CHAPTER 2
The Way the Earth Works: Examining Plate Tectonics

GOALS

Introduce the basic principles of the plate tectonic theory.

Show students how plate tectonic principles were deduced over hundreds of years, starting with European exploration of Africa and the New World and advancing rapidly in the late twentieth century as new technologies were developed.

Guide students through the geologic reasoning used to integrate apparently unconnected types of information into the plate tectonic theory.

Through carefully scaffolded exercises, replicate discoveries that reveal the direction and rate of processes at plate boundaries.

BACKGROUND

Coverage of plate tectonics should come early in an introductory geology course to serve as context for the mineralogy, petrology, structure, internal processes, and Earth history that follow. Most students have learned about plate tectonics in high school or middle school and know some of the language and basic concepts. Unfortunately, few understand the diverse lines of evidence and complex reasoning that have led geologists to view plate tectonics as the best explanation for the way Earth works. Students now take the next step in their training in geologic reasoning that began in Chapter 1: text and exercises help them reproduce the foundational observations and logic of plate tectonics—not just memorize the words again.

CHAPTER 2 IN THE CLASSROOM

Some instructors prefer a detailed treatment early, others a brief discussion in the first or second lecture followed later in the semester by a more thorough treatment. This chapter can be used with either approach. It provides a brief summary of plates, plate boundaries, and the processes by which oceans form and disappear, continents split and merge, and mountains are built. Early exercises require relatively simple reasoning skills appropriate for a first or second laboratory session, but later ones require more sophisticated thinking and more extensive background.

Exercises follow the historic development of plate tectonics, giving students insight into how science builds on basic observations and how development of new technology leads to previously unimaginable advances. We begin with the simple geographic observations that led sixteenth- and seventeenth-century cartographers to consider a former fit of South America and Africa (Exercise 2.2). A brief discussion of paleoclimate indicators that led Wegener to propose continental drift is followed by another observation-based analysis, this time involving the locations of recent earthquakes and volcanic activity (Exercise 2.3). Modern paleomagnetic and GPS data show how the plate tectonic model is constantly being tested and refined.

Having presented the evidence for plate tectonics and guided students through the reasoning that led to acceptance of the theory, the rest of Chapter 2 focuses on details of processes at divergent, convergent, and transform plate boundaries. Exercises provide "hands-on" experience with interpreting seafloor spreading and measuring how fast it operates; interpreting current continental rifting; using the structure of arc-trench complexes to interpret steepness of subduction zones; estimating the extent and rate of continental transform displacement; and plotting plate motion using hot-spot seamount tracks.

SUGGESTIONS

As in all chapters, it will not be possible to complete all the exercises in a standard 3-hour laboratory session. Choose the sequence of topics and exercises best suited for *your* course. Remember, some activities are appropriate for all classes, others are perhaps best used with honors students or science majors, and others are most effectively used for homework. For example, several adopters report that they assign Exercise 2.2—the fit of South America and Africa—as a pre-lab activity to save time in the classroom and give an active, hands-on approach to what is usually presented as a passive lesson in the history of science.

At Queens College, we do the first few exercises early in the course and revisit paleomagnetism, subduction zone geometry, hot spots, and continental transform faults later in the semester. Our students have then learned about basalts, flux and decompression melting, and the relationship of deformation and regional metamorphism and can think more intelligently about the exercises.

It is useful to compare results from different exercises or from exercises and text that deal with the same process. For example, do results about motion of the Pacific Plate based on seafloor spreading (Exercise 2.6) agree with those based on hot-spot tracks (Exercises 2.11 and 2.12) and with GPS measurements of current plate motion (Figure 2.10)? Several years ago, one of our labs decided that discrepancies between the first two approaches meant that they had done something wrong. They hadn't—that's how science works—but the discussion was one of the better learning experiences that semester. Three weeks later, a *Science* article postulated that mantle plumes moved.

As with some of the arithmetic-based exercises in Chapter 1, it is often helpful to work through exercises—or the first part of the more complex exercises—as a group or to assign different parts of an exercise to different students and have the two groups discuss their findings.

Many students have a major misconception about how scientists work and think that science is boring because we already have all the answers and there's nothing for them to discover. One of the reasons for this in geology is that plate tectonics, like its sister theory of evolution, is presented as fact to be memorized, not the outcome of many years of false starts and misinterpretations. One way to reverse this misconception is to discuss previous theories—now supplanted by plate tectonics—about mountain building and the evolution of continents and oceans. We use a brief summary of early theories of an expanding, shrinking, or pulsating Earth and show how observations disproved these ideas. And then talk about why plate tectonics does a better job of explaining so many different phenomena.

Concentration of most earthquakes in linear belts that correspond to what are now recognized to be plate boundaries was an important piece of evidence for the plate tectonic model. Have students log on to http://earthquake.usgs.gov/earthquakes/map/, the USGS site that lists recent earthquakes worldwide, to update and supplement Figure 2.5. The map at this site initially shows earthquakes in the United States: zoom out to explore worldwide seismic activity or focus on specific locations. Magnitude is shown by the size of the circle used to locate each epicenter. *This can lead to class discussion of tectonic activity at different plate boundaries—tempered by the realization that this site lists activity for a very short period of* <u>*human*</u> *time and a miniscule, perhaps nonrepresentative slice of geologic time.*

ANSWERS TO EXERCISES

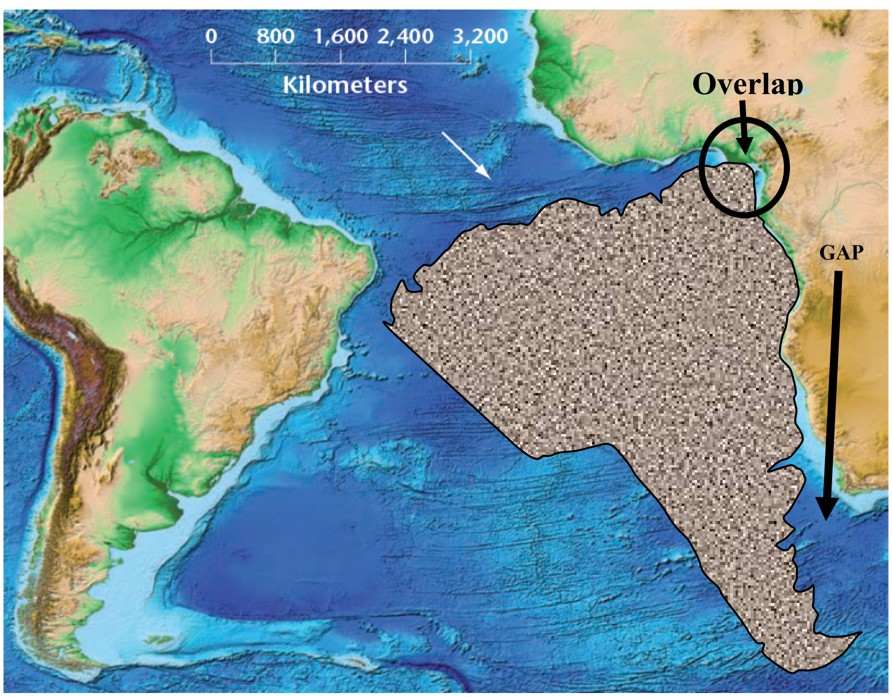
EXERCISE 2.1: Recognizing Plates and Plate Boundaries

(a) The United States is part of the **North American** Plate.
(b) The North American Plate contains **both continental and oceanic lithosphere**.
(c) The Atlantic Ocean lithosphere forms **at the Mid-Atlantic Ridge** by eruption of MORB (mid-ocean ridge basalt).
(d) The west coast of South America is adjacent to a **convergent plate boundary** (subduction zone).
(e) The west coast of Africa is **not a plate boundary**. Like the east coast of North America, the nearest plate boundary is the Mid-Atlantic Ridge.

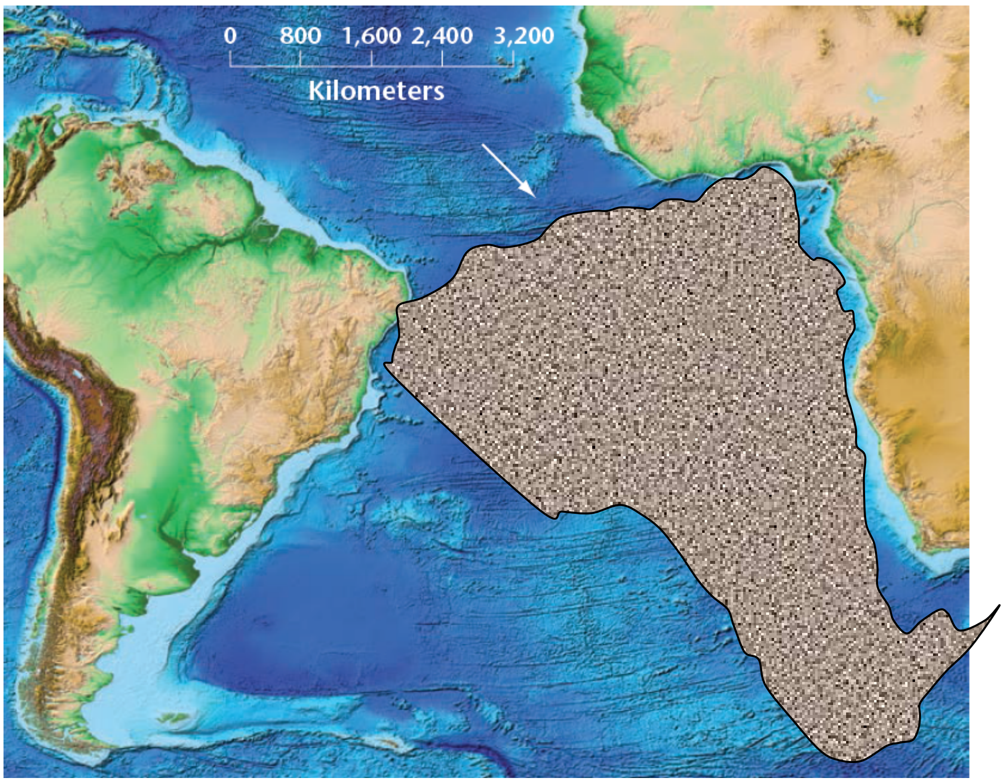
EXERCISE 2.2: Geographic Evidence for Plate Tectonics

(a) The shorelines fit reasonably well, but there's a broad gap near the southern tip of Africa and an overlap at what was the eastern "horn" of South America.
(b) Shorelines reflect not only tectonic activity but also sea-level change and millions of years of erosion and deposition since the continents rifted. A rise of sea level (as is happening today) changes the shapes of the deep embayments along the east coast of South America and west coast of Africa and makes matching the continents difficult.

Parts (c) to (f) are at first glance a simple exercises, but the three components (matching coastlines, matching continental shelves, using ocean fracture zones to control rotation of continents during seafloor spreading) reinforce basic plate tectonic concepts and lead to deeper understanding; for example, the fact that the shelf break is the actual edge of a continent, rather than the current shoreline. This also reinforces concepts about oceanic and continental crust presented in Chapter 1.



(c) The reconstruction based on matching the edges of the continental shelves (second reconstruction—on next page) produces a better fit than that using the shorelines. There are still gaps, but the shelf edges fit better.
(d) The true edge of a continent is the edge of its continental shelf, not its shoreline.
(e) The continents fit well when using the fracture zones as paths to joining them.
(f) This suggests that the fracture zones formed at the same time that the continents split apart and are somehow related to the process by which that happened.



EXERCISE 2.3: Putting the Early Evidence Together

(a) Earthquakes and volcanic activity appear to be concentrated in the same locations along the west coast of North America. There are far fewer earthquakes and no active volcanoes in the mid-continent United States (or, for that matter, along the east coast as well).
(b) The volcanoes and earthquakes (of the Mid-Atlantic Ridge) define a zone of tectonic activity located between the North American and South American plates to the west and the European and African plates to the east. As the plates split apart, magma rises to the ridge crest, producing volcanic eruptions.
(c) This fossil data combined with the fit of South America and Africa demonstrated in Exercise 2.1 suggests that at one time the two continents were joined and the Mid-Atlantic Ridge didn't exist. They have split apart and over time moved farther apart. The current tectonic activity at the Mid-Atlantic Ridge suggests that the processes that formed the ridge were responsible for breaking the continents apart.

EXERCISE 2.4: Interpreting Ocean Ridge Magnetic Stripes

(a) The magnetic anomaly stripes are oriented parallel to one another and parallel to the crests of both the Juan de Fuca and Mid-Atlantic ridges.

This simple, straightforward relationship is critical to the Vine-Matthews-Morley explanation of the magnetic reversals and is the reason for what seems like a very simple question. But even after making this observation, students don't always connect cause and effect—that seafloor spreading <u>*combined with magnetic reversals*</u> *causes the anomaly stripes. Hence the next question.*

(b) Magnetic domains in magnetite crystallizing in basalt are aligned with Earth's magnetic field that exists at the time the lava cools below the mineral's Curie point. The magnetic field measured over basalt crystallizing today will exhibit a positive magnetic anomaly because Earth's current magnetic field strength is supplemented by the remanent magnetization of the basalt. Because eruptions are occurring along the entire length of the ridges, the anomaly parallels the ridge. As rifting occurs, the seafloor spreads and the anomaly widens. When a magnetic reversal occurs, the new basalt repeats the process, but the older basalt that had produced a positive anomaly is now magnetized with the opposite polarity and becomes a negative anomaly band—still parallel to the ridge crest and symmetrical on opposite sides.

This question requires students to put all the pieces together as did Vine, Matthews, and Morley. Many are not familiar with this reasoning and may need help.

(c) There are three possible explanations: (1) assuming a <u>constant spreading rate</u>, the polarity of the magnetic field stayed constant for a longer time (producing a broad stripe) or shorter time (narrower stripe). (2) The rate of seafloor spreading is faster at some times than at others. The faster the rate, the broader the anomaly stripe; the slower the rate, the narrower the stripe. (3) A combination of these explanations.

EXERCISE 2.5: Estimating Seafloor Spreading Rates

(a) Distance between South America and Africa along the fracture zone is **4,100** km.
(b) Average South Atlantic spreading rate: **341** km/million years = **0.0000341** km/yr = **3.41** cm/yr = **34** mm/yr.
(c) The Atlantic Ocean will become **341** cm wider during a 100-year lifetime.

EXERCISE 2.6: Comparing Seafloor Spreading Rates of Different Ocean Ridges

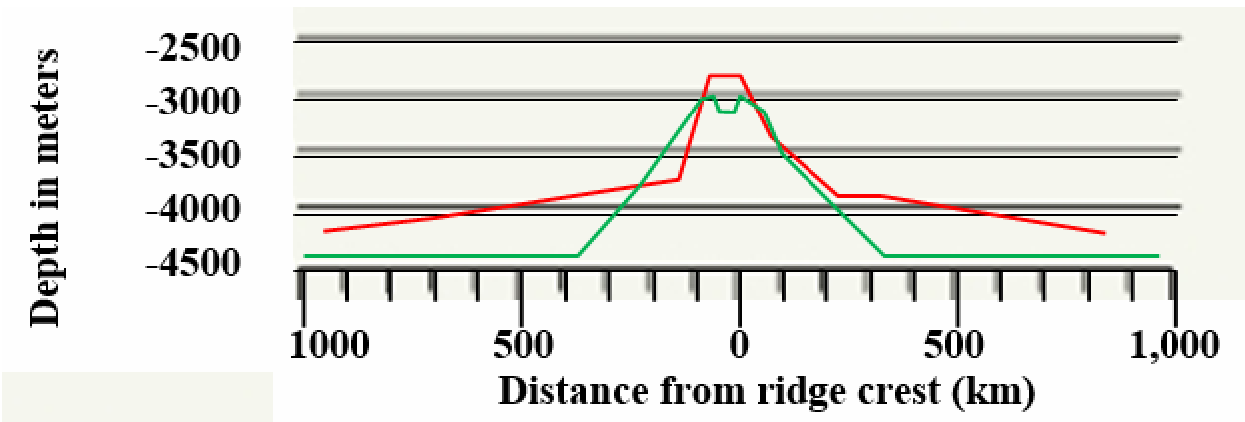
(a) The width of the South Atlantic Ocean segment shown is approximately **2,850** km.
(b) Calculation: width in km × 100,000 (to get width in cm) divided by 80,000,000 years = **2,860** ~~km~~ × 100,000 cm/~~km~~/80,000,000 years = **3.58** cm/year
(c) The width of the South Pacific Ocean for the same time span is greater than that of the South Atlantic, indicating a faster spreading rate on the East Pacific Rise than on the Mid-Atlantic Ridge in the South Atlantic Ocean.

(d) The width of the South Pacific Ocean for the time period shown is **6,100** km.
(e) The average spreading rate of the East Pacific Rise for the 80 Ma time span is **76** km/million years.

These spreading rates are typical of the range measured throughout the world's oceans and represent "fast spreaders" and "slow spreaders." They give students an appreciation for how the same process can operate at different rates at different geographic locations.

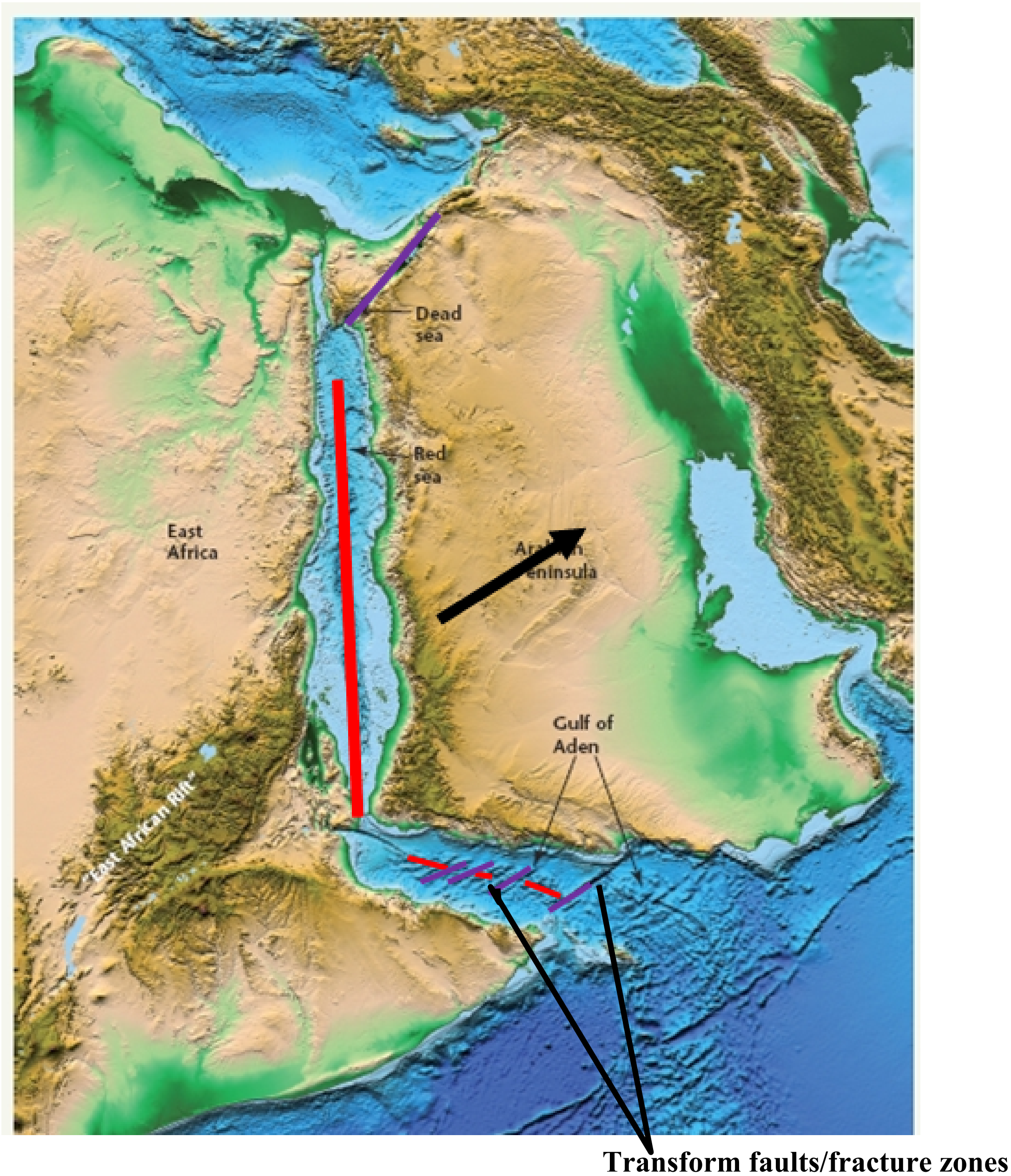
EXERCISE 2.7: A Tale of Two Ridges

(a) The mid-ocean ridge in the South Atlantic Ocean has the deepest, most well developed, and longest rift valley.
(b) The wider band of shallow water over the East Pacific Rise crest indicates that the band of young mid-ocean basalt is wider there than in the South Atlantic, suggesting, as seen in the previous exercise, that the East Pacific Rise is spreading faster.
(c)



(d) The rate at which the depth increases with distance from the ridge decreases with time. This suggests that the greatest density change in the cooling mid-ocean ridge basalt occurs relatively shortly after spreading moves it from the ridge crest. Subsequent density increases are less than the initial change, resulting in a slower rate of increase in water depth with distance from the ridge crest.

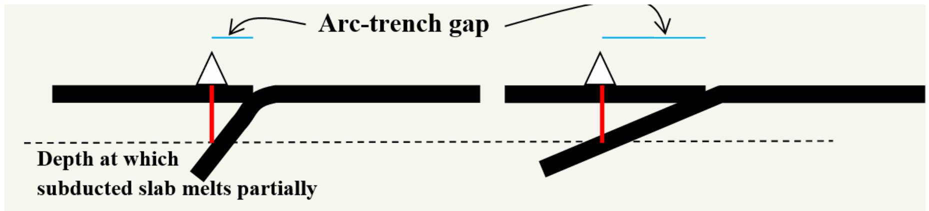
EXERCISE 2.8: Continental Rifting: Forming the Next Ocean



EXERCISE 2.9: Estimating the Steepness of Subduction Zones

(a) The major factor controlling the width of the arc-trench gap is the steepness at which the lower plate is subducted beneath the upper plate. A steep subduction angle brings the plate to the required melting depth in a shorter horizontal distance than that for a gentle subduction angle.

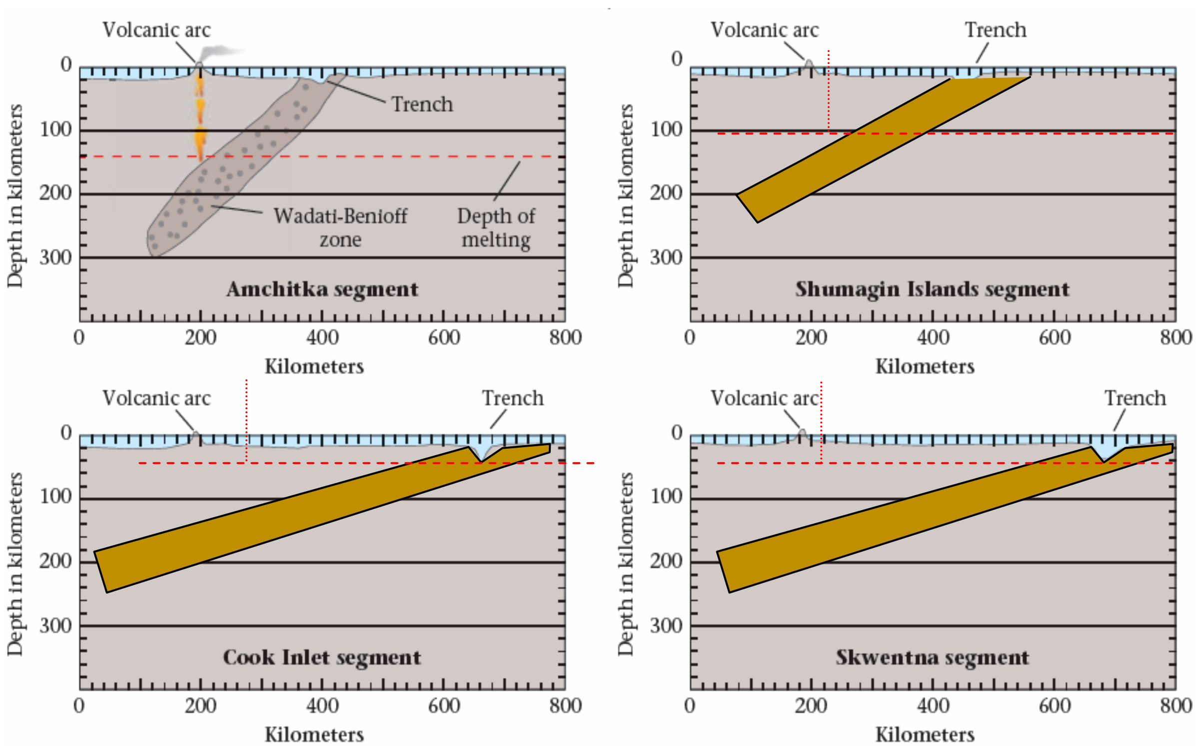
(b)



(c) The boundaries of the subducted plate are drawn so that they enclose the zone of earthquakes in the Wadati-Benioff zone.

(d) Melting begins beneath the Amchitka arc at about **150** km. Melting occurs directly below the arc, so its depth was calculated from the intersection of a vertical line drawn downward from the active arc to the upper part of the Wadati-Benioff zone.

(e)



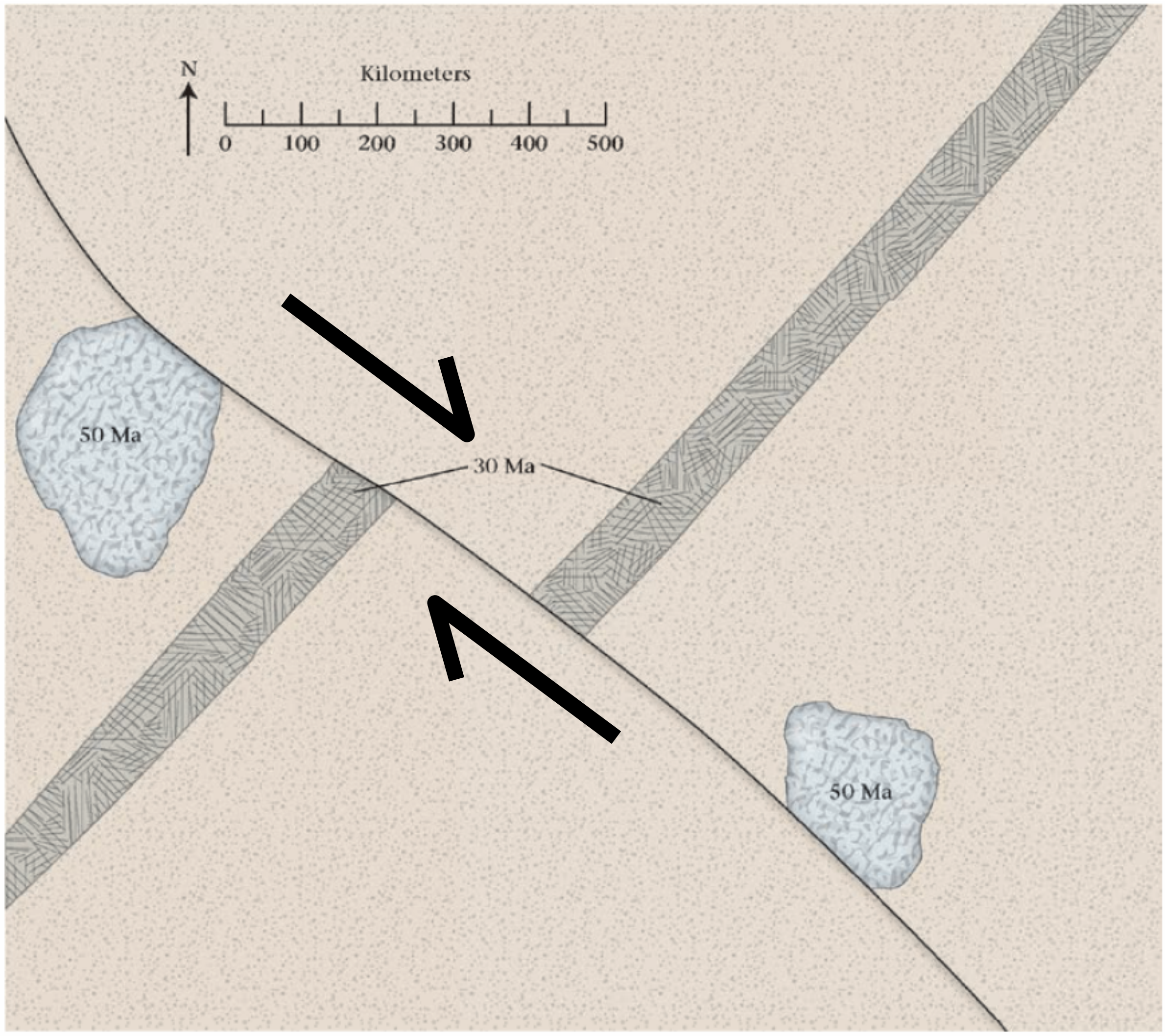
(f)

	Amchitka	Shumagin Islands	Cook Inlet	Skwentna
Arc-trench gap (km)	200	250	450	460
Subduction angle (°)	44°	27°	15°	14°

(g) The steeper the angle of subduction, the narrower the arc-trench gap will be. The gentler the angle of subduction, the wider the arc-trench gap will be.

EXERCISE 2.10: Estimating the Amount and Rate of Motion in a Continental Transform Fault

(a) The northeast fault block has moved to the right (SE) relative to the southwest block.



(b) The 50-Ma granite body was offset **1,050** km.

(c) The rate of offset for the last 50 million years was **21** mm/yr:
1,050 km/50 Ma = **21 km/Ma** = 0.000021 km/yr = 2.1 cm/yr = **21 mm/yr**.

(d) The 30-Ma marble was offset **300** km.

(e) If the fault moved at a constant rate for the past 30 million years: **300** km/30 million years; **10** km/million years; **10** mm/year.

(f) The fault has not moved at a constant rate. For the past 30 Ma, offset was 10 mm/yr, as indicated by the displacement of the 30-Ma marble but the average rate of offset for the granite body is more than twice that—21 mm/yr—and that includes the movement for the past 30 Ma. This means that between the intrusion of the granite at 50 Ma and the intrusion of the vertical layer of marble at 30 Ma, the fault blocks must have been offset much more rapidly.

It is possible to estimate the average rate of offset between 50 Ma and 30 Ma. First, subtract the amount of offset since 30 Ma from the total offset of the granite (result: 750 km). This is the offset that happened during the 20 Ma between intrusion of the granite and intrusion of the dike. Now calculate the average offset rate for that distance over 20 Ma (= 37.5 km/Ma = 35.5 mm/yr).

(g) Arrows on the map indicate the direction in which the ridge segments have been offset.

(h) San Francisco and Los Angeles are approximately 600 km apart. If the fault blocks are moving at the average rate of 35.5 mm/yr calculated earlier, it would take 16,901,408 years (16.9 m.y.) for the two cities to be adjacent to one another across the fault.

What Do You Think?

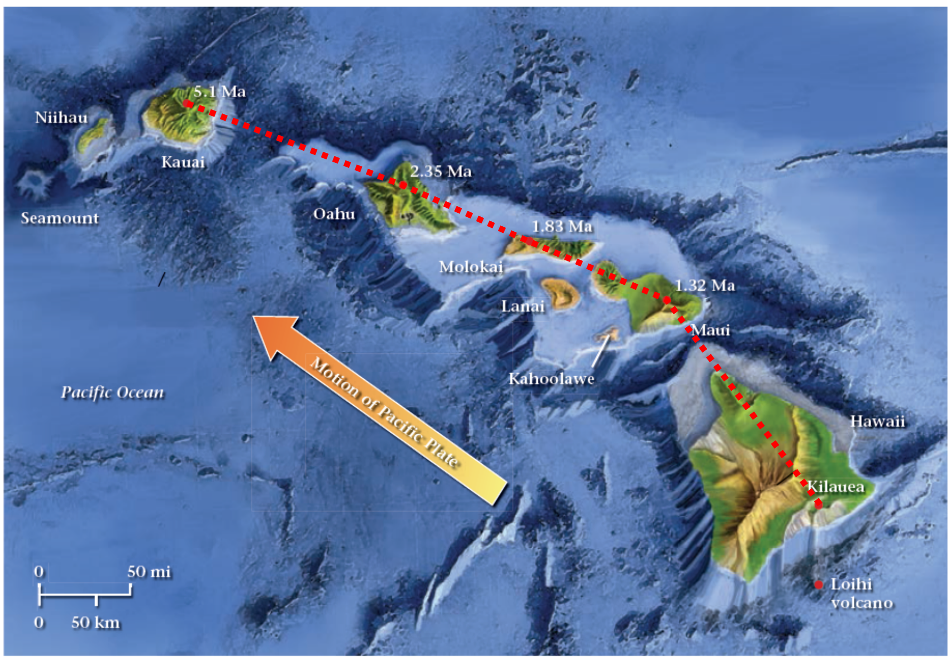
This discussion should include such issues as:

- Risk assessment: how frequent are earthquakes in the New York City metropolitan area compared with those in San Francisco?
- How much damage did the New York City area earthquakes cause compared with those in San Francisco?
- What are the populations of the two cities?
- What hazards exist in New York City that are not present in San Francisco, and vice versa.

EXERCISE 2.11: Plate Direction: Footprints of a Moving Plate

(a) The mantle plume responsible for the Hawaiian Islands is today nourishing both Kilauea (more than 30 years of continuous eruptive activity) and Loihi. It is reasonable to suggest that the mantle plume is located between the two.

(b)



(c) Directions using the azimuth system: A: **296°** B: **077°** C: **153°** D: **254°**

(d)

	Distance between volcanic centers (km)	Number of years of plate motion	Rate of plate motion (mm/yr)	Azimuth direction of plate motion
Hawaii to Maui	180	1,320,000	136	340°
Maui to Molokai	80	510,000	157	313°
Molokai to Oahu	83	520,000	160	310°
Oahu to Kauai	118	2,750,000	43	296°

EXERCISE 2.12: Long-Term Movement of the Pacific Plate

(a) If the Pacific Plate had always moved in the same direction, the line of seamounts and volcanoes would be straight. Even in the relatively short time span of Hawaiian Island volcanism, the direction has changed slightly, as shown in Exercise 2.11. The sharp bend in the line of seamounts northwest of the Kimei seamount indicates a significant change of direction.

(b) The change in direction of the Pacific Plate occurred a few million years before 40 Ma (the age of Kimei). The essentially straight line between volcanos in the big island of Hawaii and Kimei shows a constant direction. Some time before Kimei erupted but after Nintoku (56.5 Ma), the change occurred. Because the elbow is closer geographically to Kimei, the time of the change is closer to the age of that seamount.

(c) The early direction of the Pacific Plate is indicated by the straight line defined by the ***oldest*** seamounts; that is, Meiji and Nintoku. That direction was more northerly than the current direction, **approximately 350°.**

(d) The Meiji seamount has moved approximately **2,150 km** from the time it was situated above the hot spot. *The direction must be measured along the hot-spot track, not in a straight line.*

(e) Distances between seamounts and their ages yield plate movement rates of:
   - i. **52** km/Ma based on Hawaii-Midway
   - ii. **66** km/Ma based on Hawaii-Kimei
   - iii. **34** km/Ma based on Kimei-Meiji

(f) The Meiji seamount has moved at different rates at different times in its history. Based on the answer to (e), it moved relatively slowly for the first 31.4 m.y. but faster for the last 40 m.y.

(g) The best indication of the direction in which the Pacific Plate is moving today is information from the Hawaiian Islands—the youngest volcanoes in the Hawaiian–Emperor seamount chain. As determined in Exercise 2.11, that direction is 340° (not including Loihi).

(h) If the Hawaii-Kauai direction (340°) is maintained, the Meiji seamount will eventually be subducted beneath the eastern end of the Kurile-Japan trench. If the path is more similar to that represented by the Hawaii-Kimei trend, Meiji will be subducted beneath the central part of the Kurile-Japan trench. If the apparently more northerly trend represented by the Loihi-Kilauea transition is maintained, Meiji would be subducted beneath the western end of the Aleutian trench.

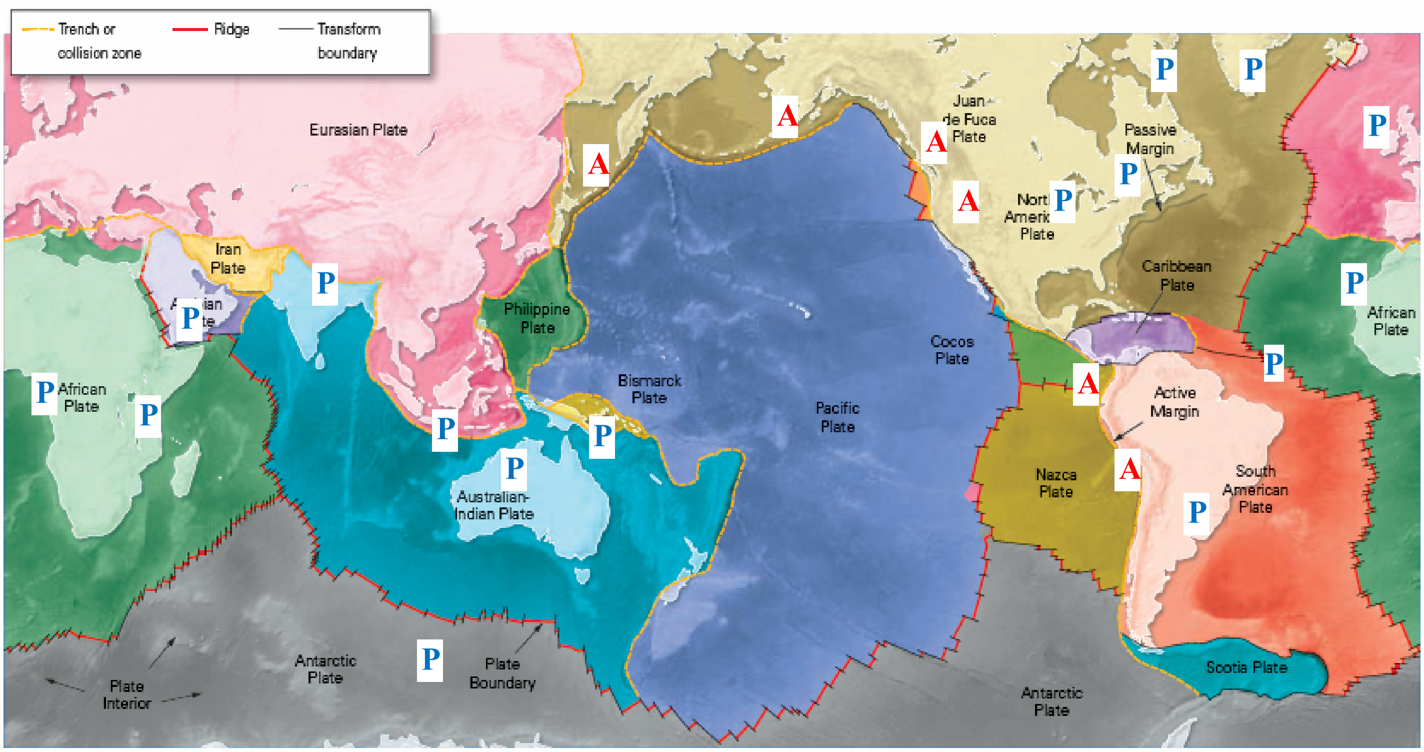
EXERCISE 2.13: Why Are There More Earthquakes and Volcanoes on One Side of Some Continents than on the Other?

(a) Not all continental coastlines coincide with plate boundaries. For example, the west coast of North America is close to two plate boundaries—a transform fault boundary and a subduction zone, but the east coast is located in the center of the North American Plate.

(b) The west coast of Africa has a broad continental shelf, but the shelf off the west coast of South America is very narrow. A subduction zone is close to the west coast of South America—part of the Pacific Plate is being subducted beneath the continent—but the nearest plate boundary to west Africa is the Mid-Atlantic Ridge, thousands of miles to the west.

Because most earthquakes and volcanic eruptions occur at plate boundaries, these phenomena would be expected to be more frequent off the west coast of South America than off the west coast of Africa.

(c)



ANSWERS TO PRE-CLASS WORKSHEETS

1c; 2a; 3d; 4c; 5d; 6a; 7d; 8d; 9b; 10d; 11b; 12b; 13a; 14c; 15b.