside Earth
- 1.2 Continental Drift
- 1.3 Seafloor Spreading
- 1.4 Theory of Plate Tectonics
- 1.5 References



Like just about everything in Earth Science, this strange feature is related to plate tectonics. It's really just a hot geyser like the ones found at Yellowstone National Park, except this geyser is found under 10,000 feet of seawater. These features, called hydrothermal vents, are found where lava eruptions hit seawater in regions where new ocean crust is being created. The hot water coming from the vent explodes from the release of pressure. Once in the cold seawater, sulfide minerals precipitate out, creating the "smoke" in the photo. As the sulfide minerals fall, they create the chimney-like structure in the photo.

Many hydrothermal vents are home to unusual life forms.

1.1 Inside Earth

Lesson Objectives

- Compare and describe each of these Earth layers: lithosphere, oceanic crust, and continental crust.
- Compare some of the ways geologists learn about Earth's interior.
- Describe how convection takes place in the mantle.
- Compare the two parts of the core and describe why they are different from each other.

Vocabulary

- conduction
- continental crust
- convection
- convection cell
- core
- crust
- lithosphere
- mantle
- meteorite
- oceanic crust
- P-waves
- S-waves
- seismic waves

Introduction

Before you can learn about plate tectonics, you need to know something about the layers that are found inside Earth. These layers are divided by composition into core, mantle, and crust or by mechanical properties into lithosphere and asthenosphere. Scientists use information from earthquakes and computer modeling to learn about Earth's interior.

Exploring Earth's Interior

How do scientists know what is inside the Earth? We don't have direct evidence! Rocks yield some clues, but they only reveal information about the outer crust. In rare, a mineral, such as a diamond, comes to the surface from deeper down in the crust or the mantle. To learn about Earth's interior, scientists use energy to "see" the different layers of the Earth, just like doctors can use an MRI, CT scan, or x-ray to see inside our bodies.

Seismic Waves

One ingenious way scientists learn about Earth's interior is by looking at how energy travels from the point of an earthquake. These are **seismic waves** (Figure 1.1). Seismic waves travel outward in all directions from where the ground breaks at an earthquake. These waves are picked up by seismographs around the world. Two types of seismic waves are most useful for learning about Earth's interior.

- **P-waves** (primary waves) are fastest, traveling at about 6 to 7 kilometers (about 4 miles) per second, so they arrive first at the seismometer. P-waves move in a compression/expansion type motion, squeezing and unsqueezing earth materials as they travel. This produces a change in volume for the material. P-waves bend slightly when they travel from one layer into another. Seismic waves move faster through denser or more rigid material. As P-waves encounter the liquid outer core, which is less rigid than the mantle, they slow down. This makes the P-waves arrive later and further away than would be expected. The result is a P-wave shadow zone. No P-waves are picked up at seismographs 104° to 140° from the earthquakes focus.

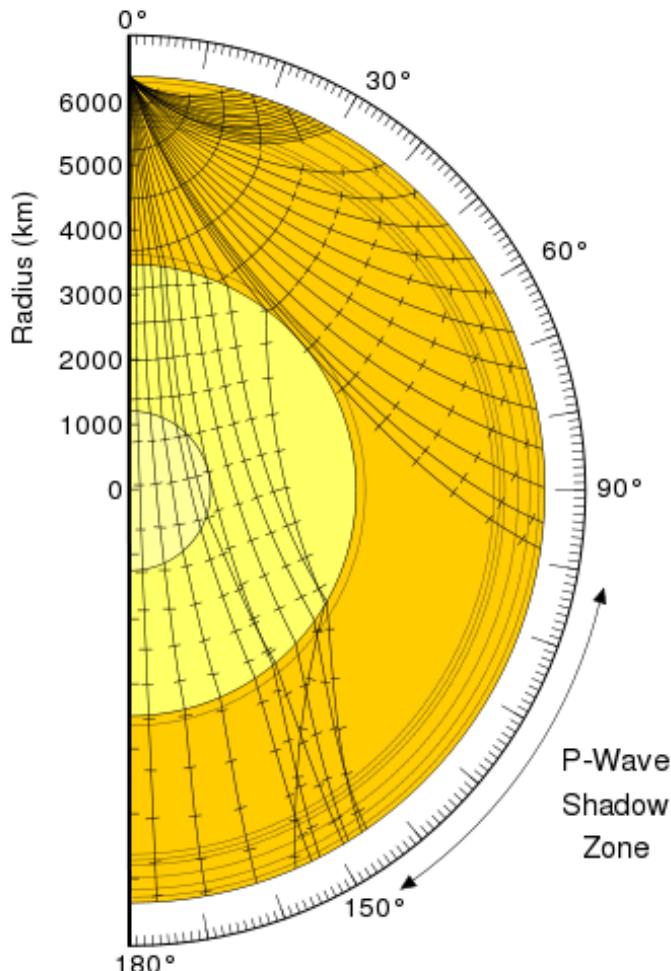
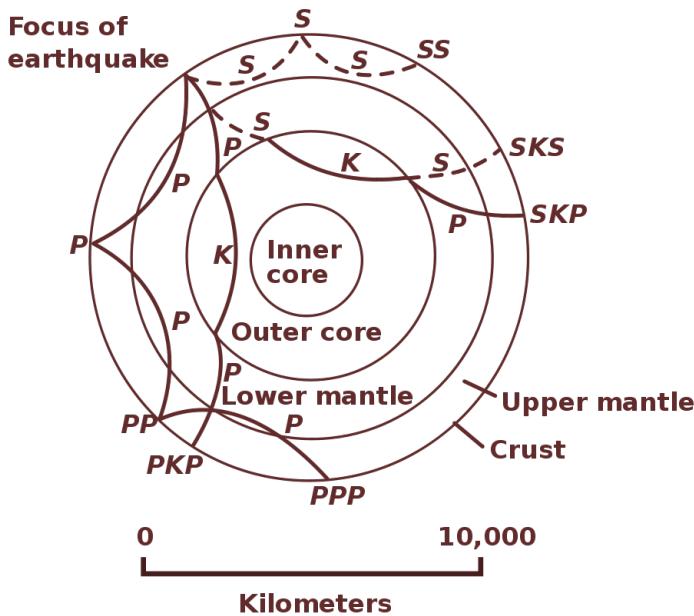


FIGURE 1.1
How P-waves travel through Earth

- **S-waves** (secondary waves) are about half as fast as P-waves, traveling at about 3.5 km (2 miles) per second, and arrive second at seismographs. S-waves move in an up and down motion perpendicular to the direction of wave travel. This produces a change in shape for the earth materials they move through. Only solids resist a change in shape, so S-waves are only able to propagate through solids. S-waves cannot travel through liquid.

By tracking seismic waves, scientists have learned what makes up the planet's interior ([Figure 1.2](#)).

- P-waves slow down at the mantle core boundary, so we know the outer core is less rigid than the mantle.
- S-waves disappear at the mantle core boundary, so the outer core is liquid.

**FIGURE 1.2**

Letters describe the path of an individual P-wave or S-wave. Waves traveling through the core take on the letter K.

This animation shows a seismic wave shadow zone: http://earthquake.usgs.gov/learn/animations/animation.php?flash_title=Shadow+Zone&flash_file=shadowzone&flash_width=220&flash_height=320.

Other Clues about Earth's Interior

1. Earth's overall density is higher than the density of crustal rocks, so the core must be made of something dense, like metal.
2. Since Earth has a magnetic field, there must be metal within the planet. Iron and nickel are both magnetic.
3. **Meteorites** are the remains of the material that formed the early solar system and are thought to be similar to material in Earth's interior (**Figure 1.3**).

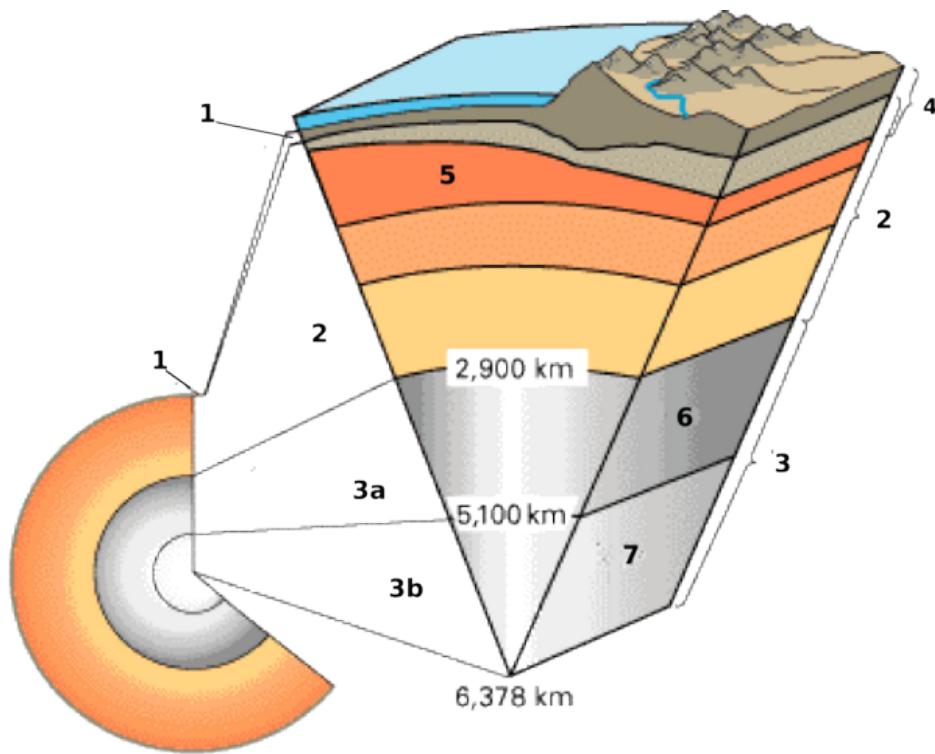
**FIGURE 1.3**

This meteorite contains the mafic minerals olivine and pyroxene. It also contains metal flakes, similar to the material that separated into Earth

The Earth's Layers

The layers scientists recognize are pictured below (**Figure 1.4**).

Core, mantle, and crust are divisions based on composition:

**FIGURE 1.4**

A cross section of Earth showing the following layers: (1) crust (2) mantle (3a) outer core (3b) inner core (4) lithosphere (5) asthenosphere (6) outer core (7) inner core.

1. The **crust** is less than 1% of Earth by mass. The **oceanic crust** is mafic, while **continental crust** is often more felsic rock.
2. The **mantle** is hot, ultramafic rock. It represents about 68% of Earth's mass.
3. The **core** is mostly iron metal. The core makes up about 31% of the Earth.

Lithosphere and asthenosphere are divisions based on mechanical properties:

1. The lithosphere is composed of both the crust and the portion of the upper mantle that behaves as a brittle, rigid solid.
2. The asthenosphere is partially molten upper mantle material that behaves plastically and can flow.

This animation shows the layers by composition and by mechanical properties: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_layers.html.

Crust and Lithosphere

Earth's outer surface is its crust; a cold, thin, brittle outer shell made of rock. The crust is very thin, relative to the radius of the planet. There are two very different types of crust, each with its own distinctive physical and chemical properties, which are summarized in **Table 1.1**.

TABLE 1.1: Oceanic and Continental Crust

Crust	Thickness	Density	Composition	Rock types
Oceanic	5-12 km (3-8 mi)	3.0 g/cm ³	Mafic	Basalt and gabbro
Continental	Avg. 35 km (22 mi)	2.7 g/cm ³	Felsic	All types

Oceanic crust is composed of mafic magma that erupts on the seafloor to create basalt lava flows or cools deeper down to create the intrusive igneous rock gabbro ([Figure 1.5](#)).

**FIGURE 1.5**

Gabbro from ocean crust. The gabbro is deformed because of intense faulting at the eruption site.

Sediments, primarily muds and the shells of tiny sea creatures, coat the seafloor. Sediment is thickest near the shore where it comes off the continents in rivers and on wind currents.

Continental crust is made up of many different types of igneous, metamorphic, and sedimentary rocks. The average composition is granite, which is much less dense than the mafic rocks of the oceanic crust ([Figure 1.6](#)). Because it is thick and has relatively low density, continental crust rises higher on the mantle than oceanic crust, which sinks into the mantle to form basins. When filled with water, these basins form the planet's oceans.

**FIGURE 1.6**

This granite from Missouri is more than 1 billion years old.

The **lithosphere** is the outermost mechanical layer, which behaves as a brittle, rigid solid. The lithosphere is about 100 kilometers thick. Look at [Figure 1.4](#). Can you find where the crust and the lithosphere are located? How are they different from each other?

The definition of the lithosphere is based on how earth materials behave, so it includes the crust and the uppermost mantle, which are both brittle. Since it is rigid and brittle, when stresses act on the lithosphere, it breaks. This is what we experience as an earthquake.

Mantle

The two most important things about the mantle are: (1) it is made of solid rock, and (2) it is hot. Scientists know that the mantle is made of rock based on evidence from seismic waves, heat flow, and meteorites. The properties fit the

ultramafic rock peridotite, which is made of the iron- and magnesium-rich silicate minerals (**Figure 1.7**). Peridotite is rarely found at Earth's surface.

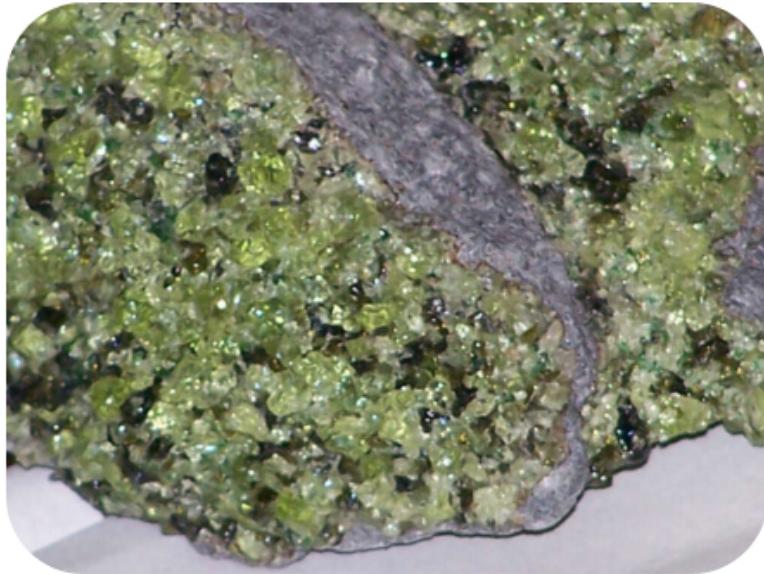


FIGURE 1.7

Peridotite is formed of crystals of olivine (green) and pyroxene (black).

Scientists know that the mantle is extremely hot because of the heat flowing outward from it and because of its physical properties.

Heat flows in two different ways within the Earth:

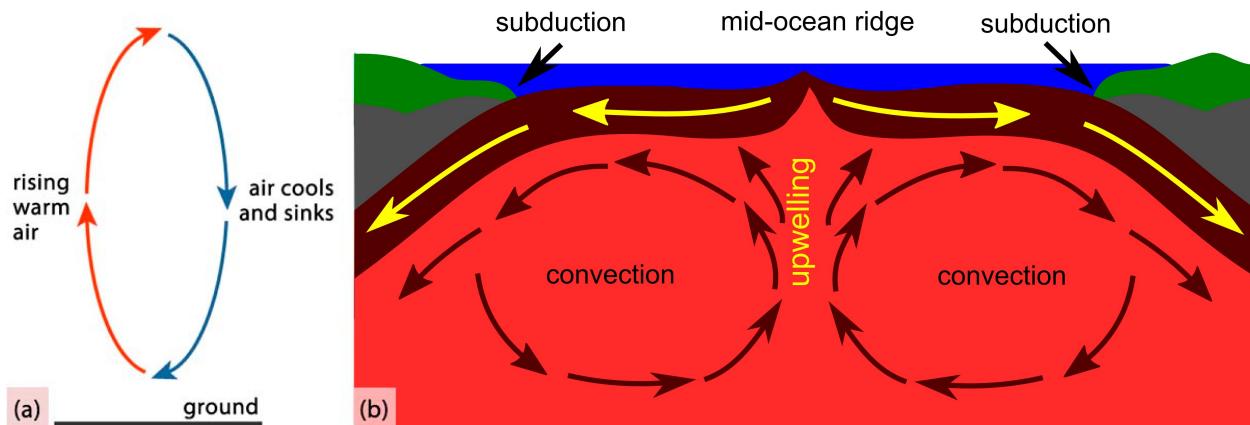
1. **Conduction:** Heat is transferred through rapid collisions of atoms, which can only happen if the material is solid. Heat flows from warmer to cooler places until all are the same temperature. The mantle is hot mostly because of heat conducted from the core.
2. **Convection:** If a material is able to move, even if it moves very slowly, convection currents can form.

Convection in the mantle is the same as convection in a pot of water on a stove. Convection currents within Earth's mantle form as material near the core heats up. As the core heats the bottom layer of mantle material, particles move more rapidly, decreasing its density and causing it to rise. The rising material begins the convection current. When the warm material reaches the surface, it spreads horizontally. The material cools because it is no longer near the core. It eventually becomes cool and dense enough to sink back down into the mantle. At the bottom of the mantle, the material travels horizontally and is heated by the core. It reaches the location where warm mantle material rises, and the mantle **convection cell** is complete (**Figure 1.8**).

Core

At the planet's center lies a dense metallic core. Scientists know that the core is metal because:

1. The density of Earth's surface layers is much less than the overall density of the planet, as calculated from the planet's rotation. If the surface layers are less dense than average, then the interior must be denser than average. Calculations indicate that the core is about 85% iron metal with nickel metal making up much of the remaining 15%.
2. Metallic meteorites are thought to be representative of the core. The 85% iron/15% nickel calculation above is also seen in metallic meteorites (**Figure 1.9**).



In a convection cell, warm material rises and cool material sinks. In mantle convection, the heat source is the core.

Diagram of convection within Earth's mantle.

FIGURE 1.8

Convections



FIGURE 1.9

An iron meteorite is the closest thing to the Earth

If Earth's core were not metal, the planet would not have a magnetic field. Metals such as iron are magnetic, but rock, which makes up the mantle and crust, is not.

Scientists know that the outer core is liquid and the inner core is solid because:

1. S-waves stop at the inner core.
2. The strong magnetic field is caused by convection in the liquid outer core. Convection currents in the outer core are due to heat from the even hotter inner core.

The heat that keeps the outer core from solidifying is produced by the breakdown of radioactive elements in the inner core.

Lesson Summary

- Earth is made of three layers: the crust, mantle, and core.
- The brittle crust and uppermost mantle are together called the lithosphere.
- Beneath the lithosphere, the mantle is solid rock that can flow, or behave plastically.
- The hot core warms the base of the mantle, which causes mantle convection.

Review Questions

1. What are the two main ways that scientists learn about Earth's interior and what do these two things indicate?
2. What is the difference between crust and lithosphere? Include in your answer both where they are located and what their properties are.
3. How do the differences between oceanic and continental crust lead to the presence of ocean basins and continents?
4. What types of rock make up the oceanic crust and how do they form?
5. What types of rock make up the continental crust?
6. How do scientists know about the liquid outer core? How do scientists know that the outer core is liquid?
7. Describe the properties of each of these parts of the Earth's interior: lithosphere, mantle, and core. What are they made of? How hot are they? What are their physical properties?
8. When you put your hand above a pan filled with boiling water, does your hand warm up because of convection or conduction? If you touch the pan, does your hand warm up because of convection or conduction? Based on your answers, which type of heat transfer moves heat more easily and efficiently?

Points to Consider

- Oceanic crust is thinner and denser than continental crust. All crust sits atop the mantle. What might Earth be like if this were not true?
- If sediments fall onto the seafloor over time, what can sediment thickness tell scientists about the age of the seafloor in different regions?
- How might convection cells in the mantle affect the movement of solid crust on the planet's surface?

1.2 Continental Drift

Lesson Objectives

- Explain the continental drift hypothesis.
- Describe the evidence Wegener used to support his continental drift idea.
- Describe later evidence for continental drift.

Vocabulary

- apparent polar wander
- continental drift
- magnetic field
- magnetic polarity
- magnetite
- magnetometer

Introduction

The continental drift hypothesis was developed in the early part of the 20th century, mostly by Alfred Wegener. Wegener said that continents move around on Earth's surface and that they were once joined together as a single supercontinent. While Wegener was alive, scientists did not believe that the continents could move.

The Continental Drift Idea

Find a map of the continents and cut each one out. Better yet, use a map where the edges of the continents show the continental shelf. That's the true size and shape of a continent. Can you fit the pieces together? The easiest link is between the eastern Americas and western Africa and Europe, but the rest can fit together too ([Figure 1.10](#)).

Alfred Wegener proposed that the continents were once united into a single supercontinent named Pangaea, meaning *all earth* in ancient Greek. He suggested that Pangaea broke up long ago and that the continents then moved to their current positions. He called his hypothesis **continental drift**.

Evidence for Continental Drift

Besides the way the continents fit together, Wegener and his supporters collected a great deal of evidence for the continental drift hypothesis.

- Identical rocks, of the same type and age, are found on both sides of the Atlantic Ocean. Wegener said the rocks had formed side-by-side and that the land had since moved apart.
- Mountain ranges with the same rock types, structures, and ages are now on opposite sides of the Atlantic Ocean. The Appalachians of the eastern United States and Canada, for example, are just like mountain ranges in eastern Greenland, Ireland, Great Britain, and Norway ([Figure 1.11](#)). Wegener concluded that they formed as a single mountain range that was separated as the continents drifted.

**FIGURE 1.10**

The continents fit together like pieces of a puzzle. This is how they looked 250 million years ago.

**FIGURE 1.11**

The similarities between the Appalachian and the eastern Greenland mountain ranges are evidences for the continental drift hypothesis.

- Ancient fossils of the same species of extinct plants and animals are found in rocks of the same age but are on continents that are now widely separated (Figure 1.12). Wegener proposed that the organisms had lived side by side, but that the lands had moved apart after they were dead and fossilized. He suggested that the

organisms would not have been able to travel across the oceans.

- Fossils of the seed fern *Glossopteris* were too heavy to be carried so far by wind.
- *Mesosaurus* was a swimming reptile but could only swim in fresh water.
- *Cynognathus* and *Lystrosaurus* were land reptiles and were unable to swim.

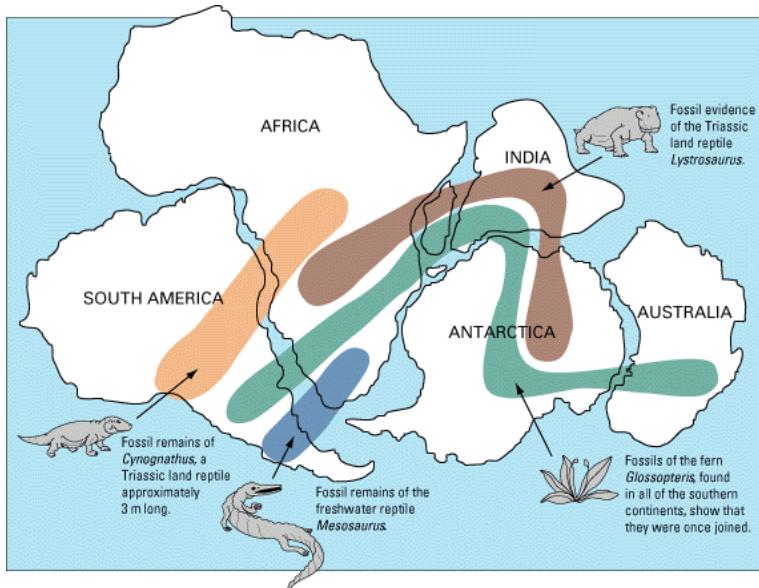


FIGURE 1.12

Wegener used fossil evidence to support his continental drift hypothesis. The fossils of these organisms are found on lands that are now far apart.

- Grooves and rock deposits left by ancient glaciers are found today on different continents very close to the equator. This would indicate that the glaciers either formed in the middle of the ocean and/or covered most of the Earth. Today glaciers only form on land and nearer the poles. Wegener thought that the glaciers were centered over the southern land mass close to the South Pole and the continents moved to their present positions later on.
- Coral reefs and coal-forming swamps are found in tropical and subtropical environments, but ancient coal seams and coral reefs are found in locations where it is much too cold today. Wegener suggested that these creatures were alive in warm climate zones and that the fossils and coal later had drifted to new locations on the continents.

An animation showing that Earth's climate belts remain in roughly the same position while the continents move is seen here: <http://www.scotese.com/paleocli.htm>.

An animation showing how the continents split up can be found here: <http://www.exploratorium.edu/origins/antarctica/ideas/gondwana2.html>.

Although Wegener's evidence was sound, most geologists at the time rejected his hypothesis of continental drift. Why do you think they did not accept continental drift?

Scientists argued that there was no way to explain how solid continents could plow through solid oceanic crust. Wegener's idea was nearly forgotten until technological advances presented even more evidence that the continents moved and gave scientists the tools to develop a mechanism for Wegener's drifting continents.

Magnetic Polarity Evidence

Puzzling new evidence came in the 1950s from studies on the Earth's magnetic history (**Figure 1.13**). Scientists used **magnetometers**, devices capable of measuring the magnetic field intensity, to look at the magnetic properties

of rocks in many locations.

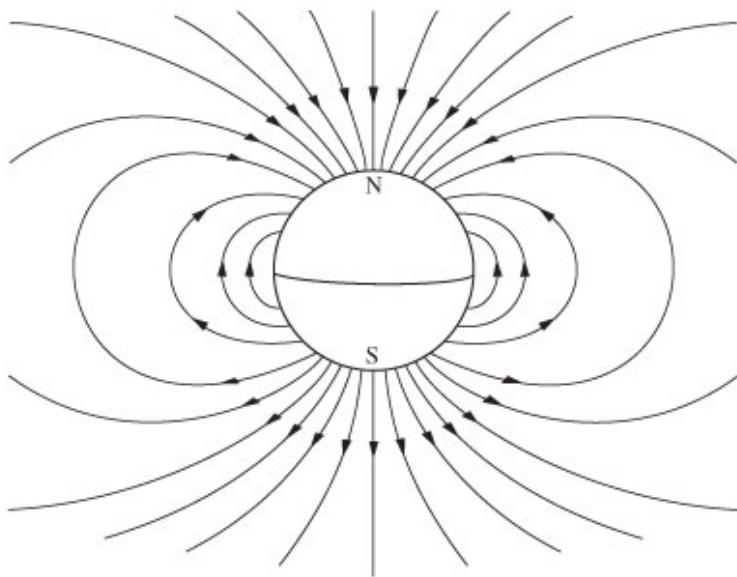


FIGURE 1.13

Earth

Magnetite crystals are like tiny magnets that point to the north magnetic pole as they crystallize from magma. The crystals record both the direction and strength of the **magnetic field** at the time. The direction is known as the field's **magnetic polarity**.

Magnetic Polarity on the Same Continent with Rocks of Different Ages

Geologists noted important things about the magnetic polarity of different aged rocks on the same continent:

- Magnetite crystals in fresh volcanic rocks point to the current magnetic north pole ([Figure 1.14](#)) no matter what continent or where on the continent the rocks are located.
- Older rocks that are the same age and are located on the same continent point to the same location, but that location is not the current north magnetic pole.
- Older rock that are of different ages do not point to the same locations or to the current magnetic north pole.

In other words, although the magnetite crystals were pointing to the magnetic north pole, the location of the pole seemed to wander. Scientists were amazed to find that the north magnetic pole changed location through time ([Figure 1.15](#)).

There are three possible explanations for this:

1. The continents remained fixed and the north magnetic pole moved.
2. The north magnetic pole stood still and the continents moved.
3. Both the continents and the north pole moved.

Magnetic Polarity on Different Continents with Rocks of the Same Age

Geologists noted that for rocks of the same age but on different continents, the little magnets pointed to different magnetic north poles.

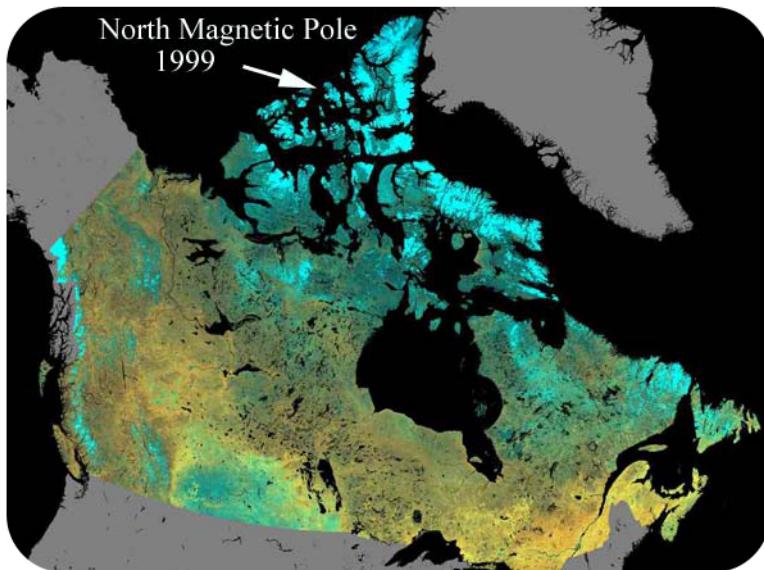


FIGURE 1.14

Earth

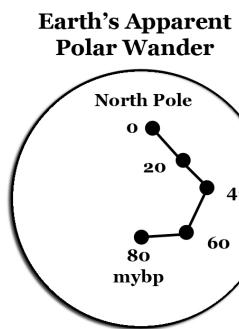


FIGURE 1.15

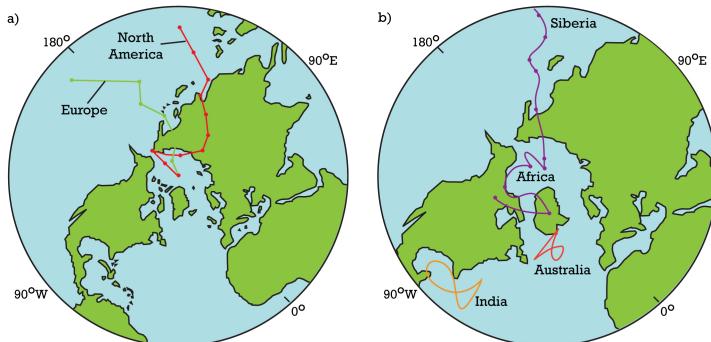
The location of the north magnetic north pole 80 million years before present (mybp), then 60, 40, 20, and now.

- 400-million-year-old magnetite in Europe pointed to a different north magnetic pole than the same-aged magnetite in North America.
- 250 million years ago, the north poles were also different for the two continents.

The scientists looked again at the three possible explanations. Only one can be correct. If the continents had remained fixed while the north magnetic pole moved, there must have been two separate north poles. Since there is only one north pole today, the only reasonable explanation is that the north magnetic pole has remained fixed but that the continents have moved.

To test this, geologists fitted the continents together as Wegener had done. It worked! There has only been one magnetic north pole and the continents have drifted (**Figure 1.16**). They named the phenomenon of the magnetic pole that seemed to move but actually did not **apparent polar wander**.

This evidence for continental drift gave geologists renewed interest in understanding how continents could move about on the planet's surface.

**FIGURE 1.16**

On the left: The apparent north pole for Europe and North America if the continents were always in their current locations. The two paths merge into one if the continents are allowed to drift.

Lesson Summary

- In the early part of the 20th century, scientists began to put together evidence that the continents could move around on Earth's surface.
- The evidence for continental drift included the fit of the continents; the distribution of ancient fossils, rocks, and mountain ranges; and the locations of ancient climatic zones.
- Although the evidence for continental drift was extremely strong, scientists rejected the idea because no mechanism for how solid continents could move around on the solid earth was developed.
- The discovery of apparent polar wander renewed scientists interest in continental drift.

Review Questions

1. Why can paper cutouts of the continents including the continental margins be pieced together to form a single whole?
2. How can the locations where ancient fossils are found be used as evidence for continental drift?
3. To show that mountain ranges on opposite sides of the Atlantic formed as two parts of the same range and were once joined, what would you look for?
4. What are the three possible explanations for apparent polar wander? Considering all the evidence, which explanation is the only one likely to be true and why?
5. With so much evidence to support continental drift, how could scientists reject the idea?
6. Look at a world map. Besides the coast of west Africa and eastern South America, what are some other regions of the world that look as they could be closely fit together?

Points to Consider

- Why is continental drift referred to as a hypothesis (or idea) and not a theory?
- What did Wegener's idea need for it to be accepted?
- What other explanations did scientists come up with to explain the evidence Wegener had for continental drift?

1.3 Seafloor Spreading

Lesson Objectives

- Describe the main features of the seafloor.
- Explain what seafloor magnetism tells scientists about the seafloor.
- Describe the process of seafloor spreading.

Vocabulary

- abyssal plains
- echo sounder
- seafloor spreading
- trench

Introduction

World War II gave scientists the tools to find the mechanism for continental drift that had eluded Wegener. Maps and other data gathered during the war allowed scientists to develop the seafloor spreading hypothesis. This hypothesis traces oceanic crust from its origin at a mid-ocean ridge to its destruction at a deep sea trench and is the mechanism for continental drift.

Seafloor Bathymetry

During World War II, battleships and submarines carried **echo sounders** to locate enemy submarines ([Figure 1.17](#)). Echo sounders produce sound waves that travel outward in all directions, bounce off the nearest object, and then return to the ship. By knowing the speed of sound in seawater, scientists calculate the distance to the object based on the time it takes for the wave to make a round-trip. During the war, most of the sound waves ricocheted off the ocean bottom.

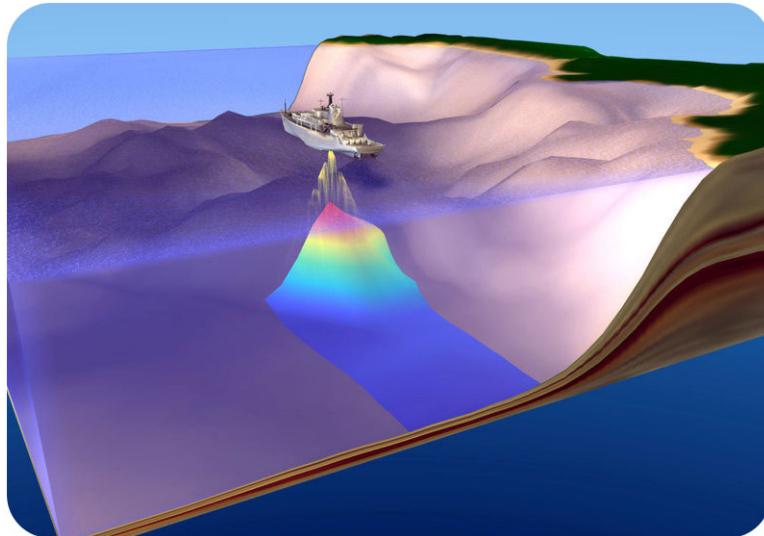
This animation shows how sound waves are used to create pictures of the sea floor and ocean crust: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_sonar.html.

After the war, scientists pieced together the ocean depths to produce bathymetric maps, which reveal the features of the ocean floor as if the water were taken away. Even scientist were amazed that the seafloor was not completely flat ([Figure 1.18](#)).

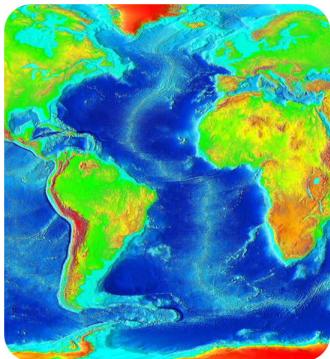
The major features of the ocean basins and their colors on the map in [Figure 1.18](#) include:

- mid-ocean ridges: rise up high above the deep seafloor as a long chain of mountains; e.g. the light blue gash in middle of Atlantic Ocean.
- deep sea **trenches**: found at the edges of continents or in the sea near chains of active volcanoes; e.g. the very deepest blue, off of western South America.
- **abyssal plains**: flat areas, although many are dotted with volcanic mountains; e.g. consistent blue off of southeastern South America.

When they first observed these bathymetric maps, scientists wondered what had formed these features.

**FIGURE 1.17**

This echo sounder has many beams and creates a three dimensional map of the seafloor. Early echo sounders had a single beam and created a line of depth measurements.

**FIGURE 1.18**

A modern map of the southeastern Pacific and Atlantic Oceans.

Seafloor Magnetism

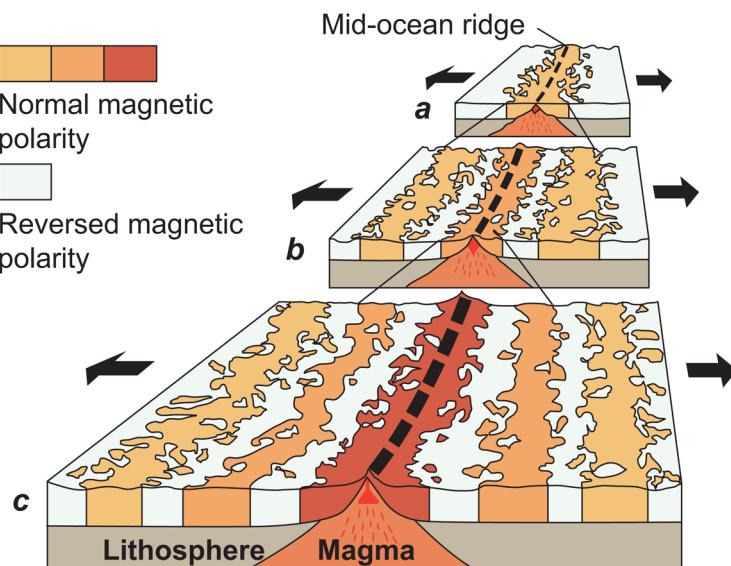
Sometimes – no one really knows why – the magnetic poles switch positions. North becomes south and south becomes north.

- Normal polarity: north and south poles are aligned as they are now.
- Reversed polarity: north and south poles are in the opposite position.

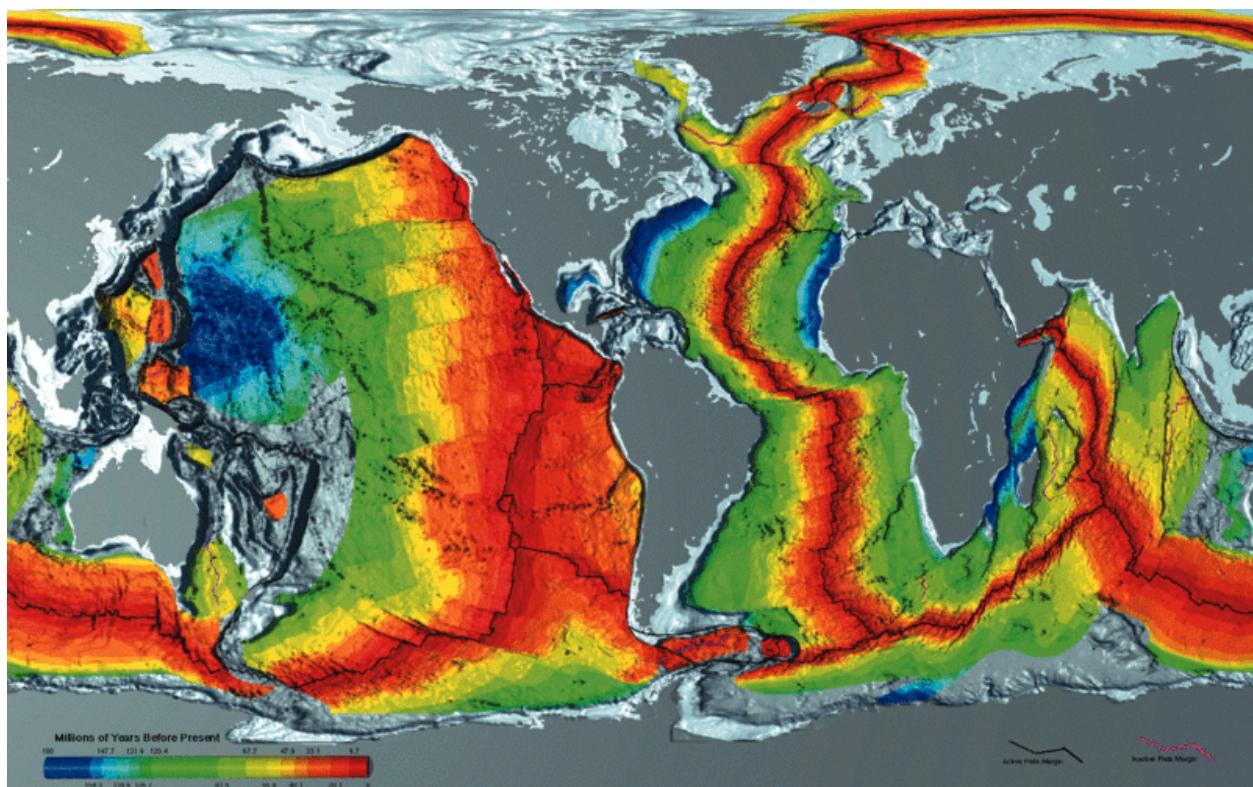
During WWII, magnetometers attached to ships to search for submarines located an astonishing feature: the normal and reversed magnetic polarity of seafloor basalts creates a pattern.

- Stripes of normal polarity and reversed polarity alternate across the ocean bottom.
- Stripes form mirror images on either side of the mid-ocean ridges (**Figure 1.19**).
- Stripes end abruptly at the edges of continents, sometimes at a deep sea trench (**Figure 1.20**).

The characteristics of the rocks and sediments change with distance from the ridge axis as seen in the **Table 1.2**.

**FIGURE 1.19**

Magnetic polarity is normal at the ridge crest but reversed in symmetrical patterns away from the ridge center. This normal and reversed pattern continues across the seafloor.

**FIGURE 1.20**

Seafloor is youngest at the mid-ocean ridges and becomes progressively older with distance from the ridge.

TABLE 1.2: Characteristics of crustal rocks with distance from ridge axis

	Rock ages	Sediment thickness	Crust thickness	Heat flow
At ridge axis	youngest	none	thinnest	hottest
With distance from axis	becomes older	becomes thicker	becomes thicker	becomes cooler

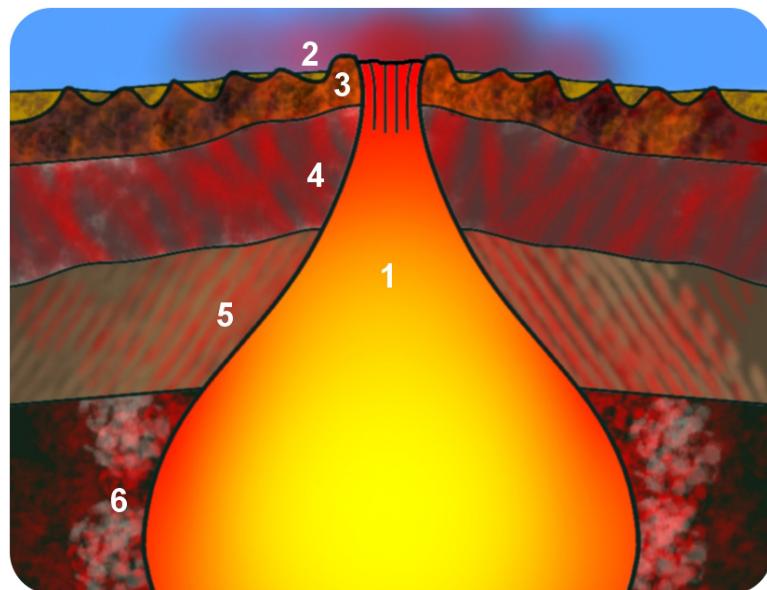
A map of sediment thickness is found here: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_sedimentthickness.html.

The oldest seafloor is near the edges of continents or deep sea trenches and is less than 180 million years old (**Figure 1.20**). Since the oldest ocean crust is so much younger than the oldest continental crust, scientists realized that seafloor was being destroyed in a relatively short time.

This 65 minute video explains “The Role of Paleomagnetism in the Evolution of Plate Tectonic Theory”: <http://online.wr.usgs.gov/calendar/2004/jul04.html>.

The Seafloor Spreading Hypothesis

Scientists brought these observations together in the early 1960s to create the **seafloor spreading** hypothesis. In this hypothesis, hot buoyant mantle rises up a mid-ocean ridge, causing the ridge to rise upward (**Figure 1.21**).

**FIGURE 1.21**

Magma at the mid-ocean ridge creates new seafloor.

The hot magma at the ridge erupts as lava that forms new seafloor. When the lava cools, the magnetite crystals take on the current magnetic polarity. As more lava erupts, it pushes the seafloor horizontally away from ridge axis.

These animations show the creation of magnetic stripes of normal and reversed polarity at a mid-ocean ridge: <http://www.nature.nps.gov/GEOLOGY/usgsnps/animate/A49.gif>; <http://www.nature.nps.gov/GEOLOGY/usgsnps/animate/A55.gif>.

The magnetic stripes continue across the seafloor.

- As oceanic crust forms and spreads, moving away from the ridge crest, it pushes the continent away from the ridge axis.

- If the oceanic crust reaches a deep sea trench, it sinks into the trench and is lost into the mantle.
- The oldest crust is coldest and lies deepest in the ocean because it is less buoyant than the hot new crust.

Seafloor spreading is the mechanism for Wegener's drifting continents. Convection currents within the mantle take the continents on a conveyor-belt ride of oceanic crust that over millions of years takes them around the planet's surface.

The breakup of Pangaea by seafloor spreading is seen in this animation: <http://www.scotese.com/sfsanim.htm>.

The breakup of Pangaea with a focus on the North Atlantic: <http://www.scotese.com/natlanim.htm>.

An animation of the breakup of Pangaea focused on the Pacific Ocean: <http://www.scotese.com/pacifanim.htm>.

Seafloor spreading is the topic of this Discovery Education video: <http://video.yahoo.com/watch/1595570/5390151>.

The history of the seafloor spreading hypothesis and the evidence that was collected to develop it are the subject of this video (3a): http://www.youtube.com/watch?v=6CsTTmvX6mc&feature=rec-LGOUT-exp_fresh+div-1r-2 (8:05).



MEDIA

Click image to the left for more content.

Lesson Summary

- Using technologies developed to fight World War II, scientists were able to gather data that allowed them to recognize seafloor spreading as the mechanism for Wegener's drifting continents.
- Bathymetric maps revealed high mountain ranges and deep trenches in the seafloor.
- Magnetic polarity stripes give clues to seafloor ages and the importance of mid-ocean ridges in the creation of oceanic crust.
- Seafloor spreading processes create new oceanic crust at mid-ocean ridges and destroy older crust at deep sea trenches.

Review Questions

1. Describe how sound waves are used to develop a map of the features of the seafloor.
2. Why is the oldest seafloor less than 180 million years when the oldest continental crust is about 4 billion years old?
3. Describe the major features and the relative ages of mid-ocean ridges, deep sea trenches, and abyssal plains.
4. Describe how continents move across the ocean basins as if they are on a conveyor belt.
5. If you were a paleontologist who studies fossils of very ancient life forms, where would be the best place to look for very old fossils: on land or in the oceans?
6. Imagine that Earth's magnetic field was fixed in place and the polarity didn't reverse. What effect would this have on our observations of seafloor basalts?
7. Look at a map of the Atlantic seafloor with magnetic polarity stripes and recreate the history of the Atlantic Ocean basin.

Further Reading / Supplemental Links

- A basic description of sea floor spreading with animations: <http://www.pbs.org/wnet/savageearth/hellsrust/index.html>.

Points to Consider

- How were the technologies that were developed to fight World War II used by scientists for the development of the seafloor spreading hypothesis?
- In what two ways did magnetic data lead scientists to understand more about continental drift and plate tectonics?
- How does seafloor spreading provide a mechanism for continental drift?
- Look at the features of the North Pacific Ocean basin and explain them in seafloor spreading terms.
- What would have to happen if oceanic crust was not destroyed at oceanic trenches, but new crust was still created at mid-ocean ridges?

1.4 Theory of Plate Tectonics

Lesson Objectives

- Describe what a plate is and how scientists can recognize its edges.
- Explain how mantle convection moves lithospheric plates.
- List the three types of boundaries. Are they prone to earthquakes or volcanoes?
- Describe how plate tectonics processes lead to changes in Earth's surface features.

Vocabulary

- batholith
- continental arc
- continental rifting
- convergent plate boundary
- divergent plate boundary
- epicenter
- hotspot
- intraplate activity
- island arc
- plate
- plate boundary
- plate tectonics
- subduction
- subduction zone
- supercontinent cycle
- transform fault
- transform plate boundary

Introduction

When the concept of seafloor spreading came along, scientists recognized that it was the mechanism to explain how continents could move around Earth's surface. Like the scientists before us, we will now merge the ideas of continental drift and seafloor spreading into the theory of plate tectonics.

Continental drift and the mechanism of seafloor spreading create plate tectonics: <http://video.yahoo.com/watch/1595682/5390276>.

Earth's Tectonic Plates

Seafloor and continents move around on Earth's surface, but what is actually moving? What portion of the Earth makes up the "plates" in plate tectonics? This question was also answered because of technology developed during war times - in this case, the Cold War. The **plates** are made up of the lithosphere.

During the 1950s and early 1960s, scientists set up seismograph networks to see if enemy nations were testing atomic bombs. These seismographs also recorded all of the earthquakes around the planet. The seismic records could be

used to locate an earthquake's **epicenter**, the point on Earth's surface directly above the place where the earthquake occurs.

Earthquake epicenters outline the plates. Mid-ocean ridges, trenches, and large faults mark the edges of the plates, and this is where earthquakes occur (**Figure 1.22**).

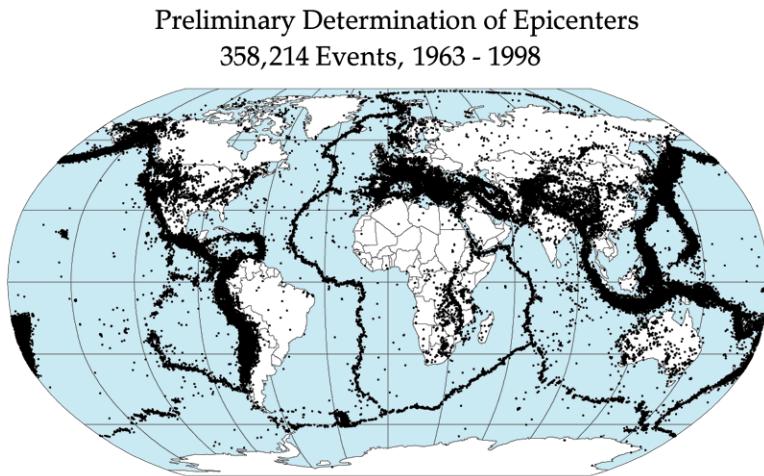


FIGURE 1.22

Earthquakes outline the plates.

The lithosphere is divided into a dozen major and several minor plates (**Figure 1.23**). The plates' edges can be drawn by connecting the dots that mark earthquakes' epicenters. A single plate can be made of all oceanic lithosphere or all continental lithosphere, but nearly all plates are made of a combination of both.

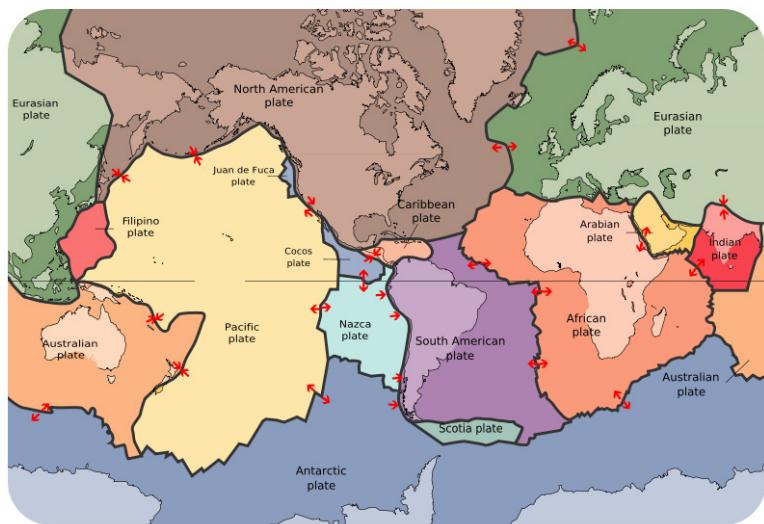


FIGURE 1.23

The lithospheric plates and their names. The arrows show whether the plates are moving apart, moving together, or sliding past each other.

Movement of the plates over Earth's surface is termed **plate tectonics**. Plates move at a rate of a few centimeters a year, about the same rate fingernails grow.

How Plates Move

If seafloor spreading drives the plates, what drives seafloor spreading? Picture two convection cells side-by-side in the mantle, similar to the illustration in [Figure 1.24](#).

1. Hot mantle from the two adjacent cells rises at the ridge axis, creating new ocean crust.
2. The top limb of the convection cell moves horizontally away from the ridge crest, as does the new seafloor.
3. The outer limbs of the convection cells plunge down into the deeper mantle, dragging oceanic crust as well. This takes place at the deep sea trenches.
4. The material sinks to the core and moves horizontally.
5. The material heats up and reaches the zone where it rises again.

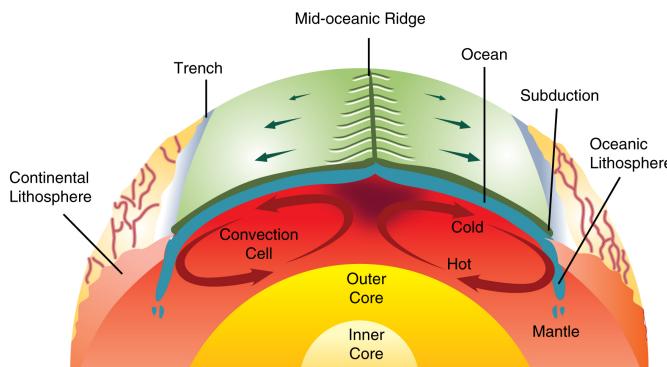


FIGURE 1.24

Mantle convection drives plate tectonics. Hot material rises at mid-ocean ridges and sinks at deep sea trenches, which keeps the plates moving along the Earth

Mantle convection is shown in these animations:

- http://www.youtube.com/watch?v=p0dWF_3PYh4
- http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_convection2.html

Plate Boundaries

Plate boundaries are the edges where two plates meet. Most geologic activities, including volcanoes, earthquakes, and mountain building, take place at plate boundaries. How can two plates move relative to each other?

- **Divergent plate boundaries:** the two plates move away from each other.
- **Convergent plate boundaries:** the two plates move towards each other.
- **Transform plate boundaries:** the two plates slip past each other.

The type of plate boundary and the type of crust found on each side of the boundary determines what sort of geologic activity will be found there.

Divergent Plate Boundaries

Plates move apart at mid-ocean ridges where new seafloor forms. Between the two plates is a rift valley. Lava flows at the surface cool rapidly to become basalt, but deeper in the crust, magma cools more slowly to form gabbro. So the entire ridge system is made up of igneous rock that is either extrusive or intrusive. Earthquakes are common at

**FIGURE 1.25**

(a) Iceland is the one location where the ridge is located on land: the Mid-Atlantic Ridge separates the North American and Eurasian plates; (b) The rift valley in the Mid-Atlantic Ridge on Iceland.

mid-ocean ridges since the movement of magma and oceanic crust results in crustal shaking. The vast majority of mid-ocean ridges are located deep below the sea ([Figure 1.25](#)).

USGS animation of divergent plate boundary at mid-ocean ridge: http://earthquake.usgs.gov/learn/animations/animation.php?flash_title=Divergent+Boundary&flash_file=divergent&flash_width=500&flash_height=200.

Divergent plate boundary animation: http://www.iris.edu/hq/files/programs/education_and_outreach/aotm/11/AOTM_09_01_Divergent_480.mov.

Can divergent plate boundaries occur within a continent? What is the result? In **continental rifting** ([Figure 1.26](#)), magma rises beneath the continent, causing it to become thinner, break, and ultimately split apart. New ocean crust erupts in the void, creating an ocean between continents.

**FIGURE 1.26**

The Arabian, Indian, and African plates are rifting apart, forming the Great Rift Valley in Africa. The Dead Sea fills the rift with seawater.

Convergent Plate Boundaries

When two plates converge, the result depends on the type of lithosphere the plates are made of. No matter what, smashing two enormous slabs of lithosphere together results in magma generation and earthquakes.

Ocean-continent: When oceanic crust converges with continental crust, the denser oceanic plate plunges beneath the continental plate. This process, called **subduction**, occurs at the oceanic trenches ([Figure 1.27](#)). The entire region is known as a **subduction zone**. Subduction zones have a lot of intense earthquakes and volcanic eruptions. The subducting plate causes melting in the mantle. The magma rises and erupts, creating volcanoes. These coastal volcanic mountains are found in a line above the subducting plate ([Figure 1.28](#)). The volcanoes are known as a **continental arc**.

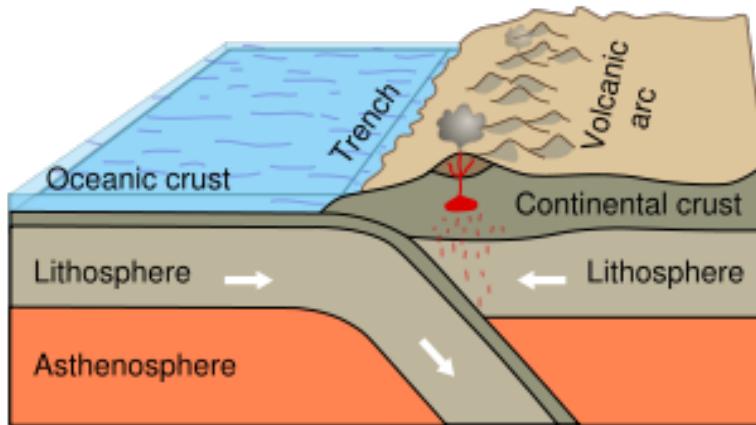


FIGURE 1.27

Subduction of an oceanic plate beneath a continental plate causes earthquakes and forms a line of volcanoes known as a continental arc.

The movement of crust and magma causes earthquakes. A map of earthquake epicenters at subduction zones is found here: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_earthquakesubduction.html.

This animation shows the relationship between subduction of the lithosphere and creation of a volcanic arc: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_subduction.html.

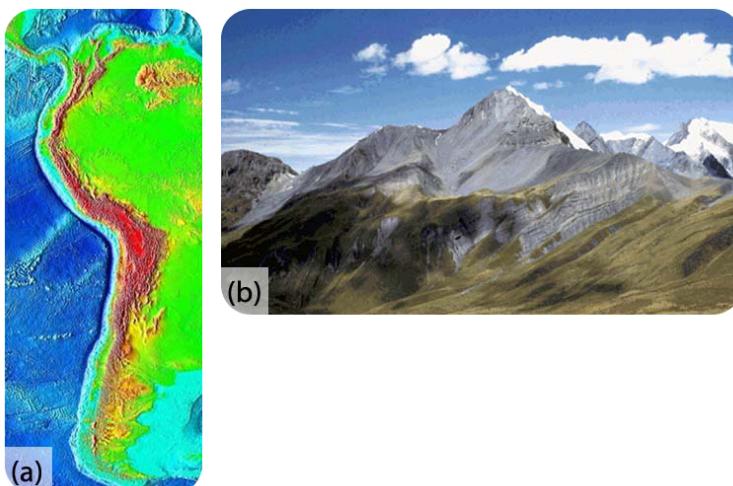


FIGURE 1.28

(a) At the trench lining the western margin of South America, the Nazca plate is subducting beneath the South American plate, resulting in the Andes Mountains (brown and red uplands); (b) Convergence has pushed up limestone in the Andes Mountains where volcanoes are common.

The volcanoes of northeastern California—Lassen Peak, Mount Shasta, and Medicine Lake volcano—along with the

rest of the Cascade Mountains of the Pacific Northwest are the result of subduction of the Juan de Fuca plate beneath the North American plate (**Figure 1.29**). The Juan de Fuca plate is created by seafloor spreading just offshore at the Juan de Fuca ridge.

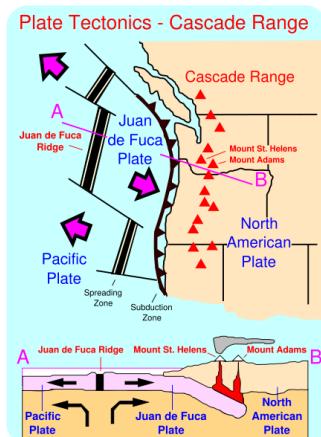


FIGURE 1.29

The Cascade Mountains of the Pacific Northwest are a continental arc.

If the magma at a continental arc is felsic, it may be too viscous (thick) to rise through the crust. The magma will cool slowly to form granite or granodiorite. These large bodies of intrusive igneous rocks are called **batholiths**, which may someday be uplifted to form a mountain range (**Figure 1.30**).



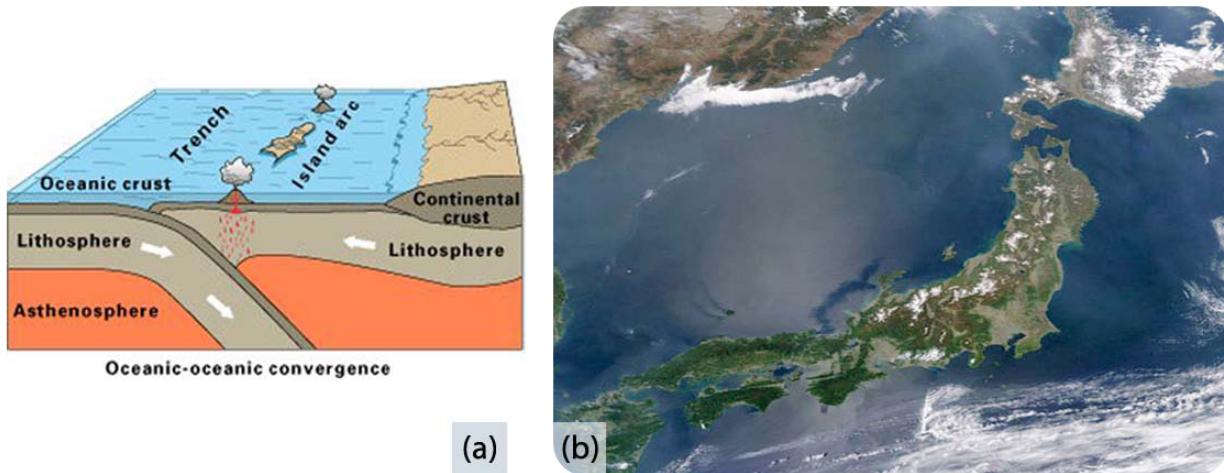
FIGURE 1.30

The Sierra Nevada batholith cooled beneath a volcanic arc roughly 200 million years ago. The rock is well exposed here at Mount Whitney. Similar batholiths are likely forming beneath the Andes and Cascades today.

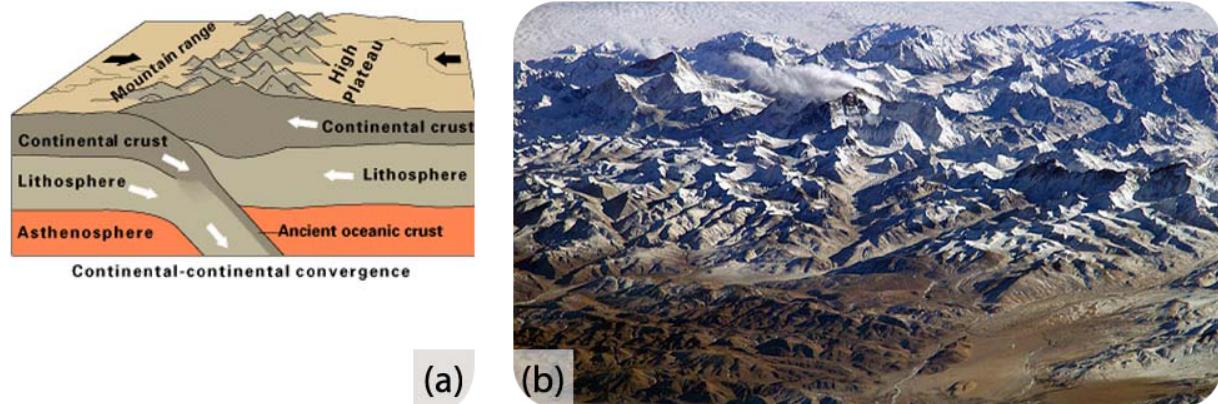
Ocean-ocean: When two oceanic plates converge, the older, denser plate will subduct into the mantle. An ocean trench marks the location where the plate is pushed down into the mantle. The line of volcanoes that grows on the upper oceanic plate is an **island arc**. Do you think earthquakes are common in these regions (**Figure 1.31**)?

An animation of an ocean continent plate boundary is seen here: http://www.iris.edu/hq/files/programs/education_and_outreach/aotm/11/AOTM_09_01_Convergent_480.mov.

Continent-continent: Continental plates are too buoyant to subduct. What happens to continental material when it collides? Since it has nowhere to go but up, this creates some of the world's largest mountains ranges (**Figure 1.32**). Magma cannot penetrate this thick crust so there are no volcanoes, although the magma stays in the crust. Metamorphic rocks are common because of the stress the continental crust experiences. With enormous slabs of crust smashing together, continent-continent collisions bring on numerous and large earthquakes.

**FIGURE 1.31**

(a) Subduction of an ocean plate beneath an ocean plate results in a volcanic island arc, an ocean trench and many earthquakes. (b) Japan is an arc-shaped island arc composed of volcanoes off the Asian mainland, as seen in this satellite image.

**FIGURE 1.32**

(a) In continent-continent convergence, the plates push upward to create a high mountain range. (b) The world

A short animation of the Indian Plate colliding with the Eurasian Plate: <http://www.scotese.com/indianim.htm>.

An animation of the Himalaya rising: http://www.youtube.com/watch?v=ep2_axAA9Mw&NR=1.

The Appalachian Mountains are the remnants of a large mountain range that was created when North America rammed into Eurasia about 250 million years ago.

Transform Plate Boundaries

Transform plate boundaries are seen as **transform faults**, where two plates move past each other in opposite directions. Transform faults on continents bring massive earthquakes (**Figure 1.33**).

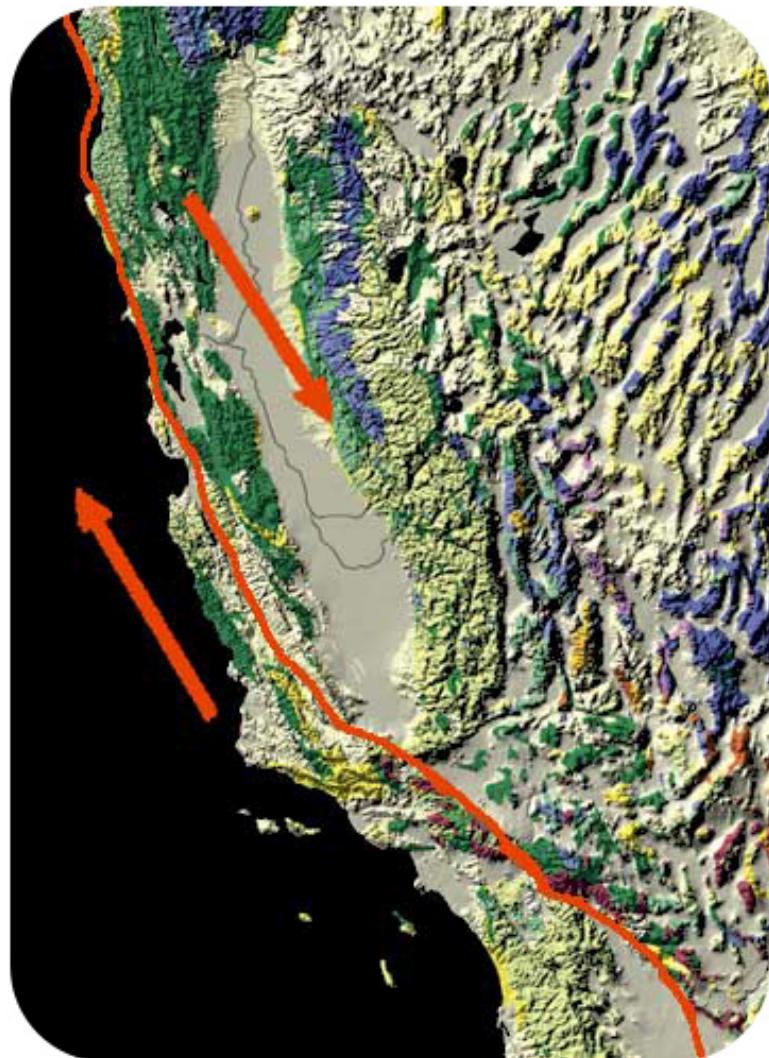


FIGURE 1.33

At the San Andreas Fault in California, the Pacific Plate is sliding northeast relative to the North American plate, which is moving southwest. At the northern end of the picture, the transform boundary turns into a subduction zone.

California is very geologically active. What are the three major plate boundaries in or near California (**Figure 1.34**)?

1. A transform plate boundary between the Pacific and North American plates creates the San Andreas Fault, the world's most notorious transform fault.
2. Just offshore, a divergent plate boundary, Juan de Fuca ridge, creates the Juan de Fuca plate.
3. A convergent plate boundary between the Juan de Fuca oceanic plate and the North American continental plate creates the Cascades volcanoes.

A brief review of the three types of plate boundaries and the structures that are found there is the subject of this wordless video (3b): <http://www.youtube.com/watch?v=ifke1GsjNN0> (4:50).

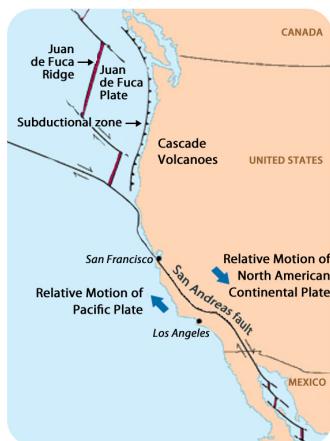


FIGURE 1.34

This map shows the three major plate boundaries in or near California.



MEDIA

Click image to the left for more content.

Earth's Changing Surface

Geologists know that Wegener was right because the movements of continents explain so much about the geology we see. Most of the geologic activity that we see on the planet today is because of the interactions of the moving plates.

In the map of North America ([Figure 1.35](#)), where are the mountain ranges located? Using what you have learned about plate tectonics, try to answer the following questions:

1. What is the geologic origin of the Cascades Range? The Cascades are a chain of volcanoes in the Pacific Northwest. They are not labelled on the diagram but they lie between the Sierra Nevada and the Coastal Range.
2. What is the geologic origin of the Sierra Nevada? (Hint: These mountains are made of granitic intrusions.)
3. What is the geologic origin of the Appalachian Mountains along the Eastern US?

Remember that Wegener used the similarity of the mountains on the west and east sides of the Atlantic as evidence for his continental drift hypothesis. The Appalachian mountains formed at a convergent plate boundary as Pangaea came together ([Figure 1.36](#)).

Before Pangaea came together, the continents were separated by an ocean where the Atlantic is now. The proto-Atlantic ocean shrank as the Pacific ocean grew. Currently, the Pacific is shrinking as the Atlantic is growing. This **supercontinent cycle** is responsible for most of the geologic features that we see and many more that are long gone ([Figure 1.37](#)).

This animation shows the movement of continents over the past 600 million years beginning with the breakup of Rodinia: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_plate_reconstruction_blaekey.html.

**FIGURE 1.35**

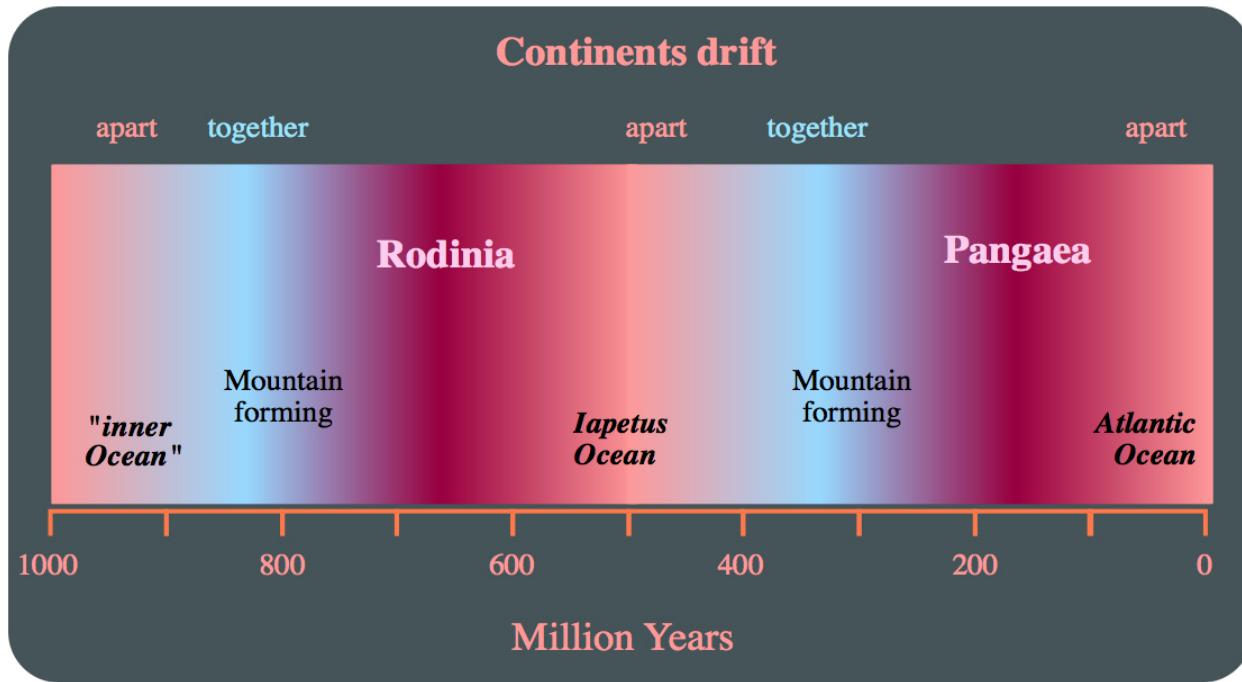
Mountain ranges of North America.

**FIGURE 1.36**

About 200 million years ago, the Appalachian Mountains of eastern North America were probably once as high as the Himalaya, but they have been weathered and eroded significantly since the breakup of Pangaea.

Intraplate Activity

A small amount of geologic activity, known as **intraplate activity**, does not take place at plate boundaries but within a plate instead. Mantle plumes are pipes of hot rock that rise through the mantle. The release of pressure causes melting near the surface to form a **hotspot**. Eruptions at the hotspot create a volcano. Hotspot volcanoes are found in a line ([Figure 1.38](#)). Can you figure out why? Hint: The youngest volcano sits above the hotspot and volcanoes become older with distance from the hotspot.

**FIGURE 1.37**

Scientists think that the creation and breakup of a supercontinent takes place about every 500 million years. The supercontinent before Pangaea was Rodinia. A new continent will form as the Pacific ocean disappears.

An animation of the creation of a hotspot chain is seen here: http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_hawaii.html.

Geologists use some hotspot chains to tell the direction and the speed a plate is moving (**Figure 1.39**).

Hotspot magmas rarely penetrate through thick continental crust. One exception is the Yellowstone hotspot (**Figure 1.40**).

Plate Tectonics Theory

Plate tectonics is the unifying theory of geology. Plate tectonics theory explains why:

- Earth's geography has changed through time and continues to change today.
- some places are prone to earthquakes while others are not.
- certain regions may have deadly, mild, or no volcanic eruptions.
- mountain ranges are located where they are.

Plate tectonic motions affect Earth's rock cycle, climate, and the evolution of life.

Lesson Summary

- Plates of lithosphere move because of convection currents in the mantle. One type of motion is produced by seafloor spreading.

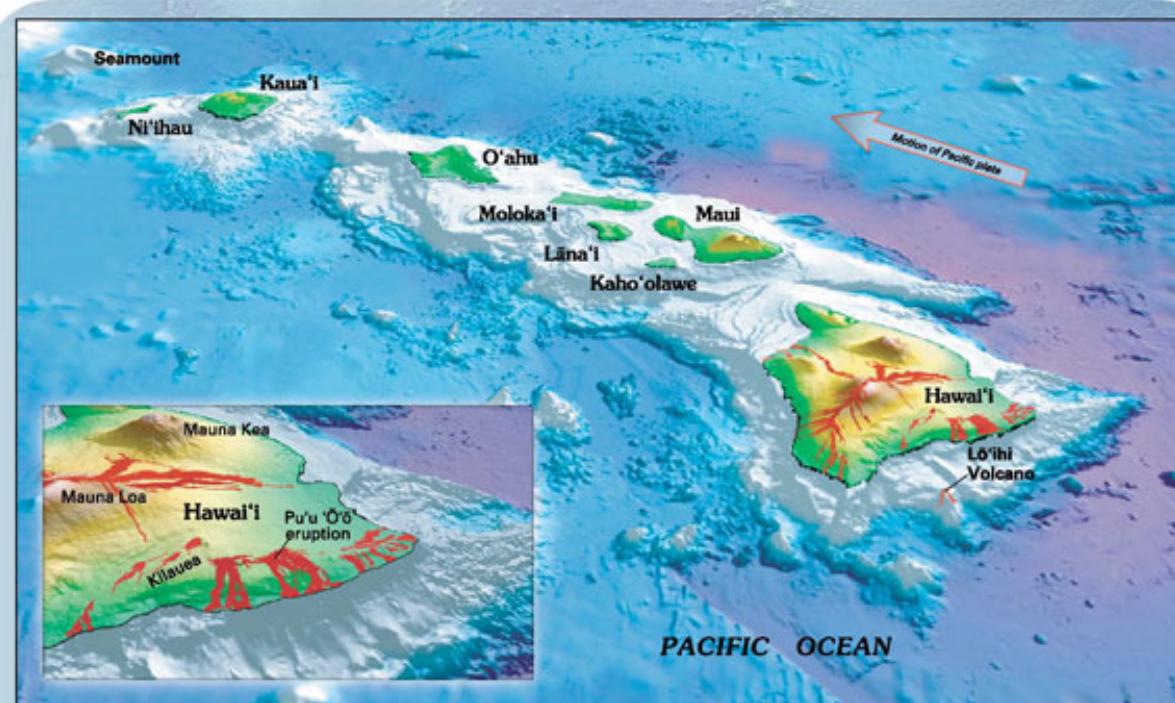


Figure 2.—Oblique view of the principal Hawaiian Islands and (the still submarine) Lō'ihi Volcano. Inset gives a closer view of three of the five volcanoes that form the Island of Hawa'i (historical lava flows are shown in red). The longest duration historical eruption on Kilauea's east-rift zone at Pu'u 'O'o (inset), which began in January 1983, continues unabated (as of spring 2006). View prepared by Joel E. Robinson (USGS).

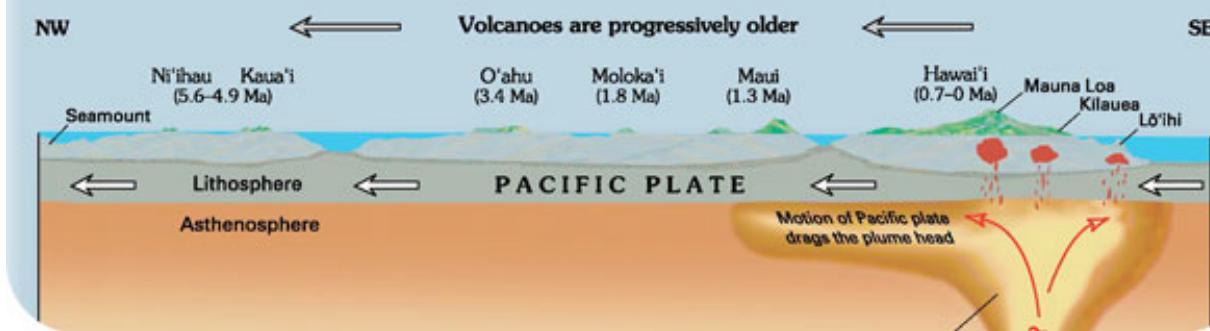
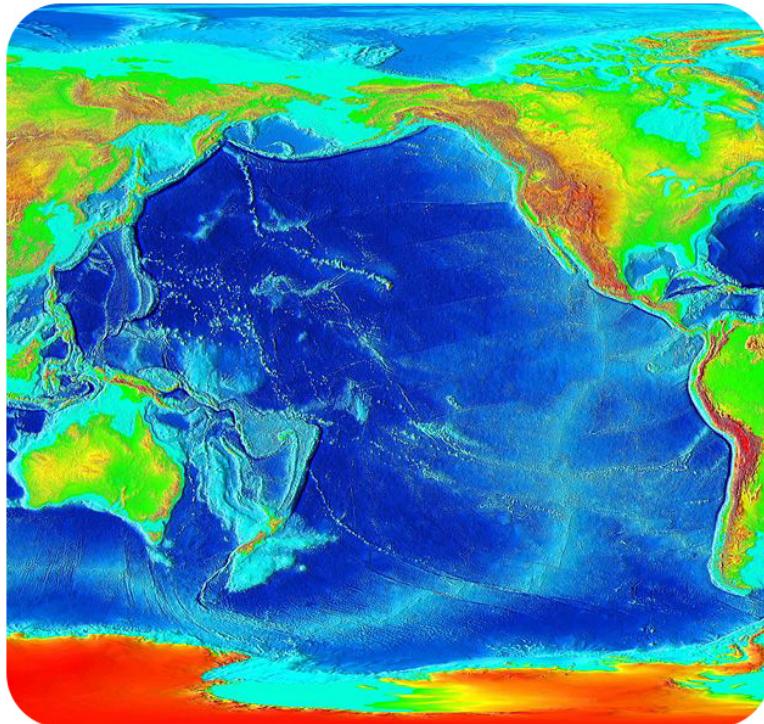


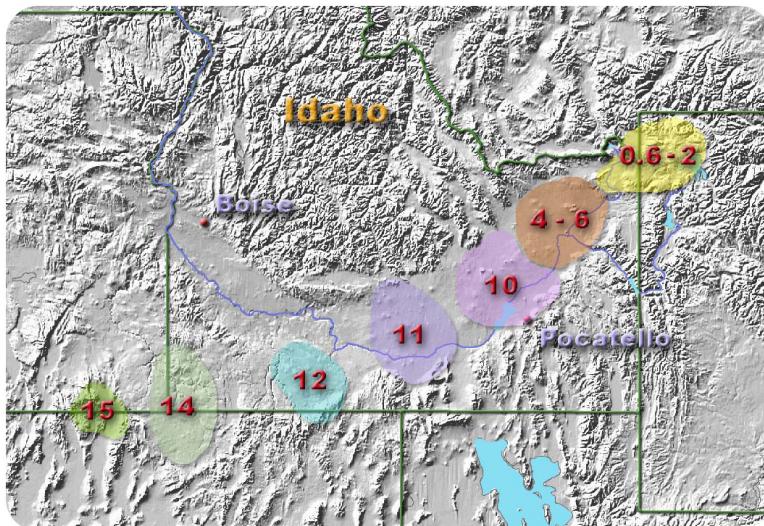
FIGURE 1.38

The Hawaiian Islands are a beautiful example of a hotspot chain. Kilauea volcano lies above the Hawaiian hotspot. Mauna Loa volcano is older than Kilauea and is still erupting, but at a lower rate. The islands get progressively older to the northwest because they are further from the hotspot. Lō'ihi, the youngest volcano, is still below the sea surface.

- Plate boundaries can be located by outlining earthquake epicenters.
- Plates interact at three types of plate boundaries: divergent, convergent and transform.
- Most of the Earth's geologic activity takes place at plate boundaries.
- At a divergent boundary, volcanic activity produces a mid ocean ridge and small earthquakes.

**FIGURE 1.39**

The Hawaiian chain continues into the Emperor Seamounts. The bend in the chain was caused by a change in the direction of the Pacific plate 43 million years ago. Using the age and distance of the bend, geologists can figure out the speed of the Pacific plate over the hotspot.

**FIGURE 1.40**

Volcanic activity above the Yellowstone hotspot on the North American Plate can be traced from 15 million years ago to its present location.

- At a convergent boundary with at least one oceanic plate, an ocean trench, a chain of volcanoes develops and many earthquakes occur.
- At a convergent boundary where both plates are continental, mountain ranges grow and earthquakes are common.
- At a transform boundary, there is a transform fault and massive earthquakes occur but there are no volcanoes.
- Processes acting over long periods of time create Earth's geographic features.

Review Questions

Use this diagram to review this chapter (**Figure 1.41**).

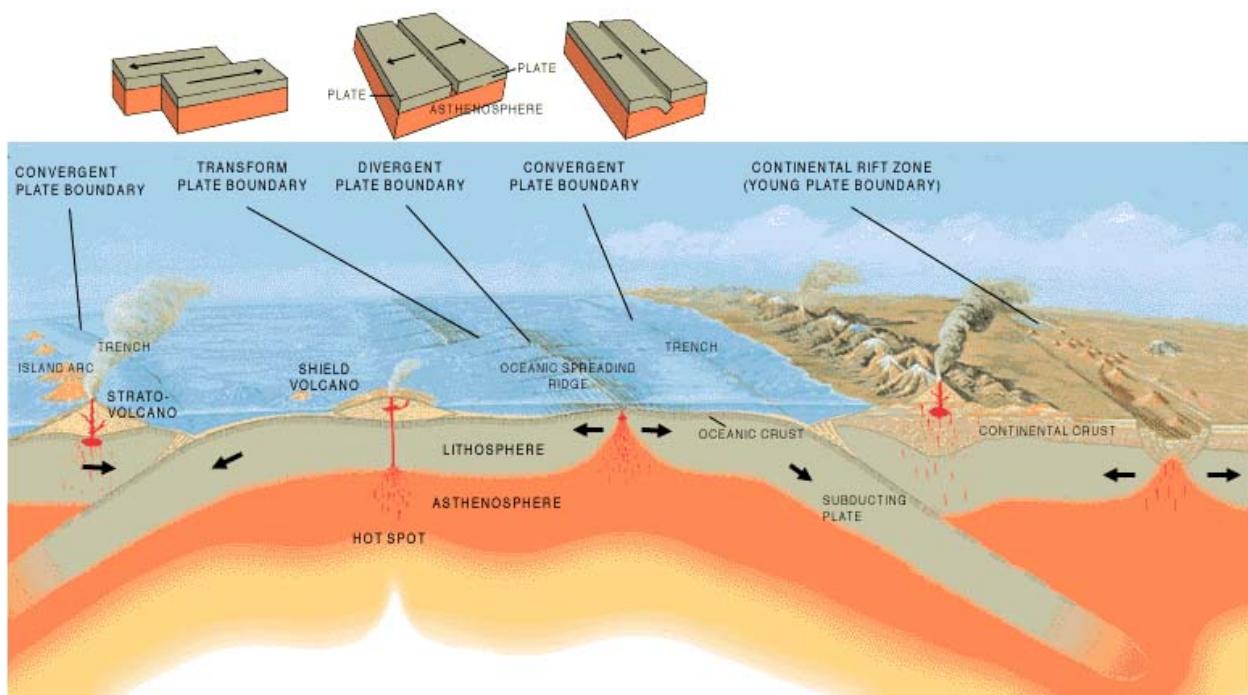


FIGURE 1.41

Plate boundaries

1. What are the three types of plate boundaries and what type of geologic activity is found at each?
2. As a geologist, you come across a landscape with a massive fault zone that produces a lot of large earthquakes but has no volcanoes. What type of plate boundary is this? What are the movements of plates there? Where is this type of boundary found in California?
3. Next you find a chain of volcanoes along a coast on land, not too far inland from the ocean. The region experiences frequent large earthquakes. What type of plate boundary is this? What types of plates are involved? Where is this type of boundary found in California?
4. What is the driving force behind the movement of lithospheric plates on the Earth's surface? About how fast do the plates move?
5. How does the theory of plate tectonics explain the locations of volcanoes, earthquakes, and mountain belts on Earth?
6. What causes earthquakes and at what types of plate boundaries are earthquakes common? Explain.
7. Thinking about the different types of plate boundaries, where do mountain ranges that do not include volcanoes occur and why?
8. Why are there no volcanoes along transform plate boundaries? At continent-continent convergent plate boundaries?

Points to Consider

- On the map in **Figure 1.23**, the arrows show the directions that the plates are going. The Atlantic has a mid-ocean ridge, where seafloor spreading is taking place. The Pacific Ocean has many deep sea trenches, where subduction is taking place. What is the future of the Atlantic plate? What is the future of the Pacific plate?
 - Using your hands and words, explain to someone how plate tectonics works. Be sure you describe how continents drift and how seafloor spreading provides a mechanism for continental movement.
 - Now that you know about plate tectonics, where do you think would be a safe place to live if you wanted to avoid volcanic eruptions and earthquakes?
-
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