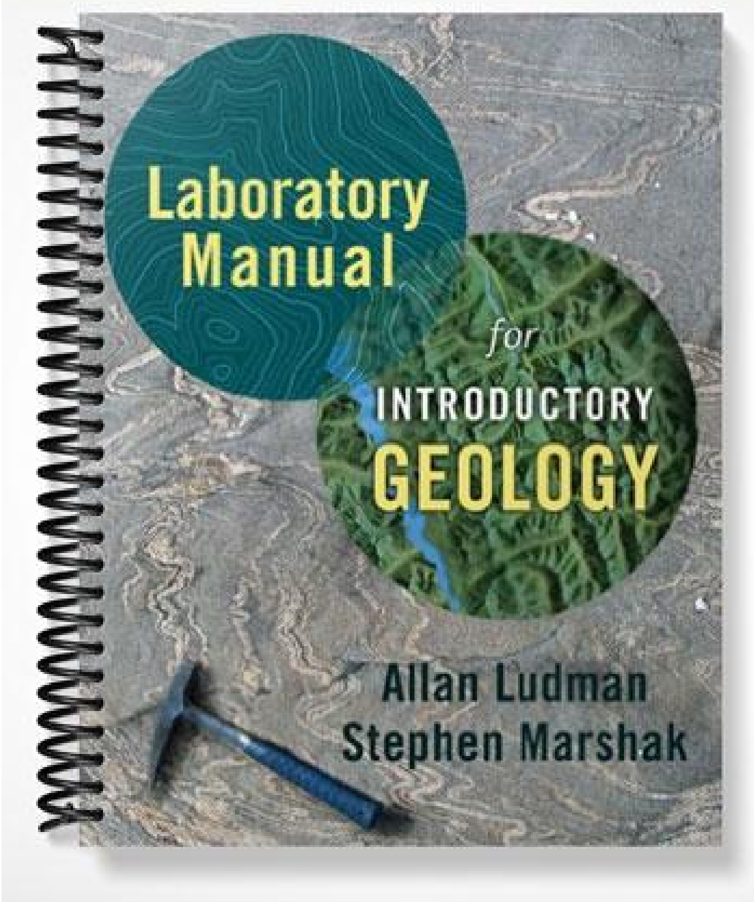
SOLUTIONS MANUAL



CHAPTER 2
THE WAY THE EARTH WORKS: EXAMINING PLATE TECTONICS

Coverage of plate tectonics is required early in introductory Geology as context for the mineralogy, petrology, structure, internal processes, and Earth history that follow. Some instructors prefer a detailed treatment early, while others like a brief discussion in the first or second lecture followed by a more thorough treatment later in the semester. 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 and continents split and merge, setting the context for earthquakes, volcanoes, etc. The exercises include various rigor: some require relatively simple reasoning skills appropriate for a first or second laboratory session, while others require more sophisticated thinking and background knowledge. Just choose the exercises and sequence most appropriate for the approach used in your course.

Exercises follow to some extent the historic development of plate tectonics, beginning with simple geographic observations that led sixteenth and seventeenth century cartographers to consider a former fit of South America and Africa (Ex. 2.2) and paleoclimate indicators that led Wegener to propose continental drift (Ex. 2.3). Paleomagnetic evidence for plate tectonics is discussed slowly and clearly next, followed by an application of magnetic reversals to understanding sea-floor spreading (Ex. 2.4). Sea-floor spreading rates are estimated geographically (Ex. 2.5) and students compare spreading rates at different ridges using magnetic anomalies (Ex. 2.6) and bathymetry (Ex. 2.7).

Students estimate the direction and rate of plate motion in Exercises 2.8 and 2.9, learning how hotspots form and provide evidence for both short-term (Hawaiian Islands) and long-term (Emperor seamount chain) plate movement. Continental rifting is explored in Exercise 2.10 by examining the ongoing separation of the Arabian Peninsula from East Africa.

The remaining exercises examine convergent and transform plate boundaries. Students estimate the steepness of Aleutian subduction in Exercise 2.11, using the varying sizes of the arc-trench gap in that boundary. Exercise 2.12 shows how displacement is estimated along a continental transform (San Andreas Fault) by matching unique rock types and structures that have been offset. The chapter ends with a comparison of active and passive margins.

EXERCISE 2.1 **Recognizing Plates and Plate Boundaries**

Name: ______________________ Section: __________
Course: ______________________ Date: __________

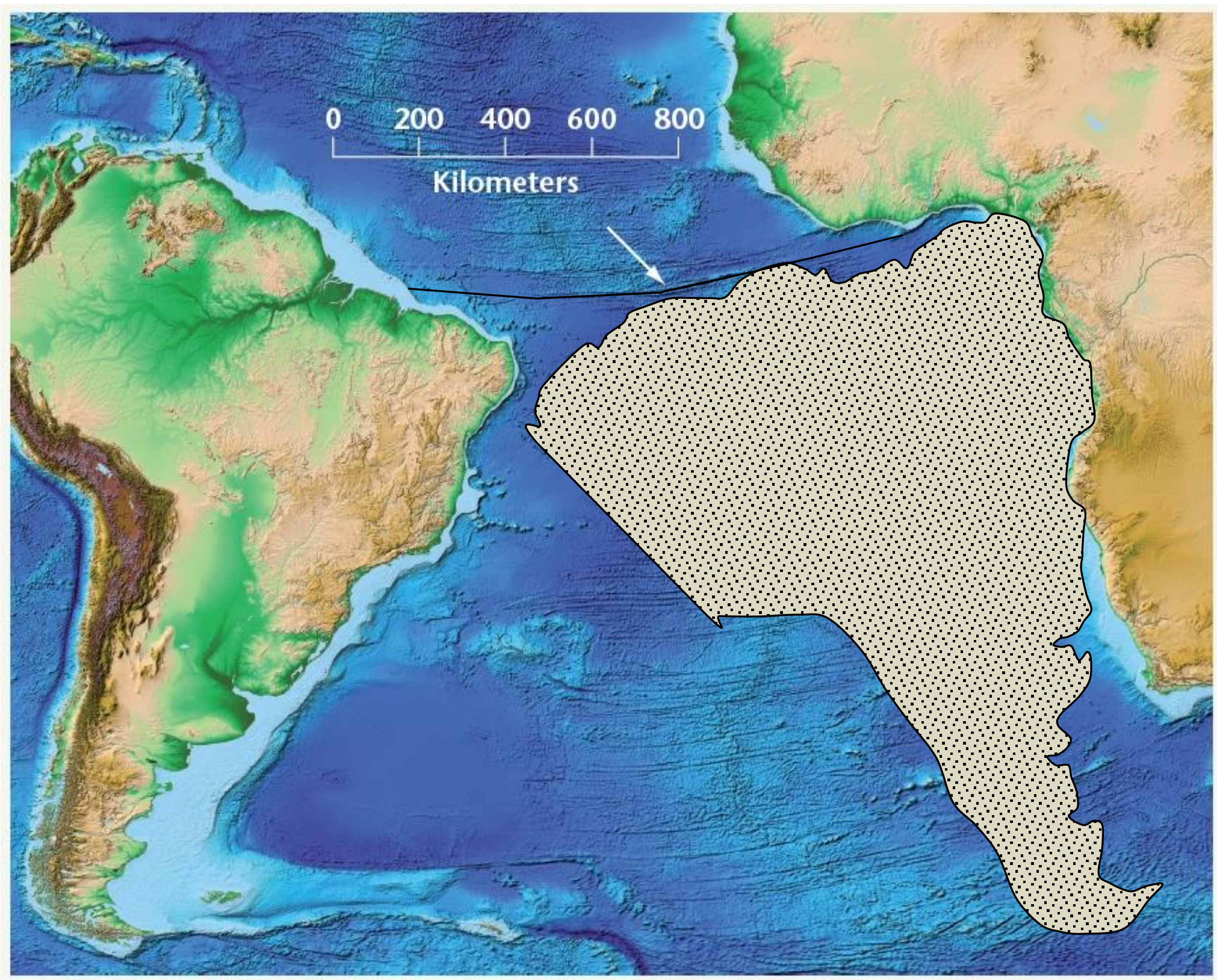
(a) What is the name of the plate on which the United States resides? **the North American Plate**

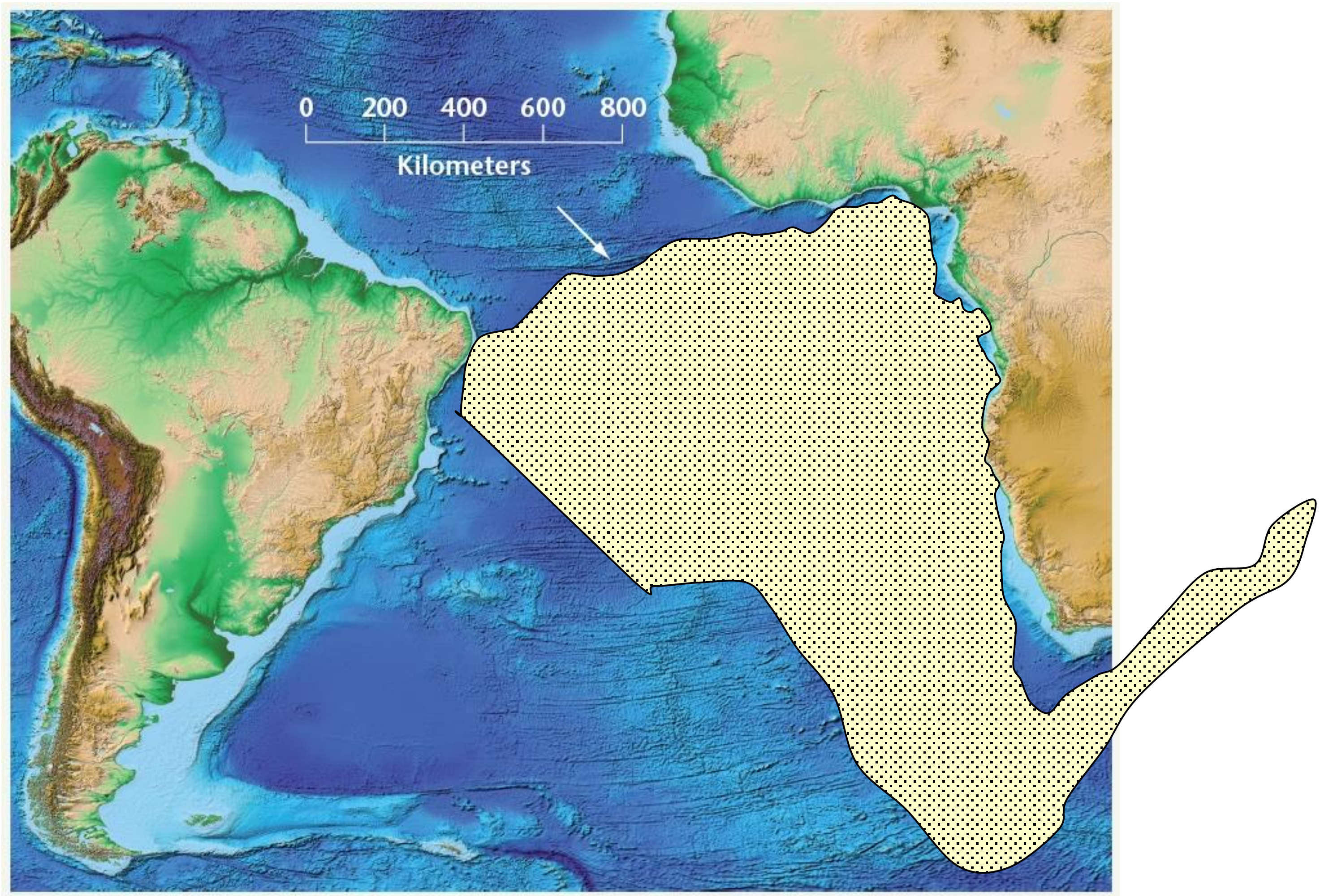
(b) Does this plate consist of continental lithosphere? Oceanic lithosphere? Or both? **both**

(c) Where does the lithosphere of the Atlantic Ocean form? **at the Mid-Atlantic Ridge**

(d) What kind of plate boundary occurs along the west coast of South America? **convergent-ocean/continent**

(e) Is the west coast of Africa a plate boundary? **No. The boundary of the African plate is the Mid-Atlantic Ridge.**





Note on Exercsie 2.2: At first glance, this is a "simple" exercise. However, the three components of basic plate tectonic concepts –matching coastlines, matching continental shelves, and using ocean fracture zones to control rotation of continents during sea-floor spreading–are reinforced and help lead to a deeper understanding of the fact that the edge of a continent is the continental shelf and not the current shoreline. This also reinforces concepts about oceanic and continental crust presented in Chapter 1.

EXERCISE 2.2 Geographic Evidence for Plate Tectonics

Name: ____________________ Section: ________
Course: ____________________ Date: ________

(a) Sketch the shorelines of South America and Africa in Figure 2.3 on separate pieces of tracing paper. Rearrange the continents so that they fit snugly without overlapping or leaving large gaps. How well do the continents fit? Where are the problem areas?

See diagrams above. The fit is "OK" but not perfect, with gaps at the northern part of South America and southern part of Africa. These gaps could be closed but only by producing overlaps of the two continents.

(b) If Africa and South America split apart tens of millions of years ago, would their shorelines be the best indicators of the shapes of the original pieces, or the true extent of either continent? What factors other than rifting and sea-floor spreading could have modified the shape of the current shorelines?

Erosion of the coast over millions of years would change its shape. Changes in sea level would also change shoreline shape.

EXERCISE 2.2 continued

Name: ____________________ Section: ________
Course: ____________________ Date: ________

(c) Trace the outlines of the continents again, this time using the edges of their continental shelves (the shallow, flat areas adjacent to the land) rather than the shoreline, and attempt to join them. Which reconstruction produces the best fit? In what ways is it better than the other?

The continental shelf fit is better, with fewer and smaller gaps (see figure above)

(d) Based on this evidence, what is the true edge of a continent?

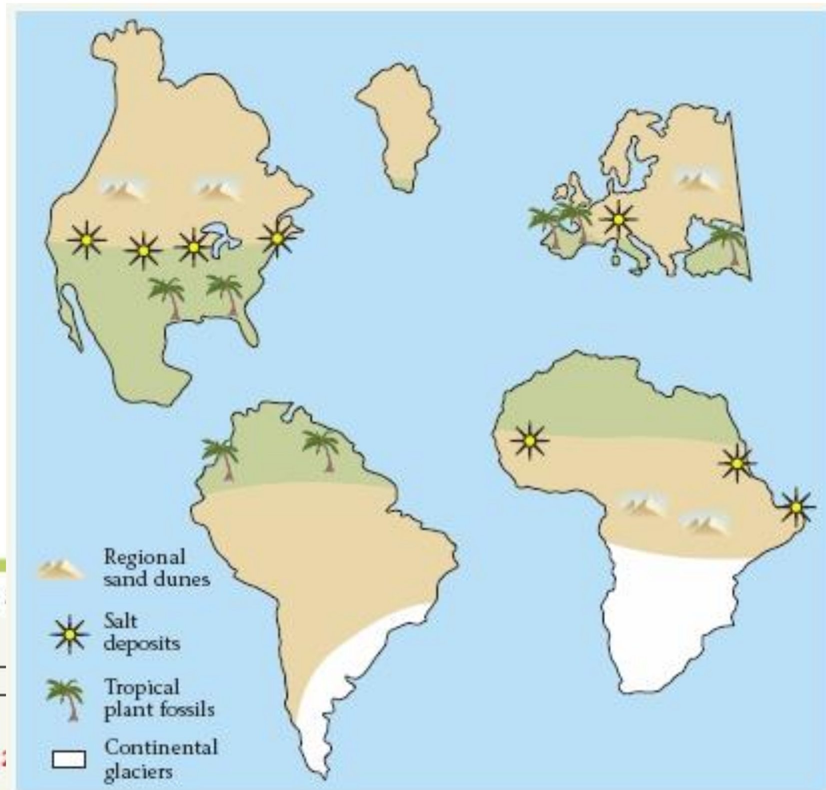
Based on this exercise, the true edge of a continent is the edge of its continental shelf .,

(e) When you fit the continents together, you could rotate them however you wished. However, Figure 2.3 also contains clues that show exactly how Africa and South America spread apart. Place the *best-fit* tracings of South America and Africa over those continents on Figure 2.3. Now bring them closer to one another until they join, *using the oceanic fracture zones to guide the direction in which you move the two plates*. Do the continents fit well when moved this way?

The fit is, again, "reasonable."

(f) What does this suggest about the age and origin of the fracture zones?

This suggests that the fracture zones formed at the same time that the continents rifted and separated by sea-floor spreading.


Regional sand dunes
Salt deposits
Tropical plant fossils
Continental glaciers

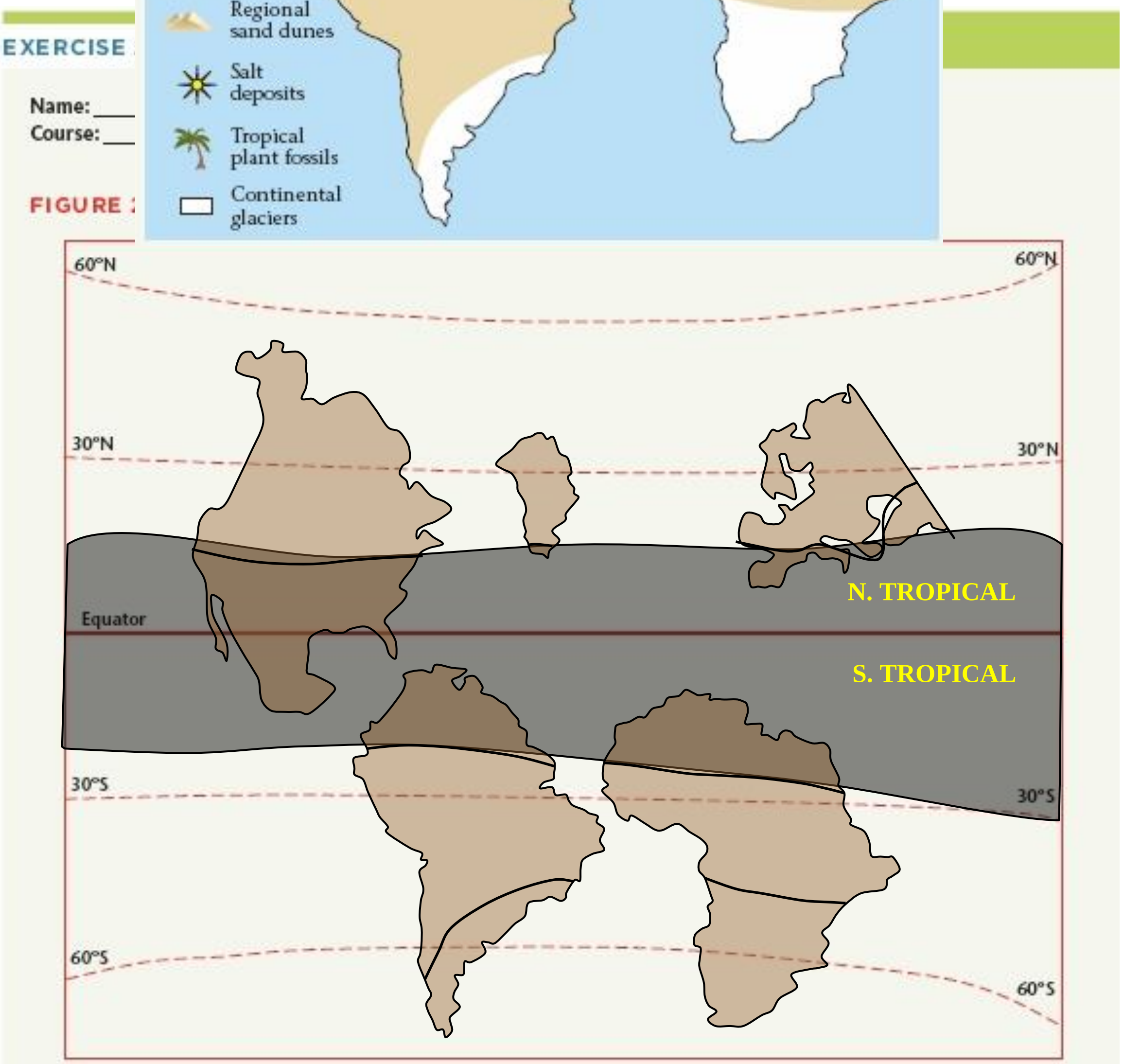

EXERCISE
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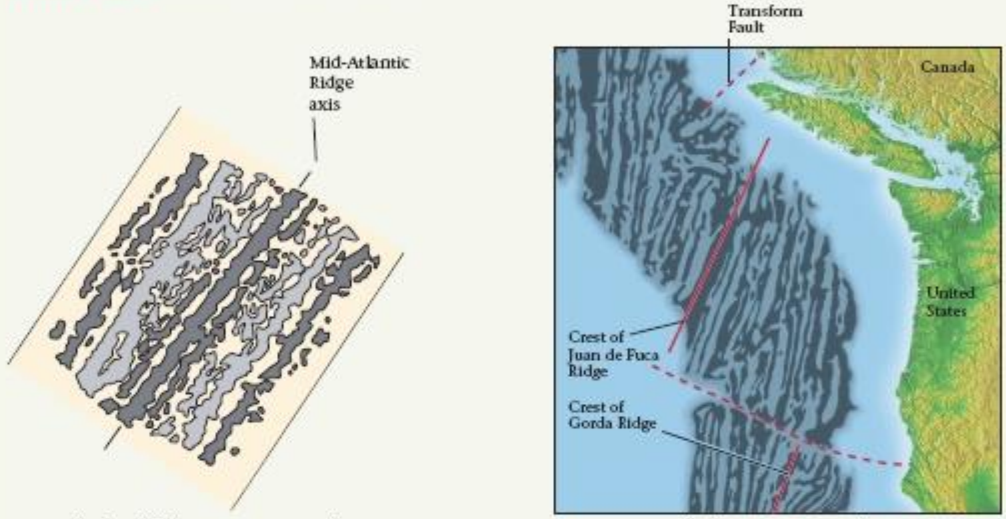
FIGURE 2.9 Magnetic anomaly stripes.



dark and light gray = + anomaly
beige = – anomaly

(a) The Mid-Atlantic Ridge southwest of Iceland.

dark gray = + anomaly
light gray = – anomaly

(b) The Juan de Fuca and Gorda ridges in the North Pacific off Washington and British Columbia.

EXERCISE 2.4 Magnetic Anomaly Stripes and Oceanic Ridges

Name: ______________________ **Section:** __________

Course: ______________________ **Date:** __________

Examine the magnetic anomaly stripes in the North Atlantic and North Pacific oceans (Fig. 2.9).

(a) Compare the orientation of the magnetic stripes with those of the two ridge axes. Are they parallel? Perpendicular? At some other angle?

The magnetic stripes are nearly parallel to the Juan de Fuca and Gorda ridge axes.

(b) Describe the relationship between the ages of magnetic stripes and their distance from the ridge crests.

The current ridge crest hosts a positive magnetic anomaly. Alternating negative and positive anomalies follow, with anomaly ages increasing with increased distance from the ridge crest.

(c) Explain how the process of sea-floor spreading can produce these orientations and relationships.

As the sea-floor spreads, a positive anomaly will form because the current and paleomagnetic polarities are the same. This produces a band of positive anomaly centered at the ridge. If a reversal occurs, this "old" + anomaly becomes a negative anomaly and a new + anomaly forms at the ridge crest. Repetition of this process produces the parallel anomaly stripes.

(d) Some magnetic stripes are wider than others. Knowing what you do about sea-floor spreading and magnetic reversals, suggest an explanation.

The varied widths of magnetic anomaly "stripes" can be explained by two important variables in the process described in 2.4c: the span of time for any particular state of polarity (the longer the time, the greater the width at any given spreading rate) and/or the rate of spreading (the faster the spreading rate, the wider an anomaly stripe will be for a given time span). *Either or both* variables may change to produce the variations in width noted in Figure 2.9.

EXERCISE 2.5 **Estimating Sea-Floor Spreading Rates**

Name: ______________________________ Section: __________
Course: ______________________________ Date: __________

The South Atlantic Ocean formed by sea-floor spreading at the Mid-Atlantic Ridge. Geologists can get a rough estimate of the spreading rate (i.e., the relative motion of South America with respect to Africa) by measuring the distance between the two continents in a direction parallel to the fracture zones and determining the time over which the spreading occurred.

(a) Measure the distance between South America and Africa along the fracture zone indicated by the arrow in Figure 2.3. __~ 1,200__ km

The oldest rocks in the South Atlantic Ocean, immediately adjacent to the African and South American continental shelves, are 120,000,000 years old.

(b) Calculate the average rate of sea-floor spreading for the South Atlantic Ocean over its entire existence. Express your answer in __10__ km/million years = __0.00001__ km/yr = __1.0__ cm/yr = __10__ mm/yr

(c) Assuming someone born today lives to the age of 100, how much wider will the Atlantic Ocean become during his or her lifetime? __100__ cm = 1 meter

EXERCISE 2.6 Comparing Sea-Floor Spreading Rates at Different Ridges

Name: ______________________ Section: __________
Course: ______________________ Date: __________

Magnetic reversals are found worldwide, so magnetic stripes should be the same width in every ocean *if the rate of sea-floor spreading is the same at all ridges*. If a particular anomaly is wider in one ocean than another, however, it must result

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EXERCISE 2.6 continued

Name: ______________________ Section: __________
Course: ______________________ Date: __________

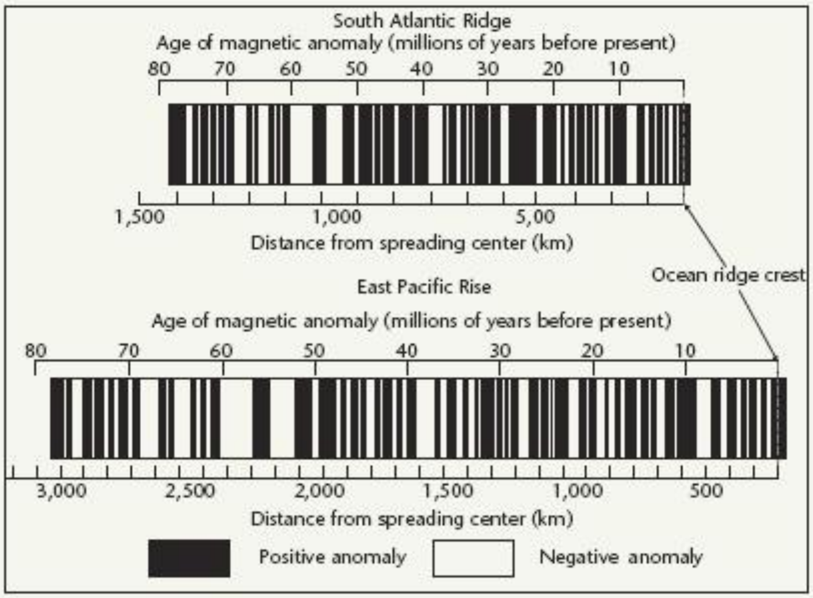


FIGURE 2.10 Magnetic anomalies associated with different ocean ridges.

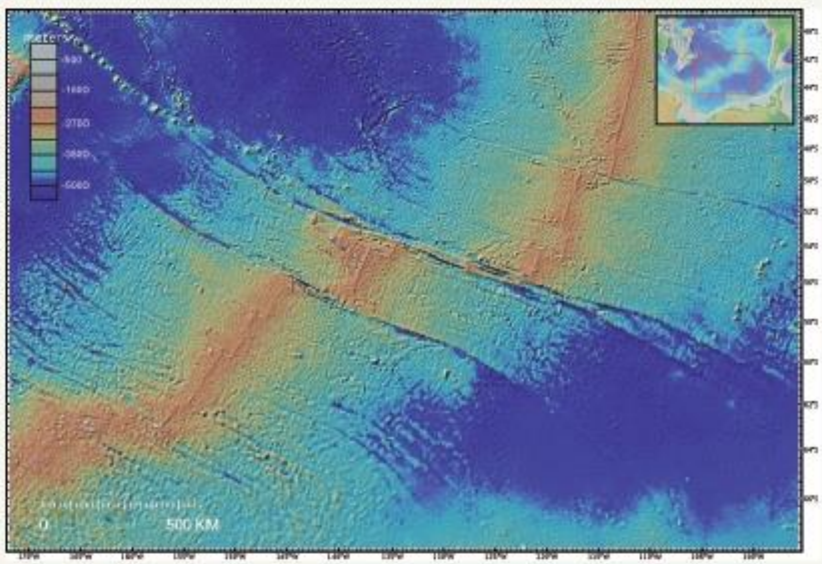
(a) Measure the distance from the spreading center to the farthest magnetic anomaly stripe in each ocean and determine the age of that anomaly.
South Atlantic **1,390** km age: **~77 million years**
North Pacific **~3,000** km age: **~77 million years**

(b) Divide the distance by the age to determine the average rate of spreading. [*Then double this rate, because the data are for only one side of the oceanic ridge.*]
South Atlantic **36** mm/yr North Pacific ______ mm/yr

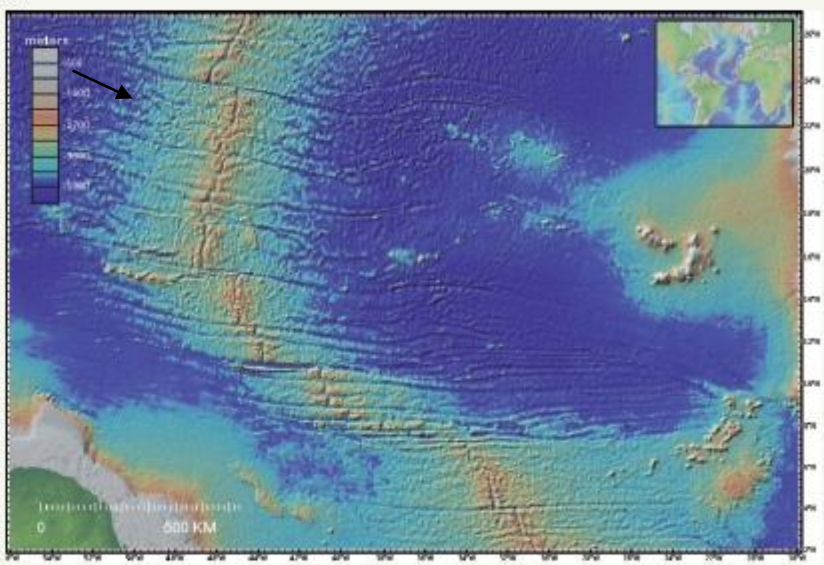
(c) Have these two ocean ridges spread at the same rate?
No. The East Pacific Rise has spread nearly three times faster than the South Atlantic.

(d) Compare the results of this exercise with those from Exercise 1.10b. Are the two estimates for the opening of the South Atlantic Ocean the same? If not, what factors could explain the difference?
The estimate for the South Atlantic spreading rate here is about 20% greater than for the North Atlantic in Exercise 1.10b. The North Atlantic began opening about 60 million years earlier than the South Atlantic

(e) Why are the anomalies in the North Pacific wider than those in the South Atlantic?
The time span for each individual anomaly is the same for the entire Earth but because of the faster spreading rate in the East Pacific Rise , the anomaly stripes in the Pacific will be wider.



(a) The East Pacific Rise in the South Pacific Ocean.



(b) The Mid-Atlantic Ridge off South America.

Note on Exercsie 2.7: There are a few errors in the graph in Exercise 2.7c in both vertical and horizontal scales, as well as the layout of the diagram, which as written permits profiling only half of each ridge. These errors have been corrected in the answer provided.

EXERCISE 2.7 continued

Name: ______________________ Section: __________

Course: ______________________ Date: __________

(a) Ocean ridges typically have a rift valley at their axes. Which of the two ridges in Figure 2.11 has the best developed rift valley?

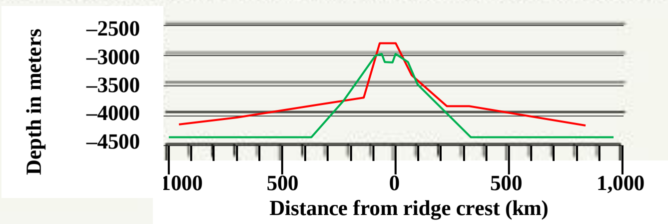
The Mid-Atlantic Ridge has a better developed axial rift valley than the East Pacific Rise.

Do all ocean ridges have the same shape? Most are similar, but different spreading rates cause variations in shape because of the way the cooling lithosphere behaves. Lithosphere near the ridge axis is young, thin, still hot, and therefore has a lower density than older, colder lithosphere far from the axis. As a result, the ridge axis area floats relatively high on the underlying asthenosphere and the water above it is relatively shallow. As sea-floor spreading moves the oceanic lithosphere away from the ridge axis, the rocks cool and get thicker and denser. The farther it is from the ridge axis, the lower the oceanic lithosphere sits on the asthenosphere and the deeper the water will be. This concept is known as the **age versus depth relationship**.

(b) Keeping in mind the age versus depth relationship, why is the belt of shallow sea wider over the East Pacific Rise than over the Mid-Atlantic Ridge?

The wider band of shallow water over the East Pacific Rise crest indicates that the band of young mid-ocean ridge 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) On the graph provided, plot depth (on the vertical axis) against distance from the ridge axis (on the horizontal axis) for both the East Pacific Rise and the Mid-Atlantic Ridge. Use five to ten points for each ridge. Connect the dots for the East Pacific Rise with red pencil and those for the Mid-Atlantic Ridge with green pencil to make cross sections of each ridge.



(d) Does the rate at which the depth with distance from the ridge stay the same over time, decrease over time, or increase over time?

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 Plate Direction: Footprints of a Moving Plate

Name: ______________________________ Section: __________

Course: ______________________________ Date: __________

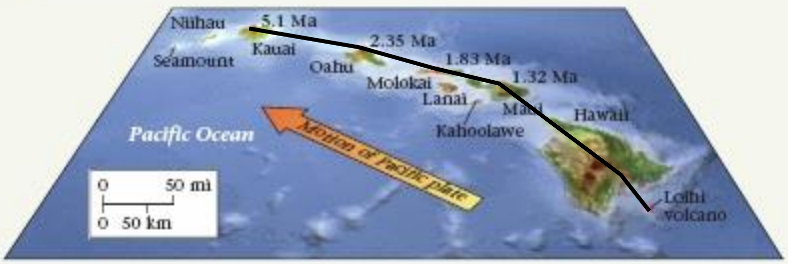
The Hawaiian Islands, located in the Pacific Ocean far from the nearest oceanic ridge, are an excellent example of hot-spot volcanic islands (Fig. 2.13). Volcanoes on Kauai, Oahu, and Maui haven't erupted for millions of years, but the island of Hawaii hosts five huge volcanoes, one of which (Kilauea) has been active for the past 20 years. In addition, a new volcano, Loihi, is growing on the Pacific Ocean floor just southeast of Kilauea. As the Pacific Plate moves, Kilauea will become extinct and Loihi will be the only active volcano.

(a) Where is the Hawaiian hot spot located today? Explain your reasoning.

Both Kilauea and Loihi are being nourished by heat from the hotspot, so it is reasonable to infer that the hotspot lies somewhere between the two. (This assumes a narrow heat source, but that is also reasonable considering the fact that Kilauea is active, not Mauna Loa.)

(b) Draw a line connecting the volcanic centers (highlighted in red) on Hawaii and Maui. Do the same for Maui to Molokai, Molokai to Oahu, and Oahu to Kauai.

FIGURE 2.13 Ages of Hawaiian volcanoes in millions of years before present.



(c) Measure the direction and distance between these centers using a ruler, a protractor, and the map scale. Calculate the rate of plate motion (distance between volcanoes divided by the time interval between eruption ages) and fill in Table 2.1. Express the rates in millimeters per year. Use the protractor in your toolkit to measure direction using the azimuth system (see below).

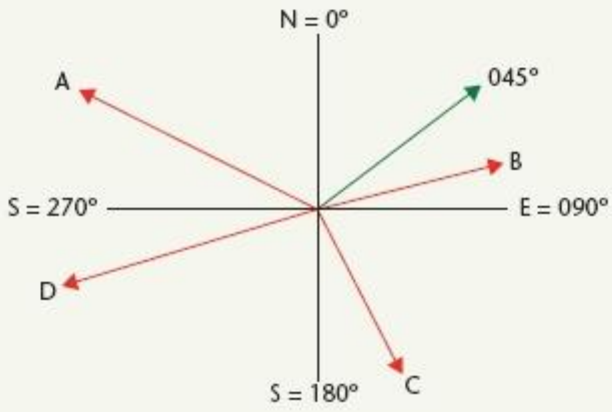
TABLE 2.1 Movement of the Pacific Plate over the Hawaiian hot spot.

	Distance between islands (km)	Number of years of plate motion	Rate of plate motion (mm/yr)	Azimuth direction of plate motion (e.g., 325°)
Hawaii to Maui	**180**	**1,320,000**	**136 (13.6 cm)**	**340°**
Maui to Molokai	**80**	**510,000**	**157 (15.7 cm)**	**313°**
Molokai to Oahu	**83**	**520,000**	**160 (16.0 cm)**	**310°**
Oahu to Kauai	**118**	**2,750,000**	**43 (4.3 cm)**	**296°**

EXERCISE 2.8 continued

Name: ____________________ Section: __________
Course: ____________________ Date: __________

FIGURE 2.14 The azimuth system.



A: 298° B: 077° C: 153° D: 253°

EXERCISE 2.9 **Long-Term Movement of the Pacific Plate**

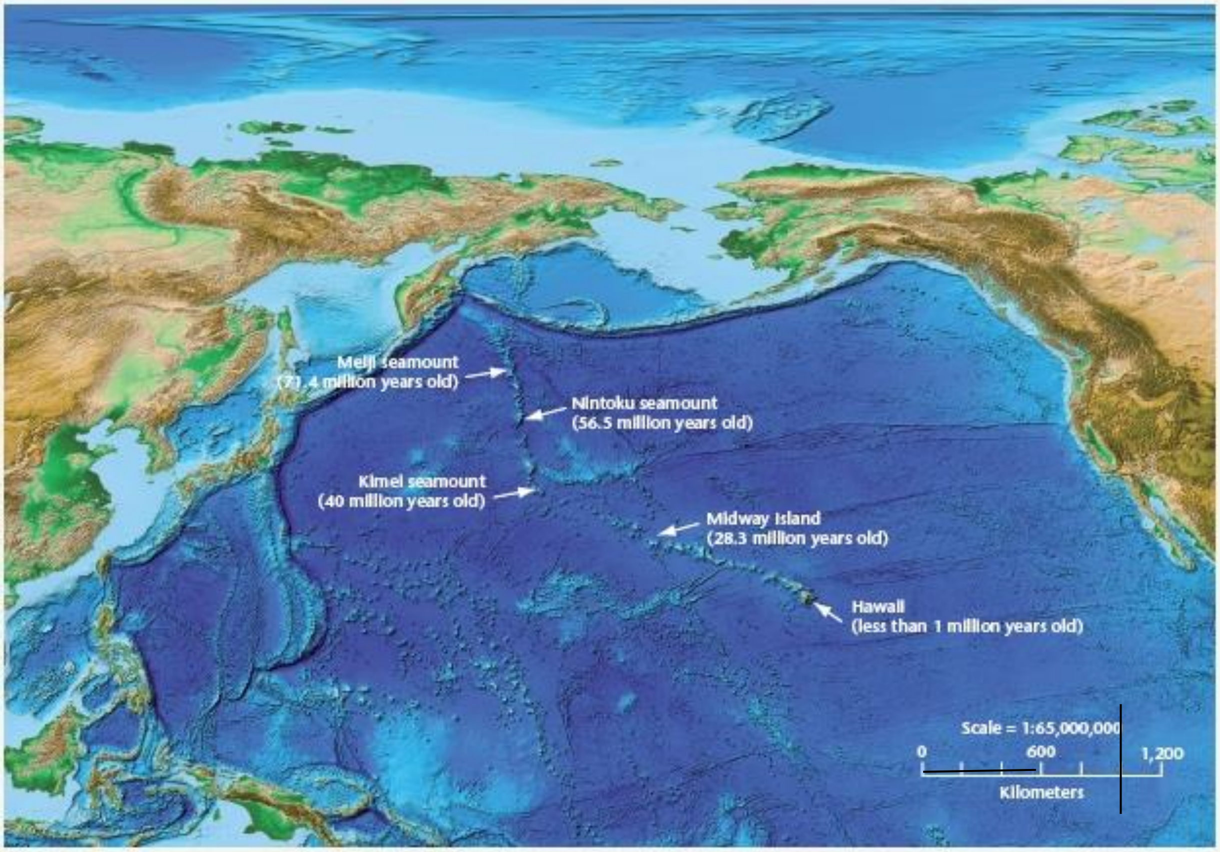
Name: ____________________ Section: __________
Course: ____________________ Date: __________

The oldest volcano of the Hawaiian-Emperor seamount chain was once directly above the hot spot, but is now in the northern Pacific, thousands of kilometers away (Fig. 2.15). Seamount ages show that the hot spot has been active for a long time and reveal the direction and rate at which the Pacific Plate has moved.

(a) What evidence is there that the Pacific Plate has not always moved in the same direction?

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 Islands volcanism, the direction has changed slightly, as shown in Exercise 2.8. With some slight variation, the Pacific Plate has moved at roughly 275° between the time that the Kimei volcano erupted and the present.

continued



(b) How many years ago did it change direction? Explain your reasoning.

It changed direction about 40 million years ago. The hotspot "track" is almost a straight line trending 275° and records volcanic activity from today's Kilauea and Loihi to that of the volcano that forms the Kimei seamount. Earlier, the hotspot "track" trends much more northerly.

(c) Based on the information in Figure 2.15, in what direction did the Pacific Plate move originally?

A more northerly direction (342°) is indicated for the seamount chain between Kimei and Meiji, corresponding to the time between 40 and 71.4 million years ago. Earlier movement at about 305° is suggested by seamounts older than Meiji.

(d) How far has the Meiji seamount moved from the hot spot? Explain your reasoning.

The distance must be measured along the hotspot track, not in a straight line connecting Kilauea/Loihi and Meiji, i.e., ~ 2,150 km.

EXERCISE 2.9 continued

Name: ____________________ Section: __________
Course: ____________________ Date: __________

(e) At what rate has the Pacific Plate moved

(i) based on data from the Hawaiian Islands alone? **75 mm/yr (average)**
(ii) based on data from the Hawaii-Midway segment? **52 mm/yr**
(iii) based on data from the Hawaii-Kimei segment? **66 mm/yr**
(iv) based on data from the Kimei-Meiji segment? **34 mm/yr**

(f) What is the best set of data to use for estimating the rate of motion of the Pacific Plate over the full 71-million-year span? Explain.

The *average velocity* could be obtained by dividing total distance traveled by total time involved. More detailed information about separate legs can be determined as in (e) and weighted averages calculated for parts of the system.

(g) Has the Meiji seamount moved at a constant rate? Explain your reasoning.

No. It moved relatively slowly for the first 31.4 million years [as shown in (e)] but moved faster for the later 40 million years.

(h) In what direction is the Pacific Plate moving today? Explain your reasoning.

Based on the Hawaii-Emperor seamount chain as shown in Figure 2.15, the Pacific plate is moving in the direction 297°. Based on more detailed information for the most recent movement of the Hawaiian Islands only (Fig. 2.13) the direction is 340°.

(i) Assuming that the current direction of motion continues, what will be the eventual fate of the Meiji seamount? Explain in as much detail as possible.

Meiji seamount will be subducted, whichever direction from (h) is used. If the direction is 297°, it will be subducted below the Kurile-Japan island arc system. If the direction is 340°, it will be subducted beneath the Aleutian island arc system.

EXERCISE 2.10 continued

Name: __________
Course: __________

Answers on next page

Rifting has split Africa from the Arabian Peninsula to form the Red Sea. A new ocean ridge and ocean lithosphere have formed in the southern two-thirds of the Red Sea. A narrow belt of deeper water defines the trace of this ridge. At the northern end of the Red Sea, the ridge/rift axis is cut by a transform fault that runs along the eastern side of the Sinai Peninsula and through the Dead Sea.

(a) Use a red line to show the trace of the Red Sea rift/ridge axis. Use a purple line to show the trace of the Dead Sea transform fault.

(b) The narrow ocean bordering the southeast edge of the Arabian Peninsula is the Gulf of Aden. Use red and purple lines to trace the ridge segments and transform fault in this narrow sea.

(c) Based on the geometry of the ridges and transform faults in the Red Sea and Gulf of Aden, draw an arrow showing the motion of the Arabian Peninsula (the Arabian Plate) relative to Africa.

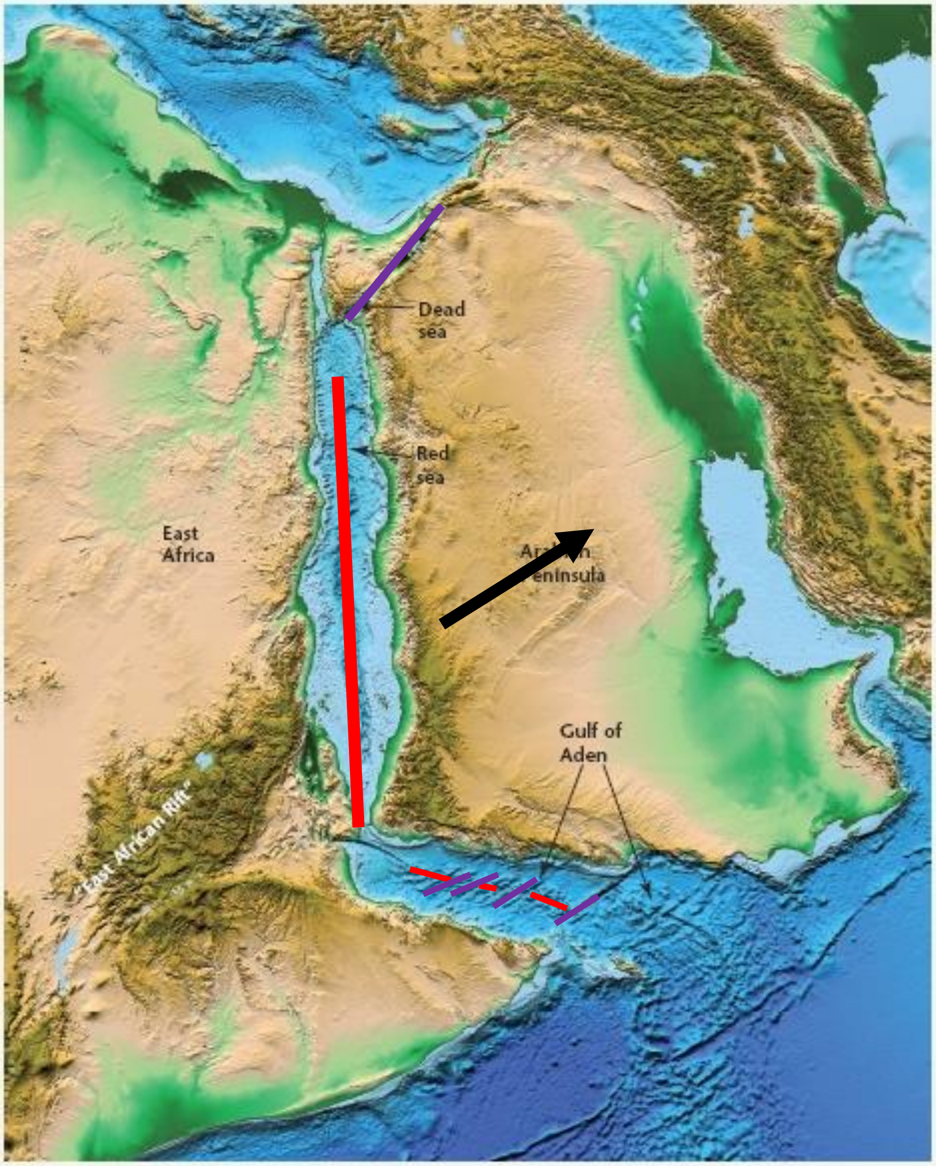
EXERCISE 2.10 Continental Rifting: Forming the Next Ocean

Name: ______________________________ Section: __________

Course: ______________________________ Date: __________

Examine the bathymetric/physiographic map of the region that includes eastern Africa, the Red Sea, and the western Indian Ocean (Fig. 2.16). Eastern Africa is beginning to break away from the western part. The split is occurring along the East African Rift, a deep valley locally filled with lakes and bordered by steeply uplifted land.

FIGURE 2.16 Red Sea rift zone.



EXERCISE 2.11 Subduction Zones

Name: ______________________ Section: __________
Course: ______________________ Date: __________

(a) Based on island arc-trench geometry illustrated in Figure 2.17, what factors determine the width of the arc-trench gap? Explain.

The steepness of subduction determines the width of the arc-trench gap. The steeper the subduction, the more rapidly the descending plate reaches melting depth and the narrower the gap. The gentler the subduction, the greater the horizontal distance needed to reach the melting depth, and therefore the greater the arc-trench gap will be.

(b) Based on your answer to (a), sketch two island arc-trench systems, one with a wider arc-trench gap than the other.

Figure 2.18 shows profiles across four segments of the Aleutian island arc, which extends westward from mainland Alaska. The positions of the volcanic arc and trench are indicated in each profile.

(c) In the profiles showing the earthquakes (on the next page), sketch the upper and lower boundaries of the subducted plate, assuming that the deepest part of the Aleutian Trench is at the middle of the trench. Explain why you drew the boundaries where you did.

See the following diagrams. The depth of melting can be estimated from the Amchitka segment by drawing a line downward from the arc until it intersects the upper region of the earthquake foci (as shown). Draw a horizontal line from there to the depth scale to determine the melting depth. Use this depth for the other Aleutian arc segments.

(d) At what depth does melting apparently begin beneath the Amchitka segment of the arc? Explain your reasoning.

~ 140 km as discussed above.

(e) *Assuming that melting occurs at the same depth everywhere* beneath the Aleutian arc, complete the other three profiles by drawing the subducted plates.

(f) From these profiles, estimate the arc-trench gap for the four segments of the Aleutian arc.

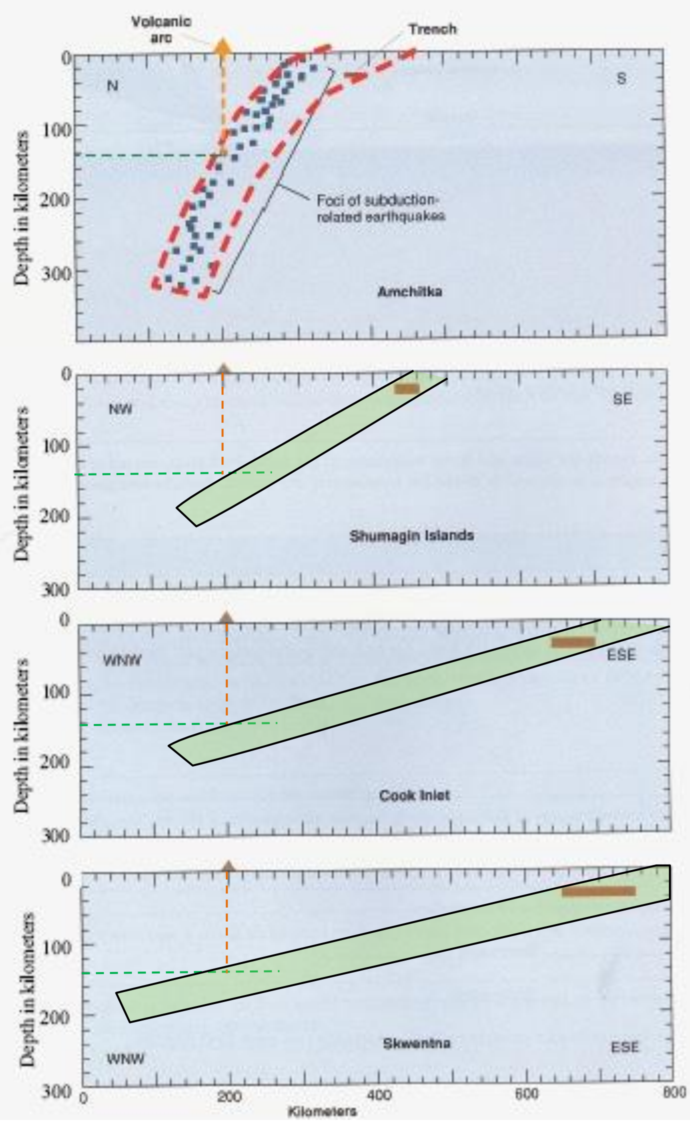
	Amchitka	Shumagin Islands	Cook Inlet	Skwentna
Arc-trench gap (km)	**150**	**250**	**530**	**540**

EXERCISE 2.11 continued

Name: ______________________________ Section: __________

Course: ______________________________ Date: __________

FIGURE 2.18 Profiles across the Aleutian island arc-trench system. Orange and green dash/dot lines illustrate calculation of melting depth.



EXERCISE 2.12 **Movement on Continental Transform Faults**

Name: ____________________ Section: __________
Course: ____________________ Date: __________

The San Andreas Fault system is a continental transform that links the East Pacific Rise, an actively spreading oceanic ridge segment in the Gulf of California, with another ridge segment to the northwest in the Pacific Ocean (Fig. 2.19a). Figure 2.19b shows four groups of distinctive rocks separated by the San Andreas system. The bodies shown in green are thought to have been a single mass at one time and are now separated by offset movement along the San Andreas transform fault system. The same conclusion has been reached about the other pairs of similarly colored rocks.

FIGURE 2.19 San Andreas Fault system.

(a) Geologic setting of the San Andreas Fault system. At its northern end, the sun Andreas links to the Cascade Trench and an oceanic tranform; at is southern end, it links to a mid-ocean ridge in the Gulf of California.

(b) Amount of fault movement indicated by offset bodies of identical rock.

continued

EXERCISE 2.12 continued

Name:______________________________ Section: ____________
Course: ______________________________ Date:______________

(a) Based on the offset of the rock bodies shown in Figure 2.19b, draw arrows to indicate the sense of slip along the San Andreas Fault system.

(b) Measure the amount of offset for each of the four rock types and record it below.

	Type of offset rock	Measured offset (km)	Average rate of fault motion (mm/yr)
Sedimentary		**320**	**16**
Volcanic igneous		**812**	**41**
Metamorphic		**375**	**188**
Intrusive igneous		**300**	**150**

(c) Motion along the San Andreas Fault system is thought to have begun around 20 Ma. Assuming that the four offset bodies of rock are older than 20 million years, calculate the average rate of fault motion for each.

(d) If an offset igneous body was dated at 10 million years old, how would its mapped displacement differ from that of these rocks? Why might the estimate of displacement rate be different?

Because this igneous body is more than 10 million years younger than the others, it would have experienced faulting for only half the time that the fault was active, whereas the others would have been offset for the entire span of fault activity. Therefore, the younger body would record less separation along the fault trace

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

Name: ______________________ Section: __________

Course: ______________________ Date: __________

Try to explain why some continental margins are active and others passive based on what you know about plate tectonics.

(a) Are all continental coastlines plate boundaries? *Explain.*

No. Only where a continental coastline coincides with either a transform fault or subduction zone will this be the case.

(b) Compare the west coast of South America with the west coast of Africa. Which has a broad continental shelf? A narrow shelf? Which is close to an ocean trench? Which coast would you expect to have the most earthquakes? Explain.

The west coast of South America has a very narrow continental shelf while that of Africa is much wider in most places. The west coast of South America is adjacent to the Peru–Chile trench, beneath which part of the Pacific Plate is being subducted. Earthquakes would be expected much more commonly on the west coast of South America, as evidenced by the Chilean earthquakes of 2010.

(c) On the plate tectonic map of the world (Fig. 2.1), label active continental margins with a red letter A and passive margins with a blue letter P.