LABORATORY 2

Plate Tectonics and the Origin of Magma

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View of a rift valley, looking north across Thingvelir National Park, Iceland. Cliffs in the foreground (west side of rift) are part of the North American Plate. Hills in the background are across the rift valley, on the Eurasian Plate. The plates are diverging (moving apart). (Photo by Ragnar Sigurdsson/Arctic/Alamy)

BIG IDEAS

Tectonics is the study of global processes that create and deform lithosphere. Plate tectonics is the theory that Earth's lithosphere is broken into dozens of plates (thin curved pieces). The plates are created and destroyed, move about, and interact in ways that cause earthquakes and create major features of the continents and ocean basins (like volcanoes, mountain belts, ocean ridges, and trenches).

FOCUS YOUR INQUIRY

THINK About It | Is the lithosphere beneath your feet really moving?

THINK About It | What causes plate tectonics?

THINK About It | How are plate boundaries identified? How and at what rates does plate tectonics affect Earth's surface?

THINK About It | What are hot spots, and how do they help us explain plate tectonics?

THINK About It | How and where does magma form?

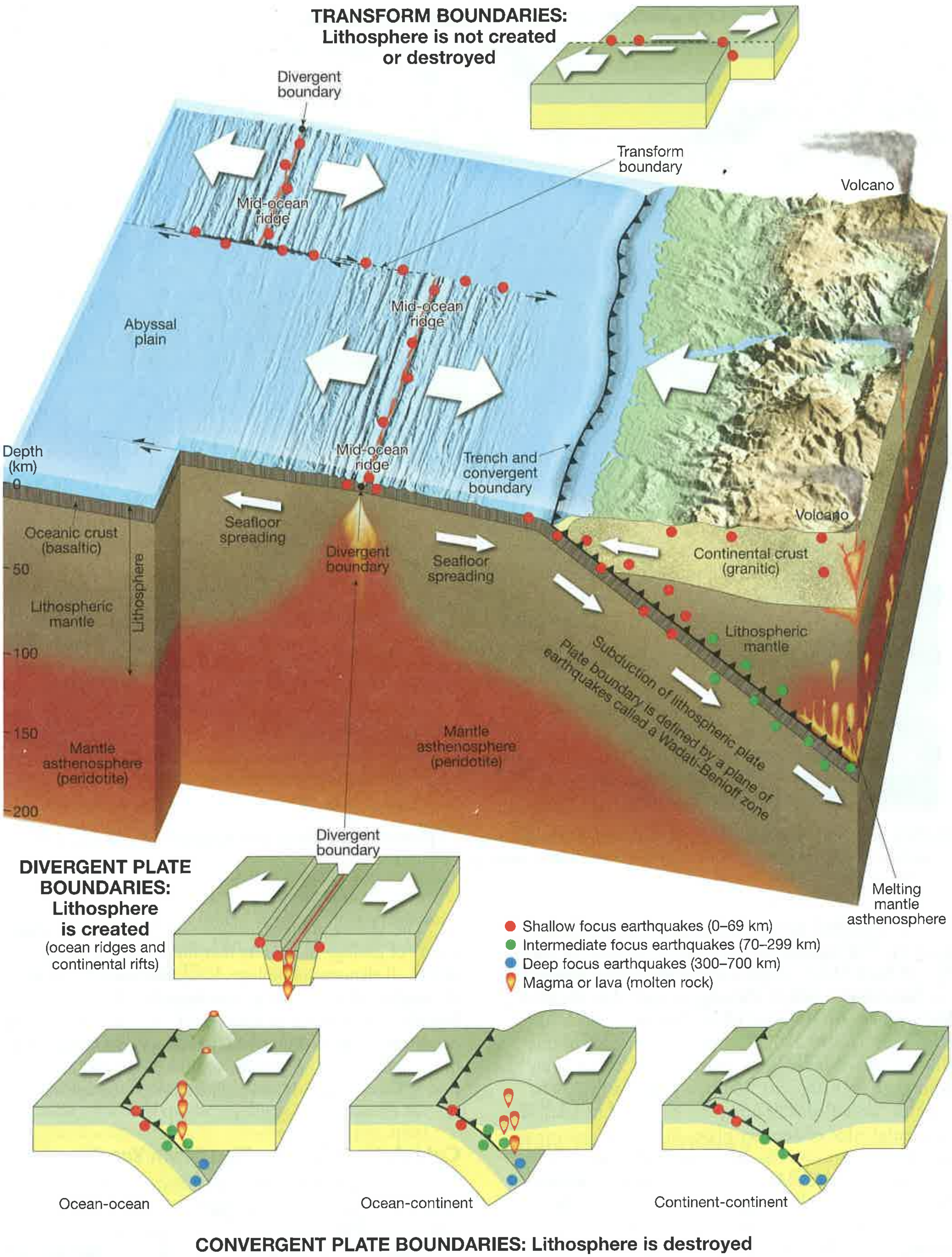


FIGURE 2.2 Three kinds of plate boundaries: divergent, convergent, and transform boundaries. White arrows indicate motions of the lithospheric plates. Half arrows on the transform fault boundary indicate relative motion of the two blocks on either side of the fault. The focus of an earthquake is the exact location where an earthquake occurred (shallow, intermediate, or deep). Water in subducted plates can lower the melting point of rock just above them at intermediate depths and lead to formation of volcanoes.

ACTIVITY 2.1 Plate Motion Inquiry Using GPS Time-Series

THINK About It | **Is the lithosphere beneath your feet really moving?**

OBJECTIVE Use NASA GPS (Global Positioning System) time series to determine the vector direction and rate of lithospheric plate motion where you live.

PROCEDURES

1. **Before you begin**, read about the GPS time series below. Also, this is **what you will need** to do the activity:
   - ____ calculator, ruler
   - ____ protractor (optional), cut from GeoTools Sheet 4 at the back of the manual.
   - ____ Activity 2.1 Worksheets (pp. 55–56) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

GPS—Global Positioning System

The Global Positioning System (GPS) is a technology used to make *precise* (exact) and *accurate* (error free) measurements of the location of points on Earth. It is used for geodesy—the science of measuring changes in Earth's size and shape, and the position of objects, over time.

The GPS technology is based on a constellation of about 30 satellites that take just 12 hours to orbit Earth. They are organized among six circular orbits (20,200 km, or 12,625 mi above Earth) so that a minimum of six satellites will be in view to users anywhere in the world at any time. The GPS constellation is managed by the United States Air Force for operations of the Department of Defense, but it is free for anyone to use anywhere in the world. Billions of people rely on GPS daily.

How GPS Works

Each GPS satellite communicates simultaneously with fixed ground-based Earth stations and other GPS satellites, so it knows exactly where it is located relative to the center of Earth and Universal Time Coordinated (UTC, also called Greenwich Mean Time). Each GPS satellite also transmits its own radio signal on a different channel, which can be detected by a fixed or handheld GPS receiver. If you turn on a handheld GPS receiver in an unobstructed outdoor location, then the receiver immediately acquires (picks up) the radio channel of the strongest signal it can detect from a GPS satellite. It downloads the navigational information from that satellite channel, followed by a second, third, and so on. A receiver must acquire and process radio transmissions from at least four GPS satellites to triangulate a determination of its exact position and elevation—this is known as a fix. But a fix based on more than four satellites is more accurate. In North America and Hawaii, the accuracy of the GPS constellation is also augmented by WAAS (Wide Area Augmentation System) satellites operated by the Federal Aviation Administration. WAAS uses ground-based reference stations to measure small variations in GPS satellites signals and correct them. The corrections are transmitted up to geostationary WAAS satellites, which broadcast the corrections back to WAAS-enabled GPS receivers on Earth.

GPS Accuracy

The more channels a GPS receiver has, the faster and more accurately it can process data from the most satellites. Most 12-channel GPS receivers are accurate to within 9 meters of your precise location. Comparable WAAS-enabled GPS receivers are accurate to within 3 meters. The best GPS receivers have millimeter accuracy and can be used to measure things like the movement of lithospheric plates over years of time.

Using Gps to Study Lithospheric Plate Motion

NASA compiles geodetic information from receivers located at more than 2000 GPS reference stations throughout the world. At each GPS station, there is a rigid GPS monument (concrete and steel structure) attached firmly to bedrock (solid rock that is beneath the soil and a part of the lithosphere) or a building that is anchored in bedrock. A GPS receiver antenna is firmly attached to the monument, so it will not move unless its bedrock anchor moves. The bedrock may move in response to volcanic activity or earthquakes. It will also move as the lithospheric plate (that it is a part of) moves.

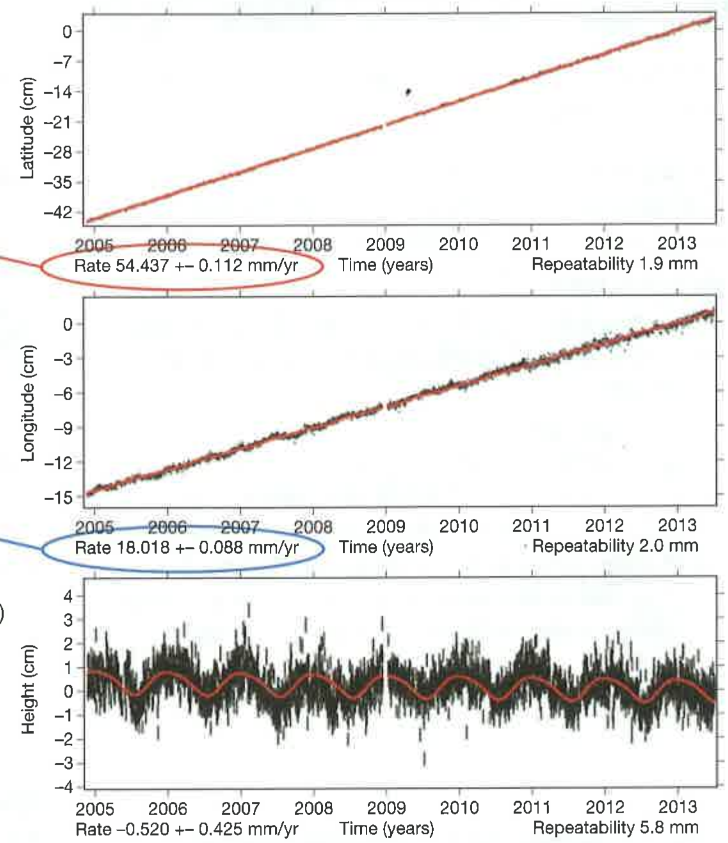
GPS Time Series

The exact location and elevation of each NASA GPS station has been monitored over time, as a **time series** (a series of observations made over time, FIGURE 2.3), by the California Institute of Technology's Jet Propulsion Laboratory (under NASA contract). Because each GPS station is anchored in bedrock of the lithosphere, the time series data provide data on movement (if any) of the lithospheric plate to which it is attached. Plate motion is determined using one graph of time series data for how the GPS station changed its latitude (position north or south) and another graph of time series data for how the GPS station changed its longitude (position east or west). The average rates of motion, in mm/yr or cm/yr, are provided with the

HOW TO PLOT AN ABSOLUTE PLATE MOTION VECTOR FROM NASA GPS TIME-SERIES AND CALCULATE VELOCITY OF THE PLATE MOTION

A. Choose a data location (geodetic position) at http://sideshow.jpl.nasa.gov/post/series.html and left-click on the green dot to open a small time-series box. Double-click on the box to enlarge. The time-series data in this example are for Sydney, Australia.

Time series for SYDN.



B. Record Latitude vector direction and velocity (be sure to note mm/yr or cm/yr).

- Positive value indicates North Latitude
- Negative value indicates South Latitude

Rate = 54.4 mm/yr
Positive value indicates North Latitude
(a negative value would indicate South Latitude)

C. Record Longitude vector direction and velocity (be sure to note mm/yr or cm/yr).

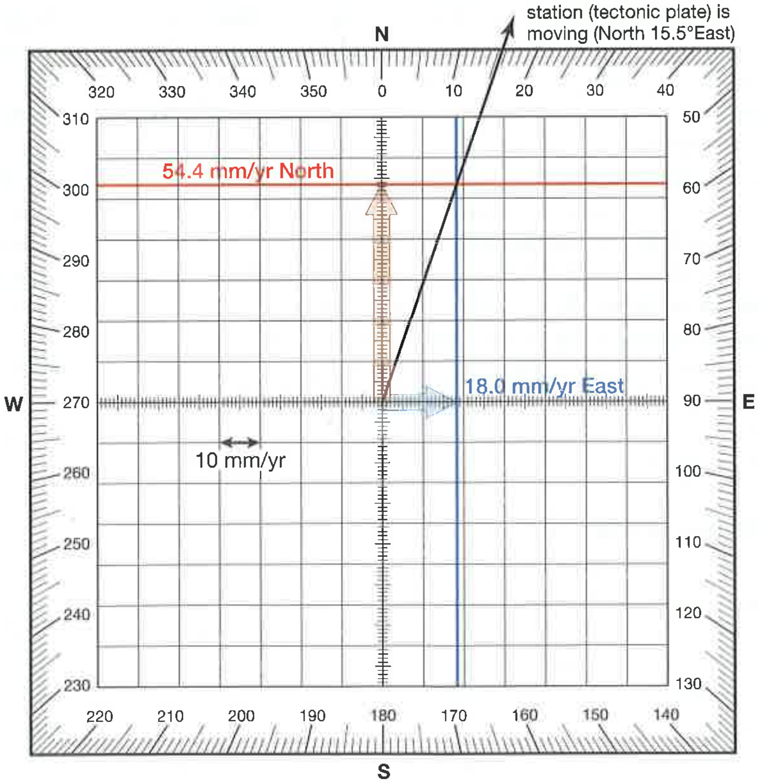
- Positive value indicates East Latitude
- Negative value indicates West Latitude

Rate = 18.0 mm/yr
Positive value indicates East Longitude
(a negative value would indicate West Longitude)

D. Plot the vector data on a Plate Motion Plotter like the one used here. In this example:

- The plotter has no numerical scale, so a determine the scale you wish to use (in this case 10 mm/yr scale was noted in black on the graph).
- Plot line (red) for 54.4 mm/yr North Latitude.
- Plot line (blue) for 18.0 mm/yr East Longitude.
- Draw line (black arrow) from the origin (center point in the graph), through the point where the Latitude (red) and Longitude (blue) lines intersect, and on through the compass edge of the plotter. Read the direction that the GPS station is moving (North 15.5 degrees East).

Black arrow is the vector direction that the GPS station (tectonic plate) is moving (North 15.5°East)



E. Calculate the velocity that the GPS station is moving as follows:

$$\text{Velocity} = \sqrt{(\text{Latitude velocity})^2 + (\text{Longitude velocity})^2}$$

In this example:

$$\text{Velocity} = \sqrt{(54.4\ \text{mm/yr})^2 + (18.0\ \text{mm/yr})^2}$$

$$= 57.3\ \text{mm/yr}$$

F. Sydney, Australia sits on a lithospheric plate that is moving North 15.5° East, at a velocity of 57.3 mm/yr.

FIGURE 2.3 How to determine direction and velocity of lithospheric plate motion using JPL-NASA GPS time-series data. (From the California Institute of Technology's, Jet Propulsion Laboratory. http://slideshow.jpl.nasa.gov/post/series.html) time series graph. You will need to combine the latitude and longitude data to determine the overall direction and rate of plate motion for the years that the data were collected. See **FIGURE 2.3**.

ACTIVITY

2.2 Is Plate Tectonics Caused by a Change in Earth's Size?

THINK About It | **What causes plate tectonics?**

OBJECTIVE Are Plate Tectonics Caused by a Change in Earth's Size?—Analyze and interpret Earth's tectonic forces and plate boundaries to infer if plate tectonics is caused by a change in Earth's size.

PROCEDURES

1. **Before you begin**, read below about what could cause plate tectonics and study **FIGURE 2.5**. Also, this is **what you will need** to do the activity:
   ____ calculator, ruler
   ____ Activity 2.2 Worksheets (pp. 57–58) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

What Causes Plate Tectonics?

Recall that geoscientists have historically tried to understand the cause of Earth's oceans, mountains, and global tectonics by questioning if Earth could be shrinking, expanding, or staying the same in size. This question can be evaluated by studying Earth's natural forces and faults in relation to those that you might predict to occur if the size of Earth were changing. By comparing your predictions to observations of the kinds of strains and faults actually observed, it is possible to determine if Earth's size is changing and infer whether a change in Earth's size could cause plate tectonics.

Earth Forces and the Faults They Produce

Three kinds of directed force (stress) can be applied to a solid mass of rock and cause it to deform (strain) by bending or even faulting (**FIGURE 2.4**). **Compression** compacts a block of rock and squeezes it into less space. This can cause *reverse faulting* (also known as thrust faulting) in which the hanging wall block is forced up the footwall block in opposition to the pull of gravity (**FIGURE 2.4**). **Tension** (also called *dilation*) pulls a block of rock apart and increases its length. This can cause *normal faulting*, in which gravity pulls the hanging wall block down and forces it to slide down off of the footwall block (see **FIGURE 2.4**). **Shear** offsets a block of rock from side to side and may eventually tear it apart into two blocks of rock that slide past each other along

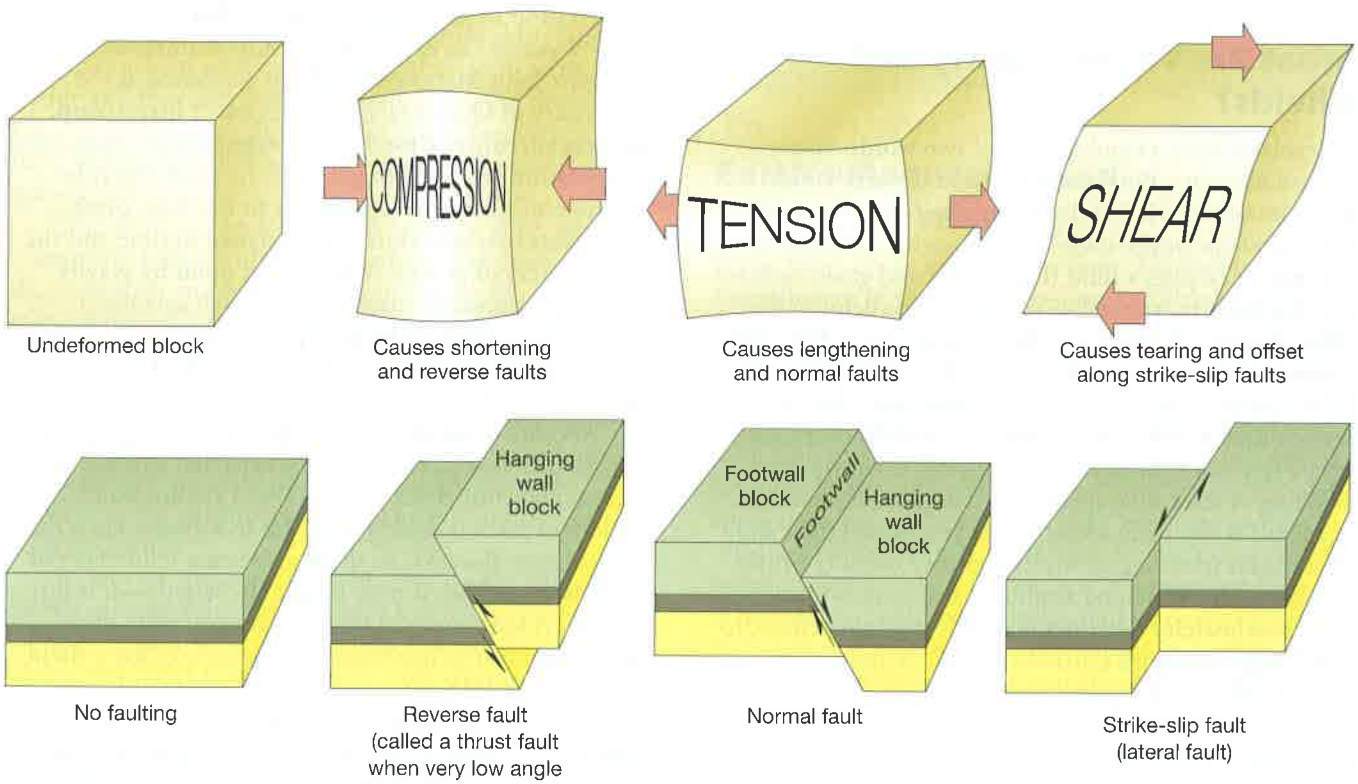


FIGURE 2.4 Stress and strain. Three kinds of stress (applied force, as indicated by arrows) cause characteristic strain (deformation) and faulting types.

a lateral or *strike-slip fault* (**FIGURE 2.4**). Plate tectonic forces can be understood by how the lithosphere is strained and faulted.

ACTIVITY

2.3 Lava Lamp Model of Earth

THINK About It | **What causes plate tectonics?**

OBJECTIVE Investigate viscoelasticity and rheidity, then evaluate a lava lamp model of mantle convection.

PROCEDURES

1. **Before you begin**, read about viscoelasticity, rheids, mantle convection, and seismic tomography below. Also, this is **what you will need** to do the activity:
   ____ blue and red colored pencils or pens
   ____ plastic ruler or popsicle stick
   ____ Activity 2.3 Worksheets (pp. 59–60) and pencil
   ____ Silly Putty™ and Lava lamp (provided in lab)
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

What Are Viscoelasticity and Rheids?

Viscoelasticity is a combination of two words: viscosity and elasticity. Both terms describe the mechanical behavior of materials and whether their deformation (change shape under stress) is permanent or reversible. Viscosity describes a fluid (like liquids and gases) behavior that leads to irreversible plastic-ductile deformation (like shaping a lump of clay into a new form). The solid cannot recover from its plastic-ductile deformation. Elasticity describes a behavior of solids that bend or stretch (like a rubber band) but return to their original shape (recover from their deformation) when you stop bending or stretching them. The deformation of elastic materials is not permanent, unless you exceed their ability to bend (their elastic limit) and they break (a brittle behavior, like stretching a rubber band until it breaks). So **viscoelasticity** describes materials that can behave, to some degree, as both elastic-brittle solids and very viscous liquids (plastic-ductile solids).

Many materials that you may regard as rigid solids are actually viscoelastic materials. The degree to which they behave more or less as solids is determined by their level of internal energy (*temperature*) and/or amount of *stress* (force, pressure) acting upon them over a given amount of *time*. To understand how temperature affects viscoelastc materials, think about steel. Red hot steel has a great amount of thermal energy, so it has more of a plastic-ductile behavior (can easily be hammered into new shapes) than cold steel. Cold steel is less plastic-ductile and more brittle than red hot steel. The effects of stress and time are more variable. Using lots of stress like hard hammer strikes, you can hammer a small ball of red hot steel into a flat disk in seconds. Alternatively, you can press on the steel with giant cold steel rolling pins over minutes of time to roll the steel into a flat disk. The effect is the same; the difference is the amount of stress and the amount of time it is applied. One study of these effects has been carried out at the University of Queensland since 1927.

Physicist Thomas Parnell has studied the properties of pitch, a black solid material derived from naturally occurring asphalt. Unless heated, pitch normally behaves as a brittle solid with little elasticity, so it shatters when struck with a hammer. But at the same temperature, under the stress of gravity, Parnell found that Pitch also behaves as a viscous fluid. In 1927, he heated some pitch to make it a liquid, and then poured it into a funnel with a sealed stem at its base. There, it solidified into its rigid solid form. He waited 3 years, and then cut one the stem of the funnel to see what would happen. After several years it began to flow like a viscous fluid, and 8 years later a drop of the pitch fell from the stem of the funnel. Since then, a drop of pitch drops from the funnel about every 9 years. The experiment is now maintained by physicist John Mainstone and can be viewed at the University of Queensland via webcam at **http://smp.uq.edu.au/content/pitch-drop-experiment**. Although, temperature and the funneling of the pitch towards the stem of the funnel are factors in the flow, pitch clearly has two behaviors based relative to time and the stress (force) of gravity. When acted upon by gravity on a short timescale (days or less), pitch acts like a solid. When acted up by gravity on a longer timescale (years), pitch acts like a viscous fluid. The main difference is time.

Rheidity is the time it takes for a solid material under stress to lose its elastic-brittle behavior, entirely, and just permanently deform (flow) like a viscous fluid. The rheidty of pitch is several years. Ice in a glacier has a rheidity of several weeks. At the time when a solid material exceeds its rheidity it is no longer viscoelastic—it is just viscous. A solid material that has changed from viscoelastic behavior to just viscous behavior is called a **rheid** (pronounced RAY-id).

Rocks can become rheids. For example, inside Earth it gets hotter with depth. So as you go deeper into the Earth, the rocks stop acting like elastic to brittle solids (rigid rocks) and change their behavior to that of viscous, plastic-ductile solids. The zone where this happens even has a name—the *brittle-ductile transition zone.* So mantle rocks are rheids—they flow and permanently deform (change shape) like viscous fluids. Rocks of the lithosphere and rock samples in your hand are not. They are viscoelastic solids that behave much more like elastic (to brittle) solids than viscous fluids.

Mantle Convection

While much is known about plate tectonics, and the plates have been identified and named (**FIGURE 2.5**), there has been uncertainty about how mantle rocks beneath the asthenosphere may influence this process. In the 1930s, an English geologist named Arthur Holmes speculated that the mantle may contain convection cells in which there is a circular flow of material like in boiling pot of soup. He proposed that such flow could carry continents about the Earth like a giant conveyor belt. This idea was also adapted in the 1960s by Harry Hess, who hypothesized that mantle flow is the driving mechanism of plate tectonics. New technologies provide an opportunity to evaluate this hypothesis. For example, seismic tomography now provides sound evidence that processes at least 660 kilometers deep inside the mantle may have dramatic effects on plate tectonics at the surface.

Seismic Tomography

Earth's mantle is nearly 3000 km thick and occurs between the crust and the molten outer core. Although mantle rocks behave like a brittle solid on short timescales associated with earthquakes, they seem to become rheids and flow like a viscous fluid on longer timescales of hundreds to thousands of years. Geologists use a technique called *seismic tomography* to detect this mantle flow.

The word *tomography* (Greek: *tomos* = slice, *graphe* = drawing) refers to the process of making drawings of slices through an object or person. Geologists use seismic tomography to view slices of Earth's interior similar to the way that medical technologists view slices of the human body. The human body slices are known as CAT (computer axial tomography) scans and are constructed using X-rays to penetrate and image the human body. The tomography scans of Earth's interior are constructed using seismic waves to penetrate and image the body of Earth.

In seismic tomography, geologists collect data on the velocity (rate and direction) of many thousands of seismic waves as they pass through Earth. The waves travel fastest through rocks that are the densest and presumed to be coolest. The waves travel slower through rocks that are less dense and presumed to be warmer. When a computer is used to analyze all of the data, from all directions, it is possible to generate seismic tomography images of Earth. These images can be viewed individually or combined to form three-dimensional perspectives. The computer can also assist in false coloring seismic tomography images to show bodies of mantle rock that are significantly warmer or cooler than the rest of the mantle (**FIGURE 2.6**).

ACTIVITY 2.4 Paleomagnetic Stripes and Seafloor Spreading

THINK About It **How are plate boundaries identified? How and at what rates does plate tectonics affect Earth's surface?**

OBJECTIVE Analyze paleomagnetic stripes and infer how seafloor spreading is related to Cascade Range volcanoes.

PROCEDURES

1. **Before you begin**, read about Earth's magnetism and paleomagnetism below. Also, this is **what you will need** to do the activity:
   ____ calculator, ruler
   ____ Activity 2.4 Worksheets (pp. 61–62) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

Earth's Magnetism and Paleomagnetism

If you drop a pen, it falls to the floor. The pen is under the influence of Earth's gravity—an invisible force field that pulls everything and everyone towards the center of our planet. But Earth has another force field that is not so obvious, its magnetic field. It is as though a giant bar magnet resides inside Earth, giving our planet both a magnetic north pole and a magnetic south pole. Invisible lines of the magnetic force field arc out through space from the south magnetic pole, travel around the outside of Earth at its equator, then arc back into the north magnetic pole. The strength of a magnetic field is measured in units called teslas, and a microtesla is a millionth of a tesla. Small magnets used to hold notes on refrigerator doors have a strength of about 50,000 microteslas, and Earth's magnetic field strength ranges from just 30 microteslas at the equator to about 50 microteslas at the poles. Therefore, a refrigerator magnet

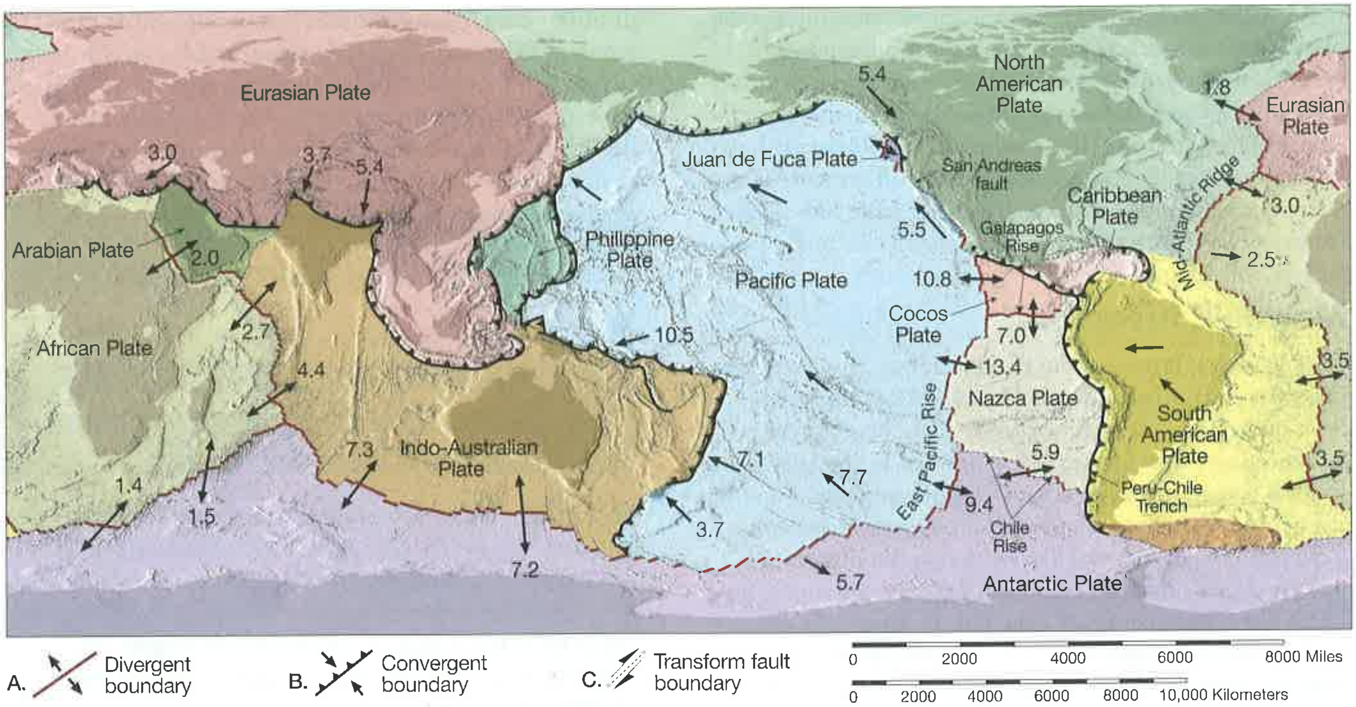


FIGURE 2.5 Earth's lithospheric plates and their boundaries. Numerals indicate relative (in relation to each other) rates of plate motion in centimeters per year (cm/yr); not the actual (absolute) rates of individual plate motion that you may have studied in Activity 2.1. Divergent plate boundaries (red) occur where two adjacent plates form and move apart (diverge) from each other. Convergent plate boundaries (hachured with triangular "teeth") occur where two adjacent plates move together. Transform fault plate boundaries (dashed) occur along faults where two adjacent plates slide past each other. Refer back to FIGURE 2.2 for another perspective of the three kinds of plate boundaries.

is three orders of magnitude (1000 times) stronger than Earth's magnetic field. Even so, you can use the tiny magnetic needle in a compass to detect Earth's magnetic field. Magnetic compass needles are not attracted to the geographic North Pole. Instead, they are attracted to the magnetic north pole, which is located in the Arctic Islands of Northern Canada, about 700 km (450 mi) from the geographic North Pole.

Paleomagnetism

Tiny crystals of iron-rich minerals, such as magnetite (Fe_3O_4), acquire and retain the directional signature of Earth's magnetic field when they form. This ancient magnetism is called **paleomagnetism**. Magnetic mineral crystals lose this magnetism if heated above the *Curie Point* of about 580°C. Only when they cool below the Curie Point do mineral crystals acquire and retain the signature of Earth's magnetic field for the time and place where they cooled. This happens when volcanic lava cools and crystallizes below the Curie Point.

Magnetic Reversals

When geologists first started detecting paleomagnetism in layers of cooled lava (volcanic rock) stacked one atop the other, they discovered that Earth's magnetic field has not always been the same. It has undergone periodic **reversals**. During times of **normal polarity**, the north-seeking end of a compass needle (and tiny iron-bearing mineral crystals in volcanic rock) points in the direction of Earth's present north magnetic pole. But during times of **reversed polarity**, the north-seeking end of a compass needle points in the opposite direction (geographic south).

Magnetic Anomalies and Paleomagnetic Stripes

Magnetic anomalies are deviations from the average strength of the magnetic field in a given area. Areas of higher than average strength are positive anomalies, and areas of less than average strength are negative anomalies. In the 1950s the U.S. Coast and Geodetic Survey scanned the ocean for magnetic anomalies and discovered that rocks of the sea floor contained alternating striped patterns of high and low magnetic anomalies, called **paleomagnetic stripes**. They also discovered that the pattern of paleomagnetic stripes was symmetrical on opposite sides of mid-ocean ridges. In 1963, geologists Fred Vine, Drummond Matthews, and Lawrence Morley discovered that the symmetrical pattern of paleomagnetic stripes in seafloor rocks was the result of two processes: the formation of seafloor and reversals of Earth's magnetic field. They proposed that as volcanoes

Seismic Tomography (80 km depth)

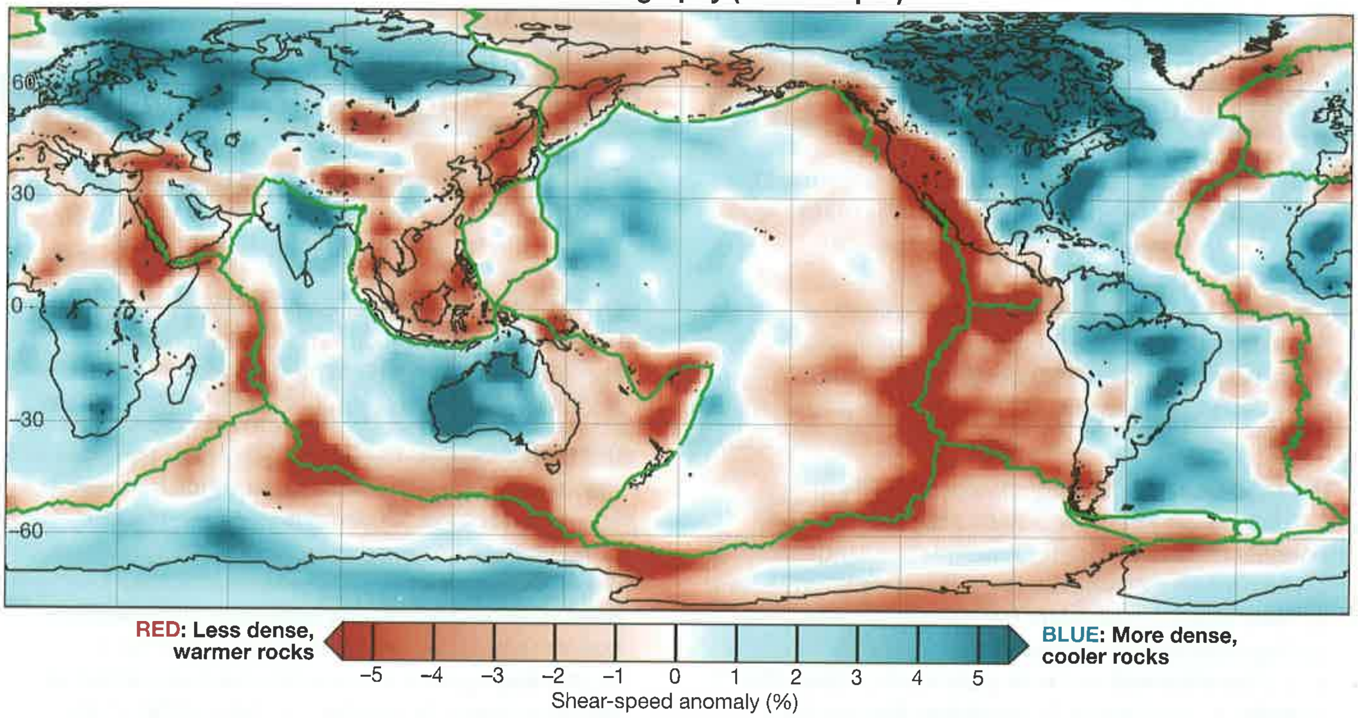


FIGURE 2.6 Seismic tomography image (horizontal slice) of Earth's mantle at a depth of 80 km. Note scale indicating the percent change in shear speed of the seismic waves. Red false coloring indicates slower shear speed in warmer rock that is less dense and ascending. Blue false coloring indicates faster shear speed in cooler rock that is static or descending. (Image constructed by Sergei Lebedev, Dublin Institute for Advanced Studies, and Rob D. van der Hilst, MIT/IRIS Consortium, based on a large global data set retrieved from IRIS (Incorporated Research Institutions for Seismology). Used with permission.)

erupted along a mid-ocean ridge, the lava cooled below the Curie Point and recorded reversals of Earth's paleomagnetic field. Rocks formed during times of normal polarity now have magnetic signatures that add to the modern field strength and create a positive anomaly. Rocks formed during times of reversed polarity have magnetic signatures that oppose the modern field and create a negative anomaly. The symmetrical pattern of paleomagnetic stripes developed as new crust was formed and magnetized and older crust moved down and spread away from both sides of the ridge under the influence of gravity (a process that Harry Hess called **seafloor spreading**).

Polar Reversal Time Scale

Radiometric dating of volcanic rocks containing paleomagnetism enables geologists to time the pattern of Earth's paleomagnetic field reversals. The **polar reversal time scale** is a column of named *chrons* (time intervals) of normal and reversed polarity, from oldest at the bottom to youngest at the top, combined with a time scale in millions of years. We are living in the Brunhes normal chron, which began 0.78 million years ago, after the Matayama reversed chron. Most chrons are also subdivided into named subchrons. In Activity 2.4, you will use a simpler version of a polar reversal time scale in which the time intervals have been color coded (instead of named) so they are easy to recognize on sight.

ACTIVITY

2.5 Atlantic Seafloor Sreading

THINK About It **How are plate boundaries identified? How and at what rates does plate tectonics affect Earth's surface?**

OBJECTIVE Infer how fracture zones and shapes of coastlines provide clues about how and when North America and Africa were once part of the same continent.

INTRODUCTION If you did Activity 2.4, then you have already studied sea floor spreading about the Gorda and Juan de Fuca Ridges off the northwest coast of the United States. This activity is an investigation of seafloor spreading about the Mid-Atlantic Ridge.

PROCEDURES

1. This is **what you will need** to do the activity:
   ____ red and blue pencils or pens
   ____ calculator, ruler
   ____ Activity 2.5 Worksheet (p. 63) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

ACTIVITY 2.6 Using Earthquakes to Identify Plate Boundaries

THINK About It How are plate boundaries identified? How and at what rates does plate tectonics affect Earth's surface?

OBJECTIVE Apply earthquake data from South America to define plate boundaries, identify plates, construct a cross section of a subduction zone, and infer how volcanoes may be related to plate subduction.

INTRODUCTION Earthquakes occur at depths of 0–700 km inside Earth. Most occur along the mobile boundaries between plates (inter-plate earthquakes), which enables geologists to map the plate boundaries as linear zones of abundant earthquake activity. Earthquakes occur with less frequency within the rigid plates themselves (intra-plate earthquakes). The exact location where rocks break and displace (slip past one another) to make an earthquake is called the **focus** of the earthquake. Shallow focus earthquakes (0–69 km deep) are the most common kind of earthquakes and occur at all three main kinds of plate boundaries (divergent, convergent, and transform: FIGURE 2.2). Intermediate (70–299 km deep) and deep focus earthquakes (300–700 km deep) occur mostly in *Wadati-Benioff zones* of earthquake activity associated with plate subduction at convergent plate boundaries (FIGURE 2.2).

PROCEDURES

1. This is **what you will need** to do the activity:
   ____ red pencil or pen
   ____ ruler
   ____ Activity 2.6 Worksheets (pp. 64–65) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

ACTIVITY 2.7 San Andreas Transform-Boundary Plate Motions

THINK About It How are plate boundaries identified? How and at what rates does plate tectonics affect Earth's surface?

OBJECTIVE Analyze maps of geology and GPS-based plate motion vectors data to determine absolute and relative plate motions along the San Andreas Fault to transform boundaries.

INTRODUCTION California's San Andreas Fault is a boundary between the Pacific and North American lithospheric plates. Movement along the plate boundary can be characterized and measured using geologic maps that show how rock units have been *offset* (cut by the fault and separated in distance) by plate movement along the fault. GPS (Global Positioning System) data reveals strain (deformation) patterns caused by absolute motions of the plates.

PROCEDURES

1. **Before you begin**, read about the GPS time series below. Also, this is **what you will need** to do the activity:
   ____ calculator, ruler
   ____ Activity 2.7 Worksheets (pp. 66–67) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

ACTIVITY 2.8 Hot Spots and Plate Motions

THINK About It What are hot spots, and how do they help us explain plate tectonics?

OBJECTIVE Determine rates and directions of plate motions as they have moved over hot spots.

PROCEDURES

1. **Before you begin**, read about plate tectonics and hot spots below. Also, this is **what you will need** to do the activity:
   ____ calculator, ruler
   ____ Activity 2.8 Worksheets (pp. 68–69) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

Evaluating Plate Tectonics and Hot Spots

The Plate Tectonics Model is widely applied by geoscientists to help explain many regional and global features of the geosphere. Another regional feature of Earth is hot spots, centers of volcanic activity that persist in a stationary location for tens-of-millions of years. Geologists think they are either a) the result of long-lived narrow *plumes* of hot rock rising rapidly from Earth's mantle (like a stream of heated lava rising in a lava lamp), or b) the slow melting of a large mass of hot mantle rock in the upper mantle that persists for a long interval of geologic time.

The Hawaiian Hot Spot and Pacific Plate Motion

As a lithospheric plate migrates across a stationary hot spot, a volcano develops directly above the hot spot. When the plate slides on, the volcano that was over the hot spot becomes dormant, and over time, it migrates many kilometers from the hot spot. Meanwhile, a new volcano arises as new lithosphere passes over the hot spot. The result is a string of volcanoes, with one end of the line located over the hot spot and quite active, and the other end distant and inactive. In between is a succession of volcanoes that are progressively older with distance from the hot spot. The Hawaiian Islands and Emperor Seamount chain (**FIGURE 2.7**) are thought to represent such a line of volcanoes that formed over the Hawaiian hot spot.

ACTIVITY

2.9 The Origin of Magma

THINK About It How and where does magma form?

OBJECTIVE Apply physical and graphical models of rock melting to infer how magma forms in relavtion to pressure, temperature, water, and plate tectonics.

PROCEDURES

1. **Before you begin**, read about the origin of magma below. Also, this is **what you will need** to do the activity:
   ____ Materials provided in lab: hot plate, aluminum foil, sugar cubes, water, dropper
   ____ calculator, ruler
   ____ Activity 2.9 Worksheets (pp. 70–72) and pencil
2. **Answer every question on the worksheet in a way that makes sense to you** and be prepared to compare your work and inferences with others.

The Origin of Magma

If you have watched videos of the fountains and rivers of lava produced by Kilauea volcano in Hawaii, you may have wondered how much of Earth's interior is made up of melted rock, or magma. Seismic studies indicate that nearly all of Earth's mantle and crust are solid rock—not magma. Therefore, except for some specific locations where active volcanoes occur, there is no reservoir or layer of magma beneath Earth's surface just waiting to erupt. On a global scale, the volume of magma that feeds active volcanoes is actually very small. What, then, are the special conditions that cause these rare bodies of upper mantle and lower crust magma to form?

Magma generally forms in three plate tectonic settings (divergent plate boundaries, convergent plate boundaries, and hot spots). Its origin (rock melting) is also influenced by underground temperature, underground pressure (lithostatic pressure), and the kind of minerals that comprise underground rocks.

Temperature (T)

Rocks are mostly masses of solid mineral crystals. Therefore, some or all of the mineral crystals must melt to form magma. According to the Kinetic Theory, a solid mineral crystal will melt if its kinetic energy (motion of its atoms and molecules) exceeds the attractive forces that hold together its orderly crystalline structure. Heating a crystal is the most obvious way to melt it. If enough heat energy is applied to the crystal, then its kinetic energy level may rise enough to cause melting. The specific temperature at which crystals of a given mineral begin to melt is the mineral's **melting point.**

Partial Melting. All minerals have different melting points. So when heating a rock comprised of several different kinds of mineral crystals, one part of the rock (one kind of mineral crystal) will melt before another part (another kind of mineral crystal). Geologists call this **partial melting** of rock. But where would the heat come from to begin melting rocks below the ground?

Geothermal Gradient. Unless you live near a volcano or hot spring, you probably are not aware of Earth's body heat. But South African gold miners know all about it. The deeper they mine, the hotter it gets. In the deepest mine (**FIGURE 1.6**), 3.8 kilometers below ground, rock temperatures are 60 °C (140 °F) and the mine must be air conditioned. This gradient of increasing temperature with depth is called the **geothermal gradient**. This gradient also varies between ocean crust and continental crust, but the global average for all of Earth's crust is about 25 °C (77 °F) per kilometer. In other words, rocks located 1 kilometer below your house are about 25 °C warmer than the foundation of your house. If the geothermal gradient continued at this rate through the mantle, then the mantle would eventually melt at depths of 100–150 kilometers. Seismology shows that this does not occur, so temperature is not the only factor that determines whether a rock melts or remains solid. Pressure is also a factor.

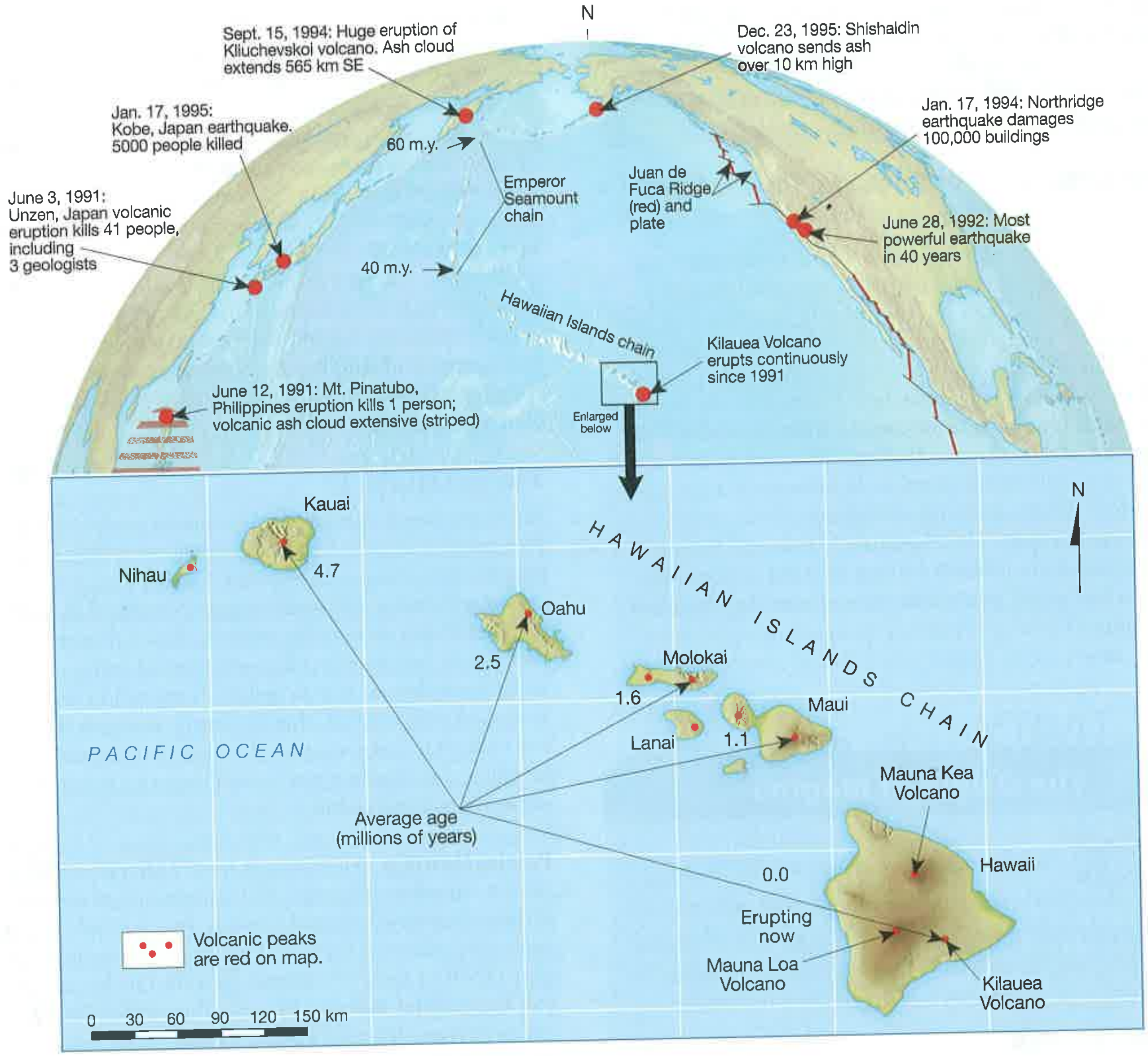


FIGURE 2.7 Effects of a hot spot on the Pacific seafloor. Top map shows the northern Pacific Ocean, adjacent landmasses, some notable geologic hazards (natural disasters), the Hawaiian Islands chain, and the Emperor Seamount chain. Lower map shows details of the Hawaiian Islands chain, including locations of volcanic peaks.

Pressure (P)

When you press your hand against something like a bookshelf, you can apply all of your body *weight* against the surface *area* under your hand. Therefore, **pressure** is expressed as amount of weight applied per unit of area. For example, imagine that you weigh 100 pounds and that your hand is 5 inches long and 4 inches wide. If you exert all of your weight against a wall by leaning against the wall with one hand, then you are exerting 100 pounds of weight over an area of 20 square inches (5 inches × 4 inches × 20 square inches). This means that you are exerting 5 pounds of pressure per square inch of your hand.

Confining Pressure. Atoms and molecules of air (atmosphere) are masses of matter that are pulled by gravity toward the center of Earth. But they cannot reach Earth's center because water, rocks, and your body are in their path. As a result, the weight of the air presses against surfaces of water, rocks, and your body. If you stand at sea level, then your body is confined by 14.7 pounds of weight pressing on every square inch of your body (14.7 lbs/in^2). This is called atmospheric **confining pressure.** Scientists also refer to this as one *atmosphere* (1 atm) of pressure.

You do not normally feel one atmosphere of confining pressure, because your body exerts the same pressure to keep you in equilibrium (balance) with your surroundings.

But if you ever dove into the deep end of a swimming pool, then you experienced the confining pressure exerted by the water plus the confining pressure of the atmosphere. The deeper you dove, the more pressure you felt. It takes 10 m (33.9 ft) of water to exert another 1 atm of confining pressure on your body.

Rocks are about three times denser than water, so it takes only about 3.3 m of rock to exert a force equal to that of 10 m of water or the entire thickness of the atmosphere! 100 m of rock exert a confining pressure of about 30 atm, and 1 km (1000 m) of rock exerts a confining pressure of about 300 atm. At 300 atm/km, a rock buried 5 km underground is confined by 1500 atm of pressure!

Decompression Melting. The confining pressure under kilometers of rock is so great that a mineral crystal cannot melt at its "normal" melting point observed on Earth's surface. The pressure confines the atoms and molecules and prevents them from flowing apart. More heat is required to raise the kinetic energy level of atoms and molecules in the crystal enough to melt the crystal. Consequently, an increase in confining pressure causes an increase in the melting point of a mineral. Reducing confining pressure lowers the melting point of a mineral. This means that if a mineral is already near its melting point, and its confining pressure decreases enough, then it will melt. This is called **decompression melting**.

Pressure-Temperature (P-T) Diagrams

Geologists understand that rock melting (the origin of magma) is related to both temperature and pressure. Therefore, they heat and pressurize rock samples under controlled conditions in geochemical laboratories to determine how rock melting is influenced by specific combinations of both pressure and temperature. Samples are pressurized and heated to specific P-T points to determine if they remain solid, undergo partial melting, or melt completely. The data are then plotted as specific points on a **pressure-temperature (P-T) diagram** such as the one in FIGURE 2.8 for mantle peridotite. Mantle

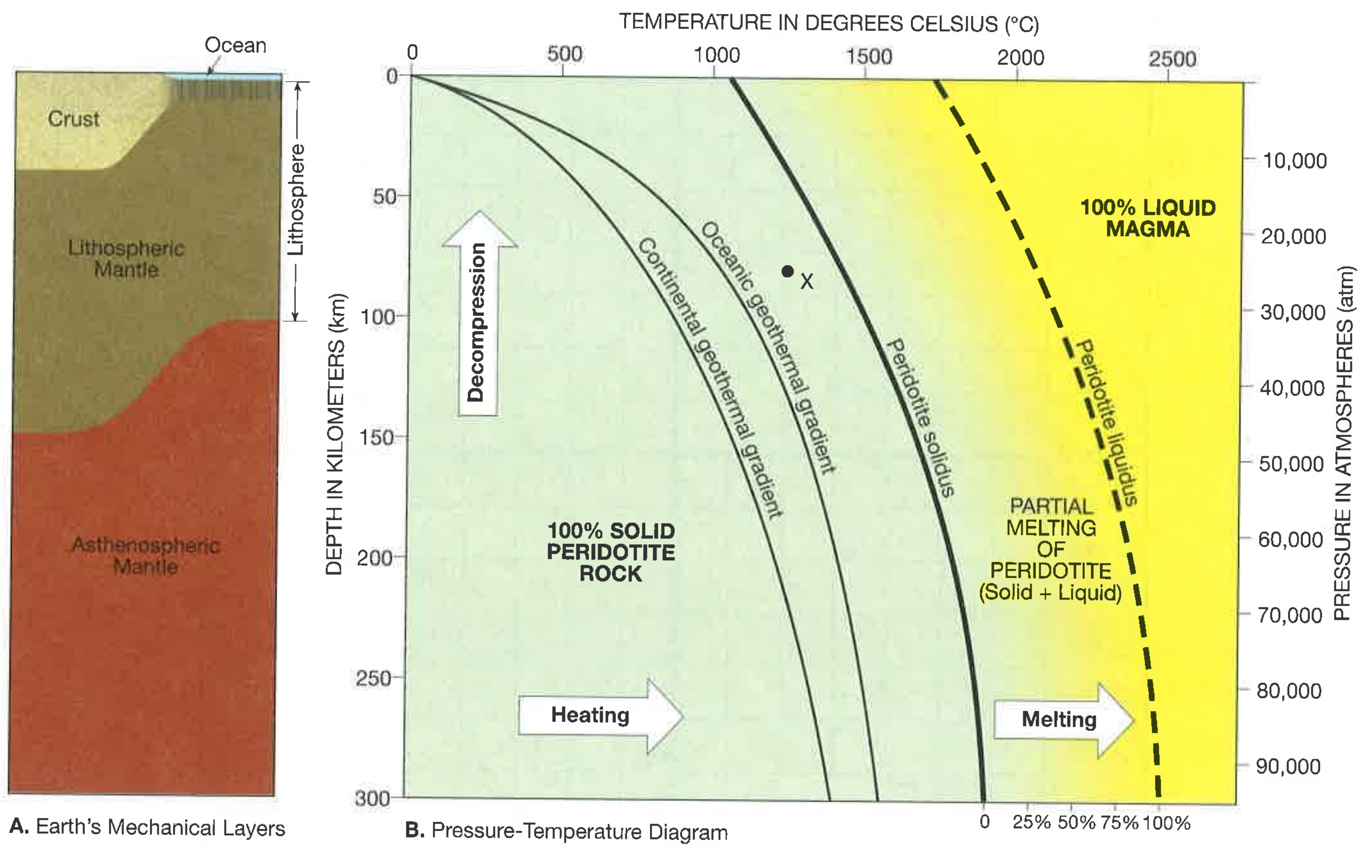


FIGURE 2.8 Pressure-Temperature diagram relative the geosphere. A. The physical layers of the geosphere vary in physical properties, such as melting point, depending on the temperature and pressure. B. The pressure-temperature (P-T) diagram shows the environmental conditions that exist across the physical layers shown in A. The diagram shows how P-T conditions affect peridotite rock (made of olivine, pyroxene, amphibole, and garnet mineral crystals). At P-T points below (to the left of) the *peridotite solidus*, all mineral crystals in the rock remain solid. At P-T points above (to the right of) the *peridotite liquidus*, all mineral crystals in the rock melt to liquid. At P-T points between the solidus and liquidus, the rock undergoes partial melting—one kind of mineral at a time, so solid and liquid are present. Continental and oceanic geothermal gradients are curves showing how temperature normally varies according to depth below the continents and ocean basins. Temperatures along both of these geothermal gradients are too cool to begin partial melting of peridotite. Both gradients occur below (to the left of) the peridotite solidus (1 atm 5 about 1 bar).

peridotite is made of olivine, pyroxene, amphibole, and garnet mineral crystals. Therefore, this diagram also shows the combined effects of pressure and temperature on a rock made of several different minerals. At P-T points below (to the left of) the *solidus*, all mineral crystals in the rock remain solid. At P-T points above (to the right of) the *liquidus*, all mineral crystals in the rock melt to liquid. At P-T points between the solidus and liquidus, the rock undergoes partial melting—one kind of mineral at a time. Therefore, a P-T diagram also reveals stability fields for states (phases) of matter. In this case (see **FIGURE 2.8**), there are stability fields for solid, solid + liquid, and liquid.

Notice that lines for the continental and oceanic geothermal gradients are also plotted on **FIGURE 2.8**. They show how temperature normally varies according to depth below the continents and ocean basins. Temperatures along both of these geothermal gradients are not great enough tô begin melting peridotite. Both gradients occur along temperatures below (to the left of) the peridotite solidus.

ACTIVITY 2.1 Plate Motion Inquiry Using GPS Time Series

Name: ______________________ **Course/Section:** ______________________ **Date:** ____________

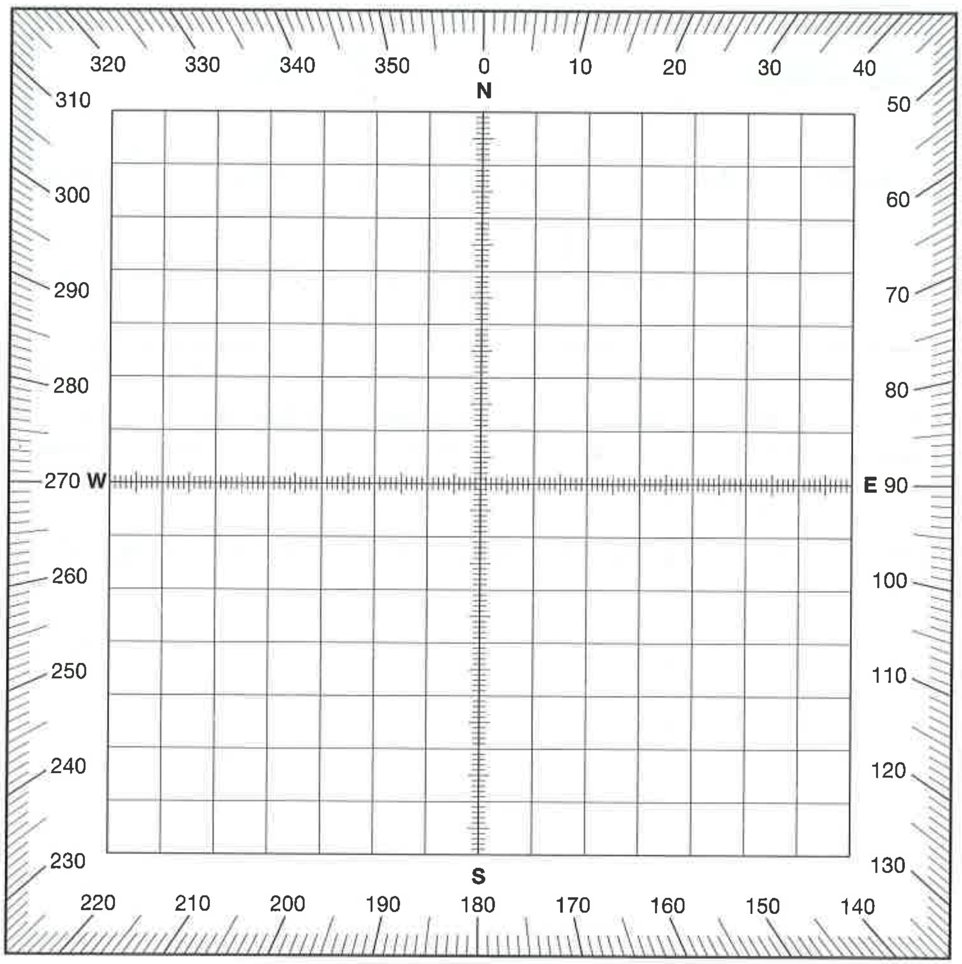
A. Analyze **FIGURE 2.1**. On what lithospheric plate do you live? ______________________

B. Go to the **JPL-NASA GPS Time Series website** at **http://sideshow.jpl.nasa.gov/post/series.html**. The map displays GPS stations as small green dots with a yellow line. The yellow line points away from the green dot in the direction that the GPS station (and lithospheric plate to which it is anchored) is moving. Notice that you can scroll in on the map to enlarge it and reveal more GPS stations. Find the GPS station that is the closest to where you live. Record the station name, then complete the Plate Motion Plotter below for the station by following the directions in **FIGURE 2.3**.

1. GPS Station Name:

2. Latitude vector direction (North or South) and velocity: ______________________

3. Longitude vector direction (East or West) and velocity: ______________________



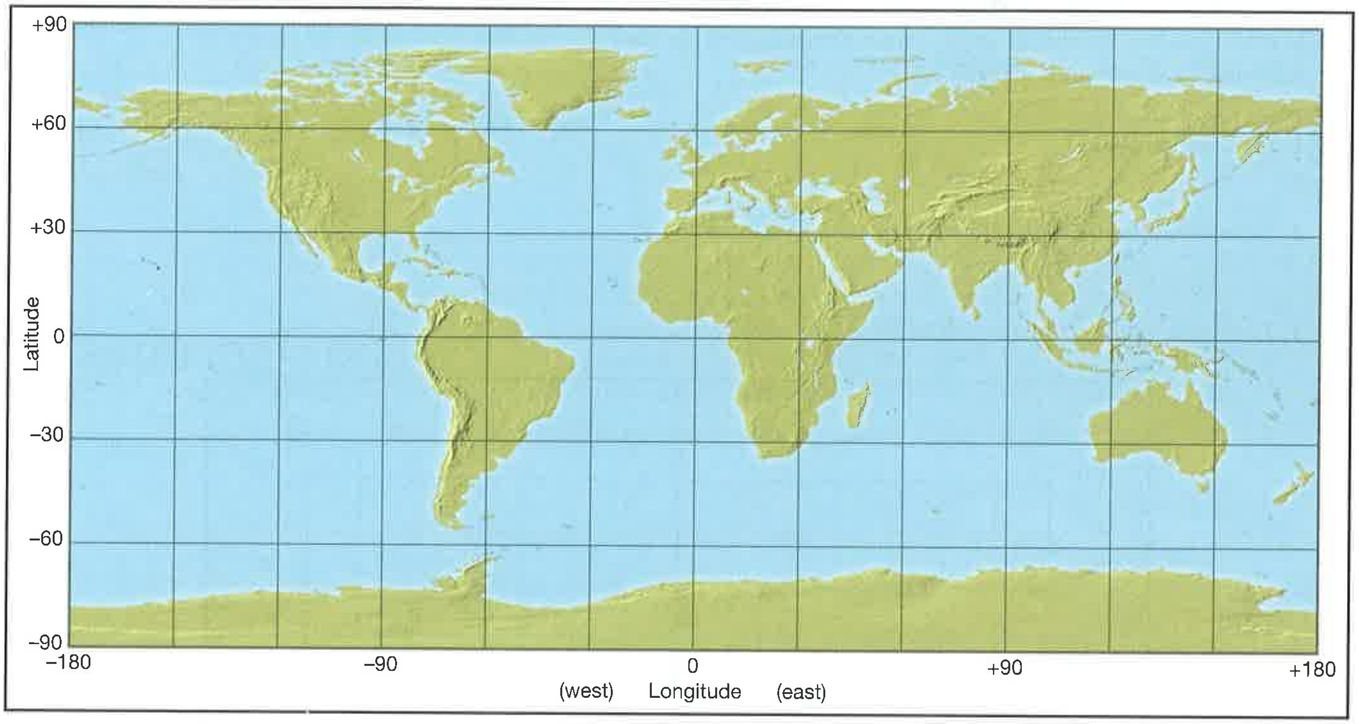
4. In what direction is this GPS station moving?

5. At what velocity is this GPS station (and lithospheric plate to which it is attached) moving?

6. Return to the **JPL-NASA Time Series website,** and click on "Geodetic Positions and Velocities" above the map. Scroll down to the name of your station, and record its current coordinate position in latitude and longitude below. For latitude, notice that a positive number indicates degrees North Latitude, and a negative number indicates degrees South Latitude. For longitude, a positive number indicates degrees East Longitude, and a negative number indicates West Longitude.

Current Latitude: ______________________ Current Longitude: ______________________

7. Use the latitude and longitude coordinates to plot the location of your GPS station on the map below as a dot. Then add an arrow to show the direction that the station is moving (from #4 above). Beside the arrow, write the velocity that the GPS station (and lithospheric plate) is moving (from part 5 above).



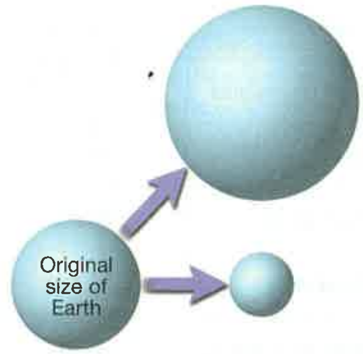
C. Return to the **JPL-NASA Time Series website**, and view the map. From the website map, draw arrows on the map above to show the general direction that South America, Africa, North America, and Europe are currently moving.

D. **REFLECT & DISCUSS** Does your work above help to verify the Plate Tectonic Theory or falsify it? Explain.

ACTIVITY 2.2 Is Plate Tectonics Caused by a Change in Earth's Size?

Name: ______________________ **Course/Section:** ______________________ **Date:** ____________

A. Recall that geoscientists have historically tried to understand the cause of oceans, mountains, and global tectonics by questioning if Earth could be shrinking or expanding in size. This question can be evaluated by studying Earth's natural forces and faults in relation to those that you might predict to occur if the size of Earth were changing. Analyze **FIGURE 2.4** to see how three kinds of faults are caused by three kinds of stress (applied force). To the right of this diagram, predict what kind of faulting you would mostly expect to find in Earth's lithosphere if Earth were expanding or contracting (shrinking).



What kind of faulting would you most expect to find in the lithosphere if:

1. Earth is expanding?

2. Earth is contracting?

B. Refer to **FIGURES 2.2** and **2.4**. Fill in the table below to indicate what kind of stress and faulting characterizes each kind of plate boundary.

Plate Boundary Type	Main Stress (applied force)	Main Fault Type
Divergent		
Convergent		
Transform		

C. Refer to **FIGURE 2.5**, a map showing the distribution of Earth's lithospheric plates and three main kinds of plate boundaries: divergent (red), convergent (hachured), and transform (dashed). Also note in **FIGURE 2.2** that there are two kinds of divergent boundaries (continental rifts, mid-ocean ridges) and three kinds of convergent boundaries (ocean-ocean, ocean-continent, and continent-continent).

1. Geologist Peter Bird conducted a classical study of Earth's lithospheric plates and plate boundaries in 2003. He found that the lithosphere is actually broken into 52 plates, many of which are too small to see on a world map. So the typical global map of about 13 main plates shown in **FIGURE 2.5** and most textbooks is quite generalized. He also identified the total combined lengths of all of the different kinds of plate boundaries, as summarized in the two left-hand columns of the table on the back of this page. Complete the two right-hand columns of the table.

Lithospheric Plate Boundary Type	Total Length (kilometers)	Total Length of the three main plate boundary types	Percentage of each of the three main plate boundary types
Ocean-ocean convergent boundaries	17,449	Convergent	Convergent
Ocean-continent convergent boundaries	51,310		
Continent-continent convergent boundaries	23,003		
Continental rift divergent boundaries	27,472	Divergent	Divergent
Mid-ocean ridge divergent boundaries	67,338		
Ocean transform fault plate boundaries	47,783	Transform	Transform
Continental transform fault plate boundaries	26,132		

2. Do you think Earth's size is increasing (expanding), decreasing (shrinking), or staying about the same in size? Justify your answer by citing evidence from your work above.

3. Peter Bird also calculated that Earth's lithosphere is being created at a rate of 3.4 km^2/yr and being destroyed at a rate of 3.4 km^2/yr. At these rates, and the fact that Earth's surface area is 510,000,000 km^2, how long would it take to recycle Earth's entire lithosphere? Show your work.

B. REFLECT & DISCUSS Do you think that plate tectonics is being caused by a change in Earth's size, or something else? If something else, then what do you suggest? Explain.

ACTIVITY 2.3 Lava Lamp Model of Earth

Name: ______________________ **Course/Section:** ______________________ **Date:** ____________

A. Earthquake shear waves travel through both the crust and mantle of Earth. Such waves cannot travel through fluids (liquids, gases), so rocks of both crust and mantle are mostly solid rock, not liquid rock. Yet Plate Tectonic Theory states that lithospheric plates are made of rigid, stiff bodies of elastic-brittle rock (crust and lithospheric mantle) that rest on asthenosphere and deeper parts of the mantle made of weak, ductile rock that flows like soft plastic or a viscous (thick) fluid. Explore how solid rock can be rigid and stiff in the lithosphere but soft and fluid-like in the asthenosphere.

1. Obtain a piece of Silly Putty™ from your instructor. Perform the following tests on it, check the boxes to indicate whether the test results characterize Silly Putty™ as a solid or a liquid, and answer the two questions.

Test	Behaves like a solid	Behaves like a liquid (fluid)
1. Roll the Silly Putty™ into a ball and bounce it on the table.		
2. Hold opposite ends of the mass of Silly Putty™, and pull it apart slowly.		
3. Hold opposite ends of the mass of Silly Putty™, and pull it apart as fast as you can.		
4. Roll the Silly Putty™ into a ball, then press down on it with your thumb.		
5. Roll the Silly Putty™ into a ball, and allow it to sit for 2-3 minutes, or longer.		
Under what conditions of pressure and time does Silly Putty™ behave like a solid?	Under what conditions of pressure and time does Silly Putty™ behave like a liquid?	

2. What is a rheid? Is Silly Putty™ a rheid?

3. REFLECT & DISCUSS How does your research on Silly Putty™ help explain how rocks may behave in the lithosphere and beneath the lithosphere?

B. A "lava lamp" is inactive when the light is off, but a lighted lava lamp is dynamic and ever changing. Observe the rising and sinking motion of the lava-like wax in a lighted lava lamp.

1. Describe the motions of the "lava" that occur over one full minute of time, starting with lava at the bottom of the lamp and its path through the lamp.

2. What causes the "lava" to move from the base of the lamp to the top of the lamp? (Be as specific and complete as you can.)

3. What causes the "lava" to move from the top of the lamp to the base of the lamp? (Be as specific and complete as you can.)

4. What is the name applied to this kind of cycle of change? (*Hint:* Refer to **FIGURE 1.6** on page 13.)

C. Observe the seismic tomography image in **FIGURE 2.6**: a slice through Earth's mantle at a depth of 350 kilometers. Unlike the lava lamp that you viewed in a vertical profile from the side of the lamp, this image is a horizontal slice of Earth's mantle viewed from above. This image is also false colored to show where rocks are significantly warmer and less dense (colored red) versus cooler and more dense (colored blue).

1. How is Earth's mantle like a lava lamp?

2. How is Earth's mantle different from a lava lamp?

D. Compare the tectonic plates and plate boundaries in **FIGURE 2.5** to the red and blue regions of the seismic tomography image in **FIGURE 2.6**.

1. Under what kind of plate tectonic feature do the warm, less dense rocks (red) occur most often?

2. Under what kind of plate tectonic feature do the cool, more dense rocks (blue) occur most often?

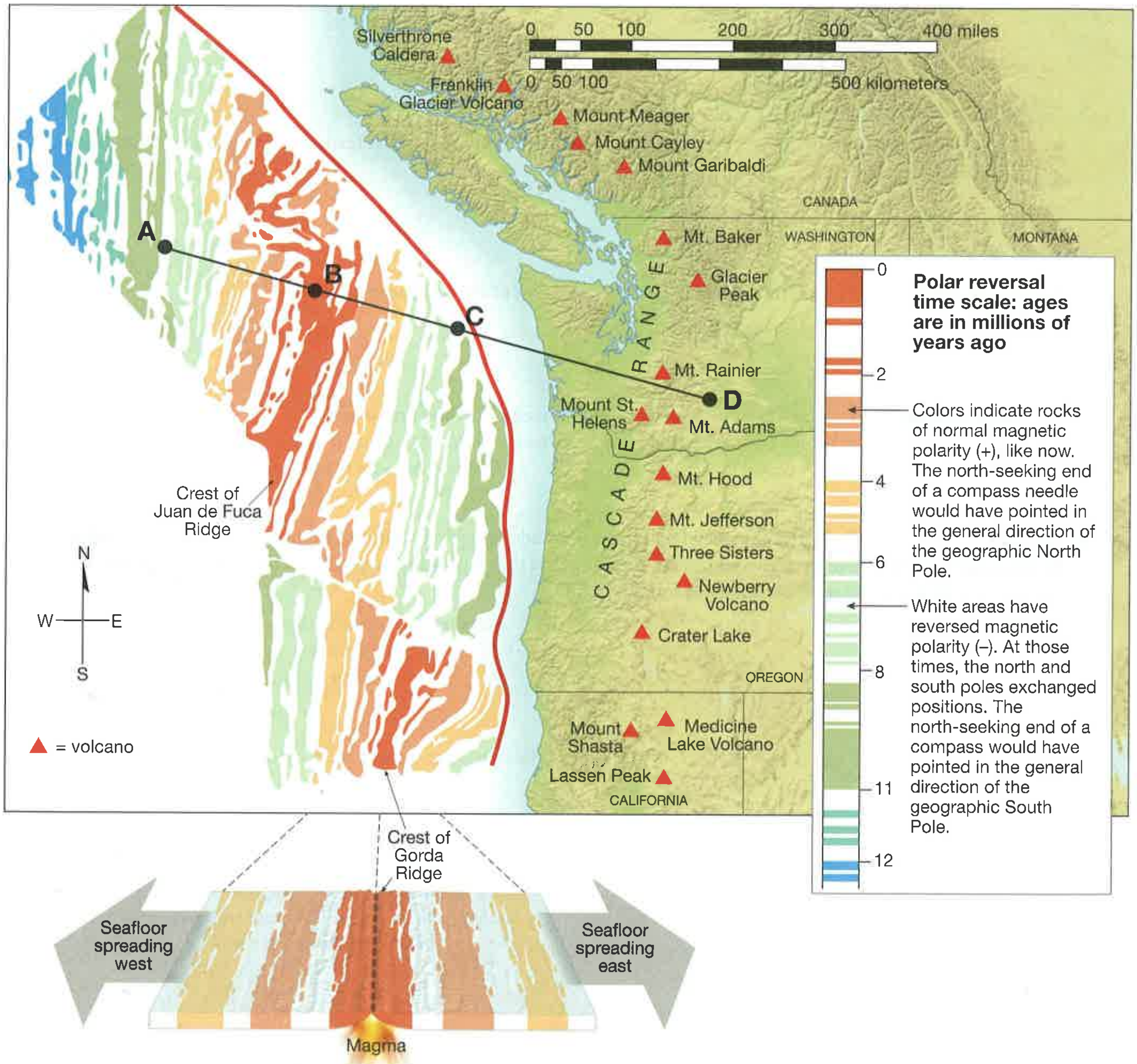
E. **REFLECT & DISCUSS** Based on your work in **B–D**, draw a vertical cross section (vertical slice) of Earth that shows how mantle convection may be related to plate tectonics. Include and label the following features in your drawing: mid-ocean ridge (divergent plate boundary), lithospheric plate(s) with ocean crust, subduction zone (convergent plate boundary), lithospheric plate with continental crust, arrows to indicate the convection motion of the mantle. Use colored pencils to show where the mantle rocks in your vertical cross section would be red and blue like the false colored mantle rocks in **FIGURE 2.6.**

ACTIVITY 2.4 Paleomagnetic Stripes and Seafloor Spreading

Name: ______________________ **Course/Section:** ______________ **Date:** __________

A. Analyze the seafloor part of the map below, just off the Pacific Coast, west of California, Oregon, Washington, and southwest Canada. The colored bands are seafloor magnetic anomalies. Colored bands are rocks with a positive (+) magnetic anomaly, so they have normal polarity, like now. The white bands are rocks with a negative (-) magnetic anomaly, so they have reversed polarity. Different colors indicate the ages of the rocks, in millions of years as shown in the polar reversal time scale provided.

1. Using a pencil, draw a line on the sea floor to show where new ocean crust and lithosphere is forming now (zero millions of years old). Using FIGURE 2.2 as a guide, label the segments of your line that are **Juan de Fuca Ridge** and **Gorda Ridge** (divergent plate boundaries). Then label the segments of your pencil line that are **transform fault** plate boundaries. **Add half-arrows to the transform fault boundaries** to show the relative motion of the rocks.



2. What has been the average rate and direction of seafloor spreading in cm per year (cm/yr) west of the Juan de Fuca Ridge, from **B** to **A**? Show your work.

3. What has been the average rate and direction of seafloor spreading in cm per year (cm/yr) east of the Juan de Fuca Ridge, from **B** to **C**? Show your work.

4. Notice that rocks older than 11 million years are present west of the Juan de Fuca Ridge, but not east of the ridge. What could be happening to the seafloor rocks along line segment **C-D** that would explain why rocks older than 11 million years no longer exist on the sea floor east of the ridge?

5. Notice the red line running through point **C**:

   a. If you could take a submarine to view the sea floor along this line, then what feature would you see? (Hint: see **FIGURE 2.2**.)

   b. Based on **FIGURE 2.1**, what lithospheric plate is located east of the red line at point **C**?

   c. Based on **FIGURE 2.1**, what lithospheric plate is located west of the red line at point **C**?

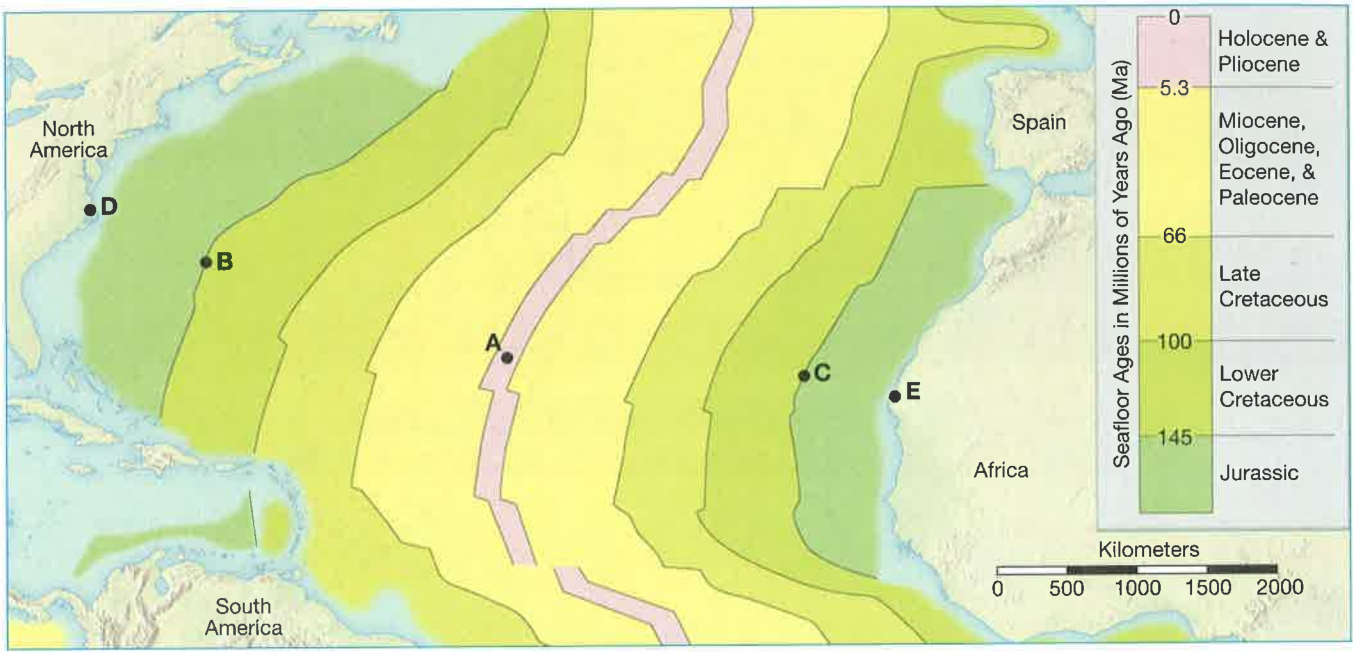
6. **REFLECT & DISCUSS** Notice the line of volcanoes (Cascade Range volcanic arc) running from northern California to southern Canada. These are active volcanoes, meaning that they still erupt from time to time. What sequence of plate tectonic events is causing these volcanoes to form?

ACTIVITY 2.5 Atlantic Seafloor Spreading

Name: ______________________ **Course/Section:** ______________________ **Date:** ____________

A. The map below shows the ages of seafloor basalt (the actual floor of the ocean, beneath the modern mud and sand) between North America and Africa.

1. Draw a red line on the map to show the exact location of the divergent plate boundary between the North American Plate and the African and Eurasian Plates. Refer to **FIGURE 2.5** for assistance as needed.
2. Draw two blue lines on the map to show the exact position of two different transform fault plate boundaries. Refer to **FIGURE 2.2** for assistance as needed.



B. Notice that points B and C were together 145 million years ago, but did the sea floor spread apart at exactly the same rate on both sides of the mid-ocean ridge? How can you tell?

C. How far apart are points B and C today, in kilometers? ______________ km

1. Calculate the average rate, in km per million years, that points B and C have moved apart over the past 145 million years. Show your work.

2. Convert your answer above from km per million years to mm per year.

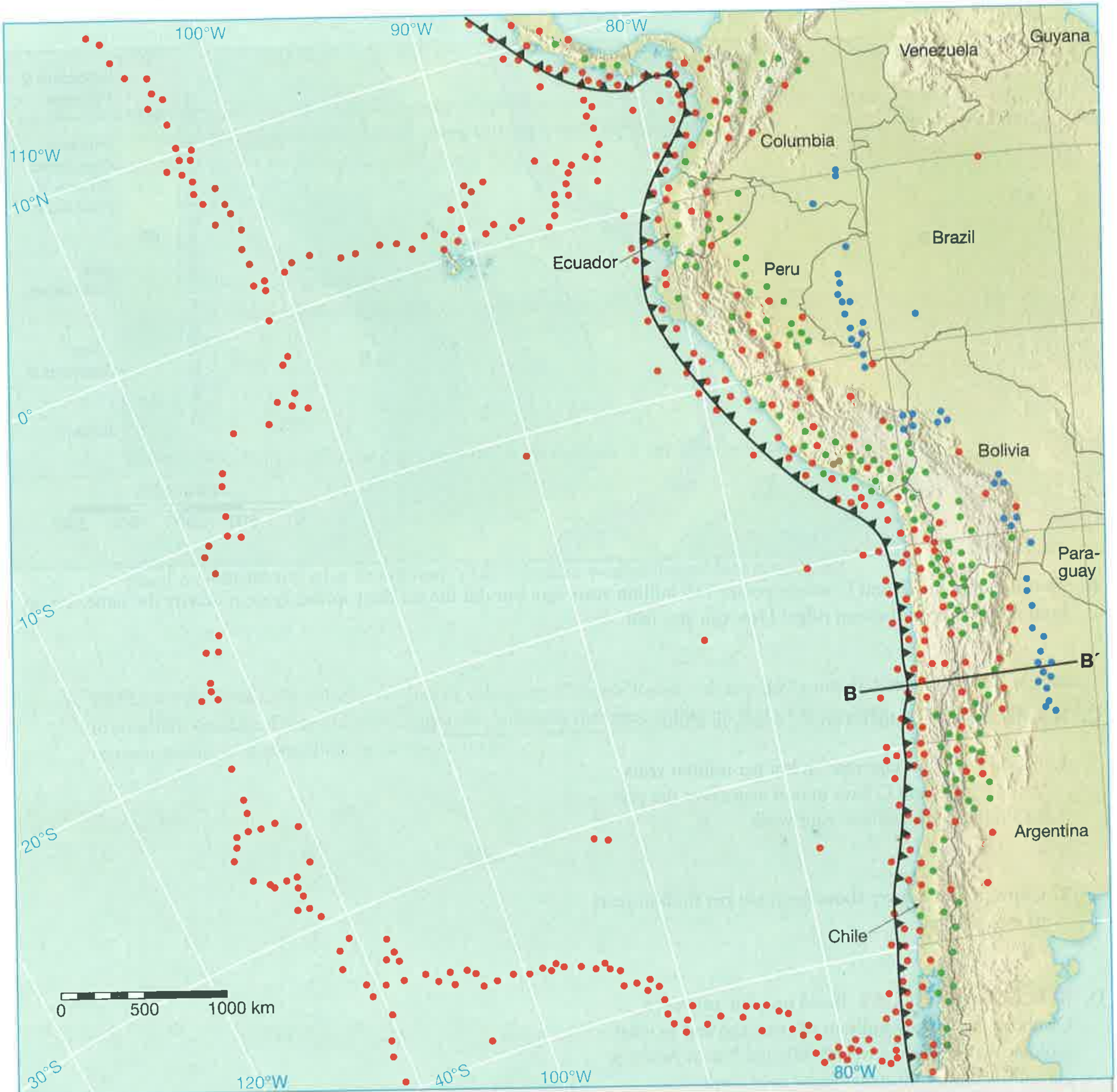
D. **REFLECT & DISCUSS** Based on your answer in **C1** above, how many millions of years ago and in what geologic period of time were Africa and North America part of the same continent? Show your work.

E. **REFLECT & DISCUSS** Based on your answer in **C2** above, how far in meters have Africa and North America moved apart since the United States was formed in 1776?

ACTIVITY **2.6** **Using Earthquakes to Identify Plate Boundaries**

Name: ______________________________ **Course/Section:** __________________ **Date:** __________

A. Refer to **FIGURE 2.2** for background on how the depth of earthquake foci is related to plate tectonics. On the map below, use a red colored pencil or pen to draw lines (as exactly as you can) that indicate where plate boundaries occur at Earth's surface. Then label the East Pacific Rise, Galapagos Rise, Chile Rise, and all of the plates (refer to **FIGURE 2.5**).



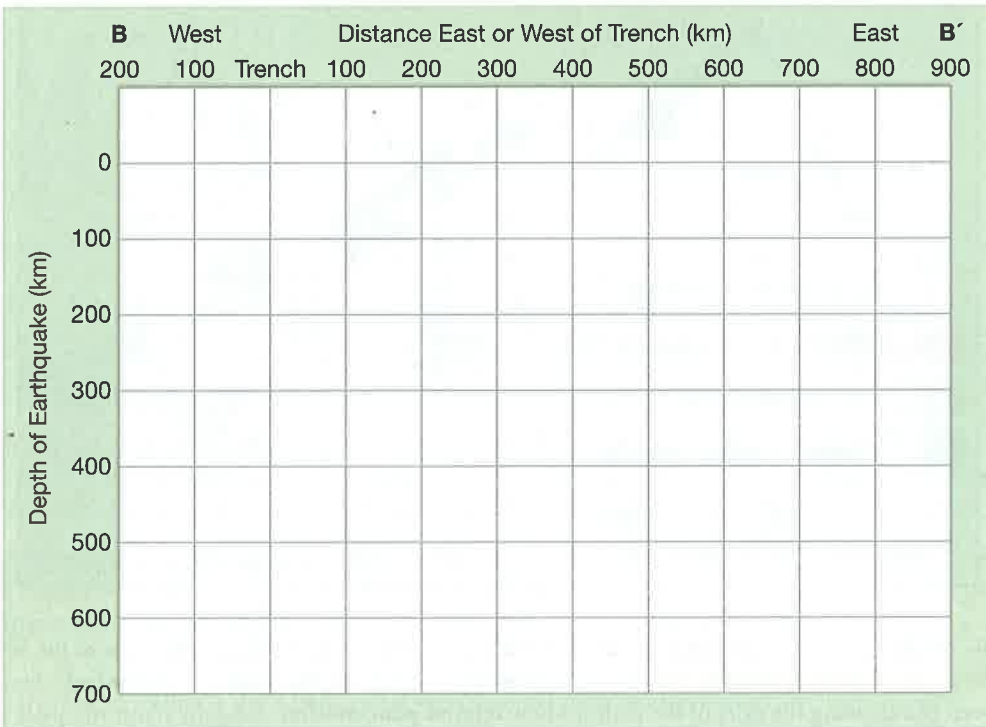
Map of Earthquake Activity in the Eastern Pacific Ocean and South America

- Shallow-focus earthquakes 0–69 km deep
- Intermediate-focus earthquakes 70–299 km deep
- Deep-focus earthquakes 300–700 km deep
- Trench

(Data from U.S. Geological Survey)

B. Notice line B–B' on the map in Part **A** and the fact that shallow, intermediate, and deep earthquakes occur along it. Volcanoes also occur at Earth's surface along this line. Plot the locations of earthquake foci (depth of earthquake vs. its location east or west of the trench) on the cross section below using data in the accompanying table (provided by the U.S. Geological Survey). For volcanoes, draw a small triangle on the surface (depth of zero).

Location East or West of Trench	Depth of Earthquake (or volcano location)	Location East or West of Trench	Depth of Earthquake (or volcano location)	Location East or West of Trench	Depth of Earthquake (or volcano location)
200 km West	20 km	220 km East	30 km	410 km East	150 km
160 km West	25 km	250 km East	volcano	450 km East	50 km
60 km West	10 km	260 km East	120 km	450 km East	150 km
30 km West	25 km	300 km East	volcano	470 km East	180 km
0 (trench)	20 km	300 km East	110 km	500 km East	30 km
10 km East	40 km	330 km East	volcano	500 km East	160 km
20 km East	30 km	330 km East	40 km	500 km East	180 km
50 km East	60 km	330 km East	120 km	540 km East	30 km
51 km East	10 km	350 km East	volcano	590 km East	20 km
55 km East	30 km	390 km East	volcano	640 km East	10 km
60 km East	20 km	390 km East	40 km	710 km East	30 km
80 km East	70 km	390 km East	140 km	780 km East	530 km
100 km East	10 km	410 km East	volcano	800 km East	560 km
120 km East	80 km	410 km East	25 km	820 km East	610 km
200 km East	110 km	410 km East	110 km	880 km East	620 km



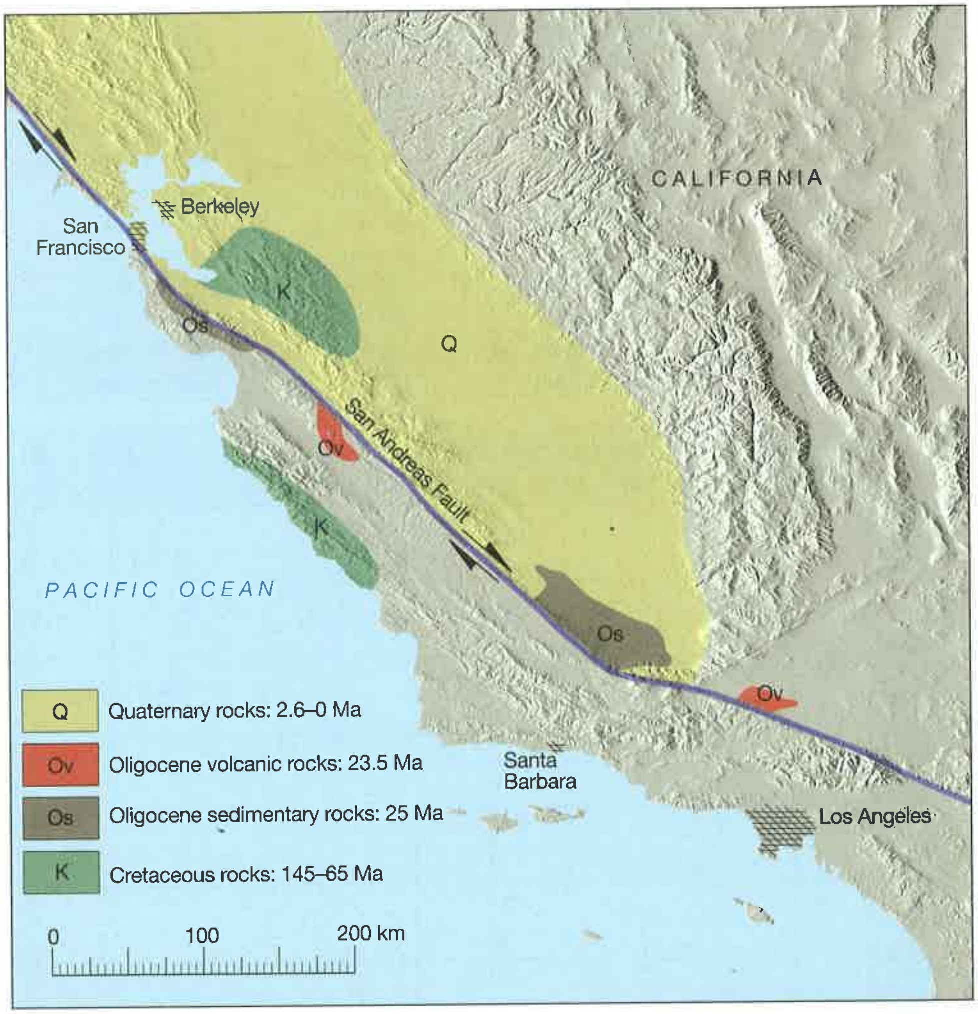
1. What kind of plate boundary is shown in your cross section? ______________________
2. Draw a line in the cross section to show the probable top surface of the subducting plate.
3. Label the part of your cross section that probably represents earthquakes in the lithosphere.
4. At what depth does magma probably originate here just above the subducting plate: ______________________ km
   How can you tell?

5. **REFLECT & DISCUSS** What is the deepest earthquake plotted on your cross section? Do you think there is a lower limit below which earthquakes are not likely to occur? Explain your answer. (Hint: Think about how pressure and temperature influence the behavior of rock in the upper mantle).

2.7 San Andreas Transform-Boundary Plate Motions

Name: ______________________ **Course/Section:** ______________ **Date:** __________

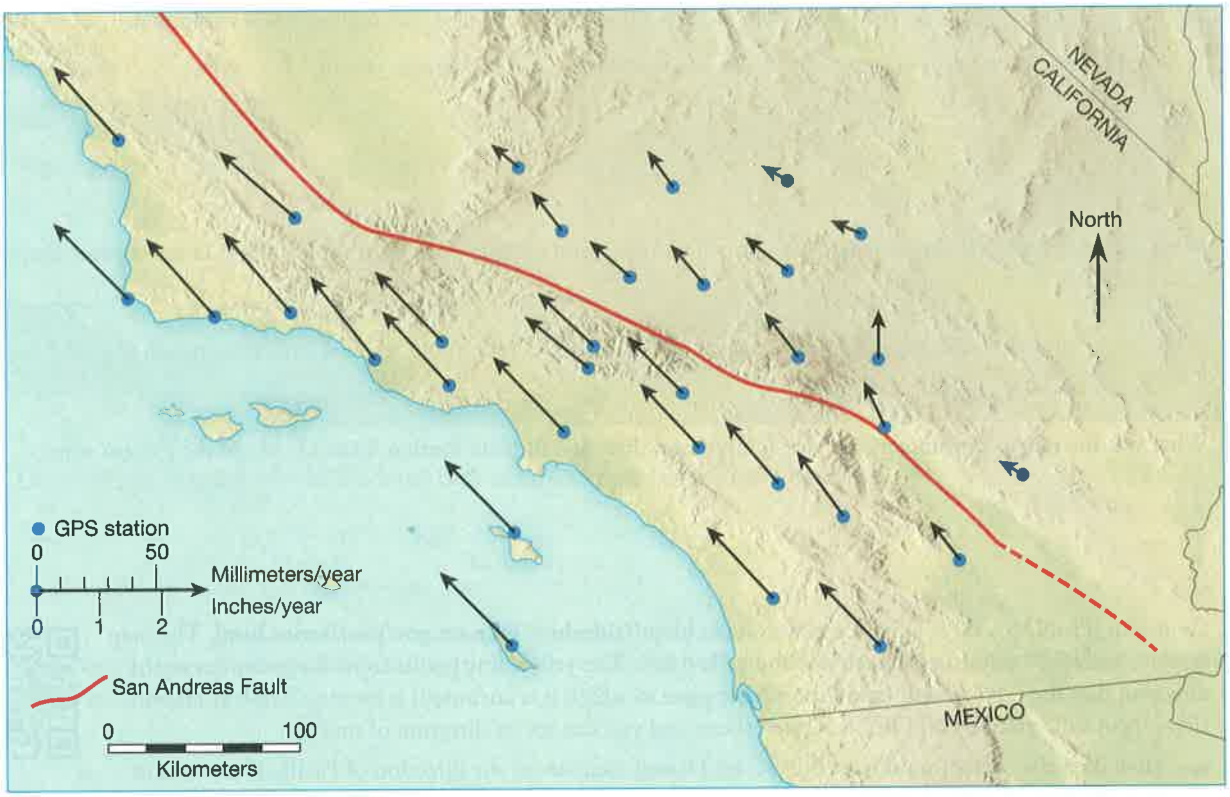
Study the geologic map of southern California below, showing the position of the famous San Andreas Fault, a transform plate boundary between the North American Plate (east side) and the Pacific Plate (west side). It is well known to all who live in southern California that plate displacements along the fault cause frequent earthquakes, which place humans and their properties at risk.



A. The two bodies of Oligocene volcanic rocks (about 23.5 million years old) located along either side of the San Andreas Fault (map above) were once one body of rock, but they have been separated by displacements along the fault. Note that half arrows have been placed along the sides of the fault to show **relative plate motion** along the transform plate boundary here.

1. You can calculate the average annual rate of relative plate motion (displacement) along the San Andreas Fault by measuring how much the Oligocene volcanic rocks have been offset by the fault and by assuming that these rocks began separating soon after they formed. What is the average rate of fault displacement in centimeters per year (cm/yr)? Show your work.

2. An average displacement of about 5 m (16 ft) along the San Andreas Fault was associated with the devastating 1906 San Francisco earthquake that killed people and destroyed properties. Assuming that all displacement along the fault was produced by Earth motions of this magnitude, how often must such earthquakes have occurred in order to account for the total displacement? Show your work.



B. The above map shows some Global Positioning System (GPS) reference stations and observations from the JPL-NASA GPS Time Series website at **http://sideshow.jpl.nasa.gov/post/series.html**. Length of the arrows indicates **absolute plate motion**, the direction and rate that the plate is moving in mm/yr at the GPS station (which is attached to bedrock of the plate).

1. Notice that both plates are moving northwest here. Estimate in cm/year how much faster the Pacific Plate is moving than the North American Plate. ____________________ cm/yr
2. Add half arrows along the San Andreas Fault to show the relative movement between the two plates.

C. REFLECT & DISCUSS What is the difference between absolute plate motion and relative plate motion?

ACTIVITY 2.8 Hot Spots and Plate Motions

Name: ______________________ **Course/Section:** ______________ **Date:** __________

As a lithospheric plate migrates across a stationary hot spot, a volcano develops directly above the hot spot. When the plate slides past the hot spot the overlying volcano becomes dormant, and over time, it migrates many kilometers from the hot spot. Meanwhile, a new volcano arises as a new part of the plate passes over the hot spot. The result is a string of volcanoes, with one end of the line located over the hot spot and quite active, and the other end distant and inactive. In between is a succession of volcanoes that are progressively older with distance from the hot spot.

A. FIGURE 2.7 shows the distribution of the Hawaiian Islands chain and Emperor Seamount chain. The numbers indicate age in millions of years old or ago (Ma), obtained from the basaltic igneous rock of which each island is composed.

1. In general, how is the Emperor Seamount chain related to the Hawaiian Islands chain?

2. What was the rate in centimeters per year (cm/yr) and direction of plate motion of the 2300 km long Emperor Seamount Chain from 20 to 40 Ma?

3. What was the rate in centimeters per year (cm/yr) and direction of plate motion in the Hawaiian region from 4.7 to 1.6 Ma?

4. What was the rate in centimeters per year (cm/yr) and direction of plate motion from 1.6 Ma to the present time?

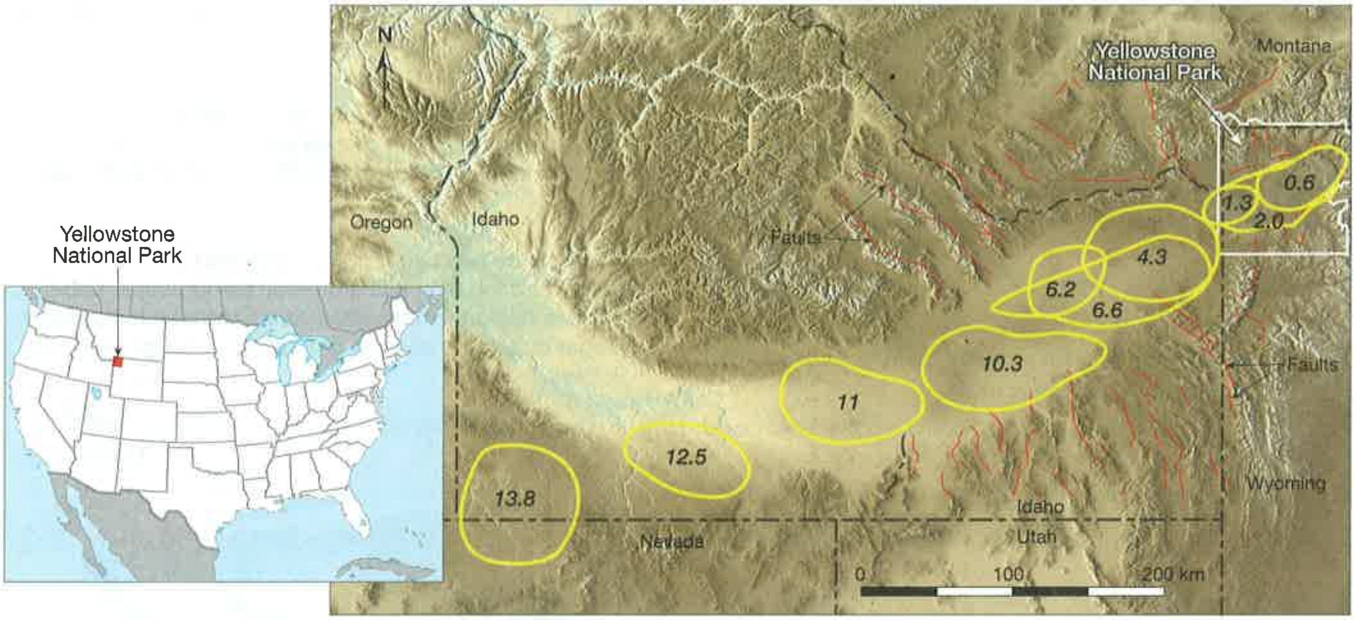
5. Go to the JPL-NASA GPS Time Series website at **http://sideshow.jpl.nasa.gov/post/series.html**. The map displays each GPS station as a green dot and yellow line. The yellow line points from the green dot to the direction that the GPS station (and lithospheric plate to which it is anchored) is moving. Look at Hawaii. JPL-NASA GPS station "NPOC" is located there, and you can see its direction of motion.

   a. How does the current motion of NPOC on Hawaii compare to the direction of Pacific Plate motion over the past 40 million years?

   b. The NPOC GPS station on Hawaii, and the Pacific Plate to which it is attached, has the following motion: Latitude vector direction & velocity: +1.4825 cm/yr, Longitude vector direction & velocity: –5.1612 cm/yr
   Using the formula in FIGURE 2.3, Part E, what is the current velocity (in cm/yr) of Pacific Plate motion at Hawaii? Show your work.

B. **REFLECT & DISCUSS** Based on all of your work above, explain how the direction and rate of Pacific Plate movement changed over the past 60 million years.

C. The map below shows the distribution of volcanic calderas (sub-circular depressions caused by repeated volcanic explosions and the associated faulting, tilting, and collapse of the crust) in Wyoming, Idaho, and Nevada. Geologist, Mark Anders mapped and dated these calderas. He also discovered that all of them are now inactive except for the one located directly over the Yellowstone National Park region. The hot springs, geysers, and earthquakes at Yellowstone indicate that the site is still volcanically active.



1. Do you think that Yellowstone National Park could be located over a hot spot? Why?

2. Based on the map, what was the rate in centimeters per year (cm/yr) and direction of North American Plate motion at Yellowstone since 10.3 Ma?

Add an arrow (vector) and rate label to the USA map above to show this movement.

3. **REFLECT & DISCUSS** How do hot spots help us understand plate tectonic processes and rates?

ACTIVITY 2.9 The Origin of Magma

Name: ____________________ **Course/Section:** ____________________ **Date:** ____________

A. Examine the pressure-temperature (P-T) diagram for mantle peridotite in **FIGURE 2.8**, and locate point **X**. This point represents a mass of peridotite buried 80 km underground.

1. According to the continental geothermal gradient, rocks buried 80 km beneath a continent would normally be heated to what temperature?

2. According to the oceanic geothermal gradient, rocks buried 80 km beneath an ocean basin would normally be heated to what temperature?

3. Is the peridotite at point **X** a mass of solid, a mixture of solid and liquid, or a mass of liquid? How do you know?

4. What would happen to the mass of peridotite at point **X** if it were heated to 1750 °C?

5. What would happen to the mass of peridotite at point **X** if it were heated to 2250 °C?

B. At its current depth, the peridotite at point **X** in **FIGURE 2.8** is under about 25,000 atm of pressure.

1. At what depth and pressure will this peridotite begin to melt if it is uplifted closer to Earth's surface and its temperature remains the same?

   Depth: ________ Pressure: ________

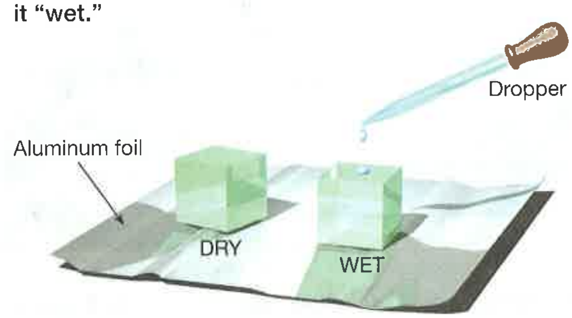
2. What is the name applied to this kind of melting?

3. Name a process that could uplift mantle peridotite to start it melting in this way, and name a specific plate tectonic setting where this may be happening now. (*Hint:* Study **FIGURES 2.2**, **2.5**, and **2.6**.)

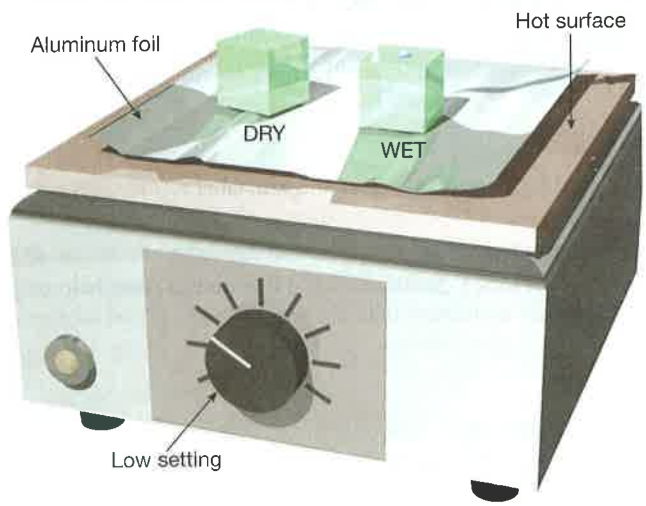
PROCEDURES FOR MELTING EXPERIMENT IN ACTIVITY 2.9

1. Turn the hot plate on a low setting (about 2 or 3 on most commercial hot plates) and allow it to heat up in a safe location (be careful not to touch hot surfaces directly).

2. Next, place two sugar cubes on a flat piece of aluminum foil or in aluminum foil baking cups. Label (on the foil) one sugar cube "dry." Moisten the second sugar cube with about 4 or 5 drops of water and label it "wet."



3. Carefully place the aluminum foil with the labeled sugar cubes onto the hot plate and observe what happens. When one of the sugar cubes begins to melt, use crucible tongs and/or hot pads to remove the foil and sugar cubes from the hot plate and avoid burning the sugar.



4. Turn off and un-plug the hot plate as soon as you finish #3 above. Be careful not to touch the hot surface!

FIGURE 2.9 Procedures for melting experiment in Activity 2.9. Be careful not to burn yourself on the hot surface or in molten sugar. Do not create a hazard by burning the sugar until it smokes or catches fire.

C. **REFLECT & DISCUSS** Based on your answers above, what are two environmental changes that can cause the peridotite at point **X** (see **FIGURE 2.8**) to begin partial melting?

D. Obtain the materials shown in **FIGURE 2.9**. Turn the hot plate on a low setting (about 3 on most commercial hot plates) and allow it to heat up in a safe location. Next place two sugar cubes on a flat piece of aluminum foil. Label (on the foil) one sugar cube "dry." Moisten the second sugar cube with a few drops of water, and label it "wet." Carefully place the aluminum foil (with the sugar cubes) onto the hot plate and observe what happens. (*Note:* Turn off the hot plate when one cube begins to melt.)

1. Which sugar cube melted first?

2. The rapid melting that you observed in the moistened sugar cube is called "flux melting," because flux is a material that promotes (speeds up) melting. What was the flux?

3. How would the P-T diagram in **FIGURE 2.9** change if all of the peridotite in the diagram was "wet" peridotite?

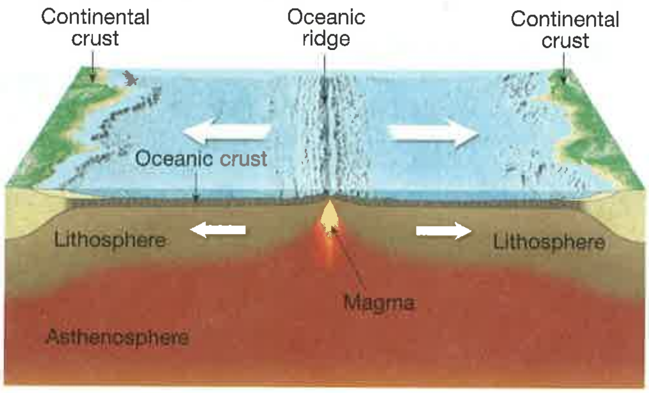
4. In what specific kind of plate tectonic setting could water enter Earth's mantle and cause flux melting of mantle peridotite? (*Hint:* **FIGURE 2.3**)

E. **REFLECT & DISCUSS** Examine this cross section of a plate boundary.

1. What kind of plate boundary is this?

2. Name the specific process that led to the formation of magma in this cross section.

3. Describe the sequence of plate tectonic and magma generating processes that led to formation of the volcanoes (oceanic ridge) in this cross section.



F. **REFLECT & DISCUSS** Examine this cross section of a plate boundary.

1. What kind of plate boundary is this?

2. Name the specific process that led to the formation of magma in this cross section.

3. Describe the sequence of plate tectonic and magma generating processes that led to formation of the volcanoes (continental volcanic arc) in this cross section.