Determining Earth’s Internal Structure

May, 2010 v3.2  Michael Hubenthal – hubenth@iris.edu

Adapted from Earth’s Interior Structure - Seismic Travel Times in a Constant Velocity Sphere. (Braile, 2000), Earth’s Interior Structure: Addendum (Hubenthal, 2006) and What’s THAT Inside our Earth? DLESE Teaching Boxes (2008).

**Time** – 80-90 Minutes  
**Suggested Level** – Intermediate
Easily modified for high school or undergraduates

**5E Phase** - Exploration. Students should have already learned about earthquakes and seismic waves prior to beginning this investigation.

**Materials List**
- **Introduction**
  - 1 Blown egg (one for each section you teach as they may break)
  - Classroom computer and video projector
  - Slide presentation
  - www.iris.edu/hq/resource/determining_internal_structure
- **Activity 1**
  - Theoretician’s worksheets (enough for half of class)
    - Semi-Circle Earth Scale Model – both left and right half
    - Meter sticks
    - Rulers
    - Protractors
    - Tape
  - Seismologist’s worksheets (enough for half of class)
    - Seismic record section (see Appendix A)
    - Rulers
  - Seismologist/Theoretician spreadsheet
  
- **Activity 2** (class set)
  - Full Circle Earth Scale Model
  - Scissors
  - Rulers
  - Protractors

**Content Objectives** - By the end of the exercise, students should be able to:
- Demonstrate that Earth can’t be 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.
- Discuss how working in a team to make data-gathering and procedural decisions provides an efficient means for completing tasks, provides peer support to check work and to develop conceptual understanding.

**Lesson Description**

In this unique lesson (Table 1), students complete two related activities to examine seismic evidence and determine that the Earth must have a layered internal structure and cannot have a homogeneous composition. This lesson is also unique in its approach to the process of science. Using an inquiry approach, students are divided into two teams (theoreticians and seismologists) 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 a recent earthquake 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.

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<tr>
<th>OPERA</th>
<th>Time (min)</th>
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<tbody>
<tr>
<td>Open</td>
<td>5</td>
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<tr>
<td><strong>Prior knowledge</strong></td>
<td>10</td>
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<tr>
<td><strong>Explore/Explain</strong></td>
<td>30</td>
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<tr>
<td>Reflect</td>
<td>15</td>
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<td>Apply</td>
<td>20</td>
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<td><strong>Total</strong></td>
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Table 1. This instructional sequence includes two activities. The procedure for each activity is described below.

**Instructional Sequence**

**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 as 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) **Slides 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. 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. 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 - 19

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 22 - 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 - 29
Activity 1 – Comparing model data with observations

Teacher Preparation

- Copy student handouts (half the class will be seismologists and the other half theoreticians)
- Print out and copy a Record Section for each seismologists group (either the sample from http://www.iris.edu/hq/resource/determining_internal_structure or use the instructions in Appendix A of this document to obtain one from a recent earthquake)
- Measure each half of the Semi-circle Earth Scale Model to verify that it printed with a radius of 19.9cm. 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
- Make enough copies of the Semi-circle Earth Scale Model for each theoretician group to have one.

Procedure

1. Assign students into small groups; groups of three work well.
2. Divide the groups into half. For the exercise one half will be Seismologists while the remaining students will be Theoreticians.
3. Distribute the following to the seismologists:
   - Seismologist worksheet
   - Record Section
   - Rulers
4. Distribute the following to the Theoreticians:
   - Theoretician worksheet
   - Semi-Circle Earth Scale Model
   - Meter sticks
   - Rulers
   - Protractors
   - Tape
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 to they have a sense of what the other group is doing.
8. Allow the groups time to complete the assignment using the worksheets.
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: This works best to collect the predicted model 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
Determining Earth's Internal structure: http://www.iris.edu/hq/resource/determining_internal_structure

- 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 multi-discipline 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.

9. Interpret the data with students

   There are several items that can be discussed with students when examining their data. Figure 1 below shows sample student data. Your students’ observed data might look slightly different depending on the density of seismic stations thus the # of degrees below are approximate:

   - 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

   - 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 to reach each station becomes proportionally less the close on the far side of Earth. 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 1: Student graph of model versus observed arrival times](http://www.iris.edu/hq/resource/determining_internal_structure)
Activity 2 – Examining the implications

Teacher Preparation

- Measure the Full-circle Earth Scale Model to verify that it printed with a radius of 5cm. 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
- Make copies of the Full-circle Earth Model for each student.

Procedure

1. Provide each student with the following:
   - copy of Full-circle Earth Scale Model
   - protractor
   - ruler
   - scissors

2. Students should indicate the epicenter of an earthquake at 0 degrees on the right edge of the Earth A of their model with a dot. **Slide 22**

3. Examine the graph of the observed data they previously generated to determine where the interruption of the seismic waves appears to occur.

4. Students should measure a geocentric angle based on their data (108 degrees based on the example data above. You data may vary slightly), 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 23**

5. Repeat this procedure but mark the southern hemisphere’s surface. **Slide 24**

6. Label the area inside the angles drawn as the P-wave shadow zone. **Slide 25**

7. 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 and consider how this “shadow zone” might be like a persons shadow on the ground.

8. 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.

9. 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 26**
10. 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 27**

11. Students should trace the straight edges of the wedge to indicate the area where P-waves from the earthquake do not arrive.

12. Have students repeat this procedure for a number of earthquakes at different locations, each time tracing out the P wave shadow zone. This is an excellent time to explore the idea of how much data is adequate. **Slide 28**

![Figure 3. By mapping the P-wave shadow zone for multiple earthquakes, Earth structure becomes apparent.](image)

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.” 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. (Slide 29)

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?

Sources of error include: accuracy of tools used, issues of scale etc, students miss-interpretation 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).
Teacher Background

Discovery of Earth’s Core

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 within the shadow zone. As you can see in the record section, Figure 5, 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, it is 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. Rather it is an area that is not able to receive direct light but does receive light that has refracted around the student or has reflected off of nearby objects.

Current research now suggests that P wave shadow zone actually begins at ~98 degrees away from the epicenter. However, strong arrivals from P waves diffracting around the core of Earth 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.
Figure 6. Seismic data from the 2/27/10 M8.8 Chile earthquake. Note the diffracted P arrivals highlighted within the orange box.
Appendix A – Obtaining Seismic Record Sections

A record section (Figure 6 above) is a set of seismograms from a single earthquake recorded at various stations around the globe. These seismograms are plotted vertically with time on the Y-axis and distance away from the epicenter in degrees on the X-axis. To obtain a record section for use with this activity two options exist.

**Option 1**
A seismic record section from the Haiti earthquake has been provided for use with this activity in the downloadable file “Earth_Structure_Handouts.zip” available at [http://www.iris.edu/hq/files/programs/education_and_outreach/lessons_and_resources/docs/REVEarthStructure/Earth_Structure_Handouts.zip](http://www.iris.edu/hq/files/programs/education_and_outreach/lessons_and_resources/docs/REVEarthStructure/Earth_Structure_Handouts.zip)

**Option 2**
To get a record section for a recent newsworthy event, visit the Rapid Earthquake Viewer (REV) at: [http://rev.seis.sc.edu/](http://rev.seis.sc.edu/). Please note that REV does not contain all earthquakes that occur. Instead, to make it easier for non-seismologists to get reasonable data, REV provides only earthquakes that have occurred recently, are larger than M 4.0 and have reasonably good data available.

1. Click on Earthquake view
2. Select an earthquake of interest from the world map. Recent events > M 6 but < M 8 are ideal for this activity as they are large enough to have been adequately recorded globally but not so large that the diffracted P phase is strongly recorded in the P wave shadow zone (described previously).
3. The next page (shown at right) has three components
   a. An event information box in the upper left,
   b. A record section displayed on the right side of the page
   c. A list of stations in the record section across the bottom of the page
4. Examine the record section and determine if it has a relatively even distribution of seismograms ~ every 10 to 12 degrees. This is especially important between 100 degrees and 120 degrees.
5. If not, add additional stations at the desired location from the drop-down menu found in the details box at the top left of the page. In some cases, stations may not be available at the specific distance you would like for two reasons. First, there may be no station there because of the oceans. Alternatively, the stations at that distance may not have good data available.
6. Continue to add stations until the record section has an adequate distribution of seismograms.
7. Select the save as PDF button from the event information box.
8. Print this pdf.