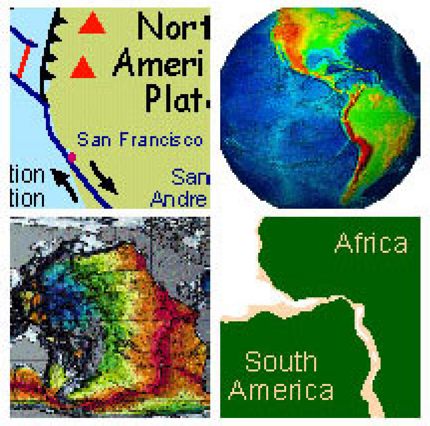
Plate Tectonics



> This curious world we inhabit is more wonderful than convenient; more beautiful than it is useful; it is more to be admired and enjoyed than used.
>
> Henry David Thoreau

Introduction

- Earth's lithosphere is divided into mobile plates.
- Plate tectonics describes the distribution and motion of the plates.
- The theory of plate tectonics grew out of earlier hypotheses and observations collected during exploration of the rocks of the ocean floor.

You will recall from a previous chapter that there are three major layers (crust, mantle, core) within the earth that are identified on the basis of their different compositions (Fig. 1).

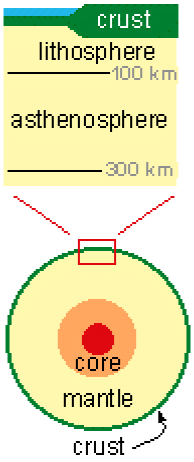


Figure 1. The outermost part of Earth is divided into two mechanical layers, the lithosphere and asthenosphere.

The uppermost mantle and crust can be subdivided vertically into two layers with contrasting mechanical (physical) properties. The outer layer, the **lithosphere**, is composed of the crust and uppermost mantle and forms a rigid outer shell down to a depth of approximately 100 km (63 miles). The underlying **asthenosphere** is composed of partially melted rocks in the upper mantle that acts in a plastic manner on long time scales. The asthenosphere extends from about 100 to 300 km (63-189 miles) depth. The theory of plate tectonics proposes that the lithosphere is divided into a series of plates that fit together like the pieces of a jigsaw puzzle.

Although **plate tectonics** is a relatively young idea in comparison with unifying theories from other sciences (e.g., law of gravity, theory of evolution), some of the basic observations that represent the foundation of the theory were made many centuries ago when the first maps of the Atlantic Ocean were drawn. Geographer Abraham Ortellus noted the similarity between the coastlines of Africa, Europe and the Americas in the third edition of his *Thesaurus Geographicus*, published in 1596. Ortellus, adapting Plato's story of the demise of Atlantis, suggested that America was *"torn away"* from Europe and Africa and that the *"projecting parts of Europe and Africa"* would fit the *"recesses"* of America.

Such observations were little more than idle speculation until Austrian climatologist **Alfred Wegener** used the fit of opposing coastlines as one of the pieces of evidence to support his hypothesis of continental drift. Continental drift proposed that the continents were once assembled together as a single supercontinent Wegener named **Pangaea**. Wegener was unable to suggest a suitable mechanism to explain the motion of the continents across Earth's surface and his hypothesis received relatively little support until technology revealed the secrets of the ocean floor. Scientists gradually amassed additional data that would resurrect Wegener's hypothesis over 30 years after his death. By the 1960s the building blocks were in place to support a new hypothesis, Seafloor spreading, that would provide the mechanism for continental drift. Together these concepts would become the theory of plate tectonics.

The theory of plate tectonics provides an example of the evolution of scientific thought. The first two sections of the chapter reveal the basic observations that were used to make predictions on the geologic processes that shaped the face of Earth. The theory of plate tectonics links Earth's internal processes to the distribution of continents and oceans; it is the big picture view of how the earth works. Plate tectonics reveals that the lithosphere is divided into eight major pieces ("plates") with several smaller plates (Fig. 2). The plates are **mobile**, moving in constant, slow motion measured in rates of centimeters per year. The movements of plates over millions of years resulted in the opening and closure of oceans and the formation and disassembly of continents.

Plates interact along plate boundaries. There are three principal types of plate boundary (divergent, convergent, and transform). Plates move apart at divergent plate boundaries such as the oceanic ridge system that separates the North American and Eurasian plates in the north Atlantic Ocean. Plates crash into each other along convergent plate boundaries marked by volcanoes and mountain belts. Finally, plates slide past each other along a transform plate boundary such as the San Andreas Fault, California, that separates the North American and Pacific plates.

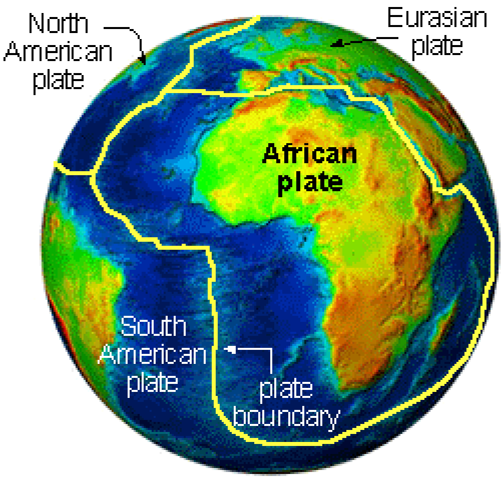


Figure 2. The African plate is composed of both oceanic lithosphere (below Atlantic and Indian Oceans) and continental lithosphere (beneath Africa). The boundary with the adjacent North American and South American plates lies along the center of the Atlantic Ocean. Globe image from NOAA National Geophysical Data Center.

Continental Drift

- Alfred Wegener proposed the hypothesis that the continents were once assembled together as a supercontinent he named Pangaea.
- He noted that opposing coastlines were similar on opposite sides of the Atlantic Ocean, mountains belts matched when continents were reassembled, fossils matched between different continents, and climate evidence suggested continents were once in different locations.
- Wegener's observations supported his hypothesis but he could not offer a suitable explanation for how the continents had moved around Earth.

The concept of continental drift was proposed by Alfred Wegener. Wegener suggested that the earth's continents once formed a single super-continent landmass that he named **Pangaea** (Fig. 3). He suggested that Pangaea split apart into its constituent continents about 200 million years ago and the continents "drifted" to their current positions.

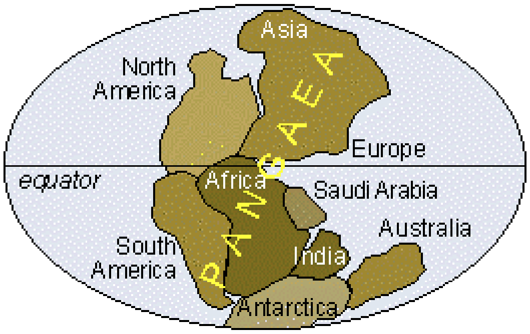


Figure 3. A reconstruction of the supercontinent Pangaea.

Wegener’s principal observations were:

- **Fit of the continents**: The opposing coastlines of continents often fit together. An even better fit occurs if the edge of the continent shelf is used, a little offshore (Fig. 4). Wegener was not the first person to notice the similarities between continental coastlines. Early map makers several centuries before had made the same observation.

- **Match of mountain belts, rock types**: If the continents are reassembled as Pangaea, mountains in west Africa, North America, Greenland, and western Europe match up.

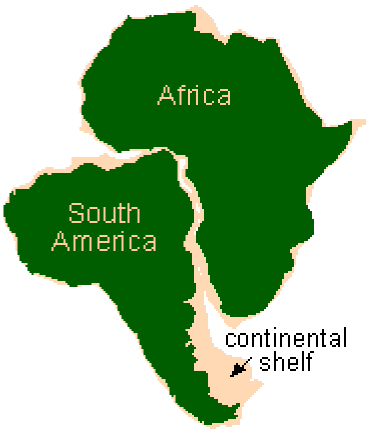


Figure 4. Fit between Africa and South America along continental shelf.

- **Distribution of fossils**: The distribution of plants and animal fossils on separate continents forms definite linked patterns if the continents are reassembled (Fig. 5). For example, fossils of the reptile **Mesosaurus** are found in both southern Africa and South America. The fossil is preserved in rocks deposited in streams so it is concluded that the reptile lived in freshwater environments. Mesosaurus could not have traveled across an ocean between the continents. Either the continents were side-by-side or Mesosaurus evolved separately on two continents at the same time, an unlikely explanation. A fossil fern, **Glossopteris**, is found on several continents with different climates today. Wegener believed the distribution of Glossopteris could be accounted for by initially spreading across Pangaea prior to the breakup of the supercontinent.

- **Paleoclimates**: Wegener assembled geologic evidence that showed that rocks formed 200 million years ago in India, Australia, South America, and southern Africa all exhibited evidence of continental **glaciation** (Fig. 6). Such a glaciation would have required a global ice age if the continents were in their present positions. However, at the same time there were **tropical swamps** in southern Ohio and much of the eastern U.S. Clearly, the rest of the world was not in a deep freeze. Such apparently widespread glaciation could be explained if the continents were located close to the South Pole.

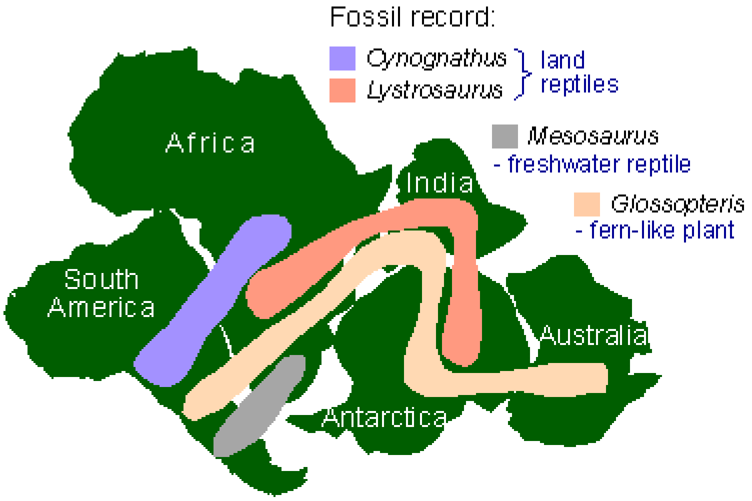


Figure 5. Distribution of key fossils between continents.

Evidence for continental drift was embraced by some scientists but was rejected by others, primarily because Wegener was unable to propose an acceptable **mechanism** to cause the continents to move. He suggested that the continents pushed through the rocks of the ocean floor because of tidal forces; much like a plow cuts through the soil. Unfortunately for Wegener this idea was shown to be physically impossible. Consequently, continental drift, although providing a compelling explanation for the distribution of common features on different continents, would wait another 50 years to make a triumphant return.

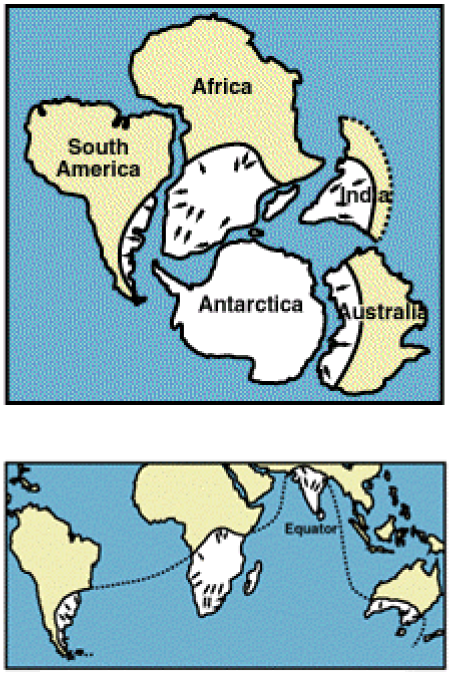


Figure 6. Evidence of ancient glaciation indicated that parts of southern Africa, India, Australia, and South America were covered by a large ice sheet. Arrows indicate direction of ice movement.

Seafloor Spreading

- An oceanic ridge system can be identified in all the world's oceans.
- Deep, narrow trenches are present along some continental margins and nearby volcanic island chains.
- Compass needles point to magnetic north during periods of normal polarity and to the magnetic South Pole during intervals of reverse polarity.
- The ocean floor rocks reveal a pattern of stripes that correspond with episodes of normal and reverse polarity in Earth's history.
- The youngest rocks in the oceans are present along the ocean ridge system; the oldest rocks are present along the margins of ocean basins.
- Seafloor spreading proposed that rising magma was forming new oceanic crust along the oceanic ridges and that old crust was destroyed at oceanic trenches.
- The concept of seafloor spreading was combined with the earlier idea of continental drift to create the theory of plate tectonics.

Scientists gradually amassed additional data that would resurrect Wegener's hypothesis in the 30 years following his death. By the 1960s the building blocks were in place to support the new hypothesis, **seafloor spreading**, that would provide the mechanism for continental drift. Together these concepts would become the theory of plate tectonics. The observations used to build support for seafloor spreading came from a range of specialists including oceanographers (studies of the seafloor), geophysicists (magnetic properties of rocks), seismologists (earthquakes), and geochronologists (determination of the age of rocks).

Seafloor Topography

The ocean floor varies considerably in depth and character. Beginning at the edge of the continents we can recognize four principal depth zones. The first depth level is the **continental shelf**, shallow ocean floor (0-150 meters; 0-500 feet) immediately adjacent to continental land masses. Beyond the shelf, the ocean floor steps down to the second depth level, the deep ocean basins known as the **abyssal plains** often over 4 kilometers below sea level.

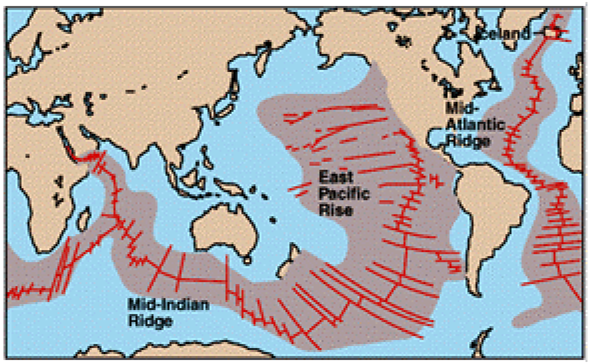


Figure 7. Oceanic ridge systems dominate the floor of the world's oceans. Three principal sections of the ridge system are recognized: Mid-Atlantic Ridge, East Pacific Rise, and Mid-Indian Ridge.

The ocean floor rises to a third level approaching the **oceanic ridge system**, a submarine mountain chain that can be traced around the world (Fig. 7). The ocean floor is relatively shallow, less than 3 km (nearly 2 miles) deep along the ridge system. The ocean ridge system dominates the floor of the Atlantic Ocean, occupying over half its width (Fig. 8). Scientists surveying the ocean floor discovered that **heat flow** was high along oceanic ridges and suggested that the ridge system was a source of volcanic activity. Volcanism can be observed first-

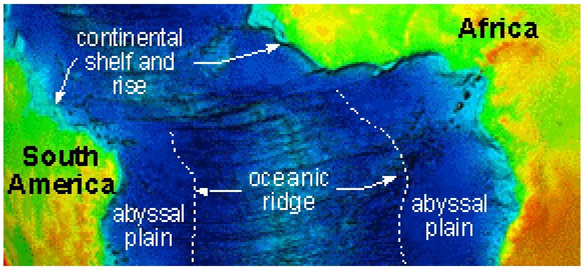


Figure 8. Principal topographic features of the floor of the southern Atlantic Ocean. The oceanic ridge occupies more than half the width of the ocean floor. Image modified from original at NOAA's National Geophysical Data Center.

hand where the oceanic ridge comes to the surface of the North Atlantic Ocean in Iceland.

The final depth level in the oceans is apparent in narrow, deep (> 7 km; 4 miles) **oceanic trenches** found along the margins of some continents (Fig. 9) such as South America or adjacent to volcanic island chains like the Aleutian Islands, Alaska. Despite the nearby volcanism, heat flow is relatively low along trenches. Geophysicists have long recognized that **deep earthquakes** are associated with trenches down to depths of 700 to 800 km (440-500 miles), far below the ocean floor. Shallow earthquakes are mainly located near trenches and oceanic ridges.

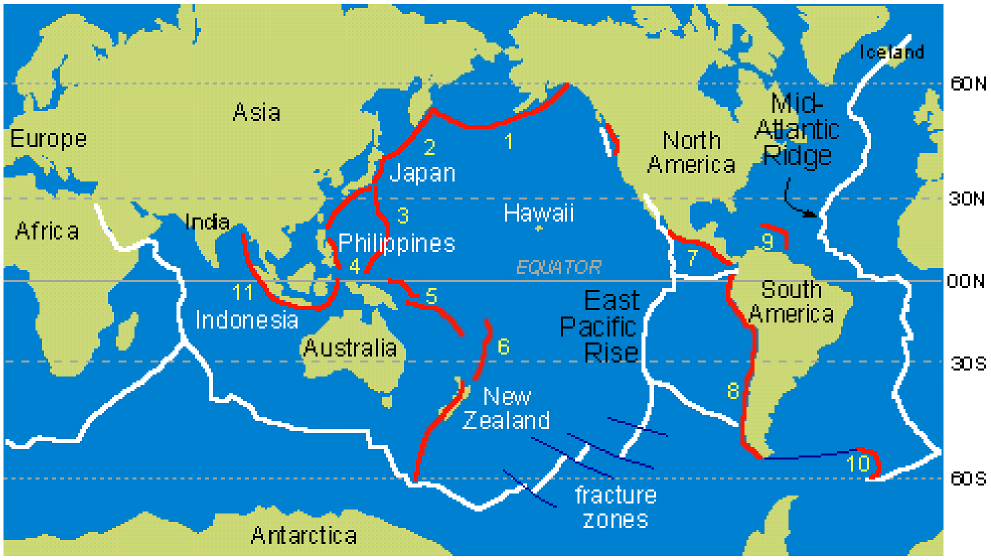
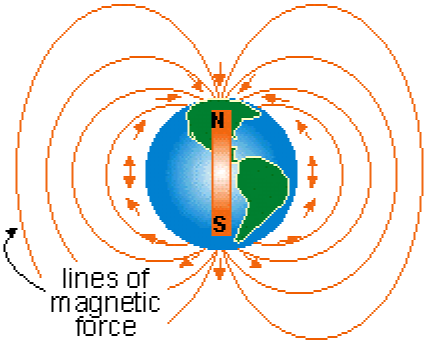


Figure 9. Distribution of ocean ridges and trenches on the sea floor. Oceanic ridges (white) form a network of submarine mountains on the seafloor. Oceanic ridges are often offset at fracture zones (shown here only for the southern Pacific Ocean). Trenches (red) are concentrated around the margins of the Pacific Ocean. Numbered trenches are: 1. Aleutian; 2. Kurile-Japan; 3. Mariana; 4. Philippine; 5. Bougainville; 6. Tonga-Kermadec; 7. Central America; 8. Peru-Chile; 9. Puerto Rico; 10. South Sandwich; 11. Java.

Paleomagnetism and the Ocean Floor

Earth's **magnetic field**, originating from the partially molten rocks of the **outer core**, causes compass needles to point toward the **magnetic poles**. While the magnetic poles are found at high latitudes they are seldom coincident with the geographic poles. Just as we can define magnetic poles, it is also possible to generate a magnetic equator and lines of magnetic latitude. The orientation of the magnetic field varies with latitude and resembles a giant dipole magnet located in the Earth's interior (Fig. 10). The orientation of the magnetic field can be defined by its **declination** and **inclination**. Declination defines the orientation of the lines of magnetic force that stretch from one magnetic pole to another. The declination direction therefore points toward the magnetic poles. The

Figure 10. The inclination of the Earth's magnetic field varies with latitude. The field is horizontal at the magnetic equator, steeper at high latitudes, and vertical at the magnetic poles. The magnetic field is inclined downward in the Northern Hemisphere and upward (away from Earth's surface) in the Southern Hemisphere. The magnetic and geographic poles are considered to be coincident in this figure.

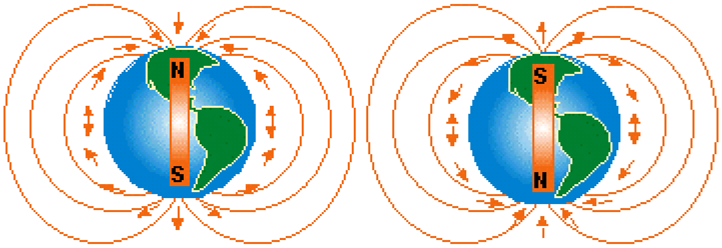


inclination of the magnetic field varies between horizontal and vertical. The magnetic field is horizontal at the magnetic equator, steeper at high latitudes, and vertical at the magnetic poles. The magnetic field is inclined downward in the Northern Hemisphere and upward in the Southern Hemisphere.

Magnetic minerals, most commonly those with a high iron content, align parallel to Earth's magnetic field when they form during the cooling of magma. These minerals represent "fossil" compasses that record the orientation of the magnetic field at their time of formation (**paleomagnetism** - fossil magnetism). Magnetized minerals in ancient lava flows can therefore be interpreted to record the original latitude of the cooling magma when the rock formed.

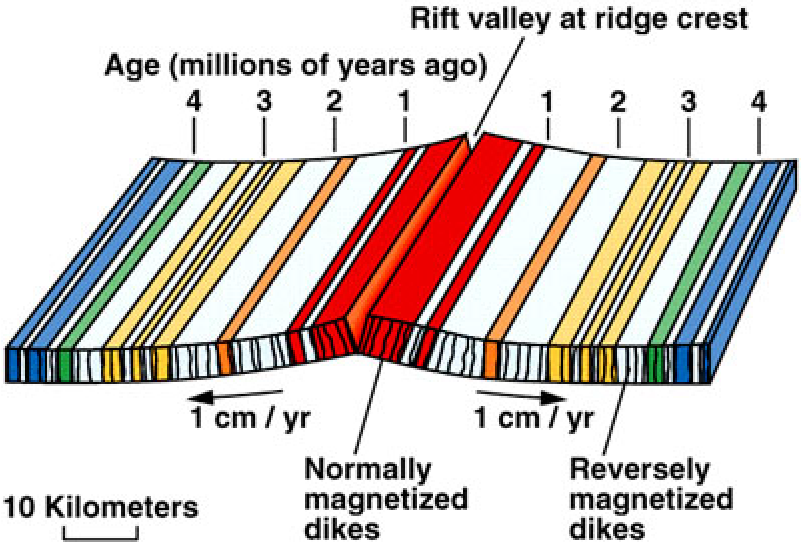
Studies of continental igneous rocks revealed that Earth's magnetic field has changed **polarity** (north and south magnetic poles have switched positions) for intervals of 100,000's to millions of years throughout the history of the planet. The magnetic field is said to have **normal polarity** when the magnetic North Pole and the geographic North Pole are adjacent. The magnetic field is inclined downward in the Northern Hemisphere during periods of normal polarity. The magnetic field exhibits **reverse polarity** when the magnetic "North Pole" lies adjacent to the south geographic pole (Fig. 11). The magnetic field would be inclined toward Earth's

Figure 11. Normal polarity (left) and reverse polarity (right) conditions alternate when the Earth's magnetic field reverses orientation.



interior in the Southern Hemisphere during intervals of reverse polarity.

Measurement of magnetism in the rocks of the oceanic crust revealed stripes of high and low **magnetic intensity** corresponding with areas of normal and reverse polarity, respectively. These stripes are oriented parallel to adjacent oceanic ridges. Ocean floor rocks reveal a **symmetrical** pattern of magnetic polarity (stripes) on either side of oceanic ridges. For example, a sequence of magnetic reversals (switch from normal to reverse polarity and back) in the western Atlantic, offshore from the Carolinas, can be matched with a similar sequence in the eastern Atlantic off the coast of West Africa. These patterns were interpreted to suggest that new crust was divided in half as it formed along the oceanic ridges and each half moved in opposite directions away from the ridge (Fig. 12)



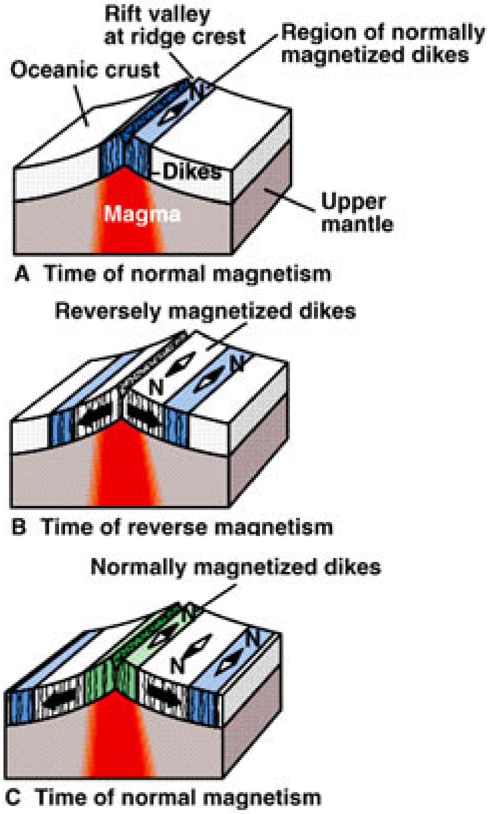


Figure 12. The orientation of Earth's magnetic field and the polarity of rocks of the ocean floor relative to the oceanic ridge. Above: A and C: Rocks with normal polarity (blue, green) form when the compass points to the magnetic North Pole (as it does today); B: conditions of reverse polarity (white) represent periods when the compass arrow points to the South Pole. Left: Alternation of normal and reverse magnetic fields produces a striped pattern of magnetism in the ocean floor rocks.

Age of the Ocean Floor

Ages of igneous rocks on land can be determined using radioactive dating techniques (For a discussion of how geologists determine the absolute age of rocks, see Numerical Time section of the Geologic Time chapter). Ages can be matched with the history of magnetic reversals to identify the sequence and length of intervals of normal and reverse polarity. The patterns of polarity in rocks of the ocean floor were used to establish the ages of rocks in the ocean basins.

Analysis of rock samples from the ocean floor reveals that the oceanic crust is relatively young in comparison to the continents. The oldest oceanic rocks are **less than 200 Myrs (million years) old**. In contrast the maximum age of the continental crust has been established as **four billion years** (4,000 million).

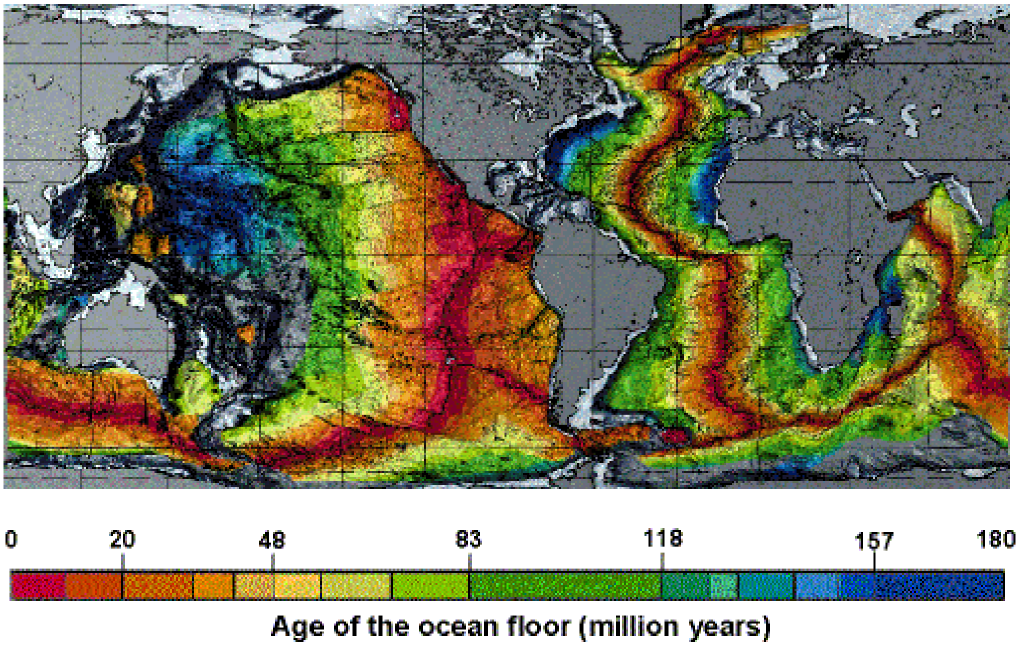


Figure 13. Age of oceanic crust: map. Ages range from young (less than one million years old) along the oceanic ridges (red color) to old (180 million years old) along the ocean margins (e.g., northwest Pacific Ocean). The difference in oldest ages in the northern and southern Atlantic oceans has been interpreted to show that the northern Atlantic Ocean began to form approximately 40 million years before the southern Atlantic Ocean. Original images from the NOAA's National Geophysical Data Center.

The age of the ocean floor varies with location and is consistently **youngest at the oceanic ridges** and older along the ocean margins (Fig. 13). The age of the oceanic crust increases symmetrically with distance from the ridge system in the Atlantic Ocean. Oceanic rocks along the North American and African coastlines are approximately 180 Myrs old whereas rocks adjacent to the ridge may be less than one million years old. The **absence of rocks older than 200 Myrs** was interpreted to suggest that all of the older oceanic crust has been destroyed. This suggests Earth has a **crustal recycling system** that constantly creates young crust at oceanic ridges and destroys old crust elsewhere. The presence of the older oceanic floor along the trenches was used to infer that the oceanic lithosphere was being consumed at the trenches.

Seafloor Spreading

Scientists surveying the ocean floor learned that **heat flow** was greatest along the oceanic ridge system. The ridge system was recognized as a source of volcanic activity. These observations were combined with the knowledge that the ocean floor was young along the ridges, and exhibited symmetrical polarity patterns that paralleled the ridges, to infer that new oceanic lithosphere was being continuously formed along the ridge system by magma rising from the mantle below. In the early 1960s, scientists Harry Hess and Robert Dietz interpreted that the ocean floors "spread" from the ridges and move toward the trenches.

The **seafloor spreading** hypothesis lead to the conclusion that new ocean floor was created at the oceanic ridges. The oceanic lithosphere gradually moved away from the ridge creating a gap to fill with new material rising from below. The hypothesis implies the ocean basins (and hence Earth) will increase in size unless an additional mechanism can be found to compensate for the creation of new oceanic lithosphere. That mechanism was the destruction of old oceanic lithosphere along the trenches. When the concept of seafloor spreading was matched with Wegener's earlier idea of continental drift, the new theory of **plate tectonics** was born (Fig. 14).

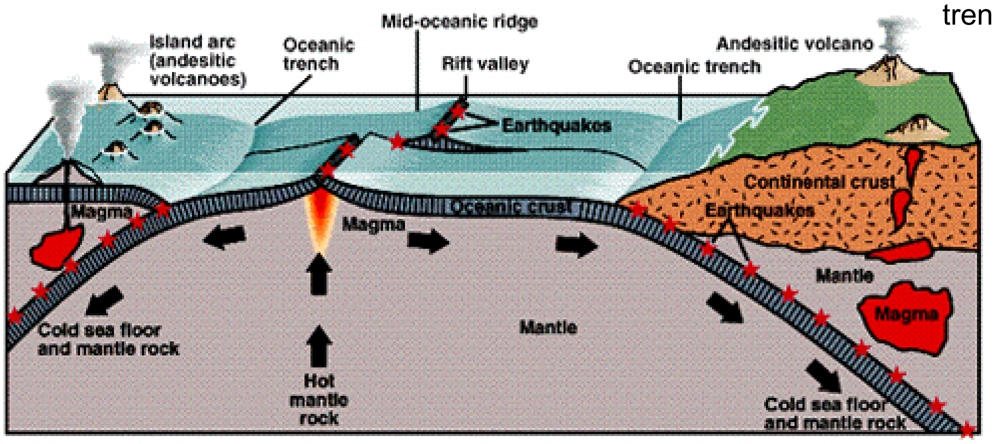


Figure 14. Young oceanic lithosphere forms at the oceanic ridge system and is consumed at trenches. Magma rises to the surface at oceanic ridges, increasing heat flow. Shallow earthquakes are located at ridges and trenches but deep earthquakes only occur at trenches.

Think about it . . .

Make a concept map of the characteristics of the ocean floor using the features described above. Focus on finding common features related to topography, age, and paleomagnetism of the oceanic crust.

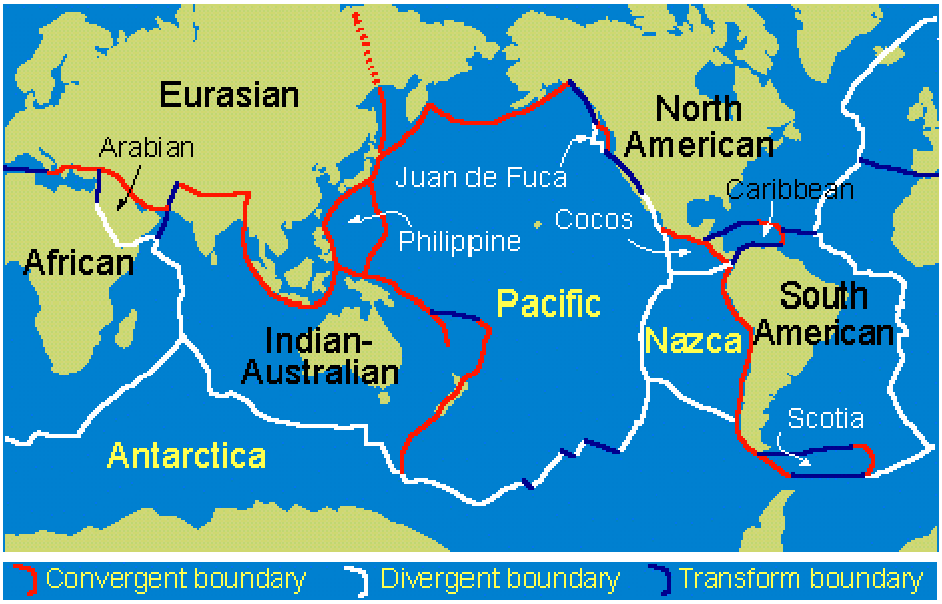
Plate Tectonics

- Earth's lithosphere is divided into a series of major and minor mobile plates.
- Plates move at rates of centimeters per year.
- Plates may be composed of continental and/or oceanic lithosphere.
- The destruction of oceanic lithosphere below oceanic trenches explains the occurrence of earthquakes and volcanoes adjacent to trenches.

Lithospheric Plates

The theory of plate tectonics proposes that the lithosphere is divided into **eight major plates** (North American, South American, Pacific, Nazca, Eurasian, African, Antarctic, and Indian-Australian) and several smaller plates (e.g., Arabian, Scotia, Juan de Fuca) that fit together like the pieces of a jigsaw puzzle (Fig. 15). These plates are mobile, moving in constant, slow motion measured in rates of centimeters per year. The movements of plates over millions of years resulted in the opening and closure of oceans and the formation and disassembly of continents. The theory links Earth's internal processes to the distribution of continents and oceans; it is the big picture view of how Earth works.

Figure 15. Distribution of tectonic plates with type of plate boundary.



Plates are typically composed of both continental and oceanic lithosphere. For example, the South American plate contains the continent of South America and the southwestern Atlantic Ocean. Plate boundaries may occur along continental margins (**active margins**) that are characterized by volcanism and earthquakes. Continental margins that do not mark a plate boundary are known as passive margins and are free of volcanism and earthquakes. The Atlantic coastlines of North and South America are examples of **passive margins**.

Earthquakes and Volcanoes

Scientists had long recognized that volcanoes and earthquakes were present in greatest concentrations around the rim of the Pacific Ocean (**Ring of Fire**). Seismologists Kiyoo Wadati and Hugo Benioff noted that the focal depths of earthquakes became progressively deeper underlying ocean trenches (Fig. 16). Prior to the seafloor spreading hypothesis there was no obvious explanation for the presence of these **Wadati-Benioff zones**. Now it is widely accepted that earthquakes occur as one plate bends and fractures as it descends beneath another into the asthenosphere.

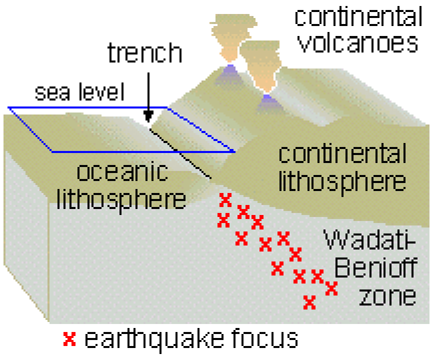


Figure 16. Inclined zone of earthquake foci adjacent to oceanic trench slopes downward under the overriding plate. The distribution of foci define the Wadati-Benioff zone.

The ocean floor was being pulled or pushed into the mantle were it was heated to form magma which in turn generated volcanoes. The destruction of the oceanic lithosphere caused earthquakes down to depths of 700 to 800 km (440-500 miles), explaining the presence of the deepest earthquakes adjacent to oceanic trenches. The term **subduction zone** was coined to refer to locations marked by Wadati-Benioff zones where the oceanic lithosphere is consumed adjacent to a trench.

Plate tectonics theory (Fig. 17) joined continental drift to sea-floor spreading to propose:

- The plate boundaries are mainly represented by oceanic ridges and trenches.
- Interactions at plate boundaries cause volcanic activity and earthquakes.
- The plates are in motion, moving away from ridges and toward trenches.
- Plates descend into the mantle below trenches in subduction zones.
- Plates typically contain both oceanic and continental lithosphere.
- Oceanic lithosphere is continually created and destroyed.
- Continental lithosphere can not be destroyed but continents can be subdivided and assembled into supercontinents.

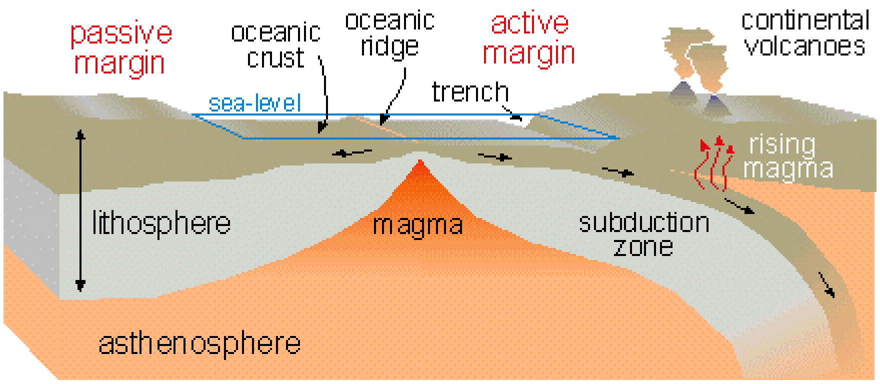


Figure 17. Illustration of the plate tectonic cycle. Oceanic lithosphere created by magma rising from the asthenosphere. Plates move away from the oceanic ridge and descend beneath a trench at the subduction zone.

Plate Motions

The rates and directions of plate motions were originally determined by computing the distance of oceanic floor of a known age from the oceanic ridge system. Rates were computed by dividing age (years) by distance (centimeters). Such simple but effective calculations were compared to motion rates determined using the age of volcanic islands formed above mantle **hot spots** (e.g., Hawaii; Fig. 18). Some volcanic islands in the interiors of plates form above fixed plumes of magma rising from the mantle. The locations of these mantle plumes are known as hot spots. The islands form as the plate moves over the magma source, much like a tectonic conveyer belt. Islands are progressively older with increasing distance from the hot spot. The relationship between age and distance yields the rate of plate motion.

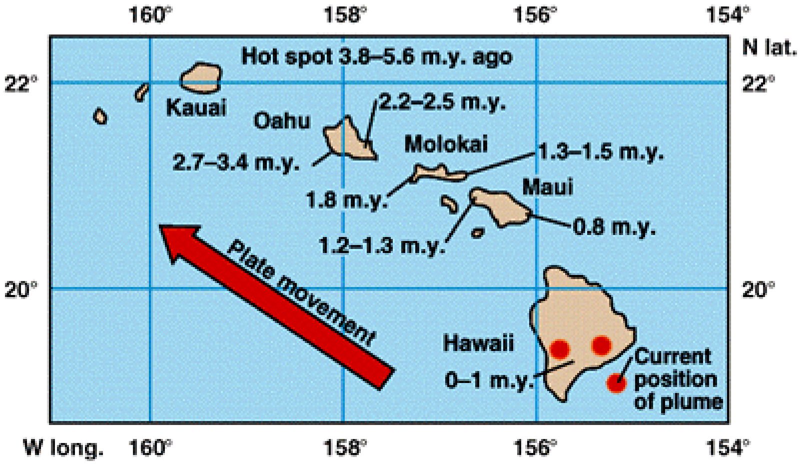


Figure 18. Relative ages and locations of Hawaiian Islands relative to hot spot (mantle plume). Kauai has traveled from the location of the plume to its present site over the last five million years. A submarine volcano, Loihi, is forming over the current position of the plume.

Today satellite technology is used to determine the current rates of plate motion. Satellites anchored in space can record tiny movements of fixed sites on Earth, thus constraining the motions of plates (Fig. 19). Rates of seafloor spreading range from a little as 1-2 centimeters per year along the oceanic ridge in the northern Atlantic Ocean to more than 15 cm/yr along the East Pacific Rise spreading center. Current seafloor spreading rates are approximately five times higher for the East Pacific Rise than the Mid-Atlantic Ridge. Spreading rates changed through time but consistently higher rates in the Pacific)cean basin can account for the contrast in size of the Atlantic and Pacific Oceans. The Pacific Ocean floor would be even wider if oceanic crust were not consumed at subduction zones along much of its margin.

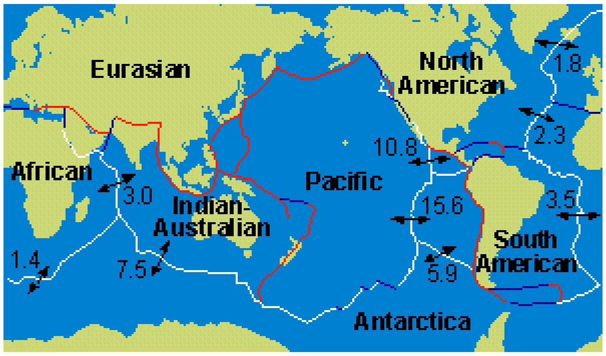


Figure 19. Directions and rates of plate motions (centimeters per year) along oceanic ridge systems. Spreading rates in the Pacific Ocean are nearly five times faster than in the Atlantic.

Think about it . . .

1. Name as many plates as you can on the blank map of the world plates found at the end of the chapter and locate the features on the associated list.
2. Print the blank map of the world found at the end of the chapter and draw the major plate boundaries and label the names of the plates.
3. Examine the idealized plate map at the end of the chapter, answer the associated questions, and draw a cross section through the map to show the relationship between the featured plates.

Divergent Plate Boundaries

- The three types of plate boundaries are divergent, convergent, and transform.
- Divergent boundaries begin by splitting apart segments of continental crust along rift valleys.
- Narrow oceans represent youthful divergent boundaries and wide oceans are indications of a long-lived ocean basin.

Ocean ridges and subduction zones are boundaries between plates of lithosphere. A gap is created when oceanic lithosphere separates along the oceanic ridge. The gap is filled by magma that rises from the asthenosphere. The magma cools and solidifies to create new oceanic lithosphere.

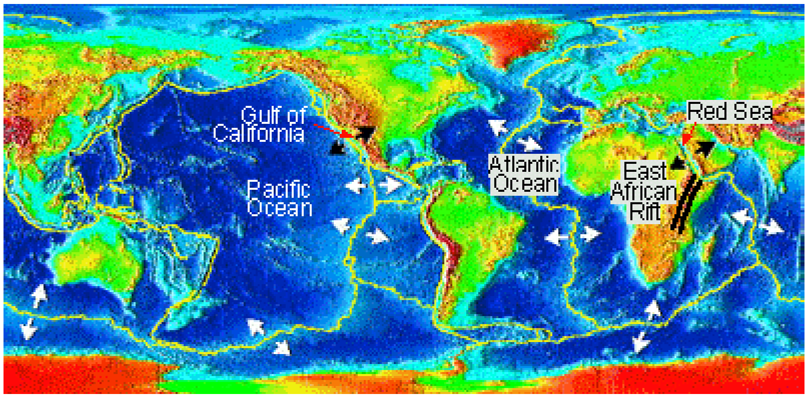


Figure 20. Locations of divergent plate boundaries and sense of plate motion indicated by arrows. Map courtesy of NOAA National Geophysical Data Center.

Divergent Boundary

The evolution of a divergent plate boundary has three recognizable stages. The **birth** of a divergent boundary requires that an existing plate begin to divide. This is happening today in East Africa, in an area known as the **East African Rift** zone (Fig. 20). The African continent is slowly splitting in two. As the continental crust divides, magma from the asthenosphere fills in the gap. Several volcanoes are present in the rift zone.

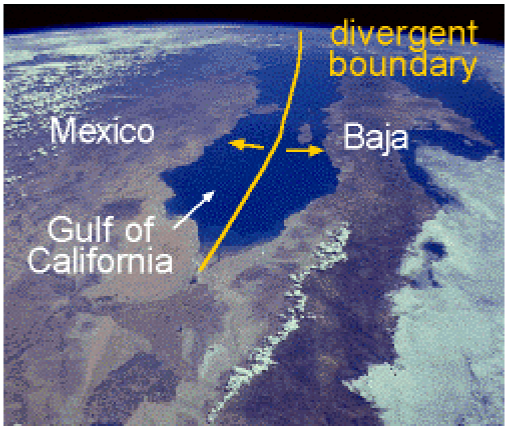


Figure 21. View to the south along the Gulf of California between Baja peninsula and the mainland of Mexico. The Gulf represents a young oceanic ridge. Seafloor spreading is pushing Baja further away from the mainland. Image from NASA.

Eventually the gap will form a **narrow ocean** (youth) much like the Red Sea to the north of the East African Rift zone. The Red Sea separates Saudi Arabia from Africa (Fig. 20). A similar narrow sea, the **Gulf of California**, lies between much of Mexico and Baja California (Fig. 21).

It takes millions of years to form a **mature ocean**, as rates of plate motions are slow (10-100 mm/yr). The oldest oceanic crust in the Atlantic and Pacific Oceans is the same age (~180

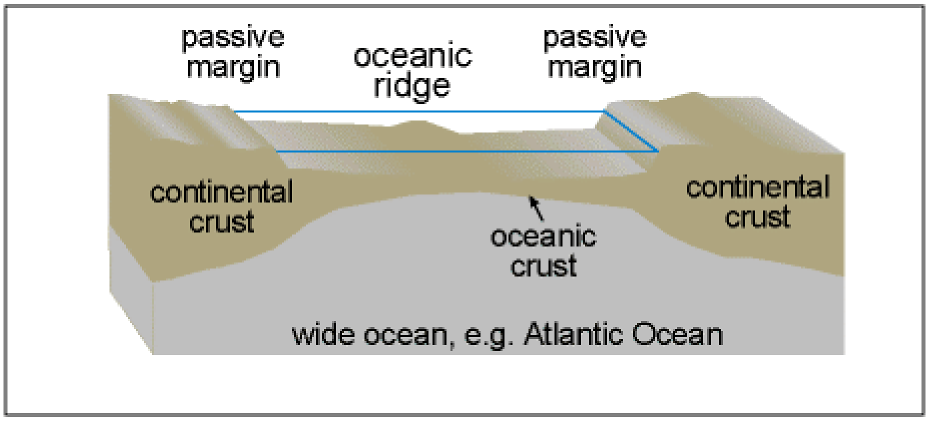


Figure 22. A mature ocean basin formed between two continents.

million years) but the Pacific is much wider than the Atlantic because it is spreading 2 to 3 times as fast (Figs. 20, 22).

Think about it . . .
Print the blank map of the plates found in the Plate Motions exercise the end of the chapter. Identify the divergent plate boundaries and label them young or mature. Can you identify some of the pairs of locations that are getting further apart because they lie on opposite sides of a divergent boundary?

Convergent Plate Boundaries

- The three types of plate boundaries are divergent, convergent, and transform.
- Interactions along convergent boundaries involve the collision of pairs of plates where oceanic lithosphere is often destroyed at subduction zones.
- Convergent boundaries may juxtapose oceanic lithosphere with oceanic lithosphere, continental lithosphere with oceanic lithosphere, and continents with continents.

Ocean ridges and subduction zones are boundaries between plates of lithosphere. Oceanic lithosphere is destroyed at subduction zones where lithosphere descends into the mantle beneath trenches. This older lithosphere melts to form magma. The magma rises through the overlying lithosphere and may form volcanoes at Earth's surface.

Convergent Boundary

Convergent boundaries come in three varieties depending upon the type of lithosphere that is juxtaposed across a subduction zone.

Oceanic Plate vs. Oceanic Plate Convergence
The older of the two plates descends into the subduction zone when plates of oceanic lithosphere collide along a trench. The descending plate carries water-filled sediments from the ocean floor downward into the mantle. The presence of water alters

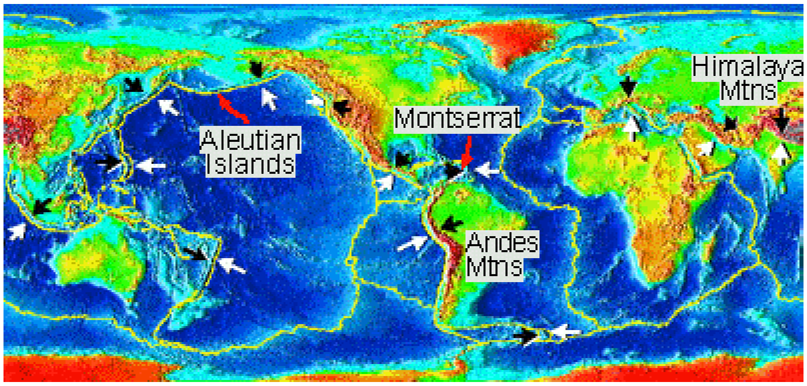


Figure 23. Locations of convergent plate boundaries and sense of plate motion indicated by arrows. Map courtesy of NOAA National Geophysical Data Center.

the physical and chemical conditions necessary for melting and causes magma to form. The magma rises up through the overriding oceanic plate, reaching the surface as a volcano. As the volcano grows, it may rise above sea level to form an island.

Trenches often lie adjacent to chains of islands (**island arcs**) formed by magma from the subducted plate. The Aleutian Islands (Fig. 23) off the tip of Alaska were formed by magma generated when the Pacific Plate descended below some oceanic lithosphere on the margin of the North American Plate. Current volcanic activity on the island of Montserrat in the Caribbean is the result of subduction of the South American Plate below an island arc that marks the edge of the Caribbean Plate (Fig. 24).

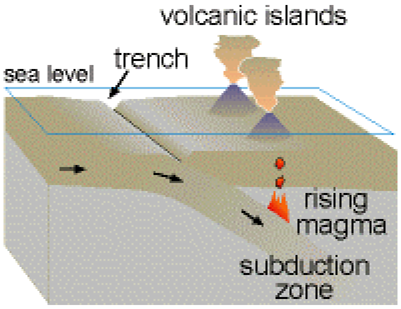


Figure 24. Features associated with a convergent plate boundary where two oceanic plates collide. The plate with the older (cooler, more dense) crust descends into the subduction zone. A chain of volcanic islands (island arc) forms on the overriding plate.

Oceanic Plate vs. Continental Plate Convergence

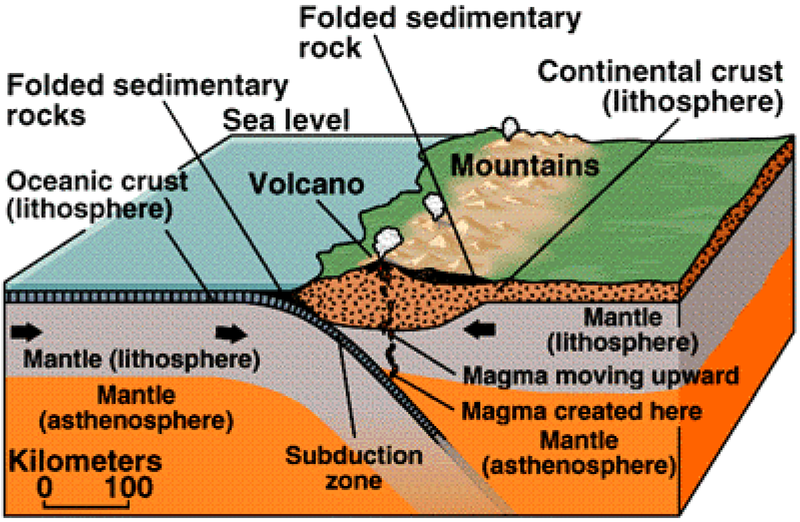
When oceanic lithosphere collides with continental lithosphere, the oceanic plate will descend into the subduction zone (Fig. 25). Oceanic lithosphere is denser than continental lithosphere and is therefore consumed preferentially. Continental lithosphere is almost never destroyed in subduction zones.

The Nazca Plate dives below South America in a subduction zone that lies along the western margin of the continent. Convergence between these plates has resulted in the formation of the Andes Mountains (the second highest mountain range on Earth), extensive volcanism, and widespread earthquake activity (Fig. 23). The largest earthquakes are concentrated along subduction zones.

Continental Plate vs. Continental Plate Convergence

The tallest mountains in the world were formed (and continue to grow) as a result of continental collision. The Himalayan mountains mark the boundary between the Indian and Eurasian plates (Fig. 23). The collision of the plates began over 40 million years ago when India smashed into the belly of Asia. Continental lithosphere is relatively light and is deformed adjacent to subduction zones rather than consumed.

Figure 25. Summary diagram of processes at a convergent plate boundary between an oceanic and continental plate.



Think about it . . .

1. Print the blank map of the plates in the Plate Motions exercise found at the end of the chapter, identify the convergent plate boundaries and label them as one of the three types described above. Can you identify some of the pairs of locations that are moving closer together because they lie on opposite sides of a convergent boundary?
2. Use the two-part Venn diagram located at the end of the chapter to compare and contrast the characteristics of divergent and convergent plate boundaries. Choose from the list of features to complete the diagram.
3. Use the three-part Venn diagram at the end of the chapter to compare and contrast the characteristics of the three types of convergent plate boundary.

Transform Plate Boundaries

- The three types of plate boundaries are divergent, convergent, and transform.

- Plates slide past each other at transform boundaries; lithosphere is neither destroyed nor created.
- The San Andreas Fault, California, is a transform boundary that separates the North American and Pacific Plates.

Like the nuts and bolts that hold massive structures together, transform plate boundaries are the underappreciated members of the plate tectonics machine. New lithosphere is not created at transform boundaries, neither is old lithosphere destroyed; consequently, these boundaries are sometimes termed **conservative** plate boundaries. Plates slide past their neighbors like traffic on a two-way street, moving in opposite but parallel directions.

Transform Boundary

Transform boundaries join sections of convergent and/or divergent boundaries. Most transform boundaries occur in ocean basins where they offset oceanic ridges (Fig. 26). Plates on either side of a transform boundary slide past each other without either plate being consumed and without a gap opening between the plates (Fig. 27). Recent analysis of satellite altimeter data has allowed scientists to use slight variations in the elevation of the ocean surface to determine the topography of the seafloor. Examination of oceanic ridges along the East Pacific Rise or Mid-Atlantic Ridge show offsets along transform boundaries.

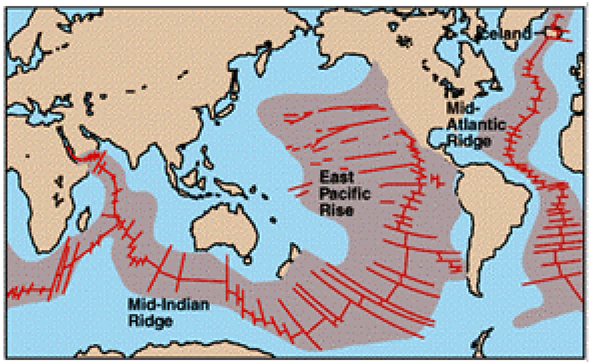


Figure 26. Oceanic ridge systems are offset along fracture zones and transform faults.

Some transform boundaries such as the San Andreas Fault in California or the North Anatolian Fault in Turkey occur on land. The San Andreas Fault joins two oceanic ridges. The southern end of the fault begins in the Gulf of California at the north end of a young ocean (Fig. 28). The northern end of the fault becomes the Mendocino fracture zone offsetting a section of the oceanic ridge that defines one side of the small Juan de Fuca plate offshore from Washington and Oregon.

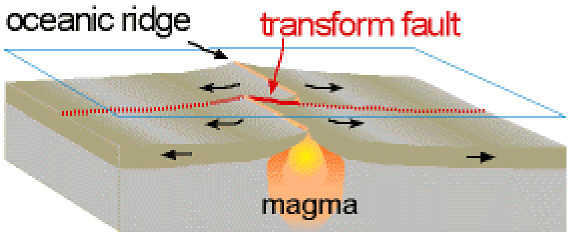


Figure 27. Plates move in opposite directions on either side of the transform boundary, causing earthquakes. Plates move in similar directions on either side of the fracture zone (red dashed line), resulting in fewer earthquakes.

Land on the west side of the San Andreas fault, including Los Angeles and San Diego, is part of the Pacific Plate. San Francisco lies east of the fault and is on the North American Plate. Western California is being slowly displaced to the northwest relative to the rest of the state. It is not going to drop off into the ocean but it will eventually migrate along the western boundary of the North American Plate, eventually colliding with Alaska millions of years from now.

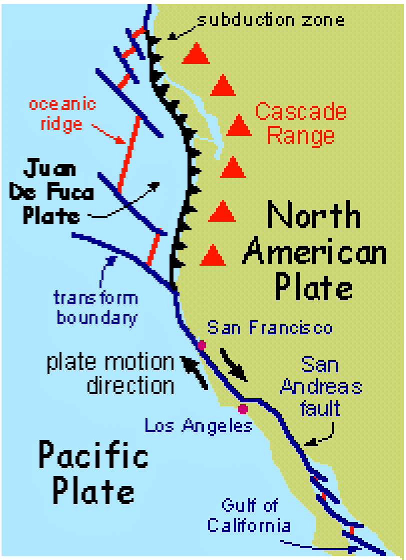


Figure 28. The San Andreas Fault is a transform boundary that separates the North American and Pacific Plates. The smaller Juan de Fuca Plate lies between these two plates opposite Oregon, Washington, northern California, and part of British Columbia. The Pacific Plate moves northwest relative to the North American Plate. Los Angeles will migrate toward San Francisco over the next several million years.

Summary

1. What is the theory of plate tectonics?

The theory of plate tectonics proposes that the lithosphere (uppermost mantle and crust) is divided into a series of plates that fit together like the pieces of a jigsaw puzzle. These plates are mobile, moving in constant, slow motion measured in rates of millimeters per year. The movements of plates measured over millions of years resulted in the opening and closure of oceans and the formation and disassembly of continents.

2. What is the origin of the theory of plate tectonics?

The theory of plate tectonics is a combination of two earlier hypotheses, continental drift and seafloor spreading.

3. What is continental drift?

The concept of continental drift was proposed by Alfred Wegener who suggested that the continents once formed a single landmass he named Pangaea. He suggested that Pangaea split apart into its constituent continents about 200 million years ago and that the continents "drifted" to their current positions.

4. What observations did Wegener use to support the hypothesis of continental drift?

Wegener's principal observations were: (a) Opposing coastlines of continents often fit together suggesting the continents were once a single continent. (b) Mountain belts match across continental margins if the continents are reassembled as Pangaea. (c) The distribution of fossils on separate continents match if the continents are reassembled as Pangaea. (d) Continents located near the South Pole during the assembly of Pangaea exhibit evidence of glaciation; rocks deposited on continents near the equator provide evidence of tropical conditions.

5. Why did Wegener and his concept of continental drift not receive more support from the scientific community?

Wegener's observations were ignored because he was unable to propose a mechanism to cause the continents to "drift". He suggested that the continents plowed through the ocean basins as a result of tidal forces but that idea was quickly discredited.

6. How are features on the seafloor related to the concept of seafloor spreading?

The ocean floor varies considerably in depth. An oceanic ridge system can be traced around the world. The deepest parts of the ocean (~10 km) are trenches found along the margins of some continents or adjacent to volcanic island chains. Sea-floor spreading proposed that rising magma was forming new oceanic crust along the oceanic ridges, the ocean floor was moving away from the ridges, and that old crust was destroyed at oceanic trenches.

7. What is magnetic polarity?

Magnetic polarity refers to the orientation of Earth's magnetic field. The magnetic field has switched polarity at irregular intervals during Earth history. Lines of magnetic force are oriented downward in the Northern Hemisphere during periods of normal polarity. During intervals of reverse polarity the inclination of the magnetic field is downward in the Southern Hemisphere.

8. What is paleomagnetism?

Paleomagnetism is the record of Earth's magnetic field preserved in rocks.

9. How do the ages of rocks on the ocean floor compare to the ages of rocks on the continents?

Rocks of the ocean floor are considerably younger (0-180 million years) than the majority of rocks that make up the continents (0-4 billion years). The age of the ocean floor varies with location and is consistently younger at the oceanic ridges and older along the ocean margins. The age of the oceanic crust increases symmetrically with distance from the ridge system in the Atlantic Ocean.

10. What are the principal elements in the theory of plate tectonics?

The plates are in motion, moving away from ridges and toward trenches. Plates descend into the mantle below trenches in regions termed subduction zones. Plates typically contain both oceanic and continental lithosphere. Oceanic lithosphere is continually created and destroyed. Continental lithosphere cannot be destroyed but continents can be subdivided and assembled into supercontinents. Interactions at plate boundaries cause volcanic activity and earthquakes.

11. Why are earthquakes and volcanoes associated with convergent plate boundaries?

The depth of earthquakes becomes progressively deeper underlying ocean trenches. Prior to the sea-floor spreading hypothesis there was no obvious explanation for the presence of these "Wadati-Benioff" zones. Earthquakes occur because of physical changes in the descending plate as it pushes into the asthenosphere. The oceanic lithosphere in the descending plate was heated to form magma which in turn generated volcanoes.

12. What are the three types of plate boundary?
Divergent plate boundary - where plates move apart.
Convergent plate boundary - where plates converge.
Transform plate boundary - where plates slide past each other.

13. Describe the evolution of a divergent plate boundary.
The evolution of a divergent plate boundary has three recognizable stages. It begins with the separation of an existing plate along a rift zone (e.g., East African Rift); next a narrow ocean forms, much like the Red Sea; finally, continued sea-floor spreading creates a wide ocean basin like the Atlantic Ocean.

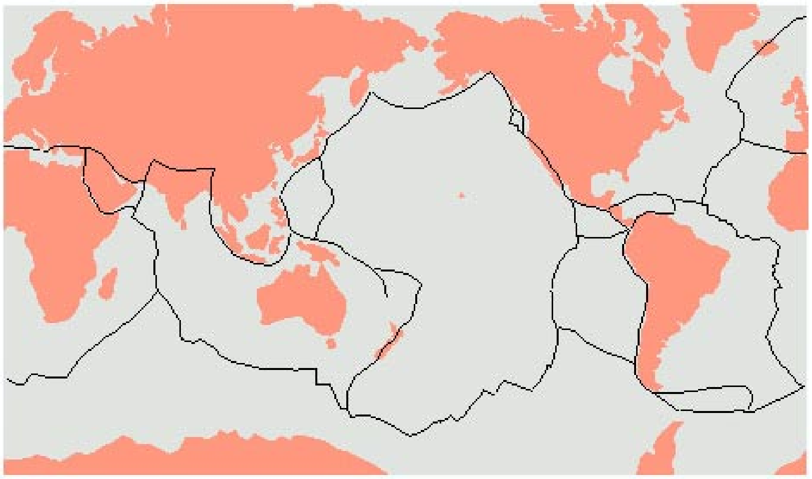
14. What are the different types of convergent plate boundary?
There are three types of convergent plate boundary, identified by the types of lithosphere (oceanic vs. continental) on either side of the boundary. Ocean-ocean convergence is recognized by the presence of a volcanic islands along the margin of the overriding plate. Ocean-continent convergence results in a chain of volcanoes on the continental margin as continents always override oceanic lithosphere. Continent- continent collision forms mountain ranges but has no associated volcanism.

15. What are the characteristics of transform plate boundaries?
Transform boundaries join sections of convergent and/or divergent boundaries. Plates on either side of a transform boundary slide past each other without either plate being consumed and without a gap opening between the plates.

16. Will western California drop into the ocean because of movements along the San Andreas Fault?
Nope. The San Andreas is a transform fault that separates the North American Plate form the Pacific Plate. Western California (including Los Angeles) makes up a thin slice of continental lithosphere on the Pacific Plate. The relative motions of the two plates results in western California moving northward relative to the rest of the state. Continued movement on the San Andreas Fault will cause Los Angeles to move north toward San Francisco (on the North American Plate) but won't dump California into the Pacific Ocean.

World Plates and Their Features

1. Label as many plates as you can on the blank map below.



2. Identify and label the map with as many of the features on the associated list as you can.

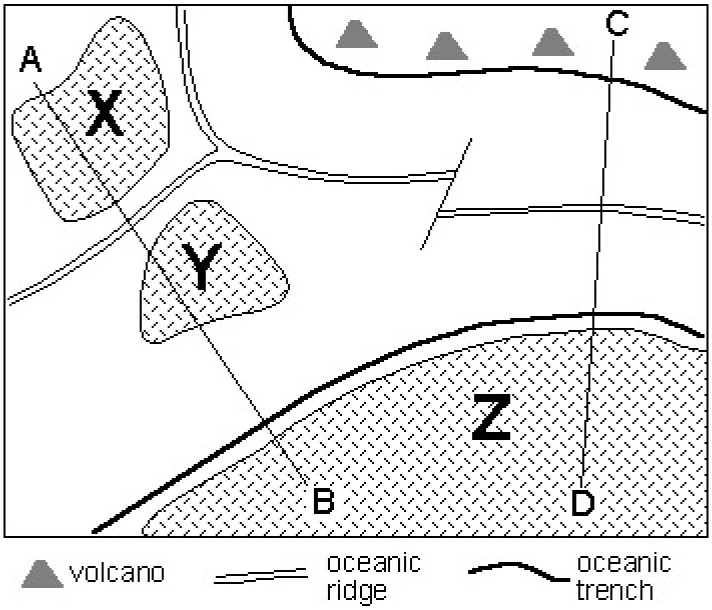
   a. a subduction zone
   b. a plate that is 99% oceanic lithosphere
   c. a plate that is 90+% continental lithosphere
   d. a pair of plates moving toward each other
   e. a plate nearly surrounded by oceanic ridges
   f. a plate moving approximately north
   g. a plate moving approximately east
   h. a fast moving plate
   i. a zone of deep earthquakes
   j. a passive continental margin
   k. the site of the oldest oceanic crust
   l. an oceanic ridge
   m. the location of rocks with normal polarity
   n. a pair of plates moving away from each other
   o. a hot spot
   p. a slow-moving plate
   q. the site of very young rocks (0-5 Myrs)
   r. a zone of shallow earthquakes
   s. a chain of volcanoes on a continent

Locate the Plate Boundaries

Draw the major plate boundaries and label the names of the plates on the map below.

Idealized Plate Boundary Map and Cross Sections

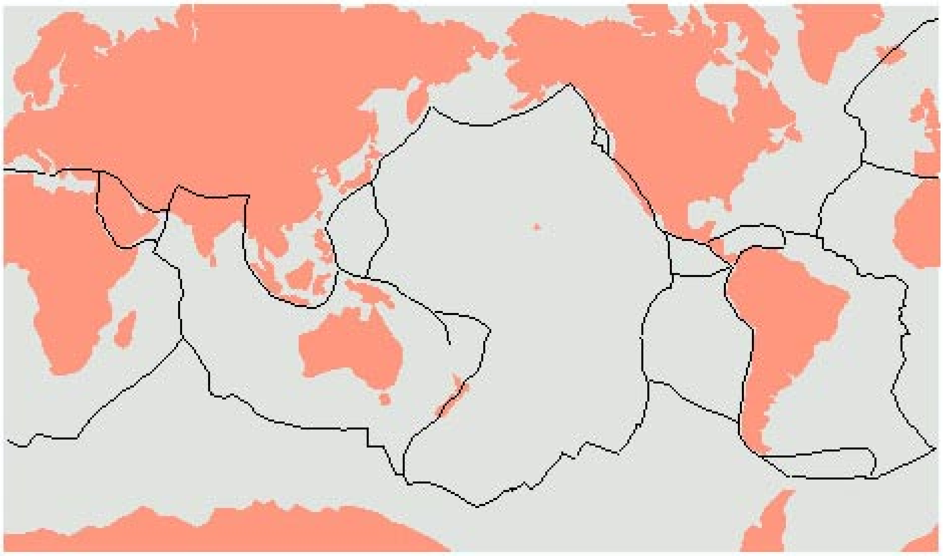
Examine the map and answer the questions that follow. The patterned areas labeled X, Y, and Z represent continents; assume the rest of the map is ocean.



1. How many plates are present? ________
2. Draw arrows on the map showing the relative directions of plate motions.
3. Color the youngest lithosphere red and color zones of deep earthquakes blue.
4. In the space below draw two cross sections through the lithosphere along lines A-B and C-D illustrating the characteristics of plate boundaries with depth.

Plate Motions

1. Identify the following on the map below:
   a) divergent plate boundaries - color them differently if they are young or mature;
   b) convergent plate boundaries - color them differently if they are (i) oceanic/oceanic, (ii) oceanic/continental, or (iii) continental/continental;
   c) transform plate boundaries.



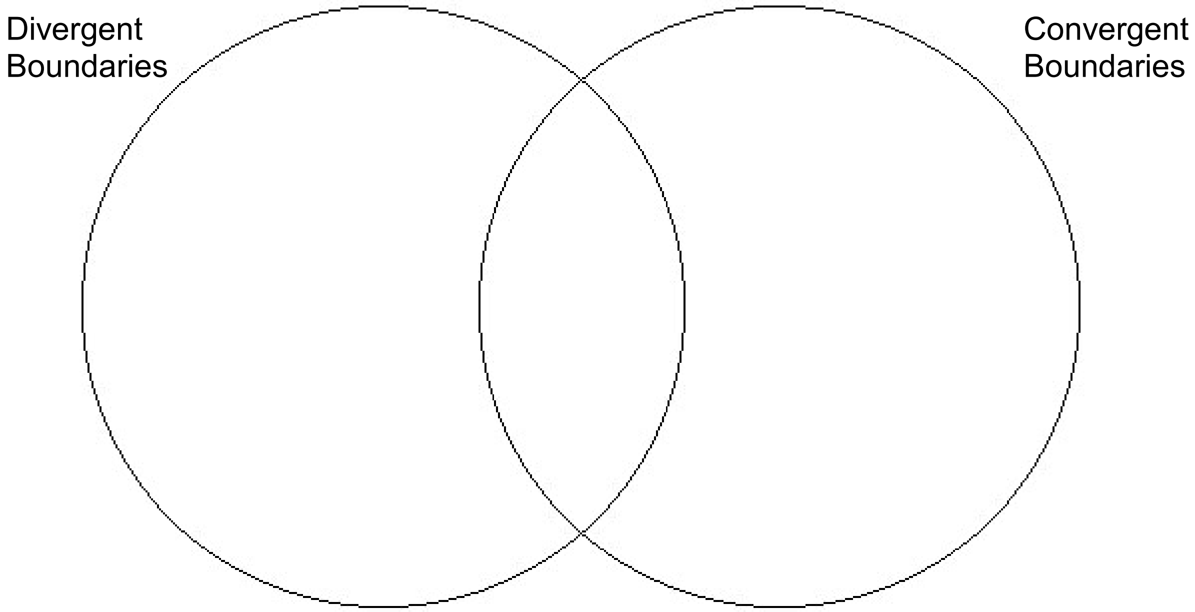
2. Based upon the distribution of divergent and convergent plate boundaries, which of the following locations are moving closer together, further apart or show no change.

Locations	Closer	Further	No Change
London (U.K.) & New York			
Honolulu, Hawaii & Tokyo, Japan			
Mecca, Saudi Arabia & Cairo, Egypt			
New York & Mexico City			
Rio de Janeiro, Brazil & Cape Town, S. Africa			
Honolulu, Hawaii & Los Angeles			
Cape Town, S. Africa & Bombay, India			
Los Angeles & San Francisco, California			
Sydney, Australia & Bombay, India			

Venn Diagram: Divergent vs. Convergent Plate Boundaries

Use the Venn diagram, below, to compare and contrast the similarities and differences between divergent and convergent plate boundaries. Write features unique to either group in the larger areas of the left and right circles; note features that they share in the overlap area in the center of the image. Place the numbers corresponding to the list of characteristics below in the most suitable locations on the diagram.

1. Magma rises to the surface.
2. Rocks on either side of boundary are the same age.
3. Deep earthquakes may occur.
4. Associated with island arcs.
5. Example: Nazca and South American Plate boundary.
6. Plates move toward each other.
7. Plates move away from each other.
8. Continental lithosphere on one side of plate boundary, oceanic lithosphere on the other.
9. Associated with mountains.
10. Rocks on either side of boundary may be different ages.
11. Characterized by young rocks.
12. Oceanic lithosphere on both sides of the plate boundary.
13. Example: Nazca and Pacific Plate boundary.
14. Associated with oceanic ridges.
15. Associated with oceanic trenches.



Venn Diagram: Convergent Plate Boundaries

Use the Venn diagram, below, to compare and contrast the similarities and differences between the three styles of convergent plate boundaries. Print this page and write features unique to each group in the larger areas of the circles; note features that the different boundaries share in the overlapping areas of the circles.