Chapter 2

Inside Earth

Standard 2: Students will understand Earth's internal structure and the dynamic nature of the tectonic plates that form its surface.

How does the internal structure of the earth affect the temperature of the earth?

Standard 2, Objective 1: Evaluate the source of Earth's internal heat and the evidence of Earth's internal structure.

Section 1: Earth's Internal Heat

If you think about a volcano, you know Earth must be hot inside. The heat inside Earth moves continents, builds mountains and causes earthquakes. Where does all this heat inside Earth come from?

Earth was hot when it formed. A lot of Earth's heat is leftover from when our planet formed, four-and-a-half billion years ago. Earth is thought to have arisen from a cloud of gas and dust in space. Solid particles, called "planetesimals" condensed out of the cloud. They're thought to have stuck together and created the early Earth. Bombarding planetesimals heated Earth to a molten state. So Earth started out with a lot of heat.

Earth makes some of its own heat. Earth is cooling now - but very, very slowly. Earth is close to a steady temperature state. Over the past several billion years, it might have cooled a couple of hundred degrees. Earth keeps a nearly steady temperature, because it makes heat in its interior.

In other words, Earth has been losing heat since it formed, billions of years ago. But it's producing almost as much heat as it is losing. The process by which Earth makes heat is called **radioactive decay** (the process in which the nucleus becomes unstable and loses particles or begin break apart). It involves the disintegration of natural radioactive elements inside Earth - like uranium, for example. Uranium is a special kind of element because when it decays, heat is produced. It's this heat that keeps Earth from cooling off completely.

Terms to know

- Radioactive Decay
- Heat of formation
- Asthenosphere
- Mesosphere
- Lithosphere
- Composition
- Outer Core
- Inner Core
- Physical properties
- Convection
- Continental Drift Theory
- Geologic record
- Magnetic Striping
- Mid-ocean ridge
- Oceanic trenches
- Magnetic striping
- Plate Tectonics
- Mantle plumes
- Seafloor spreading
- Lithosphere plate
- Tectonic Plate
- Convergent
- Divergent
- Transform boundaries

Many of the rocks in Earth's crust and interior undergo this process of radioactive decay. This process produces subatomic particles that zip away, and later collide with surrounding material inside the Earth. Their energy of motion is converted to heat.

Without this process of radioactive decay, there would be fewer volcanoes and earthquakes - and less building of Earth's vast mountain ranges.

(1a text from http://earthsky.org/earth/what-is-the-source-of-the-heat-in-the-earths-interior)

Heat of Formation

A relatively straightforward chemical reaction is one in which elements are combined to form a compound. A chemical reaction can give off heat, therefore, the source of the earth's internal heat comes from **radioactive decay**, and **heat of formation** (the production of heat through a chemical reactions) through chemical reactions within the earth

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 instances, 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.

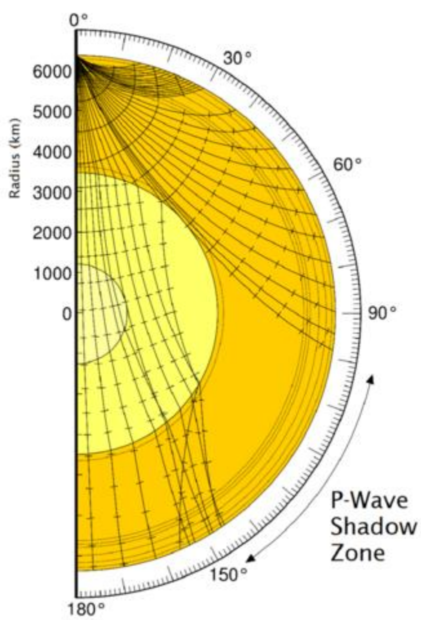
Seismic Waves

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 below). 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 104o to 140o from the earthquakes focus.

- 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 (See the figure below).



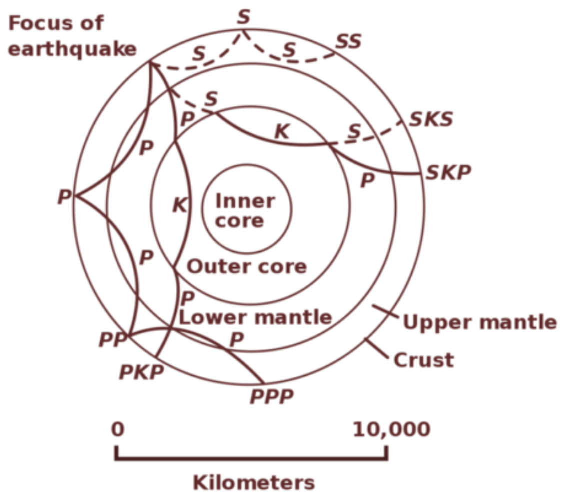
How P-waves travel through Earth's interior.

- 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.

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.

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



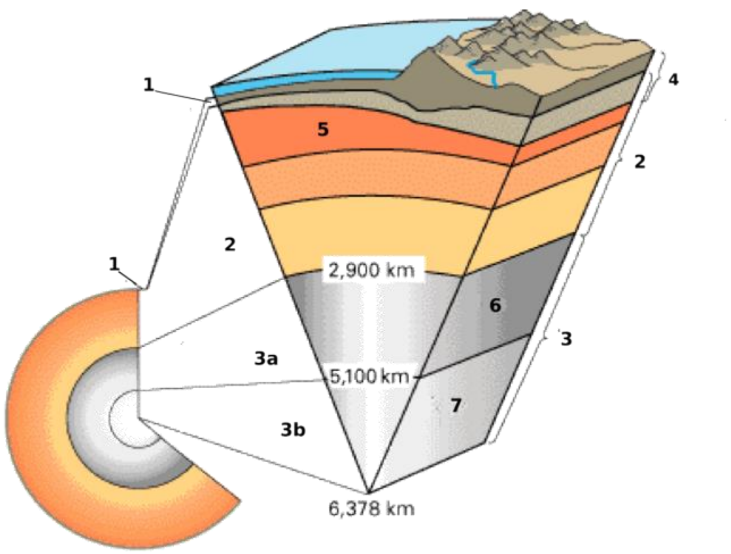
Other Clues about Earth's Interior

- Earth's overall density is higher than the density of crustal rocks, so the core must be made of something dense, like metal.
- Since Earth has a magnetic field, there must be metal within the planet. Iron and nickel are both magnetic.
- 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 below).

This meteorite contains silica minerals and iron-nickel. The material is like the boundary between Earth's core and mantle. The meteorite is 4.2 billion years old.

Section 2: The Earth's Layers

The layers scientists recognize are pictured below.



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.

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

- The crust is less than 1% of Earth by mass. The oceanic crust is mafic (minerals with high levels of ferromagnesian), while continental crust is often more felsic (minerals that are primarily made of feldspars and quartz) rock.
- The mantle is hot, ultramafic rock. It represents about 68% of Earth's mass.
- The core is mostly iron metal. The core makes up about 31% of the Earth.

Lithosphere and asthenosphere are divisions based on mechanical properties:

- The **lithosphere** is composed of both the crust and the portion of the upper mantle that behaves as a brittle, rigid solid.
- The **asthenosphere** is partially molten upper mantle material that behaves plastically and can flow.
- The **mesosphere** refers to the mantle in the region under the lithosphere, and the asthenosphere, but above the outer core. The difference between mesosphere and asthenosphere is likely due to density and rigidity differences, that is, physical factors, and not to any difference in chemical composition.

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 below.

Crust	Thickness	Density	Composition	Rock types
Oceanic	5-12 km (3-8 mi)	3.0 g/cm3	Mafic	Basalt and gabbro
Continental	Avg. 35 km (22 mi)	2.7 g/cm3	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 below).

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 below). 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.

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 the figure above. 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.

The **lithosphere** plate is a piece of the lithosphere. For example, a lithosphere plate represents on small piece of the entire puzzle (lithosphere).

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 below). Peridotite is rarely found at Earth's surface.

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

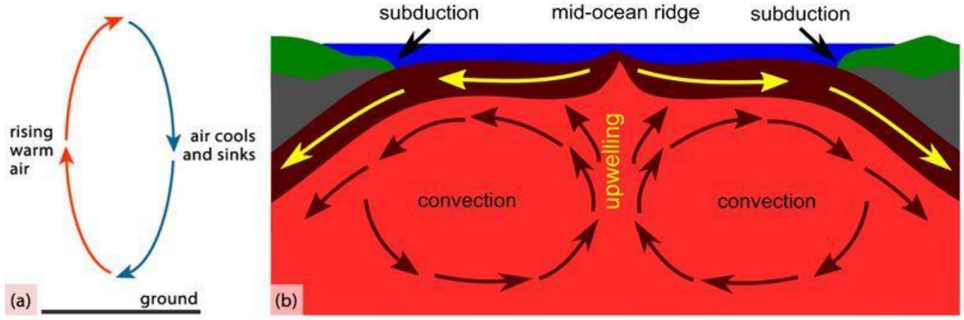
Scientists know that the mantle is extremely hot because of the heat flowing outward from it and because of its physical properties.

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 below).



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.

Core

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

- 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%.
- Metallic meteorites are thought to be representative of the core. The 85% iron/15% nickel calculation above is also seen in metallic meteorites (See the figure on the following page).

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.

An iron meteorite is the closest thing to the Earth’s core that we can hold in our hands.

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.

Think like a geologist

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

9. 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?

10. If sediments fall onto the seafloor over time, what can sediment thickness tell scientists about the age of the seafloor in different regions?

11. How might convection cells in the mantle affect the movement of solid crust on the planet's surface?

What causes earthquakes and volcanoes?

Standard 2, Objective 2: Describe the development of the current theory of plate tectonics and the evidence that supports this theory.

Terms to know

- Continental drift hypothesis
- Geologic record
- Mid-ocean ridges
- Oceanic trenches
- Magnetic striping
- Plate tectonics
- Mantle plumes
- Sea floor spreading
- Earthquakes
- volcanoes

"Doesn't the east coast of South America fit exactly against the west coast of Africa, as if they had once been joined? This is an idea I'll have to pursue." - Alfred Wegener said to his future wife, in December, 1910. We can't really get into Alfred Wegener's head, but we can imagine that he started his investigations by trying to answer this question: Why do the continents of Africa and South America appear to fit together so well? Is it a geometric coincidence that they do, or is there some geological reason?

Section 1: Wegener's Idea

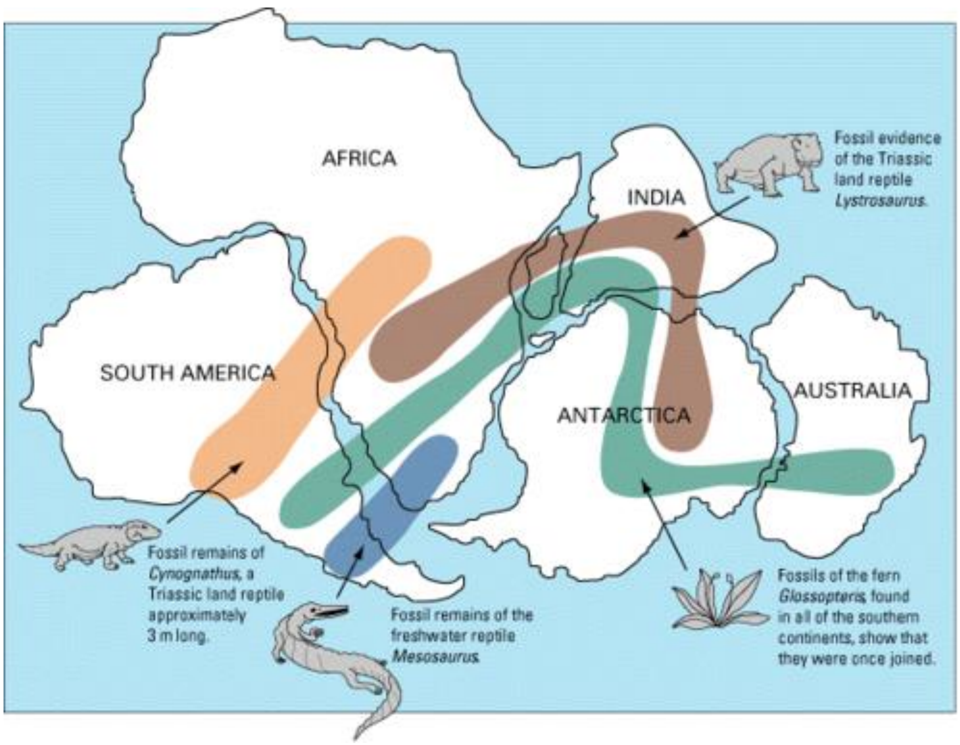
Alfred Wegener, born in 1880, was a meteorologist and explorer. In 1911, Wegener found a scientific paper that listed identical plant and animal fossils on opposite sides of the Atlantic Ocean. Intrigued, he then searched for and found other cases of identical fossils on opposite sides of oceans. The explanation put out by the scientists of the day was that land bridges had once stretched between these continents. Instead, Wegener pondered the way Africa and South America appeared to fit together like puzzle pieces. Other scientists had suggested that Africa and South America had once been joined, but Wegener was the idea's greatest supporter. Wegener obtained a tremendous amount of evidence to support his hypothesis that the continents had once been joined. Imagine that you're Wegener's colleague. What sort of evidence would you look for to see if the continents had actually been joined and had moved apart?

Wegener’s Evidence

Here is the main evidence that Wegener and his supporters collected for the continental drift hypothesis:

1. The continents appear to fit together.

2. 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. Wegener proposed that the organisms had lived side by side, but that the lands had moved apart after they were dead and fossilized. His critics suggested that the organisms moved over long-gone land bridges, but Wegener thought that the organisms could 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.

3. 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.

4. 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 (See Figure 2.2a Image 3). Wegener concluded that they formed as a single mountain range that was separated as the continents drifted.

5. 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.

6. 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 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.

7. Wegener thought that mountains formed as continents ran into each other. This got around the problem of the leading hypothesis of the day, which was that Earth had been a molten ball that bulked up in spots as it cooled (the problem with this idea was that the mountains should all be the same age and they were known not to be).

Problems with his Theory

Even with many forms of evidence that the continents had once fit together and had since moved apart into their present locations, the scientific community at the time could not fully accept his theory. The biggest reason for the rejection of his evidence was that Wegener could not provide an explanation for how something as large as continents could move or by which force they could collide into one another. Wegener incorrectly proposed that the continents were plowing through the ocean floor, but there was no obvious mechanism for how this could be accomplished. Because of this lack of an explanation, Alfred Wegener's hypothesis of continental drift was not widely accepted in his day. However, modern discoveries in plate tectonic theory have greatly led to a further understanding and wider acceptance of his theory.

Magnetic Polarity Evidence

The next breakthrough in the development of the theory of plate tectonics came two decades after Wegener's death. Magnetite crystals are shaped like a tiny bar magnet. As basalt lava cools, the magnetite crystals line up in the magnetic field like tiny magnets. When the lava is completely cooled, the crystals point in the direction of magnetic north pole at the time they form. How do you expect this would help scientists see whether continents had moved or not?

You have just learned of a new tool that may help you. A magnetometer is a device capable of measuring the magnetic field intensity. This allows you to look at the magnetic properties of rocks in many locations, including basalt along the ocean floor.

What causes the Magnetic Stripes on the seafloor?

This pattern of magnetic stripes could represent what scientists see on the seafloor. Note that the stripes are symmetrical about the central dusky purple stripe. In the oceans, magnetic stripes are symmetrical about a mid-ocean ridge axis. What could cause this? What could it possibly mean?

Seafloor Magnetism

During World War II, ships towed magnetometers in the ocean in order to find enemy submarines. They observed that the magnetic field strength changed from normal to reversed polarity as they sailed across the ocean. When scientists plotted the points of normal and reversed polarity on a seafloor map they made an astonishing discovery: 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.
- Stripes end abruptly at the edges of continents, sometimes at a deep sea trench.

Seafloor Age

By combining magnetic polarity data from rocks on land and on the seafloor with radiometric age dating and fossil ages, scientists came up with a time scale for the magnetic reversals. The scientists noticed that the rocks got older with distance from the mid-ocean ridges. The youngest rocks were located at the ridge crest and the oldest rocks were located the farthest away, next to continents. Scientists also noticed that the characteristics of the rocks and sediments changed with distance from the ridge axis as seen in the Table below.

Data From the Sea Floor

	Rock Ages	Sediment Thicknesses	Crust Thicknesses	Heat Flow
At mid-ocean ridge	Youngest	None	Thinnest	Hottest
With distance from mid-ocean ridge	Becomes older	Becomes thicker	Becomes thicker	Becomes cooler

Away from the ridge crest, sediment becomes older and thicker, and the seafloor becomes thicker. Heat flow, which indicates that ocean crust is highest at the mid-ocean ridge.

The oldest seafloor is near the edges of continents or deep sea trenches and is less than 180 million years old (See Figure 2.3). Since the oldest ocean crust is so much younger than the oldest continental crust, scientists realized that something was happening to the older seafloor.

How can you explain the observations that scientists have made in the oceans? Why is rock younger at the ridge and oldest at the farthest points from the ridge? The scientists suggested that seafloor was being created at the ridge. Since the planet is not getting larger, they suggested that it is destroyed in a relatively short amount of geologic 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.`

Section 2: The Development of the Plate Tectonics Theory

Harry Hess was a geology professor and a naval officer who commanded an attack transport ship during WWII. Like other ships, Hess’s ship had echo sounders that mapped the seafloor. Hess discovered hundreds of flat-topped mountains in the Pacific that he gave the name guyot. He puzzled at what could have formed mountains that appeared to be eroded at the top but were more than a mile beneath the sea surface. Hess also noticed trenches that were as much as 7 miles deep.

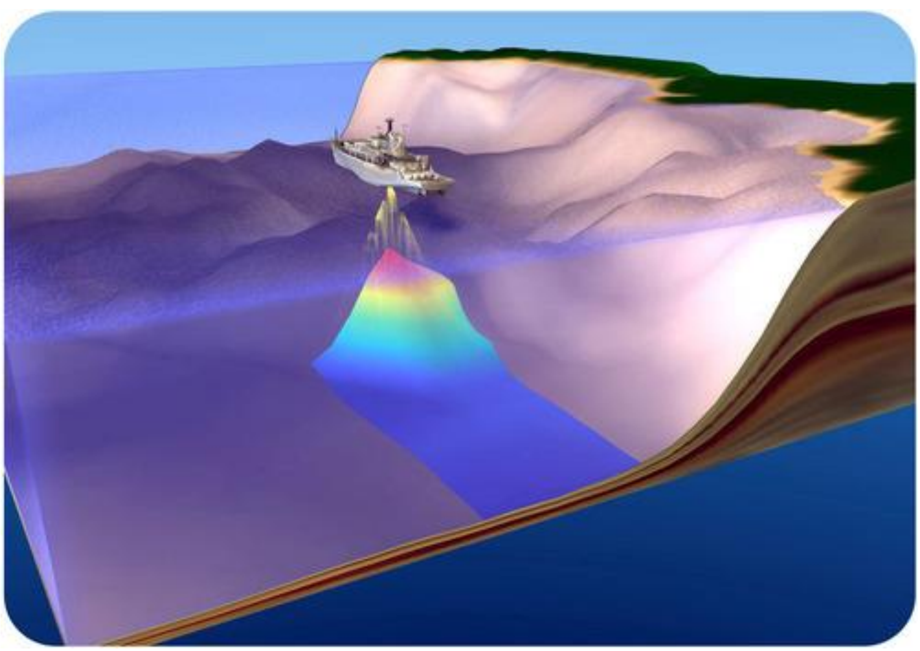
Meanwhile, other scientists like Bruce Heezen discovered the underwater mountain range they called the Great Global Rift. Although the rift was mostly in the deep sea, it occasionally came close to land. These scientists thought the rift was a set of breaks in Earth’s crust. The final piece that was needed was the work of Vine and Matthews, who had discovered the bands of alternating magnetic polarity in the seafloor symmetrically about the rift.

What discovery was made during World War II that revived the idea of the continental drift hypothesis?

Section 1: Seafloor Spreading

Seafloor Bathymetry

During World War II, battleships and submarines carried echo sounders to locate enemy submarines (Figure below). 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 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.

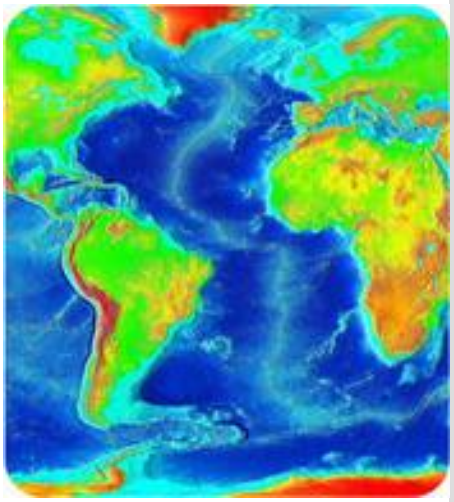
This animation shows how sound waves are used to create pictures of the sea floor and ocean crust:

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 right).

The major features of the ocean basins and their colors on the map in Figure right 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.



A modern map of the southeastern Pacific and Atlantic Oceans.

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

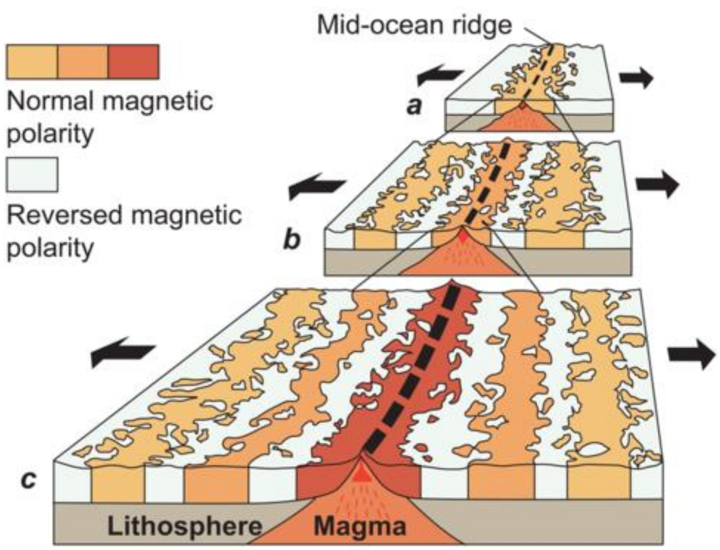
Seafloor Magnetism

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

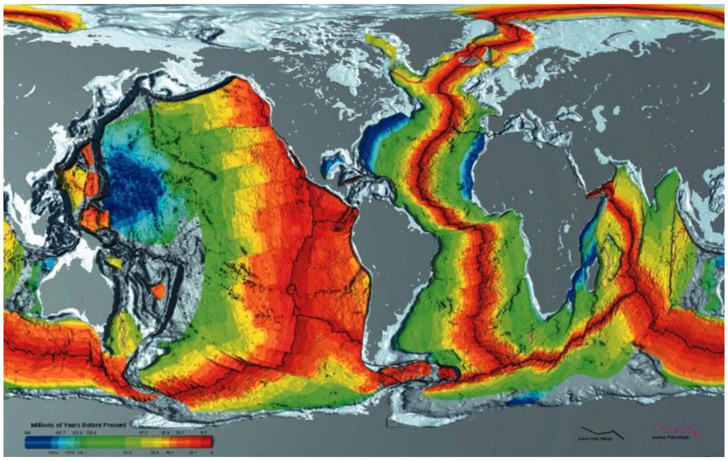
- Normal polarity: north and south poles are aligned as they are now.
- Reversed polarity: north and south poles are in the opposite position.

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 below).
- Stripes end abruptly at the edges of continents, sometimes at a deep sea trench (Figure below).



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.



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

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

	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`

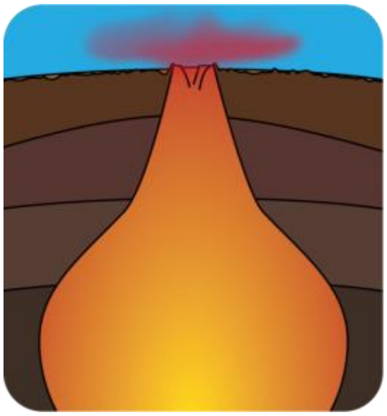
The oldest seafloor is near the edges of continents or deep sea trenches and is less than 180 million years old (Figure above). Since the oldest ocean crust is so much younger than the oldest continental crust, scientists realized that seafloor was being destroyed in a relatively short time.

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 right).



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.

The Mechanism for Continental Drift

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 spreading plate takes along any continent that rides on it.

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:

http://www.youtube.com/watch?v=6CsTTmvX6mc&feature=rec-LGOUT-exp_fresh+div-1r-2 (8:05)

The Theory of Plate Tectonics—What is a Plate?

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

Why is this relevant? It turns out that earthquake epicenters outline the plates. This is because earthquakes occur everywhere plates come into contact with each other. In addition to this, a vast number of volcanoes from around the world are also located where plates meet. With this evidence and the combined evidences about Sea Floor Spreading, magnetic striping of the ocean floor, and more, the answer to what could cause the Continents to Drift apart became real.

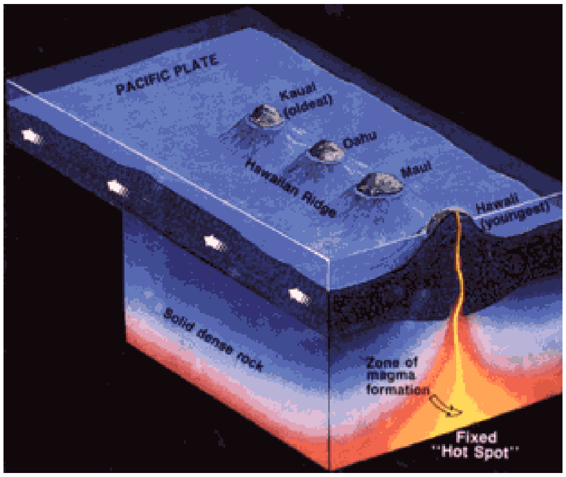
The Plate Tectonics theory provides the answers to the two questions that Alfred Wegener could not explain. 1) What causes plates to move, and what force could cause this to happen? Today, our general understanding about the Plate Tectonic Theory is that the Earth is divided into several crustal plates composed of oceanic lithosphere and thicker continental lithosphere, each topped by its own kind of crust. Tectonic plates are able to move because the Earth's lithosphere has a higher strength and lower density than the underlying asthenosphere. Along convergent boundaries, subduction carries plates into the mantle; the material lost is roughly balanced by the formation of new (oceanic) crust along mid-ocean ridges by seafloor spreading. In this way, the total surface of the globe remains the same. Tectonic plates are able to move because the Earth's lithosphere has a higher strength and lower density than the underlying asthenosphere. Plate movement is thought to be driven by a combination of the motion of the seafloor away from the mid-ocean ridges (due to variations in topography and density of the crust, which result in differences in gravitational forces) and drag, downward suction, at the subduction zones.

Section 2: Mantle Plumes & Hot Spots

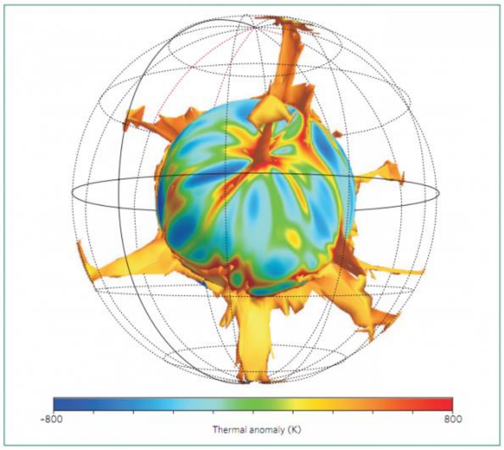
(This section is adapted from *http://pubs.usgs.gov/gip/dynamic/hotspots.html*)

The vast majority of earthquakes and volcanic eruptions occur near plate boundaries, but there are some exceptions. For example, the Hawaiian Islands, which are entirely of volcanic origin, have formed in the middle of the Pacific Ocean more than 3,200 km from the nearest plate boundary. How do the Hawaiian Islands and other volcanoes that form in the interior of plates fit into the plate-tectonics picture?

In 1963, J. Tuzo Wilson, the Canadian geophysicist who discovered transform faults, came up with an ingenious idea that became known as the "hot spot" theory. Wilson noted that in certain locations around the world, such as Hawaii, volcanism has been active for very long periods of time. This could only happen, he reasoned, if relatively small, long-lasting, and exceptionally hot regions -- called hot spots -- existed below the plates that would provide localized sources of high heat energy (thermal plumes) to sustain volcanism. Specifically, Wilson hypothesized that the distinctive linear shape of the Hawaiian Island-Emperor Seamounts chain resulted from the Pacific Plate moving over a deep, stationary hotspot in the mantle, located beneath the present-day position of the Island of Hawaii. Heat from this hotspot produced a persistent source of magma by partly melting the overriding Pacific Plate. The magma, which is lighter than the surrounding solid rock, then rises through the mantle and crust to erupt onto the seafloor, forming an active seamount. Over time, countless eruptions cause the seamount to grow until it finally emerges above sea level to form an island volcano. Wilson suggested that continuing plate movement eventually carries the island beyond the hotspot, cutting it off from the magma source, and volcanism ceases. As one island volcano becomes extinct, another develops over the hotspot, and the cycle is repeated. See Figure below. This process of volcano growth and death, over many millions of years, has left a long trail of volcanic islands and seamounts across the Pacific Ocean floor.



http://www.dailykos.com/story/2011/07/13/994211/--Transient-convective-uplift-Buried-Ancient-Continent-Off-Scotland-says-Ross-A-Hartley. © Kos Media, used with permission.

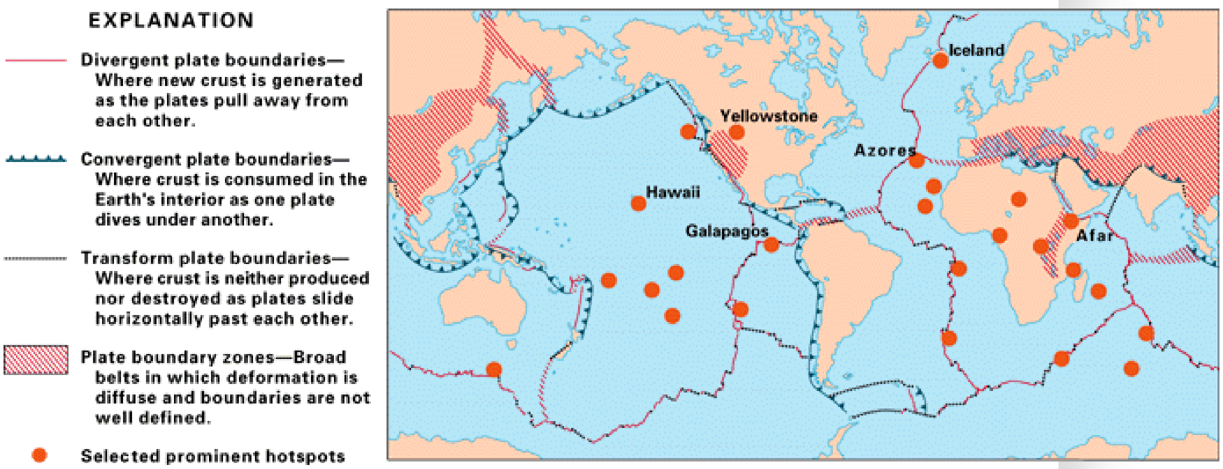


Other known hot spots from around the world can be found in the figure on the following page.

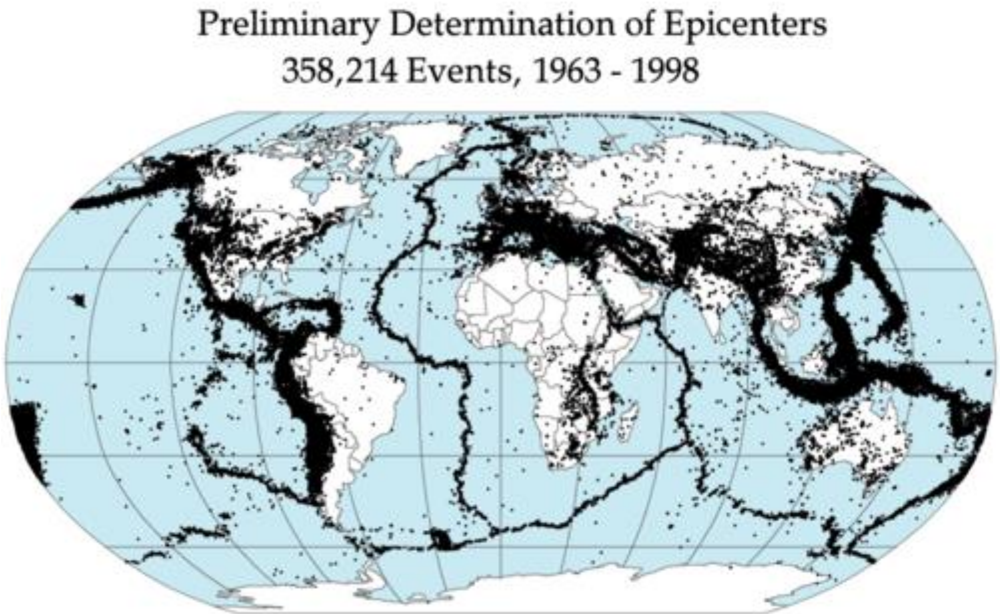
Earth's Tectonic Plates

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.

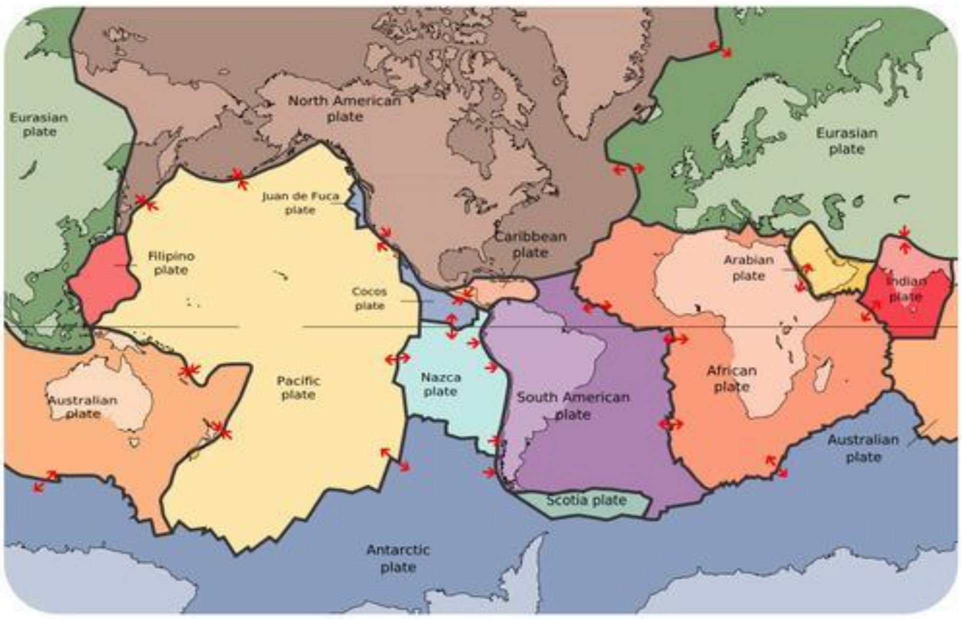


Earthquake epicenters outline the plates. Mid-ocean ridges, trenches, and large faults mark the edges of the plates, and this is where earthquakes occur (Figure below).



Earthquakes outline the plates.

The lithosphere is divided into a dozen major and several minor plates (Figure below). 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.



The lithospheric plates and their names are shown in the figure above. 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.

Section 3: Volcanoes

During a volcano, the heat energy is transferred through lava to the Earth's surface. The magma may come up to the surface as maglavama bringing heat energy with it. The volcanoes which erupt on the island of Hawaii are an example of this transfer of heat energy. Notice, the lava is very hot as it comes up to the surface. The lava immediately begins to cool. As the heat escapes, the lava hardens to dark black rock.

Magma which becomes trapped below the surface can build up pressure that must be released as mechanical energy. An example of this release of mechanical energy was the eruption of Mt. Saint Helens in Washington State. As the heat energy in the magma built up below the surface of the mountain, the pressure increased. This pressure was released in a gigantic explosion which blew off the top of the mountain.

Section 4: Earthquakes

The transfer of earthquake energy happens in the form of waves. These waves can happen in a couple of different ways.

The energy from an earthquake arrives in three distinct waves. The fastest and therefore the first to arrive was named the Primary wave or p-wave. The second to arrive was named the secondary wave or s-wave. The slowest and last to arrive was named the surface wave.

P-wave: P-waves are a form of longitudinal waves. These waves vibrate in a direction parallel to the direction in which the energy is transferred. For example, in an east moving p-wave objects vibrate in an east-west direction. This is the type of wave demonstrated in the first two videos above.

S-wave: S-waves are a form of transverse waves. These waves vibrate in a direction perpendicular to the direction in which the energy is transferred. For example, in an east moving s-wave, objects vibrate in a north-south direction. This is more destructive than the vibrations in a p-wave. This is the type of wave demonstrated in the third video above.

Surface Wave: Also known as a Love wave, the surface wave is much slower than the p-wave or s-wave. A surface wave is a combination of a transverse and a longitudinal wave in which the particles vibrate both perpendicularly and parallel to the direction of energy transfer. An object struck by a surface wave would vibrate both north-south and east-west. The result is that the objects move in a circle. This is the most destructive of the three types of wave. A surface wave is similar to the ripples you see when an object is dropped into a body of water. Observe a QuickTime video of this type of wave. If you watch closely, you can see the circular motion.

http://utahscience.oremjr.alpine.k12.ut.us/sciber08/8th/geology/html/wavenrgy.htm

Lesson Summary

- Seafloor spreading brought together the mantle convection idea of Holmes, the continental drift idea of Wegener, new bathymetric and magnetic data from the seafloor, and made a coherent single idea.
- Harry Hess called his idea “an essay in geopoetry,” possibly because so many ideas fit together so well, or more likely because at the time he didn’t have all the seafloor data he needed for evidence.
- Seafloor spreading is the mechanism for the drifting continents.
- Data from magnetometers dragged behind ships looking for enemy submarines in WWII discovered amazing magnetic patterns on the seafloor.
- Rocks of normal and reversed polarity are found in stripes symmetrically about the mid-ocean ridge axis.
- The age of seafloor rocks increases from the ridge crest to rocks the farthest from the ridges. Still, the rocks of the ocean basins are much younger than most of the rocks of the continents.
- Alfred Wegener did some background reading and made an observation. Wegener then asked an important question and set about to answer it. He collected a great deal of evidence to support his idea. Wegener’s evidence included the fit of the continents, the distribution of ancient fossils, the placement of similar rocks and structures on the opposite sides of oceans, and indicators of ancient climate found in locations where those climates do not exist today.

Think Like a Geologist

1. How did Wegener become interested in the idea that continents could move?

2. What did he need to do to explore the question and make it into a reasonable hypothesis?

3. How did Wegener use fossil evidence to support his hypothesis?

4. How did Wegener use climate evidence from rocks to support his hypothesis? How does the pattern of magnetic stripes give evidence for seafloor spreading?

5. How does the topography of the seafloor give evidence for seafloor spreading?

6. How does seafloor spreading fit into the idea that continents move about on Earth's surface?

Practice: Use this resource to answer the questions that follow.

`http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_seafloorspreading.html )`

7. Where does seafloor spreading occur?

8. What is the average elevation of the ocean ridges?

9. What are the characteristics of the seafloor near these ridges?

10. Explain why a ridge exists.

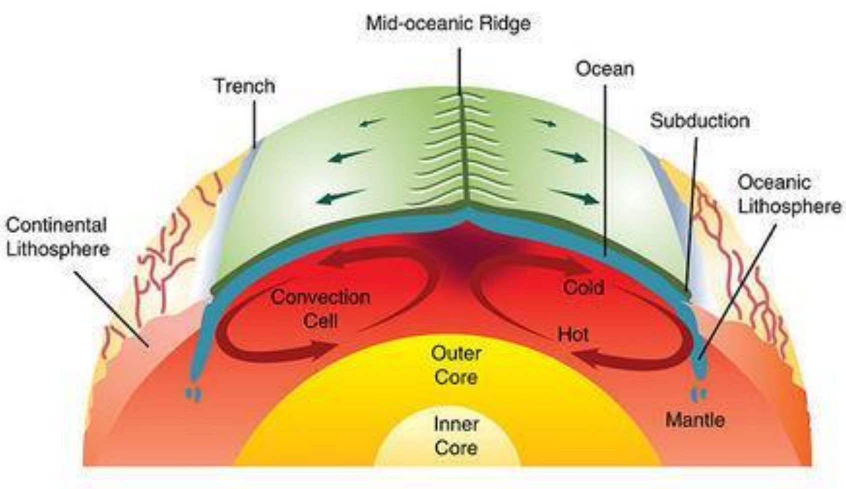
11. How fast is the spreading occurring?

Does the movement of Earth's plates affect all living things?

Standard 2, Objective 3: Demonstrate how the motion of tectonic plates affects Earth and living things.

Section 1: 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 below.
- Hot mantle from the two adjacent cells rises at the ridge axis, creating new ocean crust.
- The top limb of the convection cell moves horizontally away from the ridge crest, as does the new seafloor.
- 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.
- The material sinks to the core and moves horizontally.
- The material heats up and reaches the zone where it rises again.



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's surface.

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

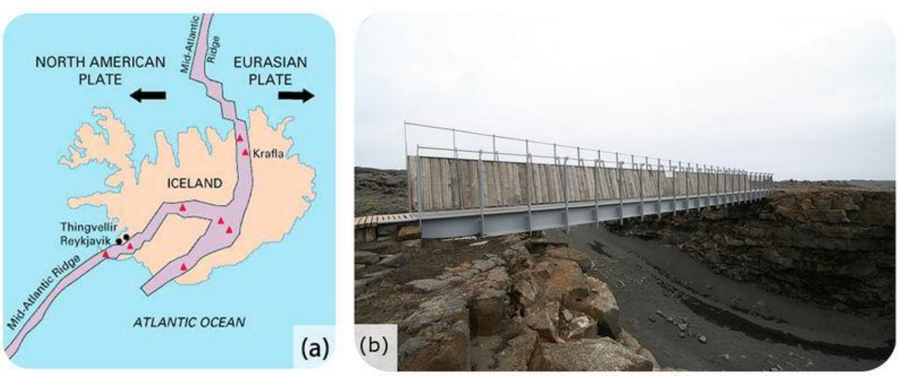
Plate boundaries are the edges where two plates meet. Most geologic activities, including volcanoes, earthquakes, and mountain building, take place at plate boundaries. How can two plates move relative to each other?

- 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.

Section 2: 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 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 below).

(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.

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

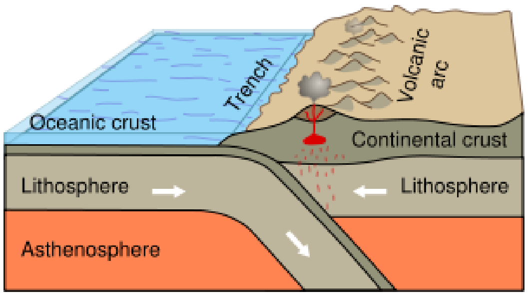
Can divergent plate boundaries occur within a continent? What is the result? In continental rifting (Figure right), magma rises beneath the continent, causing it to become thinner, break, and ultimately split apart. New ocean crust erupts in the void, creating an ocean between continents.

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

Section 3: 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 below). 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 on next page) The volcanoes are known as a continental arc.



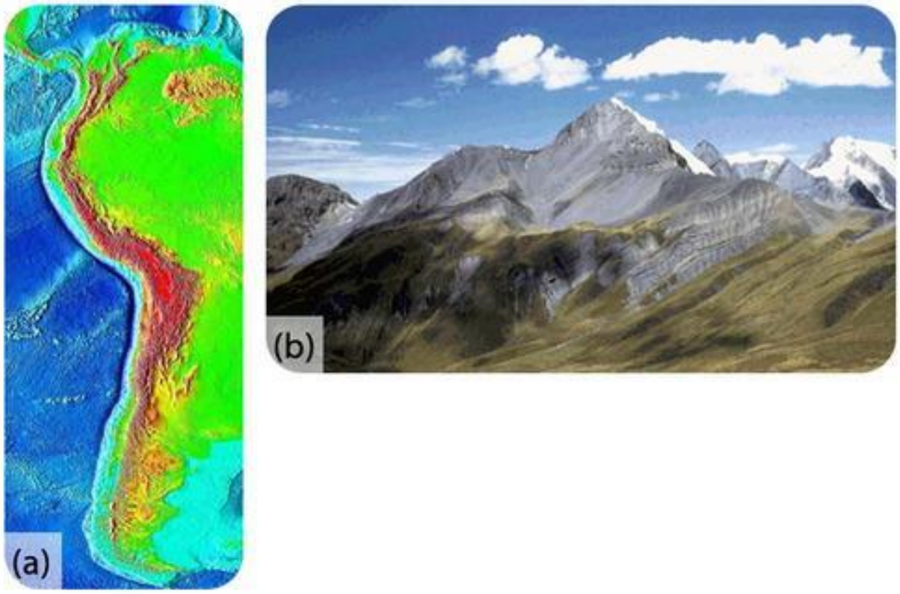
Subduction of an oceanic plate beneath a continental plate causes earthquakes and forms a line of volcanoes known as a continental arc.

The movement of crust and magma causes earthquakes. A map of earthquake epicenters at subduction zones is found here:

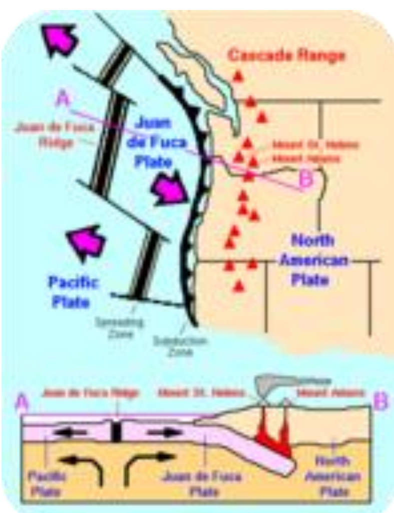
http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/p_earthquakessubduction.html

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.



(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.



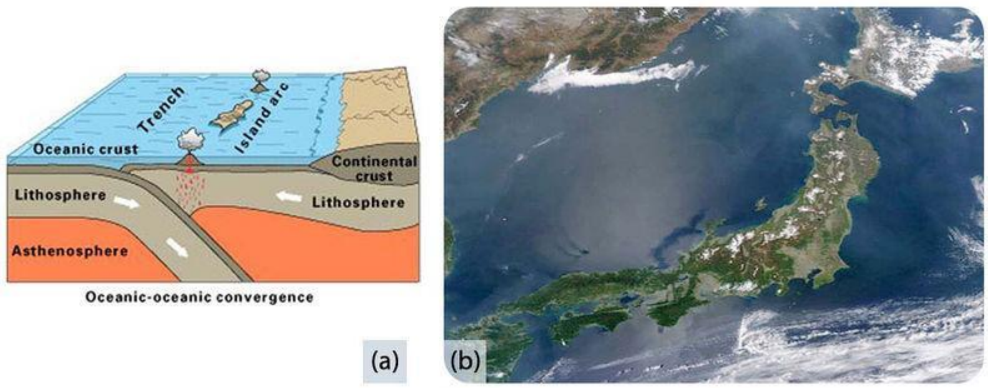
The volcanoes of northeastern California—Lassen Peak, Mount Shasta, and Medicine Lake volcano—along with the rest of the Cascade Mountains of the Pacific Northwest are the result of subduction of the Juan de Fuca plate beneath the North American plate (Figure right). The Juan de Fuca plate is created by seafloor spreading just offshore at the Juan de Fuca ridge.

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 below).

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

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?

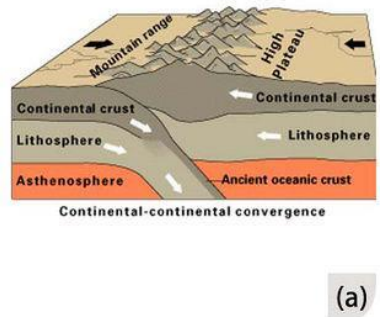


(a) Subduction of an ocean plate beneath an ocean plate results in a volcanic island arc, an ocean trench and many earthquakes. (b) Japan is an arc-shaped island arc composed of volcanoes off the Asian mainland, as seen in this satellite image.

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 opposite). 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.



(a) In continent-continent convergence, the plates push upward to create a high mountain range. (b) The world's highest mountains, the Himalayas, are the result of the collision of the Indian Plate with the Eurasian Plate, seen in this photo from the International Space Station.

A short animation of the Indian Plate colliding with the Eurasian Plate:

http://www.scotese.com/indianim.htm

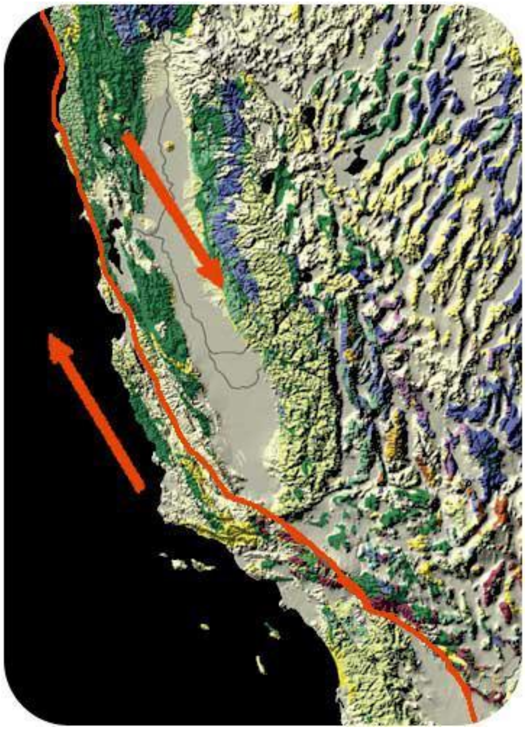
An animation of the Himalaya rising:

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.

Section 4: Transform Plate Boundaries

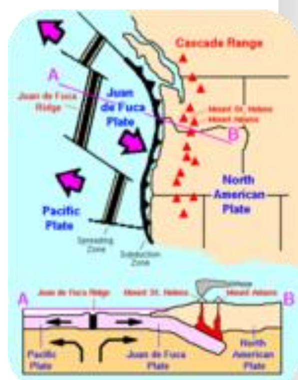
Transform plate boundaries are seen as transform faults, where two plates move past each other in opposite directions. Transform faults on continents bring massive earthquakes (Figure on next page).



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 below)?

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



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

A brief review of the three types of plate boundaries and the structures that are found there is the subject of this wordless video:

`http://www.youtube.com/watch?v=ifke1GsjNN0 (4:50)`

Think like a Geologist

1. Describe a lithospheric plate.
2. Draw and identify the major tectonic plates of Earth.
3. How does a volcano transfer energy from Earth's interior to the surface?
4. What is a convergent boundary and what are the results of its movement?
5. What is a divergent boundary and what are the results of its movement?
6. What is a transform boundary and what are the results of its movement?
7. Explain how gravity, density and convection cause tectonic plates to move.

Glossary

- **Asthenosphere** – a layer of the Earth just below the lithosphere that has the characteristic of plasticity
- **Composition** – what something is made of
- **Continental drift hypothesis -** the hypothesis that Earth's continents were once all one, and then drifted apart
- **Convection-** the transfer of energy by a warmer, less dense substance rising and a cooler, less dense substance sinking
- **Convergent Boundary**– a place where two or more tectonic plates move towards each other and collide. Also known as a destructive plate boundary
- **Divergent Boundary** – a place where two tectonic plates move away from each other. Also known as a constructive plate boundary
- **Earthquakes** – a shaking or trembling of the earth that is either volcanic or tectonic in origin
- **Geologic record** – the layers of rock deposits laid down by volcanoes or weathering that contain a record of Earth's past history
- **Heat of formation -** the production of heat through a chemical reactions
- **Inner core –** the innermost layer of Earth, it is a solid
- **Lithosphere -** the rigid outer layer of Earth
- **Lithospheric plate** – earth's rigid outer crust that is broken into tectonic plates
- **Magnetic striping –** permanent magnetism in rocks resulting from the orientation of the Earth's magnetic field at the time the rock formed
- **Mantle plumes** – also called hot spots, are a place in the upper mantle of the Earth where hot magma from the lower mantle upwells to melt through the crust

- **Mesosphere –** a layer of Earth below the asthenosphere but above the outer core, also called the mantle.
- **Mid-ocean ridges** – an underwater mountain system formed by plate tectonic movement

- **Oceanic trenches** – long narrow depressions on the sea floor, they are the deepest parts of the oceans

- **Outer core –** a liquid layer of Earth below the mesosphere, but above the inner core

- **Physical Properties** – any property that describes the characteristics of a substance

- **Plate Tectonics** – the scientific theory that describes the large scale motions of Earth's crust

- **Radioactive decay-** the process in which the nucleus becomes unstable and loses particles or begin break apart

- **Sea floor spreading -** a process that occurs at mid-ocean ridges, where new oceanic crust is formed through volcanic activity and then gradually moves away from the ridge

- **Tectonic plates -** earth's rigid outer crust that is broken into moving sections or plates

- **Transform boundaries** – a place where two tectonic plates move horizontally in either direction. Also known as a conservative plate boundary.

- **Volcanoes -** an opening, or rupture, in the surface or crust of the Earth which allows hot lava, volcanic ash and gases to escape from the magma chamber below the surface.