LABORATORY 2

Plate Tectonics

Pre-Lab Video 2

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▲ The triangular Sinai Peninsula is part of a microplate between the African/Nubian Plate to the left (west) and the Arabian Plate to the right (east).

BIG IDEAS

Earth's solid outermost layer is the lithosphere, which includes the crust and the uppermost part of the upper mantle. The lithosphere is divided into plates that move relative to each other, and we can detect those motions using GPS and other technologies. Interactions between lithospheric plates along their boundary zones produce earthquakes, volcanoes, mountain ranges, mid-ocean ridges, and deep ocean trenches. Plate tectonics is the study of the motion of lithospheric plates and the geologic effects of those motions.

FOCUS YOUR INQUIRY

Think About It How do we detect and measure plate motion?

ACTIVITY 2.1 Reference Frames and Motion Vectors (p. 41, 55)

ACTIVITY 2.2 Measuring Plate Motion Using GPS (p. 44, 57)

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Think About It How does our knowledge of how materials deform help us to understand plate tectonics?

ACTIVITY 2.4 How Earth's Materials Deform (p. 50, 61)

Think About It How does rock magnetism help us date the oceanic crust and measure sea-floor spreading?

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Think About It How do earthquakes help us locate and understand plate boundaries?

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Introduction

We use modern technology to directly measure the present-day motion of various parts of Earth's outer surface relative to other parts of that surface—continental Africa moving away from continental South America, for example. Whether continents move relative to each other is no longer in dispute—they do. The relative motion of various parts of Earth's surface causes or contributes to many geological phenomena that are important to us, such as earthquakes, volcanism, elevation of mountain ranges and subsidence of basins, concentrations of valuable minerals, occurrence of energy resources, circulation of water in ocean basins, variations in climate, and changes in global sea level. The synthesis of knowledge related to the motion of big pieces of Earth's outer surface relative to each other over time is called **plate tectonics**.

Plate tectonics provides a context within which we can understand how different geological events and processes relate to one another. But at its core, plate tectonics is a description of the motion of plates. In a series of laboratory activities, we are going to explore some aspects of plate tectonics, emphasizing the motion of plates and some of the effects of that motion.

Earth's Outer Layers, Defined by Seismology

Pioneering studies by seismologists (geoscientists who use earthquake waves to study Earth's structure) in the late 1800s and early 1900s demonstrated that Earth has a thin, solid **crust** on top of a thick, solid **mantle**. The layers of Earth composed of rock—the crust and mantle—occur over a core composed mostly of iron with a liquid outer core and a solid inner core. The boundary between the crust and uppermost mantle was discovered in 1909 by Croatian seismologist Andrija Mohorovičić in whose honor it is called the **Moho** (pronounced MOE-hoe—pronouncing Mohorovičić is more complicated).

Earth has two fundamentally different types of crust above the Moho: oceanic and continental. **Oceanic crust** and **continental crust** differ in composition, thickness, density, average rock type, and the way they form. We will learn more about the composition of continental and oceanic crust later when we learn about minerals and rock. Oceanic crust is found beneath the deeper seafloor of major ocean basins, covering around 63% of Earth's surface. Continental crust underlies the part of Earth's surface from a couple of km below sea level to the top of Earth's highest peak.

The mantle is below the Moho and extends to a depth of ~2890 km or almost half-way to Earth's center. The mantle is composed of rock whose density is significantly greater than that of the crust. The average density of the crust is less than ~2.9 g/cm^3 whereas the density of the mantle ranges from ~3.3 to 5.6 g/cm^3. The iron-rich core below the mantle is much denser than the mantle.

Earth's Outer Layers, Defined by Strength

Geoscientists established the broad layering of Earth's deep interior by the end of the 1930s. As early as the 1920s, geoscientists had begun to realize that the great heat present in the core combined with the heat produced by radioactivity in the crust and mantle is likely to affect the strength or weakness of different parts of the mantle. (We use terms like *strong* and *weak* to indicate generally how difficult or easy it is to deform the material. A rock specimen you might encounter in lab is considered strong in comparison to wet clay or the inside of a banana.)

Based on laboratory experiments and theoretical modeling, the temperature at the center of Earth is interpreted to be approximately 6000°C, or about the same as the surface temperature of the Sun. Thankfully, the temperature at the ground surface where we live is much cooler, so there is a significant change in temperature with depth in Earth—a significant **geothermal gradient**. The relatively cold crust is solid and tends to break (i.e., to fracture and fault) when it is deformed. In contrast, solid rock that is heated to more than half of its melting temperature becomes softer, and very hot rock can actually flow in the solid state.

We know that liquid molten rock (**magma**) can flow. We can watch it flow in online videos of magma flowing from Kilauea Volcano in Hawaii. It seems strange that very hot **solid** rock can also flow, slowly changing its shape without fracturing or faulting. A convenient example of a solid that can flow even though it is not in the liquid state is Silly Putty™. If you mold Silly Putty into a sphere, you can bounce it on the floor just like an elastic rubber ball, and the putty will not deform during the short time it takes to impact and rebound. But if you set the ball of Silly Putty down, it will flow slowly under the force of gravity until it forms a flattened dome over the course of a half hour or less.

Earth's outermost ~100 km is a solid layer called the **lithosphere** that includes the crust and the uppermost part of the upper mantle (**Fig. 2.1**). The lithosphere is the relatively strong, cooler outer layer of Earth with a temperature ranging from below 0°C in some places at the ground surface to perhaps ~1300°C at the base of the lithosphere. Beneath the lithosphere is a hotter, much weaker layer in the mantle called the **asthenosphere**. The asthenosphere is hot enough to contain a tiny bit of magma, and that makes it particularly weak. The asthenosphere is almost entirely solid, but is weak and able to flow like Silly Putty.

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Lithospheric Plates

Many or most geoscientists prior to the mid-1900s assumed that Earth's solid outer layer was essentially continuous, like the unbroken shell of an egg. Global maps of earthquakes, active volcanoes, the mid-ocean ridge system, and deep ocean trenches produced in the 1950s and early 1960s led to the realization that the lithosphere is not a continuous layer but rather is a collection of pieces geoscientists call **lithospheric plates** or simply **plates** (**Fig. 2.1**). Lithospheric plates move horizontally over the

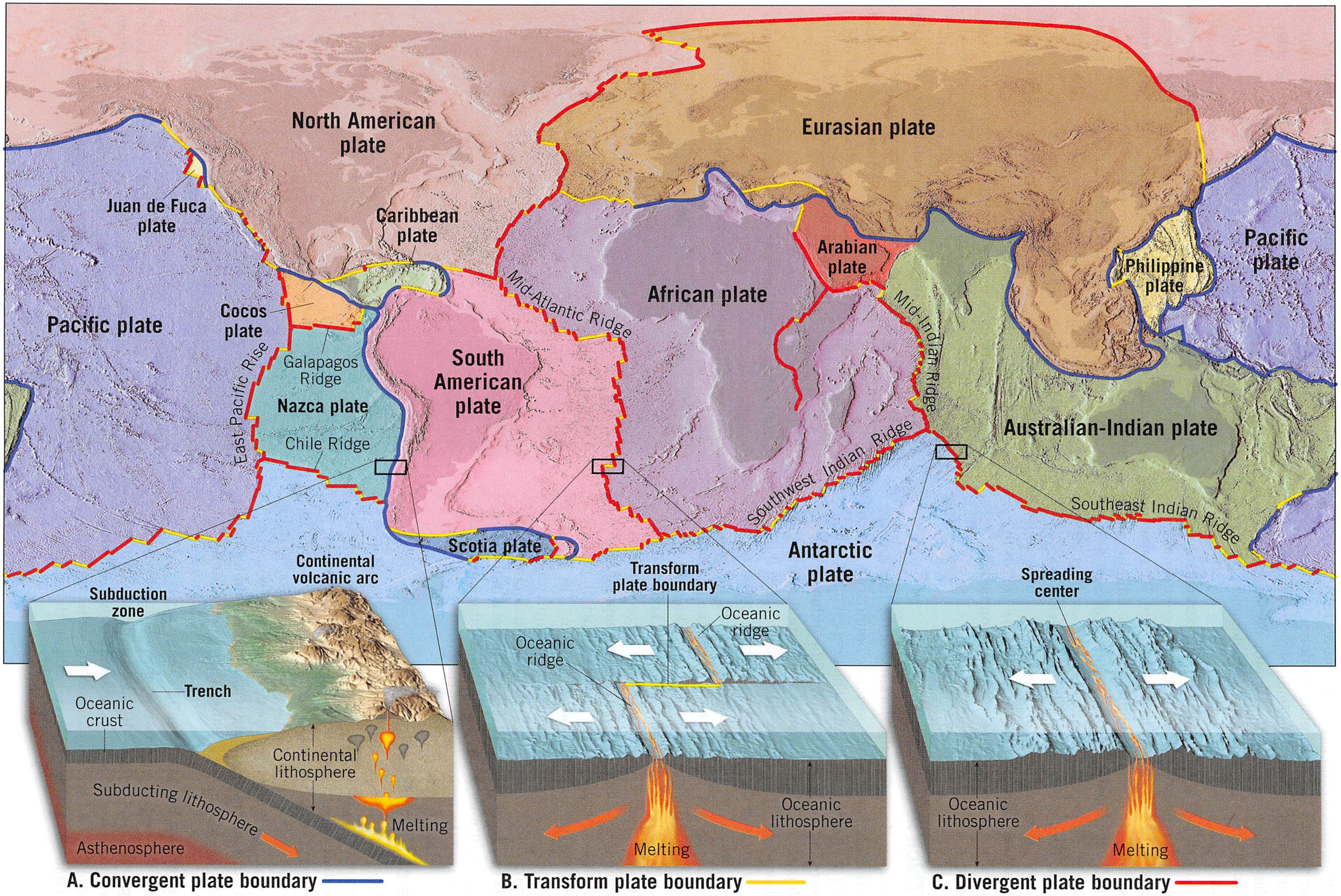


Figure 2.1 **Earth's major lithospheric plates.** Many smaller plates are not shown. Divergent (red line on map), convergent (blue), and transform (yellow) boundaries are illustrated in the block diagrams.

weak asthenosphere, and each plate moves relative to the other plates. The rate of plate motion is very slow—on the order of millimeters to centimeters per year along many plate-boundary segments—but the displacement across plate boundaries can be tens of kilometers over a million-year timespan.

The upper part of the lithosphere in a particular location might be composed of oceanic crust or continental crust, or perhaps some sort of transitional crust. We sometimes use the term **continental lithosphere** for lithosphere that includes continental crust (**Fig. 2A**), and **oceanic lithosphere** for lithosphere containing oceanic crust (**Figs. 2B** and **C**). The Pacific, Nazca, and Juan de Fuca Plates are examples of plates that are entirely or almost entirely composed of oceanic lithosphere. Most plates, like the North American Plate, include both oceanic and continental lithosphere.

How Thick Are Plates?

It is not easy to determine the thickness of the lithosphere, because the lithosphere-asthenosphere boundary is difficult to find by analyzing seismic data. The deepest part of the lithosphere and the shallowest part of the asthenosphere are both part of the upper mantle and share the same general composition. The primary difference between the two is temperature and the consequent difference in strength.

The thinnest oceanic lithosphere is along the plate boundary along a mid-ocean ridge, where the entire lithosphere is only as thick as the ~5–7 km thickness of the oceanic crust. The oceanic lithosphere thickens as it cools while moving away from the mid-ocean ridge plate boundary, ultimately reaching a thickness of perhaps 100 km before it sinks into the mantle in the subduction process. (We will learn more about subduction later.) The thickness of continental lithosphere has been even more difficult to interpret. It might be only as thick as the thinned continental crust (~20 km) in places where the continent is rifting apart, or it might be ~150–250 km thick under the oldest parts of the major continents.

Types of Plate Boundaries

In the late 1960s, geoscientists used a simplified model of plate tectonics in which Earth's surface is entirely covered by more than a dozen large lithospheric plates and some smaller microplates. Each of these plates was considered to be essentially rigid, meaning that there was little or no deformation except in the immediate vicinity of plate boundaries. Our current understanding is a bit more complex but includes many of the broad features of earlier models.

Divergent Plate Boundaries.

The boundary between two plates that are moving away from each other is called a **divergent boundary** (**Fig. 2.1C**). The more common type of divergent boundary involves oceanic lithosphere along mid-ocean ridges. Partial melting of the asthenosphere below a mid-ocean ridge generates magma that rises in small blobs, eventually making it to a **magma chamber** in the lower oceanic crust. As the two plates move apart perpendicular to the ridge crest, also known as the **ridge axis**, **tension** cracks develop along the axis that are filled in with magma. (If you grab a thin stick of chalk or a piece of string cheese and pull it apart, it will break along a tension crack oriented roughly perpendicular to the direction you pulled.) Some of the magma that intrudes the cracks continues on to the seafloor, resulting in volcanism along the axial valley of the mid-ocean ridge. Newly crystallized volcanic rock is added to the trailing edges of both plates along a mid-ocean ridge, forming new oceanic lithosphere. We call this process **sea-floor spreading**. Studies of oceanic crust formed along mid-ocean ridges indicate that about as much new crust is added to both sides of the boundary over long periods of time, although differences do occur.

Divergent boundaries in **continental lithosphere**—lithosphere with continental crust—are known as **continental rift zones**. Continued continental rifting eventually results in the generation of a new ocean basin with a mid-ocean ridge. For example, the East Africa Rift Zone might evolve into an ocean basin, just as the Red Sea and Gulf of Aden developed as the Arabian Plate rifted away from the African Plate (**Fig. 2.2**).

Convergent Plate Boundaries.

The boundary between two plates that are moving toward each other is called a **convergent boundary** (**Fig. 2.1A**). If the convergent

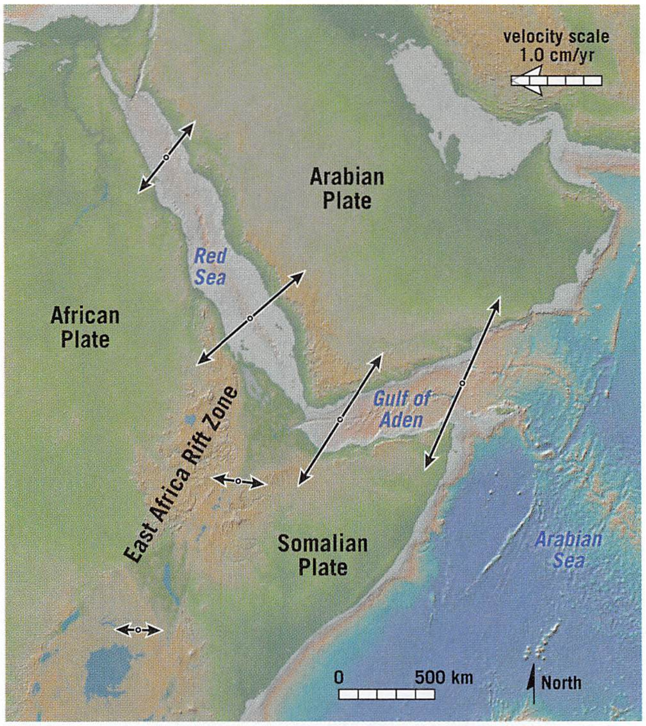


Figure 2.2 **New ocean basins and continental rift.** The Red Sea and Gulf of Aden are new ocean basins formed as the Arabian Plate diverged from the African Plate. The East Africa Rift is a divergent boundary that is separating the Somalian Plate from the African Plate. The arrows indicate plate motion relative to the divergent boundaries.

boundary involves oceanic lithosphere on one side of the boundary, a process called **subduction** will occur in which the oceanic lithosphere slips down beneath the other plate and sinks into the mantle (**Fig. 2.1A**). Earthquakes occur within the subducting slab of oceanic lithosphere as well as in the overriding plate, and magma begins to rise from the area above the subducting slab as it reaches depths of ~100 km. The magma feeds the chains of active volcanoes observed above subduction zones in places like the Cascades, the Andes, the Aleutians, and Japan. The oceanic lithosphere is mostly mantle material, and the oceanic crust is derived from the partial melting of the mantle, so subduction is a process in which oceanic lithosphere is recycled into the mantle. Where continental lithosphere converges with continental lithosphere, the crust is deformed into a mountain range like the Appalachians and the Himalaya.

Transform Plate Boundaries. The third principal type of plate boundary occurs where the edges of two adjacent plates are parallel to the direction in which one of the plates is moving relative to the other plate. This is called a **transform boundary**. Most transform boundaries are made up of **transform faults**—vertical or near-vertical faults oriented parallel to the direction one plate is moving relative to the other plate. A **fault** is a surface (or thin zone) along which rock bodies slip past one another, remaining in contact with each other along the fault. A vertical fault is like the surface between your favorite book and the book next to it on a tightly packed bookshelf. When you pull your favorite book horizontally away from the bookshelf, its cover slides along the cover of the adjacent book. So the "fault" between the books is vertical, and the slip direction between the books along the fault is horizontal. The books remain in contact with each other until you pull your favorite book entirely out of the bookshelf.

Transform faults are common between spreading segments along mid-ocean ridges (**Fig. 2.1B**). Other transform boundaries are more diffuse as along the western edge of the North American Plate where the relative motion between the North American and Pacific Plates is distributed across a broad zone involving several active structures. Faults within transform boundaries in continental crust can generate large earthquakes that are particularly damaging because they usually originate at shallow depths within ~15 km of the ground surface. The San Andreas Fault in California is an important part of this broader transform boundary zone (**Fig. 2.3**). Earthquakes on transform faults located along mid-ocean ridges are often even shallower because the oceanic crust is thinner, but these earthquakes usually result in little or no damage because most occur far from population centers.

Calculating Rates—The Math You Need

Several of the activities in this laboratory require you to calculate rates. You can review and learn more about calculating rates and do some practice problems at The Math You Need, When You Need It website. This site includes math tutorials for students in introductory geoscience courses: **http://serc.carleton.edu/mathyouneed/rates/index.html**

http://goo.gl/ZnOer5

ACTIVITY 2.1

Reference Frames and Motion Vectors, (p. 55)

Think About It How do we detect and measure plate motion?

Objective Learn about reference frames, displacement, and velocity vectors related to plate motions.

Before You Begin Read the Introduction and the section below: Where Are Plates Going?

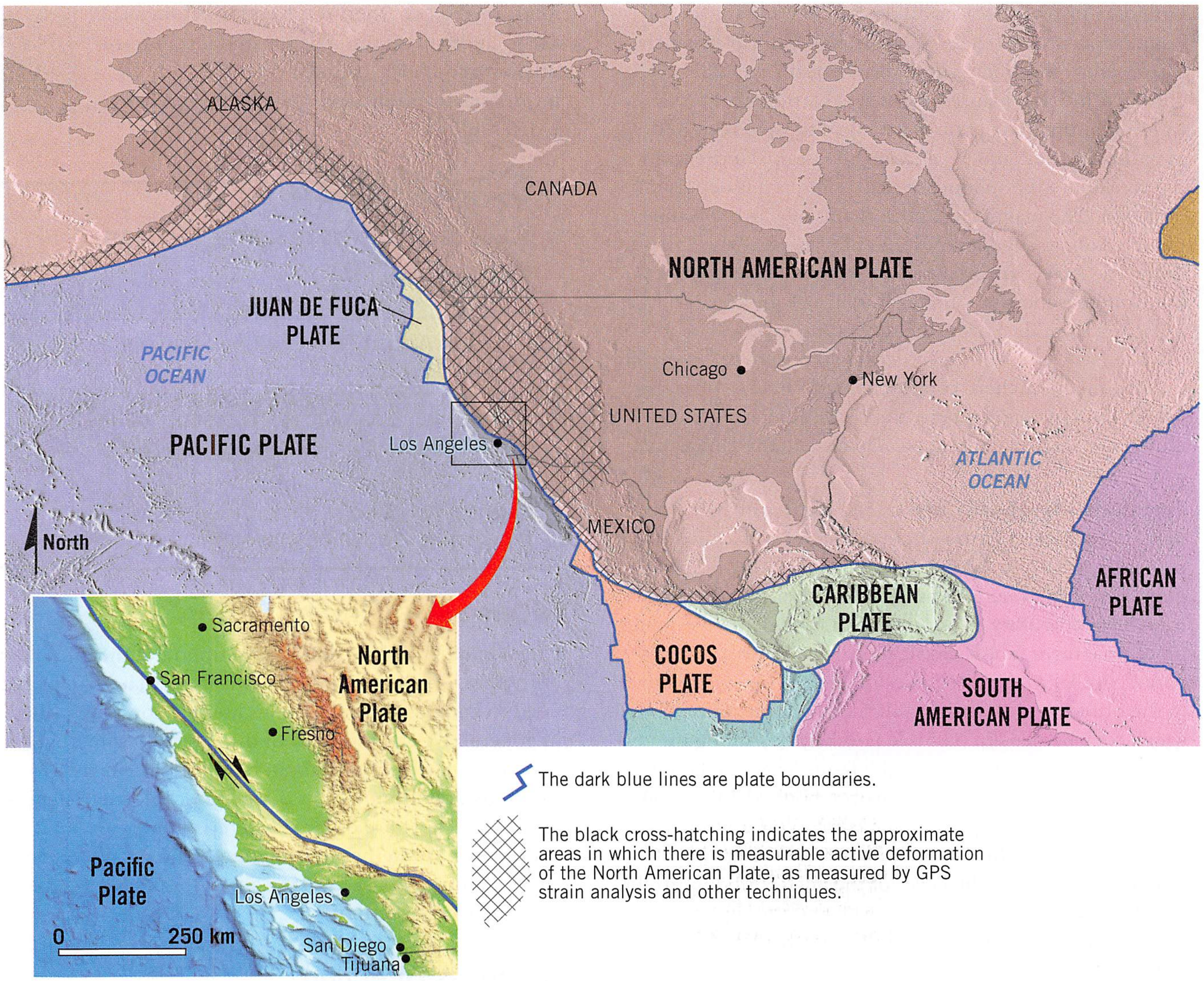
Where Are Plates Going?

Plate tectonics is, at its core, a description of the motion of lithospheric plates. In order to talk about plate motion, we need to know a few things about how motion is described in general. We can think about the direction something is moving in. We can think about how fast it is moving. We can think about whether its direction or velocity changes over time. There are other characteristics we can think about, such as whether it is rotating, but for the moment, let's limit ourselves to thinking about simple horizontal motion at a constant rate.

Compass Direction

You probably have a general idea of what we mean by the words *north, south, east,* and *west.* North is the direction toward the north spin axis of Earth, currently located in the arctic between Canada and Russia. South is toward the south spin axis in Antarctica. Looking north, east is to your right and west is to your left (**Fig. 2.4**). The conventional way of describing direction beyond these four cardinal compass directions is to measure an angle on a horizontal plane from the north direction to the direction you are interested in describing. The method we will use is called the **azimuth method** in which north is defined as having an azimuth of 0°, and the azimuth angle (or simply the **azimuth** or **compass bearing**) increases in a clockwise rotation from north. (A clockwise rotation is the same direction that the fingers on your left hand curl when they are at rest and your thumb is pointing up, so we sometimes call this a left-handed or negative rotation.) East has an azimuth of 90°, south is 180°, west is 270°, and as we swing back toward North, we approach 360°. The full circle of azimuths spans 360°.

Four arrows are shown in **Fig. 2.4**. If you were asked, "In what direction is arrow *A* pointing," the answer would be that arrow *A* is pointing toward azimuth 34°,



The dark blue lines are plate boundaries.

The black cross-hatching indicates the approximate areas in which there is measurable active deformation of the North American Plate, as measured by GPS strain analysis and other techniques.

Figure 2.3 **Tectonic setting of North America.** The western part of North America (crosshatch) is actively deforming. The San Andreas Fault (blue curve in the detail map at lower left) is a major part of the transform boundary between the Pacific Plate and the North American Plate.

or approximately toward the northeast. Arrow B is pointing toward 150°, C toward 255°, and arrow D is pointing toward azimuth 315°.

Dust off the Pythagorean Theorem

A long time ago when you were much younger, a math teacher introduced you to a simple bit of mathematics called the *Pythagorean equation* or *Pythagorean theorem*. It's OK if you don't remember, and there's no need to deny that you have ever heard of it because you are going to learn what you need to know right now. Think about a triangle in which two sides form a right angle—that is, the two sides are 90° or *perpendicular* to each other (**Fig. 2.5**). The length of the green side at the bottom of the triangle in **Fig. 2.5** is represented by a variable we will call a, the length of the blue side is b, and we want to know the length of the orange side, which we will call c. (You might recall that the orange side represents the *hypotenuse* of the right triangle.) About 2500 years ago, Pythagoras proved that

$$a^2 + b^2 = c^2,$$

which is known as the **Pythagorean equation**. We don't want to know what c^2 is, but rather we want to know what c is: the length of the hypotenuse. We find c^2 by taking the *square root* of the quantity $(a^2 + b^2)$, or

$$c = \sqrt{a^2 + b^2}$$

Nobody computes square roots by hand anymore. Just find a calculator or an app that can do the computational work for you.

Example. Imagine that we have a right triangle in which one side has a length of $a = 2$ and the length of the other side is $b = 3$. We want to know the hypotenuse length, c, and we are going to use the Pythagorean equation to find it. The order of mathematical operations in this case is to

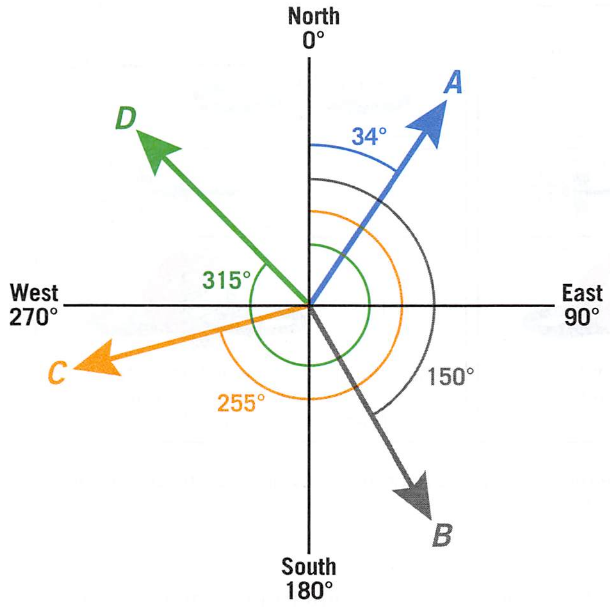


Figure 2.4 **Measuring compass directions using the azimuth method.** Azimuth is measured in a horizontal plane with a clockwise rotation from north. The azimuth of direction *A* is 34°, and the azimuths of directions *B*, *C*, and *D* are as shown.

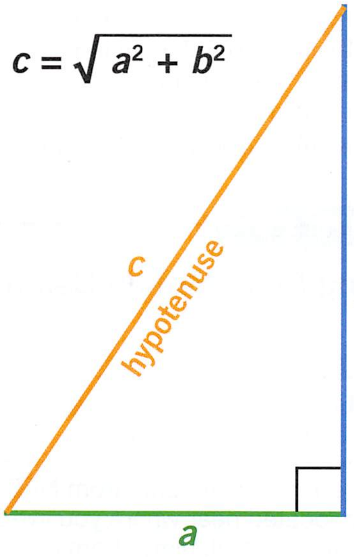


Figure 2.5 **Length of a hypotenuse.** Given a right triangle with sides of length *a* and *b*, we use a form of the Pythagorean equation to find the length of the hypotenuse, *c*.

square *a* and *b* first, then add them together, and then take the square root of the sum. Squaring a number is just multiplying the number by itself once, so

$$a^2 = a \times a = 2 \times 2 = 4, \text{ and}$$
$$b^2 = b \times b = 3 \times 3 = 9.$$

Using a form of the Pythagorean Theorem, we find that

$$c = \sqrt{a^2 + b^2} = \sqrt{4 + 9} = \sqrt{13} \simeq 3.6$$

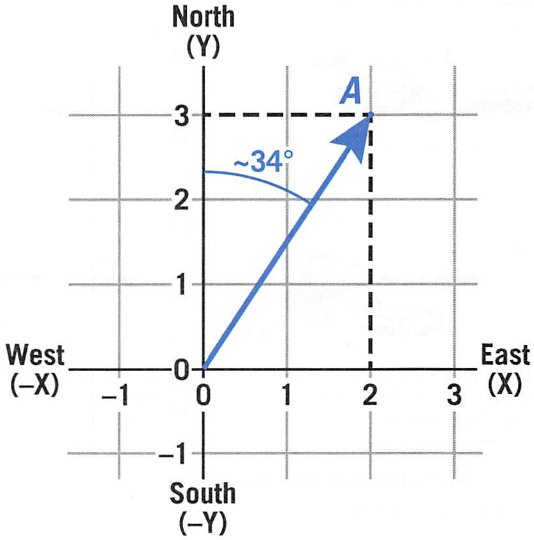


Figure 2.6 **2-dimensional vector.** The coordinate system we will use to define vectors will be a horizontal plane with axes aligned east–west and north–south. Directions are measured clockwise from north using the azimuth method.

So the length of the hypotenuse is approximately equal to 3.6. We are going to need this little bit of math.

2-D Vectors

A **vector** is a mathematical representation of something that has a **magnitude** and **direction**. We can think of a vector as an arrow extending from the origin of an X-Y coordinate system at point {0, 0} to another point, say {2, 3} (**Fig. 2.6**). The first number listed in the curly brackets is the X coordinate, and the second is the Y coordinate. We say that the coordinates of vector ***A*** are {2, 3}, meaning that the vector extends from {0, 0} to {2, 3} (**Fig. 2.6**).

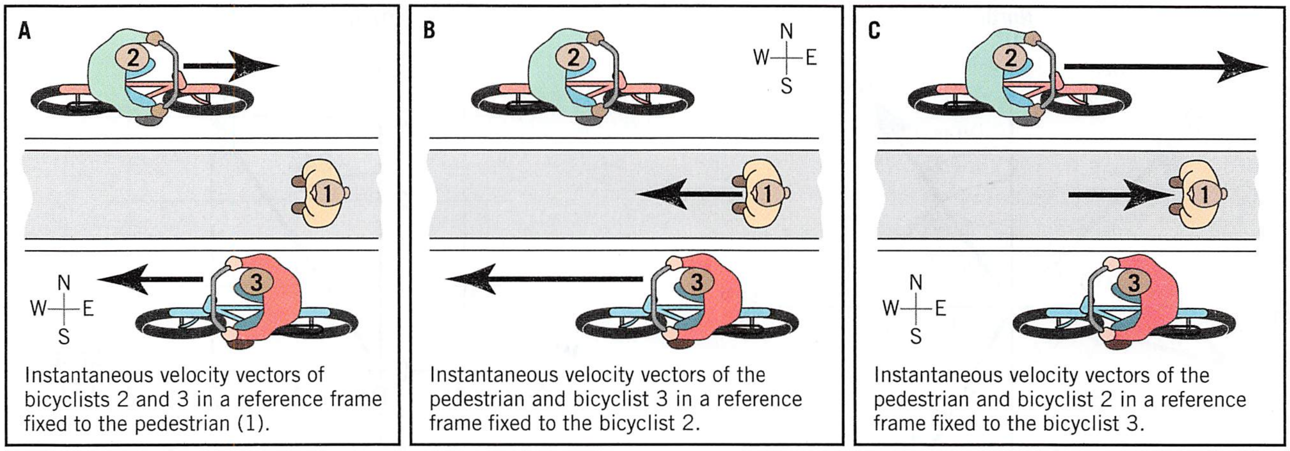
The way we will define our vector coordinate system in this lab is to align the positive Y axis with north and the positive X axis with east. That allows us to use the azimuth method to describe the direction of vector ***A*** (**Fig. 2.6**). We measure the azimuth clockwise from north to vector ***A*** using a protractor and find the azimuth to be ~34°. (We can also use trigonometry to determine the angle more exactly, but measurement with a protractor will do for now.) The length or magnitude of vector ***A*** can be determined using the Pythagorean equation.

$$\text{magnitude of } \boldsymbol{A} = \sqrt{2^2 + 3^2} \simeq 3.6$$

Velocity is a vector quantity because it has a magnitude (the **speed**) and a direction in which the object is moving. Displacement is another vector quantity because it can be expressed as the vector from a starting location to a different location.

Motion, but Relative to What?

Every time we experience **displacement** (a change from an initial position to another position) or a **velocity** (a displacement during a time interval), our description



Instantaneous velocity vectors of bicyclists 2 and 3 in a reference frame fixed to the pedestrian (1).

Instantaneous velocity vectors of the pedestrian and bicyclist 3 in a reference frame fixed to the bicyclist 2.

Instantaneous velocity vectors of the pedestrian and bicyclist 2 in a reference frame fixed to the bicyclist 3.

Figure 2.7 **Visualizing reference frames.** A person (1) standing on a median in a road and two bicyclists (2 and 3) with arrows representing instantaneous velocities.

depends on the **reference frame** in which we experienced it. Any report of a displacement or velocity begs the question, "Relative to what?" That is, what was the reference frame in which the velocity was measured?

Imagine standing on a median strip in a roadway watching as a bicyclist passes you on your left and another passes on your right (**Fig. 2.7**). From your perspective—that is, in a reference frame that is fixed to you—both riders are moving, but you are not (**Fig. 2.7A**). In the reference frame experienced by rider 2, you and rider 3 are both moving west but at different speeds (**Fig. 2.7B**). Rider 3's speed relative to rider 2 is equal to the combined speeds of both riders as you measure them in your reference frame. In a similar way, rider 3 sees you and rider 2 moving east at different rates (**Fig. 2.7C**). The speed of rider 2 as observed from rider 3 is the same as the speed of rider 3 as observed from rider 2, but the directions are opposite.

We work with several reference frames in the study of plate tectonics. Sometimes we are interested in how one plate moves as observed from another plate. In that case, the reference frame is fixed to the observer's plate. Sometimes we want to describe the motion of the plates on both sides of a plate boundary, and so we use a reference frame that is fixed to that boundary (e.g., **Fig. 2.2**). Sometimes we want to know how an individual plate is moving relative to a reference frame that is not fixed to a plate or a plate boundary but rather is fixed to something else that is external to the lithosphere. A **hotspot** in the mantle below the lithosphere that generates a trail of volcanoes as a plate moves over it can be used to define an external reference frame to describe plate motions. (We will develop the hotspot idea later in this lab.)

One important kind of external reference frame that is used to express the motion of an individual plate relative to the rest of the Earth is called a "no-net-rotation" (NNR) reference frame. The details of the **NNR reference frame** are complicated, but a simplified explanation is all we will need. We can just think of the NNR reference frame as a way of measuring displacements and velocities in a reference frame that is centered on Earth but is not attached to any of the plates or their boundaries. You can think of NNR as a view of plate motion from a vantage point in the deep mantle.

Instantaneous versus Finite Displacements and Velocities

Plates have been moving for billions of years. When geoscientists consider a displacement between two plates that occurs over a year, a few years, or even a few thousand years, we consider that an **instantaneous displacement**, and the rate of displacement would be an **instantaneous velocity**. In contrast, if geoscientists are working with displacements or velocities that involve millions of years or more, we consider those **finite displacements** or **finite velocities**.

ACTIVITY 2.2

Measuring Plate Motion Using GPS, (p. 57)

Think About It How do we detect and measure plate motion?

Objective Use velocity data from NASA for a GPS station located near where you live along with a Plate Motion Calculator from UNAVCO to determine the direction and rate that your plate is moving near your home.

Before You Begin Read the following sections: GPS—Global Positioning System and Using GPS to Study Lithospheric Plate Motion.

Plan Ahead This activity requires that data be gathered from websites hosted by NASA-JPL and UNAVCO. If you will not be able to access the web during your lab session, you will need to collect data from these websites before coming to lab. You might also need to bring a calculator that can compute a square root so that you can use the Pythagorean Theorem to compute a velocity.

GPS—Global Positioning System

The United States has established a constellation of more than two dozen navigation satellites and their ground stations that we call the Global Positioning System or **GPS**. (Russia, the European Union, India, Japan, and China also have satellite navigation systems in operation or development. These systems, along with GPS, are jointly called the Global Navigation Satellite System or **GNSS**. For simplicity, we will simply refer to GPS in this lab.) This technology allows us to determine the location of a GPS receiver that might be embedded in a phone, a car, or other devices. In addition to its other civilian and military applications, GPS is used in **geodesy**—the science of measuring changes in Earth's size and shape and the position of different parts of Earth's surface over time. We will use geodetic GPS data in this lab to help us determine the motion of lithospheric plates.

Each GPS satellite orbits Earth every 12 hours at a height of ~20,183 km. These satellites are arranged in 6 different orbital planes with at least 4 satellites in each plane. The orbital geometry was designed to ensure that between 8 and 12 satellites are always visible above the horizon by any GPS receiver anywhere on Earth. The positions of these satellites are constantly monitored by 16 sites around the globe and are precisely known. Each GPS satellite transmits radio signals that are received by GPS antennas on Earth. It takes the signals from at least four GPS satellites for a GPS receiver on Earth to compute its location through a process of **trilateration**.

Geoscientists have established networks of fixed GPS sites throughout the world. By "fixed," we mean that the antenna is attached to a building or a rigid stand that is firmly attached to the ground and that position data from that site are automatically recorded for years or tens of years. One such network of 1,100 GPS sites in the United States was developed as part of the EarthScope Project, and is called the Plate Boundary Observatory or **PBO** (**http://www.unavco.org/projects/major-projects/pbo/pbo.html**). The GPS antennas at PBO stations are pinned to Earth's crust via a stainless steel mount with four to five legs welded together that extend many meters into the ground (Fig. 2.8). Data from GPS satellites are collected at PBO stations every 15 seconds. Some stations collect these data at a rate of five times every second, and this wealth of data allows us to measure the displacement of Earth's surface during earthquakes. The position of each geodetic GPS site is measured to an accuracy of less than a centimeter, and the change in position is measured in millimeters per year.

Over a decade or more of measuring the position of a fixed GPS site, we can detect the slowly changing position of that part of the crust. The motion of a single GPS site does not provide enough information to characterize the motion of the entire plate that the site is a part of. We resolve a plate's motion by analyzing data from multiple GPS sites located within the plate away from GPS sites located within the plate away from plate boundaries or other areas in which the crust is actively deforming.

Figure 2.8 Example of a GPS station. Plate Boundary Observatory Station P150 on Martis Peak, California (lat 39.29238°, long −120.03386°). The antenna is under the gray dome to the left and is mounted on stainless steel pipes that extend ~15 m into the ground. Solar panels supply the energy for the electronics that acquire the data and transmit them elsewhere for analysis.

GPS stations acquire location data that are resolved into north–south, east–west, and up–down displacements from the original station position. These data are plotted on graphs with displacement along the vertical axis and time on the horizontal axis. Displacement-versus-time graphs are examples of **time-series** plots, in which we plot the variation of something as a function of time (Fig. 2.9). Displacements toward the north are considered positive displacements, and displacements toward the south are negative. East displacements are positive; west displacements are negative. The slope of the best-fit line or curve over a period of years is used to determine the speed and direction of site motion (**Fig. 2.9**).

Let's use some real data to derive the velocity of a GPS station in an NNR reference frame, using resources provided online by NASA. We are going to investigate the motion of a GPS station called SYDN in Sydney, Australia, located at latitude −33.780874256° and longitude 151.150381378°. First, we navigate to a website **http://sideshow/jpl.nasa.gov/post/series.html)** where GPS time-series data computed by NASA's Jet Propulsion Lab (JPL) are available. We look on the Google map to find the green dot on the east coast of Australia at Sydney. The yellow line extending to the north-northeast of the green dot indicates the direction and velocity the GPS station (and the crust it is attached to) is moving in the NNR reference frame. When we click on the green dot at Sydney, a small white box with some graphs appears. Double-click on that box, and it will expand to show the time-series plots, as shown in Fig. 2.10.

The vertical axis in the time-series plot shown in **Fig. 2.10A**, marked *Latitude*, indicates the north–south motion of SYDN. The time series has a positive slope, so the motion is toward north. The rate at which SYDN moves north is the same as the slope of the time series—change in position divided by the time over which that change

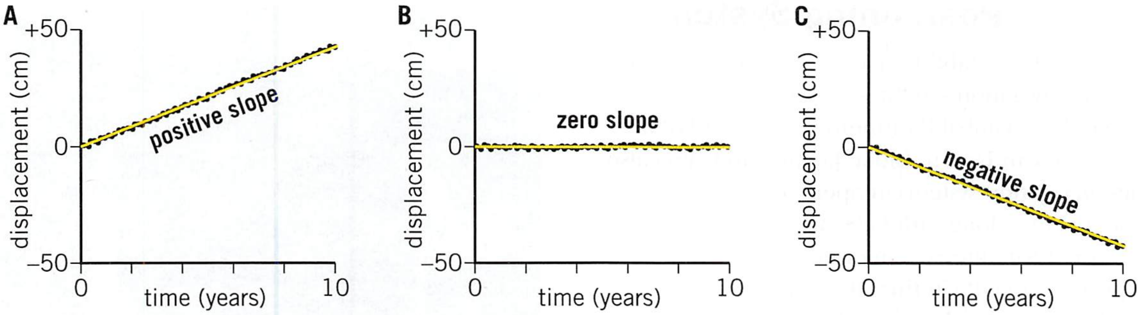


Figure 2.9 **Interpreting time-series plots.** Examples of time-series plots of displacement from some initial location. Positive displacements are toward the north; negative displacements are toward the south. **A.** Displacement is toward the north at an approximately constant rate. **B.** No north–south displacement. **C.** Displacement is toward the south at an approximately constant rate.

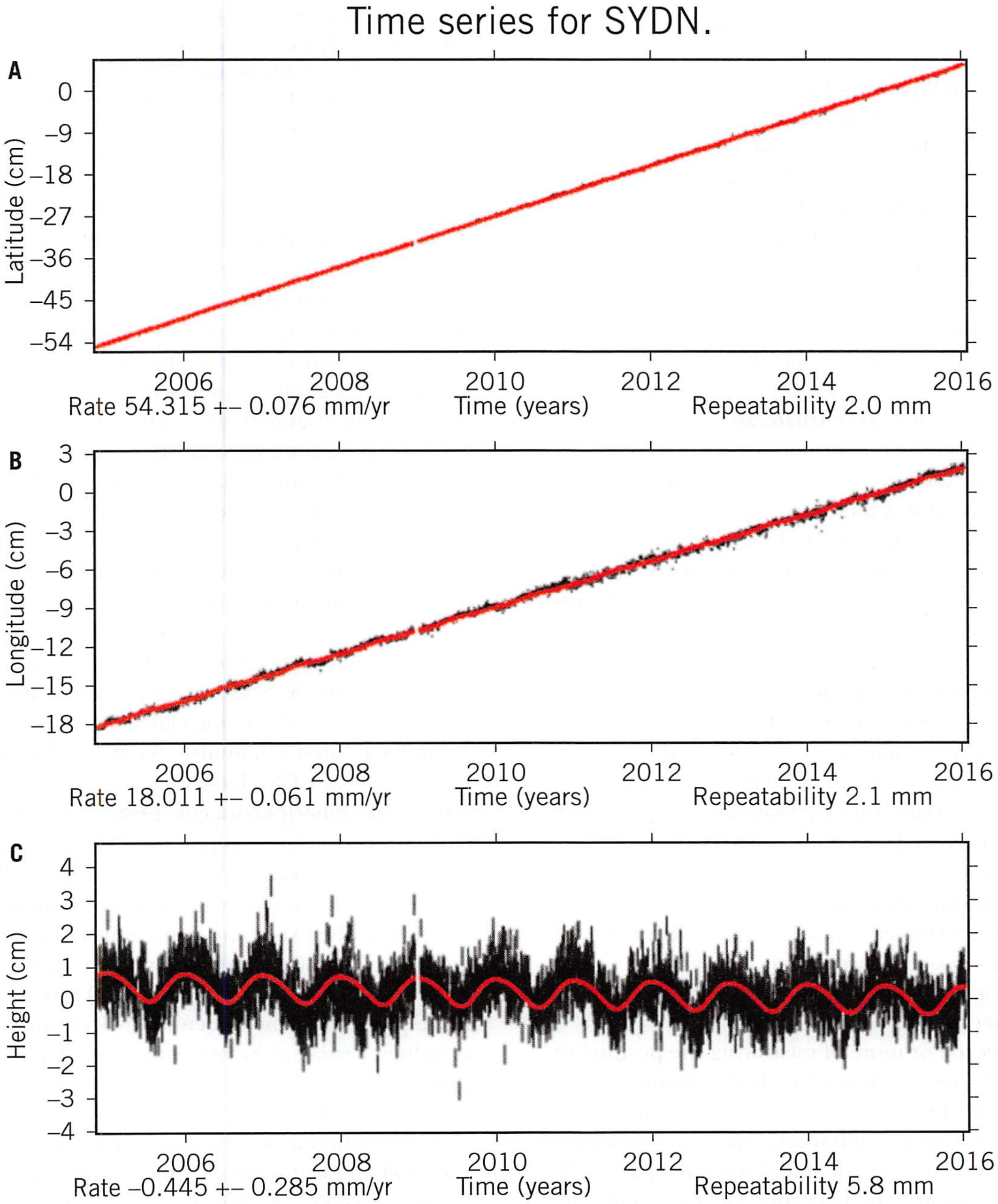


Figure 2.10 **Time-series plots for GPS station SYDN.** These plots indicate the displacement and average velocity of GPS site SYDN in Sidney, Australia, in an NNR reference frame. **A.** "Latitude" reflects displacement in a north–south direction. **B.** "Longitude" reflects displacement in an east–west direction. **C.** "Height" reflects vertical displacement. (Produced by NASA-JPL at CalTech and accessed online via **http://sideshow.jpl.nasa.gov/post/series.html** on January 17, 2016.)

occurred. The slope computed at JPL is printed just below the graph: 54.315 millimeters per year with an uncertainty of +/−0.076 mm/year. The vertical axis marked *Longitude* in **Fig. 2.10B** indicates the east–west motion of SYDN. The slope of the data is positive, so SYDN is moving east at a rate of 18.011 mm/year +/−0.061 mm/year. The time-series plot in **Fig. 2.10C** indicates the up–down motion of SYDN and shows an annual variation in elevation that is related to seasonal wetting and drying that causes the land surface to rise and fall a little bit every year. The average trend of the line is slightly downward at a rate of −0.445 mm/year +/−0.285 mm/year.

We can plot the north–south and east–west velocities as vectors to help us visualize the direction and speed that SYDN is moving in the NNR reference frame (**Figs. 2.6** and **2.11**). (Refer to the earlier section about *2-D vectors* if you need to.) Each square in the plot represents 10 mm/year. The north velocity vector (brown) is 54.315 mm/yr. long and points north because the north velocity is a positive number (**Fig. 2.11**). The east velocity vector (blue) is 18.011 mm/yr. long and points east because it too is a positive number. We find the total horizontal velocity vector of GPS site SYDN in the NNR reference frame by adding the north velocity vector and the east velocity vector together. The result is the black vector in **Fig. 2.11**, which has coordinates {18.011, 54.315} (e.g., **Fig. 2.6**).

Using the protractor that is included along the margins of the plot, we can see that the azimuth of the total-horizontal-velocity vector is about 18°. Its length can be computed using a form of the Pythagorean Theorem (e.g., **Fig. 2.5**).

$$\text{Total horizontal velocity} = \sqrt{(\text{N} - \text{S velocity})^2 + (\text{E} - \text{W velocity})^2}$$

In this example,

$$\text{Total horizontal velocity} = \sqrt{(54.315)^2 + (18.011)^2} = 57.223 \text{ mm/yr.}$$

The average horizontal velocity of GPS station SYDN relative to an NNR reference frame is 57.223 mm/yr. moving toward azimuth 18.3°.

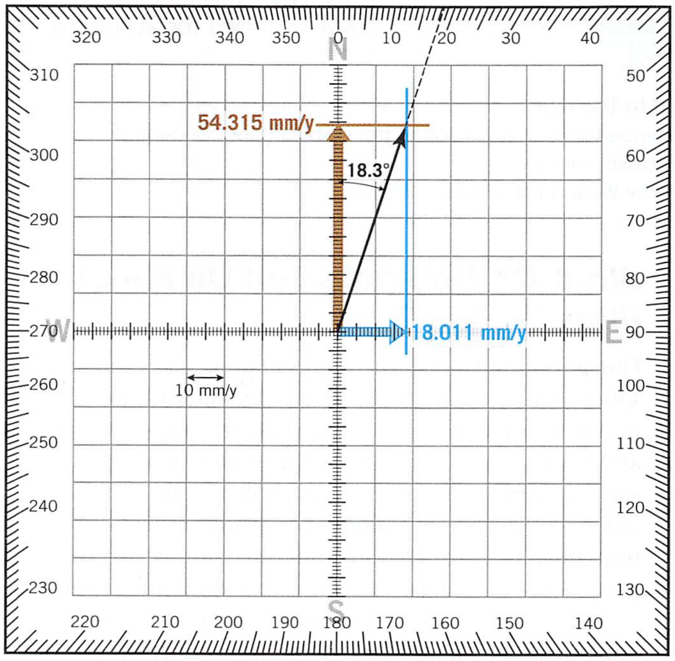


Figure 2.11 Instantaneous velocity vectors for GPS station SYDN. Plate motion plot of the north–south and east–west instantaneous velocity vectors for GPS station SYDN, which is moving toward 18.3° azimuth in an NNR reference frame.

Using GPS to Study Lithospheric Plate Motion

Availability of GPS data has allowed us to investigate the initial idea that large lithospheric plates are essentially rigid and undeforming except in the vicinity of plate boundaries. The North American Plate is a good example of a lithospheric plate that is *not* rigid from boundary to boundary. While the North American Plate is approximately rigid from its eastern boundary along the Mid-Atlantic Ridge to the Rocky Mountains in the western part of the continent, GPS and other data indicate that the plate deforms between the Rocky Mountains and the western boundary along the Pacific margin (**Figs. 2.3** and **2.12**). The slow deformation of the western North American Plate is at least partly responsible for the varied landscapes, volcanism, earthquakes, and economic mineral deposits that make this region so interesting.

GPS data also allow us to measure vertical deformation in areas of Canada, the United States, and elsewhere that were covered by heavy continental ice sheets over the past couple of million years that have since melted. The crust rebounds upward and sometimes a little bit outward like an elastic cushion when a well-fed cat jumps off the sofa.

The **NAM08 reference frame** is fixed to the stable interior of the North American Plate away from boundary deformation and areas undergoing glacial rebound and allows us to depict the motion of parts of the lithosphere beyond that approximately rigid core (**Fig. 2.12**). What we see in **Fig. 2.12** is more interesting and varied than the idea that lithospheric plates are essentially rigid from edge to edge.

Data recorded at GPS sites every day are helping geoscientists develop a more detailed picture of where and how fast the various bits and pieces of the lithosphere are moving. We are gaining a better understanding of which areas are behaving like classic lithospheric plates or microplates and which are broad deformation zones between plates. This is an exciting time in the geosciences as vast new GPS and earthquake datasets accumulate that will provide the raw material for developing new and better ideas about our planet.

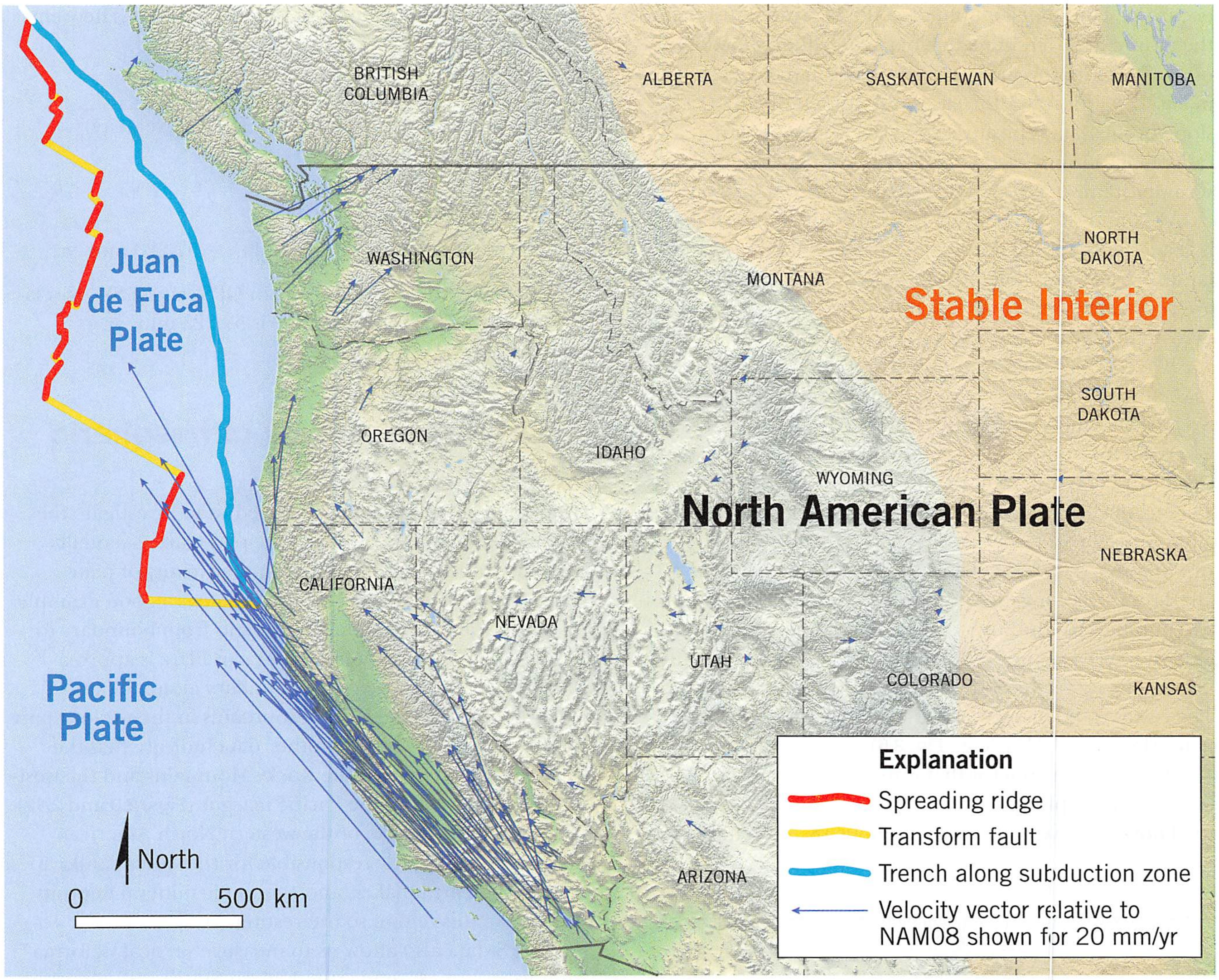


Figure 2.12 **GPS velocities in western North America relative to the North American Plate.** Selected GPS velocities (blue arrows) in western North America in the NAM08 reference frame that is fixed to the stable interior of central and eastern North America. (From the UNAVCO GPS Velocity Viewer and accessed online via **http://www.unavco.org/software/visualization/GPS-Velocity-Viewer/GPS-Velocity-Viewer.html** on June 26, 2016.)

ACTIVITY 2.3

Hot Spots and Plate Motions, (p. 59)

Think About It How do we detect and measure plate motion?

Objective Determine the rate and direction of plate motion relative to a hotspot.

Before You Begin Read the following section: What Do Hotspots Tell Us About Plate Motion?

Plan Ahead This activity requires that data be gathered from a website hosted by NASA-JPL. If you will not be able to access the web during your lab session, you will need to collect the data you need before coming to lab. You might also need to bring a calculator that can take a square root so that you can use the Pythagorean Theorem to compute velocities.

What Do Hotspots Tell Us about Plate Motion?

Hotspots are places in the upper mantle below the lithosphere where an unusually high percentage of the asthenosphere is partially molten. The magma rises buoyantly and makes its way through the lithosphere to erupt at the surface. Many geoscientists think hotspots are the result of long-lived, narrow **plumes** of buoyant hot rock that rise from deep in Earth's mantle, but others think that they are just places in the upper mantle that persistently generate a large volume of melt. Some sort of local difference in upper-mantle composition—perhaps unusually high water content—could be responsible for a melt anomaly rather than (or in addition to) a concentration of hot rock. Improving our understanding of hotspots continues to be an area of active research. However they form, hotspots and the chains of volcanoes that form as a plate moves over them can provide a way of determining plate motion relative to the deeper mantle.

The Hawaiian Hotspot and Pacific Plate Motion

As a lithospheric plate moves over a mantle hotspot, magma rises through the lithosphere and a volcano develops on Earth's surface. Continued plate motion causes the newly formed volcano to drift away from the hotspot, depriving the volcano of its magma supply and ending its eruptive activity. New volcanoes develop over the hotspot over time, leading to the development of a trail of volcanoes whose ages increase in the direction that the plate moves relative to the mantle hotspot. A chain of active and inactive volcanoes interpreted to be related to a hotspot is called a **hotspot trail**. The Hawaiian Islands and Emperor Seamount Chain (Fig. 2.13) are such a line of volcanoes that formed over the Hawaiian hotspot near the center of the Pacific plate over the last ~70 million years. The current location of the Hawaiian hotspot is interpreted to be south of Kilauea Volcano in the vicinity of Lo'ihi Seamount (around latitude 18.92°N, longitude 155.27°W).

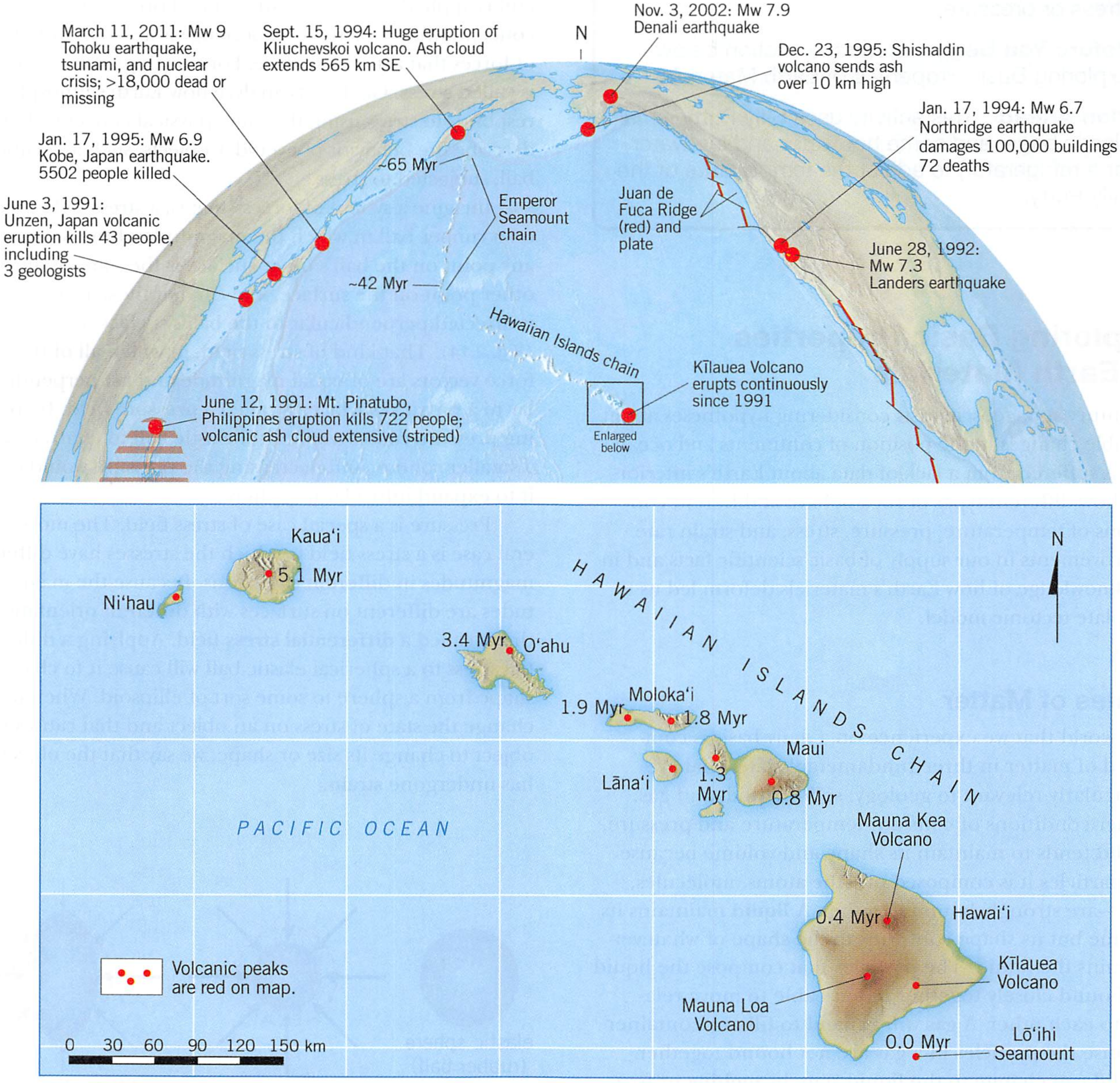


Figure 2.13 **Trail of the Hawaiian hotspot.** Top map shows the northern Pacific Ocean, adjacent landmasses, some notable geologic disasters, and the Hawaiian Islands and Emperor Seamount Chains. Lower map shows details of the eastern Hawaiian Islands Chain, including locations of major volcanoes. Myr means "million years".

ACTIVITY 2.4

How Earth's Materials Deform, (p. 61)

Think About It How does our knowledge of how materials deform help us to understand plate tectonics?

Objective Investigate how the properties of a solid are different when it is hot than when it is cold. Learn about some of the ways that materials behave when they are subjected to stress or pressure.

Before You Begin Read the section below: Exploring Basic Properties of Earth Materials.

Plan Ahead This activity uses Silly Putty, small plastic bags, and some hot water and ice water (or a refrigerator) to adjust the temperature of the Silly Putty.

Exploring Basic Properties of Earth Materials

A century ago, geoscientists considering hypotheses about possible changes in the position of continents and ocean basins suffered from a lack of data about Earth's interior and how different types of rock behave at different conditions of temperature, pressure, stress, and strain rate. Improvements in our supply of basic scientific facts and in our knowledge of how Earth's materials deform led us to the plate tectonic model.

States of Matter

The world that we experience on a daily basis is composed of matter in three fundamental states that are particularly relevant to geology: solid, liquid, and gas. Under conditions of constant temperature and pressure, a **solid** tends to maintain its shape and volume because the particles it is composed of—the atoms, molecules, ions—are strongly bound together. A **liquid** maintains its volume but its shape conforms to the shape of whatever contains the liquid. The particles that compose the liquid are bound closely together but are able to move relative to each other. A **gas** will expand to fill any container because the particles in a gas are not bound together. A solid can change to the liquid state by **melting** or to a gas state by **sublimation**. A liquid can change to the solid state by **freezing** or to the gas state by **vaporization**. A gas can change to the liquid state by **condensation** or to the solid state by **deposition**.

The only liquid layer in Earth's interior is the outer core, which is thousands of kilometers below the level of lithospheric plates. The mantle and crust are almost entirely solid rock composed of crystalline mineral grains with small local pockets of liquid magma along convergent and divergent boundaries, around hot spots, and perhaps along the asthenosphere-lithosphere boundary. The asthenosphere is probably at least 99% solid on average and is probably at least 80% solid even under mid-ocean ridges and in the wedge above subducting slabs of oceanic lithosphere.

Force, Pressure, Stress, Strain

Isaac Newton's second law of motion defines **force** as the product of **mass** times **acceleration**. Force can be thought of as a vector quantity, meaning that it has a magnitude and is applied in a specific direction. Force is an abstract concept; what we actually experience is a system or field of forces that act on a surface. Force acting over an area is called **stress**. Geologists analyze how Earth's lithosphere responds to stress using the same physical concepts that describe the behavior of everyday objects, such as a rubber ball, subjected to stress.

Imagine a system of forces (that is, a **stress field**) acting on a rubber ball in which the magnitude of the force at any point on the ball's outer surface is the same as at every other point on the surface, and each of those force vectors is directed perpendicular to the ball's surface at that point (Fig. 2.14). That kind of stress field, in which all of the force vectors are of equal magnitude and act perpendicular to a physical surface, is called a **pressure** field. Increasing pressure causes a spherical elastic ball to contract into a smaller sphere, and decreasing the pressure would cause it to expand into a larger sphere.

Pressure is a special case of stress field. The more general case is a stress field in which the stresses have different magnitudes in different directions. Because the magnitudes are different on surfaces with different orientations, this is called a **differential stress** field. Applying a differential stress to a spherical elastic ball will cause it to change shape from a sphere to some sort of ellipsoid. When we change the state of stress on an object and that causes the object to change its size or shape, we say that the object has undergone **strain**.

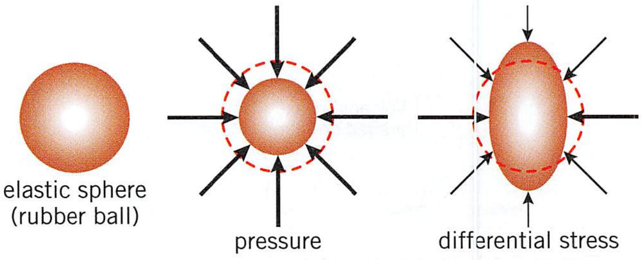


Figure 2.14 Pressure and differential stress. Arrows represent force vectors within either a pressure or differential stress field. Length and thickness of arrow indicates relative magnitude of force vector—thicker, longer arrow indicates greater force. An elastic sphere is compressed with no change in shape by increasing pressure but changes shape when subjected to a differential stress.

Rheology: Elasticity, Viscosity

Different materials respond differently to stress. Squeezing a rubber ball has a different effect than squeezing a bag of cookie dough. The way that a material strains in response to stress is called the material's **rheology**, and two of the many possible rheologies are important in helping us understand plate motion: elasticity and viscosity. An **elastic** solid will change its size or shape when we squeeze it but will return to its original size or shape when we stop squeezing it. An elastic ball will distort when it hits the floor but will return to its original size and shape when it bounces up off the floor. A **viscous** material will also strain in response to a change in differential stress, but that strain will be permanent even if the stress field reverts to the original. Viscous materials flow in response to a differential stress. Matter in the solid, liquid, and gas states can all be characterized as **fluids**. (In common English usage outside of science, the words "liquid" and "fluid" are used as if they have the same meaning. In science, "liquid" is one of the states of matter, and any material that flows under a differential stress is considered a fluid.)

Elasticity and viscosity are two of the simpler rheologies we might consider, but actual rock masses tend to have more complicated rheologies that combine properties of elasticity, viscosity, and other rheologies. Earth's crust and mantle behave as elastic solids over short time intervals, such as the time needed for an elastic wave from an earthquake to pass through them. The mantle below the lithosphere behaves as a viscous fluid over longer time intervals and is able to flow while remaining in a solid state. Simplifying, we might say that the elastic lithospheric plates move over the viscous asthenosphere, as well as *through* the asthenosphere where the plates subduct.

Brittle and Ductile Deformation

The temperature and the pressure increase from the surface of the solid Earth downward toward the core. At lower temperatures and pressures in the lithosphere, rock deforms elastically or by **brittle** processes like fracturing and faulting, especially when the deformation occurs relatively quickly (Fig. 2.15). At higher temperatures and pressures, and especially at slower deformation rates, crystalline mineral grains can change their shape without fracturing or faulting through a variety of processes we will call **ductile** processes. Ductile processes under high temperature and pressure allow a rock to flow as a fluid.

Nature does not expend any more energy to achieve a given change than is necessary. A given mineral grain or volume of rock will deform using whatever mechanism (e.g., fracturing, faulting, ductile flow) that will result in the greatest strain for a given stress.

Strength

We use the term *strength* here to broadly indicate the amount of stress a material can resist or withstand regardless of whether the material is deforming permanently or not. For example, a fresh apple is stronger than a peeled banana. A rock's strength depends on many factors, including its mineral composition, grain size, temperature, pressure, the pressure of any gasses or liquids (water, petroleum, magma) present in the spaces between solid grains, differential stress, material properties (such as viscosity or elasticity), and strain rate. While the details are still a matter of active research, the strength of the lithosphere is thought to be significantly greater than the strength of the asthenosphere. The strength difference is significant enough to allow lithospheric plates to move horizontally across the asthenosphere and to allow subducting slabs to pass through the asthenosphere on their way into the deeper mantle.

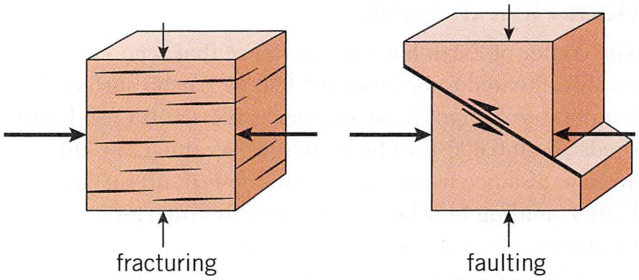


Figure 2.15 Brittle deformation: Fracturing and faulting. A brittle material subjected to a differential stress that is large enough to cause permanent deformation will develop fractures oriented roughly parallel to the greatest compressive stress direction (the longest arrows) and perpendicular to the least compressive stress direction. If that material faults, the fault surface will likely develop around 30° (and always ≤45°) to the greatest compressive stress direction and around 60° to the least compressive stress direction.

Gravity and Buoyancy

Every particle of mass that is on or in Earth is affected by Earth's gravitational attraction. Gravity is a force that acts on every bit of mass, regardless of whether it is in the solid, liquid, or gaseous state. When a mass with a greater density is surrounded by a fluid of lesser density—imagine a ball in the air—the mass with the greater density will move downward toward the center of Earth through the less dense fluid.

What if we have a mass with lesser density surrounded by a fluid of greater density as we would if we had a blob of liquid magma surrounded by relatively soft, ductile rock? In that case, the less dense mass will tend to move upward through the more dense fluid. The upward motion is caused by what physicists call the **buoyant force**. As described in Archimedes' Principle, the magnitude of the buoyant force is the difference between the mass of the less dense material and the mass of the more dense fluid that it displaces. The rate at which the less dense material can move upward is controlled by the magnitude of the buoyant force and the viscosity of the surrounding fluid. If the surrounding fluid is very viscous, the rate of ascent will be very slow.

Heat Flow in Earth

The center of Earth has a temperature that is currently estimated to be around 6,000°C. Earth's surface temperature ranges from around −90°C to 50°C, so Earth sheds about 6,000°C of heat energy over the 6,371 km average distance from its center to the ground surface. Understanding how heat flows in Earth's interior is a fundamental topic of geoscience research.

When we increase the heat of a solid, liquid, or gas, the atoms in that material vibrate or move more rapidly. When an atom or molecule with a greater vibrational energy (more heat) is next to an atom or molecule with less vibrational energy, the particle with more energy tends to increase the energy of the particle next to it. That heat transfer continues until both particles have the same vibrational energy. This kind of direct heat transfer from a hotter body to an adjacent cooler body is called **conduction**. Conduction is most important in solids.

In most viscous fluids, increasing the fluid's temperature will decrease density, which will tend to promote buoyant upward motion. That is why hot air tends to accumulate near the ceiling and why hot water rises to the top of a pan of water being heated on a stove. The motion of heated material upward and the sinking of cooled material downward in a viscous fluid is an example of heat flow by **convection**. The most important ways that heat flows in the solid Earth are by conduction in the lithosphere and convection in the mantle.

Earth's Magnetism and Paleomagnetism

Geophysicists interested in how Earth's magnetic field changes over time were among the first to recognize that some rocks retain a record of past magnetic fields. The magnetic minerals in these rocks exhibit **remanent magnetization** that developed parallel to Earth's magnetic field at the time the magnetic minerals crystallized and that is retained unless the rock is reheated. Sedimentary particles made of magnetic minerals also seem to align themselves with the **geomagnetic field** when they are deposited. Analysis of remanent magnetization in rocks of different ages led geophysicists to the hypothesis that these rock bodies had moved relative to the magnetic poles.

If you drop a pen, it falls to the floor. The pen is under the influence of Earth's gravity—a force field that pulls every bit of mass that is in, on, or around Earth toward the center of our planet. But there is another force field around Earth that is not so obvious: the geomagnetic field. It is as though a giant bar magnet is inside Earth, giving our planet both a magnetic north pole and a magnetic south pole. Invisible flow lines of the magnetic force field arc steeply up from the south magnetic pole, curve downward so that they are horizontal at the magnetic equator, then arc steeply down into the north magnetic pole. The inclination of the field at any point on Earth's surface is related to the magnetic latitude of that point between the north and south magnetic poles. Unlike a bar magnet, the geomagnetic field changes over time because it is generated by the circulation of the liquid, iron-rich, outer core.

The strength of a magnetic field is measured in units called **teslas**. A **microtesla** is a millionth of a tesla. The small magnets we use to hold notes on refrigerator doors have a field strength of about 50,000 microteslas. The geomagnetic field strength ranges from just 25 microteslas at the equator to about 65 microteslas at the poles. Therefore, a refrigerator magnet is around three orders of magnitude (~1,000 times) stronger than the geomagnetic field. Even so, you can use the tiny magnetic needle in a compass to detect the geomagnetic field. Magnetic compass needles are not attracted to the **geographic north pole**, which is along Earth's spin axis. Instead, compass needles 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

Some iron-rich minerals, like magnetite, are naturally magnetic. The small magnetic field carried by magnetic minerals is aligned with the geomagnetic field at the time the mineral cools below its **Curie temperature**, which is 585°C for magnetite. (If the grain is reheated above the Curie temperature, this remanent magnetic field in the grain will be erased.) These magnetic grains preserve a record of the geomagnetic field at the time they last cooled below their Curie temperature. This record of a past geomagnetic field is called **paleomagnetism**. The rock that forms by crystallizing from magma along a mid-ocean ridge retains a paleomagnetic record of the geomagnetic field at the time it crystallized.

Magnetic Reversals

The circulation of liquid iron in Earth's outer core generates the geomagnetic field. A curious and useful feature of the geomagnetic field is that it flips from being north directed to south directed and back again. The north-directed field, like the current magnetic field, is said to have a **normal polarity**, and the south directed field has a **reverse polarity**. The geomagnetic field spontaneously reverses itself at irregular intervals ranging from a few thousand years to tens of millions of years in duration. The time it takes for the reversal to occur appears to be quite short--perhaps as short as a full human lifetime to as long as a thousand years. Hundreds of reversals have been documented.

The end of a compass needle that points in the direction that the geomagnetic field is flowing will point toward Earth's north magnetic pole during times of normal polarity. But during times of reversed polarity, the same end of a compass needle would point in the opposite direction, toward magnetic south. The geological effect of this reversal is that rocks containing magnetic minerals will be normally magnetized if they crystallized during a time of normal polarity, and they will be reverse magnetized if they formed during a time of reversed polarity.

Geoscientists have determined the age of all of the well-documented geomagnetic reversals. We can use the pattern of normal- and reverse-magnetized rock in an undeformed, layered sequence of volcanic or fine-grained sedimentary rock to determine the age of the rock layers based on the reversal pattern documented in the **magnetic polarity time scale** that geoscientists have developed since the 1960s.

Marine Magnetic Anomalies

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 (Fig. 2.16). During World War II, marine geophysicists began to use magnetometers towed behind ships to map the magnetic fabric of the ocean basins. (They were looking for ways to find magnetic mines and submarines.) They discovered that the oceanic crust has a striped pattern of alternating high and low magnetic intensity and that the pattern of paleomagnetic stripes is symmetric on opposite sides of mid-ocean ridges. In the early 1960s, geoscientists discovered that the symmetric pattern of paleomagnetic stripes on the seafloor was the result of two processes: the formation of oceanic crust at mid-ocean ridges while plates are moving apart and reversals of Earth's magnetic field (Fig. 2.17). Unexpectedly, the oceanic crust includes a magnetic recording of its own formation in the form of alternating bands of normal and reversed magnetized rock on the seafloor.

Magnetic Polarity Time Scale

Undeformed, layered sequences of volcanic rock and fine-grained sedimentary rock deposited on continental crust also contain evidence of the same magnetic field reversals that are recorded in marine magnetic anomalies. **Radiometric dating** of rock in these continental sequences has allowed us to discover when Earth's magnetic field has flipped and to establish the detailed pattern of magnetic field reversals in the past. The result is a **magnetic polarity time scale** that allows us to use the magnetic reversal pattern in a sequence of rock to date the rock. Just as we name geologic formations, some of the more important parts of the magnetic polarity time scale have names for our convenience because we refer to them so often. For example, we are living in the **Brunhes normal chron**, named for French geophysicist Bernard Brunhes who discovered that Earth's magnetic field reverses. The Brunhes normal chron began 781,000 years ago after the **Matuyama reversed chron** named for Japanese geophysicist Motonori Matuyama. In general, each of the reversals is identified by a numbering system developed by geomagnetic stratigraphers. In Activity 2.6, you will use a simpler version of a magnetic polarity time scale in which the time intervals have been color coded (instead of named) so they are easy to recognize on sight.

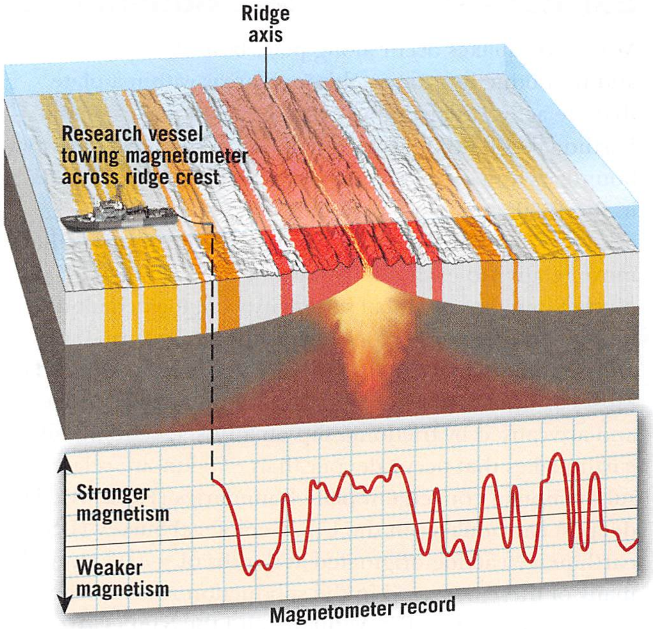


Figure 2.16 Magnetic record of sea-floor spreading. A magnetometer towed by a ship records variations in magnetic intensity, originating in the oceanic crust. A stronger magnetic field corresponds to normally magnetized rock; a weaker field indicates reverse-magnetized rock.

ACTIVITY 2.5

Paleomagnetic Stripes and Sea-Floor Spreading, (p. 63)

Think About It How does rock magnetism help us date the oceanic crust and measure sea-floor spreading?

Objective Analyze marine magnetic anomalies and infer how sea-floor spreading is related to Cascade Range volcanoes.

Before You Begin Read the section: Earth's Magnetism and Paleomagnetism.

ACTIVITY 2.6

Atlantic Sea-Floor Spreading, (p. 65)

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.

Before You Begin Read the section: Earth's Magnetism and Paleomagnetism.

Introduction If you worked on Activity 2.5, 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 sea-floor spreading about the Mid-Atlantic Ridge.

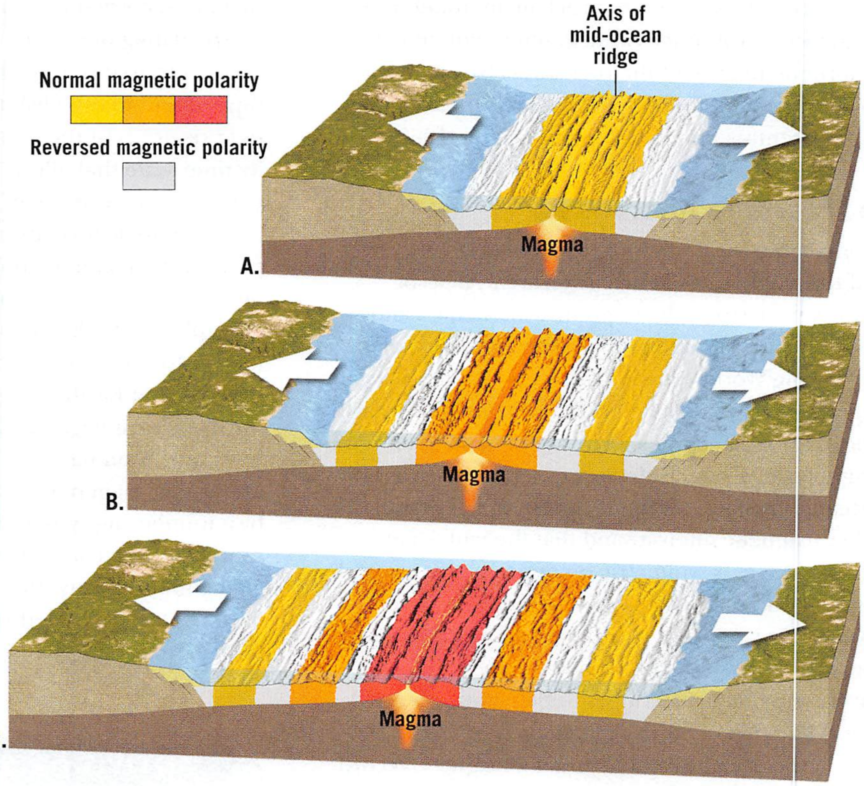


Figure 2.17 **Marine magnetic anomalies record the opening of an ocean.** Magnetic mineral grains in the rock are aligned with the geomagnetic field at the time the magma crystallizes along a mid-ocean ridge. While the plates slowly move apart and new crust crystallizes along their trailing edges along the mid-ocean ridge, the geomagnetic field flips its polarity. The result is that a paleomagnetic record of those geomagnetic reversals is frozen into the rock of the oceanic crust. Light gray stripes in the figure indicate reverse magnetized rock, and the yellow, orange, and red stripes indicate normally magnetized. This series of block diagrams depicts the progressive widening of an ocean basin through sea-floor spreading, from an early stage **(A)** to later stages **(B** and **C)**.

ACTIVITY 2.7

Using Earthquakes to Identify Plate Boundaries, (p. 67)

Think About It How do earthquakes help us locate and understand plate boundaries?

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.

Before You Begin Read the following section: Earthquakes and Plate Boundaries.

Earthquakes and Plate Boundaries

Most earthquakes occur along plate boundary zones and in subduction zones, although areas within a plate that are actively deforming produce earthquakes as well. Earthquakes tend to occur much less frequently away from boundary zones. Global maps of earthquakes produced in the 1950s and 1960s provided some of the strongest evidence that Earth's outer layer is a mosaic of plates that move relative to each other. Many of the earthquakes plotted on maps of global seismicity were located along mid-ocean ridges, deep ocean trenches, transform faults, and continental mountain ranges and rift zones (**Fig. 2.1**). Most earthquakes occur within 70 km of Earth's surface and are caused by frictional slip on faults. Essentially all earthquakes that occur deeper than ~70 km are related to subduction at convergent plate boundaries (**Fig. 2.1A**). The deepest earthquakes in the U.S. Geological Survey (USGS) earthquake catalog originated at depths of ~700 km, and many of these occurred in the subduction zones of the western Pacific near Fiji, Vanuatu, and the Santa Cruz Islands, north of New Zealand and east of Australia.

Reference Frames and Motion Vectors

Activity 2.1

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

New oceanic lithosphere crystallizes from magma injected along the axis of a mid-ocean ridge. We are going to focus on a point located at latitude 45.9°N and longitude 129.9°W along the Juan de Fuca ridge between the Pacific and Juan de Fuca Plates, about 560 km west of Portland, Oregon (**Fig. A2.1.1**).

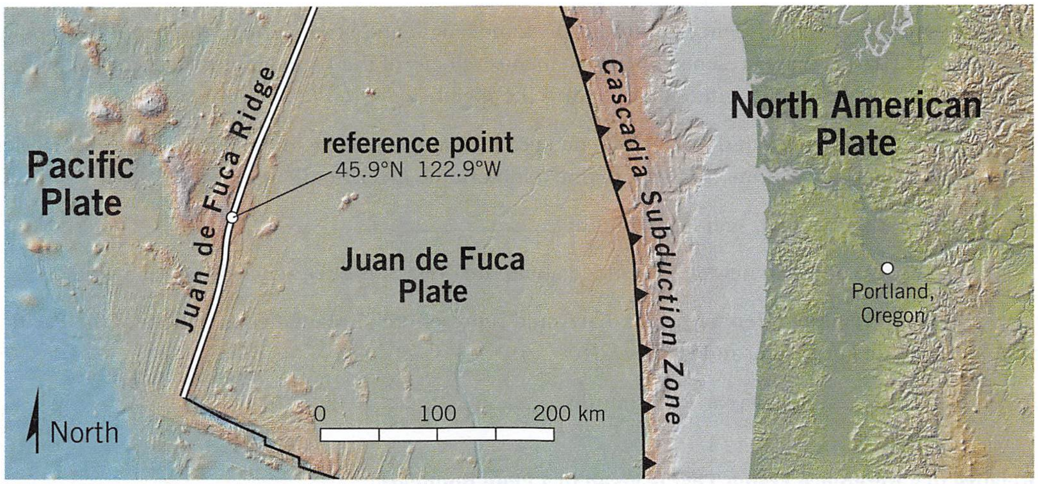


Figure A2.1.1

A **Velocity Relative to an NNR Reference Frame.** The plates move at about the same rate as that at which our fingernails grow. The Pacific plate moves at a rate of 45.7 millimeters per year (mm/yr.) toward compass azimuth 309.6° in a reference frame that is commonly used by geoscientists to define the motion of individual plates relative to the rest of the planet (a "no-net rotation," or NNR reference frame).

1. Starting at the reference point in **Fig. A2.1.2**, use a ruler to draw an arrow that is 45.7 mm long and points toward 309.6°. Label the point at the tip of the arrow *P*. This arrow represents the instantaneous velocity vector for the Pacific Plate at the reference point as that motion is observed in a NNR reference frame.

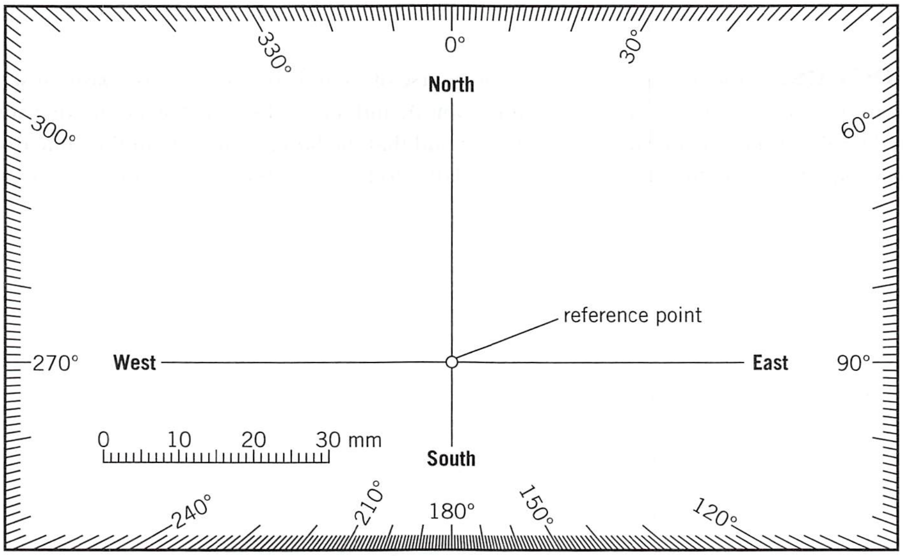


Figure A2.1.2

2. At the same reference point along the ridge axis, the Juan de Fuca Plate moves at 19.4 mm/yr. toward 42.4° relative to the NNR reference frame. That is about the rate at which your toenails grow. Starting at the reference point on **Fig. A2.1.2**, use a ruler to draw the vector—19.4 mm long pointed toward 42.4°—for the instantaneous velocity of the Juan de Fuca Plate as defined at the reference point in the NNR reference frame, and label the tip of the vector *J*.

3. We will assume that as much new lithosphere will be added to the Pacific Plate as is added to the Juan de Fuca Plate along this ridge axis for the sake of simplicity. That is, we will assume that spreading is symmetric. Find the point that is halfway between points *P* and *J*, and label that point *R* for "ridge." Draw an arrow from the reference point to *R*. That arrow represents the instantaneous velocity vector for that point along the ridge as defined in the NNR reference frame.

B Velocity Relative to a Reference Frame That Is Fixed to a Plate.

1. Draw a vector arrow from the reference point with the same length and orientation as the vector from point *P* to point *J*, and label it *P2J*. That vector represents the instantaneous velocity of the Juan de Fuca Plate relative to the Pacific Plate at the reference point, and the length of that vector is the speed.

2. How fast and toward what azimuth does the Juan de Fuca Plate move relative to the Pacific Plate at the reference point each year? Use a protractor and the north-south line to determine the azimuth as in **Fig. 2.4**.

speed *P2J*: ______________ mm/year   azimuth: ______________

That velocity is the rate at which new crust is added along the ridge at the reference point each year.

3. Draw a vector arrow from the reference point that would represent the instantaneous velocity of the Pacific Plate relative to the Juan de Fuca Plate, and label it *J2P*.

speed *J2P*: ______________ mm/year   azimuth: ______________°

C Velocity Relative to a Reference Frame That Is Fixed to a Plate Boundary.

1. Draw a vector arrow from the reference point with the same length and orientation as the vector from point *R* to point *P*, and label this vector *R2P*. This is the instantaneous velocity vector of the Pacific Plate relative to the ridge axis, determined at the reference point.

speed *R2P*: ______________ mm/year   azimuth: ______________°

2. Draw a vector arrow starting at the reference point that represents the instantaneous velocity of the Juan de Fuca Plate relative to the ridge axis, determined at the reference point, and call that vector *R2J*. These vectors indicate the rate at which new crust is added to the trailing edge of each individual plate at the reference point.

Important Reminder: We can measure a velocity or a displacement (the movement from an initial location to a different location) only relative to some reference frame. Before we describe a velocity or a displacement, it's important to ask "velocity relative to what?"

D **REFLECT & DISCUSS** You watch the Sun over the course of a day. It rises in the east, passes just south of overhead at noon (if you are in the northern hemisphere above the tropics), and sets in the west. You accept that you are observing the Sun while located on the surface of a near-spherical planet and that the Sun remains about the same distance away from that planet all day long. Describe the motion of the Sun relative to Earth as observed in your reference frame that day.

Measuring Plate Motion Using GPS

Activity 2.2

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

A Analyze **Figs. 2.1** and **2.3**. On what lithospheric plate do you live? (Notice that if you live in California, west of the San Andreas Fault, you are not considered to be on the North American Plate.) ______________

B Go to the JPL-NASA GPS Time Series website at **http://sideshow.jpl.nasa.gov/post/series.html**. The map displays the location of each GPS station as a small green dot with a yellow line that indicates direction that the GPS station is moving in a no-net rotation (NNR) reference frame. The particular NNR reference frame used for these data is called IGS08. Use the + button in the lower right corner of the map to zoom in and to reveal more GPS stations. Find the GPS station that is the closest to where you live, click on the green circle, and when the small white box with the site velocity data opens, double-click on that box to expand it. Copy the data requested in questions 1–3, then complete the Plate Motion Plot (**Fig. A2.2.1**) for the station (see **Fig. 2.11**).

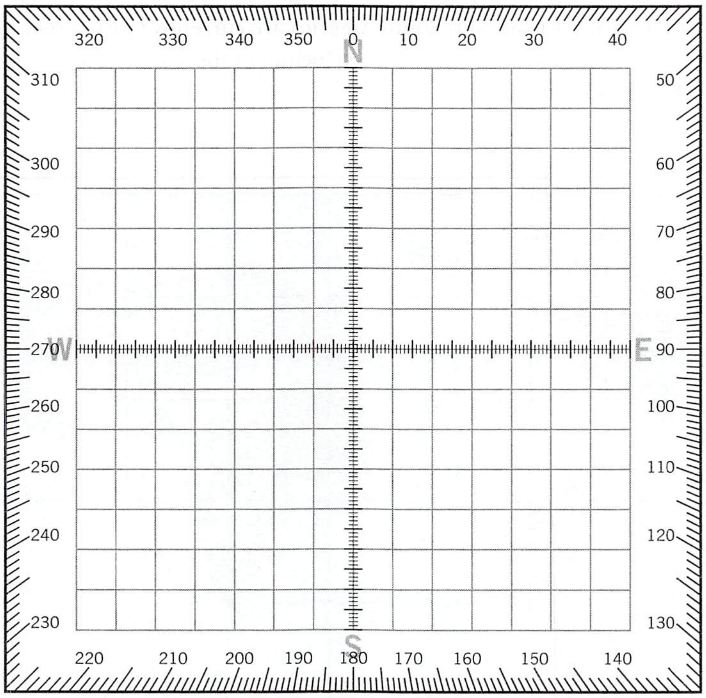


Figure A2.2.1

1. GPS station name (4 characters): ________
2. Latitude time series—the station is moving (choose one: north, south) at a rate of ________ mm/yr. with an uncertainty of ________ mm/year.
3. Longitude time series—the station is moving (choose one: east, west) at a rate of ________ mm/yr. with an uncertainty of ________ mm/year.
4. Toward what azimuth is this GPS station moving?
5. At what velocity is this GPS station 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 position in latitude and longitude in the following blanks. The coordinates are expressed in decimal degrees to nine places to the right of the decimal. All of those decimal places are meaningful for GPS sites that are located to the closest millimeter. North latitudes are positive numbers, and south are negative; east longitudes are positive, and west are negative.

   Current latitude: ______________________ Current longitude: ______________________

7. Go to the Plate Motion Calculator hosted by UNAVCO at **https://www.unavco.org/software/geodetic-utilities/plate-motion-calculator/plate-motion-calculator.html.** Enter the latitude and longitude of your GPS station, being sure to include the proper sign (+/−). Then enter the site name; choose MORVEL 2010 as your model; select your tectonic plate, NNR no-net-rotation for your reference frame, and HTML table w/ local E&N plate velocities as the output format. Ignore the rest of the input boxes. Then press submit. Record your results.

N velocity: ______ mm/yr. E velocity: ______ mm/yr. Speed: ______mm/yr. Azimuth: ______° clockwise from north

The Plate Motion Calculator provides the instantaneous velocity of a given point in a NNR reference frame, assuming that the plate is not deforming. How do the results from the Plate Motion Calculator compare with your earlier results (questions 2–5)?

____

____

The velocity of your GPS station includes the velocity of the plate it is located on as well as a component related to the deformation of the part of that plate where the GPS station is located.

C Return to the JPL-NASA Time Series website, and view the map. From the website map, draw a vector arrow from each of the green circles on the map in **Fig. A2.2.2** to show the general direction that at least one spot on Africa, Arabia, Australia, China, Europe, India, North America, Russia, and South America are currently moving relative to a NNR reference frame. In a general way, use the length of the arrows to reflect the velocities of the sites, just as the length of the yellow lines on the Time Series website indicates velocity.

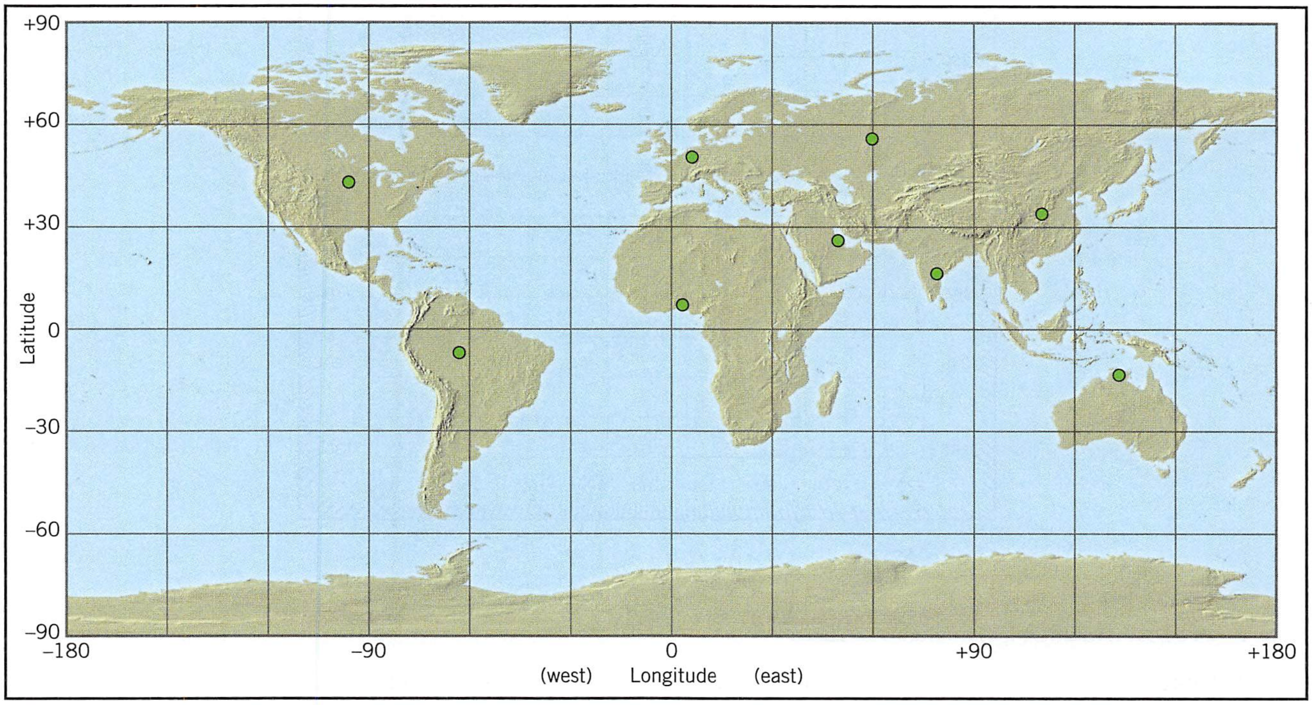


Figure A2.2.2

D **REFLECT & DISCUSS** Do you think that determining the velocity of one point on a plate is sufficient to tell where the entire plate is moving? Why or why not? *Hint*: Represent a plate using a piece of paper on a tabletop. Slide the paper a very short distance from its initial position across the tabletop, maybe with a bit of a twist of your wrist. Now consider whether you could reconstruct the motion of the piece of paper from initial to final position if you only have information about the motion of one point on the paper.

Hotspots and Plate Motions

Activity 2.3

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

As a lithospheric plate moves over a hotspot in the upper mantle below the plate, a volcano develops directly above the hot spot. As the plate continues to move, the volcano drifts away from the hotspot and eventually becomes dormant. Meanwhile, a new volcano develops over the hotspot next to the older volcano. The result is a trail 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 2.13** shows the distribution of the Hawaiian Islands Chain and Emperor Seamount Chain. The numbers indicate the average age of the volcano in millions of years (Myr) obtained from isotopic dating of the basaltic igneous rock of which each island is composed.

1. If both the Emperor and Hawaiian Islands Chains developed as a result of the same mantle hotspot, what is a possible reason that the hotspot trail changes direction at ~42 Myr?

2. What was the rate of Pacific Plate motion relative to the Hawaiian hotspot as it was developing the 2,300 km long Emperor Seamount Chain from 65 Myr to 42 Myr? Express the rate in centimeters per year (cm/yr.). In what direction was the plate moving north—relative to the hotspot during that time interval?

3. What was the rate of Pacific Plate motion relative to the Hawaiian hotspot from 5.1 to 0.8 Myr, expressed in cm/year?

4. Using Lo'ihi Seamount as the current location of the Hawaiian hotspot, what was the rate of Pacific Plate motion relative to the Hawaiian hotspot from 0.8 Myr to today, expressed in cm/yr?

5. Go to the JPL-NASA GPS Time Series website at **http://sideshow.jpl.nasa.gov/post/series.html**. The map locates each GPS station with a green dot with a yellow line that extends outward in the direction that the GPS station is moving relative to the NNR reference frame. GPS station HNLC is located on Oahu.
   (a) How does the current motion of HNLC on Oahu compare to the direction of Pacific Plate motion relative to the Hawaiian hotspot over the past ~42 million years?

   (b) GPS station HNLC on Oahu has the following component velocities relative to the NNR reference frame as of January 24, 2016: moving north at 3.6602 ± 0.0028 cm/yr. and moving west at 6.2665 ± 0.0030 cm/year. Use the Pythagorean Theorem to find the current speed of the Pacific Plate at Oahu, relative to the NNR reference frame. Show your work.

6. **REFLECT & DISCUSS** Based on all of your work above, explain how the direction and rate of Pacific Plate movement changed over the past ~70 million years.

B The map in **Fig. A2.3.1** shows the distribution of a trail of volcanic centers in Wyoming, Idaho, and Nevada. All of these volcanic centers are now inactive except the youngest one located in Yellowstone National Park. Hot springs, geysers, and earthquakes demonstrate that Yellowstone is still volcanically active.

1. What does this progressive chain of volcanic centers indicate about the possible origin of the active volcanism at Yellowstone? Support your answer with evidence.

2. Based on the map, what was the average speed and direction of North American Plate motion at Yellowstone, relative to the hotspot, since 13.8 Myr?

   Add an arrow (vector) and rate label to the map in **Fig. A2.3.1** to show this movement.

3. Plate Boundary Observatory GPS station P717 near the east gate of Yellowstone National Park had the following component velocities relative to the NNR reference frame as of January 24, 2016: moving south at 0.8200 ± 0.0088 cm/yr. and moving west at 1.4783 ± 0.0068 cm/year.

   (a) Use the Pythagorean Theorem to find the current speed of the North American Plate at P717 relative to the NNR reference frame. Show your work.

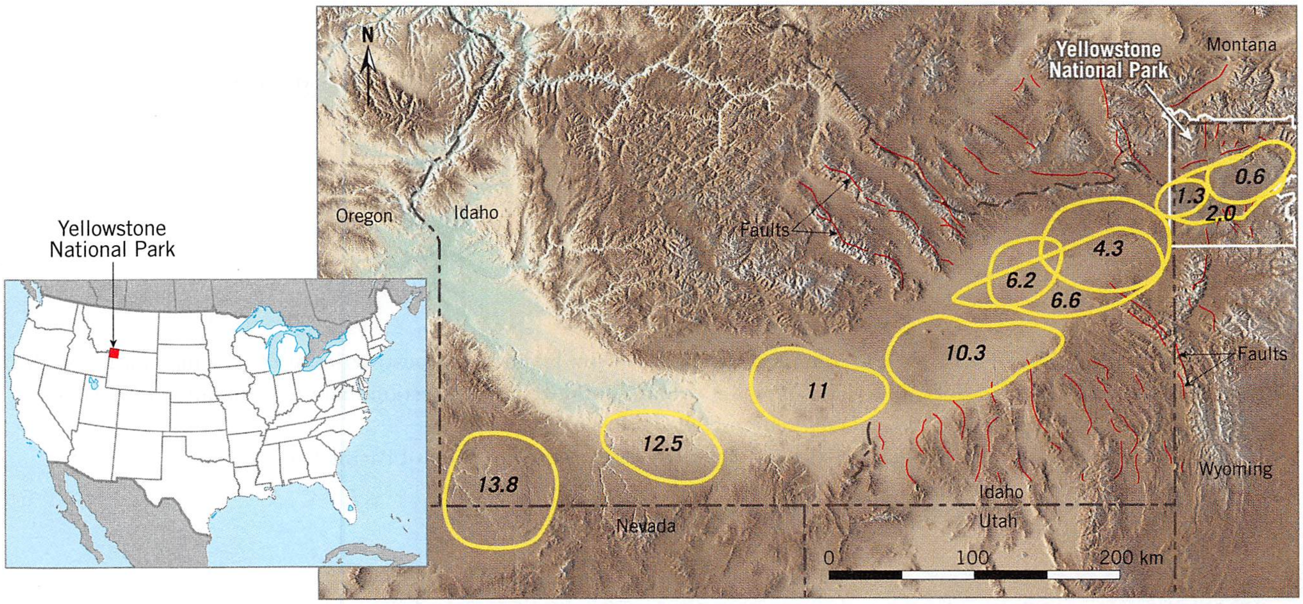


Figure A2.3.1

   (b) How do the present-day direction and speed of P717 relative to the NNR reference frame compare with your estimate of the average direction and speed of the North American Plate relative to the hotspot during the past 13.8 Myr?

4. **REFLECT & DISCUSS** How do hotspots help us understand plate tectonic processes and rates?

How Earth's Materials Deform

Activity 2.4

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

A Explore how solid rock can be rigid and stiff in the lithosphere but soft and fluidlike in the asthenosphere.

1. Obtain three pieces of Silly Putty: one that is at room temperature, one that is cold (from a refrigerator or ice chest), and one that is warm (heated in a plastic bag submerged in hot water).

   (a) Take the *room-temperature* piece of Silly Putty, roll it into a sphere, and set it on the tabletop while you do steps **(b)** and **(c)** of this experiment.

   (b) Form the *cold* Silly Putty into a cube or cylinder, and place it in the middle of a wooden board (used to protect the tabletop). Do this quickly before the putty warms up.

   (1) Hit the cold putty with a quick stroke from a hammer with the intent to deform the putty. Describe how the putty deformed at a very high strain rate.

   (2) Gather up the remains of the cold putty, form it into a single mass, and pull on it with a quick motion. Describe how the cold putty deformed at a high strain rate.

   (3) Reform the putty and pull on it slowly but steadily. Describe how the cold putty deformed at the slower strain rate.

   (c) Now take the piece of *warm* Silly Putty.

   (1) Pull on it with a quick motion. Describe how the warm putty deformed at a high strain rate.

   (2) Reform the warm putty and pull on it slowly but steadily. Describe how the warm putty deformed at the slower strain rate.

   (3) Which is more difficult to deform: warm putty or cold putty?

   (d) Examine the sphere of Silly Putty that you set aside in step **(a)**.

   (1) Describe what has happened to it.

(2) Was this change accompanied by any fractures or faults, or did it just flow? Explain.

(e) Roll the room-temperature Silly Putty into a smooth ball, bounce it on the tabletop, and then examine the ball.

(1) Was there any permanent deformation on the surface of the ball where it impacted the tabletop—any dents, fractures, or faults?

(2) What rheology did the room-temperature putty display at very high strain rate?

(f) Under what conditions of temperature (hot or cold) and strain rate (fast or slow) does Silly Putty best exhibit brittle-elastic mechanical behavior? ____________________

Under what conditions does it best exhibit ductile-viscous mechanical behavior? ____________________

2. **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 contains a mixture of colored paraffin wax and another compound that makes the solid wax just a bit denser than the clear liquid (usually mineral oil or water) in the lamp. The heat is supplied by a light bulb below the sealed glass bottle of the lamp. There is a wire heating coil in the bottom of the sealed bottle to help transfer heat energy into the wax. The top and sides of the sealed glass bottle are cooler than its heated base.

1. Observe and describe the motions of the colored wax that occur over one full minute of time, starting with wax at the bottom of the lamp and its path through the lamp.

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

4. What heat-transfer mechanism is displayed by the rising and falling molten wax in the lamp?

C Minor partial melting in the asthenosphere causes liquid magma to form. If the molten rock is able to move at all, it will leave behind the heavier solid rock that did not melt. In what direction is the molten rock most likely to move through the viscous asthenosphere? Explain your answer.

Paleomagnetic Stripes and Sea-Floor Spreading

Activity 2.5

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

A Analyze the sea-floor part of the map in **Fig. A2.5.1**, which depicts the area just off the Pacific Coast, west of California, Oregon, Washington, and southwest Canada. The colored bands are marine 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 magnetic polarity time scale provided.

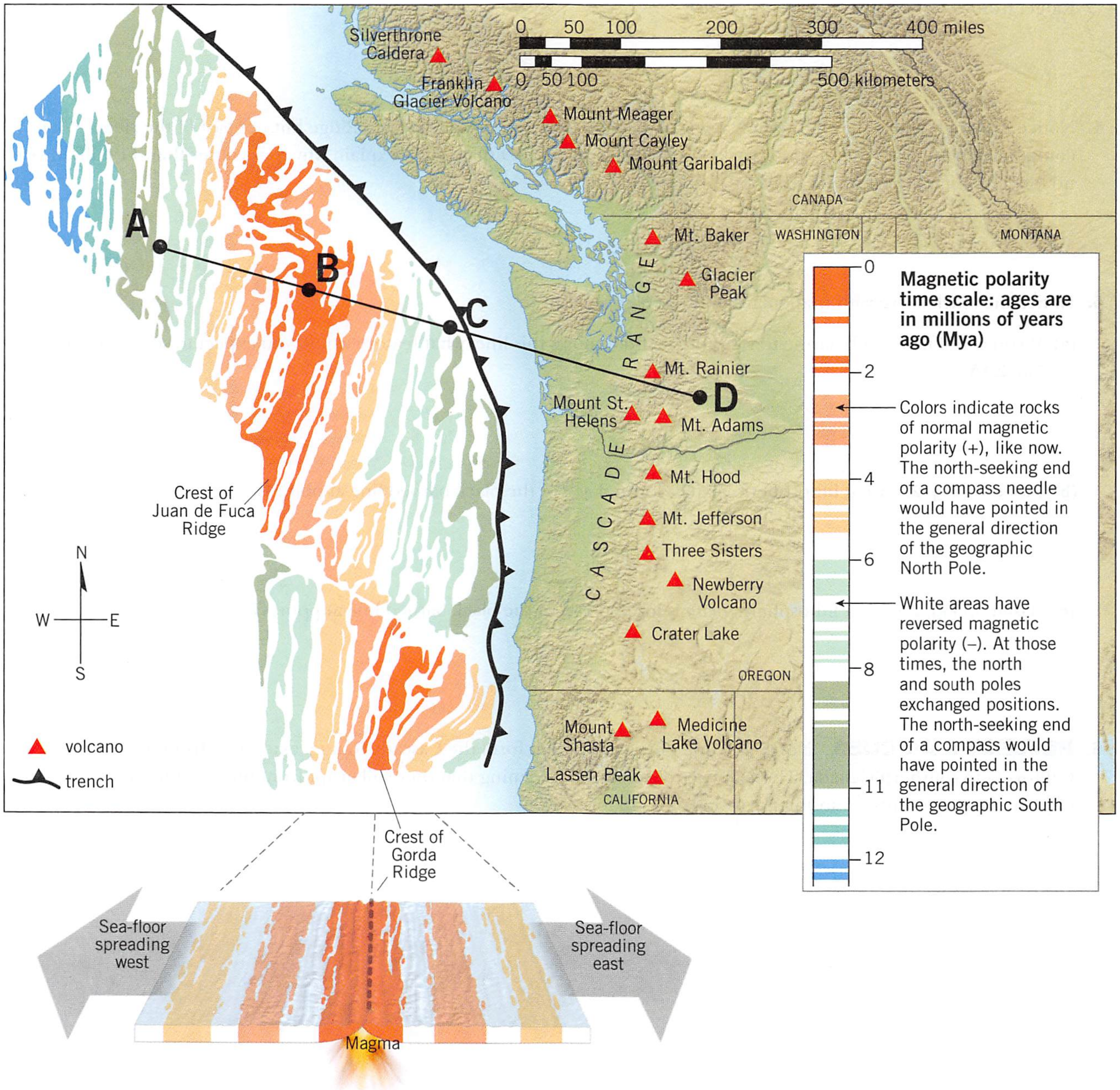


Figure A2.5.1

1. Using a pencil, draw a line on the seafloor to show where new ocean crust and lithosphere is forming now (zero millions of years old). Using **Figs. 2.1, 2.3,** and **2.12** as guides, 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 motion of the two plates relative to the transform fault.

2. What has been the average rate and direction of sea-floor 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 sea-floor 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 sea-floor rocks along line segment C-D that would explain why rocks older than 11 million years no longer exist on the seafloor east of the ridge?

5. Notice the black curve with triangular barbs just east of point C:

   (a) If you could take a submarine to view the sea floor along this line, what feature would you expect to see? (*Hint*: see **Fig. 2.1A**.)

   (b) Based on **Fig. 2.1**, what lithospheric plate is located *east* of the black barbed line at point C?

   (c) Based on **Fig. 2.1**, what lithospheric plate is located *west* of the black barbed line at point C?

6. **REFLECT & DISCUSS** Notice the line of volcanoes that form the Cascade Range, extending 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?

Atlantic Sea-Floor Spreading

Activity 2.6

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

A The map of the northern Atlantic Ocean Basin (**Fig. A2.6.1**) shows *isochrons* (lines of equal age) of the basaltic crust beneath the sediments that have accumulated on the seafloor. These isochrons were derived by Maria Seton and her colleagues (2012) from an analysis of marine magnetic anomalies, and their ages are based on the geomagnetic polarity time scale. *GPlates* (**http://www.gplates.org**) was used to help make this map. The red line on the map shows the location of the divergent boundary—the axis of the mid-ocean ridge—between the North American and African Plates.

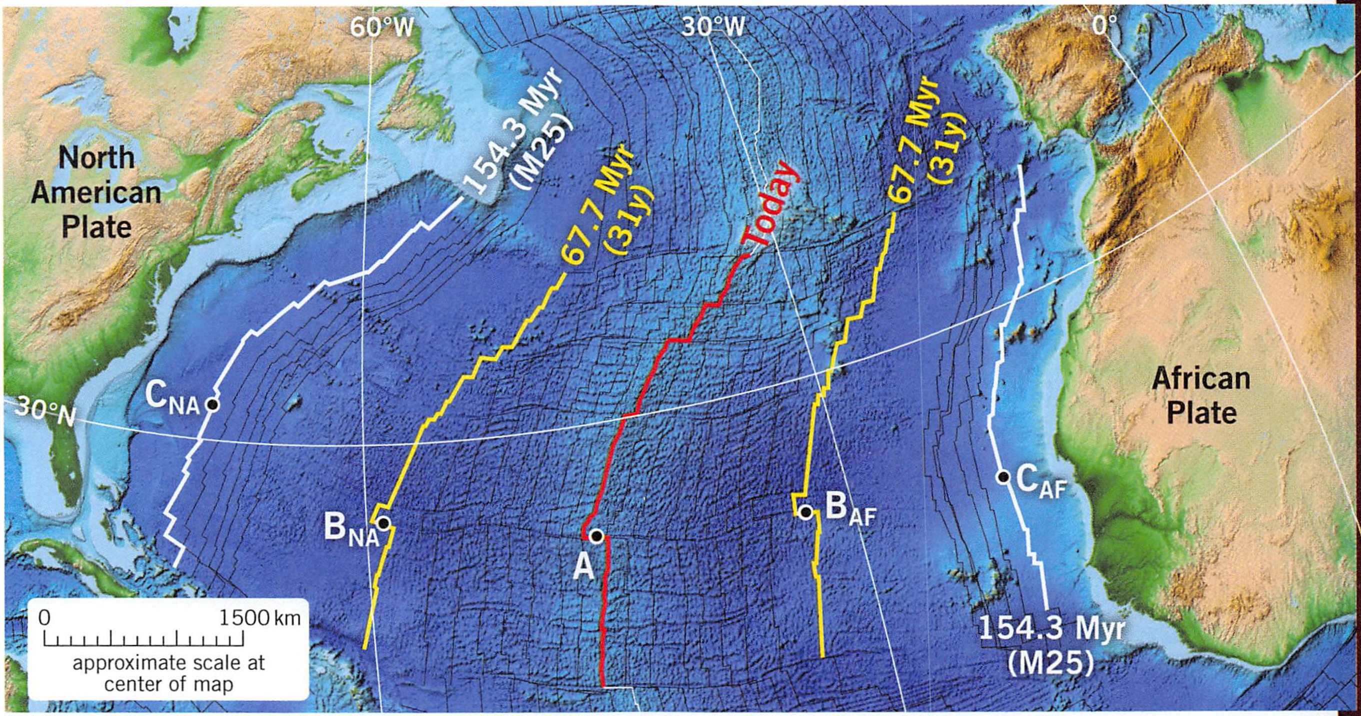


Figure A2.6.1

The approximate great-circle distances between the points identified on the map are listed here. The uncertainty in the distances provided is probably on the order of 10 km.

C_{NA} to B_{NA}	1354 km	C_{NA} to A	2617 km
B_{NA} to A	1338 km	C_{AF} to A	2599 km
B_{AF} to A	1320 km	B_{NA} to B_{AF}	2649 km
C_{AF} to B_{AF}	1279 km	C_{NA} to C_{AF}	5107 km

1. What is the average speed at which B_{NA} drifted away from the ridge at A during the past 67.7 Myr expressed in cm/yr.? __________ cm/yr.
   What is the average speed that B_{AF} drifted from A? __________ cm/yr.
   Which plate moved faster relative to the ridge over the past 67.7 Myr, if either? ______________________________

2. The area between C_{NA} and B_{NA} consists of oceanic lithosphere added along the Mid-Atlantic Ridge to the North American Plate between 154.3 and 67.7 Myr. What is the average speed at which new lithosphere was added to the North American Plate along that line? ____________ cm/yr.
   Do the same analysis for the lithosphere between points C_{AF} and B_{AF}. What is the average speed at which new lithosphere was added to the African Plate along that line? __________ cm/yr.
   Which plate moved faster relative to the ridge between 154.3 and 67.7 Myr, if either? ______________________________

B Given your answers in part **A**, did the North Atlantic Ocean Basin develop by adding lithosphere symmetrically along the mid-ocean ridge, or was new lithosphere added more rapidly to one side than the other? ______________________
If spreading was asymmetric, which plate had more lithosphere added, or did the asymmetry vary from plate to plate over time? ______________________

C Use the rates that you calculated above and the map scale to estimate when the coastlines of North America and Africa might have last touched before they were separated by the opening of the North Atlantic Ocean Basin. ______________________
____

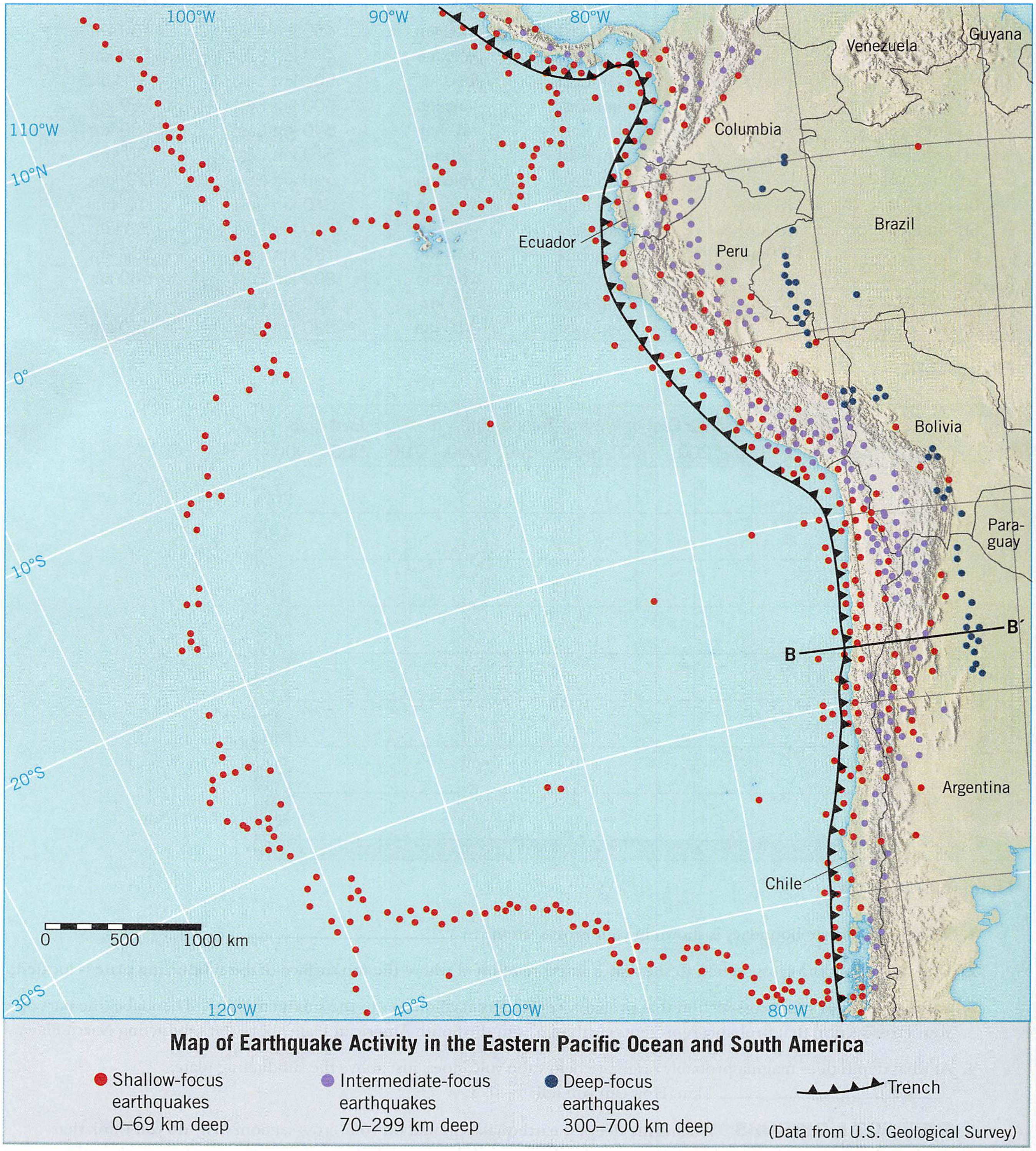
D **REFLECT & DISCUSS** Based on the rates you calculated above, estimate the number of meters that Africa and North America have moved apart since the United States was formed in 1776. Discuss what you did to accommodate the uncertainty in your estimate.

Using Earthquakes to Identify Plate Boundaries

Activity 2.7

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

A Use a red colored pencil or pen to outline the location of all plate boundaries on the map in **Fig. A2.7.1**. Do your work carefully. Then label the East Pacific Ridge, Galapagos Ridge, Chile Ridge, and all of the plates. Refer to **Fig. 2.1** for help with the tectonic features.



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)

Figure A2.7.1

B Notice line B–B' on the map in part **A** and the fact that shallow, intermediate, and deep earthquakes occur along it. [Each earthquake begins at a point beneath the surface called the *focus* (plural, *foci*).] Using data that were provided by the U.S. Geological Survey in **Fig. A2.7.2**, plot the locations of earthquake foci on the cross-section (**Fig. A2.7.3**). Volcanoes also occur at Earth's surface along line B–B'. Plot the locations of the volcanoes listed in the table by drawing a small triangle for each on the surface along the zero-depth line.

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

Figure A2.7.2

Figure A2.7.3

1. What kind of plate boundary is shown in your cross-section? ______________________
2. Draw a curve in the cross-section to show your interpretation of where the top surface of the subducting plate is located.
3. Label the part of your cross-section that probably represents earthquakes in the subducting slab. Then label the part of your cross-section that probably represents earthquakes in the South American Plate above the subducting Nazca Plate.
4. At what depth does magma probably originate below the volcanoes, just above the subducting plate: ______________________ km. How can you tell?
5. **REFLECT & DISCUSS** What is the deepest earthquake plotted on your cross-section? Why do you think that earthquakes occur at hundreds of kilometers depth along subducting slabs but not elsewhere in the mantle at that same depth?