

INTRODUCTION TO PLATE TECTONICS

Smith and Pun – Chapter 1

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Tectonics is the study of the origin and arrangement of the broad structural features of Earth's surface including:

- **Folds and faults**
- **Mountain ranges**
- **Continents**
- **Earthquake belts**

The basic premise of plate tectonics is that the Earth's surface is divided into a few large, thick plates that move slowly and change in size.

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Intense geologic activity occurs at plate boundaries where plates:

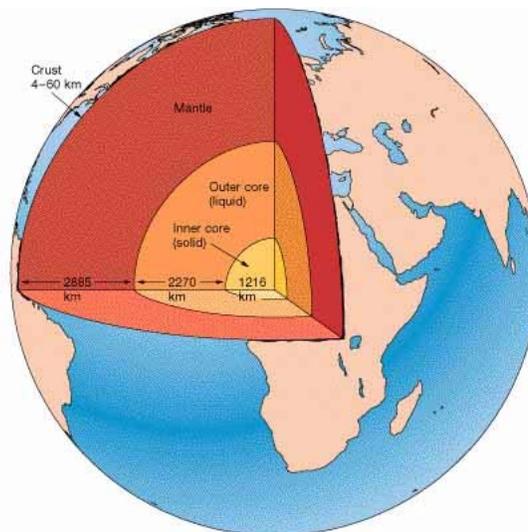
- **Move away from one another**
- **Move past one another**
- **Move towards one another**

The theory of plate tectonics is widely accepted by geologists today because it explains so many of the Earth's features.

There are eight large plates and several smaller plates that make up the outer shell of Earth (the crust and upper part of the mantle). Please see Figure 1.10 on page 13 of Smith and Pun.

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EARTH'S INTERNAL STRUCTURE (see Figure 1.3, page 5)



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THEORY OF PLATE TECTONICS

The theory of plate tectonics originated in the late 1960's by combining two pre-existing theories:

1. **Continental Drift** – The idea that continents move freely over the Earth's surface, changing their positions relative to one another
2. **Sea-Floor Spreading** – A hypothesis that the sea floor forms at the crest of the mid-oceanic ridge, then moves horizontally away from the ridge crest toward an oceanic trench

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EVIDENCE SUPPORTING CONTINENTAL DRIFT

Continents can be made to fit together like pieces of a jigsaw puzzle; the idea that continents were once joined together, and have split and moved apart has been around for more than 130 years (see Figures 12.1 and 12.2, page 309-310).

- The similarity of the Atlantic coastlines of Africa and South America has long been recognized
- In the early 1900's, Alfred Wegener, a German meteorologist noted that South America, Africa, India, Antarctica and Australia had nearly identical late Paleozoic rocks and fossils

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EVIDENCE SUPPORTING CONTINENTAL DRIFT (2)

Wegener's Work

- 2. Wegener noted that the plant *Glossopteris* is found in Pennsylvanian and Permian-age rock on all five continents and fossil remains of *Mesosaurus*, a freshwater reptile are found in Permian-age rocks only in Brazil and South Africa.**
- 3. Additionally, fossil remains of the land-dwelling reptiles *Lystrosaurus* and *Cynognathus* are found in Triassic-age rocks on all five continents.**

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EVIDENCE SUPPORTING CONTINENTAL DRIFT (3)

To support his observations:

- Wegener reassembled the continents to form one supercontinent, Pangaea**
- Wegener thought that the similar rocks and fossils were easier to explain if the continents were joined together, rather than in their present positions.**

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EVIDENCE SUPPORTING CONTINENTAL DRIFT (4)

The distribution of Late Paleozoic glaciation strongly supports the idea of Pangaea.

- **The Gondwanaland continents (southern-hemisphere continents and India) all have glacial deposits of Late Paleozoic age**
- **If these continents were spread over Earth in Paleozoic time as they are today, a climate cold enough to produce extensive glaciation would have had to prevail over nearly the whole world. No evidence of widespread glaciation in the northern hemisphere during the Paleozoic has been found.**

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EVIDENCE SUPPORTING CONTINENTAL DRIFT (5)

- **In fact, the late Paleozoic coal beds of North America and Europe were being deposited at that time in swampy, and likely warm climates.**
- **If the continents are arranged according to Wegener's Pangaea reconstruction, glaciation in the southern hemisphere is confined to a much smaller area, and the absence of widespread glaciation in the northern hemisphere is more easily explained.**
- **Additionally, the present arrangement of the continents would require that late Paleozoic ice sheets flowed from the oceans toward the continents, which is impossible.**

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EVIDENCE SUPPORTING CONTINENTAL DRIFT (6)

Wegener also reconstructed old climate zones (the study of ancient climates is called paleoclimatology).

- **Glacial till and striations indicate a cold climate near the North or South Pole; coral reefs indicate warm water near the Equator.**
- **Cross-bedded sandstones indicate ancient deserts near 30° North and 30° South latitude.**

If ancient climates had the same distribution on Earth that modern climates have, then sedimentary rocks can be used to show where the ancient poles and Equator were located.

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ARGUMENTS AGAINST CONTINENTAL DRIFT

Wegener's ideas were not widely accepted, particularly in the United States and much of the northern hemisphere.

- **Presence of land-dwelling reptiles throughout scattered continents could be explained by land bridges**
- **Fossil plants could have been spread from one continent to another by wind or ocean currents**
- **Most geologists found Wegener's proposal that continents plowed through the oceanic crust contrary to what was known about the strength of rocks at that time (see Section 12.1, page 310).**

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PALEOMAGNETISM AND CONTINENTAL DRIFT

Study of the sea floor and geophysical research, particularly in relation to rock magnetism, performed during the 1940's and 1950's resulted in the revival of continental drift and its subsequent incorporation into the theory of plate tectonics.

The magnetism of old rocks can be measured to determine the direction and strength of the magnetic field in the past. The study of ancient magnetic fields is called paleomagnetism.

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PALEOMAGNETISM AND CONTINENTAL DRIFT (2)

Magnetic lines of force dip more steeply as the north magnetic pole is approached.

As a result, the inclination (dip) of the magnetic alignment preserved in the magnetite minerals in a lava flow can be used to determine the distance of a flow from the pole at the time that the flow formed.

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RECENT EVIDENCE FOR CONTINENTAL DRIFT

As paleomagnetic evidence emerged that supported the theory of continental drift, additional work was performed to “fit” the continents together (see Figure 12.1, page 309).

By defining the edge of a continent as the middle of the continental slope, rather than the existing and constantly changing shoreline, a much more precise fit was found between continents.

The most compelling evidence for continental drift came from greatly refined rock matches between now separated continents.

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SEA FLOOR SPREADING

At the same time that the theory of continental drift was being revived, Henry Hess, a geologist at Princeton University, proposed that the sea floor might be moving as well.

Hess’s 1962 proposal hypothesized that the sea floor is moving like a conveyor belt away from the crest of the mid-oceanic ridge, down the flanks of the ridge, and across the deep ocean basin, finally disappearing by plunging beneath a continent or island arc (process referred to as subduction) Please see Figure 12.9, page 316).

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SEA FLOOR SPREADING (2)

The Mid-Oceanic Ridge

- **The existence of the mid-oceanic ridge and its high heat flow are caused by the rise of hot mantle rock. The basalt eruptions on the ridge crest are also related to the rising rock, because the mantle rock is hotter than normal here and begins to undergo partial melting.**
- **As hot rock continues to rise beneath the ridge crest, the circulation pattern splits and diverges near the surface. Mantle rock moves away from the ridge crest on each side of the ridge creating tension at the ridge crest. This tension results in cracking of the oceanic crust to form the rift valley and its associated shallow-focus earthquakes**

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SEA FLOOR SPREADING (3)

Oceanic Trenches

- **As the mantle rock moves away from the ridge crest, it carries the sea floor (basaltic oceanic crust) with it. As the hot rock moves sideways, it cools and becomes denser, and sinks deeper beneath the ocean surface. The sinking of cold rock is responsible for the existence of oceanic trenches and their low heat flow values.**
- **The interaction of the moving sea floor rock and stationary rock above can cause earthquakes associated with trenches and andesitic volcanism.**

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SEA FLOOR SPREADING (4)

Age of the Sea Floor

- The young age of sea floor rocks is explained by Hess's theory of sea floor spreading.

New, young sea floor is continually formed by basalt eruptions at the ridge crest. This basalt is then carried sideways by convection and is subducted into the mantle at an oceanic trench.

Therefore, old sea floor is continually being destroyed at trenches, while new sea floor is being formed at the ridge crest (see Figure 12.14, page 319).

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PLATES AND PLATE MOTION

By the late 1960's, the ideas of continental drift and sea floor spreading had been combined into the theory of plate tectonics.

A plate is a large, mobile slab of rock that is part of the Earth's surface. The surface of a plate may be composed entirely of sea floor (the Nazca Plate) or it may be made up of both continental and oceanic rock (the North American Plate).

Some of the smaller plates are entirely continental, but all the large plates contain some sea floor.

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PLATES AND PLATE MOTION (2)

The plates are part of a relatively rigid outer shell of Earth called the lithosphere. The lithosphere includes the rocks of the crust and uppermost mantle (see Figure 1.3, page 5).

The lithosphere beneath oceans increases in both age and thickness with distance from the crest of the mid-oceanic ridge. Young lithosphere near the ridge crest may be only 10 km thick, while very old lithosphere may be as much as 100 km thick.

Continental lithosphere is thicker, varying from approximately 125 to as much as 250 km thick.

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PLATES AND PLATE MOTION (3)

A plate is a rigid slab of rock that moves as a unit. As a result, the interior of plates tend to be relatively inactive tectonically. Plate interiors generally lack earthquakes, volcanoes, young mountain belts, and other evidence of geologic activity.

According to plate tectonic theory, these features are caused by plate interactions at plate boundaries. Plate tectonics has become a unifying theory of geology because it can explain so many diverse features of the Earth.

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PLATES AND PLATE MOTION (4)

Plate boundaries are of three general types, based on the movement of the plates relative to one another (see Figure 1.11, page 14).

- **Divergent Boundary – Boundary between plates that are moving apart**
- **Convergent Boundary – Boundary between plates that are moving toward each other**
- **Transform Boundary – Boundary at which two plates move horizontally past each other**

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EVIDENCE THAT PLATES MOVE

Marine Magnetic Anomalies

During the mid 1960's, magnetometer surveys at sea discovered some interesting characteristics of marine magnetic anomalies.

Most magnetic anomalies at sea are arranged in bands that lie parallel to the rift valley of the mid-oceanic ridge.

Alternating positive and negative anomalies form a strip-like pattern parallel to the ridge crest.

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EVIDENCE THAT PLATES MOVE (2)

Marine Magnetic Anomalies

Fred Vine and Drummond Matthews, two British geologists, made several important observations about the magnetic anomalies in the sea floor.

- 1. The pattern of magnetic anomalies on one side of the mid-oceanic ridge was a mirror image of the pattern on the other side.**
- 2. The same pattern of magnetic anomalies exists over different parts of the mid-oceanic ridge (Pattern of anomalies over the ridge in the northern Atlantic Ocean is the same as the pattern over the ridge in the southern Pacific Ocean).**

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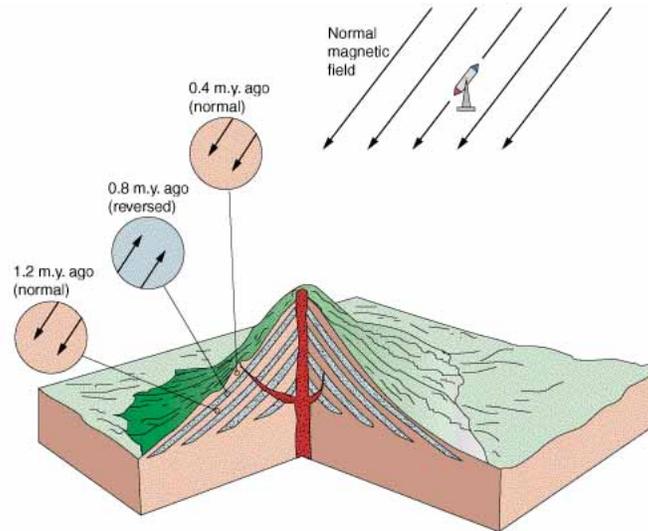
EVIDENCE THAT PLATES MOVE (3)

Marine Magnetic Anomalies

- 3. Most significant observation was that the pattern of magnetic anomalies at sea matches the pattern of magnetic reversals already known from studies of lava flows on continents.**

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MAGNETIC POLE REVERSALS



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EVIDENCE THAT PLATES MOVE (4)

Marine Magnetic Anomalies

The other important point of the Vine-Matthews hypotheses is that it can be used to predict the age of the sea floor.

To date, hundreds of rock and sediment cores recovered from holes drilled in the sea floor have been used to test these hypotheses. In general, close correspondence has been found.

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EVIDENCE THAT PLATES MOVE (5)

Fracture Zones and Transform Faults

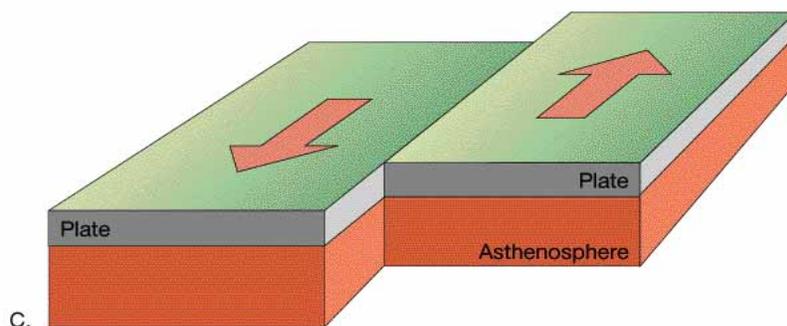
Additional evidence that plates move has been obtained by studying the seismicity of fracture zones.

Transform boundaries occur where strike-slip faults join segments of other boundary types (see Figure 12.27, page 331).

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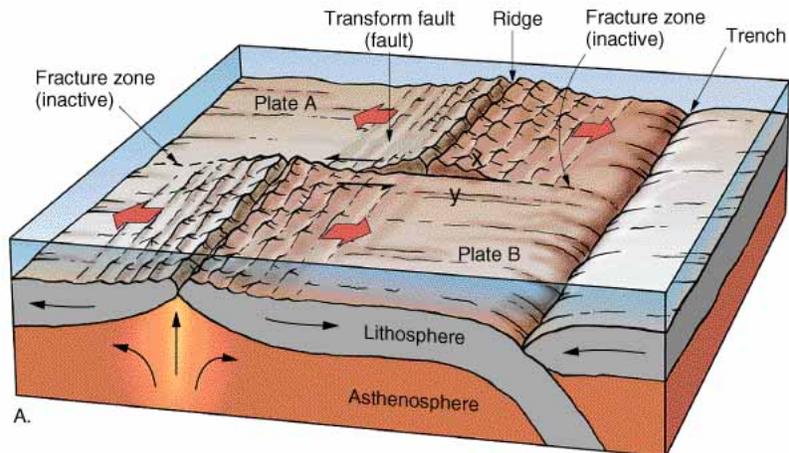
TRANSFORM FAULT BOUNDARY



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TRANSFORM FAULTS ON THE OCEAN FLOOR

(see Figure 12.29, page 332)



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DIVERGENT PLATE BOUNDARIES

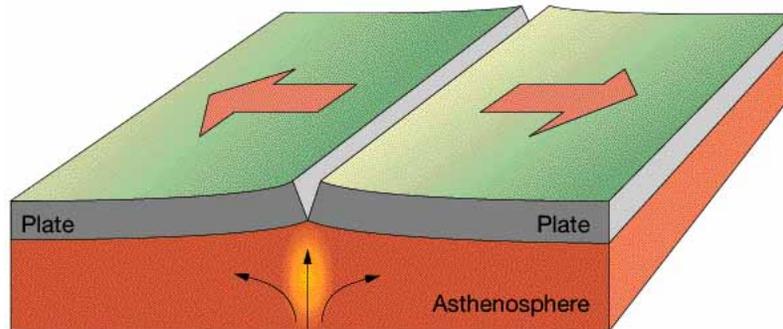
Divergent plate boundaries, where plates move away from each other, may occur in the middle of the ocean or in the middle of a continent.

Divergent plate boundaries result in the creation, or opening of new ocean basins.

When a supercontinent such as Pangaea breaks up, a divergent boundary is found in the middle of a continent. The divergent boundary is marked by rifting, basaltic volcanism and uplift.

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DIVERGENT BOUNDARY



A.

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DIVERGENT PLATE BOUNDARIES (2)

During rifting, the continental crust is stretched and thinned. This extension produces shallow-focus earthquakes on normal faults, and a rift valley forms as a central graben.

The faults provide pathways for basaltic magma rising from the mantle to erupt at the surface as cinder cones and basalt flows.

Uplift at a divergent boundary is generally caused by the upwelling of hot mantle beneath the crust.

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DIVERGENT PLATE BOUNDARIES (2)

An example of a divergent boundary is the African Rift Valleys in eastern Africa (Figure 12.19, page 322). The valleys are grabens that may mark the site of the future breakup of Africa.

An example of a divergent boundary farther along in the process is the Red Sea.

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TRANSFORM BOUNDARIES

At transform boundaries, where one plate slides horizontally past another plate, the plate motion may occur on a single fault or on a group of parallel faults.

Transform boundaries are marked by shallow-focus earthquakes in a narrow zone for a single fault, or in a broad zone for a group of parallel faults.

First-motion studies of the earthquakes indicate strike-slip movement parallel to the faults.

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TRANSFORM BOUNDARIES (2)

The name transform fault comes from the fact that the displacement along the fault abruptly ends or transforms into another type of displacement.

The most common type of transform fault occurs along fracture zones and connects two divergent plate boundaries at the crest of the mid-oceanic ridge.

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CONVERGENT PLATE BOUNDARIES

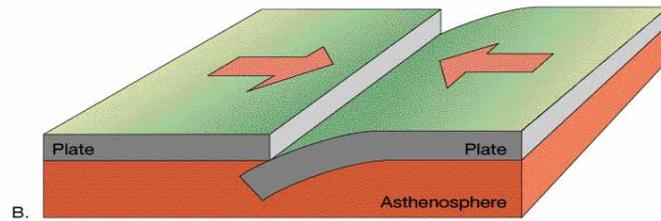
At convergent plate boundaries two plates move toward each other. The characteristics of the boundary depend partly on the type of plates that converge. There are three types of convergent plate boundaries (see Figures 12.20, 12.21 12.26, pages 324, 325, and 329).

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CONVERGENT BOUNDARY

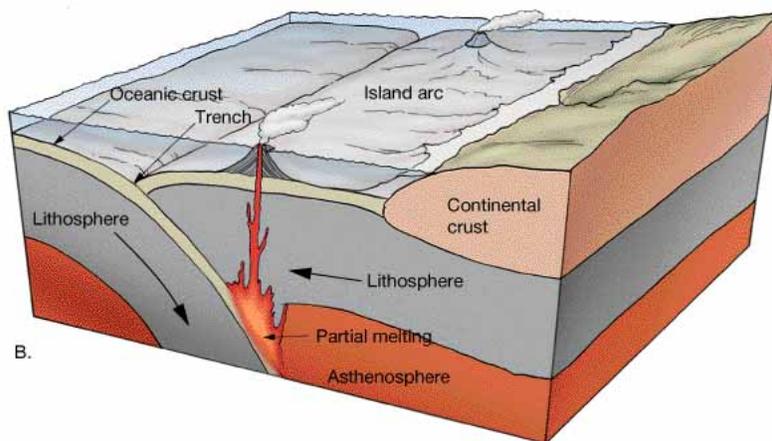
3 TYPES:

- Ocean-Continental
- Ocean-Ocean
- Continental-Continental



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OCEAN-OCEAN CONVERGENCE



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CONVERGENT PLATE BOUNDARIES (2)

Ocean-Ocean Convergence

When two plates capped by sea floor converge, one plate subducts under the other. The subducting plate bends downward, forming the outer wall of an oceanic trench, which usually forms a broad curve that is convex to the subducting plate (refer to previous slide).

The Marianas Trench is an example of where ocean-ocean convergence is ongoing.

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CONVERGENT PLATE BOUNDARIES (3)

Ocean-Continent Convergence

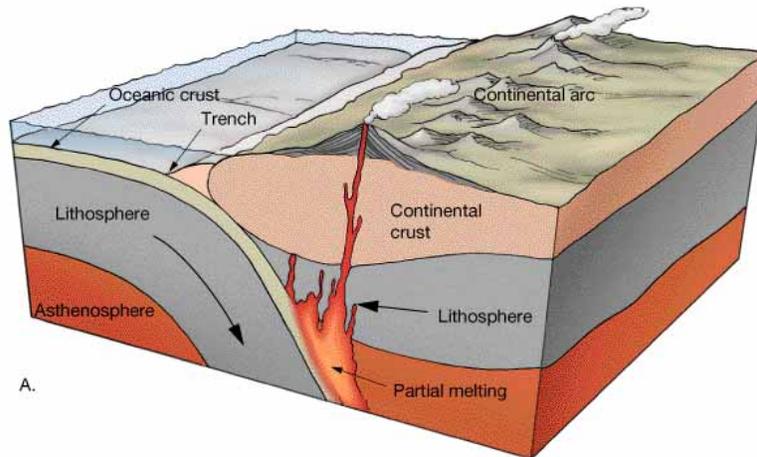
When a plate capped by oceanic crust is subducted under the continental lithosphere, an accretionary wedge and forearc basin form an active continental margin between the trench and the continent.

A Benioff zone of earthquakes dips under the edge of the continent, which is marked by andesitic volcanism and a young mountain belt.

An example of ocean-continent convergence is the subduction of the Nazca Plate under western South America.

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OCEAN-CONTINENT CONVERGENCE



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CONVERGENT PLATE BOUNDARIES (4)

Continent-Continent Convergence

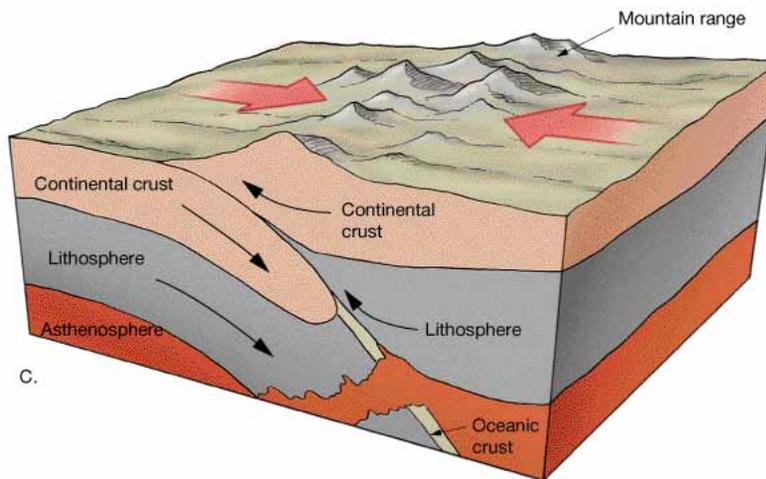
Two continents may approach each other and collide. They must be separated by an ocean floor that is being subducted under one continent and that lacks a spreading axis to create new oceanic crust.

As the sea floor is subducted, the ocean becomes narrower and narrower until the continents eventually collide and destroy or close the ocean basin. Eventually a mountain belt develops and the entire region of impact is marked by a broad belt of shallow-focus earthquakes.

The Himalayas are believed to have formed in this manner, as India collided with, and underthrust Asia.

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CONTINENT-CONTINENT CONVERGENCE



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THE MOTION OF PLATE BOUNDARIES

Almost nothing is fixed in plate tectonics. All three types of plate boundaries may move as well as the plates themselves.

In fact, California's San Andreas Fault has only been in its present position about 5 million years. Prior to that, the plate motion was taken up on seafloor faults parallel to the San Andreas. As a result of movement, the San Andreas Fault may shift to the east in the future.

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SAN ANDREAS FAULT



B.

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SUMMARIZING PLATE TECTONICS

The distribution and composition of the world's volcanoes can be explained by plate tectonics.

- **Basaltic volcanoes and lava flows form at divergent plate boundaries when hot mantle rock rises at a spreading axis.**
- **Andesitic volcanoes, particularly those in the circum-Pacific belt, result from subduction of an oceanic plate beneath either a continental plate or another oceanic plate.**

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SUMMARIZING PLATE TECTONICS (2)

The distribution and first motion of earthquakes is largely explained by plate tectonics.

- **Shallow-focus earthquakes along normal faults are caused by extension at divergent plate boundaries.**
- **Shallow-focus earthquakes also occur on transform faults when plates slide past one another.**
- **Broad zones of shallow-focus earthquakes are located where two continents collide.**
- **Dipping Benioff zones of shallow-, intermediate-, and deep-focus quakes are found along the giant thrust faults formed when an oceanic plate is subducted beneath another plate.**

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SUMMARIZING PLATE TECTONICS (3)

Young mountain belts with their associated igneous intrusions, metamorphism, and fold-thrust belts form at convergent boundaries.

- **Subduction mountains form at the edges of continents where sea floor is sliding under continents.**
- **Continental collision mountains form in continental interiors when two continents collide to form a larger continent.**
- **Old mountain belts mark the position of old, now inactive plate boundaries.**

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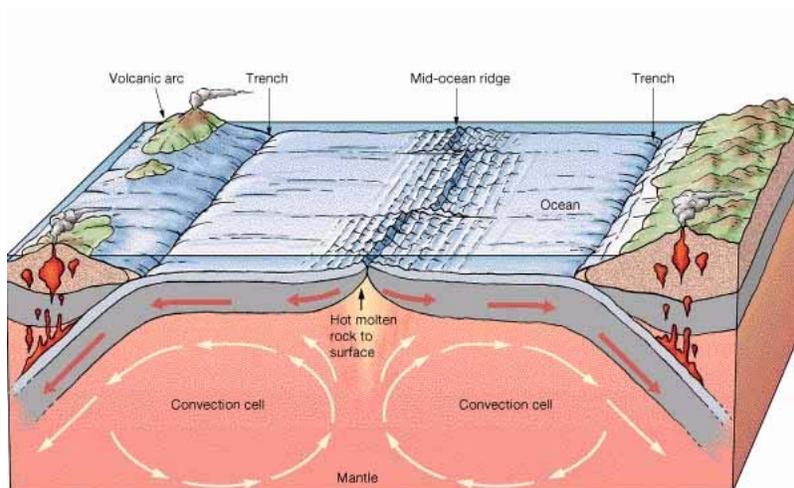
SUMMARIZING PLATE TECTONICS (4)

The major features of the sea floor can also be explained by plate tectonics.

- The mid-oceanic ridge with its rift valley forms at divergent boundaries.
- Oceanic trenches are found where oceanic plates are subducted at convergent boundaries.
- Fracture zones are created at transform boundaries.

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SUMMARY OF PLATE TECTONICS



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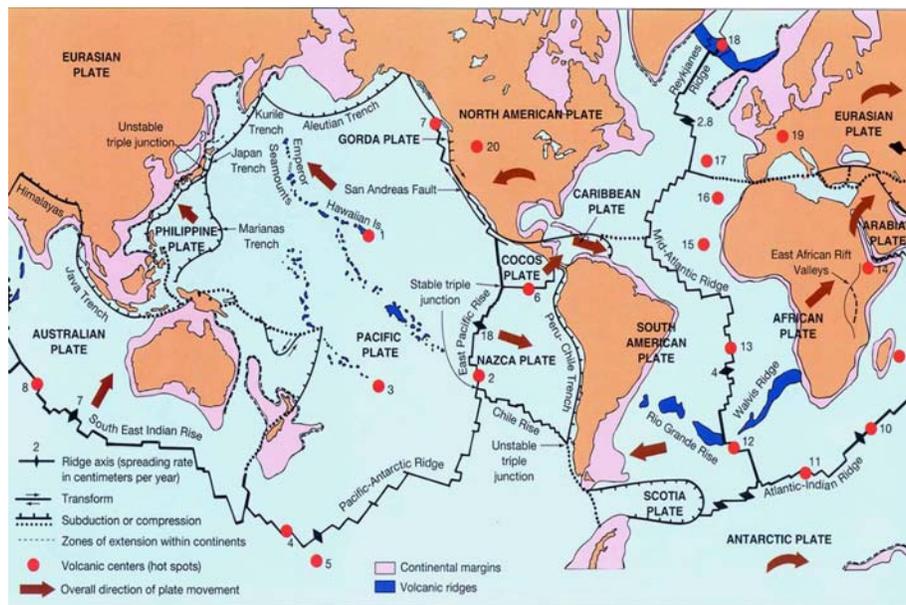
MANTLE PLUMES AND HOT SPOTS

A modification of the convection process was proposed by W. Jason Morgan of Princeton University. Morgan proposed that convection occurs in the form of mantle plumes, narrow columns of hot mantle rock that rise through the mantle, similar to smoke rising from a chimney (see Figures 12.30 and 12.31, page 333).

Mantle plumes are essentially stationary with respect to moving plates and each other. Plumes may form “hot spots” of active volcanism at Earth’s surface.

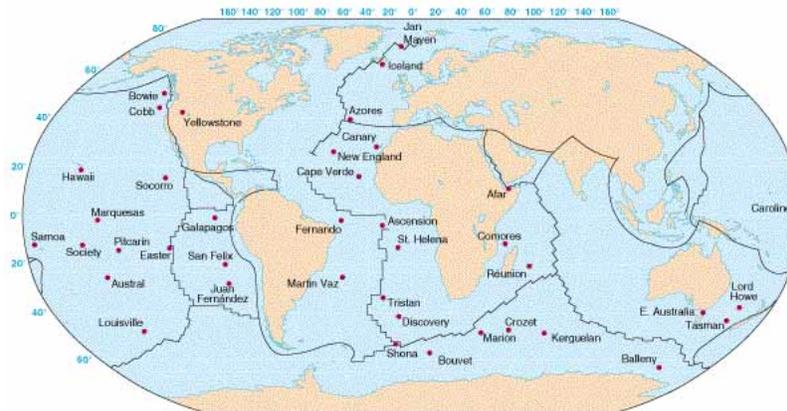
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HOT SPOTS



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WORLD HOT SPOTS



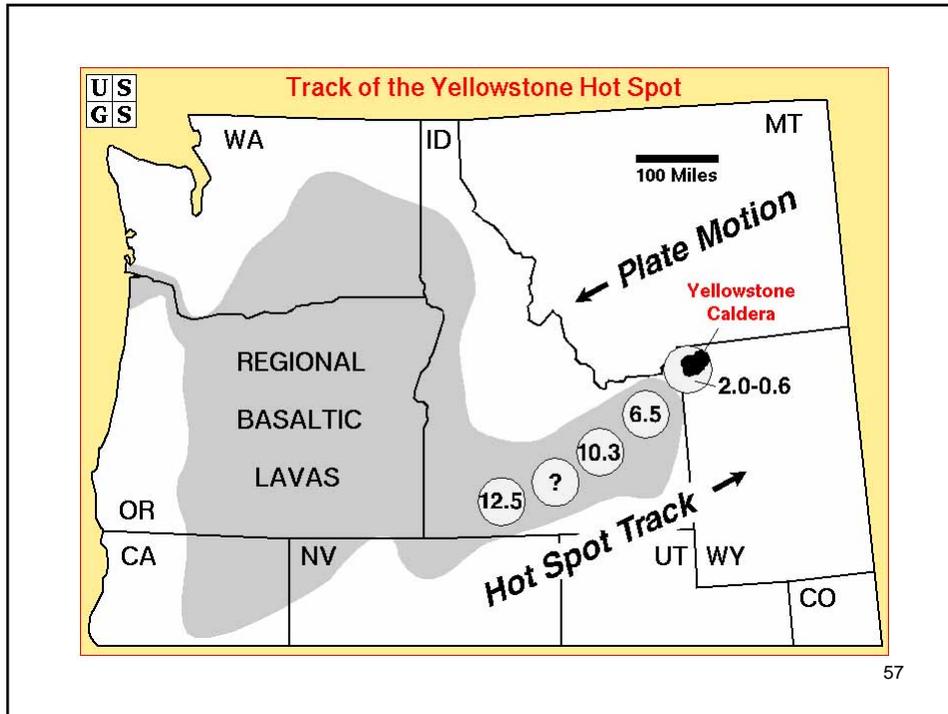
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MANTLE PLUMES AND HOT SPOTS (2)

A place where a mantle plume might now be rising beneath a continent is in Yellowstone National Park in northwestern Wyoming.

The area's volcanism, high elevation, high heat flow, and hot spring and geyser activity may all be due to this plume.

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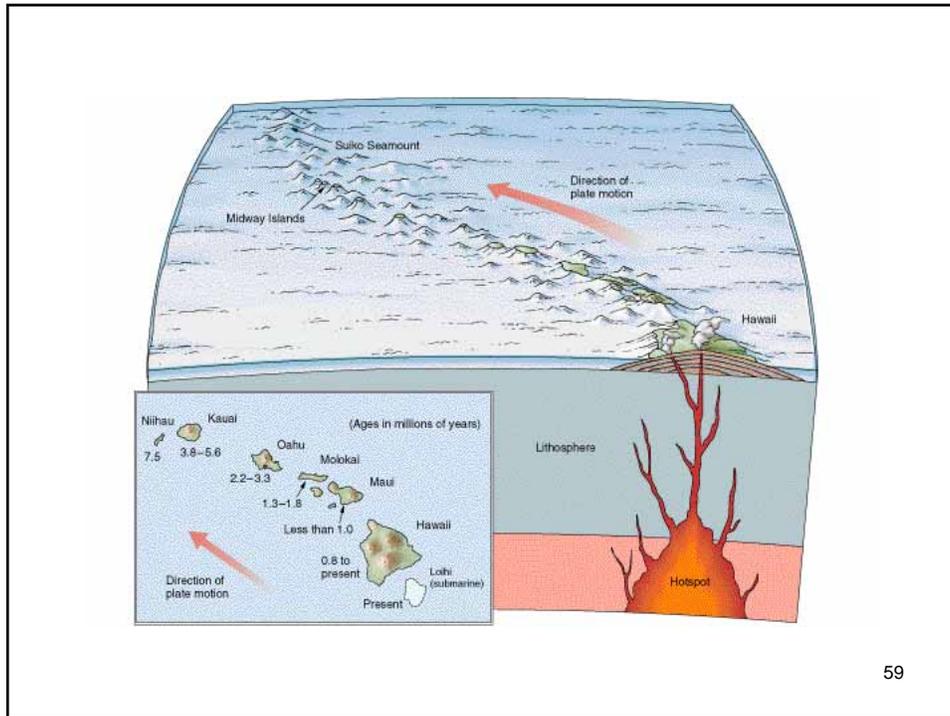


MANTLE PLUMES AND HOT SPOTS (3)

Some plumes rise beneath the centers of oceanic plates. A plume under Hawaii rises in the center of the Pacific Plate. As the plate moves over the plume, a line of volcanoes forms, creating an aseismic ridge.

Over time, the volcanoes are carried away from the eruptive center, sinking as they go as a result of cooling. The result is a line of extinct volcanoes (seamounts and guyots) that increase in age away from an active volcano directly above the plume.

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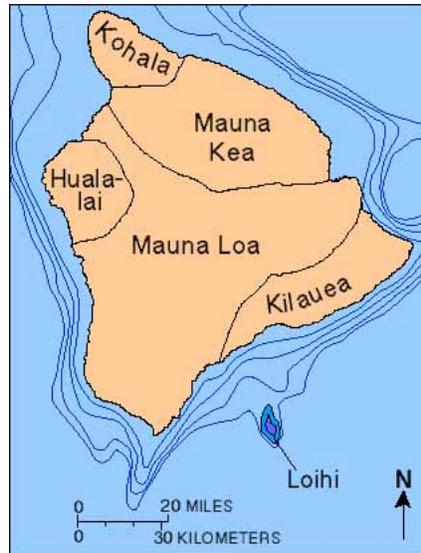
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MANTLE PLUMES AND HOT SPOTS (4)

In the Hawaiian islands, the only two active volcanoes are in the extreme southeastern corner. The isotopic ages of the Hawaiian basalts increase regularly to the northwest, and a long line of submerged volcanoes forms an aseismic ridge northwest of Kauai.

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LOIHI – NEWEST HAWAIIAN ISLAND



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THE RELATIONSHIP BETWEEN PLATE TECTONICS AND ORE DEPOSITS

Plate tectonic theory provides an overall model for the origin of metallic ore deposits that is used to explain the occurrence of known deposits and in exploration for new deposits.

Because many ore deposits are associated with igneous activity, there is a close relationship between plate boundaries and metallic ore deposits.

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