

Chapter 2: Plate Tectonics: A Unifying Theory

Chapter Outline

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 - 2.10 Hot Spots and Mantle Plumes
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 - 2.13 Plate Tectonics and the Distribution of Natural Resources
 - 2.14 Plate Tectonics and the Distribution of Life
- Key Concepts Review*

Learning Objectives

Upon completion of this material, the student should understand the following.

- Plate tectonics is the unifying theory of geology and has revolutionized geology.
- The hypothesis of continental drift was based on considerable geologic, paleontologic, and climatologic evidence.
- The hypothesis of seafloor spreading accounts for continental movement, and the idea that thermal convection cells provide a mechanism for plate movement.
- The three types of plate boundaries are divergent, convergent, and transform. Along these boundaries, new plates are formed, consumed, or slide past one another.
- Interaction along plate boundaries accounts for most of Earth's earthquake and volcanic activity.
- The rate of movement and motion of plates can be calculated in several ways.
- Some type of convective heat system is involved in plate movement.
- Plate movement affects the distribution of natural resources.
- Plate movement affects the distribution of the world's biota and has influenced evolution.

Chapter Summary

- The concept of continental movement is not new. The earliest maps showing the similarity between the east coast of South America and the west coast of Africa provided the first evidence that continents may once have been united and subsequently separated from each other.
- Alfred Wegener is generally credited with developing the hypothesis of continental drift. He provided abundant geologic and paleontologic evidence to show that the continents were once united into one supercontinent which he named Pangaea. Unfortunately, Wegener could not explain how the continents moved, and most geologists ignored his ideas.
- Various features of the continental margins and the seafloor are a reflection of plate movement. Continental margins are active or passive, depending on their relationship to plate boundaries. Oceanic trenches are long, steep-sided depressions on the seafloor near convergent plate boundaries where oceanic lithosphere is consumed by subduction. Submarine hydrothermal vents are found at or near spreading ridges and associated with divergent plate boundaries.
- The hypothesis of continental drift was revised during the 1950s when paleomagnetic studies of rocks indicated the presence of multiple magnetic north poles instead of just one as there is today. This paradox was resolved by moving so that the paleomagnetic data became consistent with a single magnetic north pole. When this was done, the rock sequences, glacial deposits and striations, and fossil distributions aligned with the reconstructed paleogeography.
- Seafloor spreading was confirmed by the discovery of magnetic anomalies in the oceanic crust that were both parallel to and symmetric around the ocean ridges, indicating that new oceanic crust must have formed as the seafloor was spreading. The pattern of oceanic magnetic anomalies matched the pattern of magnetic reversals already known from continental lava flows and showed that Earth's magnetic field has reversed itself numerous times during the past.
- Radiometric dating reveals that the oldest oceanic crust is less than 180 million years old, whereas the oldest continental crust is approximately 4 billion years old. Fossil evidence and the thickness of sediments overlying the oceanic crust further support and confirm that ocean basins are recent geologic features.
- Plate tectonic theory became widely accepted by the 1970s because the evidence overwhelmingly supports it and because it provides geologists with a powerful theory for explaining such phenomena as volcanism, earthquake activity, mountain building, global climatic changes, the distribution of the world's biota, and the distribution of mineral resources.
- Geologists recognize three types of plate boundaries: divergent boundaries, where plates move away from each other; convergent boundaries, where two plates collide; and transform boundaries, where two plates slide past each other.
- Ancient plate boundaries can be recognized by their associated rock assemblages and geologic structures. For divergent boundaries, these may include rift valleys with thick sedimentary sequences and numerous dikes and sills. For convergent boundaries, ophiolites and andesitic rocks are two characteristic features. Transform plate boundaries generally do not leave any characteristic or diagnostic features in the geologic record.
- The average rate of movement and relative motion of the plates can be calculated in several ways. The results of these different methods all agree and indicate that the plates move at different average velocities.

- The absolute motion of plates can be determined by the movement of plates over mantle plumes. A mantle plume is an apparently stationary column of magma that rises to the surface from deep within the mantle and forms either a subsurface mushroom-shaped plume head, or erupts at the surface as a volcano.
- Although a comprehensive theory of plate movement has yet to be developed, geologists think that some type of convective system is involved in plate movement. A close relationship exists between the formation of petroleum, as well as some mineral deposits, and plate boundaries. Furthermore, the formation and distribution of many natural resources are related to plate movements.
- The relationship between plate tectonic processes and the evolution of life is complex. The distribution of plants and animals is not random, but rather is controlled mostly by climate and geographic barriers, which, in turn, are influenced, to a great extent, by the movement of plates.

Enrichment Topics

Topic 1. Seeing Tectonic Plate Movement in Action. Global Positioning System (GPS) receivers are used to determine precise geodetic position measurements each day to chronicle plate movements. Horizontal movement vectors, which are the result of plate tectonic motions, are shown on the map, and motions for various locations can be graphed. <http://sideshow.jpl.nasa.gov/mbh/series.html>

Topic 2. Is Plate Tectonics Inevitable? Plate tectonics may be a necessary condition for life and so the existence of plate tectonics on other earth-like planets is important for determining whether life may exist on those planets. Using the article “Inevitability of Plate Tectonics on Super-Earths” in *The Astrophysical Journal* have the students discuss why plate tectonics may be necessary for life to exist on a planet and whether how likely these large planets are to have plate tectonics. How can astronomers test whether a large planet is tectonically active and is home to living things? <http://www.iop.org/EJ/abstract/1538-4357/670/1/L45/>

Common Misconceptions

Misconception 1: The crust moves on top of the mantle.

Fact: This is a simplified picture of plate tectonics. In reality, the lithosphere, which includes both the crust and the solid uppermost mantle, moves about on the underlying asthenosphere, the part of the mantle exhibiting plastic behavior.

Misconception 2: Earth is molten, except for its crust.

Fact: Only small pockets of magma are molten, the rest of Earth is solid. Some, like the asthenosphere, is solid but it can flow plastically.

Lecture Suggestions

1. Use animations to teach plate tectonics. Technology aids in the understanding of plate motions with these fantastic animations from the University of California, Santa Barbara. Global Tectonics topics include Mesozoic Subduction, Pangaea, Himalayan Collision, Seafloor Spreading, South Atlantic Spreading and Seafloor Spreading and Magnetic Reversals. Regional Plate Tectonics and Geologic Histories topics include Pacific Hemisphere Plate, 80 Ma to Present; N.E. Pacific and W. North American Plate History, 38 Ma to Present; and Plate Tectonic History of Southern California, 20 Ma to Present: http://emvc.geol.ucsb.edu/1_DownloadPage/Download_Page.html . More plate tectonics animations are found at the United States Geological Survey website: <http://www.nature.nps.gov/Geology/usgsnps/animate/pltecan.html> and at this University of California Berkeley site <http://www.ucmp.berkeley.edu/geology/anim1.html>

2. Relative rates of motion between tectonic plates are a difficult concept to grasp for many beginning geology students. The following is an illustration in which members of the class are designated as specific plates and plate margins that move with a set of tape measures. The setting is the western margin of North America 40 Ma, involving the Pacific, Farallon, and North American plates, a spreading ridge, and a subduction zone. Five students are designated as follows:

Student 1 = Pacific plate

Student 2 = West side of spreading ridge; reels out Pacific plate with tape measure

Student 3 = East side of spreading ridge; reels out Farallon plate with tape measure

Student 4 = Farallon plate

Student 5 = North American plate and subduction zone; reels in Farallon plate

Given: Rate of Pacific Plate with respect to North America plate = zero (therefore, students 1 and 5 are stationary in the illustration). Both students 2 and 3 reel out tape at a rate of 1 m/10 My (1m = 500km).

Set-up: Two roll-up tape measures are used with a piece of bright electrical tape attached at each 1 inch interval.

Student 1 stands on one side of the room.

Students 2, 3, and 4 start approximately 3 meters from student 1.

Student 5 stands across the room, approximately 8 meters from student 1.

Students 2 and 3 move together throughout the demonstration and reel out tape at the same rate.

Student 5 pulls in tape reeled out by student 3.

Student 4 travels along with the tape reeled out by student 3.

The following table is drawn on the blackboard:

RATES OF MOTION

Plate A relative to Plate B Rate in km/My

Pacific plate to North America plate; Given as zero

North America plate to ridge (50)

Pacific plate to ridge (50)

Farallon plate to ridge (50)

Pacific plate to Farallon plate (100)

Farallon plate to North America plate (100)

The illustration is set-up and run for each set of plates in the table. The difference in rates between each pair of students is easily ascertained.

3. Why was the concept of seafloor spreading necessary for continental drift to be accepted? How could scientists ignore the overwhelming evidence that the continents could move over the face of the earth?
4. Use this idea to explain mid ocean ridge spreading. Many students in introductory geology generally understand that new crust is created at the mid oceanic ridge (MOR) by separation of plates, but some of the subtleties can escape them. For example, the bilateral symmetry of the paleomagnetic reversal pattern, or the migration of the ridge axis can be confusing. A demonstration using students can help clear up the situation.
 - Depending on the class size, all or part of the class may be used. Classrooms that have a central aisle are ideal. The volunteers, about 20 to 30 students, gather in the central aisle. They are referred to as the magma in the chamber underlying the central ridge axis. They are told to shuffle slowly to the front of the class in pairs, and for each pair to separate, one going left and the other to the right upon reaching the front of the room. When they reach the front of the room, they are to hold their arms up if the instructor's arms are up, or leave them down if the instructor's arms are down.
 - In this way, the plates grow at the front of the room, as the students diverge from each other at the ridge axis and are subsequently replaced by other students emerging from the magma chamber.
 - Hands up are normal polarity rocks and hands down are reverse polarity rocks. The bilateral symmetry of the paleomagnetic pattern and progression of rock age from oldest (first to come out) to youngest (last to come out) should now be obvious to most students. Having the students take a small step toward the audience for each minute that they are part of the new crust will generate the subsidence that is expressed as ridge topography. By varying the rate at which the students walk and separate, various paleomagnetic reversal pattern widths and ridge topographies (East Pacific Rise vs. Mid Atlantic Ridge) can be generated.
5. Note that the direction of plate movement at any given point along a spreading ridge or subduction zone must be perpendicular to that spreading ridge or subduction zone.
6. Stress the differences between continental and oceanic crust and between the lithosphere and the asthenosphere. Note especially the rigid behavior, lower density, and brittle, highly fractured nature of the continental crust.
7. A pot of boiling soup and its surface crust is a useful analogy for describing the process of convection cell motion.

Consider This

1. Why is plate tectonics given the status of theory, while continental drift has attained only the status of hypothesis?
2. Since plate movements have been directly measured, is plate tectonics a theory or a fact? Why or why not?
3. Compare and contrast continental drift and the plate tectonic theory. What does plate tectonics have that continental drift does not?

4. What is the origin of the term “transform” in transform fault?
5. Why are transform faults associated with spreading ridges at approximately right angles to the ridge? Why don't transform faults intersect subduction zones as well?
6. Why can spreading ridges never be directly connected to subduction zones, but instead, require the linking of the two by a transform fault?

Important Terms

abyssal plain	magnetic field
active continental margin	magnetic reversals
continental-continental	magnetism
plate boundary	oceanic-continental plate boundary
continental drift	oceanic-oceanic plate boundary
continental margin	oceanic ridge
continental rise	oceanic trenches
continental shelf	paleomagnetism
continental slope	Pangaea
convergent plate boundary	passive continental margin
Curie point	plate tectonic theory
divergent plate boundary	seafloor spreading
<i>Glossopteris flora</i>	submarine hydrothermal vent
Gondwana	thermal convection cell
hot spot	transform fault
Laurasia	transform plate boundary
magnetic anomalies	

Internet Sites, Videos, Software, and Demonstration Aids

Internet Sites

1. Historical Perspective <http://pubs.usgs.gov/gip/dynamic/historical.html>
The United States Geological Survey provides an historical explanation of the development of plate tectonics theory.
2. The PLATES Project <http://www.ig.utexas.edu/research/projects/plates/index.htm>
The Institute for Geophysics at the University of Texas the PLATES project provides a resource for plate tectonics media, publications and teaching resources.
3. This Dynamic Earth <http://www.mnh.si.edu/earth/>
Four topics are covered in this website by the Smithsonian National Museum of Natural History including Plate Tectonics and Volcanoes.
4. Mantle plumes.org <http://www.mantleplumes.org/>
This blog discusses the origin of “hotspot” volcanism and is frequented by some of the top names in the field.

5. Northern California Earthquake Data Center (NCEDC) <http://quake.geo.berkeley.edu/>
The NCEDC provides updates on earthquakes in northern California, including recent epicenters.
6. GPS Time Series <http://sideshow.jpl.nasa.gov/mbh/series.html>
Global Positioning System (GPS) receivers are used to determine precise geodetic position measurements each day to chronicle plate movements.

Videos

1. Colliding Continents. National Geographic DVD (2010, 50 mins.)
Why do continents collide and what are the effects of those collisions?
2. Drain the Ocean: See What Lies Beneath Our Seas. National Geographic DVD (2010, 90 mins.)
What would we see if we could remove the water from the oceans? This uses CGI animation and is based on the latest scientific research.
3. How the Earth Was Made. DVD (2009, 450 mins.)
This 13-part series uses spectacular locations to study geological phenomena around the world.
4. Plate Tectonics. Insight Media DVD (2004, 15 mins.)
Look at the development of plate tectonics theory as an example of the process of scientific inquiry.
5. World in Motion: Plate Tectonics. Insight Media DVD (2003, 27 mins.)
What is the supporting evidence for plate tectonics?
6. Plate Tectonics. Insight Media DVD (2006, 25 mins.)
Look at the evolution of the scientific understanding of plate tectonics as an example of the process of scientific inquiry.
7. Making the Pieces Fit: Continental Drift Theory. Insight Media DVD (2003, 27 mins.)
Learn about the study of deep earthquakes and their impact on plate tectonics theory.
8. Earth Revealed. Annenberg Media <http://www.learner.org/resources/series78.html> (1992, 30 mins., free video):
 - #5: The Birth of a Theory. The development of continental drift, seafloor spreading, and plate tectonics theory.
 - #6: Plate Dynamics
The movement and interaction of tectonic plates and the geological phenomena they account for.
9. Planet Earth. Annenberg Media <http://www.learner.org/resources/series49.html>, (1986, 1 hour, free video)
 - #1: The Living Machine: The Theory of Plate Tectonics. Plate tectonics revealed at geological sites such as Kilauea volcano and the Atlantic seafloor.
 - #5: Gifts from the Earth. Earth's Natural Resources. Plate tectonics and how it has revolutionized the way geologists search for natural resources.

Answers to Figure-Related Critical Thinking Questions

» Critical Thinking Question Figure 2.3

Why is the best fit along the continental slope and not along the current coastline?

As the supercontinents (both Pangaea and Gondwana) broke apart, the rifting created downfaulting; normal-faulted grabens adjacent to the current continental blocks. These grabens underlie part of the continental shelf and create the edge for this continental slope – the “tear” line of the divergent break up. (See Chapter 10 for more.)

» Critical Thinking Question Figure 2.16

How does the age of the oceanic crust confirm the seafloor spreading theory?

The age of the continents – Billions of Years! The age of ocean crust – Hundreds of Millions! Today's ocean basins have their geologic origin back to the time of the beginning of the Pangaeian breakup. This theory dates back to the 1960s. Earthquakes, volcanoes, and mountain ranges tell us about the interaction of plate boundaries (so that's where those boundaries are). The event in human history that confirmed “sea floor spreading” occurred as the Glomar Challenger's drilling across the Atlantic continued to show the results – decrease in the age of the sediment and paleomagnetic reversals. The trend continued and was “mirrored” across the Mid-Atlantic Ridge. What a good time to be alive! Today, scientific evidence continues to pore in: GPS monitors continue to prove plate movement direction and speed.

» Critical Thinking Question Figure 2.23

If the movement along the San Andreas fault, which separates the Pacific plate from the North American plate, averages 5.5 cm per year, how long will it take before Los Angeles is opposite San Francisco?

As Lucy Jones of the Cal Berkeley Seismology Lab stated after the Northridge quake, “In about 10 million years, LA will be a suburb of San Francisco.”

» Critical Thinking Question Figure 2.30

Why is the mammalian fauna of Australia so different from elsewhere?

Unique among the continents with diverse continental ecosystems, it is isolated in the middle of its tectonic plate with no “land bridge” potentials, and has been this way since before placental mammals evolved.

Suggested Answer to Selected Short Answer Question

(Answers to question 6 and question 8 provided in the appendix to the text)

- 10. Creative Thinking Visual Question:** Using the ages (the numbers represent ages in millions of years) for each of the Hawaiian Islands, as well as the scale given in the figure below, calculate the average rate of movement per year for the Pacific plate since each island formed (Figure 1). Is the average rate of movement the same for each island?

Would you expect it to be? Explain why it may not be and why there are different ages for some of the islands.

Suggested Answer: Each of the Hawaiian Islands is generally older than the next when one moves up the island chain from southeast (the Big Island) to northwest (Kure). Because the Big Island is the only island with active volcanos, it is considered to be the hot spot from which the other islands were formed. If one uses the ages of each of the Hawaiian Islands, and divides by the distance from the Big Island of Hawaii, one can approximate the speed of movement of each island from the Big Island over time.

Student may follow these steps to answer this question:

- Using the scale on the map, find the distance from the middle of Hawaii to spots on each island matching the age listed on the map.
- Fill the information in a Data Worksheet similar to that listed below.
- Next, calculate the rate at which the Pacific Plate moved since the formation of Molokai by dividing the distance by the ages indicated. Fill the value in on their own data table.
- Determine the rate of movement since the formation of each island.
- After finding the rates of movement above, average the numbers to find the average rate of the Pacific Plate.

Sample Data Table

	Age of Islands (millions of years)	Distance from Big Island (kilometers)	Rate of Movement (km/million years)
Nihau	4.9	450	0.0109
	5.1		
Oahu	3.7	475	0.0078
	2.6		
	1.9		
Molokai	1.8	225	0.0080
	1.3		
	1.3		
	1		
Maui	0.8	150	0.0053
	0.43		
	0.38		
	0.15		
	0.01		
	0.004		
Average			0.0080

Additional Resources for this question:

- http://www.soest.hawaii.edu/GG/ASK/hawaii_volcano_age.html
- http://esa21.kennesaw.edu/activities/platespeed/plate_speed.pdf
- http://www.st.nmfs.noaa.gov/Assets/Nemo/documents/lessons/Lesson_13/Lesson_13-Teacher%27s_Guide.pdf
- <http://pubs.usgs.gov/gip/dynamic/Hawaiian.html>