Imaging Earth's Interior with Seismic Waves

Instructor's Guide

www.iris.edu/hq/inclass/lesson/174

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Incorporated Research Institutions for Seismology

NSF Award # 0942518

OVERVIEW

In this multi-step investigation, students examine seismic evidence used to infer Earth's internal structure and composition. Before beginning, students should know what earthquakes are, understand the basics of seismic wave propagation, and be able to explain the basic information contained in a seismogram and how a seismogram is recorded.

Activity 1: The lab begins with a review of seismic (body) wave propagation. Here students "become" solids or liquids kinesthetically explore how body waves move through materials in each state of matter.

Activity 2: Students test the hypothesis that Earth is composed of homogeneous rock. They then interpret seismic data from a recent earthquake and compare their observations with predicted arrival times from the homogeneous model.

Activity 3: Students transfer the observed data to a scale model to help visualize the details of Earth's interior and measure the diameter of Earth's outer core. They then compare their findings to accepted measurements.

Activity 4: Students apply their understanding of body-wave propagation to another seismic record section and ray path model of Earth to infer whether these two layers are solid or liquid.

Activity 5: Students examine a graph of viscosities of common materials to develop the idea that the asthenosphere is a solid, but that it deforms more easily than the more-rigid lithosphere.

Activity 6: Students examine results of seismic imaging to determine that the lithosphere-asthenosphere boundary varies with depth and can be a broad transition rather than a stark change as commonly indicated in textbook drawings.

Intermediate

45 min + 45 min

Whole Class → Small Group

Student Investigation

Discussion

Web-Based

OBJECTIVES

In this multi-step investigation, students :

- Estimate the size of Earth's core using a record section from an earthquake.
- Describe Earth's internal structure (concentric layers of different density and composition) and summarize how this is inferred through the analysis of seismic data, in a short argument or evidence-based essay.
- Describe how primary and secondary waves propagate.
- Differentiate between the asthenosphere and lithosphere.

TABLE OF CONTENTS

INSTRUCTOR PREPARATION

This investigation is comprised of several activities. Required materials for each activity are listed a the beginning of that activity. Therefore, to ensure instructors are adequately prepared, we recommend that instructors read through all activities ahead of time.

INSTRUCTIONAL FLOW

Activity 1 – Reviewing Seismic Waves (kinesthetically) by creating a Human Wave

Materials for the Human Wave activity

- Stop watch to time student demo.
- Paper and pencil to record times and create a time versus distance graph.

Procedure

1. Line up ~10 to 15 students from tallest to shortest. Participants need to be physically capable of balancing and bending over at the waist.
2. Instruct participants that they will represent an elastic solid. As solid particles, they should be tightly spaced snugly touching shoulder to shoulder and connected to one another chorus-line style. Each person's arms will be over their neighbor's shoulders. Since they are elastic, they should deform in response to stress, and then return to their original position.
3. Tell them that you are going to generate an earthquake. Have a student ready with the stop watch to time each "seismic wave".
   Send a P-wave by giving the first student a light push towards the next student, which signals the student to start the stopwatch. How long did it take? To send an S-wave, carefully but quickly bend the first student at the waist and have it ripple through the line. How long did that take? During each run, emphasize the following:
   a. Particle motion relative to the direction of propagation—Particles move parallel to the direction of propagation due to a P wave, while an S wave moves them perpendicular to the direction of propogation.
   b. Relative speed of each wave type— P waves are faster than S waves.
   c. Travel time for the energy to leave the source and arrive at the receiver. The time is dependent upon both the length of the path and the efficiency at which the energy is propagated.
4. Instruct all participants to become a liquid. As particles in a liquid, they should still touch shoulders but no longer be connected via their previous over-the-shoulder, chorus-line arrangement.
5. Repeat step 3, timing each wave with stop watch. First send a P-wave, then an S-wave through the line. Again, emphasize the following:
   a. Liquids have no restoring force; thus an S-wave can't propagate
   b. Particle motion is relative to the direction of propagation
   c. Travel time for the energy to leave the source and arrive at the receiver is dependent upon both the length of the path and the efficiency at which the energy is propagated.

VIDEO RESOURCE

A "Human Wave" demo in a middle-school classroom describes the process (with some caveats) of the movement of P and S waves through solids and liquids: http://www.iris.edu/hq/inclass/demo/human_wave.

Although this video includes a hand-hold version, the over-shoulder method is a more accurate depiction.

Video screen grab of start of P-wave.

TIP 1

NOTE: Have a spotter at the far end of the line to "support" overzealous participants.

TIP 2

When sending the s-wave through the liquid, anticipate that the second student in line is likely to also bend sympathetically even though not physical made to do so. If this occurs you will need to redo and emphasize they are not forced to move.

Activity 2 – Comparing model data with observations

Materials for each student:

- Seismic record section from a recent earthquake (or sample record section in Appendix A)
- Ruler for each student
- Print Student Worksheets (Pages SW-1 through SW-4)

Procedure

1. Distribute a record section, tools and worksheets to each student.
2. Instruct students to complete Part I individually.
3. Discuss student responses to Part I as a class.
4. Instruct students to complete Part II of the lab in small groups.
5. Discuss student responses to Part II as a class

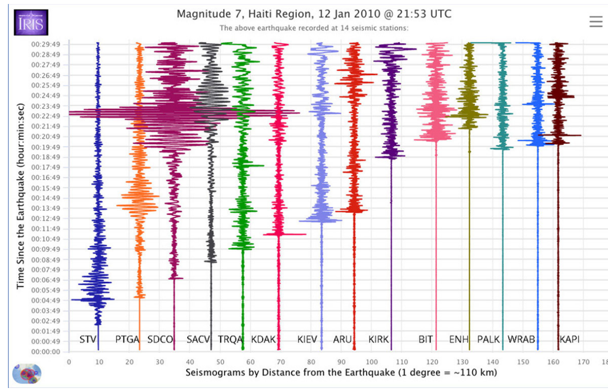


Figure 1. *Record section for Activity 2, from the 2010 Haiti Earthquake recorded across the globe. Full scale image and instructions in Appendix A.*

Activity 3 – Examining the implications

Materials for each student:

- Copy of Full-Circle Scale Model
- Ruler, Protractor, and Scissors for each student
- Student Worksheet (Pages SW-5 to SW-11) for activities 3–5.
- Imaging Earths Interior.pptx and projector.

Preparation

Preprint one copy of the Full-circle Earth Model. Measure the diameter to verify that it printed with a 5 cm radius. If not, make sure that printing options are set to "*scale the page to fit the printable area*" and "*auto-rotate and center*" are turned off . When correct, print copy for each student.

Review the slide presentation for steps.

Procedure

1. Project the slide presentation on the screen.
2. Have students complete Part III of their worksheet to apply the observed data to a scale model of Earth. By mapping out the P-wave shadow zone for multiple earthquakes, Earth's interior structure becomes apparent. (See Figure 2.)
3. Discuss the results as a class and emphasizing that while we have found the shadow zone, it is not the absence of seismic waves. Rather, it is the absence of direct seismic waves. Seismic energy that has been reflected and diffracted still arrive in this region as visible on the record section in Activity 1.

POSSIBLE SOURCES OF STUDENT ERROR

There are a number of sources of error. These include the accuracy of tools used, the scale of the models used, and students' misinterpretation of the seismic data or sparseness of data to carefully define the boundary (e.g. a record section might only have data from a station at 92 degrees and then another at 118 degrees).

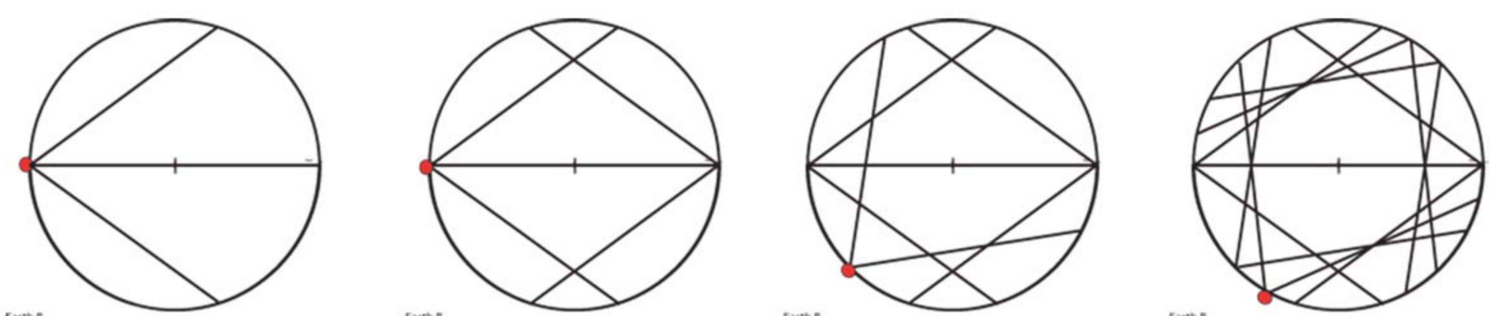


Figure 2. *By mapping the P-wave shadow zone for multiple earthquakes, Earth structure becomes apparent.*

Activity 4 – Determining States of Matter

Students apply their understanding of body wave propagation to another seismic record section and ray path model of Earth to infer whether these two layers are solid or liquid.

Materials for each student:

- Student Worksheet (Pages SW-7 through SW-9).
- Imaging Earths Interior.pptx and projector.

Preparation

Review the slide presentation for steps.

Procedure

Instruct students to complete Part IV of their worksheets.

Activity 5 – Examining viscosities of the Lithosphere & Asthenosphere

Students examine a graph of viscosities of common materials to develop the idea that the asthenosphere is a solid, that it deforms more easily than the lithosphere.

Print Student Worksheet pages SW-10 and SW-11.

Procedure

Instruct students to complete Part V of their worksheets.

Activity 6 – Lithosphere-Asthenosphere Boundary

Students examine results of seismic imaging to determine that the lithosphere-asthenosphere boundary varies with depth and can be a broad transition rather than a stark change as commonly indicated in textbook drawings.

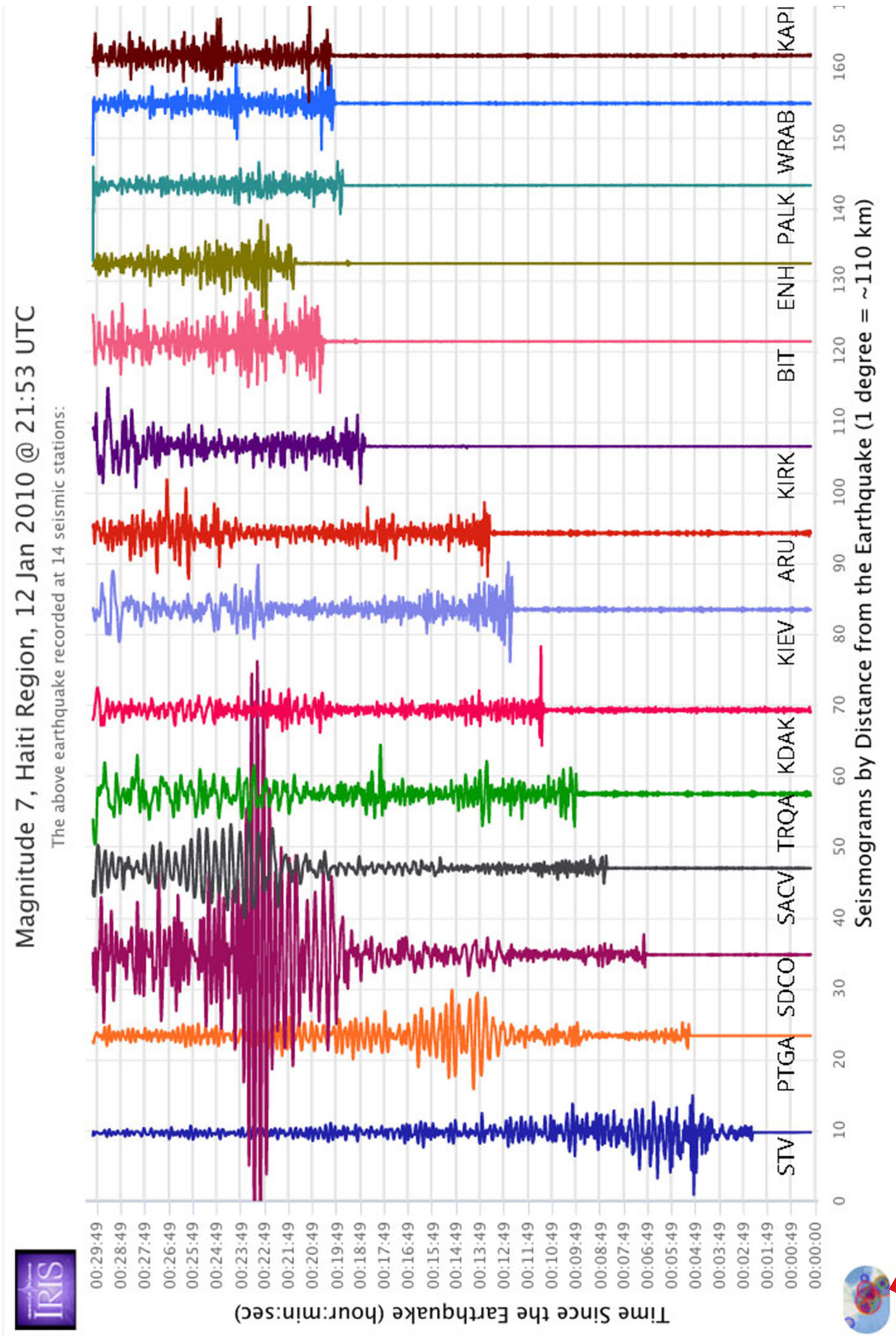
Print Student Worksheet SW-12 and SW-15.

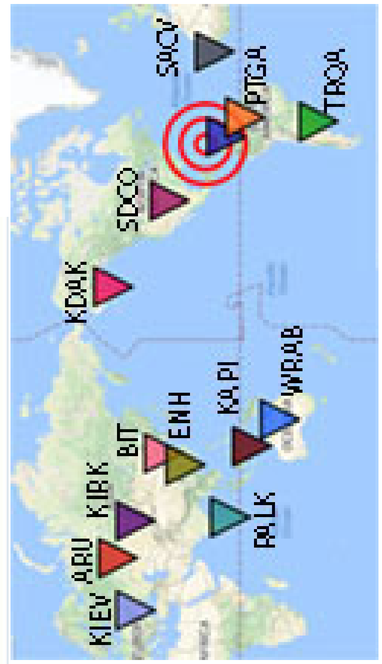
Procedure

Instruct students to complete Part VI of their worksheets.

APPENDIX A

Record section. Seismograms from the 2010 Haiti earthquake as recorded by numerous seismic stations. Distance from each station to the epicenter increases from left to right. . Colors represent stations on the map at right.

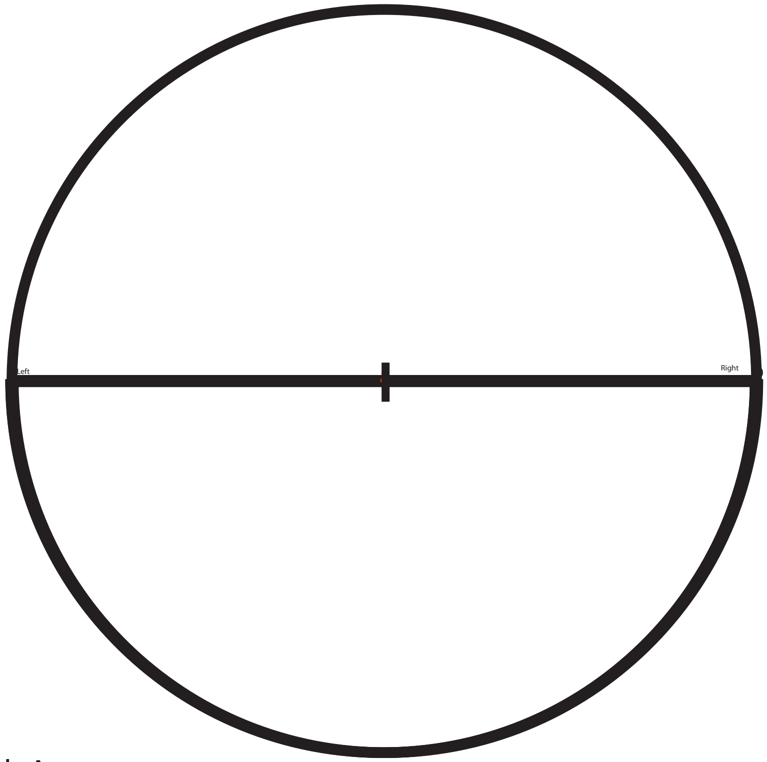




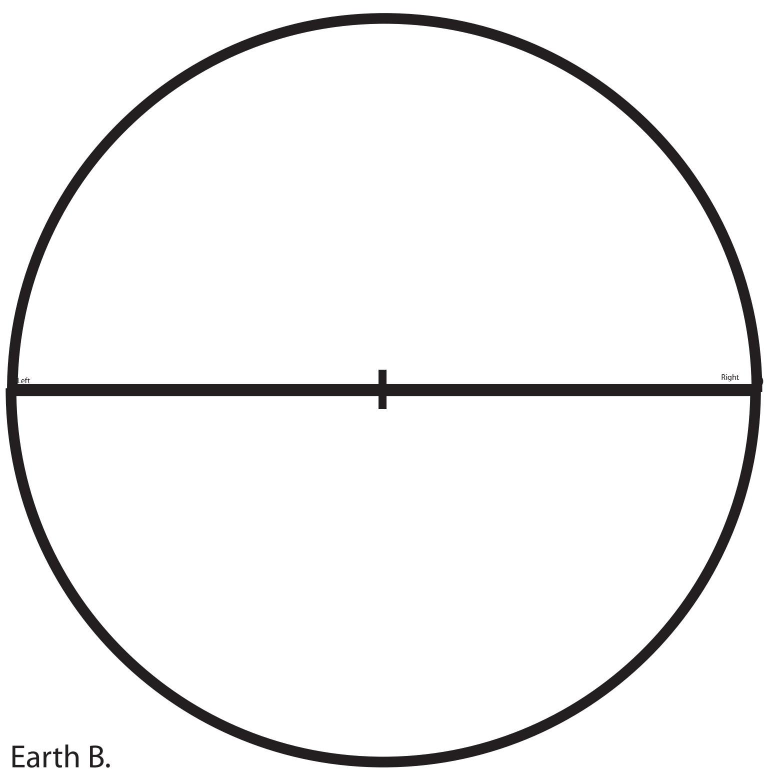
To obtain a record section from other large earthquakes, visit URL and use the map to select a earthquake and the record section will be generated for you. : http://ds.iris.edu/seismon/recsec/map.phtml?epo=0

APPENDIX B

Full-circle Earth Scale Model



Earth A.



Earth B.

APPENDIX C

This activity is part of a collection of activities based on ten questions that identify promising research directions on the frontiers of seismology as outlined in the Seismological Grand Challenges in Understanding Earth's Dynamic System. This collection has been developed to bring examples of frontier research into the undergraduate classroom while also helping to change the seismology instruction used in many lecture halls and labs in postsecondary education.

Grand Challenge #7 - *What is the Lithosphere-Asthenosphere boundary***?**

www.iris.edu/hq/files/programs/education_and_outreach/CCLI/LAB/Lithosphere_Asthenosphere_Boundary.pdf

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References:

Lay, T., Aster, R. C., Forsyth, D. W. and the Seismological Grand Challenges Writing Group (2009). *Seismological Grand Challenges in Understanding Earth's Dynamic Syste*m, http://www.iris.edu/hq/lrsps/seis_plan_final.pdf.

Nettles, M., and A.M. Dziewonski, Radially anisotropic shear velocity structure of the upper mantle globally and beneath North America, J. Geophys. Res. 113, B02303, 2008.

Name: ______________________________________

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IMAGING EARTH'S INTERIOR WITH SEISMIC WAVES

Part I

1. What is inside Earth? In the space below, sketch what you believe the interior structure of Earth to be like.

2. Describe any evidence, based on personal experience, which *YOU* have for the information you sketched above?

Part II

You probably didn't have much evidence about Earth's interior beyond what textbooks, TV, or a previous instructor described. *So how do we really know what is inside Earth?* Let's investigate!

Based on your own direct experience (e.g. digging a hole, visiting a cave or quarry, driving past a road cut) you are probably aware that below the soil is a layer of rock. Let's begin our investigation into Earth's interior by assuming that the simplest solution is correct . Thus, we will start with the hypothesis that Earth is made up entirely of this same rock material, which extends all the way to the center of Earth. This homogeneous Earth model is illustrated in Figure 1 (right).
Since the model is comprised of the same material throughout, we can assume that seismic waves will travel:

a) at a constant velocity (in this case, we will assume the P-waves travel at a velocity of 11km/s in our model), and
b) in straight lines.

We can use this model and these assumptions to make some predictions and calculations that test the accuracy of our hypothesis.

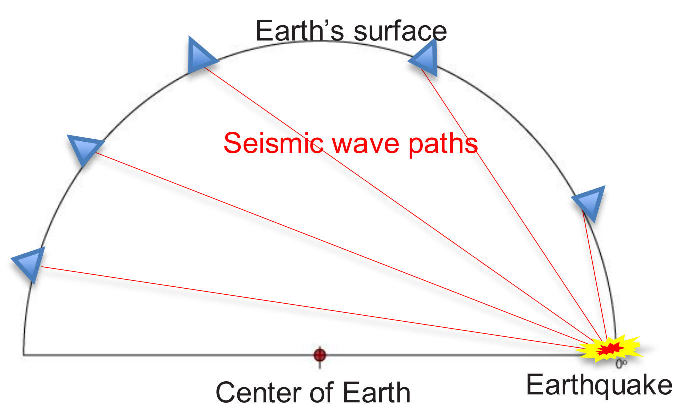

Figure 1. *A scale model of a cross section of Earth comprised entirely of rock. Triangles represent seismic stations at the surface and the red lines indicate example paths that seismic energy travels from the earthquake to each station.*

For example, we can use the model to predict how long it *should* take seismic waves to travel from an earthquake, through Earth, to various points on Earth's surface. This can be accomplished using the basic equation

$$T = D/S$$

(T) is the time it takes for a seismic wave to travel a certain distance, (S) is the speed the waves travel and (D) is the distance between the earthquake and the seismic station.

As previously mentioned we are assuming that the speed (S) of P-waves is 11km/s. Since our model is a physical scale model, we can measure the length of the seismic wave paths from the earthquake's location to various points on the model's surface. Model measurements can be scaled up to real Earth distances. This has been done for you and the predicted arrival times for our homogeneous Earth model are illustrated in Figure 2 below.

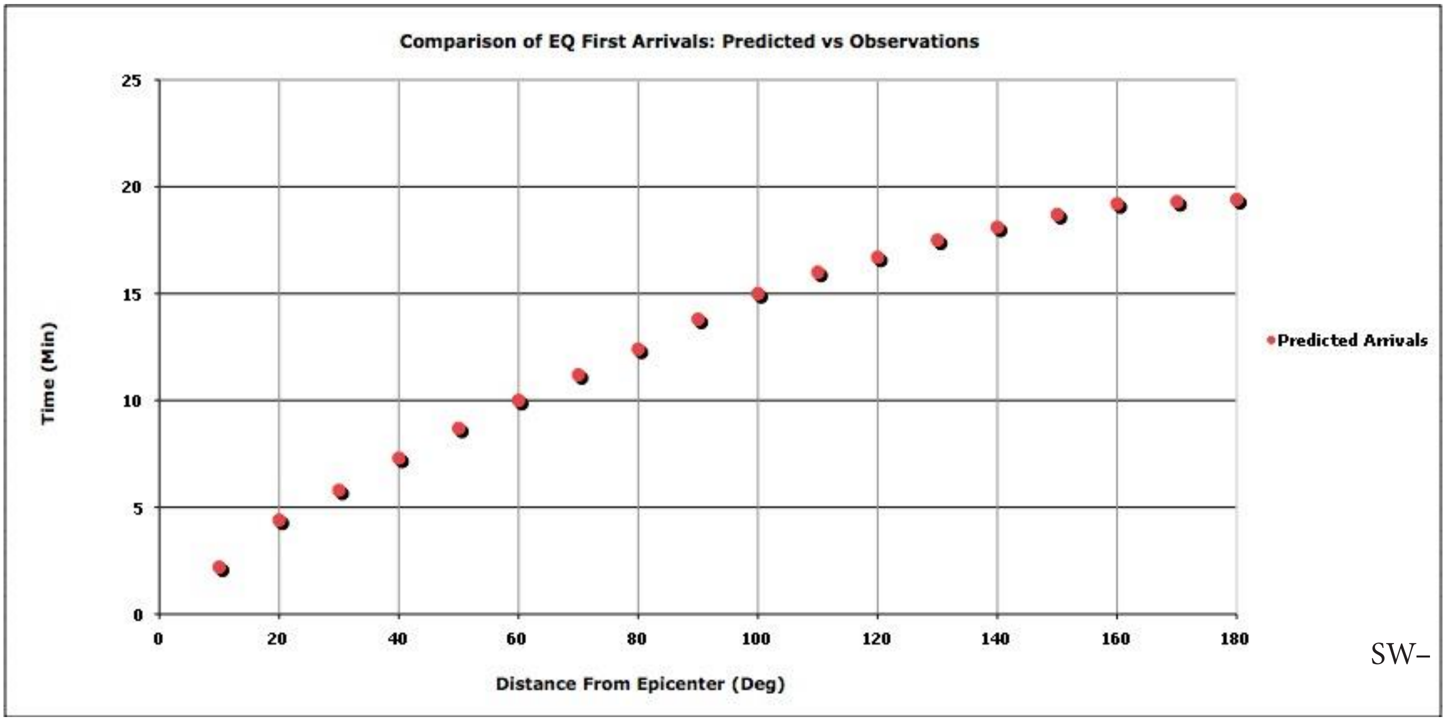

Figure 2*: Predicted arrival times for our homogeneous Earth model*

NOTE: The distances displayed on the X-axis in Figure 2 above and on the seismic record section provided with this lab use angular degrees with Earth's center as the reference point. This is known as the "geocentric angle." Each angular degree = ~111km on Earth's surface. The angular distance between an earthquake and a seismic station is referred to as the "epicentral distance."

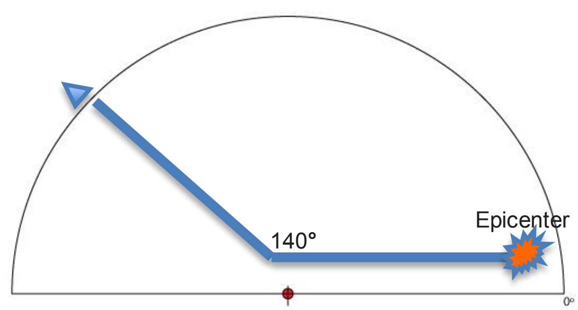

Figure 3: *Measuring distances using geocentric angle.*

Next we need to compare the predictions derived from the model to observations we make from the real Earth. Modern seismographic networks record how the ground moves in response to earthquakes at points all over the world. These recordings of ground motion, called seismograms, are freely available via the Internet. Your task is to use a collection of seismograms from a single earthquake, presented together as a record section, to determine how long it *actually* takes for P-waves to travel through Earth. Your findings form the observed Earth data will be compared to the observed data in Figure 2. If your findings match and follow similar trends as the arrivals predicted by our model, then our hypothesis that the Earth must be homogeneous rock throughout should be correct. However, if your observations do not match the predicted arrival times, then we can reasonably assume the Earth is not homogenous and does have some structure to it.

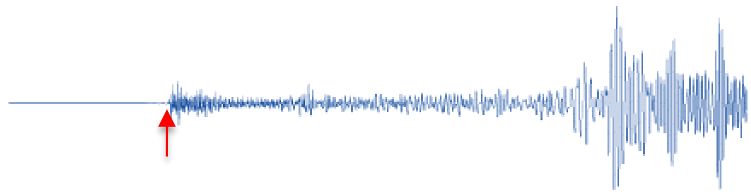

Figure 4. *The arrival of seismic energy is indicated on the seismogram by a change from the background or previous signal. In this example, the arrow denotes the arrival of the P-wave.*

1. Carefully analyze the collection of seismograms (called a record section). Identify the first arrival of seismic energy (example in Figure 4) at the station and determine how long it took the seismic energy to travel to each station. Record this information in the data table below.

Table of P-wave arrival times from a single earthquake to worldwide seismic stations:

Station Distance (degrees)	Travel time (min)
STV ~10°	~1 min 55 sec

Describe any difficulties you and your team had generating your data. Be sure to include any areas where error might have been introduced into your data set.

4. Plot your observed P-wave arrival times on Figure 2 above using triangles to indicate observed data.

5. Which of the following statements best describes the observed values you just plotted in Figure 2?
   a) A set of points that follow a straight line
   b) A set of points that follow a curved line with a smaller slope at larger distances
   c) A set of points that follow a curved line with a jump where the values increase abruptly
   d) A set of points that follow a curved line with a larger slope at larger distances

5. Analyze these two data sets (predicted vs. observed travel times) and describe what you see in your data.

6. Which of the following best describes the relationship between the observed values and predicted values in Figure 2?
   a) The observed values are similar to the predicted values except for a large difference around 110 degrees.
   b) The observed values are only similar to the predicted values at large distances.
   c) The observed values do not appear similar to the predicted values at all.
   d) The observed values are similar to the predicted values at all distances.

7. What do the results of comparing the observed arrivals to the predicted arrivals imply about our hypothesis that Earth's interior is composed of homogenous rock?
   a) The comparison implies Earth's interior is not homogeneous rock throughout.
   b) The comparison implies Earth's interior is homogeneous rock throughout.
   c) The comparison is unable to inform us about our hypothesis.

Briefly explain why you selected that response.

8. Which of the following statement is the best hypothesis for explaining the observed values in the plot?
   a) Earth's interior changes abruptly at several different depths.
   b) Earth's interior is homogeneous throughout.
   c) Earth's interior is heterogeneous but changes gradually with depth.
   d) Earth's interior is composed of homogeneous rock through some portions, but also changes abruptly at a particular depth.

Part III – Requires Full-Circle Earth Scale Model

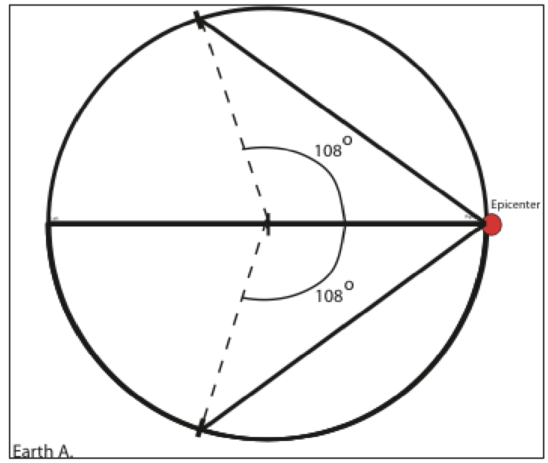

Figure 5. Based on the observed seismic data you recorded, the P-wave shadow zone can be modeled. Here, an example using 108 degrees is shown.

1. As show in Figure 5, indicate the epicenter of the earthquake with a small circle at 0 degrees on Earth A (the right edge).

2. Examine your graph of the observed arrivals on Figure 2 to determine where there is an "interruption" or "unconformity" in the observed seismic waves arrivals compared to the modeled arrivals.

3. Measure a geocentric angle equal to the "interruption" you noted above to the northern hemisphere and make a mark on Earth's surface (e.g. *108 degrees as shown in Figure 5, though your data will vary*). Use your ruler to connect the epicenter to the mark you just drew on Earth's surface.

4. Repeat this procedure but mark the southern hemisphere's surface.

5. Label the area inside the angles drawn as the P-wave shadow zone.

6. Answer the following questions:
   a. What sort of structure have we determined so far?

   b. How has the seismic data helped us determine Earth's interior structure?

   c. Examine the record section again for this area and consider how this "shadow zone" might be like a person's shadow on the ground.

   d. How might more data help us "resolve" Earth's structure?

7. Use scissors to cut out the wedge-shaped P-wave shadow zone. This represents the area that does not receive "direct" P-waves from an earthquake.

8. Next model the occurrence of additional earthquakes by placing the point of the wedge-shaped cut-out on the surface of Earth B while aligning the curved arc of the wedge with the opposite side of Earth B (*the point on the cone indicates the location of another earthquake epicenter*).

9. Trace the straight edges of the wedge to indicate the area where direct P-waves from the earthquake do not arrive.

10. Repeat this procedure for a number of earthquakes, each at a different location. Be sure to trace out the P wave shadow zone each time.

11. Answer the following questions:
    a. As additional earthquake data is added, what shape is being defined in the interior of Earth Model B?

    b. Describe what you think this new inner circle represents?

    c. Describe what has allowed our model for Earth's interior to improve since 6d above.

12. Calculate the radius of the structure that was revealed by the seismic data. The scale of Earth model B is 1:127,420,000 and there are 100,000 cm in 1 km.

Part IV

As you have seen, seismologists can explore Earth's interior by analyzing seismic wave arrivals resulting from large earthquakes. Figure 6 shows the basic structure of Earth's interior, while the connected Figure 7 shows a record section (a collection of seismograms from the same earthquake recorded at different distances from the quake). This example is from the 1994 Northridge earthquake.

1. Use the Internet to help you label the layers of Earth's interior A, B, and C as shown on Figure 6.

2. How well does the radius you calculated in **Part III** compare to the accepted values you found? Why might these differ?

3. Highlight the P-wave arrivals on the seismograms on Figure 7. Comparing these to Figure 2. which of the following statements is most accurate?
   a. The arrival times in Figure 7 follow the same overall pattern as the hypothetical values.
   b. The arrival times in Figure 7 follow the same overall pattern as the observed values.

4. In Figure 7, over what distances do the P-waves arrive "later" than the shape of the rest of the curve would predict?
   a. 10-40 degrees
   b. 80-100 degrees
   c. 110-140 degrees
   d. 140-160 degrees

5. Examine Figure 7 again. Which of the following best describes what happens to the S-wave arrivals over the same distances you identified in #4 above?
   a. No S-waves arrive at those distances.
   b. The S-waves also arrive later than the rest of the curve would predict.
   c. The S-waves arrive when the rest of the curve would predict.

6. Using what you learned about P- and S- wave propagation at the beginning of class, construct an argument, or an evidence-based statement, describing the state of matter you believe Earth's mantle and core are made of.

A ____

B. ____

C. ____

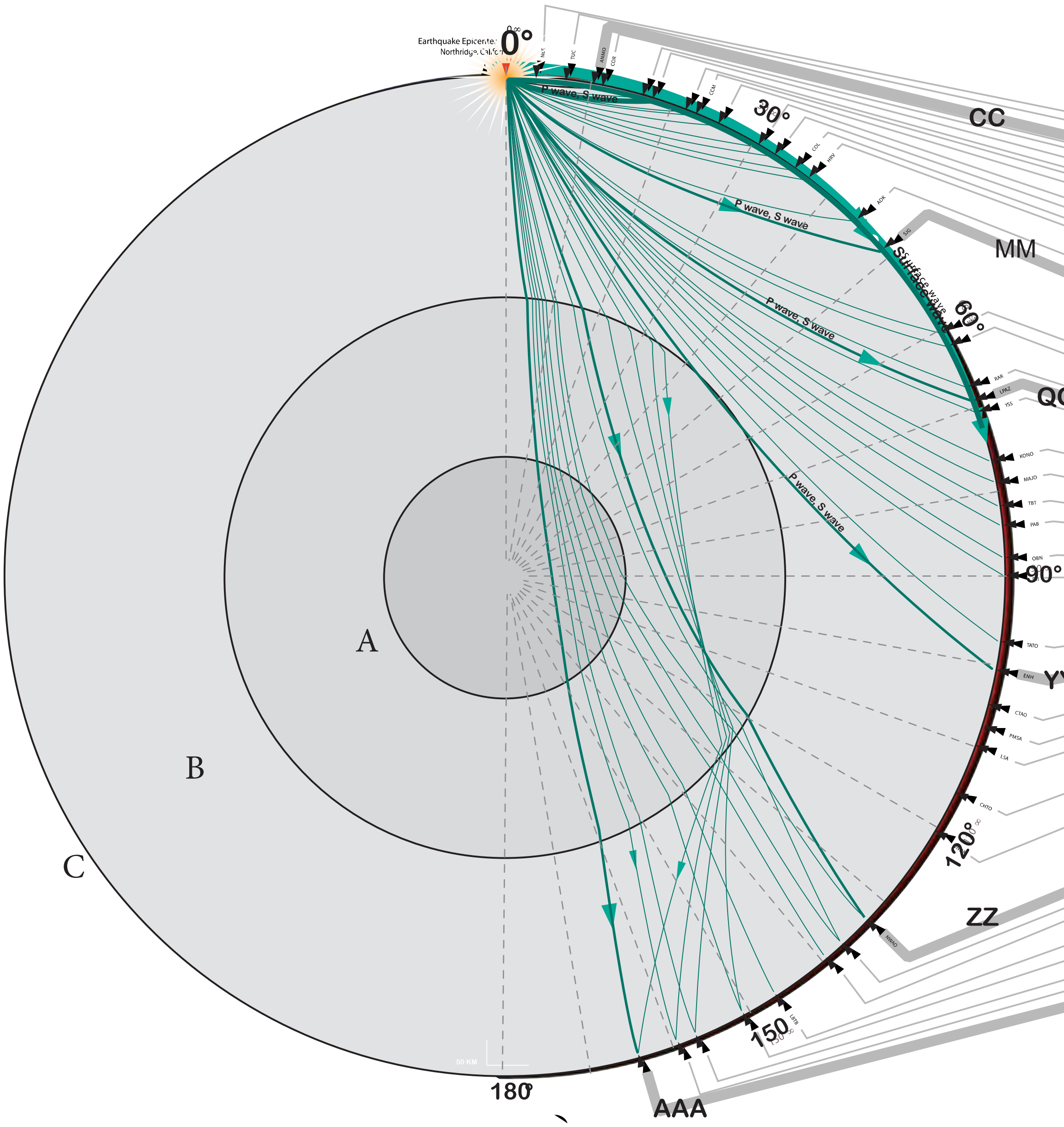

Figure 6. *The basic structure of Earth's interior as inferred from studies of the energy released by earthquakes, which travel through Earth as seismic waves.This energy is reflected and refracted at boundaries that separate regions of different materials. Shown here are the paths for seismic waves including from the 1994 Northridge earthquake that were recorded at seismic stations around the world. Seismic station locations are marked as triangles; original station codes replaced with select stations (**CC**, etc) from seismograms on next page.*

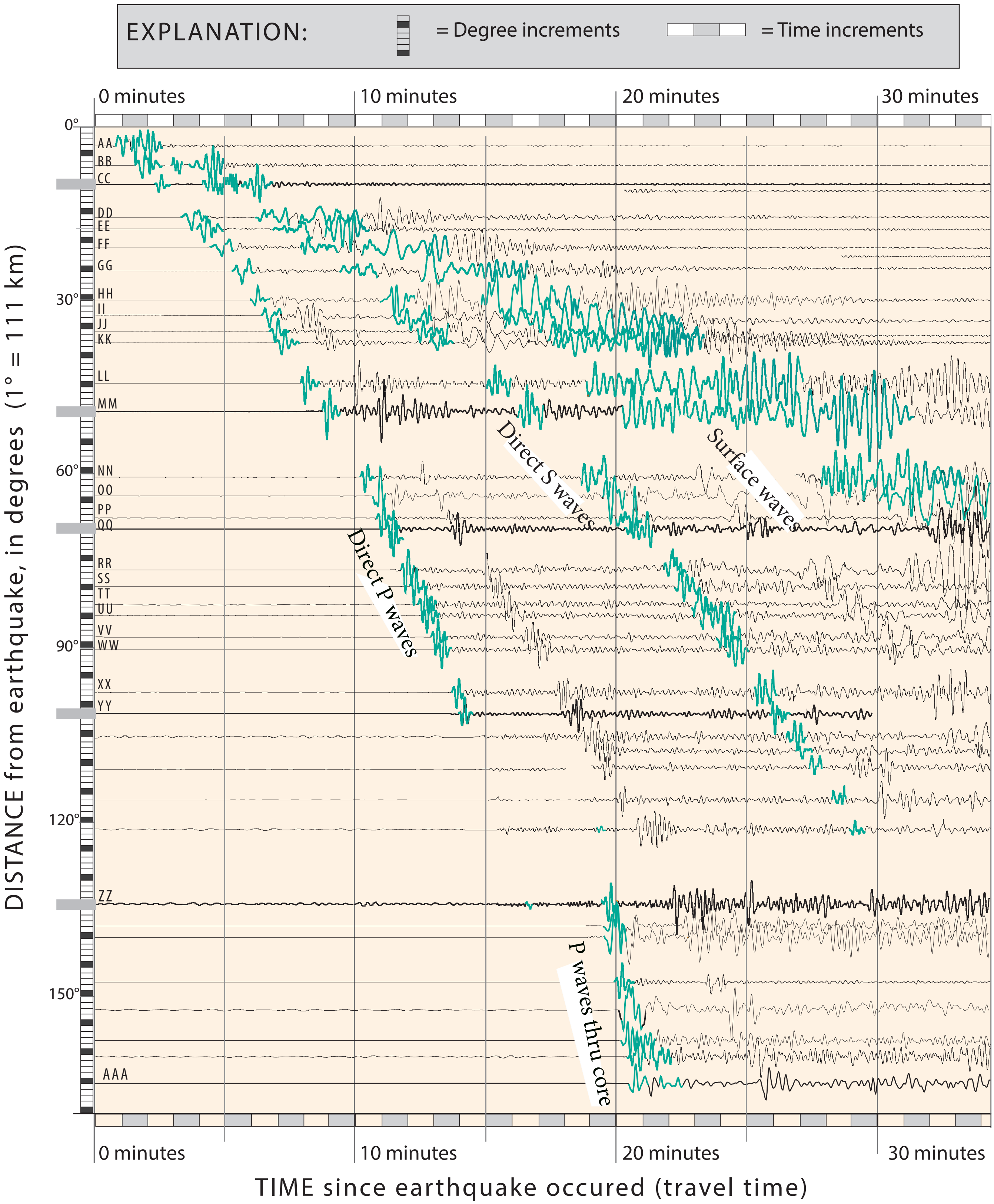

Figure 7. *Time Vs. Distance graph. Seismograms, running from left to right in time, show the arrival of seismic waves from the 1994 Northridge earthquake to stations in Figure 6. The traces are the actual ground motion recorded at the seismic stations. The direct ray paths for P-, S- and surface waves are shown in green. Seismologists compare the arrival times and amplitudes of seismic waves from many stations to determine seismic velocities and hence the structure and composition of Earth's deep interior. (Simplified from "Exploring the Earth Using Seismology" available from www.iris.edu/hq/inclass/poster/3)*

Part V—

In **Part IV**, you *should* have used the seismic waves from the 1994 Northridge earthquake (Figure 6) to establish that Earth is essentially solid from the top of Earth's crust to the base of the mantle, about 2900km below the surface. In this next section we will examine this outermost layer in more detail. While this region is solid, all solid materials are not all alike. That is, some solids are harder or softer than others, and some deform more easily than others. Take, for example, modeling clay and glass. Both materials are solids, but it is much easier to deform the clay than glass. If, however, you carefully applied a force to the glass over a very long period of time, it would eventually deform without breaking. One of the ways that geologists measure how easily a substance can deform or flow is by determining its viscosity. **Viscosity** is formally defined as the resistance of a material to flow**.** Figure 8 illustrates the viscosity of some materials with which you are probably familiar.

Current Plate Tectonics Theory suggests that the outer shell of Earth consists of a high-viscosity layer of rock called the lithosphere. This lithosphere is separated into several major and numerous minor tectonic plates that are in slow, but continuous motion. Beneath the lithosphere is a layer of rock with a lower viscosity called the asthenosphere.

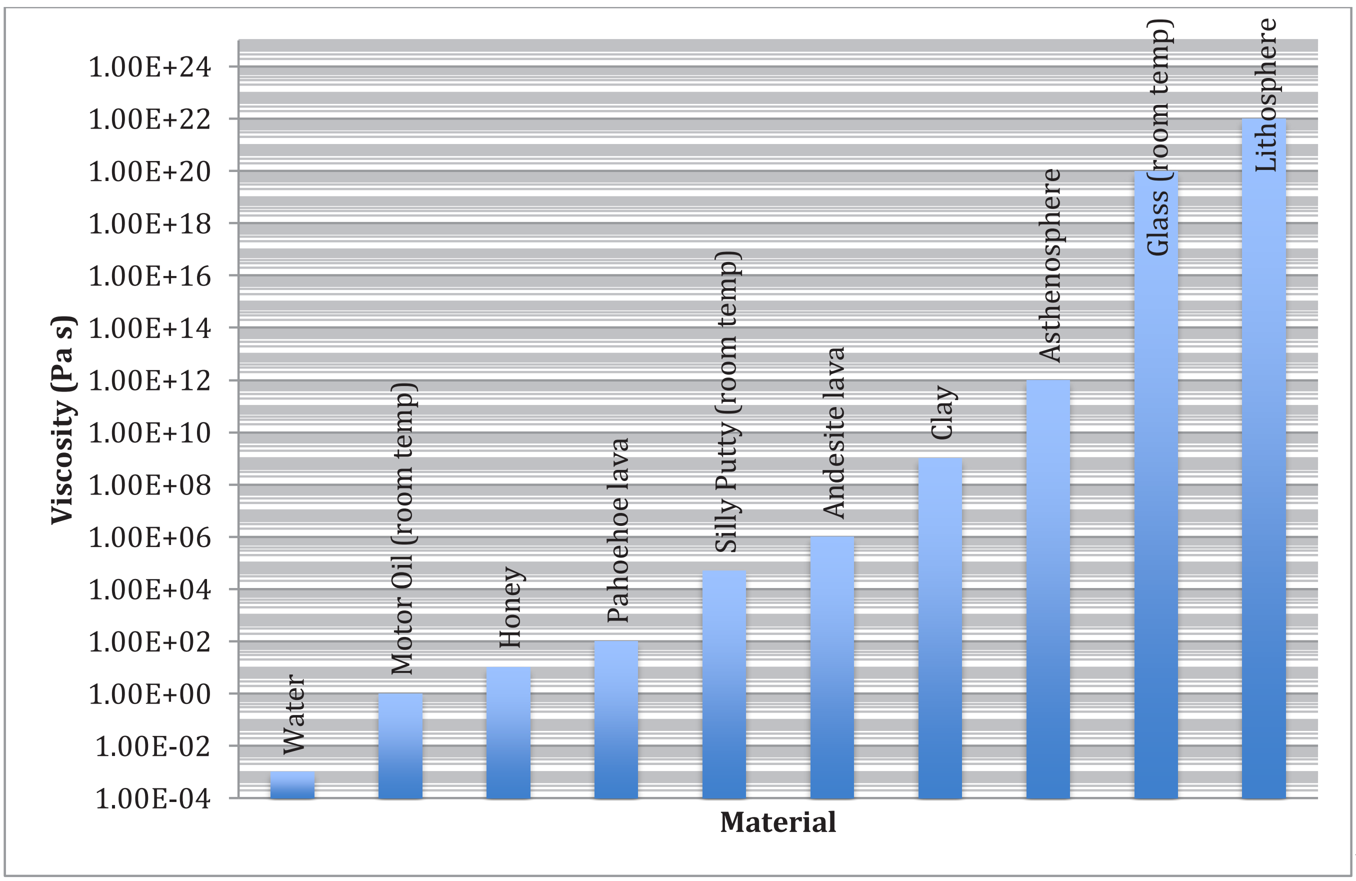

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Figure 8: *The viscosity of both common and less-uncommon materials. The unit for viscosity is Pascal-seconds (Pa-s), which is a measure of the material's resistance to flow. In this figure, viscosity units are written in scientific notation where 1.00E+2 is equal to 100, 1.00E-3 is equal to .001, and so on.*

1. Which of the following statements best describes how the asthenosphere relates to lava and glass in its resistance to flow?
    a. The asthenosphere is more similar to lava than glass in its resistance to flow.
    b. The asthenosphere is equally similar to both lava and glass in its resistance to flow.
    c. The asthenosphere is more similar to glass than lava in its resistance to flow.

2. Which of the following correctly compares the viscosity between the lithosphere and the asthenosphere?
    a. The asthenosphere is more viscous, and therefore more fluid-like than the lithosphere.
    b. The lithosphere is more viscous, and therefore more fluid-like than the asthenosphere.
    c. The asthenosphere is more viscous, and therefore less fluid-like than the lithosphere.
    d. The lithosphere is more viscous, and therefore less fluid-like than the asthenosphere.

3. Draw and describe how you might use a glass block and Silly Putty to model the interaction of Earth's layers to another student.

5. For a reality check, is the asthenosphere more similar to Silly Putty or to glass in how resistive it is to flow?

Part VI— Examining the lithosphere/asthenosphere boundary

In addition to using seismic waves to find where core-mantle boundary inside Earth, geophysicists can also use seismic waves to identify other boundaries within the solid Earth. To do so, geophysicists produce tomographic images of Earth's interior through a process that is similar to a CT scan that you might get at a hospital for your body. CT scan machines shoot X-rays through a patient's body in all directions. Instead of making just one two-dimensional (2D) image, CT scans enable three-dimensional (3D) imaging which show the patient's internal structures from different directions. Analogous to X-rays, geophysicists record P- and S–waves from earthquakes to remotely probe Earth's interior. S-waves are a particularly excellent tool for finding changes in viscosity because they are more sensitive to changes in the physical state of Earth's interior, as we learned in **Part V**.

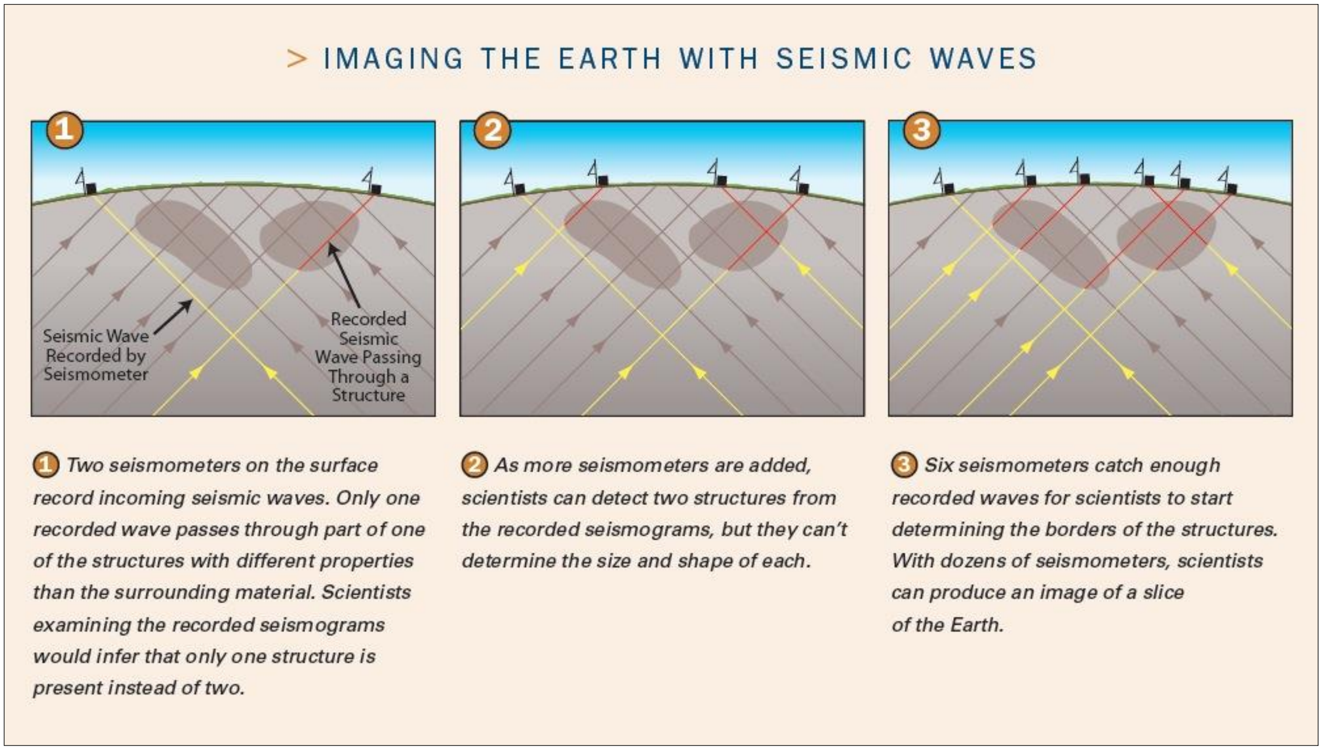


Figure 9. *Constructing tomographic images of Earth's interior.*

As illustrated in Figure 9, geophysicists use the distance the S-wave traveled to the seismometer and the time it took to get there. From this, scientists can calculate the average speed of the S-waves. They then map out large regions where the seismic waves traveled slower or faster than average. The speed of the waves depends on the type of material through which they travel. S-waves travel more slowly in lower viscosity materials and faster in higher viscosity materials. Looking at the changes in S-wave velocities, geophysicists can identify the lithosphere-asthenosphere boundary and measure the depth to it.

Frequently, geophysicists use cool colors (blue and black) to show areas inside Earth where seismic waves travel more quickly, and warm colors (red and orange) to show areas inside Earth where seismic waves travel more slowly. Figure 10 shows a vertical slice of the Earth beneath North America where a dense network of seismic stations was used to image Earth's interior. The blue/black colors illustrate areas inside Earth where S-waves travel faster than average while red colors illustrate areas where S-waves travel slower.

1. Which of the following materials would you expect and S-waves to propagate faster in?
   a. Silly putty
   b. Asthenosphere
   c. Motor oil
   d. Lithosphere

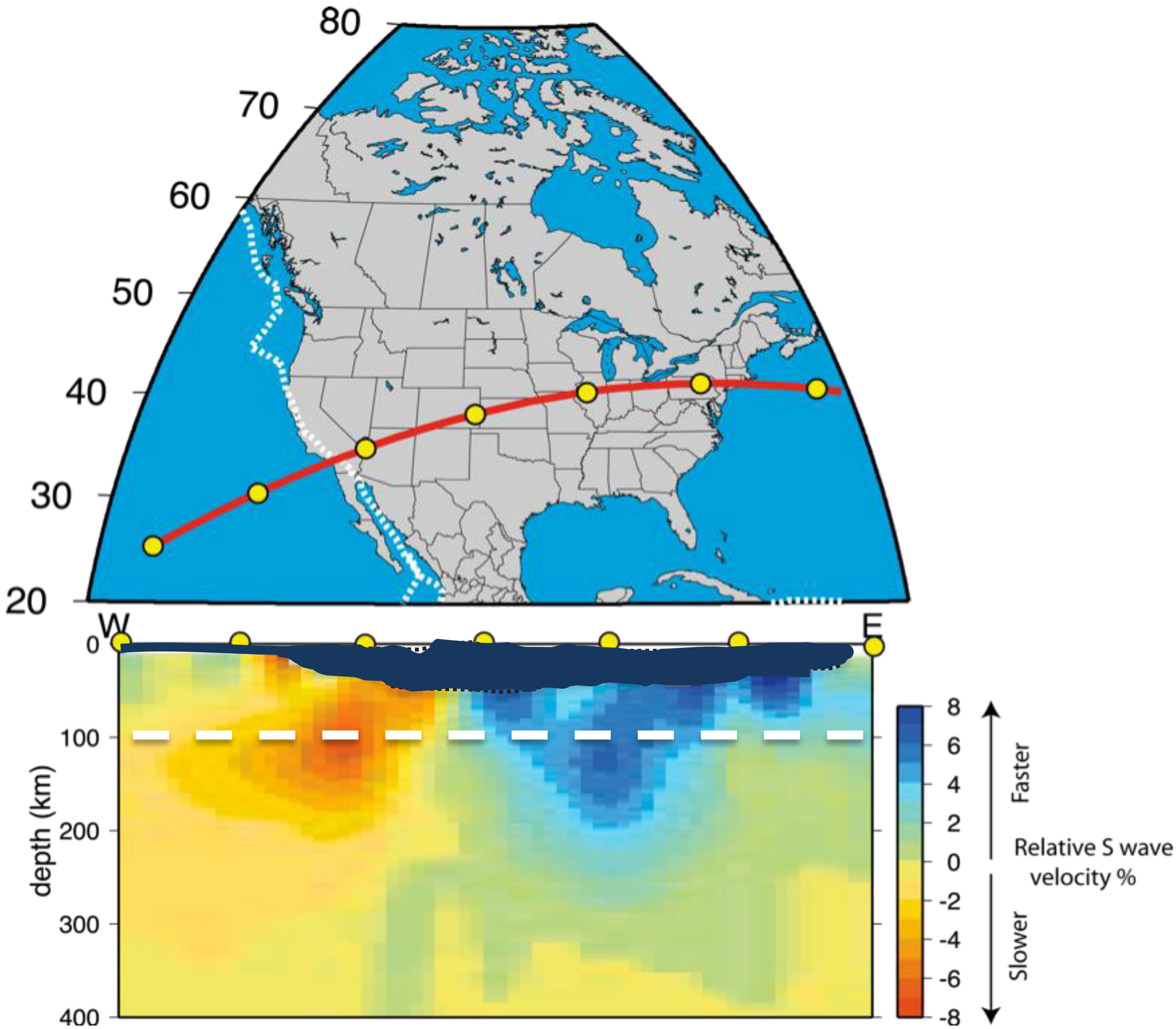


Figure 10. *A slice through an S-wave tomographic model of Earth beneath the United States. Modified from Nettles and Dziewonski, 2008.*

The dashed white line at 100km of depth is a hypothetical boundary between the lithosphere and asthenosphere. If this line truly separated these two layers, we would see only black and blue colors above the line and yellow and red colors below the line.

2. Since the white dashed line does not appear to do a good job accurately separating the lithosphere from the asthenosphere, which of the following statements best describes the lithosphere-asthenosphere boundary in this slice through North America?
   a. The lithosphere-asthenosphere boundary is about 150km deep in nearly all places.
   b. The lithosphere-asthenosphere boundary is about 50km deep in some places and shallower than 10km in other places.
   c. The lithosphere-asthenosphere boundary is less than 100km deep beneath the ocean and deeper than 150km beneath the continent.
   d. The lithosphere-asthenosphere boundary is about 50km deep in nearly all places.

3. How easy is it to decide where the lithosphere-asthenosphere boundary is?
   a. It is easy because you can use a single value to follow across the bottom of the lithosphere
   b. It is difficult because the speeds change abruptly from fast to slow.
   c. It is difficult because the speeds change from fast to slow gradually over a wide range of depths.

4. Refer back to the glass block and silly putty model you described previously. How might this simple model be different from the observed data displayed in Figure 10 above?

Next, examine the following images showing S-wave velocities at various depth slices beneath North America.

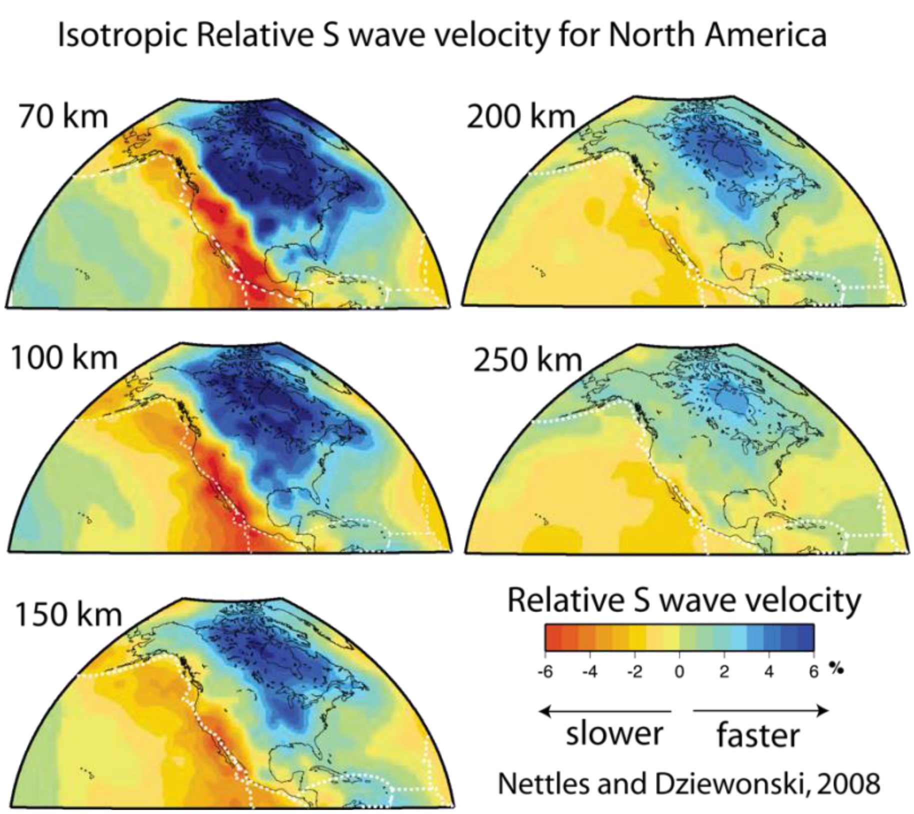


***Figure 11**. S-wave velocity structure beneath North America sliced through the Earth at 70 km, 100 km, 150 km, 200 km, and 250 km depths through the Earth. Plate boundaries around North America are plotted as white dashed lines in on the tomographic slices*

5. If S waves travel faster through high viscosity material, and slowly through lower viscosity material, where in North America do you find the thickest lithosphere?
   a. Northeastern North America
   b. Southeastern North America
   c. Southwestern North America
   d. Northwestern North America

6. Where in North America is the thinnest lithosphere?
   a. Northeastern North America
   b. Southeastern North America
   c. Southwestern North America
   d. Northwestern North America

7. Plate boundaries are shown as white dashed lines on Figure 11. How does lithospheric thickness correlate with the location of the active plate boundaries? Why do you think this might be the case?

8. Based on your experience with this lab, A) summarize the role seismic waves play in our understanding of Earth's interior. B) In what ways have your ideas remained the same, and/or changed from your answers to questions 1 and 2 of **Part I**?

Imaging Earth's interior with seismic waves

Part I

1. What is inside Earth? In the space below, sketch what you believe the interior structure of Earth to be like.

   Accept all responses. Most students will draw some variation of a series of circles within a circle. While some may include accurate labels for the layers, it is very common for students to have a poor sense of the scale of Earth's layered interior even if they are aware that Earth has one.

2. Describe any evidence, based on personal experience, which *YOU* have for the information you sketched above?

   Accept all responses.

Part II

You probably didn't have much evidence about Earth's interior beyond what textbooks, TV, or a previous instructor described. *So how do we really know what is inside Earth?* Let's investigate!

Based on your own direct experience (e.g. digging a hole, visiting a cave or quarry, driving past a road cut) you are probably aware that below the soil is a layer of rock. Let's begin our investigation into Earth's interior by assuming that the simplest solution is correct . Thus, we will start with the hypothesis that Earth is made up entirely of this same rock material, which extends all the way to the center of Earth. This homogeneous Earth model is illustrated in Figure 1 (right). Since the model is comprised of the same material throughout, we can assume that seismic waves will travel

a) at a constant velocity (in this case, we will assume the P-waves travel at a velocity of 11km/s in our model), and
b) in straight lines.

We can use this model and these assumptions to make some predictions and calculations that test the accuracy of our hypothesis.

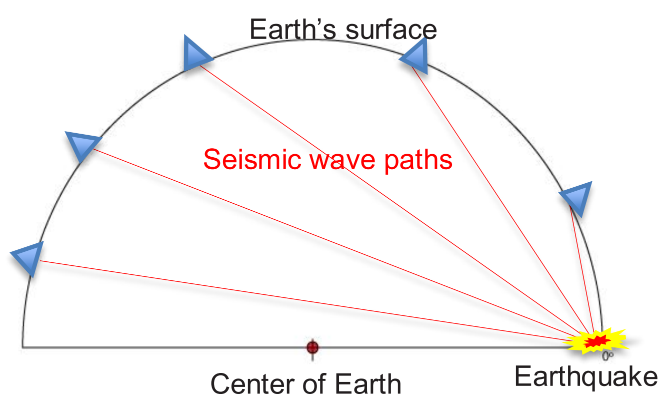


Figure 1. *A scale model of a cross section of Earth comprised entirely of rock. Triangles represent seismic stations at the surface and the red lines indicate example paths that seismic energy travels from the earthquake to each station.*

For example, we can use the model to predict how long it *should* take seismic waves to travel from an earthquake, through Earth, to various points on Earth's surface. This can be accomplished using the basic equation

$$T = D/S$$

(T) is the time it takes for a seismic wave to travel a certain distance, (S) is the speed the waves travel and (D) is the distance between the earthquake and the seismic station.

As previously mentioned we are assuming that the speed (S) of P-waves is 11km/s. Since our model is a physical scale model, we can measure the length of the seismic wave paths from the earthquake's location to various points on the model's surface. Model measurements can be scaled up to real Earth distances. This has been done for you and the predicted arrival times for our homogeneous Earth model are illustrated in Figure 2 below.

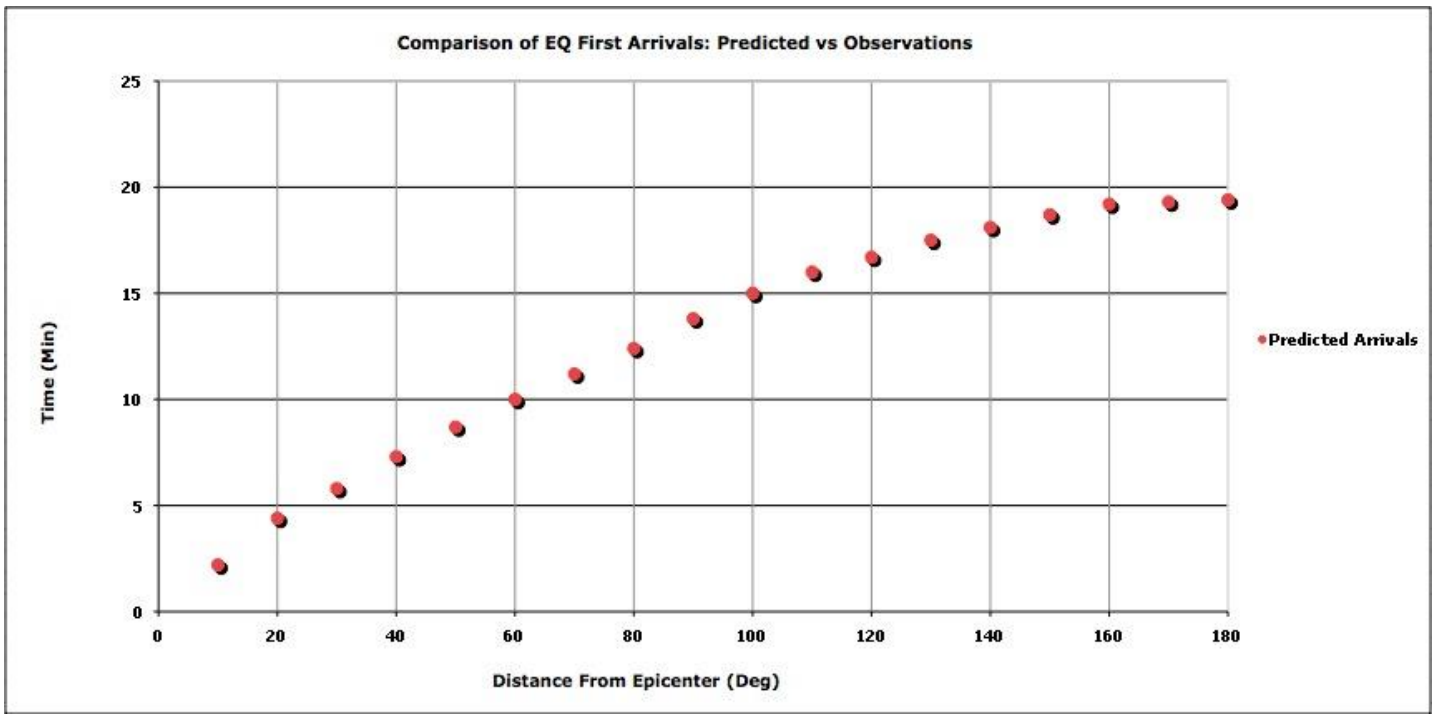


***Figure 2**: Predicted arrival times for our homogeneous Earth model*

NOTE: The distances displayed on the X-axis in Figure 2 above and on the seismic record section provided with this lab use angular degrees with Earth's center as the reference point. This is known as the "geocentric angle." Each angular degree = ~111km on Earth's surface. The angular distance between an earthquake and a seismic station is referred to as the "epicentral distance."

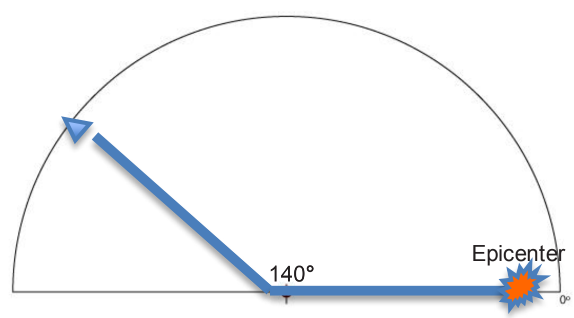


***Figure 3:** Measuring distances using geocentric angle.*

Next we need to compare the predictions derived from the model to observations we make from the real Earth. Modern seismographic networks record how the ground moves in response to earthquakes at points all over the world. These recordings of ground motion, called seismograms, are freely available via the Internet. Your task is to use a collection of seismograms from a single earthquake, presented together as a record section, to determine how long it *actually* takes for P-waves to travel through Earth. Your findings form the observed Earth data will be compared to the observed data in Figure 2. If your findings match and follow similar trends as the arrivals predicted by our model, then our hypothesis that the Earth must be homogeneous rock throughout should be correct. However, if your observations do not match the predicted arrival times, than we can reasonably assume the Earth is not homogenous and does have some structure to it.

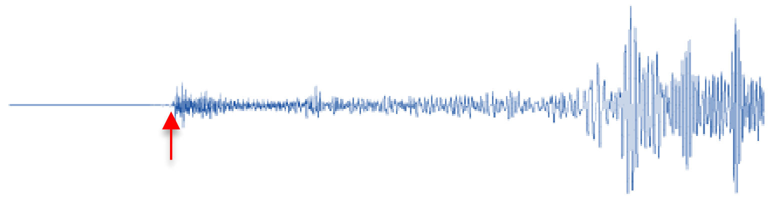


Figure 4. *The arrival of seismic energy is indicated on the seismogram by a change from the background or previous signal. In this example, the arrow denotes the arrival of the P-wave.*

1. Carefully analyze the collection of seismograms (called a record section). Identify the first arrival of seismic energy (example in Figure 7) at the station and determine how long it took the seismic energy to travel to each station. Record this information in the data table below.

Table of P-wave arrival times from a single earthquake to worldwide seismic stations:

Station Distance (degrees)	Travel time (min)
Answers not filled in,	
as instructors may use	
a different record section	

Describe any difficulties you and your team had generating your data. Be sure to include any areas where error might have been introduced into your data set.

4. Plot your observed P-wave arrival times on Figure 2 above using triangles to indicate observed data.

5. Which of the following statements best describes the observed values you just plotted in Figure 2?
   a) A set of points that follow a straight line
   b) A set of points that follow a curved line with a smaller slope at larger distances
   c) ▶▶▶▶A set of points that follow a curved line with a jump where the values increase abruptly
   d) A set of points that follow a curved line with a larger slope at larger distances

5. Analyze these two data sets (predicted vs. observed travel times) and describe what you see in your data.

Answers will vary

6. Which of the following best describes the relationship between the observed values and predicted values in Figure 2?
   a) ▶▶▶▶The observed values are similar to the predicted values except for a large difference around 110 degrees.
   b) The observed values are only similar to the predicted values at large distances.
   c) The observed values do not appear similar to the predicted values at all.
   d) The observed values are similar to the predicted values at all distances.

7. What do the results of comparing the observed arrivals to the predicted arrivals imply about our hypothesis that Earth's interior is composed of homogenous rock?
   a) ▶▶▶▶The comparison implies Earth's interior is not homogeneous rock throughout.
   b) The comparison implies Earth's interior is homogeneous rock throughout.
   c) The comparison is unable to inform us about our hypothesis.

Briefly explain why you selected that response.

I selected this response because the observed values did not match the model/predicted data. Since they don't match, Option B can't be correct. Option C can't be correct because we *can* compare the two sets of data and draw conclusions from it.

8. Which of the following statement is the best hypothesis for explaining the observed values in the plot?
   a) Earth's interior changes abruptly at several different depths.
   b) Earth's interior is homogeneous throughout.
   c) Earth's interior is heterogeneous but changes gradually with depth.
   d) ▶▶▶▶Earth's interior is composed of homogeneous rock through some portions, but also changes abruptly at a particular depth.

Part III – Requires Full-Circle Earth Scale Model

1. As show in Figure 5, indicate the epicenter of the earthquake with a small circle at 0 degrees on Earth A (the right edge).

2. Examine your graph of the observed arrivals on Figure 2 to determine where there is an "interruption" or "unconformity" in the observed seismic waves arrivals compared to the modeled arrivals.

3. Measure a geocentric angle equal to the "interruption" you noted above to the northern hemisphere and make mark on Earth's surface (e.g. *108 degrees as shown in Figure 5, though your data will vary*). Use your ruler to connect the epicenter to the mark you just drew on Earth's surface.

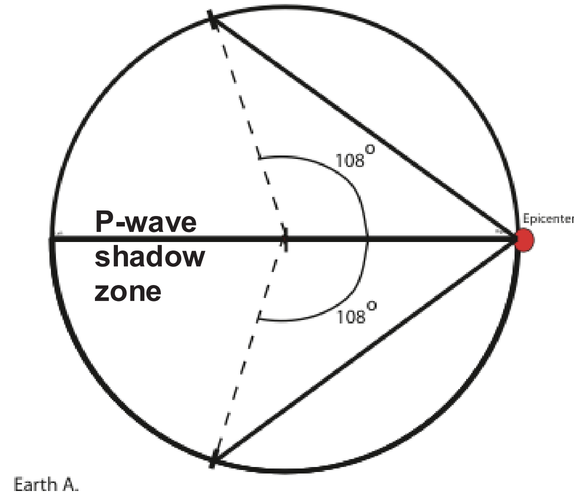


Figure 5*. Based on the observed seismic data you recorded the P-wave shadow zone can be modeled. Here, an example using 108 degrees is shown.*

4. Repeat this procedure but mark the southern hemisphere's surface.

5. Label the area inside the angles drawn as the P-wave shadow zone.

6. Answer the following questions:

   a. What sort of structure have we determined so far?
   We have determined a region where the waves arrive late. A variety of shapes/structures could fit in the space and cause the delayed arrivals.

   b. How has the seismic data helped us determine Earth's interior structure?
   We can see anomalies in the wave arrivals (e.g. slower than expected in this case).

   c. Examine the record section again for this area and consider how this "shadow zone" might be like a person's shadow on the ground.
   Shadow regions do not receive any direct light. However the shadow zone does receive light that refracts around the "blocking" object and reflects off other objects. Similarly seismic shadow zones do not receive any direct arrivals. Rather, the seismic energy that arrives there have refracted around objects or reflect off "surfaces" thus changing their travel paths; this is a process that affects their arrival time.

   d. How might more data help us "resolve" Earth's structure?

   Additional quakes distributed around Earth could help us further define the structure's shape by providing more details for their travel paths. For example, if all quakes have a similar delayed arrival starting around 110 degrees away from the earthquake, then the structure is likely to be spherical

7. Use scissors to cut out the wedge-shaped P-wave shadow zone. This represents the area that does not receive "direct" P-waves from an earthquake.

8. Next model the occurrence of additional earthquakes by placing the point of the wedge-shaped cut-out on the surface of Earth B while aligning the curved arc of the wedge with the opposite side of Earth B (*the point on the cone indicates the location of another earthquake epicenter*).

9. Trace the straight edges of the wedge to indicate the area where direct P-waves from the earthquake do not arrive.

10. Repeat this procedure for a number of earthquakes, each at a different location. Be sure to trace out the P wave shadow zone each time.

11. Answer the following questions:
    a. As additional earthquake data is added, what shape is being defined in the interior of Earth Model B?

    Additional data is helping to define a circular object.

    b. Describe what you think this new inner circle represents?

    This inner circle represents Earth's core.

    c. Describe what has allowed our model for Earth's interior to improve since 6d above.

    Additional data from more earthquakes has allows us to improve our image of Earth's interior.

12. Calculate the radius of the structure that was revealed by the seismic data. The scale of Earth model B is 1:127,420,000 and there are 100,000cm in 1km.

    Answers will vary depending on the data students use and the construction of their scale model. The example data we used (see figure 5 above) generated a core with a radius of ~2.75cm on the model or (2.57cm x 127,420,000cm) / 100,000cm = 3504km for Earth

Part IV

As you have seen, seismologists can explore Earth's interior by analyzing seismic wave arrivals resulting from large earthquakes. Figure 6 shows the basic structure of Earth's interior, while the connected Figure 7 shows a record section (a collection of seismograms from the same earthquake recorded at different distances from the quake). This example is from the 1994 Northridge earthquake.

1. Use the Internet to help you label the layers of Earth's interior A, B, and C as shown on Figure 6.

2. How well does the radius you calculated in **Part III** compare to the accepted values you found? Why might these differ?
   An accepted radius of Earth's core is 3,486km (http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html). Students' calculated radius will vary slightly depending on the data used and students' construction of their scale model. However, it is possible to get very close to the accepted value. For example, we previously determined that our example data indicated a core with a radius of 3,504km.

   Absolute Error = | accepted – calculated|

   OR |3,486km – 3,504km| = 18km   % Error = Absolute Error/accepted x 100%

   OR 18km/ 3,486km = .005 x 100% = 0.5% Error

   Thus, our value with within .0.5% of the accepted value

3. Highlight the P-wave arrivals on the seismograms on Figure 7. Comparing these to Figure 2. which of the following statements is most accurate?
   a. The arrival times in Figure 7 follow the same overall pattern as the hypothetical values.
   b. ▶▶▶▶The arrival times in Figure 7 follow the same overall pattern as the observed values.

4. In Figure 7, over what distances do the P-waves arrive "later" than the shape of the rest of the curve would predict?
   a. 10-40 degrees
   b. 80-100 degrees
   c. 110-140 degrees
   d. ▶▶▶▶140-160 degrees

5. Examine Figure 7 again. Which of the following best describes what happens to the S-wave arrivals over the same distances you identified in #4 above?
   a. No S-waves arrive at those distances.
   b. The S-waves also arrive later than the rest of the curve would predict.
   c. ▶▶▶▶The S-waves arrive when the rest of the curve would predict.

6. Using what you learned about P- and S- wave propagation at the beginning of class, construct an argument, or an evidence-based statement, describing the state of matter you believe Earth's mantle and core are made of.

   Claim: Based on the seismic wave observations, I conclude that the mantle is solid and the core is liquid.
   Evidence: S-waves and P-waves propagate through solids. Using this, we can infer that the mantle is solid because both S- and P-waves are recorded at distances where the travel path of the energy is only within the mantle. At distances such as 140 and 160 degrees, where seismic energy travels through the mantle then into the outer core and back out into the mantle, only P waves (no S-waves) are recorded. Since we know that S-waves can't travel through liquids, but that P-waves can travel through liquid, we can conclude that these waves encounter a core made of liquid.

   Note: While not explicitly included here, the core is actually comprised of two layers; a liquid outer core that students identified above, and a mostly solid inner core. The presence of this mostly solid interior was initially detected (in 1936 by Danish seismologist Inge Lehmann) from observations of seismic waves reflecting off the boundary between the liquid exterior and the mostly solid interior.

INSTRUCTOR ANSWER KEY

A. Core (or Inner and Outer Core)

B. Mantle

C. Crust

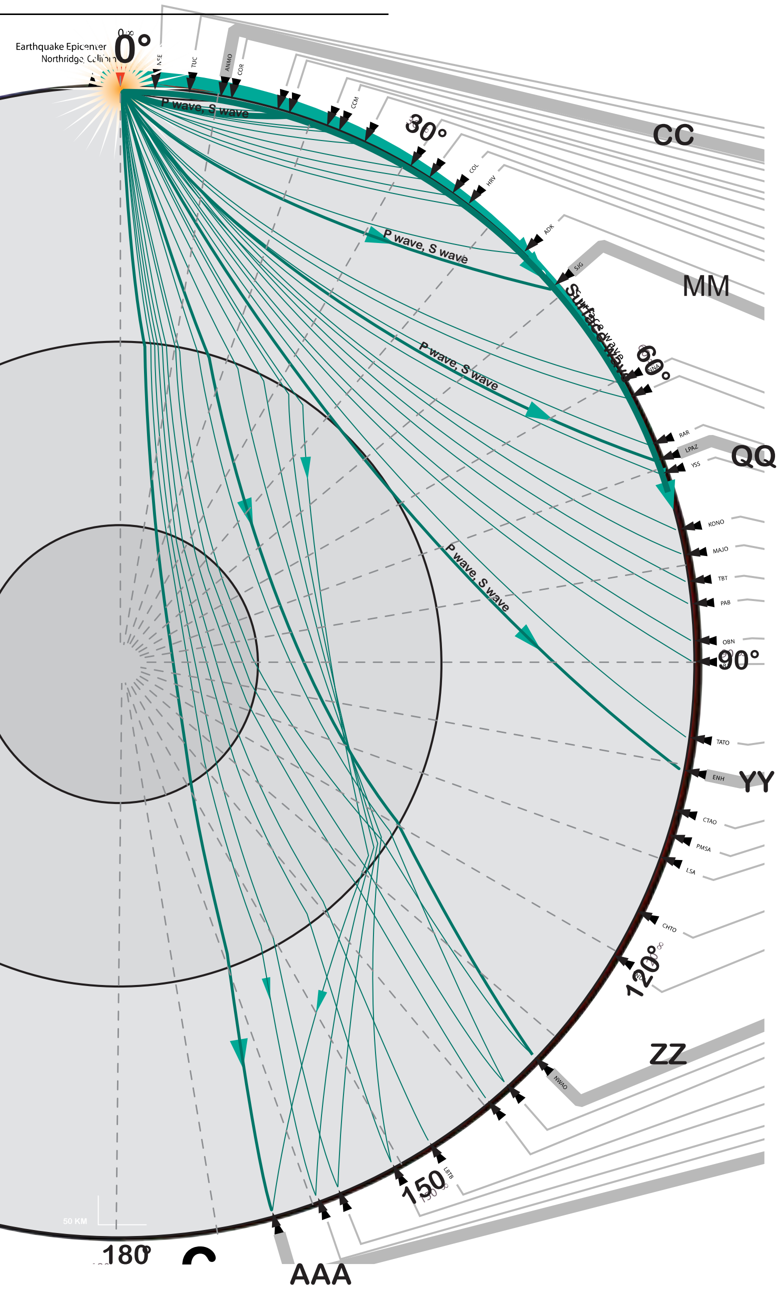


Figure 6. *The basic structure of Earth's interior as inferred from studies of the energy released by earthquakes, which travel through Earth as seismic waves.This energy is reflected and refracted at boundaries that separate regions of different materials. Shown here are the paths for seismic waves including from the 1994 Northridge earthquake that were recorded at seismic stations around the world. Seismic station locations are marked as triangles; original station codes replaced with select stations (**CC**, etc) from seismograms on next page.*

INSTRUCTOR ANSWER KEY

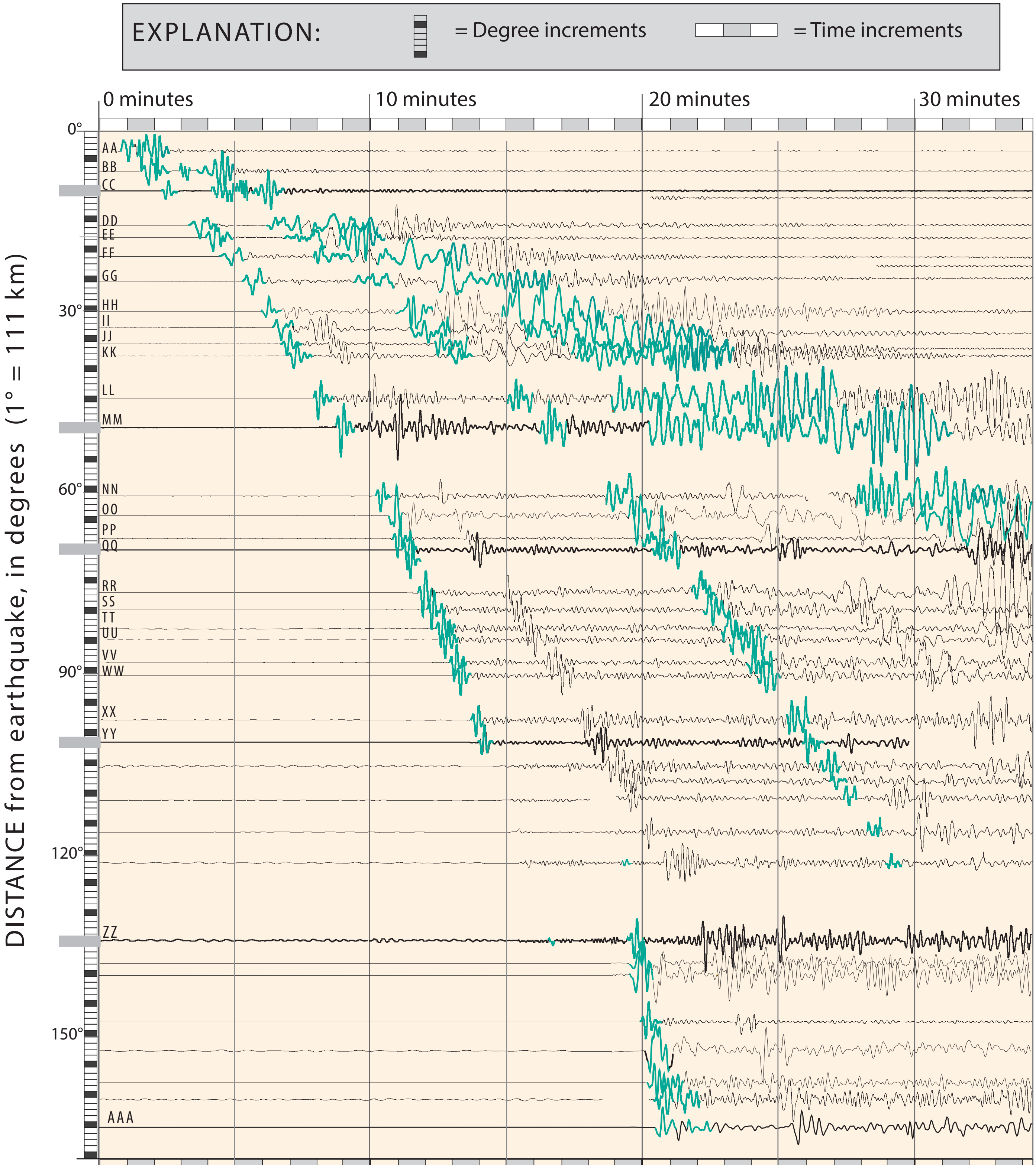
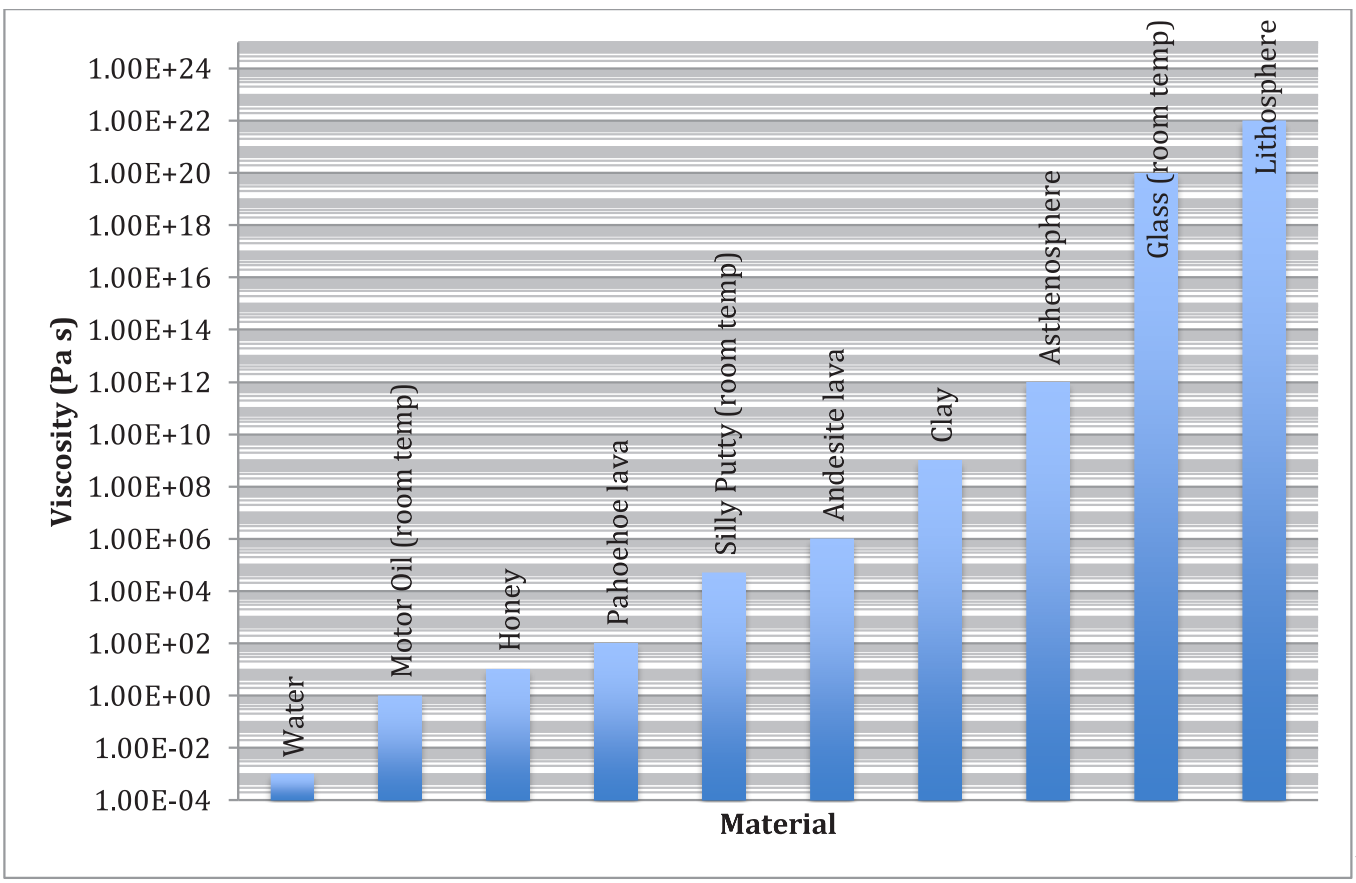


Figure 7. *Time Vs. Distance graph. Seismograms, running from left to right in time, show the arrival of seismic waves from the 1994 Northridge earthquake to stations in Figure 6. The traces are the actual ground motion recorded at the seismic stations. The direct ray paths for P-, S- and surface waves are shown in green. Seismologists compare the arrival times and amplitudes of seismic waves from many stations to determine seismic velocities and hence the structure and composition of Earth's deep interior. (Simplified from "Exploring the Earth Using Seismology" available from www.iris.edu/hq/inclass/poster/3)*

Part V— *WAIT, Part III never used the Northridge EQ!*

In **Part IV**, you *should* have used the seismic waves from the 1994 Northridge earthquake (Figure 6) to establish that Earth is essentially solid from the top of Earth's crust to the base of the mantle, about 2900km below the surface. In this next section we will examine this outermost layer in more detail. While this region is solid, all solid materials are not all alike. That is, some solids are harder or softer than others, and some deform more easily than others. Take, for example, modeling clay and glass. Both materials are solids, but it is much easier to deform the clay than glass. If, however, you carefully applied a force to the glass over a very long period of time, it would eventually deform without breaking. One of the ways that geologists measure how easily a substance can deform or flow is by determining its viscosity. **Viscosity** is formally defined as the resistance of a material to flow**.** Figure 8 illustrates the viscosity of some materials with which you are probably familiar.

Current Plate Tectonics Theory suggests that the outer shell of Earth consists of a high-viscosity layer of rock called the lithosphere. This lithosphere is separated into several major and numerous minor tectonic plates that are in slow, but continuous motion. Beneath the lithosphere is a layer of rock with a lower viscosity called the asthenosphere.



)

Figure 8: *The viscosity of both common and less-uncommon materials. The unit for viscosity is Pascal-seconds (Pa-s), which is a measure of the material's resistance to flow. In this figure, viscosity units are written in scientific notation where 1.00E+2 is equal to 100, 1.00E-3 is equal to .001, and so on.*

INSTRUCTOR ANSWER KEY

1. Which of the following statements best describes how the asthenosphere relates to lava and glass in its resistance to flow?

   ▶▶▶▶a. The asthenosphere is more similar to lava than glass in its resistance to flow.

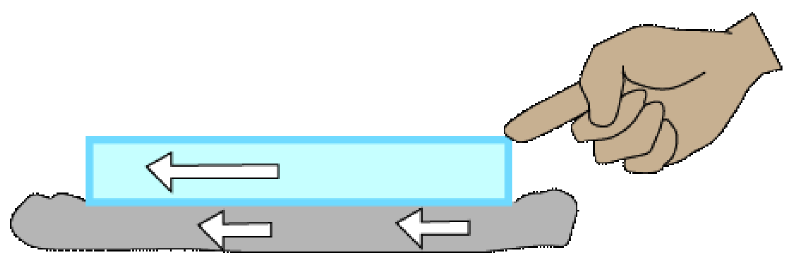
   b. The asthenosphere is equally similar to both lava and glass in its resistance to flow.
   c. The asethenosphere is more similar to glass than lava in its resistance to flow.

2. Which of the following correctly compares the viscosity between the lithosphere and the asthenosphere?
   a. The asthenosphere is more viscous, and therefore more fluid-like than the lithosphere.
   b. The lithosphere is more viscous, and therefore more fluid-like than the asthenosphere.
   c. The asthenosphere is more viscous, and therefore less fluid-like than the lithosphere.

   ▶▶▶▶d. The lithosphere is more viscous, and therefore less fluid-like than the asthenosphere.

3. Draw and describe how you might use a glass block and Silly Putty to model the interaction of Earth's layers to another student.

   The more viscous glass plate can be stacked on top of the less viscous silly putty. The Silly Putty will flow and the glass plate will move along in the direction of flow.



4. For a reality check, is the asthenosphere more similar to Silly Putty or to glass in how resistive it is to flow?

Part VI

In addition to using seismic waves to find where core-mantle boundary inside Earth, geophysicists can also use seismic waves to identify other boundaries within the solid Earth. To do so, geophysicists produce tomographic images of Earth's interior through a process that is similar to a CT scan that you might get at a hospital for your body. CT scan machines shoot X-rays through a patient's body in all directions. Instead of making just one two-dimensional (2D) image, CT scans enable three-dimensional (3D) imaging which show the patient's internal structures from different directions. Analogous to X-rays, geophysicists record P- and S–waves from earthquakes to remotely probe Earth's interior. S-waves are a particularly excellent tool for finding changes in viscosity because they are more sensitive to changes in the physical state of Earth's interior, as we learned in **Part V**.

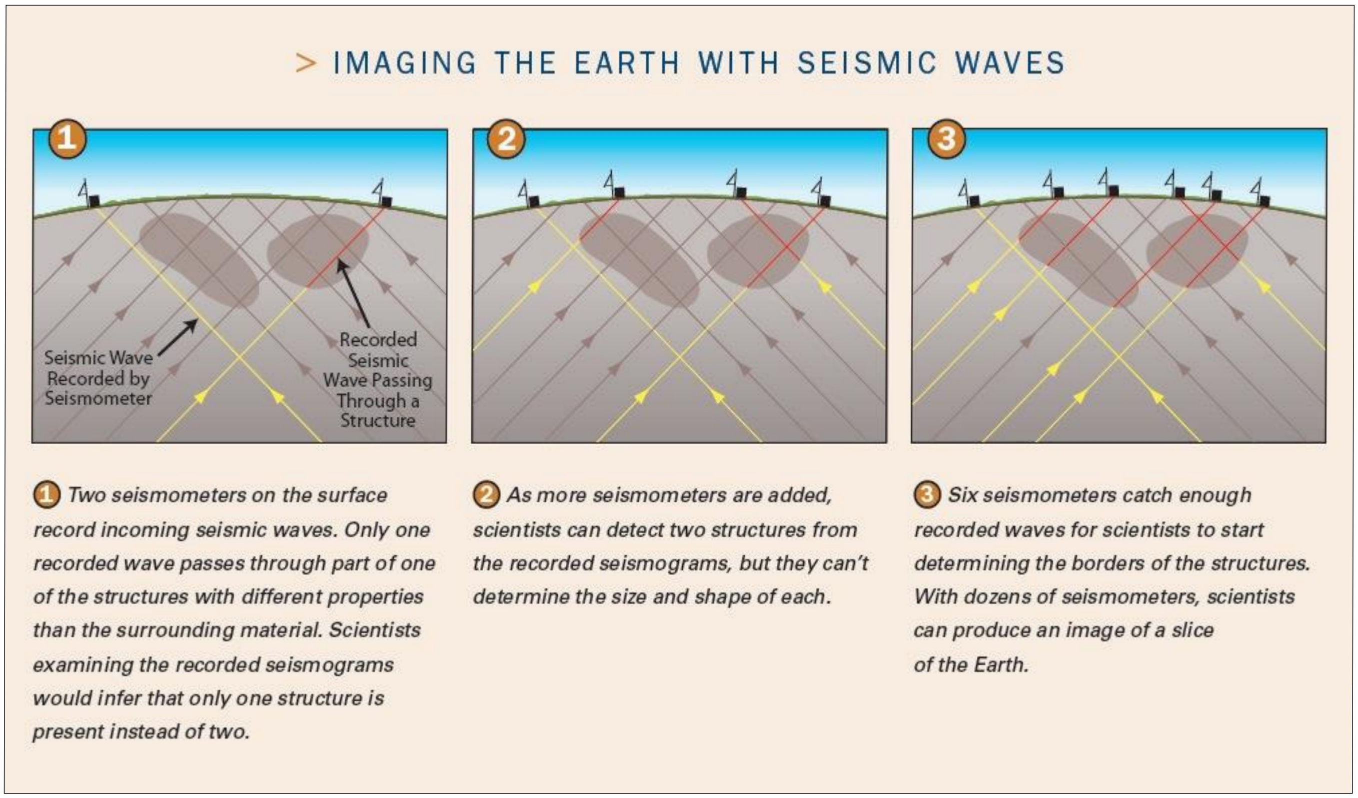


Figure 9. *Constructing tomographic images of Earth's interior.*

As illustrated in Figure 9, geophysicists use the distance the S-wave traveled to the seismometer and the time it took to get there. From this, scientists can calculate the average speed of the S-waves. They then map out large regions where the seismic waves traveled slower or faster than average. The speed of the waves depends on the type of material through which they travel. S-waves travel more slowly in lower viscosity materials and faster in higher viscosity materials. Looking at the changes in S-wave velocities, geophysicists can identify the lithosphere-asthenosphere boundary and measure the depth to it.

Frequently, geophysicists use cool colors (blue and black) to show areas inside Earth where seismic waves travel more quickly, and warm colors (red and orange) to show areas inside Earth where seismic waves travel more slowly. Figure 10 shows a vertical slice of the Earth beneath North America where a dense network of seismic stations was used to image Earth's interior. The blue/black colors illustrate areas inside Earth where S-waves travel faster than average while red colors illustrate areas where S-waves travel slower.

INSTRUCTOR ANSWER KEY

1. Which of the following materials would you expect and S-waves to propagate faster in?
   a. Silly putty
   b. Asthenosphere
   c. Motor oil
   ▶▶▶▶ d. Lithosphere

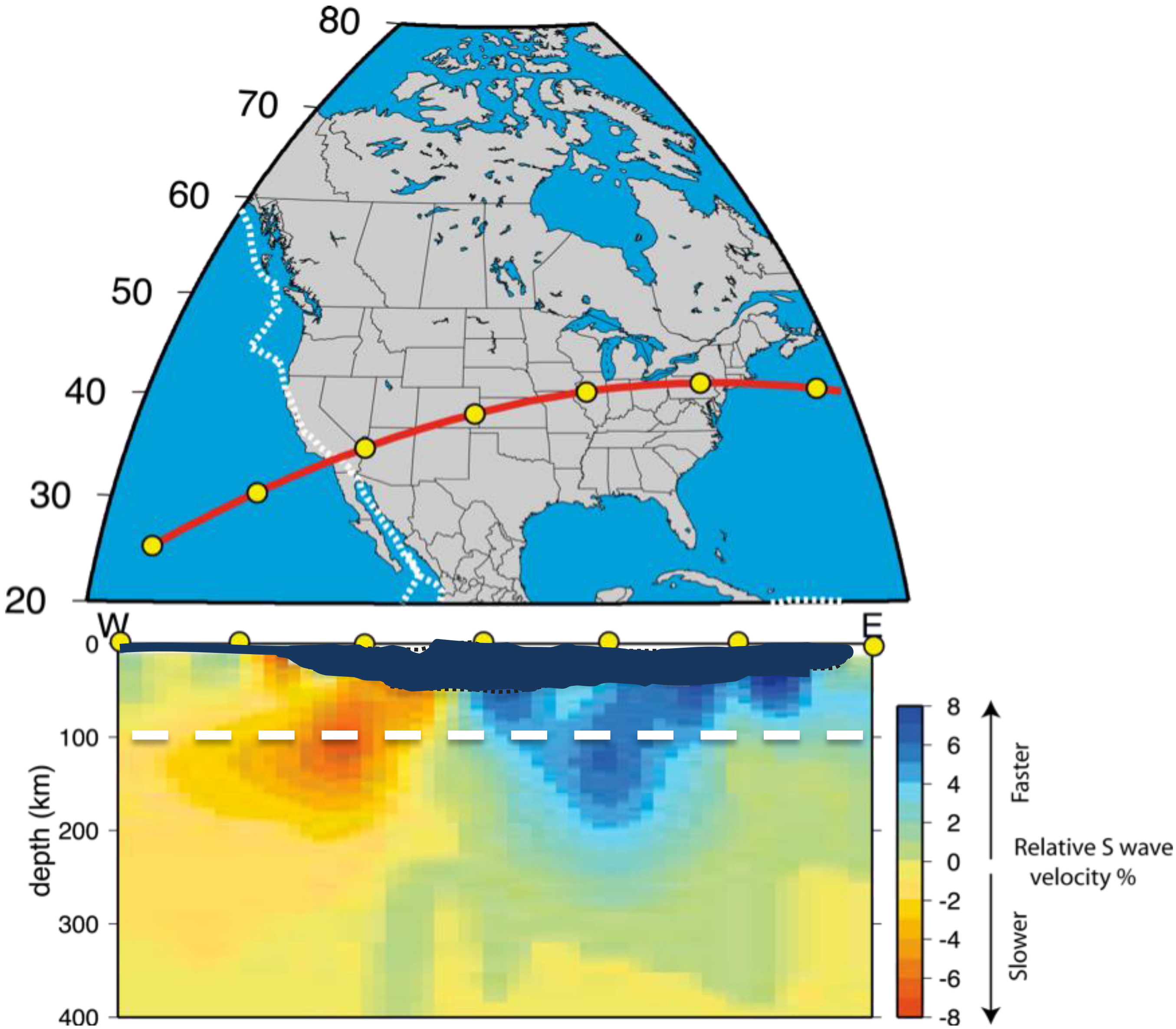


Figure 10. *A slice through an S-wave tomographic model of Earth beneath the United States. Modified from Nettles and Dziewonski, 2008.*

The dashed white line at 100km of depth is a hypothetical boundary between the lithosphere and asthenosphere. If this line truly separated these two layers, we would see only black and blue colors above the line and yellow and red colors below the line.

2. Since the white dashed line does not appear to do a good job accurately separating the lithosphere from the asthenosphere, which of the following statements best describes the lithosphere-asthenosphere boundary in this slice through North America?
   a. The lithosphere-asthenosphere boundary is about 150km deep in nearly all places.
   b. The lithosphere-asthenosphere boundary is about 50km deep in some places and shallower than 10km in other places.
   ▶▶▶▶c. The lithosphere-asthenosphere boundary is less than 100km deep beneath the ocean and deeper than 150km beneath the continent.
   d. The lithosphere-asthenosphere boundary is about 50km deep in nearly all places.

3. How easy is it to decide where the lithosphere-asthenosphere boundary is?
   a. It is easy because you can use a single value to follow across the bottom of the lithosphere
   b. It is difficult because the speeds change abruptly from fast to slow.
   ▶▶▶▶c. It is difficult because the speeds change from fast to slow gradually over a wide range of depths.

4. Refer back to the glass block and silly putty model you described previously. How might this simple model be different from the observed data displayed in Figure 10 above?

   In the glass block and silly putty model, the boundary was well defined which is unlike the tomographic model where the transition is much more gradual.

Next, examine the following images showing S-wave velocities at various depth slices beneath North America.

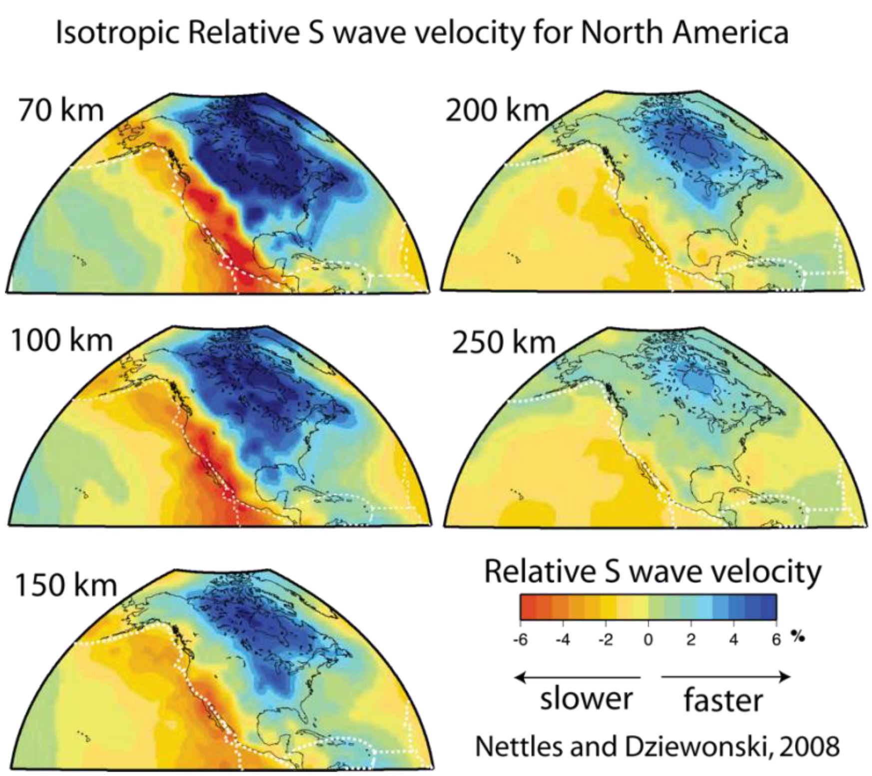


***Figure 11**. S-wave velocity structure beneath North America sliced through the Earth at 70 km, 100 km, 150 km, 200 km, and 250 km depths through the Earth. Plate boundaries around North America are plotted as white dashed lines in on the tomographic slices*

5. If S waves travel faster through high viscosity material, and slowly through lower viscosity material, where in North America do you find the thickest lithosphere?
   ▶▶▶▶a. Northeastern North America
   b. Southeastern North America
   c. Southwestern North America
   d. Northwestern North America

6. Where in North America is the thinnest lithosphere?
   a. Northeastern North America
   b. Southeastern North America
   ▶▶▶▶c. Southwestern North America
   d. Northwestern North America

7. Plate boundaries are shown as white dashed lines on Figure 11. How does lithospheric thickness correlate with the location of the active plate boundaries? Why do you think this might be the case?

   The lithosphere is thinnest near the plate boundary, especially in Southern CA and the Baja Peninsula. This is because the boundary includes a number of spreading centers where new lithosphere is being formed. The deepest lithosphere I found far from the plate boundary where the lithosphere is the oldest and coldest.

8. Based on your experience with this lab, A) summarize the role seismic waves play in our understanding of Earth's interior. B) In what ways have your ideas remained the same, and/or changed from your answers to questions 1 and 2 **of Part I**.

   Patterns in seismic wave velocities can tell us a lot about Earth's interior structure. From P-wave arrivals we can detect and measure Earth's core. From global S-wave arrivals, or more specifically, the lack of S wave arrivals between 140 and 160 degrees away from an epicenter we can infer that the outer portion of the core is a liquid. Finally we can also image the boundary between the lithosphere and asthenosphere. This can be mapped by studying the velocity of S-waves traveling through the region. Such studies reveal a boundary that has significantly more topography and lateral variation than commonly shown in textbooks.