Determining Earth's Layered Interior

Instructor's Guide

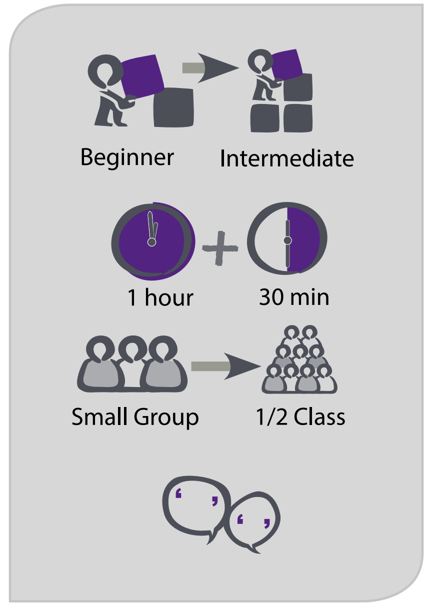
www.iris.edu/hq/inclass/lesson/16

Version 3.4

www.iris.edu/earthquake

Incorporated Research Institutions for Seismology

Adapted from *Earth's Interior Structure—Seismic Travel Times in a Constant Velocity Sphere*. (Braile, 2000)



OVERVIEW

How do we know about layers in the Earth? (Appendix A.) In this unique lesson, students complete two related activities to examine seismic evidence and determine that the Earth cannot have a homogeneous composition, but must have a layered internal structure.

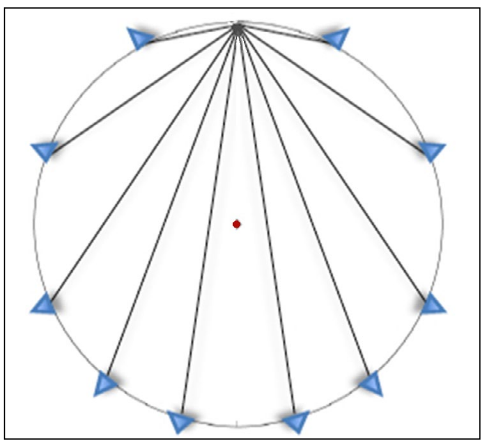


Figure 1*: Seismic ray paths to seismic stations (blue triangles) through homogeneous Earth.*

Using an inquiry approach, students are divided into two teams, theoreticians and seismologists. Their job is to test the simplest hypothesis for Earth's internal structure: a homogeneous Earth.

Theoreticians create a scale model of a homogeneous Earth and using an average seismic wave velocity make predictions about when seismic waves should arrive at various points around Earth.

Seismologists then interpret actual seismic data from the 2010 Haiti and Chile earthquakes to determine seismic arrivals at various points around Earth. Following this, the two groups then compare and interpret the implications of their data using a second scale model.

OBJECTIVES

By the end of the exercise, students should be able to:

- Demonstrate that Earth is not homogenous.
- Explain how the internal structure of Earth (concentric layers of different density and composition) is inferred through the analysis of seismic data.
- Explain the role models play in the scientific process, especially when used in combination with observational data.
- Explain how models are refined through the collection of additional data.

TABLE OF CONTENTS

MATERIALS

- 1-4 blown eggs for the Open segment of the instructional sequence (one for each section you teach as they may break).
- Classroom computer and projector
- Slide presentation: **Earths_Layered_Interior.ppt**
- Data from group tasks is entered into an Excel spreadsheet for reference: **EarthStructure_a.xls**
- See Activity's below for more "Worksheets & Materials."
- *Optional:* For Activity 1–Step 9, a class set of computers is required for the "Medium" version of combining data.

TEACHER PREPARATION

Activity 1

- **Seismologist's Worksheets & Materials**

1. Print enough "Seismologists Worksheets" for half of class (Page SW 1–2)
2. Materials for *each group of ~3* seismologists:
    - Print out and copy a Record Section (**Appendix C-1) Haiti**) for each seismologists group
    - Ruler

- **Theoretician's Worksheets & Materials**

1. There are two versions of the "Theoretician's Worksheets. Version 2 includes formula provided in data table" Print enough for half of class (Page SW 3–4 or SW5–6)
2. Materials below are for *each group of ~3* theoreticians
    - Semi-Circle Earth Scale Model (**Appendix D**)
      TIPS: Measure each half of the Semi-circle Earth Scale Model to verify that it printed with a radius of 19.9 cm. If it is not correct, make sure that printing options to "*scale the page to fit the printable area*" and "*auto-rotate and center*" are turned off and reprint.
    - Ruler
    - Protractor
    - Meter stick
    - Tape (clear)

- **Seismologist/Theoretician spreadsheet: EarthStructure_a.xls**
  See #9 on Page 5 for "Quick" vs. "Long" activity choices. One could run the activity by having students create their own graphs, or using the print ready graph provided in **Appendix F**.
  Data from **EarthStructure_a.xls.** Print as needed.

Activity 2 (Class set; one for each student)

- Full Circle Earth Scale Model (**Appendix E**).
  TIPS: Print and measure the **Full-circle Earth Scale Model** to verify that the circles printed with a radius of 5 cm. If it is not correct make sure that printing options to "*scale the page to fit the printable area*" and "*auto-rotate and center*" are turned off and reprint.
- Ruler
- Protractor
- Scissors

SLIDE PRESENTATION

The "**Instructional Sequence**" under Teacher Prep, guides you through the slide show: **Earths_Layered_Interior.ppt.**

NOTE: To make the instructional decisions of the author explicit to all teachers, a step-by-step approach is included in the speaker's notes section of the Powerpoint. While this results in a somewhat prescriptive resource, this is not the intent. We encourage all readers to alter their instruction to more fully fit their own teaching situation.

OPERA INSTRUCTIONAL SEQUENCE

This lesson, is designed around a learning cycle that can be remembered as O-P-E-R-A described in Appendix B.

The step-wise sequence for the Seismologists and Theoreticians is clarified in the Slide Presentation.

Table 1: Estimated time to complete the OPERA Instructional Sequence..

OPERA	TIME (min.)
Open	5
Prior knowledge	10
Explore/Explain	30
Reflect	15
Apply	20
Total	80-90

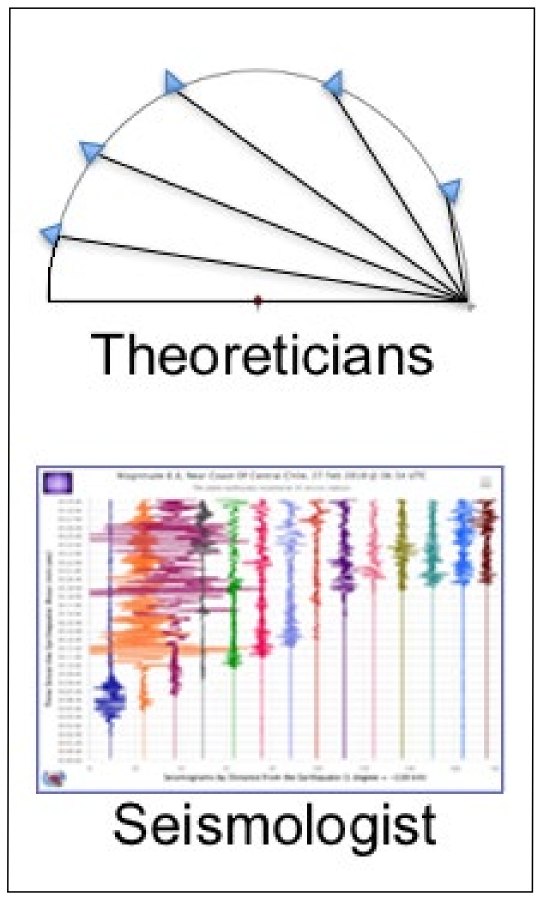
Open (5 Minutes) - Guided questioning plus the image of an egg encourages students to consider how they could "know" what is inside of something without "seeing or experiencing" it. Student attention is captured and the point is emphasized when the teacher shows and then tosses a pin-hole egg to an unsuspecting student with "unexpected" results. **Slides 2 and 3**

Prior Knowledge (10 Minutes) - Guided questioning plus the image of Earth from space is used to elicit and make explicit students' prior knowledge about Earth's interior structure as well has helping students to identify "how they know" this information. The teacher guides the discussion to suggest that students' own evidence from life experience (excluding lava seen on TV) suggests that there are rocks/dirt underground. By applying Occam's Razor, which says that the simplest explanation that explains all the data tends to be the best one, a testable hypothesis for students is that Earth is made of solid rock all the way throughout (homogeneous). Given the size of Earth, a model is needed to test this. **Slides 4 – 7**
(Optional: **Slide 8** emphasizes why models are needed in science (if you have already covered this explicitly in previous instruction this should be a review for emphasis).

Explore/Explain (30 Minutes) – **Activity 1** emphasizes the idea of testing a hypothesis by comparing modeled data to observations. Divide the class into two task groups (Figure 2 and 3) Half the students will create a scale, homogeneous Earth model to predict how long it should take seismic waves to reach various distances around Earth (Figure 2; Slide 10). Simultaneously the other half of the students will analyze a set of seismograms from a real earthquake to determine how long it takes for the seismic waves released from a real earthquake to arrive at various points on Earth's surface. Students will then graph their data and explore how well the model fits reality. Ultimately students will conclude that the observations do not match the predictions so they can reasonably assume that the Earth is not homogenous or made entirely of rock. **Slides 9 – 23**

Reflect (15 Minutes) – In Activity 2, students reflect further on the data and identify an anomalous feature in the observed data. By creating a second scale Earth model students can map this anomaly back to the real Earth that defines the P-wave shadow zone. **Slides 24 – 25**

Apply (20 Minutes) – In the continuation of Activity 2 students apply their new understanding of the P wave shadow zone to multiple earthquakes distributed around the globe. As students map out the shadow zone for each event, a pattern defining the boundary of the outer core emerges. **Slides 26 – 32**



F igure 2: *This image from **Slide 10** shows data collected by theoreticians and seismologists.*

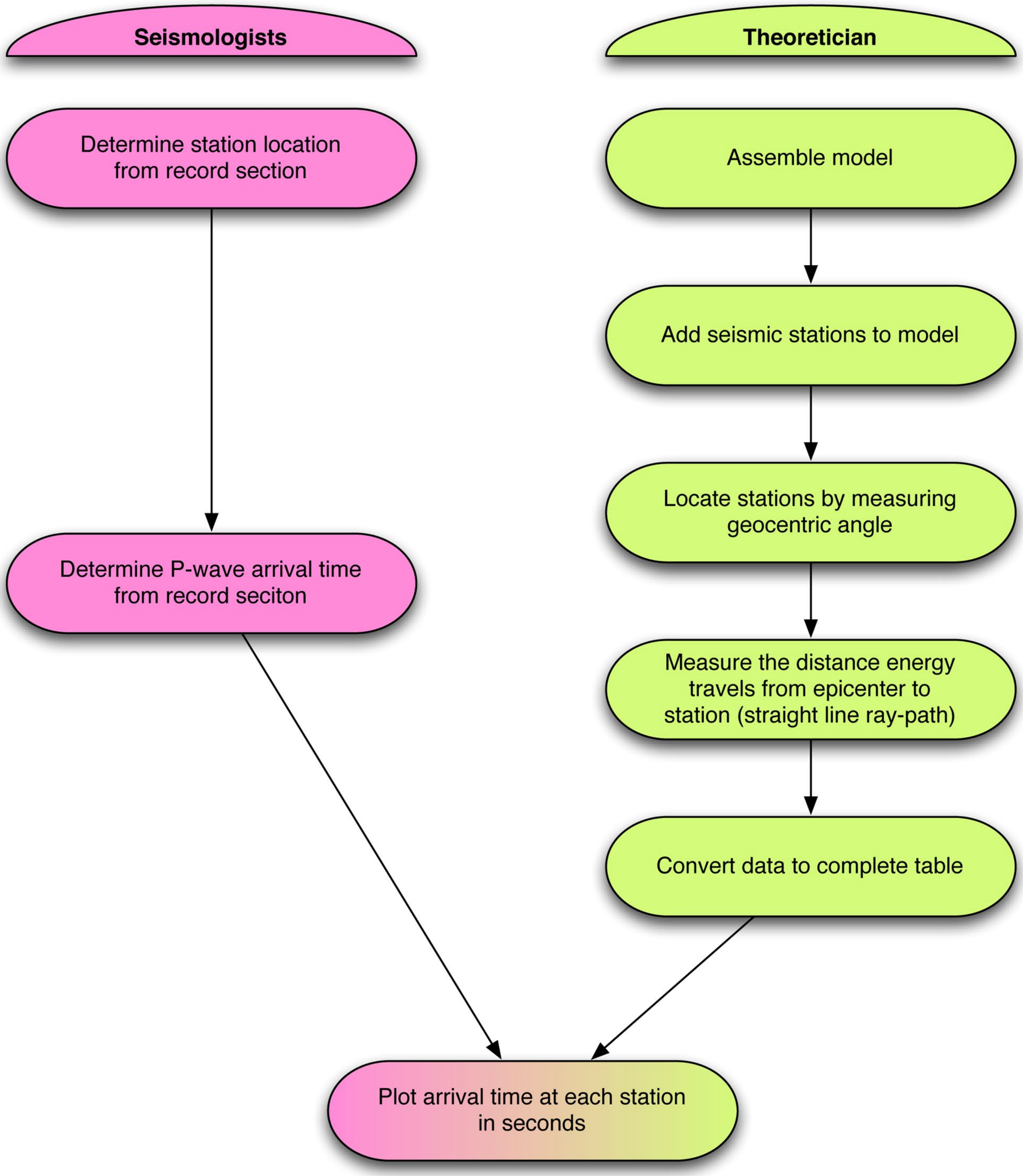


Figure 3: *Comparing model data with observations for Activity 1 (Slide 11).*

ACTIVITY 1—COMPARING MODEL DATA WITH OBSERVATIONS

LESSON DEVELOPMENT

Procedure

1. Assign students into small teams; teams of three work well.
2. Combine the small teams into two larger groups. For the exercise, one of the larger groups will be Seismologists while the other large group will be Theoreticians.
3. Distribute materials listed in Teacher Prep assigned to the Seismologists:
4. Distribute the materials (6 items listed above) assigned to the Theoreticians:
5. Indicate that you will first review the instructions for the seismologist because the Seismologist's work has the fewest steps to remember (but it takes just as long) and then the Theoreticians, who have more steps. Plus, it is very useful for both groups to listen to the others instructions so they have a sense of what the other group is doing.
6. Review Seismologist instructions: **Slides 12 – 15**. See notes panel for instructions.
7. Review Theoretician instructions: **Slides 17 – 21**.
8. Allow the groups time to complete the assignment using the Worksheets. **Slides 22-23** review the tasks and tables to be completed.
9. Have the Seismologists and the Theoreticians combine their data. There are three ways to facilitate the combination;
   - **Quick** – Groups report out their findings to the teacher who combines the data into the spreadsheet that graphs automatically. This is done using a video projector in front of the class.
     Note: Collect the predicted model data before the observed data.
   - **Medium** – Pair each group of seismologists with a group of theoreticians to create multi-discipline teams. Each group will then enter their data together onto a preformatted spreadsheet that automatically graphs the team's data.
     Note: A class set of computers is required.
   - **Long** – Pair each group of seismologists with a group of theoreticians to create multidiscipline teams. Each individual group constructs a graph of their data by hand. Next, the team then compares the two graphs to see if the predicted model matches the observations.
     Note: Graph paper is required (**Appendix F**).

10. Interpret the data with students

There are several items that can be discussed with students when examining their data. Figure 4 (**Slide 24** and the Excel spreadsheet **EarthStructure_a.xls**) shows sample data from the 2010 Haiti earthquake. Your students' observed data might look slightly different depending on the density of seismic stations thus the # of degrees below are approximate:

A) Emphasize that the model data does accurately predict reality.

- Prominent discrepancy – Something interrupts the waves
  - The model data follows a continuous curve while the observed data has a noticeable jump between ~100 and 120 degrees.
  - Students will explore this feature further in Activity 2.
- Other discrepancies - the velocity of seismic waves in the real Earth cannot be constant
  - Observed data arrives later than predicted close to the event
  - Observed data arrives earlier than predicted at ~90 degrees
  - Observed data arrives very late after ~120 degrees

B) The curving points of the model data appear surprising, as this should indicate that the seismic waves were accelerating in the model despite the assumption of a constant velocity of 11km/s. This occurs because the distances we are plotting are on a nearly spherical Earth. Thus, the distance the energy travels through the model to reach each station becomes proportionally less the closer you get to the side farthest from the source. For example, the distance the energy travels to reach a station on the model at 60 degrees = 19.8cm, 90 degrees = 28.1cm, 120 degrees = 34.2cm. and 150 degrees = 38.2cm. Thus the interval between 60 and 90 is 8.3cm, between 90 and 120 is 6.1cm, and between 120 and 150 is 4cm. Thus the energy is not accelerating.

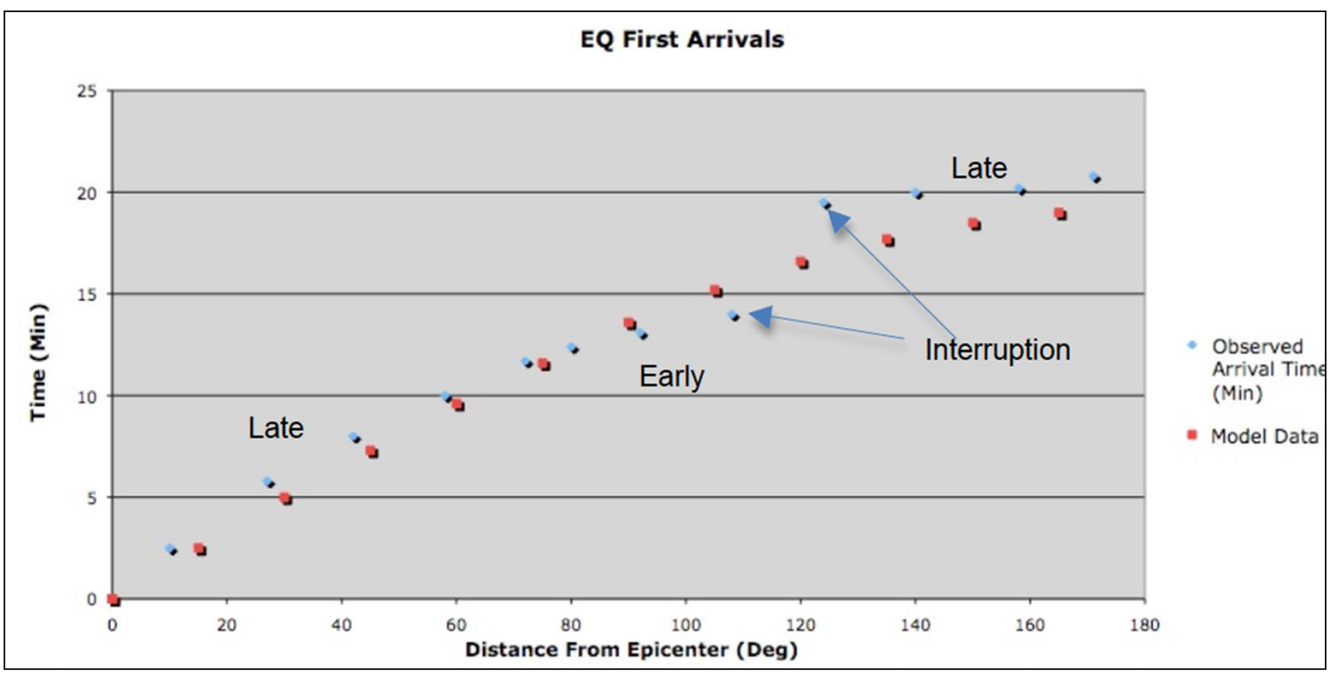


***Figure 4 :** Graph of first arrivals for the 2010 Haiti earthquake. Slide 24. Graph generated from* **EarthStructure_a.xls**

ACTIVITY 2 – EXAMINING THE IMPLICATIONS

LESSON DEVELOPMENT

Procedure

1. Provide each student with **Earth A**, full-circle Earth model. Examine the graph of the observed data they previously generated to determine where the interruption of the seismic waves appears to occur. **Slide 24**

   Questions for discussion following the graphing of the data

   ?? *How does our model data match the observed data?*

   ?? *What does this imply about our hypothesis that Earth's interior might consist of a homogenous material with a constant velocity of 11 km/s?*

   ?? *How do travel times from the observed stations compare to the model stations at similar geocentric angles?*

   ?? *What are the assumptions of your model?*

   ?? *How accurate you think your measurements are and what effect that has on your results?*

   ?? *Are there any difficulties you had? What were their impacts on our results?*

2. Students should measure a geocentric angle, on Earth A, based on their data (108 degrees based on the example data above), to the northern hemisphere and make a mark on Earth's surface. Use your ruler to connect the epicenter to the mark you just drew on Earth's surface. **Slide 26**

   (Note: Your data may vary slightly)

3. Repeat this procedure but mark the southern hemisphere's surface. (Figure 6) **Slide 27**

   ?? *What have we determined so far?*

   ?? *What sort of structure has the seismic data helped us does this scale model of the P-wave shadow zone help us determine? How?*

   ?? *How have we used the seismic waves to help use develop this picture?*

   ?? *What might this be similar too? Shape the discussion to lead students to the concept of a shadow.*

4. Label the area inside the angles drawn as the P-wave shadow zone. **Slide 28**

5. Have students reflect on the following discussion questions in their lab notebooks:

   ?? *What sort of structure have we determined so far?*

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

   ?? *Examine the record section again for this area. How might this "shadow zone" might be like a persons shadow on the ground.*

6. Now that students have developed a model of the P-wave shadow zone, lead students to see that with more data, we might develop a more revealing image.

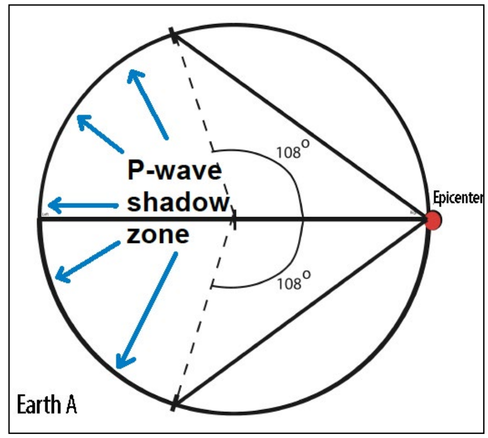


Figure 6 : *Based on seismic data students can model the P-wave shadow zone. Slide 27.*

7. Instruct students to cut out the wedge-shaped P-wave shadow zone. This represents the area that does not receive direct P-waves from an earthquake. **Slide 29**
8. To model the occurrence of additional earthquakes place the point of the wedge shaped cut-out on 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. **Slide 30**
9. Students should trace the straight edges of the wedge to indicate the area where Pwaves from the earthquake do not arrive.
10. Have students repeat this procedure for a number of earthquakes at different locations, each time tracing out the P wave shadow zone **(**Figure 7). This is an excellent time to explore the idea of how much data is adequate. **Slide 31**.

?? *What do you think this new inner circle represents?*

13. Have students reflect on the following discussion questions in their lab notebooks:

?? *As additional earthquake data is added, what shape is being defined in the interior of Earth Model B?*

?? *What do you think this new inner circle represents?*

?? *Why has our model improved from the point of previous questions?*

14. Calculate the radius of the core of their Earth Model B using the scale provided. The scale of the model is 1cm: 127,420,000 and there are 100,000cm in 1km. 15. Show students the IRIS poster "*Exploring the Earth Using Seismology*." **Slide 32**
Convey that the radius of the outer core of Earth is estimated to be ~3486km, that while this exercise reveals a smooth boundary between the core and mantle current research suggests a boundary that has a substantial amount of topography and review the concepts covered.
16. Have students reflect on the following discussion questions in their lab notebooks:

?? *How well does your model radius of the outer core match?*

?? *Where are there likely sources of error?*

?? *Considering the core was discovered only in 1906 is it possible that the current model may have further refinements?*

TEACHER TIP

Sources of error include: accuracy of tools used, issues of scale, etc, 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).

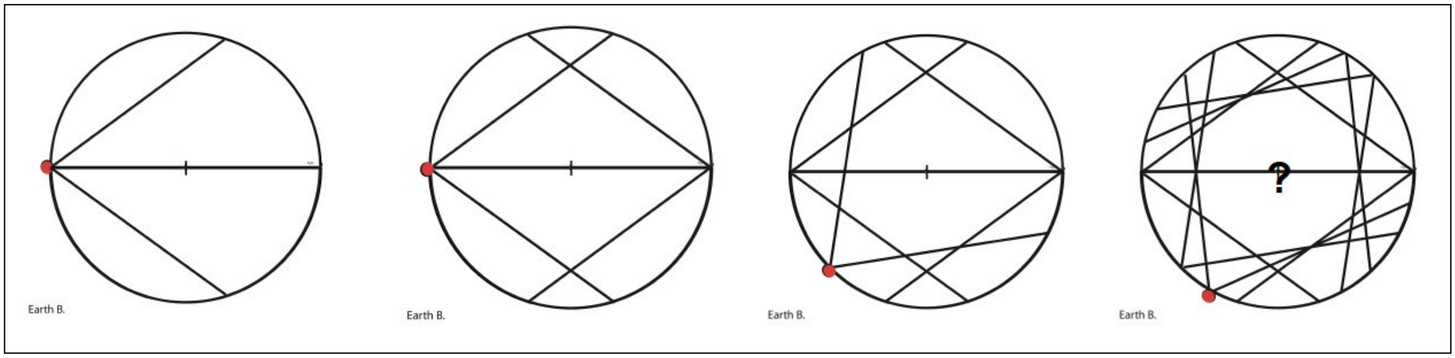


Figure 7 : *By mapping the P-wave shadow zone for multiple earthquakes, Earth structure becomes apparent.*

Teacher Background

Discovery of Earth's Core

Figure 4. Richard Oldham (1858–1936)

Irish geologist Richard Oldham made two fundamental discoveries that have greatly influenced the development of the field of seismology. First, through a detailed study of the Assam earthquake of 1897 and in 1900 Oldham was the first to identify clearly the primary (P) and secondary (S) seismic waves that had been predicted by the mathematician Siméon Poisson on theoretical grounds. Secondly, although Earth's core had been previously inferred from the Earth's gravity, Oldham provided the first direct evidence that the Earth had a central core in 1906. Similar to the activities above, he examined the arrivals of the primary waves. Oldham writes… "there remain two important questions to be answered, namely the size of the core and the rate of transmission of the waves in it. As regards the size of the core, we have seen that it is not penetrated by the wave-paths which emerge at 120°; and the great decrease at 150° shows that the wave-paths emerging at this distance have penetrated deeply into it. Now the chord of 120° reaches a maximum depth from the surface of half the radius, and we have seen that the wave paths up to this distance are convex towards the centre of the Earth, so it may be taken that the central core does not extend beyond 0.4 of the radius from the centre."

P-wave Shadow Zone

A common misconception put forth by figures in many Earth Science textbooks is that no seismic energy arrives with in the shadow zone. As you can see in the record section, Figure 7, lots of seismic waves (including compressional) are recorded by seismographs located in the shadow zone. This energy has been refracted or reflected to arrive there. Thus, 8, s only "direct" P-waves that don't arrive in the shadow zone. This phenomena is very similar to a student's shadow on the ground. Their shadow is not the absence of all light. Ra but does receive light that has refracted a objects.

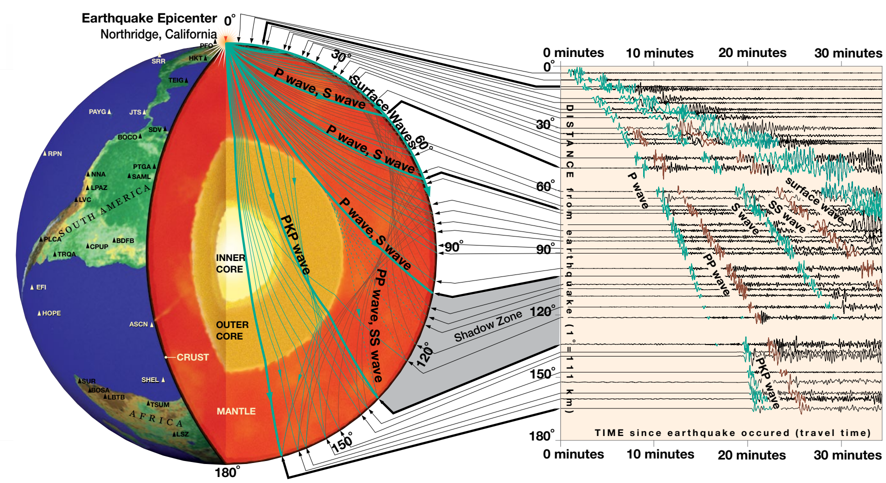


***Figure 8**: Seismic data, 1994 Northridge, CA earthquake and the energy's travel path through earth.*

Current research now suggests that P wav from the epicenter. However, strong arriva can be seen out to approximately 104 degrees away before decaying significantly. For large events, like the 2/27/10 M8.8 Chile earthquake shown in Figure 6, these diffracted P waves can be seen well beyond 120 degrees. For example, if one carefully examines the data for the stations within the shadow zone you will notice that the first arrival of seismic energy is slightly delayed and has a noticeably lower amplitude than the direct P wave arrivals at ~100 degrees.

(See Appendix C-2)

APPENDIX B

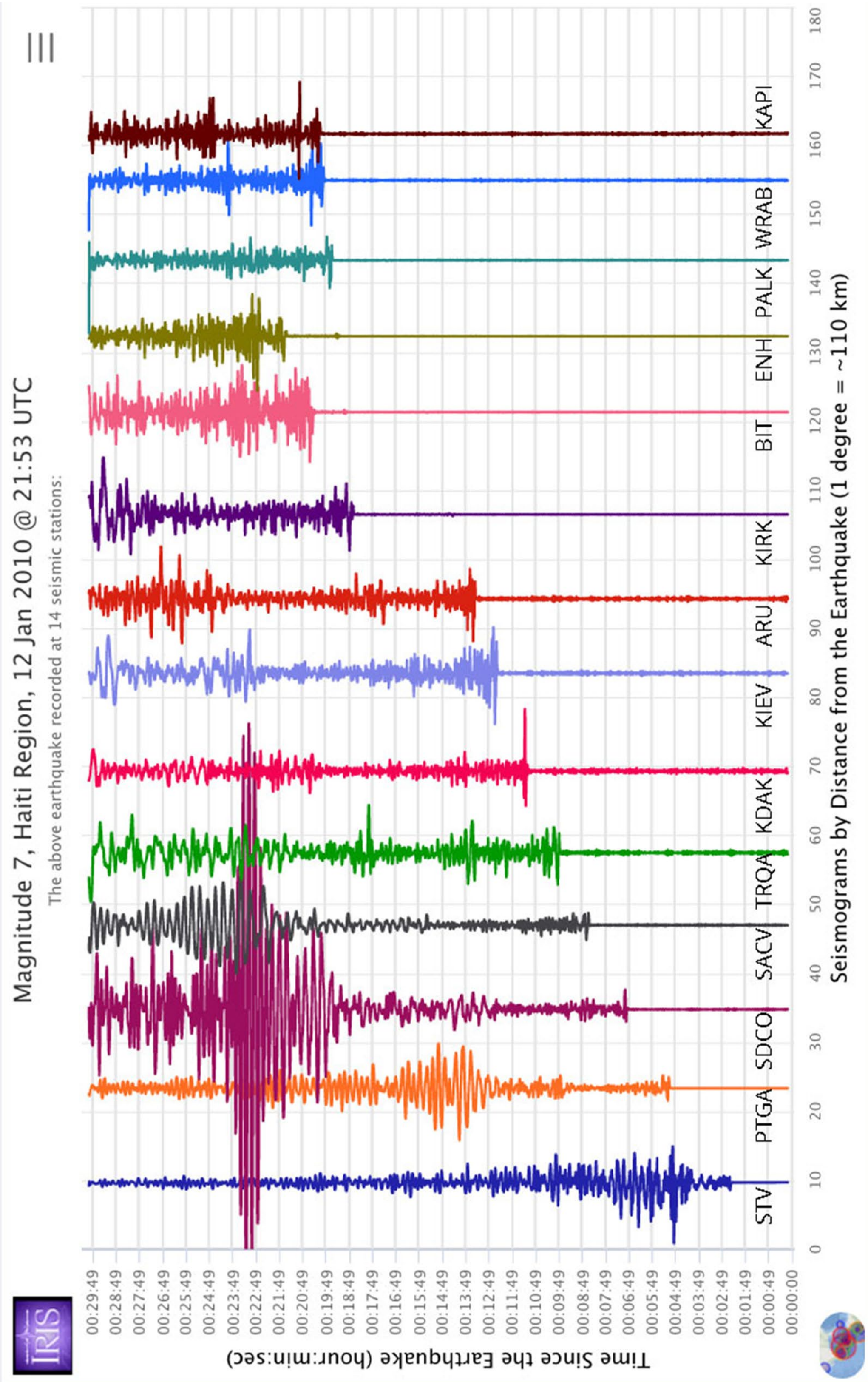
OPERA Learning Cycle

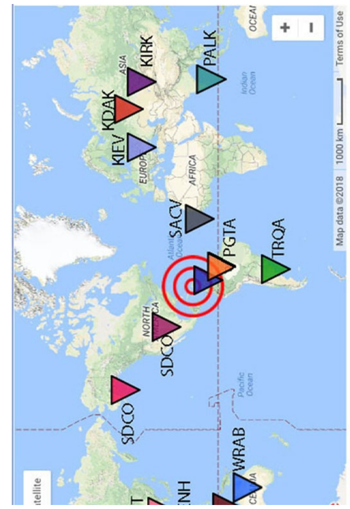
A learning cycle is a model of instruction based on scientific inquiry or learning from experience. Learning cycles have been shown to be effective at enhancing learning because by providing students with opportunities to develop their own understanding of a scientific concept, explore and deepen that understanding, and then apply the concept to new situations. A number of different learning cycles have been developed. However, all are closely related to one another conceptually, and differ primarily in how many steps the cycle is broken into. The "flavor" of learning cycle that you choose is primarily up to what works best for you, just pick one or two and use it as the basic formula for all your instruction.

This lesson, is designed around a learning cycle that can be remembered as O-P-E-R-A. OPERA is convenient when designing lesson-level instruction because one can generally incorporate all the major components into the single experience. Each phase of the OPERA cycle is briefly outlined below.

	Instructional Stage
Open	**Open** the lesson with something that captures students' attention. This is an invitation for learning and leaves students wanting to know more.
Prior knowledge	Assess students' **Prior Knowledge** and employ strategies that make this prior knowledge explicit to both the instructor and the learner.
Explore	Plan and implement a minds-on experience for students to **Explore** the content.
Reflect	**Reflect** on the concepts the students have been exploring. Students verbalize their conceptual understanding or demonstrate new skills and behaviors. Teachers introduce formal terms, definitions, and explanations for concepts, processes, skills, or behaviors.
Apply	Practice concepts, skills and behaviors by **Applying** the knowledge gained in a novel situation to extend students' conceptual understanding.

APPENDIX C —Sample record sections from 1) Haiti and 2) Chile

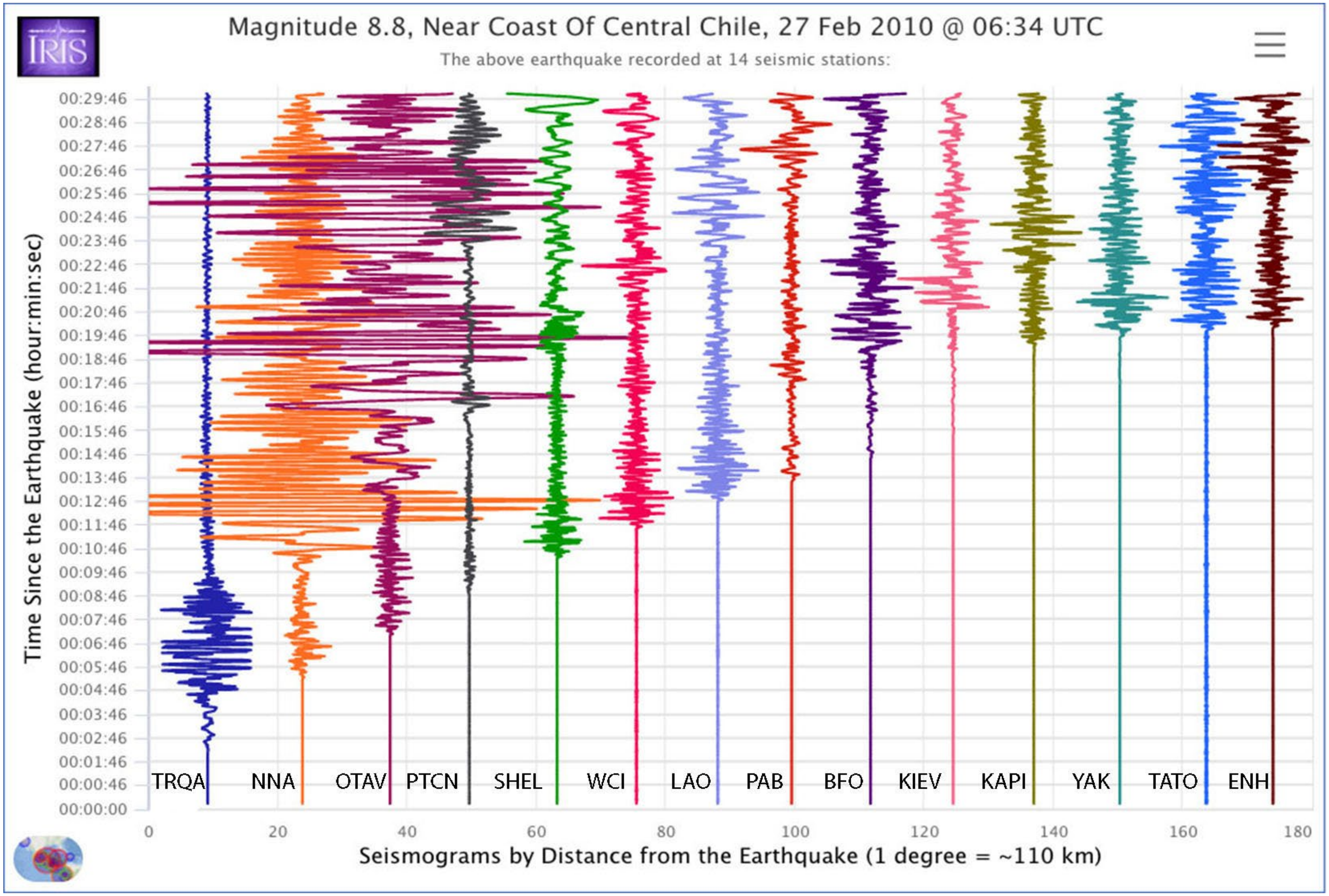


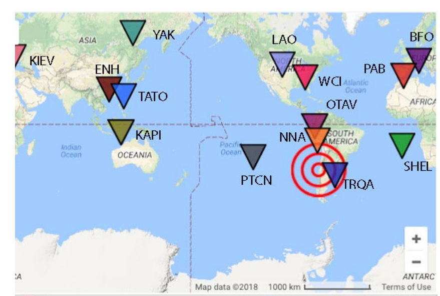


Sample record section: Seismograms generated from the 2010 Haiti earthquake taken from 14 seismic stations at increasing distance from the hypocenter.

From the IRIS Global Seismogram Plotter (GSP)

http://ds.iris.edu/seismon/recsec/tsplotForID.phtml?evid=2844986&useCache=1&epo=0&caller=map



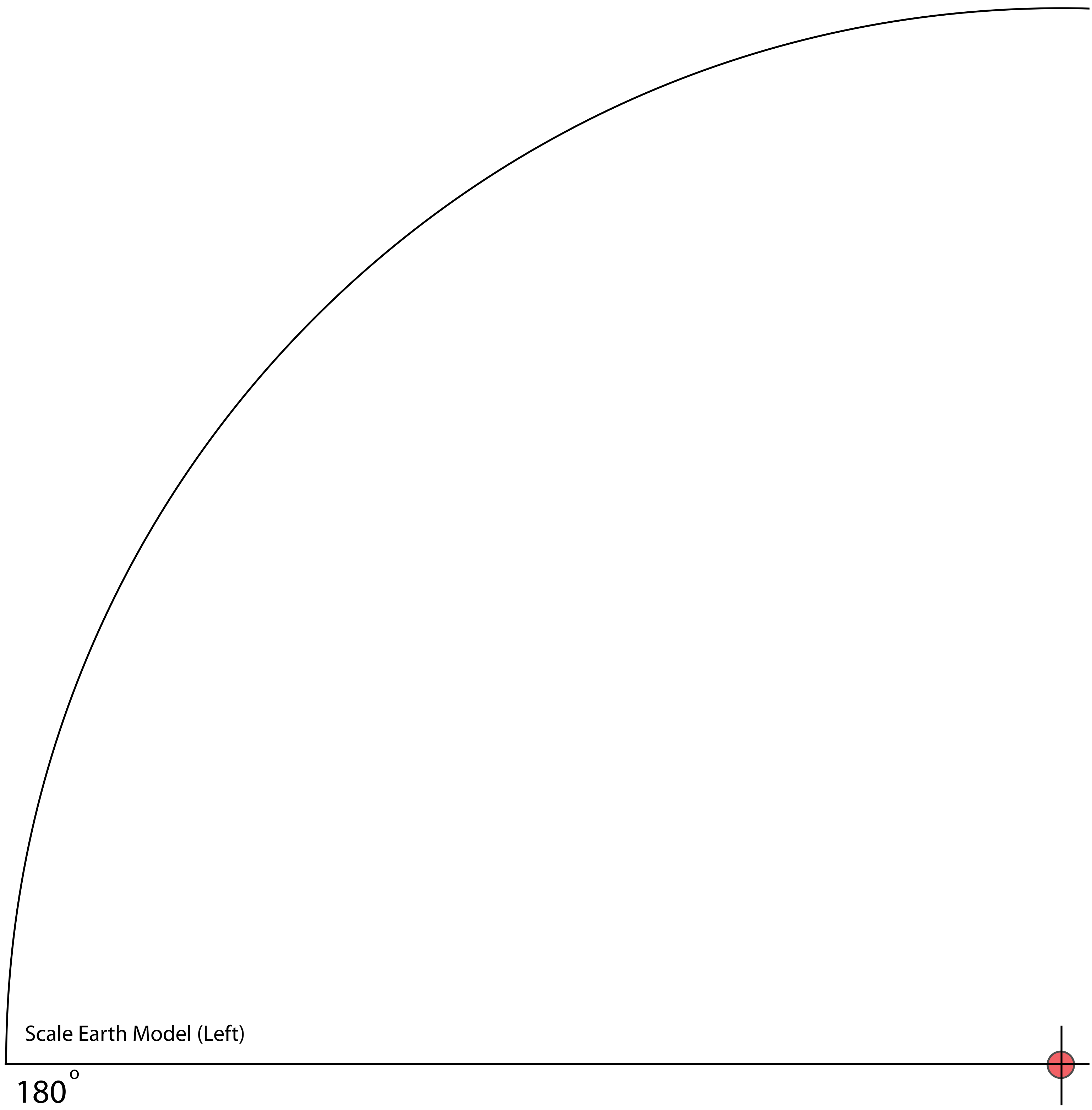


Sample record section: Seismograms generated from the 2010 Chile earthquake taken from 14 seismic stations at increasing distance from the hypocenter.

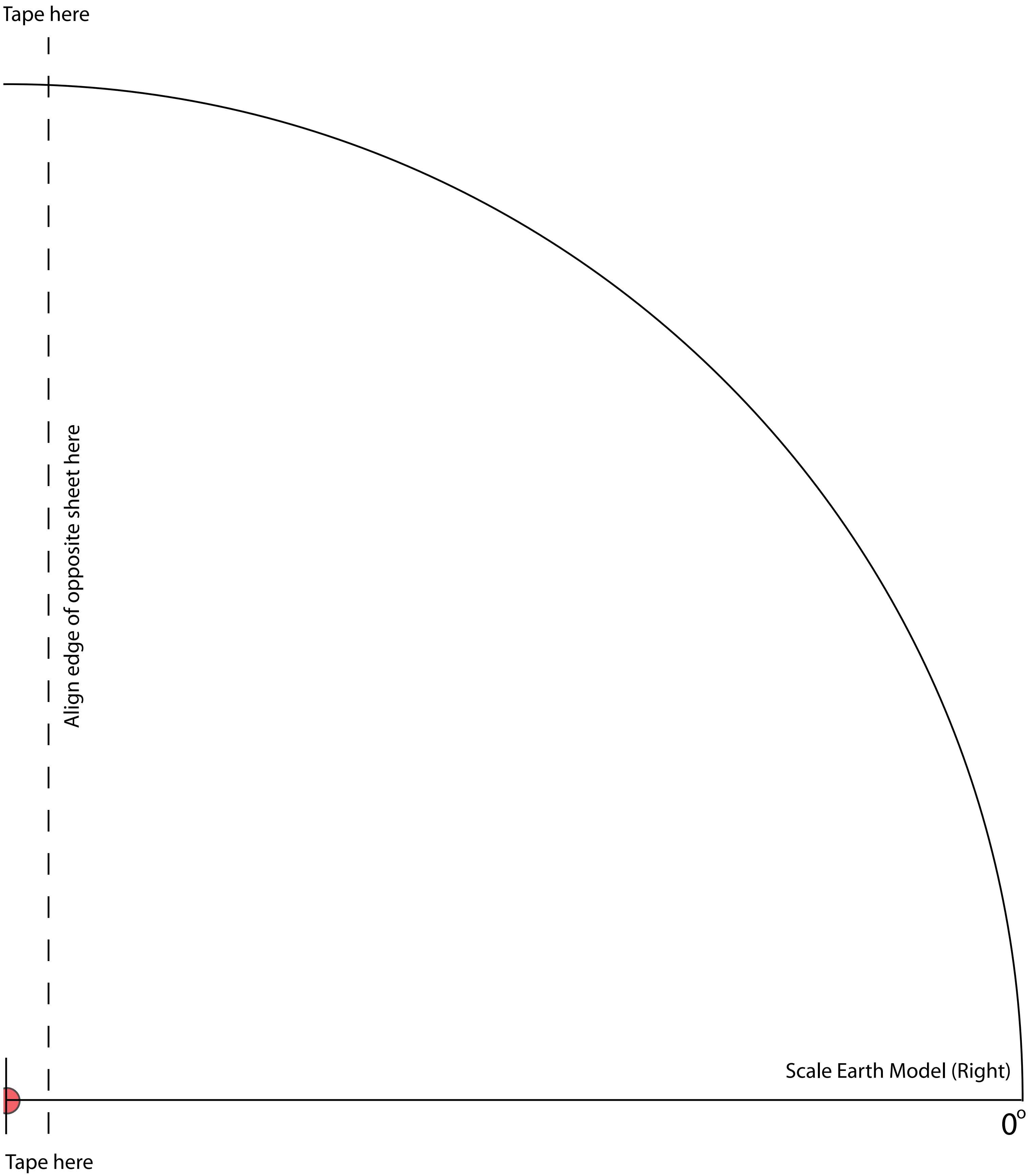
From the IRIS Global Seismogram Plotter (GSP)
http://ds.iris.edu/seismon/recsec/tsplotForID.phtml?evid=2844986&useCache=1&epo=0&caller=map

APPENDIX D

Half-Earth Scale Model Left Side

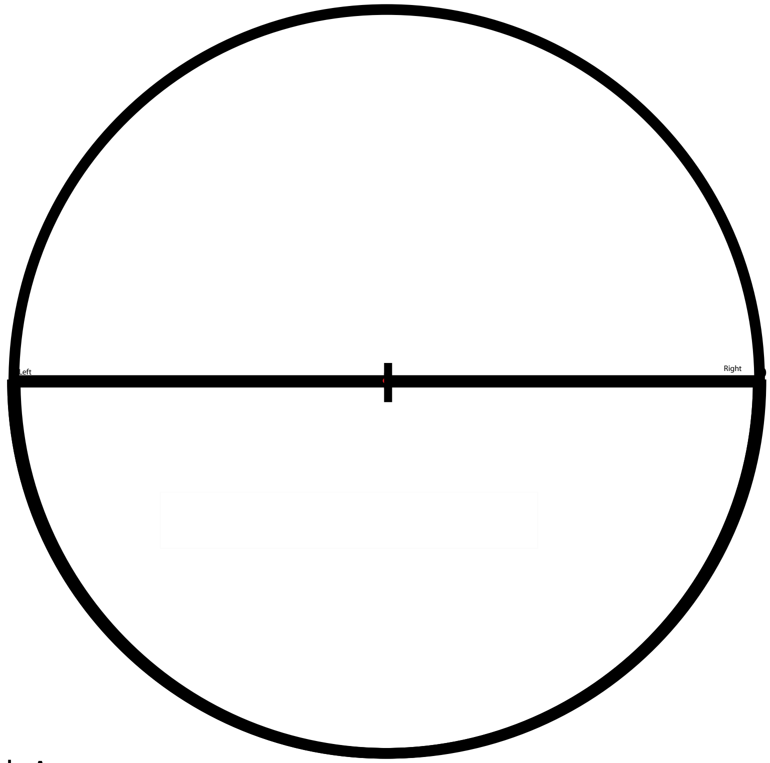


Half-Earth Scale Model Right Side

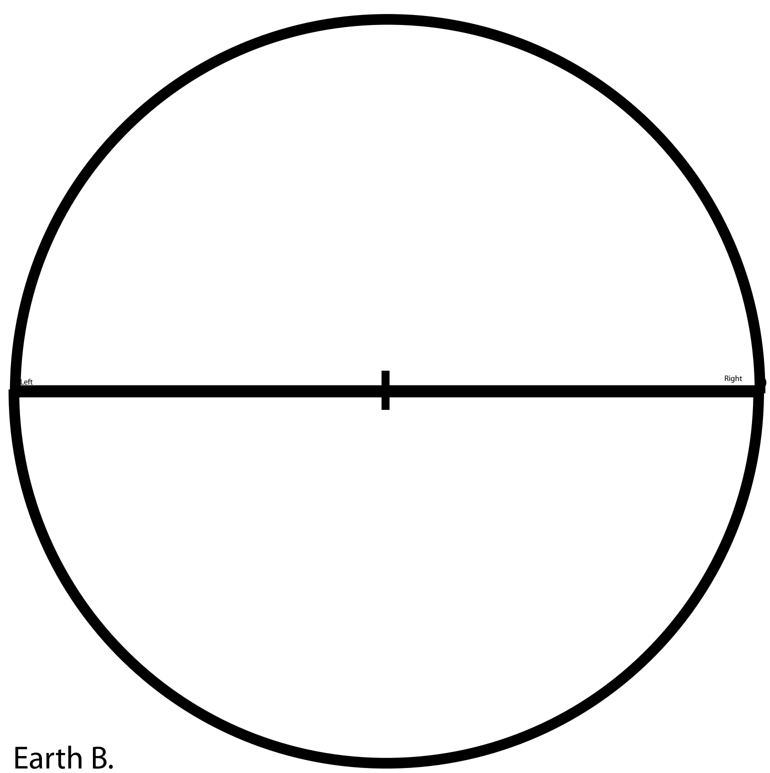


APPENDIX E

Full-circle Earth Scale Model



Earth A.

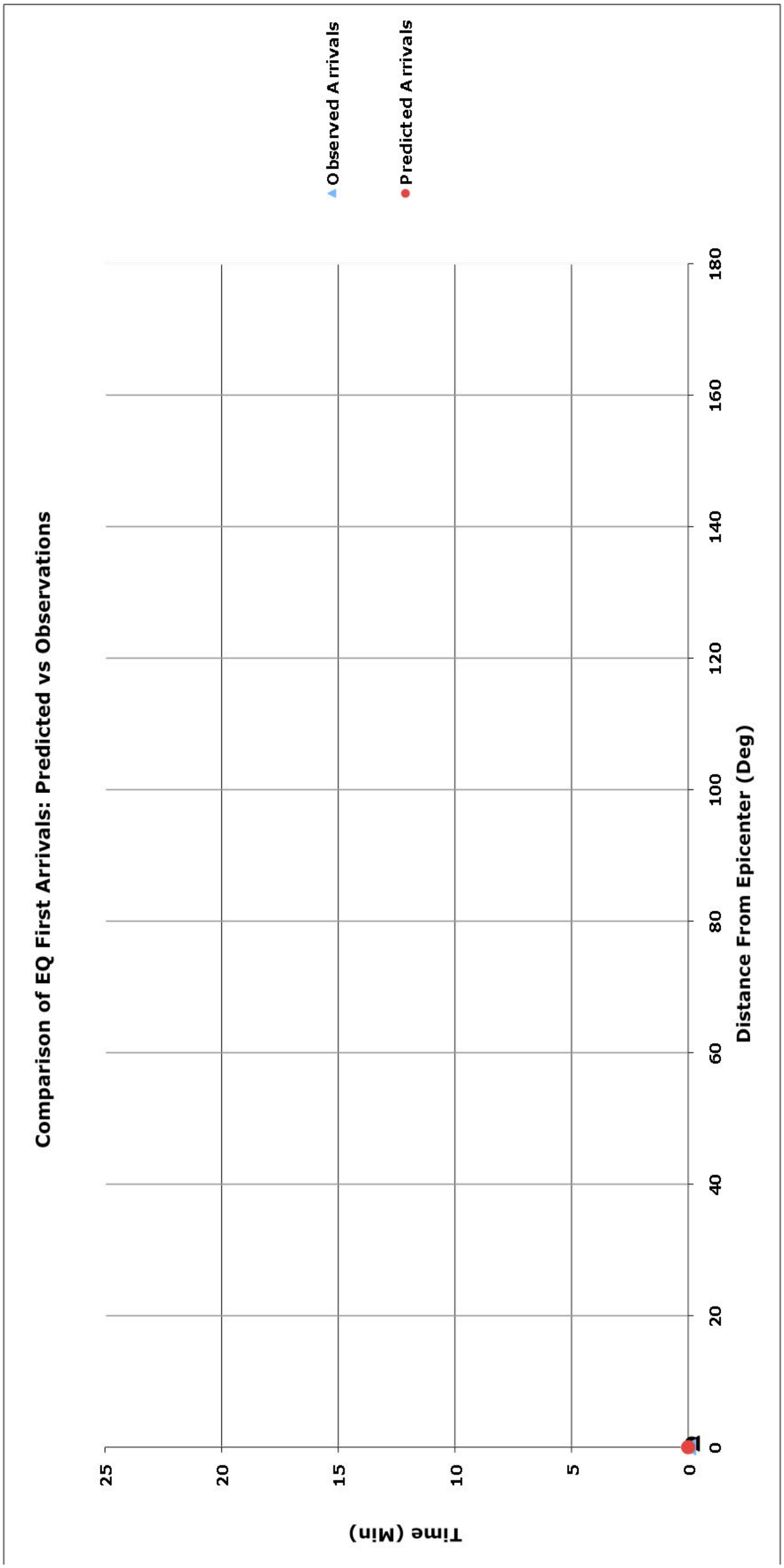


Earth B.

Earth Scale Model 2 - 1cm:127,420,000cm

APPENDIX F

Blank Graph;
print as needed



APPENDIX G— NGSS SCIENCE STANDARDS & 3 DIMENSIONAL LEARNING

Touch the url links to get more information

Waves and Their Applications in Technologies for Information Transfer:

MS-PS4-1 Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave. http://ngss.nsta.org/DisplayStandard.aspx?view=pe&id=168

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Using Mathematics and Computational Thinking Mathematical and computational thinking at the 6–8 level builds on K–5 experiences and progresses to identifying patterns in large data sets and using mathematical concepts to support explanations and arguments.	**PS4.A: Wave Properties** A simple wave has a repeating pattern with a specific wavelength, frequency, and amplitude.	**Patterns** Graphs and charts can be used to identify patterns in data..

HS-PS4-1 Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media. [Clarification Statement: Examples of data could include electromagnetic radiation traveling in a vacuum and glass, sound waves traveling through air and water, and seismic waves traveling through the Earth.] http://ngss.nsta.org/DisplayStandard.aspx?view=pe&id=116

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and Using Models Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.	**PS4.A: Wave Properties** The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing.	**Cause and Effect** Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects.

(cont.)

Earth's Systems

HS-ESS2-3 Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection. **Clarification Statement:** Emphasis is on both a one-dimensional model of Earth, with radial layers determined by density, and a three-dimensional model, which is controlled by mantle convection and the resulting plate tectonics. Examples of evidence include maps of Earth's three-dimensional structure obtained from seismic waves, records of the rate of change of Earth's magnetic field (as constraints on convection in the outer core), and identification of the composition of Earth's layers from high-pressure laboratory experiments. http://ngss.nsta.org/DisplayStandard.aspx?view=pe&id=186

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and Using Models Modeling in 9–12 builds on K–8 experiences and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed world(s)	**ESS2.A: Earth Materials and Systems** Evidence from deep probes and seismic waves, reconstructions of historical changes in Earth's surface and its magnetic field, and an understanding of physical and chemical processes lead to a model of Earth with a hot but solid inner core, a liquid outer core, a solid mantle and crust. Motions of the mantle and its plates occur primarily through thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and gravitational movement of denser materials toward the interior. (HS-ESS2-3)	**Energy and Matter** Energy drives the cycling of matter within and between systems.

APPENDIX G

Reference and Extension

What's THAT Inside our Earth? DLESE Teaching Boxes (2008). https://web.archive.org/web/20160514185816/http://www.teachingboxes.org/earthquakes/lessons/rev-WhatsTHAT.jsp

Name: ______________________

SEISMOLOGIST'S WORKSHEET

Background: The simplest solution to the question "What is beneath our feet?" is a homogeneous Earth, or one comprised entirely of the rock we see at the surface. Since seismic waves travel through Earth, they make a useful tool to "probe" the inside of Earth to discover what might actually be inside.

Task: Your task is to help test if Earth is homogeneous by analyzing a set of seismograms from a single earthquake to determine how long it actually takes for the seismic waves released from an earthquake to arrive at various points on Earth's surface.

Implications: If your findings match the findings of the theoreticians then Earth is homogeneous or all rock throughout. However, if your observations do not match the theoreticians' findings, then we can reasonably assume that the Earth is not homogenous or made entirely of rock and will need to develop a new model.

Materials (for each pair):
Record section and a ruler

Procedure to determine Travel Time for Waves

A record section (Figure 1) is a special way of displaying a collection of seismograms from a single earthquake recorded at different points on Earth. Each seismogram is plotted according to its distance from the epicenter on the x-axis (the distance from the seismograph to the epicenter is provided in degrees as measured by the geocentric angle shown in Figure 2) and the time since the earthquake on the y-axis.

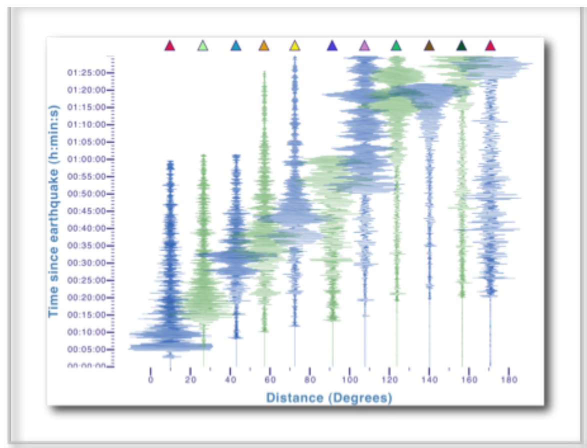


Figure 1: A record section is a special way of displaying a collection of seismograms from an earthquake.

Step 1: Number the stations on the record section from left to right starting with 1

Step 2: Record the distance of each seismograph from the earthquake (represented by its seismogram in the record section), in terms of geocentric angle in the table below.

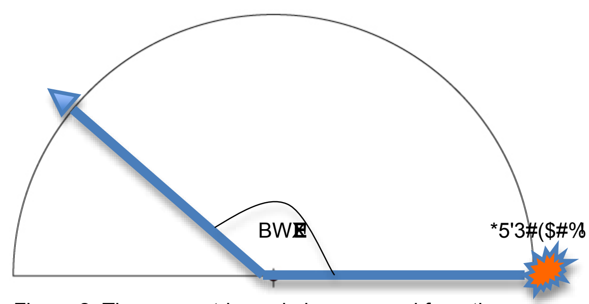


Figure 2: The geocentric angle is measured from the focus of the earthquake, through the center of Earth to the station location at the surface

Step 3: Examine each seismogram and identify the first arrival of energy at that station (Figure 3). Using a ruler read the scale on the y-axis to determine how long it took the energy to travel to that station. Record this information in the table below.

Step 4: Compare your results with another group of seismologists who used the same earthquakes and stations.

Step 5: Provide your teacher with your group's final data or enter the data from your table into the spreadsheet or graph provided by your instructor.

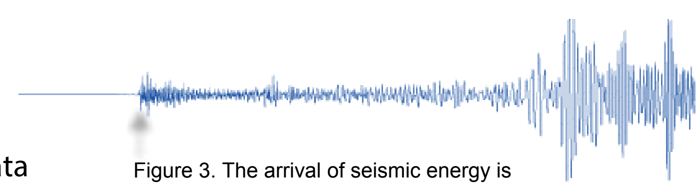


Figure 3. The arrival of seismic energy is indicated on the seismogram by a change from the background or previous signal.

Seismologist Data Table

Station Number	Station Distance (degrees)	Travel time (min)

Questions for the team to answer in their science notebook:

- Describe any difficulties you and your team had generating your data.
- Describe any areas where error might have been introduced into your data.
- Describe any trends and oddities you notice in your data.
- Compare the arrival times the theoreticians found with what the seismologists observed in Earth. Describe how they are like and unlike one another.
- What does this imply about our hypothesis that the Earth's interior is homogeneous Earth, or comprised entirely of the rock we see at the surface? How do we know?

Name: ____

THEORETICIAN'S WORKSHEET (VERSION 1)

Background: The simplest solution to the question "What is beneath our feet" is a homogeneous Earth, or one comprised entirely of the rock we see at the surface. Since seismic waves travel through Earth, they make a useful tool to "probe" the inside of Earth to discover what might actually be inside.

Task: Your task is to help test this hypothesis by creating a model of a homogeneous Earth, using the known velocity of seismic waves in rock ~ 11km/s. From this model you will predict how long it *should* take seismic waves to reach various distances around Earth.

Implications: If your findings match the findings of the seismologists then Earth is homogeneous or all rock throughout. However, if your observations do not match the seismologists' findings, than we can reasonably assume that the Earth is not homogenous or made entirely of rock and will need to develop a new model.

What is the Scale of the Model?

a. What is the radius of the model (Figure 1)?

_________cm

b. What is the scale of this model?

1cm:______________________cm

Below is some information that will help you.
The mean radius of the Earth is 6371km
1km = 100,000cm

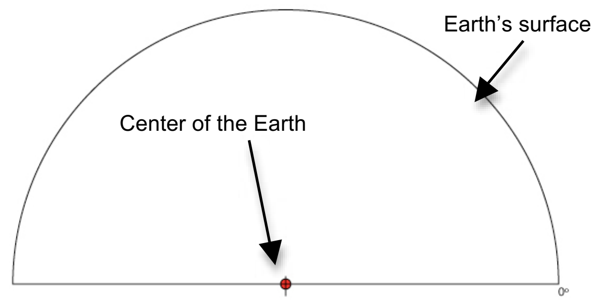


Figure 1: Scale, cross-section model of one of Earth's hemispheres.

Materials (for each pair)

1 Ruler
1 Meter stick
1 Protractor
Earth Scale Model – Both left and right halves
Tape

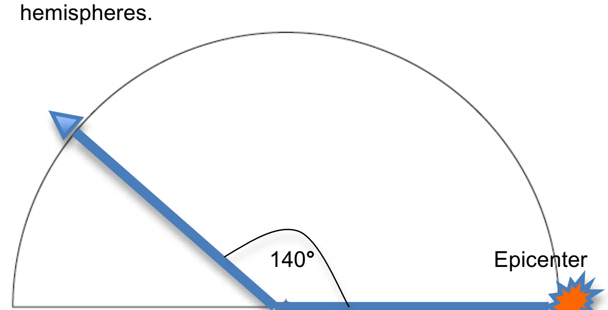


Figure 2: A **geocentric angle** is measured from the focus of the earthquake, through the center of Earth to the station location at the surface.

Procedure to Develop Predictions

Step 1: Draw a star at 0° to indicate the epicenter of the earthquake.

Step 2: Draw triangles on the surface of the model to indicate seismometers to record the arrival of the seismic waves. Assign each triangle a number and record that in Column A of the data table below. Unless instructed otherwise, you may place them anywhere you want but consider the following: What range of angles do you want the model to cover? What would be "enough" data?

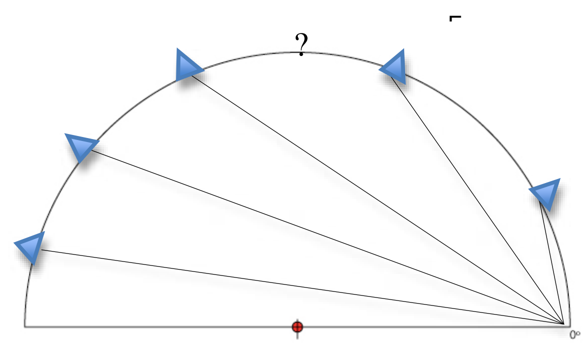


Figure 3: An earthquake occurs at 0° and seismic energy radiates out in all directions and arrives at seismic stations at the surface.

Step 3: Determine the location of the stations you added, with your protractor by measuring the *geocentric angle* (Figure 2). Record the geocentric angle for each station in Column B of the data table.

Remember: One degree of geocentric angle corresponds to an arc of ~111km on the surface!

Step 4: *Earthquake!* Draw straight lines representing seismic waves (Figure 3) from the epicenter to the seismograph. Measure the length of these paths in centimeters (cm) and record this distance in Column C of the data table.

Step 5: Convert the model distances to real Earth distances by converting (cm) in Column C to (km) in Column D. You will need the scale of the model you calculated previously.

Step 6: Calculate the time it takes the seismic waves to travel to each station using the constant velocity of the seismic waves in our model (11km/s) . Record this time in Column E of the data table. Convert the seconds to decimal minutes in Column F of the data table.

Step 7: Compare your results with another group of theoreticians.

Step 8: Provide your teacher with your group's final data or enter the data from your table into the spreadsheet or graph provided by your instructor.

Theoretician Data Table

A	B	C	D	E	F
Station Number	**Station Location** Δ (degrees)	**Distance seismic waves travel in model** (cm)	**Actual Distance seismic waves travel** (km)*	**Travel Time** (s)**	**Travel Time** (min)

Conversion Notes
*model distance (cm) scaled to distance at Earth's scale (km): Refer to 1b above. 1cm = ~32,000,000cm or 1cm on the model = 320 km
** speed of seismic waves in constant velocity Earth of 11 km/s;

Questions for the team to answer in their science notebook:

- Describe any difficulties you and your team had generating your data.
- Describe any areas where error might have been introduced into your data.
- Describe any trends and oddities you notice in your data.
- Compare the arrival times the theoreticians found with what the seismologists observed in Earth. Describe how they are like and unlike one another.
- What does this imply about our hypothesis that the Earth's interior is homogeneous Earth, or comprised entirely of the rock we see at the surface? How do we know?

Name: ____

THEORETICIAN'S WORKSHEET (VERSION 2)

Background: The simplest solution to the question "What is beneath our feet" is a homogeneous Earth, or one comprised entirely of the rock we see at the surface. Since seismic waves travel through Earth, they make a useful tool to "probe" the inside of Earth to discover what might actually be inside.

Task: Your task is to help test this hypothesis by creating a model of a homogeneous Earth, using the known velocity of seismic waves in rock ~ 11km/s. From this model you will predict how long it *should* take seismic waves to reach various distances around Earth.

Implications: If your findings match the findings of the seismologists then Earth is homogeneous or all rock throughout. However, if your observations do not match the seismologists' findings, than we can reasonably assume that the Earth is not homogenous or made entirely of rock and will need to develop a new model.

What is the Scale of the Model?

a. What is the radius of the model (Figure 1)?
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b. What is the scale of this model?

1cm:______________________cm

Below is some information that will help you.

The mean radius of the Earth is 6371km
1km = 100,000cm

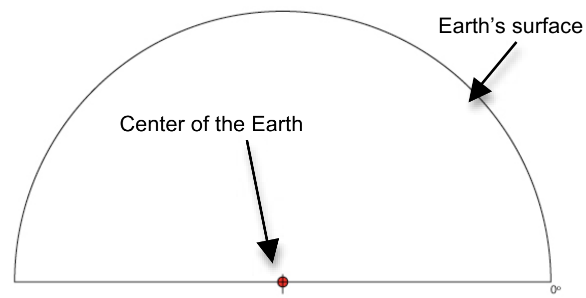

Figure 2: Scale, cross-section model of one of Earth's hemispheres.

Materials (for each pair)

1 Ruler
1 Meter stick
1 Protractor
Earth Scale Model – Both left and right halves
Tape

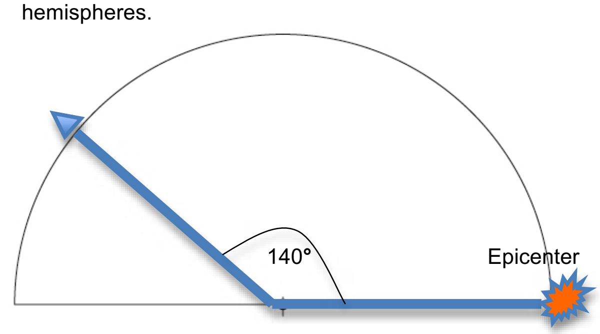

Figure 2: A **geocentric angle** is measured from the focus of the earthquake, through the center of Earth to the station location at the surface.

Procedure to Develop Predictions

Step 1: Draw a star at 0° to indicate the epicenter of the earthquake.

Step 2: Draw triangles on the surface of the model to indicate seismometers to record the arrival of the seismic waves. Assign each triangle a number and record that in Column A of the data table below. Unless instructed otherwise, you may place them anywhere you want but consider the following: What range of angles do you want the model to cover? What would be "enough" data?

Step 3: Determine the location of the stations you added, with your protractor by measuring the *geocentric angle* (Figure 2). Record the geocentric angle for each station in Column B of the data table.

Remember: One degree of geocentric angle corresponds to an arc of ~111km on the surface!

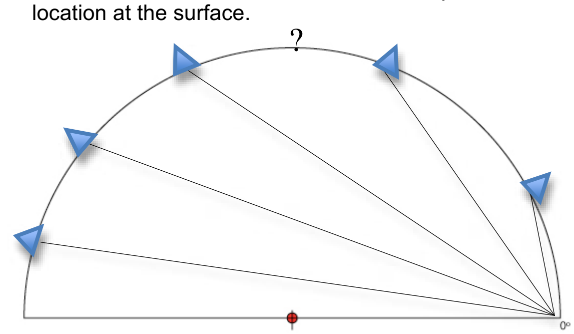

Figure 3: An earthquake occurs at 0° and seismic energy radiates out in all directions and arrives at seismic stations at the surface.

Step 4: *Earthquake!* Draw straight lines representing seismic waves (Figure 3) from the epicenter to the seismograph. Measure the length of these paths in centimeters (cm) and record this distance in Column C of the data table.

Step 5: Convert the model distances to real Earth distances by converting (cm) in Column C to (km) in Column D. You will need the scale of the model you calculated previously.

Step 6: Calculate the time it takes the seismic waves to travel to each station using the constant velocity of the seismic waves in our model (11km/s) . Record this time in Column E of the data table. Convert the seconds to decimal minutes in Column F of the data table.

Step 7: Compare your results with another group of theoreticians.

Step 8: Provide your teacher with your group's final data or enter the data from your table into the spreadsheet or graph provided by your instructor.

Theoretician Data Table

A	B	C	D	E	F
Station Number	**Station Location** Δ (degrees)	**Distance seismic waves travel in model (cm)** (measure in cm)	**Actual Distance seismic waves travel in Earth (km)** (Column C x 320km/cm)	**Travel Time (Sec)** (Column D/ 11km/s)	**Travel Time (min)** (Column E / 60s)

Conversion Notes
*model distance (cm) scaled to distance at Earth's scale (km): Refer to 1b above. 1cm = ~32,000,000cm or 1cm on the model = 320 km
** speed of seismic waves in constant velocity Earth of 11 km/s;

Questions for the team to answer in their science notebook:

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