Chapter 2

The Way The Earth Works: Plate Tectonics

Learning Objectives

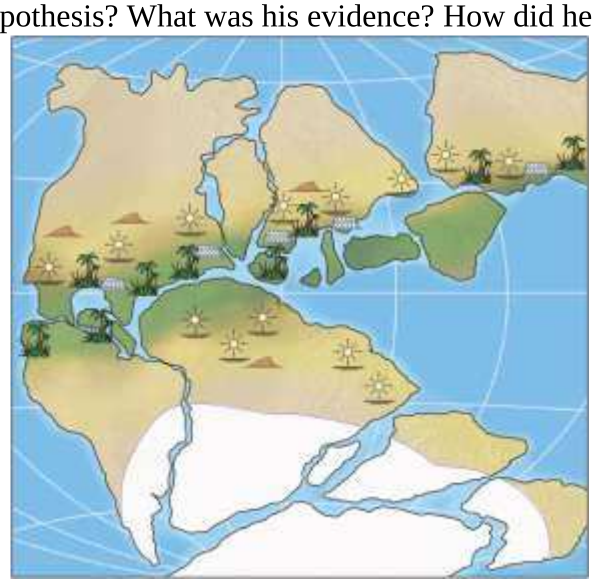
By the end of the chapter students should be able to . . .

A. discuss the evidence that Alfred Wegener used to justify his proposal that continents drift.
B. describe the process of seafloor spreading and the observations that allowed geologists to confirm it takes place.
C. contrast the lithosphere with the aesthenosphere, identify major plates of the lithosphere, and explain how the boundaries between plates can be recognized.
D. sketch the three types of plate boundaries, and describe the nature of motion that occurs across them.
E. relate types of geologic activity to types of plate boundaries, and explain how new plate boundaries can form and existing ones can cease activity.
F. outline the major ideas now included in the modern theory of plate tectonics, and reinterpret Wegener's observations in the context of this theory.
G. describe how measurements of paleomagnetism have helped to prove that plate tectonics happens.
H. explain the methods scientists use to describe and measure the velocity of plate motion.

End of chapter question answers

Review Questions

1. What was Wegener's continental-drift hypothesis? What was his evidence? How did he construct this map?



Answer: Alfred Wegener's continental-drift hypothesis suggested that the location of the continents had not remained fixed during the geologic past as had long been believed; instead he suggested that the continents had once fit together like pieces of a giant puzzle into one vast supercontinent. Over time the continents broke apart and moved into their present position. Wegener's evidence for his continental-drift hypothesis included the fit of the continents, distribution of climate belts in the past, distribution of fossils, and matching geologic units and mountain belts on different continents. His contemporaries argued that drift was impossible because no forces are strong enough to move the continents.

2. Describe discoveries made from the 1930s to the 1960s about the bathymetry of the seafloor.
Answer: Thanks to the invention of sonar, scientists were able to create a bathymetric map of the seafloor that revealed features of the ocean floor, including continental margins, ocean basins, abyssal plains, mid-ocean ridges, fracture zones, deep-sea trenches, and seamounts.

3. Do earthquakes occur randomly, or are they associated with bathymetric and topographic features? Does heat flow vary randomly, or are variations associated with bathymetric features? Explain your answers.
Answer: Earthquakes do not occur randomly; they occur in clusters along seismic belts. Seismic belts on the ocean floor correspond with trenches, mid-ocean ridge axes, fracture zones, and other faults. Heat flow does not vary randomly; heat flow beneath mid-ocean ridges is greater than that beneath abyssal plains. Bathymetric and topographic features on the ocean floor correspond with seismic zones and regions of increased heat flow; the seafloor is neither uniform nor random in nature.

4. What is the hypothesis of seafloor spreading as defined by Harry Hess? How did Hess explain how seafloor spreading could take place without an increase in Earth’s circumference?
Answer: In his seafloor spreading hypothesis, Harry Hess suggested that the seafloor stretches apart along the axis of a mid-ocean ridge, and new oceanic crust forms from magma that rises and fills the void. Once formed, new seafloor moved away from the ridge, allowing oceans to grow larger with time. Because the circumference of the Earth remains constant, as new oceanic crust is created, older oceanic crust must be destroyed in a different location. Hess proposed that old seafloor is consumed by sinking back into the mantle at deep-sea trenches and that this movement generated the seismic belts observed along trenches.

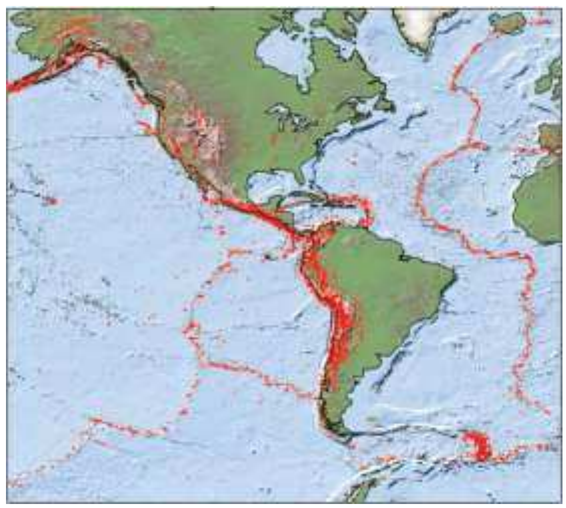
5. How did drilling into the seafloor help prove seafloor spreading?
Answer: Drilling of the seafloor helped prove seafloor spreading because it revealed that the thickness of seafloor sediments is not as great as expected, given the age of the Earth, and that the thickness of these sediments increases with distance from mid-ocean ridges. The former suggested that the seafloor is younger than the Earth, and the latter suggested that the mid-ocean ridges are younger than the abyssal plains. Thus, new seafloor must constantly be forming at the mid-ocean ridges.

6. What are the characteristics of a lithosphere plate? Is it composed of crust alone? What characteristic defines the boundary between lithosphere and asthenosphere?
Answer: The lithosphere is the rigid, outer shell of the Earth, which includes the crust and the uppermost portion of the mantle, known as the lithospheric mantle. The portion of the mantle that lies beneath the lithosphere is called the asthenosphere. The asthenosphere exhibits plastic behavior—that is, it can flow. The difference between the lithosphere and asthenosphere is behavioral, not compositional, and is the result of their different temperatures. At the base of the lithosphere, mantle rock reaches the temperature at which it can flow, 1,280°C (2,340°F).

7. How do active and passive continental margins differ?
Answer: Active continental margins coincide with plate boundaries; passive margins do not.

8. How does oceanic lithosphere differ from continental lithosphere, and how does this explain the existence of ocean basins?
Answer: Old oceanic lithosphere generally has a thickness of about 100 km, with the crustal part constituting only 7 to 10 km of the total. Continental lithosphere has a thickness of about 150 km, and the crustal part ranges from 25 to 70 km thick. The crustal part of continental lithosphere is less dense than that of oceanic lithosphere. Ocean basins exist because oceanic lithosphere is thinner and denser than continental lithosphere, so the surface of the continental lithosphere "floats" higher than the surface of oceanic lithosphere as they both rest on the underlying asthenosphere.

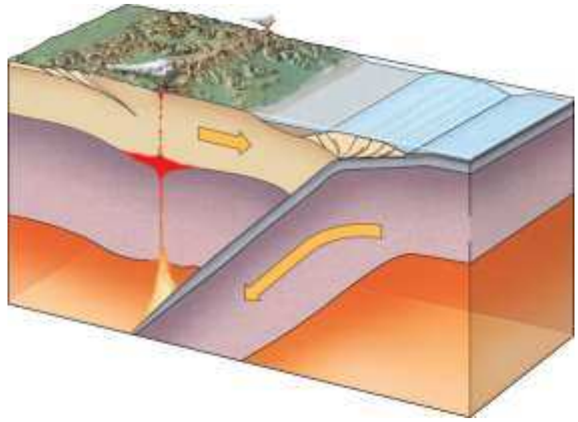
9. How do we identify a plate boundary? What plates appear on this map? Describe the three types of plate boundaries. For each, be sure to indicate the nature of relative plate motion, and name a bathymetric or topographic feature associated with that type of plate boundary.



Answer: Plate boundaries are identified by the presence of active faults. The three types of plate boundaries are divergent, convergent, and transform. Divergent boundaries, also known as spreading boundaries, occur where two plates move away from each other; this results in the formation of mid-ocean ridges and the creation of new oceanic lithosphere. Convergent boundaries are those where two plates move toward each other, allowing one plate to sink beneath the other; a subduction zone and associated volcanic arc and deep-sea trench result. Transform boundaries occur where one plate slides horizontally along the edge of another plate; this results in vertical transform faults.

10. How does oceanic crust form along a mid-ocean ridge? How does oceanic lithospheric mantle form?
Answer: As spreading takes place along a mid-ocean ridge, hot asthenosphere rises beneath the ridge. As it rises, it begins to melt, resulting in the formation of a magma chamber beneath the ridge axis. Some of this molten material erupts onto the surface and cools when in comes into contact with cold seawater. As new material makes its way to the surface, older material is forced away from the ridge axis, forming oceanic crust. At the ridge axis, lithospheric plates consist only of new crust. As this crust and the mantle directly beneath it move away from the ridge axis, further cooling takes place at greater and greater depths. Loss of heat from the mantle causes the boundary between cooler, rigid mantle and warmer, plastic mantle to become deeper. Because this boundary defines the base of the lithosphere, the oceanic lithosphere thickens as it ages.

11. Identify the major geologic features of a convergent boundary on this drawing.
Answer: Convergent boundaries, also known as subduction zones, are created as two plates come together, causing one plate to descend into the asthenosphere beneath the other. The resulting characteristic geologic features include a trench, an accretionary prism, and a volcanic arc.



12. Is new plate material formed or consumed at a transform boundary? Are all transform boundaries submarine?
Answer: At transform boundaries, plate material is neither formed nor consumed. All transform boundaries are not submarine. For example, large segments of the San Andreas fault of California are on land.

13. Describe the process of continental collision and give examples of where this process has occurred.
Answer: Continental collision occurs when two relatively buoyant pieces of crust converge at a plate boundary. Typically this takes place after the complete subduction of seafloor allows for the merging of two continental landmasses. Neither of these buoyant pieces of crust is able to subduct, so the continued convergence of the continents causes continuous mountain-building and the collisional boundary between the two landmasses to disappear. This occurred when India collided with Asia, and the Himalayas and Tibetan Plateau are the result. The Appalachian Mountains and the Alps are also consequences of continental collisions in the geologic past.

14. Describe the characteristics of a rift and give examples of where rifting takes place today.
Answer: The process of stretching and breaking a continent apart is called rifting. Near the surface of the continent, rifting leads to the formation of many faults. The faults bound blocks of crust that tilt and slip downward such that rift basins develop. The basins fill with sediments. Deeper down, where rock is warmer and softer, stretching takes place and the continental lithosphere thins. Some of the asthenosphere melts, producing magma that erupts as lava from volcanoes in the rift. Rifting is taking place today in several locations, including along the East African Rift.

15. What is a marine magnetic anomaly? How is it detected?
Answer: The term magnetic anomaly refers to the difference between the expected strength of Earth’s main dipole field at a location and the actual observed strength of the magnetic field at that location. Marine magnetic anomalies define a distinct pattern of alternating bands aligned parallel to mid-ocean ridge axes. During times in Earth’s history when polarity was normal, the basalt of the ocean floor indicates a positive anomaly. During times of reversed polarity, a negative anomaly occurs. These marine magnetic anomalies were discovered when magnetometers were towed back and forth across the ocean.

16. How is a hot-spot track produced, and how can hot-spot tracks be used to determine the past absolute motion of a plate?
Answer: A hot-spot track develops as a plate moves over a mantle plume; older, inactive volcanic islands are moved away from a hot spot, forming a chain of inactive islands and seamounts. The hot spot remains as a fixed spot in the mantle, and the lithospheric plate moves over the hot spot. As this motion takes place, volcanoes form, become extinct, and erode or subside. The remnants of these hot-spot volcanoes record past positions of the plate relative to the hot spot.

17. What is paleomagnetism? How did the discovery of apparent polar-wander paths serve as a proof that continents move?
Answer: The record of Earth's past magnetism recorded in rocks is called paleomagnetism. The apparent polar-wander path is the paleomagnetic record of the changing position of Earth's magnetic poles. If we assume that the continents have remained fixed throughout geologic time, the apparent polar-wander paths from different continents should all be the same. This was found to not be the case; each continent has a different, unique polar wander path. Thus, the continents must move relative to each other.

18. How did the observed pattern of marine magnetic anomalies form, and how did its existence help prove plate tectonics?
Answer: The observed pattern of marine magnetic anomalies formed as seafloor spreading took place. As ocean basins grew along mid-ocean ridge axes, bands of seafloor with different polarities formed and then moved away from the ridge axis, forming mirror-image patterns on either side of the ridge. The pattern of stripes and the direct relationship between the widths of the stripes and the durations of chrons serve as proof of plate tectonics.

19. Discuss the major forces that move lithosphere plates.
Answer: Convective flow, the process of circulation and heat transfer in a material that heats from below, takes place in the mantle and can influence long-term plate movements. Ridge-push force develops because the lithosphere beneath mid-ocean ridges sits higher than the lithosphere beneath adjacent abyssal plains. The elevated lithosphere spreads sideways due to gravity, and this motion drives plates in a direction pointing away from the ridge axis. Slab-pull force develops because the oceanic lithospheric mantle is cooler and denser than the warmer asthenosphere, so once a plate starts to subduct, it sinks. The subducted section slowly pulls the rest of the plate behind it.

20. Explain the difference between relative plate velocity and absolute plate velocity. Can we measure plate velocity directly?
Answer: Relative plate velocity describes the movement of one plate relative to another plate. Absolute plate velocity describes the movement of both plates relative to a fixed reference point that is not on one of the plates. Plate velocity can be measured directly using GPS, the global positioning system.

On Further Thought

21. Explain the bend in the Hawaiian-Emperor seamount chain in terms of the absolute motion of

the Pacific Plate.
Answer: Older volcanoes in the Hawaiian part of the chain run to the northwest, whereas those in the Emperor seamount portion trend more north-northwest. Because the hotspot remains stationary, we know that the absolute movement of the Pacific Plate was north-northwest as the Emperor seamount chain was forming. The movement of the plate then shifted more to the northwest during the formation of the Hawaiian Islands.

22. How does the existence of the Appalachian Mountains indicate that there was an ocean separating North America from Africa and Europe prior to the formation of Pangaea?
Answer: The Appalachian Mountains initially grew as a consequence of continental collision. For this to have taken place, an ocean basin separating North America from Africa and Europe must have been consumed by subduction as a result of convergent plate motion. Following the complete subduction of this ocean basin, North America collided with Europe and Africa, forming the Appalachian Mountains.

Narrative Art Video

BREAKUP OF PANGAEA
Length: 3 minutes, 44 seconds
Learning Objectives:
- 2C: Contrast the lithosphere with the asthenosphere, identify major plates of the lithosphere, and explain how the boundaries between plates can be recognized.
- 2F: Outline the major ideas now included in the modern theory of plate tectonics, and reinterpret Wegener's observations in the context of this theory.

Summary: This video uses paleogeographic maps to show how Pangaea formed and broke apart to produce the world we are familiar with today. Details include the rate of seafloor spreading and its variability along the mid-Atlantic ridge. The video also shows satellite imagery of folded rock in the Appalachian region that formed during the collisions that built Pangaea.
Classroom Use: This video can help the student visualize changes in the distribution of continents over time. It also gives the student an appreciation of the geological complexity of the Central American and Caribbean region. It can be viewed in shorter segments (e.g., breakup of Pangaea alone) or in its entirety.
Review and Discussion Questions:
1. Is Pangaea the only known supercontinent in Earth history?
2. Dinosaur fossils have been found on all major continents. Given that nearly all dinosaur species do not appear to be strong swimmers, how can you explain this finding?

Animations

PLATE BOUNDARIES
Learning Objectives:

- 2D: sketch the three types of plate boundaries, and describe the nature of motion that occurs across them.
- 2F: Outline the major ideas now included in the modern theory of plate tectonics, and reinterpret Wegener's observations in the context of this theory.

Summary: Relative plate motion for all major subcategories of divergent, convergent, and transform-plate boundaries are animated. The major geologic features of each boundary are described, and their origins are explained.
Classroom Use: This animation would be very helpful to students as they try to understand plate tectonics as a dynamic system. This animation can be used as a whole or as individual, self-contained components.
Review and Discussion Questions:

1. Where in the ocean basins would the oceanic lithosphere be thinnest?
2. What are the major differences between transform faults and fracture zones?

Real World Videos

SUBDUCTION TRENCH GENERATING TSUNAMI WAVES
Learning Objectives covered:

- 2F: Outline the major ideas now included in the modern theory of plate tectonics, and reinterpret Wegener's observations in the context of this theory.

Length: 0:37
Summary: This is ashort animation showing tsunami wave generation at a subduction trench.
Classroom uses: This animation allows students to visualize the mobile nature of Earth's crust.
Discussion questions:

1. How are subduction zones different from mid-ocean ridges?
2. What determines which plate will subduct below the other plate?

THE HOLOGLOBE PROJECT
Learning Objectives covered:

- 2F: Outline the major ideas now included in the modern theory of plate tectonics, and reinterpret Wegener's observations in the context of this theory.

Length: 1:09
Summary: This video describes the Earth's plate boundaries and their relationship to earthquakes and volcanoes.
Classroom uses: Use this video to help students visualize the Earth's plates and how they cause the movement of continents.
Discussion questions:

1. How many major plates make up the Earth's crust?
2. Why are volcanoes and earthquakes located near plate boundaries?
3. If new crust is formed at mid-ocean ridges, why does the size of the Earth not increase?

PLATE MOTIONS FROM 600 MILLION YEARS AGO TO TODAY
Learning Objectives covered:

- 2F: Outline the major ideas now included in the modern theory of plate tectonics, and reinterpret Wegener's observations in the context of this theory.

Length: 0:20
Summary: This video shows the Earth's plate motions from 600 million years ago to today.
Classroom uses: This video allows students to visualize the movement of continents from Pangaea to today.
Discussion questions:

1. How were the continents arranged on the planet 600 million years ago?
2. Are continents still moving today?

DEEP OCEAN VOLCANOES NEAR TONGA TRENCH
Credit: NOAA Ocean Today
Learning Objectives Covered:

- 2E: Relate types of geologic activity to types of plate boundaries, and explain how new plate boundaries can form and existing ones can cease activity.

Length: 1:50
Summary: This video describes the deepest ocean eruption ever found, the West Mata volcano. This volcano was discovered in an area between Samoa, Fiji, and Tonga nearly 4,000 feet below the surface of the Pacific Ocean.
Classroom Use: This video allow students to visualize volcanic activity in a deep ocean trench associated with a subduction zone.
Discussion Questions:

1. What type of plate movement occurs at deep ocean trenches?
2. What causes volcanoes to form at subduction zones?

<u>Activities</u>

ALFRED WEGENER
Learning Objectives Covered:

- 2A: Discuss the evidence that Alfred Wegener used to justify his proposal that continents drift.

Activity Type: Think-Pair-Share
Time in Class Estimate: 5 minutes
Recommended Group Size: 2–4 students
Classroom Procedures: Pose the question, “Consider the observations, or evidence submitted, by Alfred Wegener suggesting that the continents have not always been in their current positions. Based on knowledge at the time, how else could these observations have been explained?” Have students engage in a think-pair-share discussion for about 5 minutes with 1–2 of their immediate neighbors.
Answer Key: Much of the evidence that Wegener submitted for continental drift involved matching features on continents that are now widely separated, such as matching fossils, mountain ranges, and climate belts. Wegener proposed that these features formed as a single unit when the continents were once assembled into a single continent and then were broken apart when the continents drifted away from each other. These features could all have been instead explained as coincidence, that they just happened to occur on different continents at the same time. The way the continents fit together like a jigsaw puzzle is good, but not perfect, so the imperfect fit could be dismissed as coincidence as well.

Reflection question: Why do you think Wegener's hypothesis was initially rejected?

VELOCITY OF TECTONIC PLATES

Learning Objectives Covered:

- 2C: Contrast the lithosphere with the asthenosphere, identify major plates of the lithosphere, and explain how the boundaries between plates can be recognized.

Activity Type: Think-Pair-Share

Time in Class Estimate: 5 minutes

Recommended Group Size: 2–4 students

Classroom Procedures: Pose the question "We have learned that tectonic plates move at varying rates both absolutely and relative to each other. How might the relative velocity between two plates impact the geologic activity taking place at their boundary?" Have students engage in a think-pair-share discussion for about 5 minutes with 1–2 of their immediate neighbors.

Answer Key: In general, the faster that two plates move relative to each other, the more severe the geologic activity that takes place at their boundary. For example, the most powerful earthquakes occur when a lot of motion happens in a short period of time at a plate boundary—that is, when two plates are moving very quickly relative to each other. On average, normal movement along a plate boundary is only a few centimeters per year, much too slow for us to feel.

Reflection question: Can slow plate movements still cause major geologic activity?

OREO TECTONICS

Learning Objectives Covered:

- 2D: Sketch the three types of plate boundaries, and describe the nature of motion that occurs across them.
- 2E: Relate types of geologic activity to types of plate boundaries, and explain how new plate boundaries can form and existing ones can cease activity.

Activity Type: Hands-on demonstration

Time in Class Estimate: 10–15 minutes

Recommended Group Size: whole class

Materials: 1 unbroken Oreo (or Oreo-like) cookie for each student and the instructor

Classroom Procedures: Use the Oreo cookie to simulate each type of plate boundary, and to discuss the difference between the lithosphere (cookie portion) and asthenosphere (frosting).

- Divergent Boundary: Have students separate one of the cookies from the frosting, and break this cookie in half. Students then replace the cookie on the frosting, placing the two halves back together. To simulate a divergent boundary, gently press down and pull apart on the two halves. A small amount of frosting should well up in between the two halves, simulating a mid ocean ridge.
- Convergent Boundary: Students replace both halves on top of the frosting. They gently begin to force one half into the frosting at an angle beneath the other half. This represents subduction.
- Transform Boundary: Students once again place the two halves of the cookie next to each other on top of the frosting. The two halves are then slid laterally past each other. This results in some powdering of the cookie where the two halves meet. A transform boundary is simulated.

Reflection question(s):

1. What type of force is associated with each type of plate boundary?
2. What geologic and geographic features would likely be associated with each boundary type? Which of these features can be simulated using the Oreo?

Tarbuck Correlation Guide

Marshak&Rauber	**Tarbuck, Lutgens&Tasa, 14e**
2.1 Introduction	7.1 From Continental Drift to Plate Tectonics
2.2 Continental Drift	7.2 Continental Drift: An Idea Before Its Time
2.3 The Discovery of the Seafloor Spreading	7.5 Divergent Plate Boundaries and Seafloor Spreading
2.4 Modern Plate Tectonics Theory	7.4 The Theory of Plate Tectonics
2.5 Geologic Features of Plate Boundaries	7.5 Divergent Plate Boundaries and Seafloor Spreading 7.6 Convergent Plate Boundaries and Subduction 7.7 Transform Plate Boundaries
2.6 The Birth and Death of Plate Boundaries	7.8 How Do Plates and Plate Boundaries Change?
2.7 Special Locations in the Plate Mosaic	7.9 Testing the Plate Tectonics Model
2.8 Paleomagnetism: A Proof of Plate Tectonics	7.9 Testing the Plate Tectonics Model
2.9 The Velocity of Plate Motions	7.10 How is Plate Motion Measured