How Do We Know Where an Earthquake Originated?

Instructor's Guide & Student Worksheet

www.iris.edu/hq/inclass/lesson/439

Version: October 2019

IRIS
www.iris.edu/educate

Incorporated Institutions for Seismology
By Jeffrey Barker, Binghamton University & Michael Hubenthal, IRIS Consortium

Intermediate

50 min

Small Group Whole Class

Web-Based Materials

OVERVIEW

Millions of earthquakes occur every year around the world and are recorded by a network of seismometers. Seismometers are calibrated to sense even the smallest motion of seismic waves from distant earthquakes. By understanding how seismic waves travel, the ground-motion records, called seismograms, can be interpreted to locate an earthquake's source.

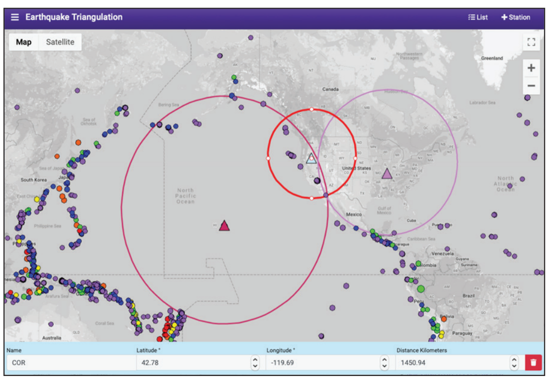


Figure 1: Determining P- and S-wave arrival times on seismogram. This example was derived from IRIS's online app "Triangulation"

In this activity, students use 3-component seismograms (motion recordings on the N/S, E/W, and up/down axes) to locate an earthquake. Students identify P and S waves in their seismograms, measure the time between arrival of the P and S wave, then use the time difference to determine how far the earthquake was from the station by using the travel-time-curve.

By combining their information with the results from at least two other students using seismograms recorded at different locations, the location of the epicenter can be determined (Figure 1)

Whereas computers now calculate epicenters, this exercise gets students familiar with the information contained within seismograms and excited about earthquakes as part of the Earth system.

OBJECTIVES

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

- Identify P and S waves on seismograms
- Determine the distance of an epicenter from a seismic station using travel time curves
- Locate the epicenter of an earthquake by triangulation
- Calculate the time of origin of an earthquake based on seismic data

TABLE OF CONTENTS

MATERIALS

Materials Needed for each group of 4 students:

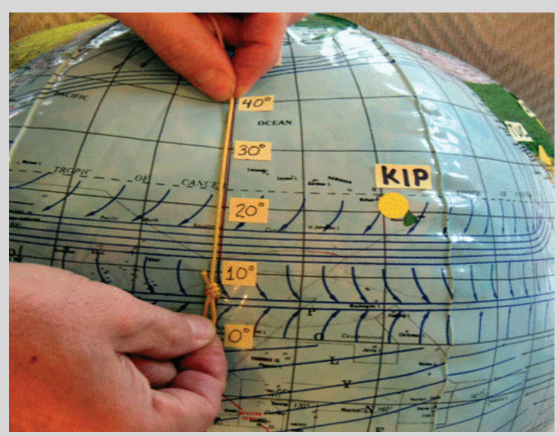
- 3 three-component seismograms for the same earthquake (Appendix C)
- 1 copy of the Travel time curve (Appendix A or B)
- 1 globe (inflatable globes are available online for $3-$7 each), or map (www.eduplace.com/ss/maps/pdf/world_country.pdf), or access to (www.iris.edu/hq/inclass/software-web-app/639) for locating epicenters online.
- String and overhead pen, if using globe, or safety compass (available online for $2), if using map
- Map with tectonic plates illustrated (www.iris.edu/hq/inclass/software-web-app/639.) Appendix D has tectonic map example from http://ds.iris.edu/ieb
- Map with global and/or regional seismicity illustrated (www.iris.edu/hq/inclass/software-web-app/639 or http://ds.iris.edu/ieb)

PRIOR KNOWLEDGE & RESOURCES

1. *Instructor Background* and *Other Things to be Aware of* (Page 5)
2. Watch video lecture about locating an earthquake's epicenter:
   www.iris.edu/hq/inclass/video/110
3. Provide students with instruction covering the basic differences between P and S waves.
   Watch animation about 3-Component Seismograms:
   www.iris.edu/hq/inclass/animation/115_
   A suggested student activity for this instruction includes the "*Human Wave*":
   - Lesson: www.iris.edu/hq/inclass/lesson/32
   - Video: www.iris.edu/hq/inclass/video/254
4. Provide students instruction on the basics of seismographs.
   - How does a seismometer work:
     www.iris.edu/hq/inclass/fact-sheet/14
   - Seismograph animation:
     www.iris.edu/hq/inclass/animation/100
   - Build your own seismograph:
     https://bcespcurriculum.wordpress.com/exercise-1-build-your-own-seismograph/

TIPS

- Due to the inherent distortion in most maps, caused by making a 3-dimensional object into 2 dimensions, the scale changes as you move north or south of the equator. In order to triangulate for earthquake location, it is important that both distance and angle from each station to the earthquake epicenter be accurate. This is possible when drawing circles on a paper map only for carefully chosen map projections centered near the earthquake location. Of course, this gives away the answer; the earthquake will be near the center of the map. However our Earthquake Triangulation app (www.iris.edu/hq/inclass/software-web-app/639) draws the "circles" for the students so that the distances are correct even though the larger "circles" may not appear to be round.
- By using a globe, the problems of map projection is eliminated. The shortest path between seismograph station to earthquake epicenter is often over the North or South pole, and this is easily measured (and seen) on a globe. To measure distance on a globe, students should measure a length of string along the equator (a great circle). Next, place one end of the string at the seismograph station location, the circle swept out by rotating the string around this gives all possible locations for the earthquake source.



Determining the distances using Great Circle

LESSON DESCRIPTION

1 Instruct students how to identify P & S waves on a seismogram (See "*Prior Knowledge*", page 2, and "*Instructor Background*", page 4.)

2. The student should be familiar with the travel time curve, and what it represents. They should be able to identify the P and S wave travel time curves (See Appendices A & B; watch animation on Travel-time Curves: www.iris.edu/hq/inclass/animation/120). Students can also explore recordings of seismogram s near them and see examples of P and S wave arrival time picks using the Station Monitor (www.iris.edu/hq/inclass/software-web-app/573).

3. Note that different time and distance scales are used on seismograms, travel time curves, globes and/or maps.

STUDENT PROCEDURES

1. Identify P and S waves in their seismograms
2. Measure the time between arrivals of the P wave and the S wave
3. Use this time to mark on the Y axis of the travel-time curve the distance the epicenter is away from the station
4. Measure out a length of string equal to the distance the earthquake epicenter is from the station. Use the distance scale on the map to determine string length. If using a globe, use the distance scale on the equator
5. Locate the station on the globe using the latitude and longitude of the station
6. Hold one end of the string on the station's location
7. Use the string to sweep out an arc on the globe representing the possible locations of the earthquake epicenter
8. Work together with other students that had the same earthquake (they should sweep out arcs from their stations as well) to narrow down the possible locations for your earthquake

POSSIBLE STUDENT PITFALLS:

1. Students may fail to realize that the three components of the seismograms indicate ground motion simultaneously in three directions. They sometimes think that one component follows the others in time.
2. Students may have trouble identifying P and S waves. Rather than interpreting the first P wave and the first S wave, they may be drawn to the largest waves.
3. Students may not measure the difference in time between the S wave arrival and the P wave arrival. Instead, they may simply measure the arrival time of one or the other wave. Students may also have difficulty with measurements on the time scale of the seismograms.
4. Students may not realize that the travel time curve likely has a different time scale than the seismograms. After measuring the time difference appropriately, students may not keep their measurements on the travel time curve aligned with the time axis. This is necessary in order to measure time difference at a single distance. Finally, students may have difficulty reading this distance from the travel time curves.
5. Students may have difficulty measuring angular distance on a globe. They may try to measure distance along lines of latitude which are not great circles. They may confuse the latitude and longitude of their station with the angular distance determined from travel time curves.
6. Students may have difficulty locating their seismograph station on a globe. They may confuse latitude and longitude, or may neglect whether these are N, S, E or W. This is a useful learning exercise. The seismograph stations have letter names which indicate the nearest town or region, but these may not be labeled on the globe.
7. Even with no apparent errors in procedure, students' triangulations may not meet at a point. The most likely cause is that the earthquake occurred at a depth significantly different than assumed for the travel time curve. With the expected level of measurement error in time and distance in the various stages of this exercise, it is not unusual to have a gap of a few degrees in triangulating. Larger misfits probably indicate misunderstandings in interpretation or incorrect procedure. If more than three students interpret seismograms from a single earthquake, some sets of three may find consistent results, while others have discrepancies. This indicates an error by one of the students in the group with discrepancies.

INSTRUCTOR BACKGROUND

The vast majority of the millions of earthquakes that occur every year around the world are too small to be felt by humans. The larger ones, greater than magnitude 5, can effect human property and life if they occur near a populated area. Because most of Earth's surface is not populated, most of the earthquakes that occur each year are not felt either because they are too small, or they are in an area where no one is around to make a direct observation of their movement.

Earthquakes help us understand both plate tectonic processes and where future earthquakes are likely to occur. Thus it is important to know how to locate earthquakes. The primary tool seismologists use to locate an earthquake's epicenter is a network of seismometers. Seismometers are designed to be sensitive enough to feel even the smallest motion of the waves coming from distant locations on Earth. By combining measurements of wave arrival times at three or more seismograph stations, the earthquake's source can be located.

There are several thousand seismic stations around the world; each one continuously monitoring the Earth's surface for earthquake shaking. Organizations such as the Incorporated Research Institutions for Seismology (IRIS) gather and archive data from these stations in a central database. These data can then be accessed by anyone interested in learning more about earthquakes. See, for example, the *Station Monitor* (www.iris.edu/hq/inclass/software-web-app/573), which is also available for smartphones.

Some other things to be aware of are that:

- Modern seismic stations produce a 3-component seismogram simultaneously. One seismogram shows vertical motion, one shows east to west motion, and another shows north to south motion (Figure 2), and see animation.
- Because body waves come up from below the surface, P wave motion is usually greatest on a vertical component seismogram, while the S wave usually registers a stronger signal on the horizontal component seismograms (Figure 3).
- Students will need help in identifying P and S waves on seismograms. The P wave is the first signal to appear on the seismogram, and is best identified on the vertical component. The S wave arrives later, and should be the first signal to arrive with its amplitude on the

VOCABULARY

Earthquake: The sudden sudden release of potential energy stored elastically in a fault, and the result¬ing ground shaking and radiated seismic energy caused by the slip.

Body Waves—waves that move within the Earth's interior or within a body of rock. P and S waves are body waves. See Surface Wave.

P Wave—the primary body wave; the first seismic wave detected by seismographs; able to move through both liquid and solid rock. Also called compressional or longitudinal waves, they compress and expand (oscillate) the ground back and forth in the directionof travel, like sound waves that move back and forth as the waves travel from source to receiver. P wave is the fastest wave.

S Waves—shear waves that are secondary body waves that oscillate the ground perpendicular to the direction of wave travel. They travel about 1.7 times slower than P waves. Because liquids will not sustain shear stresses, S waves will not travel throughliquids like water, molten rock, or the Earth's outer core. S waves produce vertical and horizontal motion in the ground surface.

Surface Wave—waves that move close to or on the outside surface of the Earth rather than through the deep interior like the faster P or S waves. Two principal types of surface waves, Love and Rayleigh waves, are generated during an earthquakes.Rayleigh waves cause both vertical and horizontal ground motion, and Love waves cause horizontal motion only. They both produce ground shaking at the Earth's surface but very little motion deep in the Earth. Because the amplitude of surface waves diminishes less rapidly with distance than the amplitude of P or S waves, surface waves are often the most important component of ground shaking far from the earthquake.

horizontal components larger than that on the vertical component. The S wave may be a broader pulse than the P wave (longer period, or lower frequency). There may be several arrivals of P waves before the S wave arrives; students will interpret only the *FIRST* P wave and *FIRST* S wave.

- Travel time curves (Appendix B) indicate the arrival times of various waves with increasing distance from the earthquake source. Time is plotted in minutes and distance is plotted in degrees (the opposite side of the Earth is at a distance of 180 degrees). The P wave curve and the S wave curve should be indicated, and these are the ones the students will use. (Watch video demo: https://www.iris.edu/hq/inclass/video/110) There are many other P and S wave curves (Appendix A), representing reflections and refractions from layers within the Earth. These will not be used, but will help students see what the later-arriving P waves and S waves represent. (Watch animations on P waves: (www.iris.edu/hq/inclass/animation/123) and S waves (www.iris.edu/hq/inclass/animation/206).
- Measuring the S wave and P wave arrival times from only one station gives the distance from that station to the epicenter. However, the earthquake could be located anywhere on a circle centered on that station with a radius equal to the calculated distance. An estimate of the time of origin can also be calculated by subtracting the P wave travel time (as determined on the plot) from the P wave arrival time.
- Measuring arrival times at two stations should give you two possible locations of the epicenter, where the two circles intersect.
- Arrival times measured at three stations, minimum, are needed to triangulate epicenter location to a single point. Using more than three stations supplies redundant information, which is helpful if any errors in measurement or interpretation occur with the data from any one of the stations.
- Each student should work on seismograms from one station. Only by cooperating with other students who have worked on the same earthquake, but at different stations, can the earthquake be located. By teaming up, sharing data, and discussing interpretations and procedures, students can find their own mistakes in calculations.
- It can be a bit unwieldy having three students simultaneously measuring distances on a single globe, but this enables them to find and visualize the intersection point needed for triangulation. It will be necessary to have several globes or to schedule their use so that groups who have interpreted seismograms for the same earthquake can access the globe together.

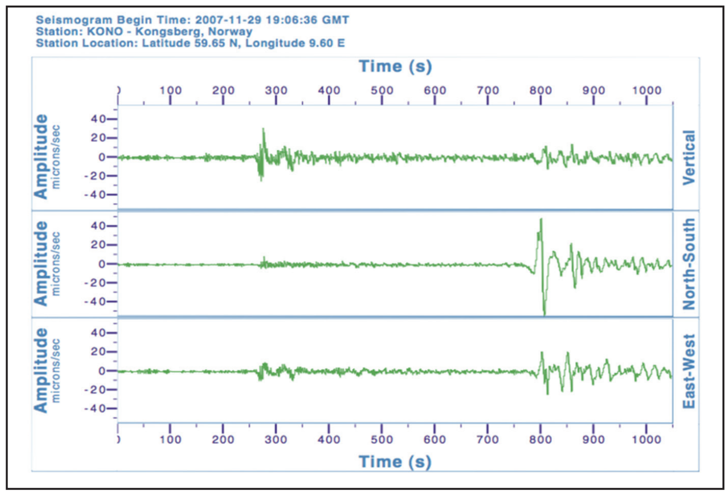


Figure 2 *– Modern seismic stations produce a 3-component seismogram.*

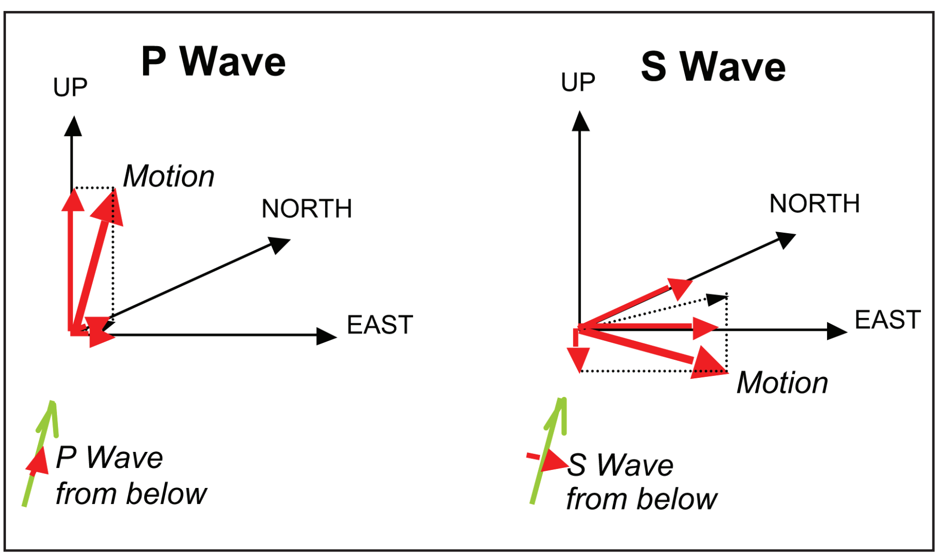


FIGURE 3 *–Since the motion of a P wave is in the direction the wave travels, for a wave coming up from below the seismograph station, the motion of the ground will be mostly vertical (up and down), with a smaller amount of motion on the horizontal components (North and East). By contrast, since the S wave motion is perpendicular to the direction of wave travel, an S wave coming up under the station will produce larger motion in a horizontal direction which will be some combination of the North and East component directions, and smaller motion on the vertical component. This concept can be clearly seen in Figure 2 and can also be shown using the animation available from* www.iris.edu/hq/inclass/animation/115.

Name ________________________________

IRIS
www.iris.edu

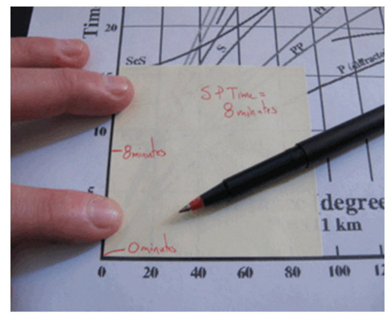
LOCATING AN EARTHQUAKE WITH SEISMIC DATA

1. Identify P and S waves on your seismogram
   What is the P arrival time? ____________________
   What is the S arrival time? ____________________

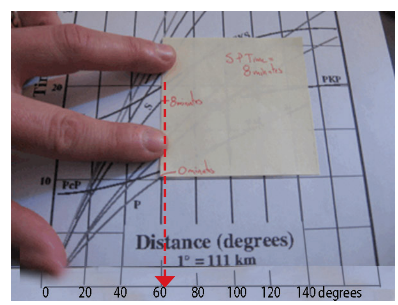
2. Determine the amount of time between arrival of the P and S wave (S minus P time) ________________

3. Determine the distance the epicenter is away from your station using the travel time curve. ________ Degrees

   a. Do this by creating a marker (on a piece of paper) on the y-axis of the graph that is equal to the S-P time you found in #2 above.



   b. Keeping the paper edge parallel with the y-axis, slide the paper to the right and upward. Find the spot in the graph where the marker you created fits between the S and P curves on the travel time curves.



   c. Read down from the edge of the marker to the x-axis to determine the distance from the station to the epicenter (see Arrow on lower picture).

4. Measure a length of string proportional to the distance from earthquake's epicenter to the station (determined in 3c above) on the globe. Hint: the equator is the best place for measuring this length.

5. Find the station on the globe using the latitude and longitude of the station

6. Hold one end of the string on the station location. Stretch out the string and use the other end to sweep out an arc on the globe. This arc represents all the possible locations of the earthquake epicenter.

7. Describe what you learned from analyzing your data alone.

8. Work together with other students that had the same earthquake to narrow down your search by having them sweep out an arc for their station.

9. What was the latitude and longitude of the location where all three (or four) strings met?

Lat: ___________________________

Long: __________________________

a) What is the nearest geographic location to this point? ______________________________

10. Describe, step-by-step, how using more data narrowed down the possible epicenter locations.

11. Locate the epicenter on the map showing Earth's tectonic plates on the last page of this handout. Based on the map, is your solution logical? Would you expect an earthquake in this area to be fairly common or rare? Explain your answer fully.

INSTRUCTOR ANSWER SHEET:

QUESTIONS

7. **Q**: Describe what you learned from your data alone.

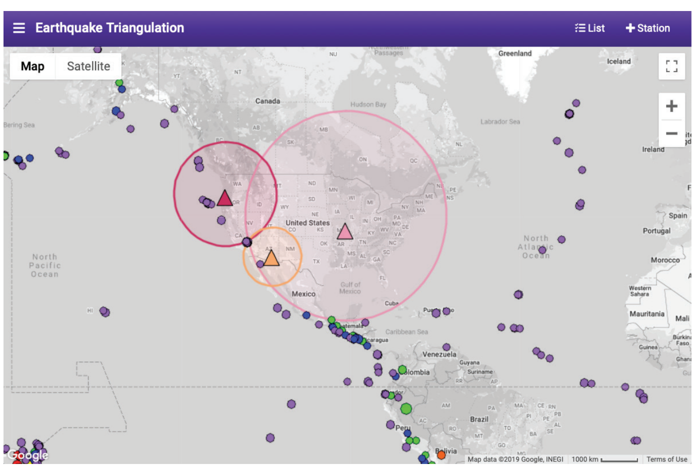
A: The student learned the distance from the epicenter to the seismic station

10. **Q**: Describe step by step how using more data narrowed down the possible epicenter locations.

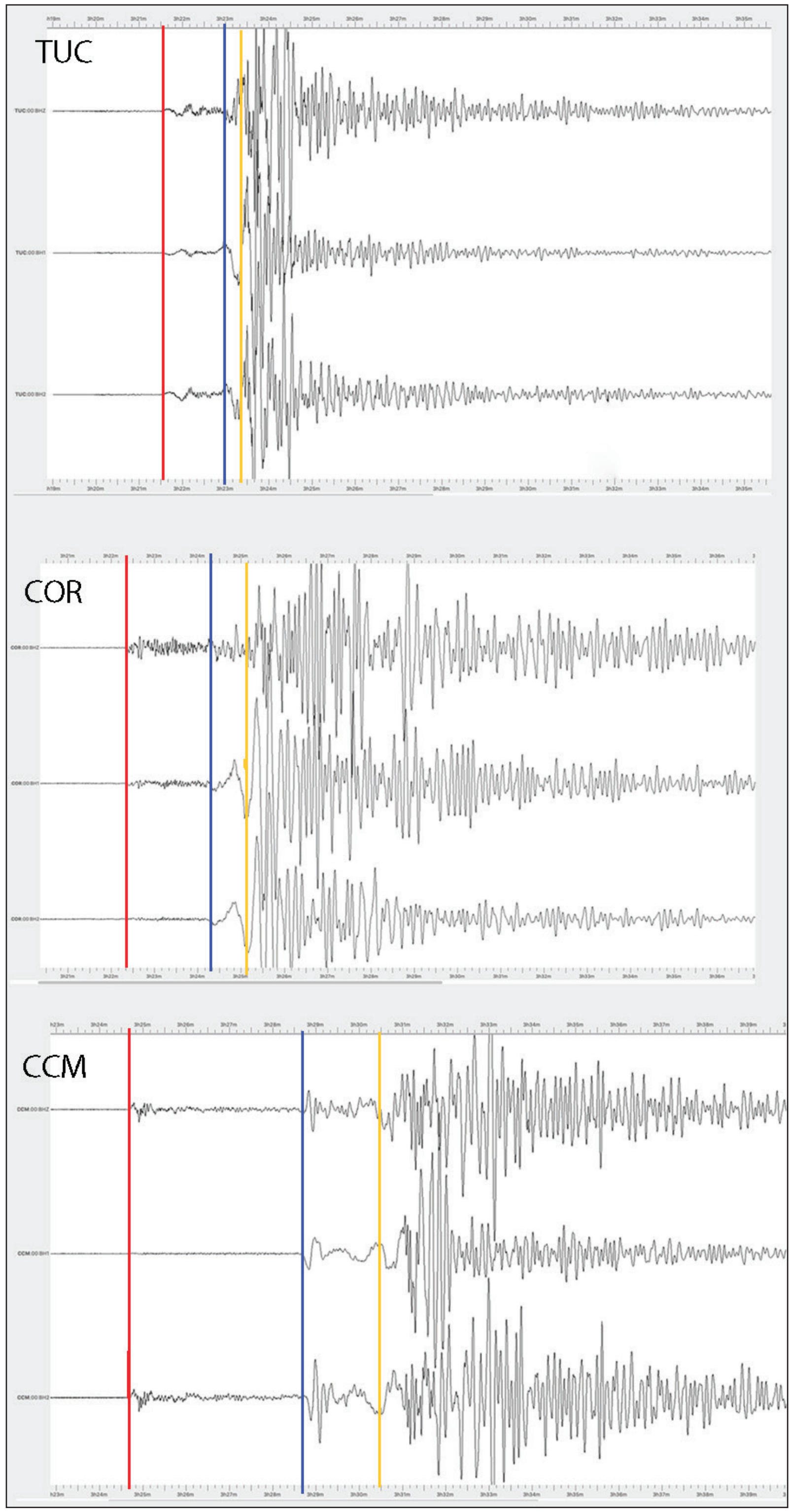
A: With one data set, the epicenter could be anywhere on the circle, two data sets narrow the possible locations to two (where the circles intersect), and three or more data sets pinpoint the location of the epicenter being where all of the circles intersect.

11. **Q**: Locate the epicenter on a map showing Earth's tectonic plates. Based on the map, would you expect an earthquake in this area to be fairly common or rare? Explain your answer fully.

A: It depends on the event. Most likely the event is located in close proximity to a plate boundary. Earthquakes are common near most plate boundaries due to the motions of one plate with respect to the adjacent plate.



Solution for triangulating the student's 3 seismic stations as derived from IRIS's online app "Triangulation".

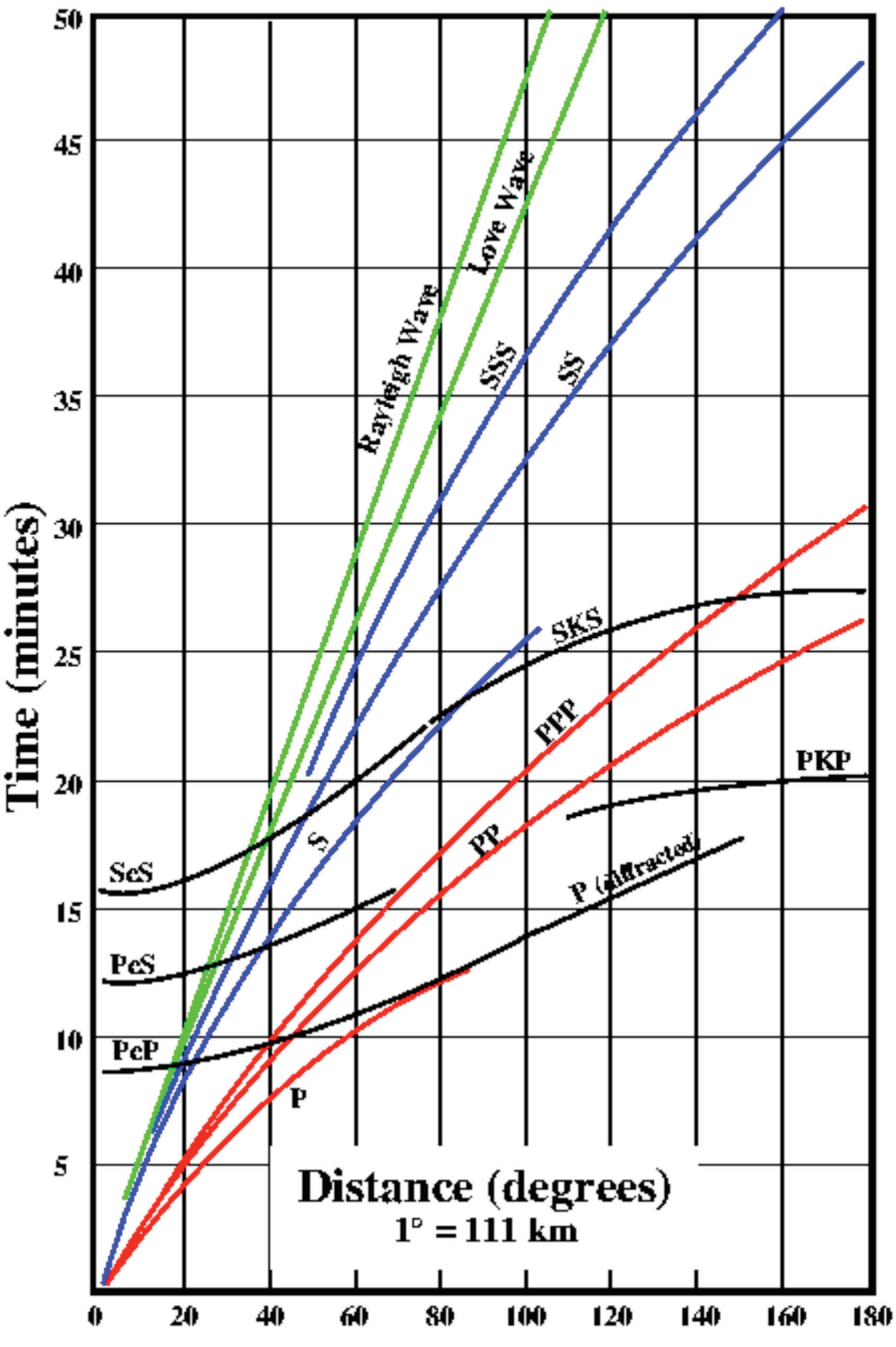


P (red), S (blue) and Surface (Yellow) wave picks for the three stations in the student worksheets

APPENDIX A

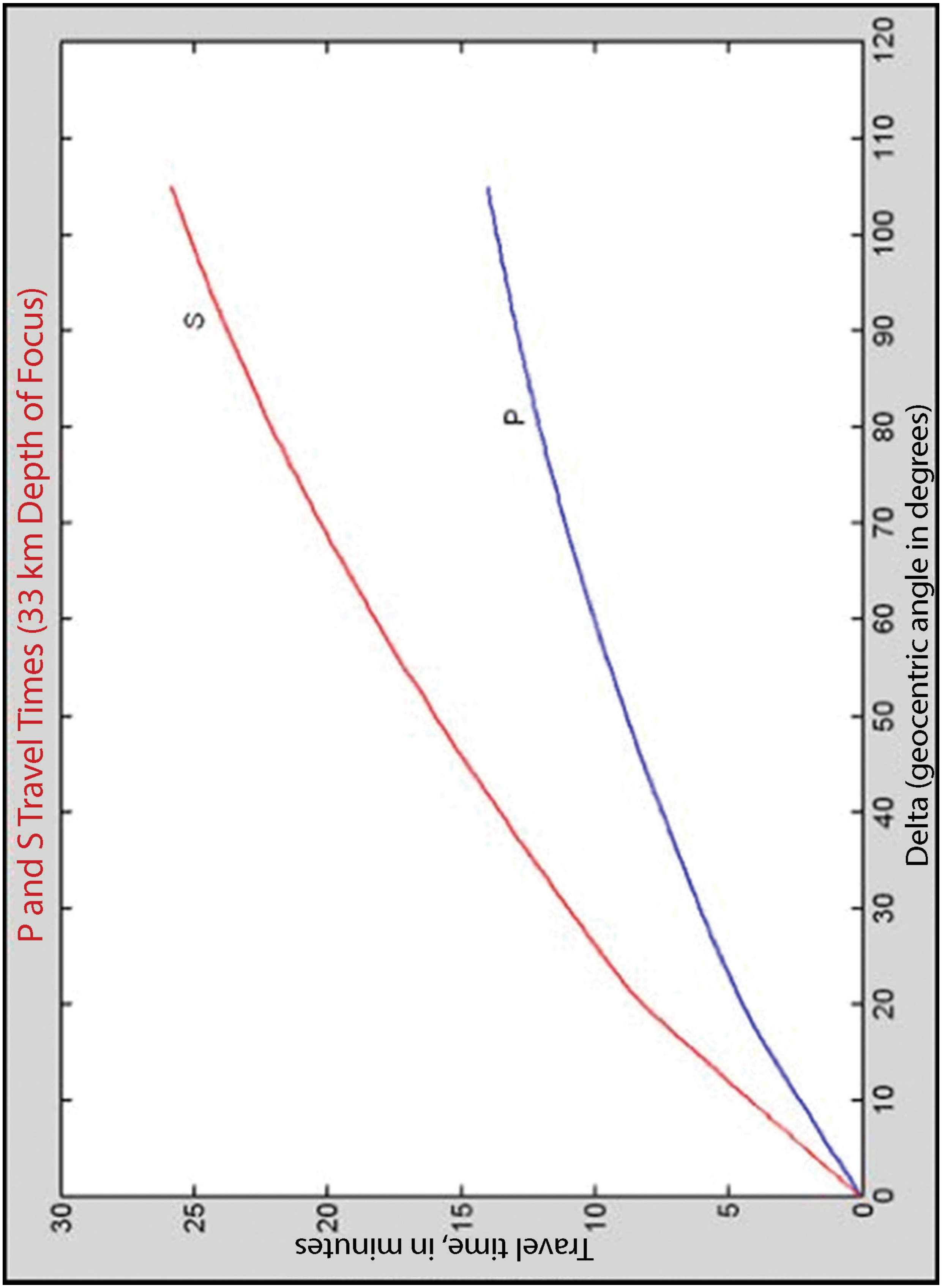
Standard Earth travel time curves for a source depth of 0 km. Travel times for many different phases (types of seismic waves and paths through the Earth) are shown. The first (or direct) P and S arrival times are shown by heavier lines. Note that the difference between the S and the P times increases smoothly with distance. Therefore, a seismogram with a given S minus P time will only match the travel time data at one specific distance.

Animation describes where travel-time curves come from: *www.iris.edu/hq/inclass/animation/120*



APPENDIX B

Standard Earth travel time curves for a source depth of 0 km. Travel times for many different phases (types of seismic waves and paths through the Earth) are shown. The first (or direct) P and S arrival times are shown by heavier lines. Note that the difference between the S and the P times increases smoothly with distance. Therefore, a seismogram with a given S minus P time will only match the travel time data at one specific distance.



Seismograms for use in locating an earthquake, as described in the exercise

How Do We Know Where an Earthquake Originated?

https://www.iris.edu/hq/inclass/lesson/439

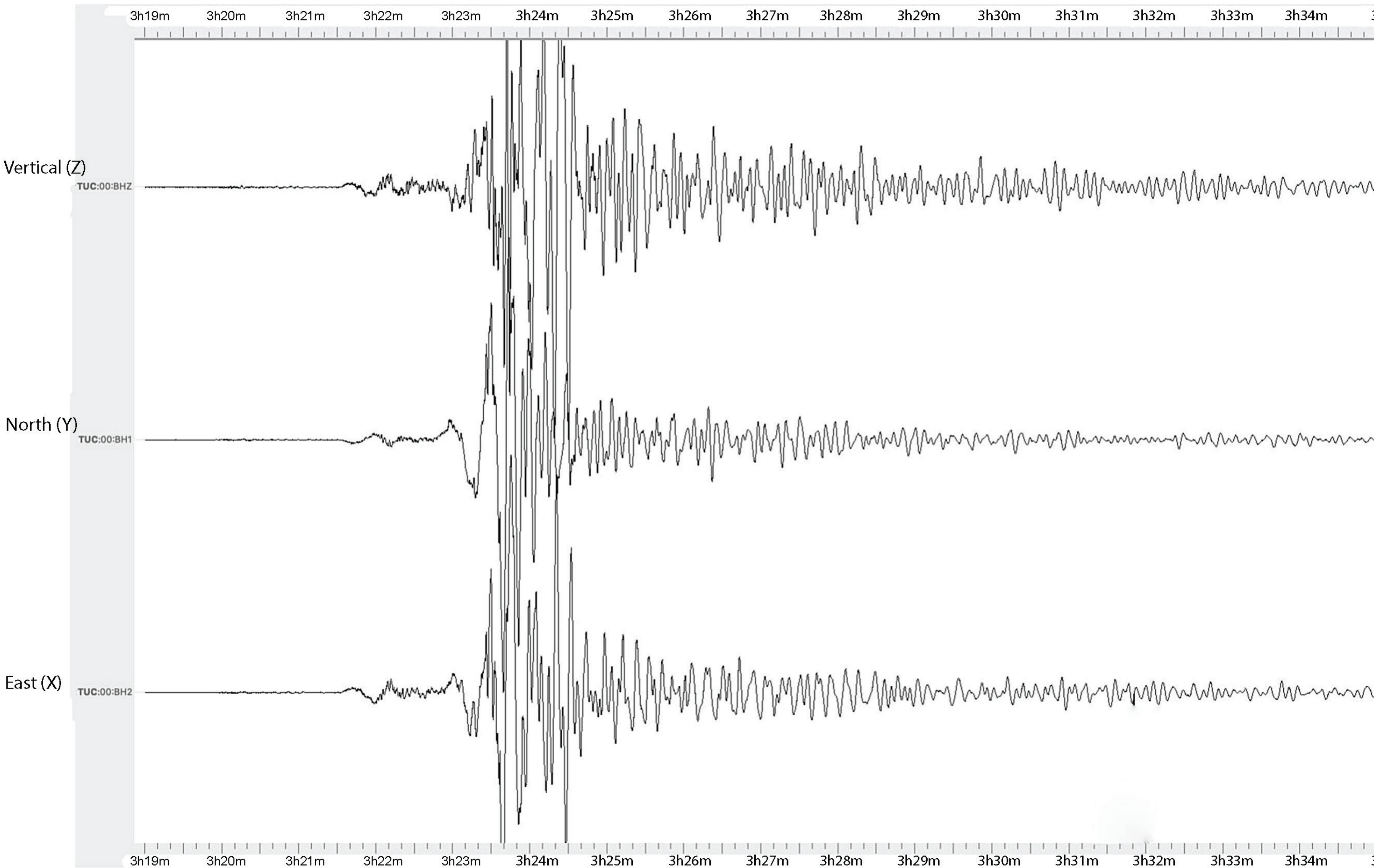
The attached three sets of 3-component seismograms can be used by students to learn about one of the ways that earthquakes can be located. The data are from three seismic stations in the U.S. that recorded the magnitude 7.1 Ridgecrest, CA earthquake that occurred on July 6, 2019 (35.76°N 117.60°W). Each of the three sets of seismograms are plotted at the same time scale, and show the vertical sensor (BHZ) and the 2 horizontal sensors (BH1 and BH2) that are perpendicular to each other. The station names and their locations are listed on each sheet. The P wave arrival is often a little clearer on the vertical and the S wave arrival is usually easier to pick out on one or both of the horizontals. For the two closer stations, TUC and COR, the S wave and surface waves arrive at nearly the same time, whereas for station CCM, the surface wave arrival is later and much larger than the S wave arrival.

The Incorporated Research Institutions for Seismology (IRIS) operates the SAGE facility, which is funded by the National Science Foundation

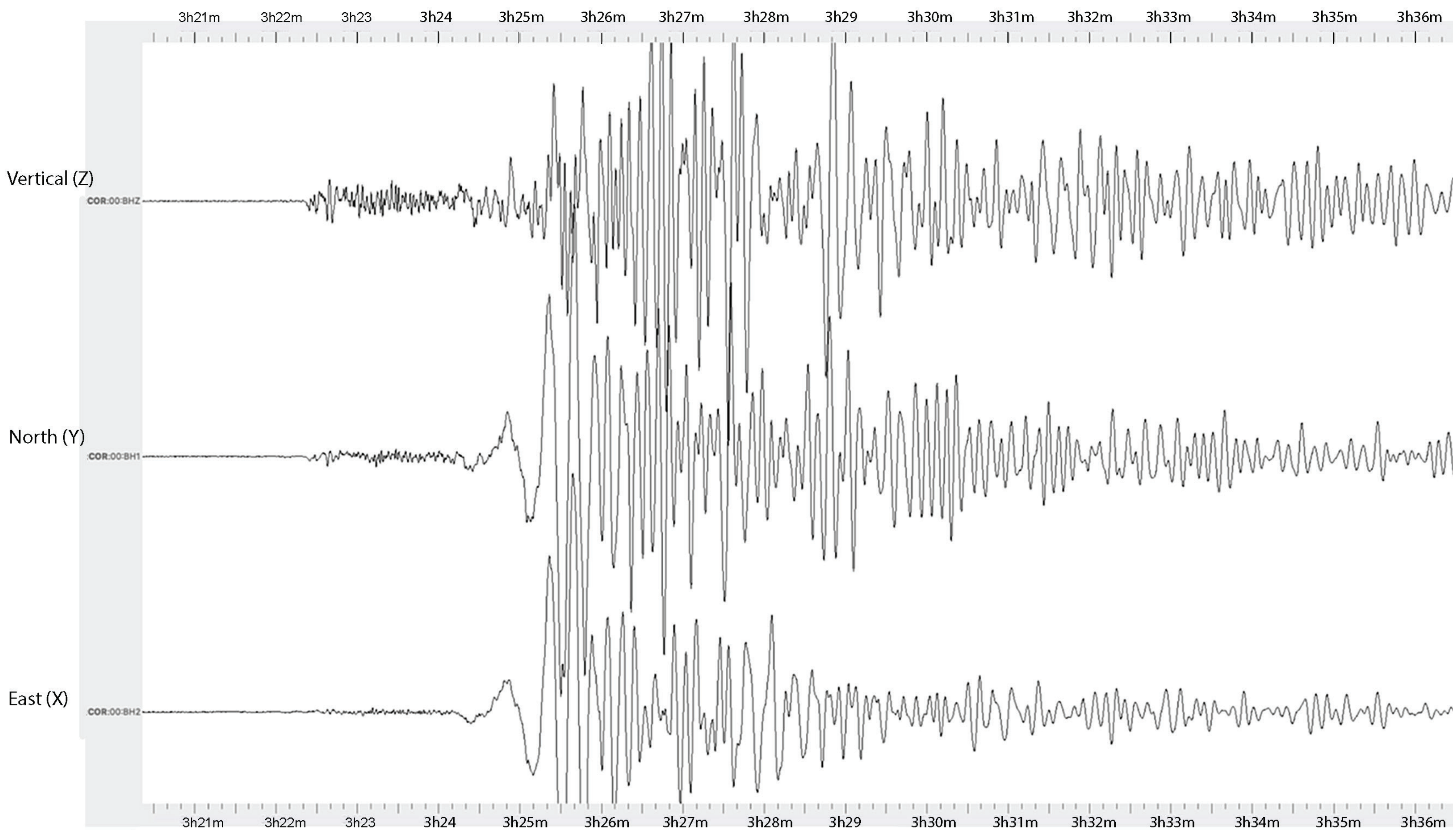
10/17/19

Seismic Station **TUC** (Tucson, AZ)

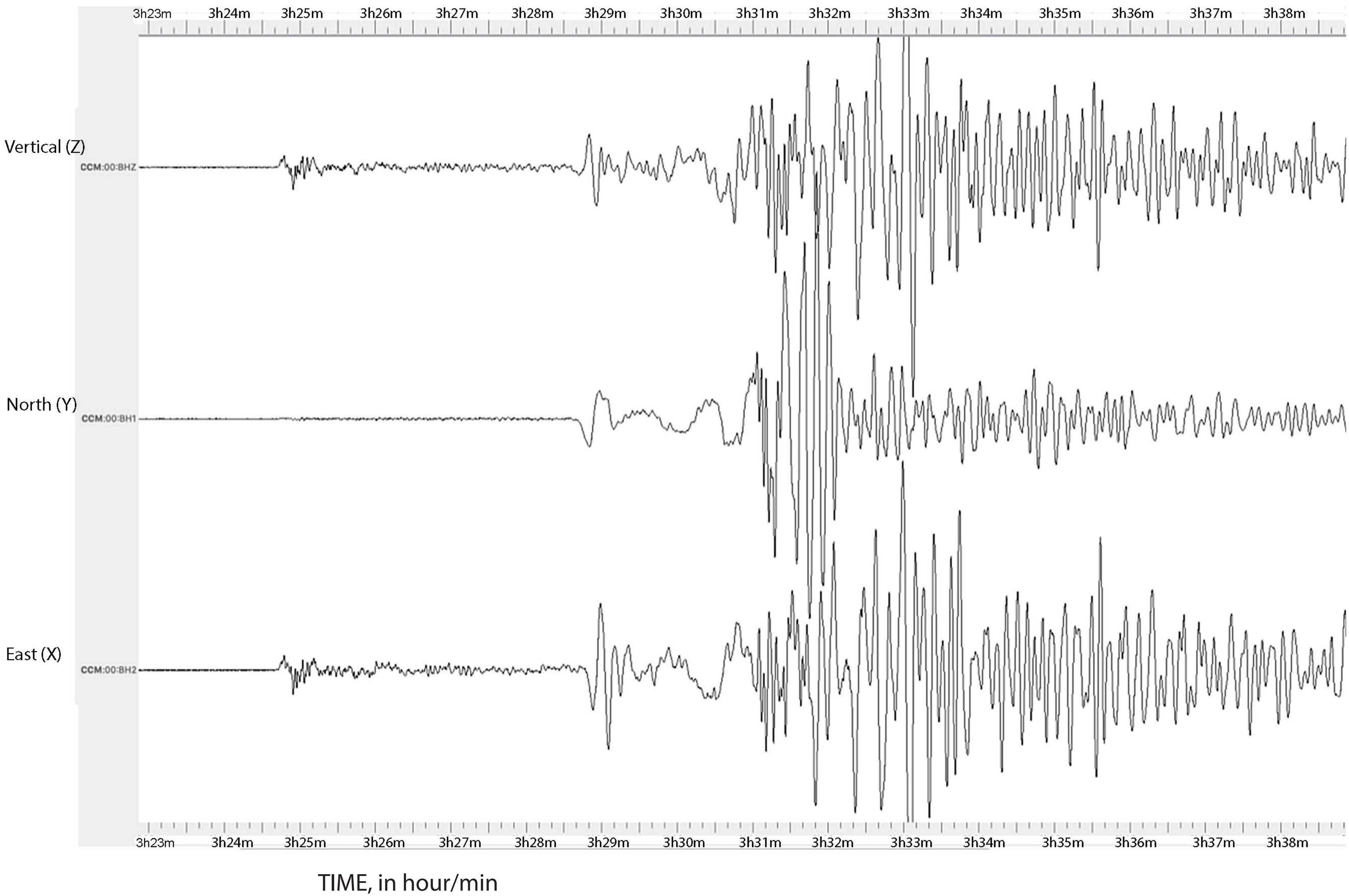
Latitude 32.31 degrees, Longitude -110.78 degrees

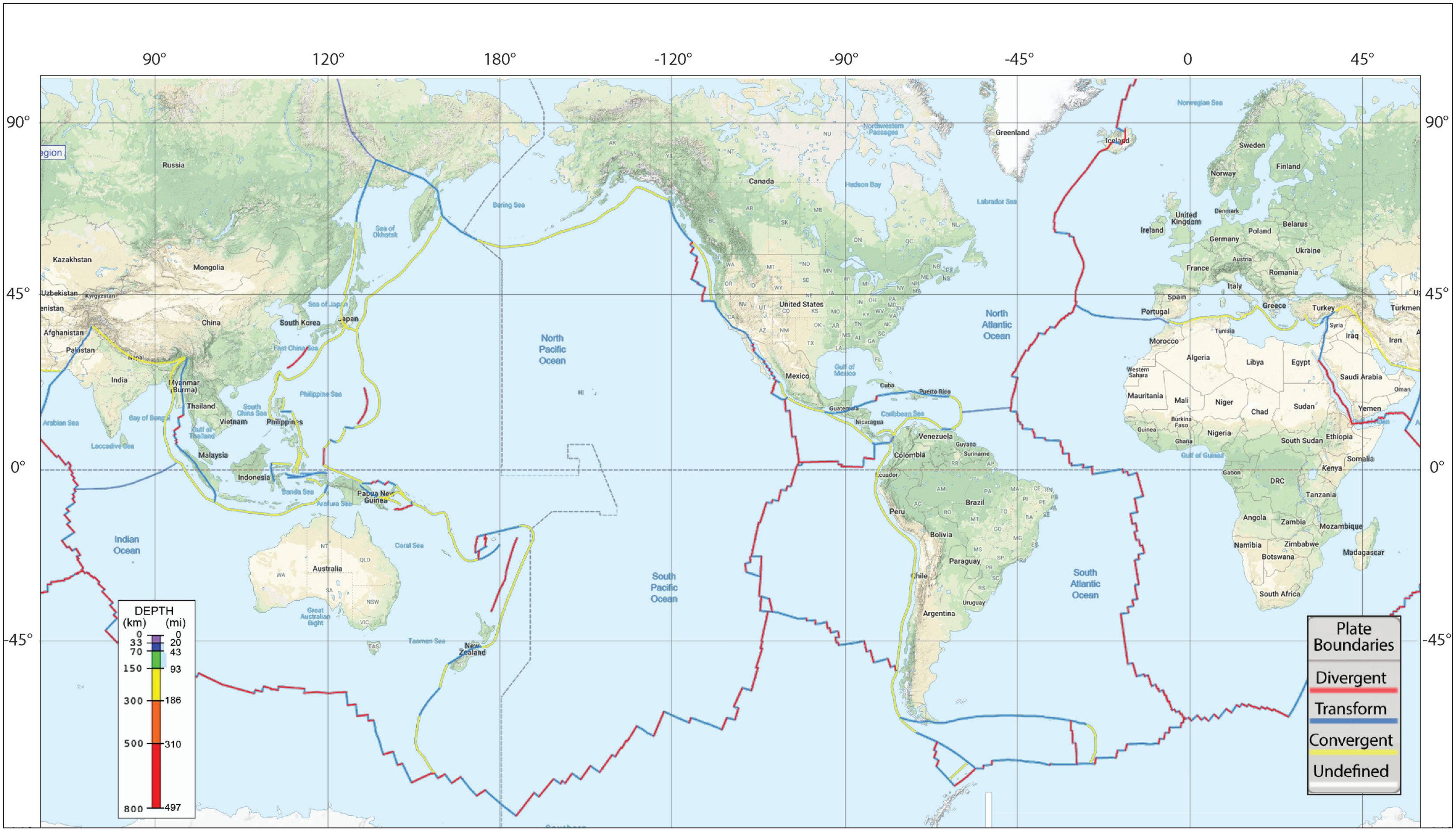


Seismic Station **COR** (Corvallis, OR)   Latitude 44.59 degrees, Longitude -123.30 degrees



Seismic Station **CCM** (Cathedral Caves, MO) Latitude 38.06, Longitude -91.24





World map from IRIS Earthquake Browser (www.iris.edu/ieb)