

Unit 2

Exploring Plate Tectonics

In this unit, you will

- *Calculate the rate of spreading of the Atlantic Ocean.*
- *Investigate whether plate spreading rates change with time or vary across the globe.*
- *Predict the ultimate fate of the Juan de Fuca plate.*
- *Use the Hawaiian Islands to determine the rate of motion of the Pacific tectonic plate.*
- *Determine when San Francisco and Los Angeles will finally be neighbors across the San Andreas Fault.*



Robert E. Wallace, USGS

Aerial view of the San Andreas fault slicing through the Carrizo Plain east of the city of San Luis Obispo, California.

Warm-up 2.1

Testing plate tectonics

You now know that Earth's plates are constantly growing, shrinking, and moving around. This means that Earth must have looked very different in the past.

Questions for thought and discussion

1. Earth's continents contain evidence that they were once in very different locations and may have had very different climates. List three signs or pieces of evidence that might indicate this.
 - a.
 - b.
 - c.

Answer the following questions on your own or in a small discussion group, as assigned by your instructor.

2. What would you do to gather the evidence described above?

Thinking deeper (optional question)

Some scientists have suggested that even small changes in the shape, location, orientation, or topography of continents or oceans could significantly affect life on Earth.

3. Describe how even a small change in Earth's surface might have a major effect on life on the planet. Draw pictures to illustrate your point.




Investigation 2.2 Investigating seafloor age

In this activity, you will investigate evidence that tectonic plates change in size, shape, and location over time. This evidence suggests that plate tectonics has occurred for hundreds of millions of years.

 Launch ArcMap, and locate and open the **ddde_unit_2.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

 In the Table of Contents, right-click the **Changing Plates** data frame and choose Activate.

 Expand the **Changing Plates** data frame.

This data frame shows differences in the age of the rocks that form the ocean floor. These ages were determined using data from several sources, and have been summarized, mapped, and color-coded. The age bands generally run parallel to the spreading ridges. Seafloor age is a critical piece of evidence for plate tectonics. It shows us where new seafloor is created and how often. It can also be used to reconstruct how ocean basins have grown in the past, and how they may change in the future.

Spend a few minutes examining the seafloor age data. Use the **Seafloor Age** legend to answer these questions.

m.y.— millions of years [ago].
This abbreviation is used to represent the age of material in past geologic time. For example, if a material is dated as “180 m.y.,” it means it is 180 million years old.

1. How many years does each colored band represent?
2. What happens to the age of the seafloor in the Atlantic Ocean as distance increases from the Mid-Atlantic Ridge?
3. How long ago did the North Atlantic Ocean begin to “open up,” or spread, near what is now the East Coast of the United States? Describe the reasoning you used to arrive at this answer.

4. Did the North Atlantic Ocean basin open up at the same time as the South Atlantic Ocean basin near South America? Describe evidence that supports your answer.

5. How could the widths of the age bands be used to figure out if the rate of plate spreading has been constant over time?

6. The oldest continental rocks formed 3.8 billion years ago. What is the age of the oldest seafloor?

7. Why do you think there is such a difference in age between the oldest seafloor and the oldest continental rocks? (Hint: Near which type of plate boundary do you find the oldest oceanic rocks?)

8. During the time since the oldest continental rocks formed, about how many times could the world's ocean floors have been completely "recycled"? (Hint: Divide the age of the oldest continental rocks [3.8 billion years] by the age of the oldest seafloor [answer to question 6].)

Hint for question 7

Turn on the **Plate Boundaries** layer if necessary.

 Quit ArcMap and do not save changes.



Reading 2.3

Determining seafloor age

Paleomagnetism

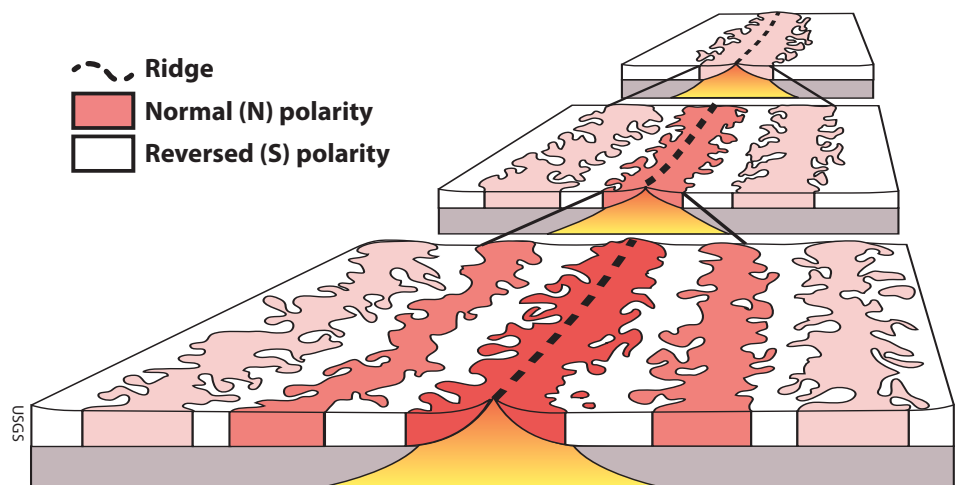
Earth has a magnetic field that is like a bar magnet — one end is positive and one is negative. For reasons that are not fully understood, Earth's magnetic field changes **polarity**. That is, the north and south magnetic poles reverse. This process has occurred at uneven intervals, roughly once every 250,000 years over the past 5 million years.

As the ocean floor spreads at mid-ocean ridges, magma from the mantle wells up and solidifies onto the plate near the ridge. This process forms the volcanic rocks that make up the ocean floor.

When the newly formed **lithosphere** (made up of the solid upper mantle and Earth's crust) cools, some of the minerals become magnetized and align with Earth's magnetic field. This “fossil magnetism” preserves a record of the direction of Earth's magnetic field at the time the rocks formed.

Some bands of oceanic lithosphere formed when Earth's magnetic field was like it is today. We call this **normal polarity**. Other bands of oceanic lithosphere formed when Earth's magnetic field had the opposite polarity. We say these bands have **reversed polarity**.

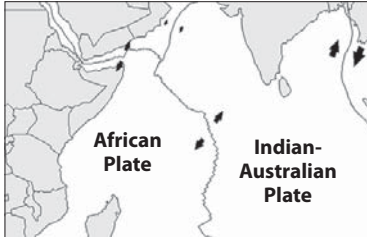
The polarity changes of Earth's magnetic field are not regular. Instead they make complex sequences of normal and reversed polarity. The combination of seafloor spreading and changes in magnetic polarity form a unique pattern similar to the bar codes on products you buy at the store. Ships carrying sensitive equipment have crisscrossed the oceans recording the patterns of these fossil magnetic fields. Geologists can use the patterns to determine the age of the oceanic lithosphere.



Constructing continents

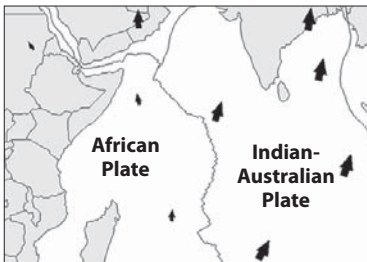
Some plates remain relatively unchanged for millions of years, but most are growing or shrinking in size. Over Earth's 4.8-billion-year history, many oceanic plates have been destroyed and new ones have been created. Continental plates have been torn apart and smashed together into new arrangements, as in the Himalayas. Plate tectonics is reshaping the face of our planet.

Relative plate motion



Arrows show the motion of the African plate and the Indian-Australian plate relative to each other.

Absolute plate motion



Arrows show the motion of the African plate and the Indian-Australian plate relative to a fixed reference point (a hot spot to the south).

Relative motion

All of Earth's plates are in motion. For this reason, it's often easier to describe a plate's motion relative to a neighboring plate.

For example, if you were standing on the eastern edge of the African plate looking at your dog Ralph (sitting very patiently) over on the bordering Indian-Australian plate, Ralph would appear to be moving away from you. To Ralph, *he* is the one sitting still while *you* move away from him. The motion is **relative to** the observer's point of view, or **frame of reference**. In actuality, however, this type of motion would occur over a very long period, geologically speaking.

Absolute motion and hot spots

When talking about entire plates, scientists often prefer to describe the plate motions relative to a common frame or point of reference. Ideally, this reference point is not moving like the plates but is **stationary**, or fixed, deep within Earth.

There are approximately 20 places around the Earth where the mantle below the lithosphere is unusually hot. These **hot spots** partially melt the plates above them, creating topographic bulges and chains of volcanoes. Although their origin is not completely understood, hot spots appear to be stationary and provide a frame of reference for measuring **absolute**, or true, plate motions.

Two of these hot spots are located in the United States. One is under the Big Island of Hawaii at the southeast end of the Hawaiian Island chain. The other is in Yellowstone National Park and is responsible for the volcanic and geothermal activity in that region.

Studying plate motions in a fixed frame of reference provides scientists with a better understanding of the forces that drive plate tectonics.

Spreading rates

Scientists measure spreading rates of oceanic lithosphere near spreading ridges as either a "half" or a "whole" rate.

The **half-spreading rate** is the rate at which newly formed lithosphere is added to either one or the other of the two plates separated by a spreading ocean ridge.

The **whole-spreading rate** is the combined rate at which the two

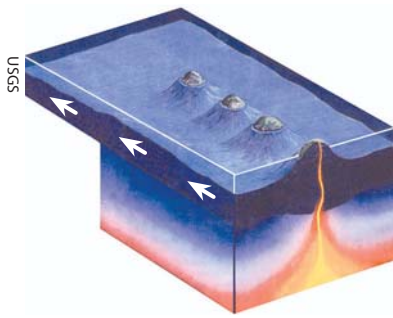


A *Titanic* example of spreading rates

The wreck of the *Titanic* rests at the bottom of the Atlantic Ocean to the west of the Mid-Atlantic Ridge. It moves about 15 mm farther west of that ridge each year. So the half-spreading rate at this location is 15 mm/yr. Thus, the whole-spreading rate is 2×15 mm or 30 mm/year.

As the Atlantic Ocean widens, the *Titanic* is slowly being carried away from where it originally left England at a rate of about 3 cm (a little over an inch) per year.

Disappearing islands



The Hawaiian and Emperor volcanic chains mark the motion of the Pacific plate over a stationary hot spot. As each volcanic island is carried past the hot spot, wave action quickly erodes the exposed island completely away, leaving a submerged **seamount**.

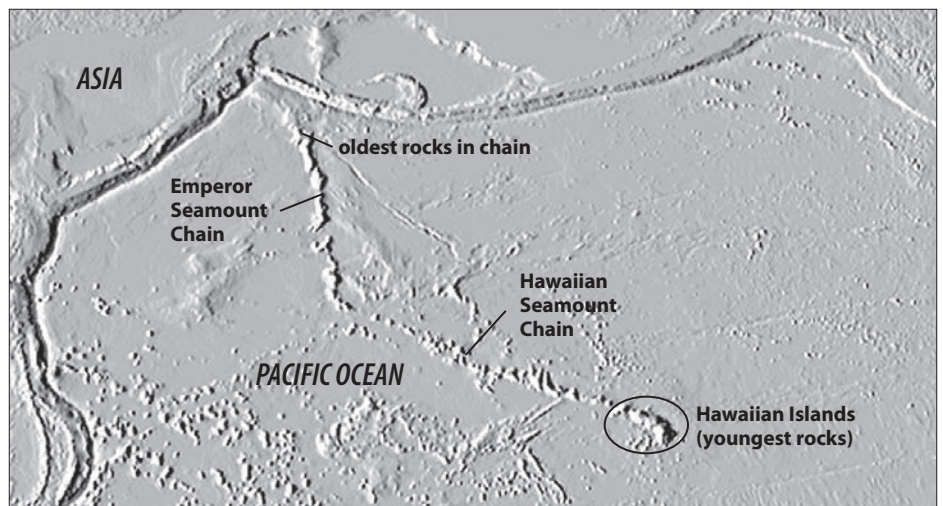
Earth's heat engine — slowly “running out of gas”

As Earth cools, the convection that drives the plates is gradually slowing down. Eventually — in billions of years — Earth will have lost most of its internal heat to space, and plate motions will slowly grind to a stop.

plates separated by a ridge are moving away from each other. Usually, equal amounts of new oceanic lithosphere are added to both plates as they move apart. The whole-spreading rate is therefore twice the half-spreading rate. This means you can measure the half-spreading rate for one plate and double it to get the whole-spreading rate.

Changes in plate motion

Spreading rates away from spreading ridges and the directions of plate motions have changed many times during the past 200 million years. The Pacific plate experienced a particularly dramatic change in direction about 43 million years ago. If you examine the pattern of volcanoes extending northwest from Hawaii in the map below, you will notice that they form two intersecting chains, the Hawaiian and the Emperor volcanic chains.



Seafloor topography of the northern Pacific Ocean basin.

By measuring the ages of rocks in each chain, we know that the “bend” in the chain occurred around 43 million years ago. Prior to that time, the Pacific plate was moving in a north-northwest direction, then abruptly (in geologic time, anyway) changed to a more west-northwest direction. Other seamount chains in the Pacific show a similar pattern.

Sudden changes in plate motion occur when two or more continents collide. Continental plates are too buoyant to be subducted. Instead, they plow into each other and pile up to form mountains. The Himalayas, the highest mountains on Earth, are being thrust upward as the Indian-Australian and the Eurasian plates collide. This has been going on continuously for the past 50 million years. Since the two plates first made contact, the rate of seafloor spreading in the Indian Ocean has decreased considerably.

Questions

1. How are magnetic minerals in the oceanic lithosphere used to determine its age?
2. What is the difference between the relative motion and the absolute motion of a plate?
3. If the half-spreading rate at a plate boundary is 3 cm/yr, what would the whole-spreading rate be at that boundary?
4. What might cause a plate to slow its rate of movement or change direction?



Investigation 2.4 Investigating plate motion

In this section, you will measure the rate at which new lithosphere has formed along the Mid-Atlantic Ridge over the past 140 million years. Then, you will examine how this rate changed as the Atlantic Ocean opened.

Rate of spreading

To calculate the whole-spreading rate, you need to know the total width of new lithosphere formed and the time it took to create it.

m.y.— million years


$$\text{whole-spreading rate} = \frac{\text{total width of new lithosphere (km)}}{\text{time required to create new lithosphere (m.y.)}}$$

An easy way to do this is to measure the *half-spreading rate*— the width of new lithosphere created on one side of the spreading ridge— and double it.

Measuring new lithosphere


 Launch ArcMap, and locate and open the **ddde_unit_2.mxd** file.

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 In the Table of Contents, right-click the **Changing Plates** data frame and choose Activate.

 Expand the **Changing Plates** data frame.

This data frame shows the spreading rates at spreading ridges located around the world. Each color band represents a 20-million-year time interval. To determine the width of new lithosphere created in the North Atlantic Ocean during each 20-million-year time interval:

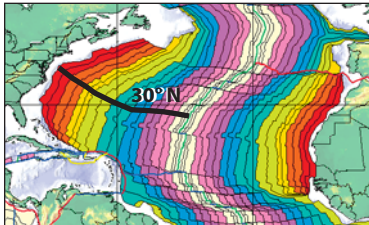
 Turn on the **Latitude/Longitude**, **Plate Boundaries**, and **Seafloor Age** layers.

 Click the QuickLoad button .

 Select **Spatial Bookmarks**, choose **Atlantic Ocean Middle** from the list, and click **OK**.

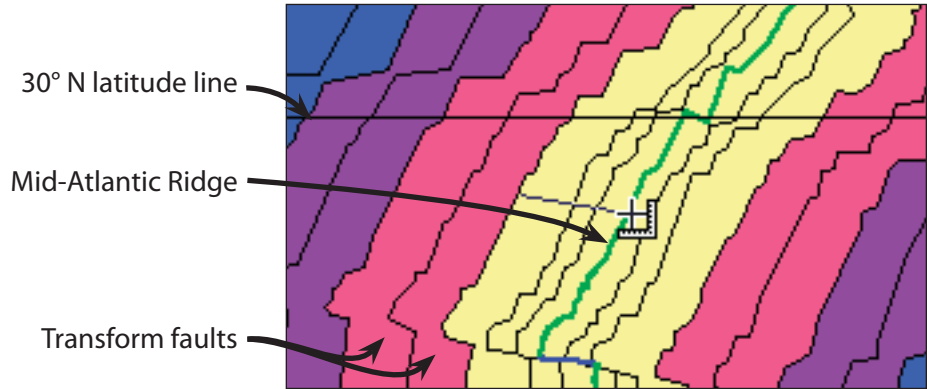
The seafloor in the middle of the Atlantic Ocean should now be centered on your map.


Locator map



Path for measuring the spreading rate of the Mid-Atlantic Ridge in the North Atlantic Ocean.

Measuring the first seafloor age interval



Using the Measure tool , click on one side of an interval, drag across to the other side of that interval, and double-click. For the 0 – 20-million-year interval (lightest), measure from the outer edge of the interval to the Mid-Atlantic Ridge (thick line, in the illustration at left). Measure perpendicularly to the spreading ridge, as shown in the illustration above.

Read the width (Total) of new lithosphere created during that time interval on the status bar, located at the bottom left corner of the map. (Your width will be different from the example below.)

Segment: 306.206774 Total: 306.206774 Kilometers

1. Record your results in the **Width** column of the table provided below. Repeat this measurement for each of the other time intervals.

Time before present <i>m.y.</i>	Width <i>km, measured</i>	Half-rate <i>mm/yr, calculated</i>	Whole-rate <i>mm/yr, calculated</i>
0-20			
21-40			
41-60			
61-80			
81-100			
101-120			
121-140			

Calculating spreading rates

Here's an example of calculating the spreading rates. Assuming the measured width is 260 km,

$$\begin{aligned}
 \text{Width} &= 260 \text{ km} \\
 \text{Half-Rate} &= \text{Width/Time} \\
 &= \frac{(260 \text{ km} \times 1,000,000 \text{ mm/km})}{20,000,000 \text{ yrs}} \\
 &= 13 \text{ mm/yr} \\
 \text{Whole-Rate} &= \text{Half-Rate} \times 2 \\
 &= 13 \text{ mm/yr} \times 2 \\
 &= 26 \text{ mm/yr}
 \end{aligned}$$

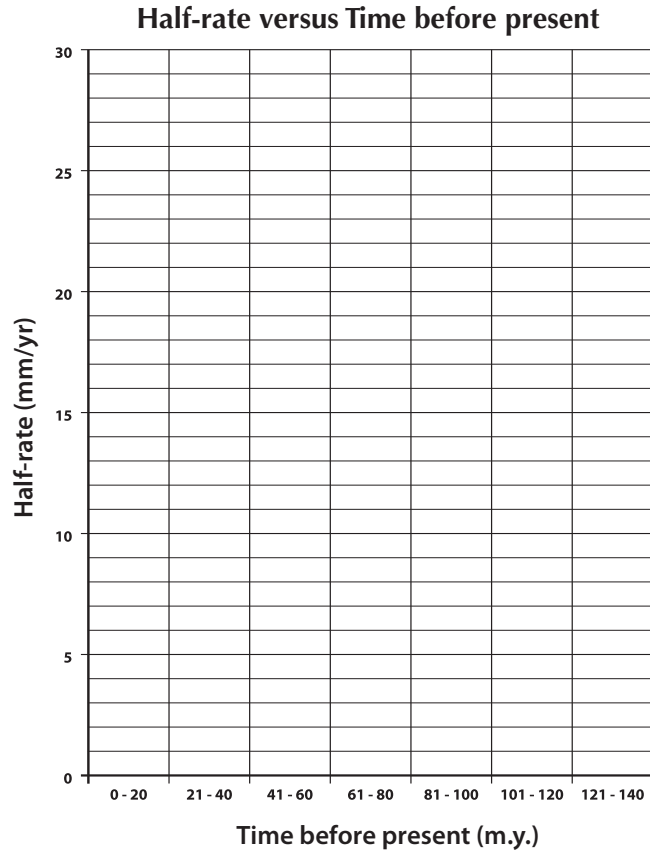
Computing the rates of spreading

Following the example shown at the left, perform the following calculations for each time interval listed in the left column of the table above.

2. Calculate the half-spreading rate, in mm/yr, and enter your answer in the **Half-rate** column. Convert units as necessary.



3. Calculate the whole-spreading rate, also in mm/yr, and enter your answer in the **Whole-rate** column of the table.
4. Use the bar graph below to plot the **Half-rate** versus **Time before present** from the table on the previous page.



5. How has the spreading rate changed over time, according to the bar graph?

Compare the Atlantic to the Pacific

Are all spreading ridges alike? Next, you will compare the seafloor age patterns in the South Pacific and South Atlantic oceans.


You could calculate the rate of spreading in the South Pacific Ocean as you did for the North Atlantic Ocean, but you can also compare the rates by comparing the width of the age bands in the South Pacific to those in the North Atlantic. This data frame distorts distances at different latitudes, so compare age bands at similar latitudes (e.g., 30° N and 30° S).



 Click the Full extent button  to view the entire map.

6. Which ridge is spreading faster (Atlantic or Pacific)? How can you tell?

Reading seafloor age

To read the age of the seafloor at any location, select the **Seafloor Age** layer and click on that location using the Identify tool . (Be sure to select the **Seafloor Age** layer in the Identify Results window.)

Which ocean is this?

If you aren't sure which ocean is which, turn on the **Ocean Labels** layer.

Juan de Fuca plate

The Juan de Fuca plate is located off the western coast of North America.



The age of the oldest rocks in an ocean basin indicates when the basin began to form.


7. Examine the seafloor ages in the South Pacific. Was the spreading rate constant over time? Describe any changes in the spreading rate that have occurred over the past 120 million years.
8. Determine which ocean basin has the oldest of the old rocks, using the **Seafloor Age** legend. (This is the oldest ocean basin.) Which has the youngest of the old rocks? (This is the youngest ocean basin.)
- Oldest —
 - Youngest —

Juan de Fuca's disappearing plate trick

The relative youth of the oldest oceanic lithosphere (less than 180 million years old) tells us that over the course of Earth's 4.8-billion-year history, many plates have come and gone. An example of a plate destined to disappear is the Juan de Fuca plate, located off the coast of Washington and Oregon. Assuming this plate continues moving at its current velocity, it should be possible to estimate when it will completely disappear.

Next, you will zoom in on the Juan de Fuca plate, located just off the northwestern coast of the U.S. (see map at left):

 Click the QuickLoad button .






 Select **Spatial Bookmarks**, choose **Juan de Fuca Plate** from the list, and click **OK**.



-  Turn on the **Plate Boundaries** layer.
-  Turn on the **Plates** layer.



9. Label the types of plate boundaries on the map below.



-  Click the Identify tool .
-  In the Identify Results window, select the **Plates** layer from the list of layers.
-  Use the Identify tool  to find the names of the three plates that form the plate boundaries.

10. On the map above, label the three plates with their names.

11. Under which plate is the Juan de Fuca plate being subducted?

-  Use the Measure tool  to measure the widest part of the Juan de Fuca plate in a northwest-southeast direction, perpendicular to the spreading ridge.

12. Based on your measurement, how many kilometers of this plate must be subducted for the plate to disappear completely?

By measuring plate motions, scientists know that the new oceanic lithosphere is being formed at the spreading ridge on the western side of the Juan de Fuca plate at a rate of about 25 mm/year, while it is being subducted at the trench on its eastern side at a rate of about 30 mm/year.

13. Overall, how fast is this plate shrinking in an east-west direction each year?

Can you find the time?

Since you know that...

$$\text{distance} = \text{speed} \times \text{time}$$





...you can rearrange the equation to find the time.

$$\text{time} = \text{distance} \div \text{speed}$$

14. At this rate, how long will it take for the Juan de Fuca plate to disappear completely?
- Convert the rate you calculated in question 13 from mm/yr to km/yr.
 - Divide the distance (km) you calculated in question 12 by the rate (km/yr) you calculated in question 14a.

The Hawaiian-Emperor Volcanic Chain






You have seen that Earth's plates are in constant motion. How does this motion affect populated areas over time? In the next two sections, you will look at how plate motions are rearranging the United States. First you will examine the Hawaiian-Emperor Volcanic Chain to see what you can learn about plate motions.

-  Click the Full extent button  to view the entire map.
-  Turn off all layers except **States**, **Countries**, and **Topography**.
-  Turn on the **Hawaiian Volcanoes (Wrap)** layer. Leave the **Hawaiian Volcanoes (No Wrap)** layer off for the moment.




The red symbols represent volcanoes in the Hawaiian-Emperor Volcanic Chain. Using radioactive dating of elements in Earth's crust, scientists have shown that the volcanoes were not all formed at the same time. Notice that the chain extends past the western (left) edge of the map and continues on the eastern (right) edge. Take a moment to explore the volcanoes.

-  Turn off the **Hawaiian Volcanoes (Wrap)** layer.
-  Turn on the **Hawaiian Volcanoes (No Wrap)** layer.
-  Select the **Hawaiian Volcanoes (No Wrap)** layer.

In this layer, the volcanoes are grouped on one side of the map for your convenience.

-  Click the QuickLoad button .
-  Select **Spatial Bookmarks**, choose **Hawaii Volcanoes** from the list, and click **OK**.
-  Click the Identify tool .



-  In the Identify Results window, select the **Hawaiian Volcanoes (No Wrap)** layer from the list of layers.
 -  Use the Identify tool  to find the age (in millions of years), latitude, and longitude of the volcano located at the northwestern-most (upper left) end of the chain. (Note: Negative latitude and longitude values indicate directions of south and west, respectively.)
15. Record the volcano’s name, age, latitude, and longitude in the first row of the table below.





Name	Age <i>m.y.</i>	Latitude <i>°N-S</i>	Longitude <i>°E-W</i>

What is “S.M.”?



The volcanoes that you identify in the **Hawaiian Volcanoes (No Wrap)** layer often have an “S.M.” after their name. This simply refers to the term “seamount”.

16. Record the names, ages, and geographic coordinates of five other volcanoes in the table. Choose volcanoes along the entire length of the chain. Make sure to go in order from northwest (upper left) to southeast (lower right), and to include the volcano at the southeastern-most end of the chain. (Zoom in, if needed, to identify this last volcano in the chain.)
17. What trend do you observe in the ages of the volcanoes as you follow the chain from the northwest to the southeast?

Assuming that the hot spot that formed these volcanoes is not moving, and that the motion of the Pacific plate over the hot spot is responsible for the existence of the chain, you can determine the rate at which the plate is moving.

-  Use the Identify tool  to locate Kinmei Seamount on the map. It’s near the bend in the chain.
18. How long ago was Kinmei Seamount formed?
-  Close the Identify Results window.
 -  Locate Kilauea Volcano at the southeast end of the island of Hawaii.



 Use the Measure tool  to measure the distance between Kinmei Seamount and Kilauea.

19. How far did the Pacific plate move in the time between the formation of Kinmei Seamount and of Kilauea?


20. Assume the Pacific plate moved at a constant rate between the formation of Kinmei Seamount and Kilauea. At what rate has it moved? (See “Rate of Spreading” on page 43.)



 Turn on the **Absolute Motion** layer.


 Select the **Absolute Motion** layer.

This layer shows the speed and direction of plate motion relative to fixed locations (hot spots) for various points around the globe.

 Click the Identify tool .

 In the Identify Results window, select the **Absolute Motion** layer from the list of layers.

 Using the Identify tool , click on the brown arrow symbol just south of the Hawaiian islands. (*Important — see tip at left.*)

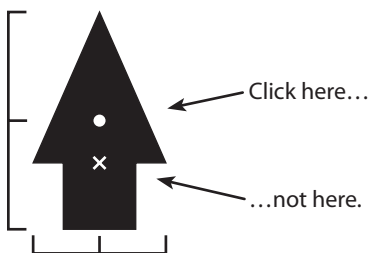
 Read the speed of the plate at that location in the Identify Results window.

21. How does the rate you calculated in the previous question compare to the absolute rate of motion near the Hawaiian Islands today?

 Close the Identify Results window.

Where to click?

Clicking on the arrow symbol can be tricky. When using the Identify tool on the **Absolute Motion** layer's arrows, you need to click on the center of the arrow. Because the “arrowhead” is longer than the “shaft,” the center is not where you expect it to be. The diagram below shows where to click.



A (future) tale of two cities






Several of Earth's plate boundaries cut through heavily populated and economically important areas.

 Click the QuickLoad button .








 Select **Data Frames**, choose **Two Cities** from the list, and click **OK**.

The San Andreas Fault is a transform plate boundary that runs along the California coast. In time, the motion along this boundary will significantly change the face of the state and the fate of its two most famous cities.





-  Click the Identify tool .
-  In the Identify Results window, select the **Plates** layer from the list of layers.
-  Use the Identify tool  to find the names of the plates on which San Francisco and Los Angeles are located.

22. On which plates are the following cities located?
- a. San Francisco
 - b. Los Angeles

-  Turn on the **Relative Motion** layer.
-  Select the **Relative Motion** layer.
-  Click the Identify tool .
-  In the Identify Results window, select the **Relative Motion** layer from the list of layers.
-  Use the Identify tool  to find the relative speed of the Pacific plate. This is how fast Los Angeles is approaching San Francisco.

23. How fast (in mm/yr) is the Pacific plate moving northwest relative to the North American plate?

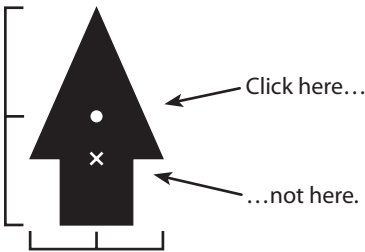
-  Use the Measure tool  to measure the present distance (in meters) between San Francisco and Los Angeles as a straight line. Read the distance in the status bar.

24. How far apart are Los Angeles and San Francisco today? Record your answer in both meters and millimeters.

25. At their current rate of relative motion, how many years will it take San Francisco and Los Angeles to become suburbs of each other? (Hint: Use the equation at left. Don't forget to use the distance in millimeters from question 24.)

Where to click?

Clicking on the arrow symbol can be tricky. When using the Identify tool on the **Relative Motion** layer's arrows, you need to click on the center of the arrow. Because the "arrowhead" is longer than the "shaft," the center is not where you expect it to be. The diagram below shows where to click.



Can you find the time?

Since you know that...

$$\text{distance} = \text{speed} \times \text{time}$$

...you can rearrange the equation to find the time.

$$\text{time} = \text{distance} \div \text{speed}$$

26. There is a lot of evidence that tropical palm trees once grew in Antarctica and the southern parts of Chile and Argentina 30 million years ago. Explain how this could have happened when these places are so far from the tropics today.

 Quit ArcMap and do not save changes.



