2

Earth's Interior
Randa Harris and Bradley Deline

2.1 INTRODUCTION

Studying the Earth's interior poses a significant challenge due to the lack of direct access. Many processes observed at the Earth's surface are driven by the heat generated within the Earth, however, making an understanding of the interior essential. Volcanism, earthquakes, and many of the Earth's surface features are a result of processes happening within the Earth.

Much of what we know regarding the Earth's interior is through indirect means, such as using seismic data to determine Earth's internal structure. Scientists discovered in the early 1900's that **seismic waves** generated by earthquakes could be used to help distinguish the properties of the Earth's internal layers. The velocity of these waves (called primary and secondary waves, or P and S waves) changes based on the density of the materials they travel through. As a result, seismic waves do not travel through the Earth in straight lines, but rather get reflected and refracted, which indicates that the Earth is not homogeneous throughout.

The Earth's interior consists of an inner and outer core, the mantle, and the crust. Located in the center of the Earth is the **inner core**, which is very dense and under incredible pressure, and is thought to be composed of an iron and nickel alloy. It is solid, and surrounded by a region of liquid iron and nickel called the **outer core**. The outer core is thought to be responsible for the generation of the Earth's **magnetic field**. A very large portion of the Earth's volume is in the **mantle**, which surrounds the core. This layer is less dense than the core, and consists of a solid that can behave in a plastic (deformable) manner. The thin outer layer of the Earth is the **crust**. The two types, continental and oceanic crust, vary from each other in thickness, composition, and density.

2.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Determine the different layers of the Earth and the distinguishing properties of each layer

- Understand how seismic waves behave within the different layers of the Earth
- Understand how seismic tomography has been used to gain a better understanding of the Earth's interior
- Understand the Earth's magnetic field and how it changes over time
- Learn how to use the program Google Earth for geological applications

2.1.2 Key Terms

- Crust
- Inner Core
- Magnetic Field
- Mantle

- Outer Core
- Polar Wandering Curves
- Seismic Tomography
- Seismic Waves

2.2 INTERIOR OF THE EARTH

The study of seismic waves and how they travel through the Earth has been very useful in helping to determine the changes in density and composition within the Earth and in locating the boundaries be-tween the inner core, outer core, mantle, and crust. **Seismic waves** are energy waves generated during earthquakes; two types known as P and S waves propagate through the Earth as wave fronts from their place of origin. P-waves are compressional waves that move back and forth like an accordion, while S-waves are shear waves that move material in a direction perpendicular to the direction of travel, much like snapping a rope. The velocity of both of these waves increases as the density of the materials they are traveling through increases. Because most liquids are less dense than their solid counterparts, and seismic velocity is dependent on density, then seismic waves will be affected by the presence of any liquid phase in the Earth's interior. In fact, S waves are not able to travel through liquids at all, as the side to side motion of S waves can't be maintained in fluids; because of this, we know that the outer core is liquid.
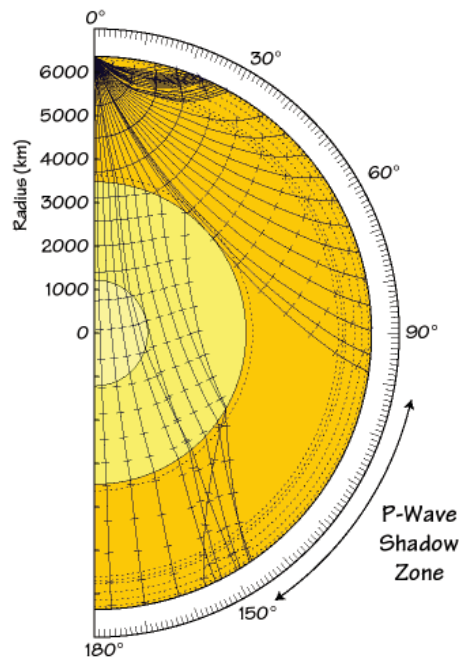

Figure 2.1 | A depiction of the P-wave shadow zone.
Author: USGS
Source: Wikimedia Commons
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If the Earth was completely homogeneous, the P and S waves would flow in straight lines. They don't behave this way, however. As the waves travel through materials of different densities, they are refracted, or bent, as their direction and velocity alter. Sometimes these refractions can result in shadow zones, which are areas along the Earth where no seismic waves are detected. Due to the presence of a liquid outer core, a P-wave shadow zone exists from 103°-143° (see Figure 2.1) from the earthquake origination point (focus), and a larger S-wave shadow zone exists in areas greater than 103° from the earthquake focus.

Based on the way that the Earth travels through space, we know that the average density of the Earth is 5.52 g/cm³. When rocks at the Earth's surface are analyzed, we find that most crustal rocks have densities in the range of 2.5-3 g/cm³, which is lower than the Earth's average. This means that there must be denser material inside the Earth to arrive at that higher average density; in fact, the core region of the Earth is estimated to have a density of 9-13 g/cm³. The composition of the Earth's layers also changes with depth. The bulk Earth composition is mostly made up of iron (~32%), oxygen (~30%), silicon (~16%), and magnesium (15%). If you examine rocks at the Earth's surface, however, you will find that oxygen is the most abundant element by far (~47%), followed by silicon (~28%) and aluminum (~8%), and lesser amounts of iron, calcium, sodium, potassium, and magnesium. Minerals made from silicon and oxygen are very important and are called silicates. So, if iron is present in lower numbers in the crustal rocks, where has that iron gone? Much of it can be found in the core of the Earth, which accounts for the major increase in density there. Review Table 2.1 below for general information about each layer of the Earth, and note how much thicker continental crust is compared to oceanic crust. Examine Figure 2.2 for a depiction of the layers of the Earth.
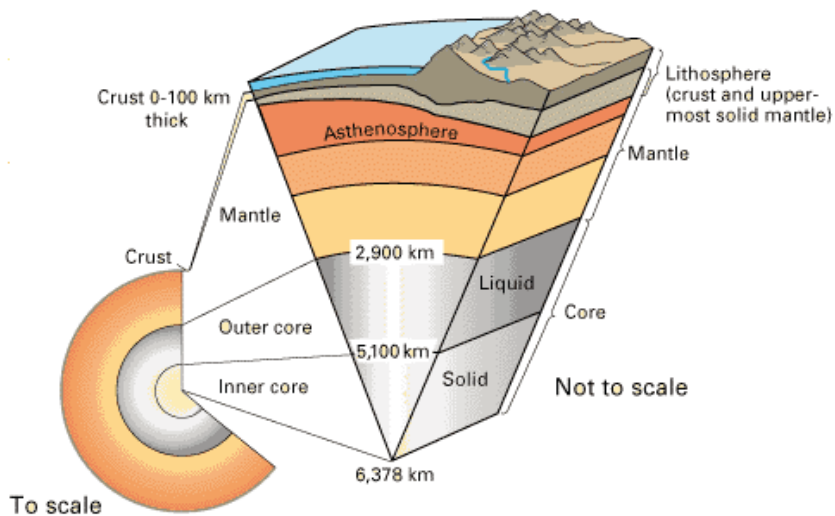

Figure 2.2 | A depiction of the inner layers of the Earth. Note that the image to the bottom left is to scale, while the image to the right is not.
Author: USGS
Source: USGS
License: Public Domain

Note that this figure includes the terms lithosphere and asthenosphere. The lithosphere is the outer, rigid part of the Earth made up of the upper mantle, oceanic crust, and continental crust. The asthenosphere is just beneath the lithosphere and, rather than being rigid, behaves plastically and flows.

Table 2.1

Earth's Layer	Density (g/cm3)	Thickness (km)	Composition
Continental Crust	~2.7-2.9	~20-70	Felsic rocks
Oceanic Crust	~3.0	~8-10	Mafic rocks
Mantle	~3.4-5.6	~2,885	Ultramafic rocks
Outer Core	~9.9-12.2	~2,200	Iron, some sulfur, nickel, oxygen, silicon
Inner Core	~12.8-13.1	~1,220	Iron, some sulfur and nickel

Relatively recent advances in imaging technology have been used to better understand the Earth's interior. **Seismic tomography** has been used to give a more detailed model of the Earth's interior. In CAT scans, x-rays are aimed at a person and rapidly rotated, generating cross-sectional images of the body. In a similar fashion, repeated scans of seismic waves are stacked to produce a three-dimensional image in seismic tomography. This technique has been used in many ways, from searching for petroleum near the Earth's surface to imaging the planet as a whole. Figure 2.3 depicts an image of the mantle created from seismic tomography.
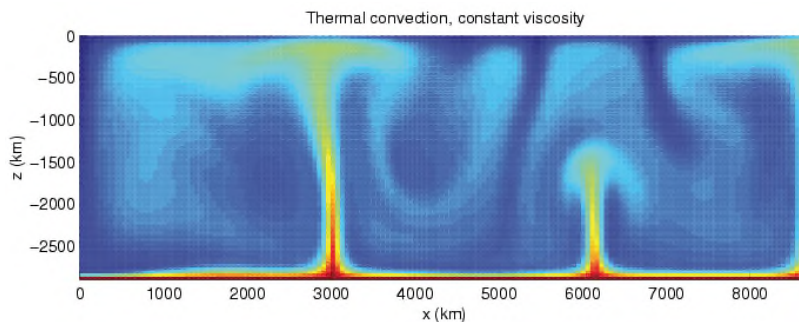

Figure 2.3 | A model of thermal convection in the mantle, created using seismic tomography. This model depicts areas of cool mantle material in blue and areas of warm mantle material in red. The thin red areas represent rising plumes.
Author: User "Harroschmeling"
Source: Wikimedia Commons
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2.3 LAB EXERCISE

Part A – Interior of the Earth

The following graph (Figure 2.4) displays seismic velocities (in kilometers per second) of P and S waves with depth (measured in kilometers) inside the Earth. Examine the graph closely and answer the following questions.
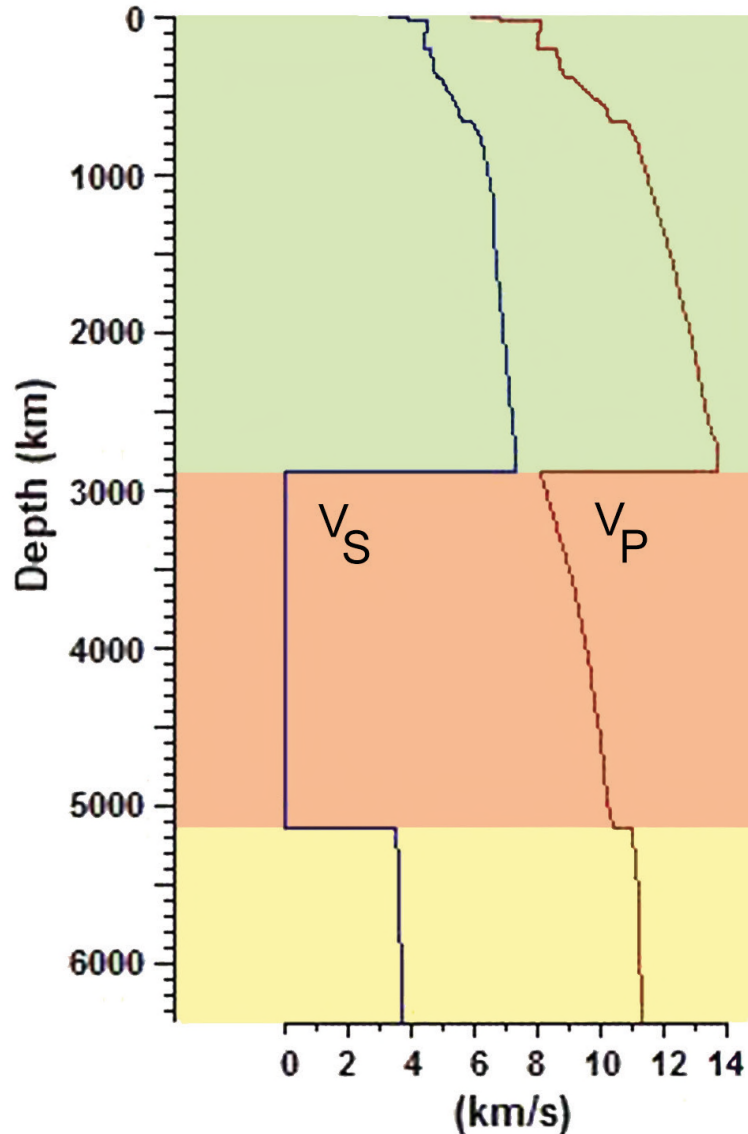

Figure 2.4 | Graph of seismic velocity with depth within the Earth's Interior.
Author: User "Actualist"
Source: Wikimedia Commons
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1. Observe the velocities of the waves on the graph. Which one travels faster?

    a. P waves   b. S waves

2. Inspect the P wave velocities. Where do the P wave velocities abruptly change?

    a. ~20 km   b. ~2,900 km   c. ~5,100 km   d. All of the above

3. In which zones do the P wave velocities appear to be steadily increasing?

    a. ~20–2,900 km   b. ~2,900-5,100 km   c. ~5,100-6,400 km   d. Both a & b

4. Observe the S wave velocities. Where do the S wave velocities abruptly change?

    a. ~20 km   b. ~2,900 km   c. ~5,100 km   d. All of the above

5. At ~2,900 km, the S wave velocity falls to 0. Why?

    a. S waves can't travel through solids, and this depth is where the solid inner core exists.

    b. S waves can't travel through liquids, and this depth is where the liquid outer core exists.

    c. S waves can't travel through solids, and this depth is where the solid mantle exists.

    d. S waves entered the shadow zone.

    Observe closely the changes in seismic wave velocity. You may add lines to your graph to denote the abrupt changes. Label each zone with the internal layers of the Earth and answer the following questions.

6. The zone from ~0-20 km represents the Earth's:

    a. crust   b. mantle   c. inner core   d. outer core

7. The zone from ~20-2,900 km represents the Earth's:

    a. crust   b. mantle   c. inner core   d. outer core

8. The zone from ~2,900-5,100 km represents the Earth's:

    a. crust   b. mantle   c. inner core   d. outer core

9. The zone from ~5,100-6,400 km represents the Earth's:

    a. crust   b. mantle   c. inner core   d. outer core

2.4 EARTH'S MAGNETIC FIELD

The thermal and compositional currents moving within the liquid outer core, coupled with the Earth's rotation, produce electrical currents that are responsible for the Earth's magnetic field. The shape of the magnetic field is similar to that of a large bar magnet. The ends of the magnet are close to, but not exactly at, the geographic poles on Earth. The north arrow on a compass, therefore, does not point to geographic north, but rather to magnetic north. The magnetic field plays a role in making the Earth hospitable to humans. Solar wind sends hot gases called plasma to Earth, and the magnetic field deflects most of this plasma. Without the work of the magnetic field, these damaging rays would harm life on the planet. As the solar wind approaches the Earth, the side of the Earth's magnetic field closest to the Sun gets pushed in, while the magnetic field on the opposite side away from the sun stretches out (Figure 2.5). You may have heard of the Aurora Borealis or "Northern Lights." Solar storms can create disturbances within the magnetic field, producing these magnificent light displays (Figure 2.6).
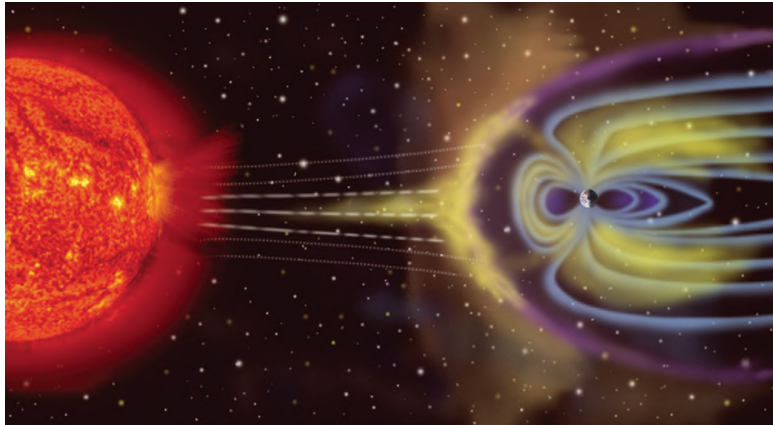

Figure 2.5 | Solar wind interacting with the Earth's magnetic field.
Author: NASA
Source: Wikimedia Commons
License: Public Domain

The magnetic field changes constantly and has experienced numerous reversals of polarity within the past, although these reversals are not well understood. Study of past reversals relies on paleomagnetism, the record of remnant magnetism preserved within certain rock types. Iron-bearing minerals that form from lava can align with the Earth's magnetic field and thus provide a record of the magnetic field in the Earth's past. However, this preserved magnetism could be lost if the mineral in the rocks has not been heated above a temperature known as the Curie point (a temperature above which minerals lose their magnetism). Essentially, the iron atoms "lock" into position, pointing to the magnetic pole. This records the alignment of the magnetic field at that time (we currently are in a normal polarity, in which north on a compass arrow aligns closely with geographic north, or the North Pole). If the magnetic field was stationary, all of the magnetic

Figure 2.6 | An example of the beautiful Aurora Borealis, light displays created by solar storm interaction with the Earth's magnetic field.
Author: User "Soerfm"
Source: Wikimedia Commons
License: CC BY-SA 3.0

minerals would point in the same direction. This is not the case, however. Reversals occur rather frequently on the geologic time scale.

Not only do magnetic poles reverse over geologic time, they also wander. Paleomagnetic data show that the magnetic poles move systematically, wandering across the globe. **Polar wandering curves** have been created to display the migration of the poles across the Earth's surface over time. Apparent polar wander refers to the perceived movement of the Earth's paleomagnetic poles relative to a continent (the continent remains fixed) (Figure 2.7). As you will learn in the Plate Tectonics chapter, polar wandering curves provide excellent evidence of the theory that the plates move, as curves for different continents do not agree on the magnetic pole locations. They all converge on the current pole location at present day, however.
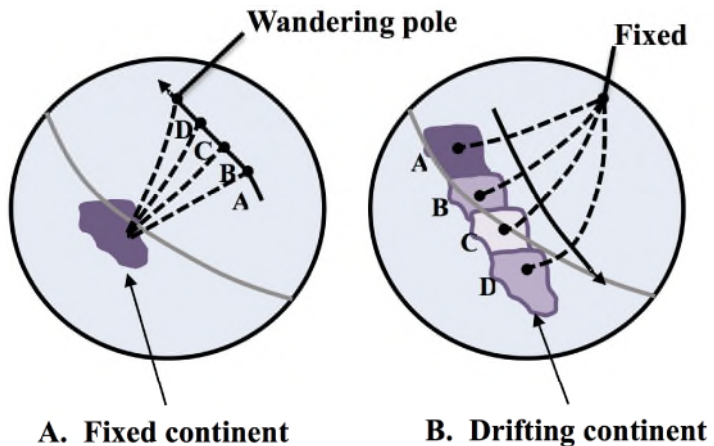

Figure 2.7 | If continents are fixed, as in A in the figure, the pole must be wandering. However, the pole is relatively fixed around the pole (with some movement), so the drifting continent (B) is the correct model.
**Author:** Randa Harris
Source: Original Work
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2.5 LAB EXERCISE

Part B – Earth's Magnetic Field

You will use the polar map given (Figure 2.8) to plot the changing locations of the magnetic pole over time. To view the polar map, imagine that you are above the North Pole looking down on it. 90° N latitude is directly in the center of the map, and the lines of latitude, measured in 2 degree increments, spread out in circles from the center. Values of longitude are also given, and are represented as lines that radiate out from the center in increments of 30 degrees. A scale bar, in kilometers, is provided. To familiarize yourself with the map, first practice plotting some of the locations given. The first two, A and B, have been done for you. You will be plotting actual locations of the magnetic North Pole over time ranging from 1400-1900 AD onto Figure 2.8. The table below includes the year and latitude and longitude (as degrees from 0 to 360) for each location. Once you have completed this, answer the questions that follow. Remember that 1,000 meters = 1 kilometer.

Point	Year	Latitude	Longitude
A	—	87.7	160.3
B	—	85.6	6.6
C	1400	84.8	228.3
D	1500	86.3	301.5
E	1600	85.6	316.7
F	1700	81.1	307.1
G	1800	81.1	297.1
H	1900	82.3	288.2
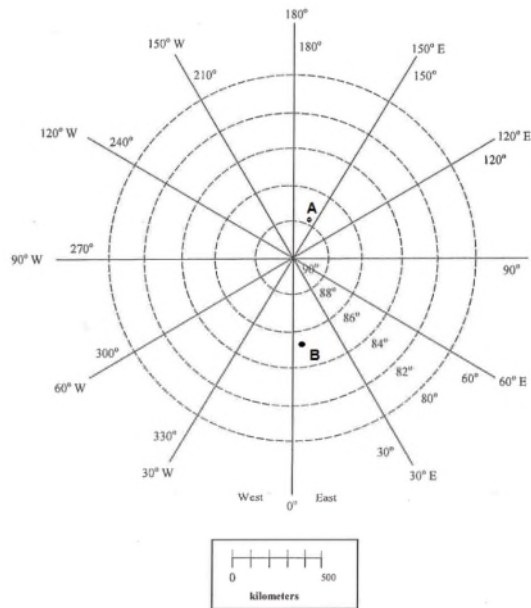
Figure 2.8 | Add the magnetic pole locations to this polar map and answer the questions below.
Author: NASA
Source: NASA
License: Public Domain

10. Measure the distance, using the bar scale, between the pole in 1400 and 1500 (locations C and D). How far did the pole move?

    a. ~50 km   b. ~150 km

    c. ~600 km   d. ~1,000 km

11. How far (in km) did the pole move in one year during this time period?

    a. 0.5 km   b. 1.5 km   c. 6 km   d. 10 km

12. How far did the pole move in meters in one year during this time period?

    a. 1,500 m   b. 500 m   c. 10,000 m   d. 6,000 m

13. Approximately how far did the pole move per day?

   • NꞒQ꞉ꞏ @   b. ~16 m   c. ~20 m   d. ~12 m

14. Measure the distance, using the bar scale, between the pole in 1400 and 1700 (locations C and F). How far did the pole move?

   a. ~50 km   b. ~150 km   c. ~600 km   d. ~1,000 km

15. Do pole movements tend to be steady every 100 years or variable?

   a. movements are steady   b. movements are variable

2.6 GOOGLE EARTH INTRODUCTION

Google Earth is a great tool to visualize and explore many of the geologic features that we will discuss in this class. This program is free and easy to use. This first Google Earth assignment will focus on familiarizing you with the program and some of the tools that we will use in later labs. Note that the optimal way to view geology is to go outside. Since that is not an option for an online class, the next best thing is using Google Earth. This is a practical and useful program that has many applications.

NOTICE: Google Earth updates versions periodically. If this occurs the instructions in the labs for this chapter may refer to the older version of the program. If you think this has occurred please let your instructor know.

If Google Earth is not already installed on the computer you are using**, then** please do the following:

1. Go to http://earth.google.com

2. Click on the Download Google Earth tab at the top of the page, **review** the Privacy Policy, and click Agree and Download to download the latest version.

3. Save the file to **your** desktop**,** open it and follow the instructions to install.

4. Open Google Earth.

Before we begin the assignment, let's first familiarize ourselves with Google Earth. Read each step and spend a few minutes trying things out, which will make things easier later. Also note that the Mac and PC versions of Google Earth are a little different.

You will use this program extensively throughout the course. Take the time to learn how to navigate it now.

Step 1 – Navigation

Watch each of the tutorial videos at: http://www.google.com/earth/learn/beginner.html#navigation. It is important that you dedicate time to review these virtual resources to help you better **understand Google Earth and its capabilities**. These will be key to mastering the tool. Navigating in Google Earth can be done in two ways:

First**,** you can use the Search panel in the upper left **hand side of the screen**. Just type in a location, address, or coordinate and it will zoom into the position (give it a try**now**).

The second approach is that you can also navigate manually:

- To move position you can left click with the mouse and drag the map or click on the hand icon in the upper right corner.

- You can zoom in and out using the mouse wheel, by right clicking and dragging the mouse up or down, or by sliding the lowest bar in the upper right corner.

- Click and hold the mouse wheel in order to rotate the map (left and right) or tilt the scenery (up and down). This can also be done using the arrows surrounding the eye icon in the upper right corner.

Along the bottom of the image it gives several important pieces of information:

1. Latitude and Longitude

2. Elevation in reference to sea level

3. Eye altitude, which indicates how zoomed in or out you are.

For example, let's check out Niagara Falls. In the Search panel in the upper left, type in Niagara Falls, NY. To better tell where the Falls are, you want to zoom out a little bit. Notice your eye altitude along the bottom right. Use the minus button for the zoom until you are at ~10,000' eye altitude. Check your latitude (~43°04'39"N – read as 43 degrees, 4 minutes, and 57 seconds North) and longitude (~79°04'28"W). It will move as you move your cursor across the screen, as will your elevation. If you want to see a picture of the Falls, just click on one of the many photo icons to see one. Note that the river is headed in a general northerly route – you can zoom in close to see the actual Falls.

Also important to understand with navigation is the concept of bearing. A bearing is the compass direction as measured between two points. It can be expressed as an azimuth
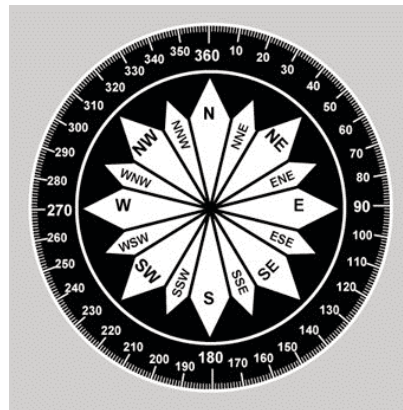

Figure 2.9 | A compass displaying the degrees.
Author: FAA
Source: Wikimedia Commons
License: Public Domain

bearing in degrees between 0 and 360, as along a circle. 0 and 360 degrees would be north, 90 degrees would be east, south would be 180 degrees, and west would be 270 degrees (Figure 2.9).

Bearing can be useful in determining how to get from point A to point B. To measure a bearing in Google Earth, follow this procedure. You want the bearing from point A to point B. Locate point A. Select the Ruler tool. Measure from A to B. In the last line in the Ruler tool box, read the Heading in degrees – that is measuring bearing (Tip: when point A is very far from point B, it can be helpful to add a placemark. Once at point A, choose the item in the menu bar right above the image that looks like a yellow pushpin. That is a placemark. Place it at point A. Also add a placemark at point B. Zoom out far enough that you can see both placemarks, then use the ruler tool to measure the heading between them. This works well for measuring headings across the entire United States). Let's practice getting a bearing again with Niagara Falls. For this example, point A will be the Scotiabank Convention Center located at 43004'34.08"N and 79005'05.98"W. Point B will be the name label for Goat Island (located across the river, just before the Falls begin). The bearing from point A to point B is ~74 degrees.

Step 2 – Measuring

In order to examine features, we will need to be able to measure them, which is easily managed in Google Earth. Measuring is done using the Ruler Tool, which can be accessed either by clicking the ruler icon in the toolbar above the image or by selecting from the menu across the top Tools, then Ruler.

There are two options with the ruler tool, line and path. The line option (which is the default option) gives the distance and direction between two points; notice the pull down menu that gives 11 different options for units of measurements. To make a measurement, after you have selected the ruler tool, you simply click on two different points. The path option gives the distance for a set of two or more points giving the ability to measure a distance that isn't a straight line.

NOTE: When measuring features you want to use the Map Length – using the ground length can lead to an incorrect answer.

Gradient will often be measured for this and future labs. Gradient is similar to slope which indicates how steep or flat an area is. It is calculated as the difference in elevation divided by the horizontal distance. When calculating gradient, maintain the same units in the numerator and denominator.

Gradient = change in elevation/horizontal distance

Let's practice again at Niagara Falls. First move the image slightly higher to fully see the start of the white water, just before the Falls begin (do this by left clicking the mouse and using the hand to move the image). With the eye altitude

still at ~10,000', let's measure the distance across the river right at the start of the whitewater before the Falls (where the whitewater stops). First click your ruler icon, then select a point on one side of the river, then move your mouse straight across to the other side. In feet, this should measure ~4,800 feet (don't stop at the island – measure all the way to the other river bank). Using the pull-down menu, you can change the feet to miles, and the result should be ~0.9 miles. Now let's practice gradient across the actual Falls. Position your cursor over the actual Falls, and zoom in to an eye altitude of ~1,000 feet. Hold your cursor over the top of the Falls and record the elevation (remember, this is located along the bottom bar). Now move your cursor to the bottom of the Falls and record the elevation. The change in elevation (highest-lowest) will be your numerator. Use the Ruler tool to measure the distance between the two places – this will be your horizontal distance (the denominator). There will be variation in this answer depending on your exact spot along the Falls, but results should be similar to this:

$$\text{Gradient} = (500' - 325') / 75' = 175'/75' = 2.3$$

Step 3 – Changing the Options

For a few tasks it will be important to change some of the default settings on Google Earth in order to see a feature better or make your work easier. These changes can all be made by going to Tools in the menu bar across the top, then Options in the PC version (for the MAC, go to Google Earth, then Preferences).

1. Changing the unit for Elevation – From the 3D view tab, in the middle of the box there is a section entitled "Units of Measurement" that you can change between metric and English units.

2. Exaggerating Features – Since differences in elevations are much smaller than geographic distances it is sometimes hard to see features. To exaggerate features (that is, make a mountain look taller than it actually is in order to see it better), click on the 3D view tab, in the lower left side at the "Terrain" section of the box, look for "Elevation Exaggeration (also scales 3D buildings and trees)". If you want to exaggerate a feature increase this value up to 3. To view the area without any exaggeration, return the value to the default of 1.

2.7 LAB EXERCISE

Part D – Google Earth

Answer the following questions using the skills discussed above. In order to prepare you for examining geologic features in Google Earth, let's first examine a more familiar area, Washington, D.C.

16. Search for the "Washington Monument" and zoom into ~3,000 feet eye altitude. What is the latitude of the monument?

    • N8X° C5'n @   b. 38° C5's @   c. 77° RR'e @   d. 77° RR'w

17. What is the longitude of the monument?

    • N8X° C5'n @   b. 38° C5's @   c. 77° RR'e @   d. 77° RR'w

18. Zoom into an eye altitude of ~500 feet. Locate the base of the monument (the base is square and is located in the center of the circle). What is the elevation of the base of the monument in feet?

    a. 15 feet   b. 40 feet   c. 65 feet   d. 80 feet

19. What is the elevation of the base of the monument in meters?

    a. 40 meters   b. 25 meters   c. 12 meters   d. 7 meters

20. How big is the base (area) of the Washington Monument in square feet? (Hint – make sure the 3D Buildings is selected in the Layers box, located in the lower left of the screen. Also, area is measured in square feet, so make sure you are multiplying two measurements.)

    a. ~1040 feet^R@   b. ~3100 feet^R@   c. ~4700 feet^R@   d. ~6030 feet^R

21. If you were standing at the Washington Monument, what direction would you need to walk to go to the United States Capitol Building?

    a. North   b. East   c. South   d. West

22. The direction system is useful, but imprecise. It is better to use a bearing. If you were standing at the Washington Monument, what bearing would you need to walk to go to the Smithsonian National Museum of Natural History, which houses many important geological specimens (Hint: Many of the buildings on the National Mall are part of the Smithsonian – make sure you get the correct building!)?

    • N8P @   b. 75°@   c. 90°@   d. 260°

23. If you decided instead to walk from the Washington Monument to the White House, how far would you have to walk, in miles (assume you could walk right to the entrance of the building)?

    a. 0.56 miles   b. 0.78 miles   c. 1.20 miles   d. 1.87 miles

24. How far is this distance in kilometers?

    a. 0.5 kilometers   b. 0.9 kilometers   c. 1.4 kilometers   d. 1.9 kilometers

25. Overall, would you be walking uphill or downhill?

    a. No change in elevation   b. Slightly uphill   c. Slightly downhill

26. How much does the elevation change in feet?

    a. 0 feet   b. 10 feet   c. 20 feet   d. 30 feet

27. What is the gradient of your walk?

    a. ~0.003   b. ~0.05   c. ~0.5   d. ~1

28. You decide to start walking from the Washington Monument to the White House, but as soon as you start a Park Ranger yells at you for walking on the grass. How far would the walk be (in miles) if you stayed on the sidewalks? There are many possible routes – try to take one of the shortest routes possible.

    a. 0.5 miles   b. 0.8 miles   c. 2 miles   d. 5 miles

29. Now, let's look at a geologic feature. Put 36 05 35.38 N 113 14 43.70 W into the search bar and zoom out to an eye altitude of ~25,000 feet. This is the Grand Canyon. If you started out in Washington, D.C., what bearing would you need to travel in to go to the Grand Canyon?

    • N⸱⸱⸱ @   b. 245° @   c. 275° @   d. 315°

30. The Grand Canyon is an extraordinarily steep area. If you go from the river at the bottom of the Canyon (36 05 35.38 N 113 14 43.70 W) straight north up the canyon rim (the area that ﬂattens out above the red layers of rock – 36 06 10.12 N 113 14 48.88 W), what is the gradient of the Grand Canyon? (**Hint:** You can tilt the image, which will make the ﬂat rim easier to see, by either pressing down on the middle mouse wheel and moving the mouse forward and backward or by clicking on the arrows above and below the eye in the upper right hand portion of the window.)

    • N⸱⸱⸱ @   b. 0.673   c. 0.976   d. 1.245

2.8 STUDENT RESPONSES

1. Observe the velocities of the waves on the graph. Which one travels faster?

   a. P waves   b. S waves

2. Inspect the P wave velocities. Where do the P wave velocities abruptly change?

   a. ~20 km   b. ~2,900 km   c. ~5,100 km   d. All of the above

3. In which zones do the P wave velocities appear to be steadily increasing?

   a. ~20–2,900 km   b. ~2,900-5,100 km   c. ~5,100-6,400 km   d. Both a & b

4. Observe the S wave velocities. Where do the S wave velocities abruptly change?

   a. ~20 km   b. ~2,900 km   c. ~5,100 km   d. All of the above

5. At ~2,900 km, the S wave velocity falls to 0. Why?

   a. S waves can't travel through solids, and this depth is where the solid inner core exists.

   b. S waves can't travel through liquids, and this depth is where the liquid outer core exists.

   c. S waves can't travel through solids, and this depth is where the solid mantle exists.

   d. S waves entered the shadow zone.

6. The zone from ~0-20 km represents the Earth's:

   a. crust   b. mantle   c. inner core   d. outer core

7. The zone from ~20-2,900 km represents the Earth's:

   a. crust   b. mantle   c. inner core   d. outer core

8. The zone from ~2,900-5,100 km represents the Earth's:

   a. crust   b. mantle   c. inner core   d. outer core

9. The zone from ~5,100-6,400 km represents the Earth's:

   a. crust   b. mantle   c. inner core   d. outer core

10. Measure the distance, using the bar scale, between the pole in 1400 and 1500 (locations C and D). How far did the pole move?

   a. ~50 km   b. ~150 km   c. ~600 km   d. ~1,000 km

11. How far (in km) did the pole move in one year during this time period?

   a. 0.5 km   b. 1.5 km   c. 6 km   d. 10 km

12. How far did the pole move in meters in one year during this time period?

   • NQLPP@ @   b. 500 m   c. 10,000 m   d. 6,000 m

13. Approximately how far did the pole move per day?

   • NQQ@ @   b. ~16 m   c. ~20 m   d. ~12 m

14. Measure the distance, using the bar scale, between the pole in 1400 and 1700 (locations C and F). How far did the pole move?

   a. ~50 km   b. ~150 km   c. ~600 km   d. ~1,000 km

15. Do pole movements tend to be steady every 100 years or variable?

   a. movements are steady   b. movements are variable

16. Search for the "Washington Monument" and zoom into ~3,000 feet eye altitude. What is the latitude of the monument?

   • NBX@S'n @   b. 38°@S's@   c. 77°@R'e @   d. 77°@R'w

17. What is the longitude of the monument?

   • NBX@S'n @   b. 38°@S's@   c. 77°@R'e @   d. 77°@R'w

18. Zoom into an eye altitude of ~500 feet. Locate the base of the monument (the base is square and is located in the center of the circle). What is the elevation of the base of the monument in feet?

   a. 15 feet   b. 40 feet   c. 65 feet   d. 80 feet

19. What is the elevation of the base of the monument in meters?

   a. 40 meters   b. 25 meters   c. 12 meters   d. 7 meters

20. How big is the base (area) of the Washington Monument in square feet? (Hint – make sure the 3D Buildings is selected in the Layers box, located in the lower left of the screen. Also, area is measured in square feet, so make sure you are multiplying two measurements.)

    a. ~1040 feet@   b. ~3100 feet@   c. ~4700 feet@   d. ~6030 feet@

21. If you were standing at the Washington Monument, what direction would you need to walk to go to the United States Capitol Building?

    a. North   b. East   c. South   d. West

22. The direction system is useful, but imprecise. It is better to use a bearing. If you were standing at the Washington Monument, what bearing would you need to walk to go to the Smithsonian National Museum of Natural History, which houses many important geological specimens (Hint: Many of the buildings on the National Mall are part of the Smithsonian – make sure you get the correct building!)?

    • N8P@   b. 75@   c. 90@   d. 260@

23. If you decided instead to walk from the Washington Monument to the White House, how far would you have to walk, in miles (assume you could walk right to the entrance of the building)?

    a. 0.56 miles   b. 0.78 miles   c. 1.20 miles   d. 1.87 miles

24. How far is this distance in kilometers?

    a. 0.5 kilometers   b. 0.9 kilometers   c. 1.4 kilometers   d. 1.9 kilometers

25. Overall, would you be walking uphill or downhill?

    a. No change in elevation   b. Slightly uphill   c. Slightly downhill

26. How much does the elevation change in feet?

    a. 0 feet   b. 10 feet   c. 20 feet   d. 30 feet

27. What is the gradient of your walk?

    a. ~0.003   b. ~0.05   c. ~0.5   d. ~1

28. You decide to start walking from the Washington Monument to the White House, but as soon as you start a Park Ranger yells at you for walking on the grass. How far would the walk be (in miles) if you stayed on the sidewalks? There are many possible routes – try to take one of the shortest routes possible.

    a. 0.5 miles   b. 0.8 miles   c. 2 miles   d. 5 miles

29. Now, let's look at a geologic feature. Put 36 05 35.38 N 113 14 43.70 W into the search bar and zoom out to an eye altitude of ~25,000 feet. This is the Grand Canyon. If you started out in Washington, D.C., what bearing would you need to travel in to go to the Grand Canyon?

    • N35°@   b. 245°@   c. 275°@   d. 315°

30. The Grand Canyon is an extraordinarily steep area. If you go from the river at the bottom of the Canyon (36 05 35.38 N 113 14 43.70 W) straight north up the canyon rim (the area that flattens out above the red layers of rock – 36 06 10.12 N 113 14 48.88 W), what is the gradient of the Grand Canyon? (**Hint:** You can tilt the image, which will make the flat rim easier to see, by either pressing down on the middle mouse wheel and moving the mouse forward and backward or by clicking on the arrows above and below the eye in the upper right hand portion of the window.)

    • N@RQT@   b. 0.673   c. 0.976   d. 1.245