How Shallow Earth Structure Is Determined: A Classroom Exercise Demonstrating Seismic Refraction Use in the Real World

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Expanded from "Looking for what you can't see" (Neal, 1998)

Time: 90 Minutes
Grade Level: 11th and 12th Grade physics students

5-E Phase:
This activity is intended as a Extend Phase activity to provide students with a real-world application for the concepts of waves. This should follow an Explore/Explain phases activity, such as the traditional light lab that explains concepts included in this lab such as reflection, refraction and transmission of energy.

Objective(s):
Explore how refracted seismic waves are used to determine earth structure.
Reinforce the concepts of reflected and refraction of waves through a real world example.

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Materials List

Download the associated powerpoint available on the web at
http://www.iris.edu/hq/resource/how_shallow_earth_structure_is_determined
Copies of student worksheets and homework found in Appendix A

Lesson Description: Quick Summary

OPERA	*Activity*	*Time*
***O**pen*	*Intro discussion about what allows us to "see" or image what is inside earth*	*10*
***P**rior Knowledge*	*Diagram reviewing reflection, refraction and ray-path angles in different materials*	*10*
***E**xplore/**E**xplain*	*Students design the geometry for an experiment, analyze data from an experiment, and use visualizations of wave fronts to correlate the data and the real phenomena*	*45*
***R**eflect*	*Connect past concepts to new situation*	*10*
***A**pply*	*Students analyze real data from New Zealand*	*15 + Homework*

Lesson Description: Teacher Instructions (*w/ Potential Questioning Sequences*)

Open – 10 Minutes

O. Taxonomy	*Question*	*Answer*
Knowledge	What is under our feet?	Accept all answers, but lead students to see that they may have a general sense of what is under our feet but they the lack resolution to see very far.
Comprehension	What do we need to be able to see inside of something like the Earth?	You are likely to get X-ray as a response.
Knowledge	Can an x-ray see through everything? What about lead or a really thick object?	Lead students to see that an x-ray won't work because the materials that make up the Earth are too dense and thick
Knowledge	An x-ray was a great idea, so maybe something like it. What IS an x-ray?	Accept all answers but lead students to the idea that an x-ray is a form of energy.
Knowledge	Maybe we could use another form of energy. What form of energy could we get to travel through the earth?	Accept all answers but lead students to seismic energy.
Comprehension	Can we create a seismic wave?	Accept all answers
	Have a student(s) go to the back of the room and put their ear to the ground on a piece of paper, while you climb onto a chair in the front of the room and jump off. Ask the student(s) to describe to the rest of the class what they experienced.	
Knowledge	What did the person jumping off the chair do?	Created the sudden pulse of energy or the seismic wave. Thus they are the source.
Knowledge	What did the person listening to the floor do?	Detected the seismic wave as it traveled to them. Thus they are the sensor.
Comprehension	Predict how your experience might have differed if we were on a mat in the gym or if they were on the wooden	Lead students to the idea that the "sensor" would have experienced the same jump differently depending on what material

	gym floor, or if we were on a giant piece of metal.	they were on. This is the same principle used to determine the shallow structure of the Earth. Seismic waves can tell us something about the material they are traveling in.

Prior Knowledge – 10 Minutes

Distribute Student Handout #1 "What do you know?" Students should have ~5 minutes to complete the handout leaving 5 Minutes for reviewing answers. When discussing answers be sure to survey the class before accepting an answer to get an idea of how confident students are about these topics. If students are unsure of these basics, a quick review may be necessary before proceeding.

P. Taxonomy	*Question*	*Answer*
Knowledge	1. Which letter indicates the direct ray?	C or B
Knowledge	2. Which letter indicates the reflected ray?	B_1
Knowledge	3. Which letter indicates the refracted ray?	B_2
Comprehension/ Analysis	4. In which layer does the energy travel the fastest? How do you know this?	Layer 2 is the fastest. You know this because the B_2 bends away from the normal. *NOTE BELOW

*Note – It is important to note that optical density (describes the speed of light in a transparent material) which students will be familiar with is not the same as mass density. The speed of seismic waves generally increase with depth as does the density (ρ = density) of Earth materials, therefore many people incorrectly assume that the velocity of seismic waves increases as density increases. However, as shown by the equation below the increase in the speed of seismic waves is a result of the rigidity (μ = resistance to shearing) and incompressibility (κ = resistance to compression) of the material increasing with depth faster than density. For example the velocity of a primary wave (V_p) is determined by $V_p = ((\kappa+4/3\mu)/\rho)^{1/2}$. We can also use this to explain why secondary waves don't travel through liquids. The velocity of an s-wave (V_s) is determined by $V_s=(\mu/\rho)^{1/2}$. Since liquids don't support shearing μ is equal to zero thus V_s in a liquid must be equal to zero.

Explore/Explain – 45 Minutes
Handout Student Worksheet #2.

E. Taxonomy	*Question*	*Answer*
Knowledge	1. Based on our previous discussion and human simulation, what two components will we need collect information about what is below the surface without digging?	We need a source and a sensor.
Comprehension	2. Draw the components you listed above on the diagram in a position or geometry that would provide us with enough information to help the school district.	Students will draw their source and sensors in a variety of different arrangements. The discussion should focus on the fact that the source will send energy out in all directions, however for each sensor

		placement (assuming that there is a bedrock layer down there) there are only two paths from source to sensor, direct and reflected/refracted. Therefore, we need multiple sensors to find out about the entire area.
Comprehension	Now that we have our experiment designed, lets pretend we go ahead and set off the explosion and the waves travel to the sensors. What can we actually measure?	Lead students to the idea that we can measure the distance from the source to each sensor, and that we can measure the time it takes for the seismic waves to travel from the source to each sensor. Thus, if we have a distance and a time we can calculate a velocity.

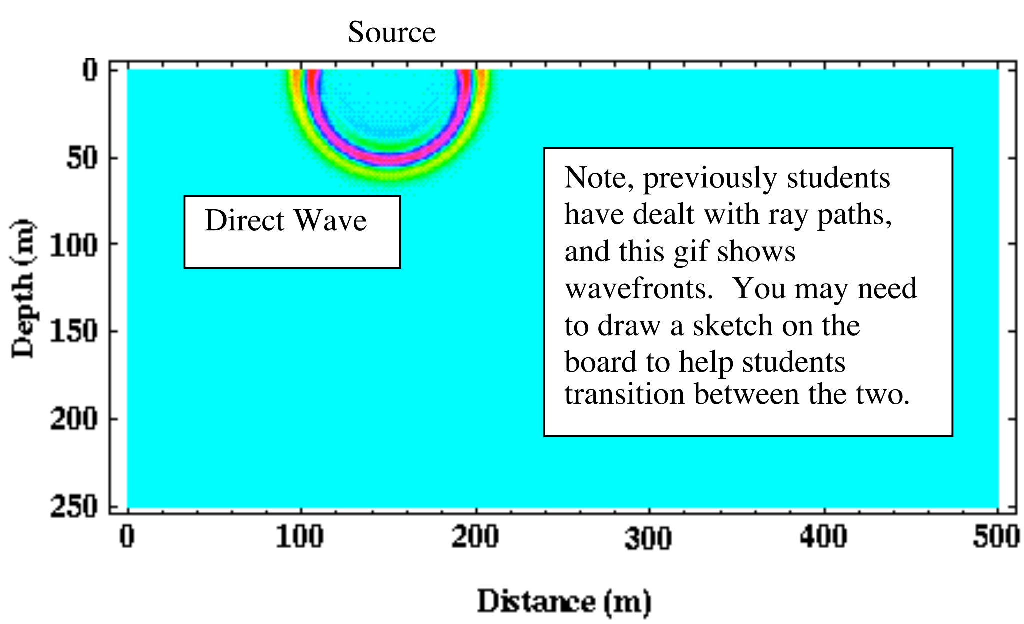
A local geophysics consulting firm has conducted the survey we have just designed and the data is now in. Distribute Student Handout #3.

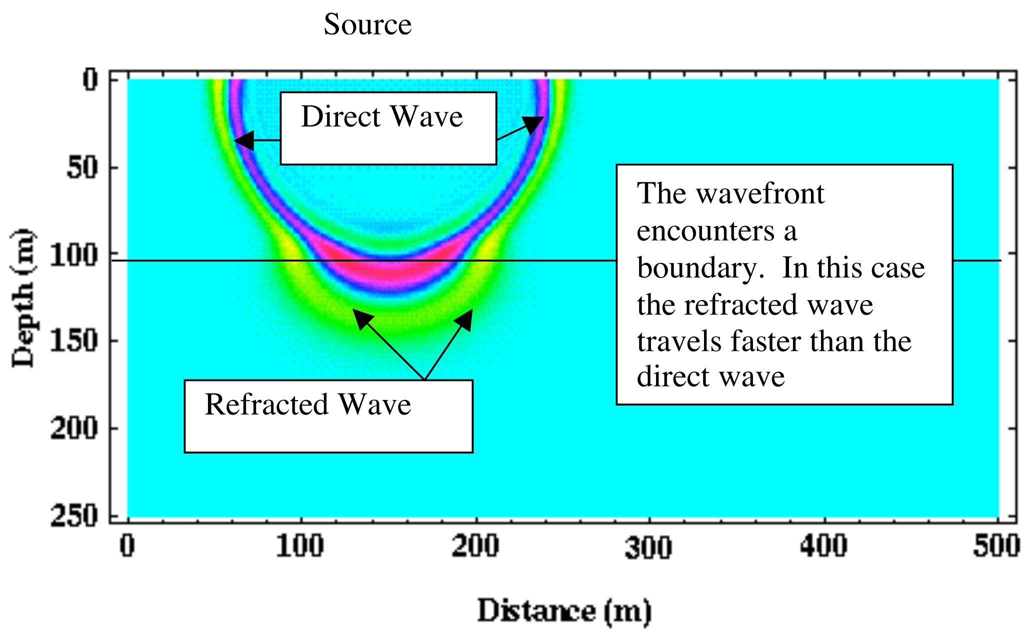
E. Taxonomy	*Question*	*Answer*
Knowledge	This is seismic data, however as I am sure you have already noticed, it is nothing more than a graph. So what information does this X-axis tell us? The Y-axis?	The X-axis shows distance from source to geophone in meters. The Y-axis shows time in seconds.
Comprehension	If you follow down the line at 30 meters you notice that for part of the way the line is nice and straight and then once it gets to 0.032 seconds the line begins to change or move back and forth. What do you suppose that this is telling us?	These are seismograms. Thus the point at which the wiggling starts is the time at which the seismic waves arrived at the geophone or sensor.
Application	So we can tell what time the seismic waves first arrive at each point! Since we know where each sensor is located and we know the time since the explosion occurred, what can we determine about the wave traveling to each point?	Since we know time and distance we can determine the velocity of the wave to each sensor.
Application	If we assume that the material the wave is traveling through is made of the same material, what would this mean for the velocity of the wave traveling though it?	If the material is the same then the velocity of the wave should be constant.
Analysis	What would the shape of a constant velocity be on a graph of distance and time?	A constant velocity shown on a distance versus time graph would be a straight line where the slope would be a function of the velocity. Given our graph the velocity is the inverse of the slope.
Once you have established that a sloping line on a distance versus time graph tells us a constant velocity,		

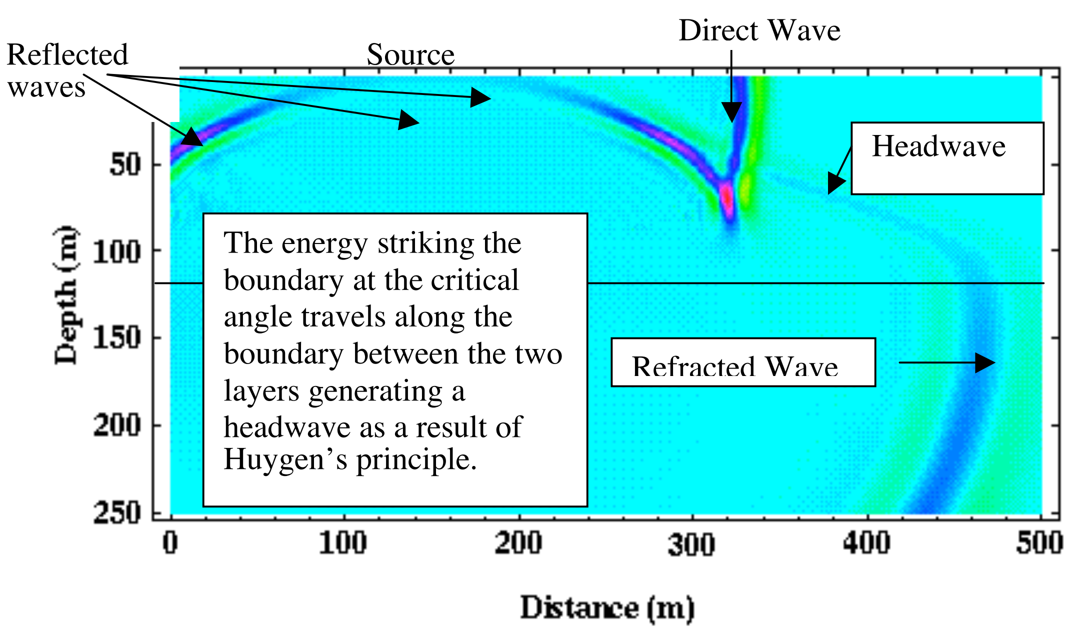
*ask students to determine the velocity of the wave by drawing a line on their graph. *Note: students will not be able to fit all points to one line. Thus many students will attempt to best fit a line to the points. The solution is that two lines or velocities must be used.*		
Analysis	If two lines must be used what does that mean about the material that the seismic wave is traveling in?	If two lines must be used then it means that the wave must be traveling through two different mediums each with a different velocity.

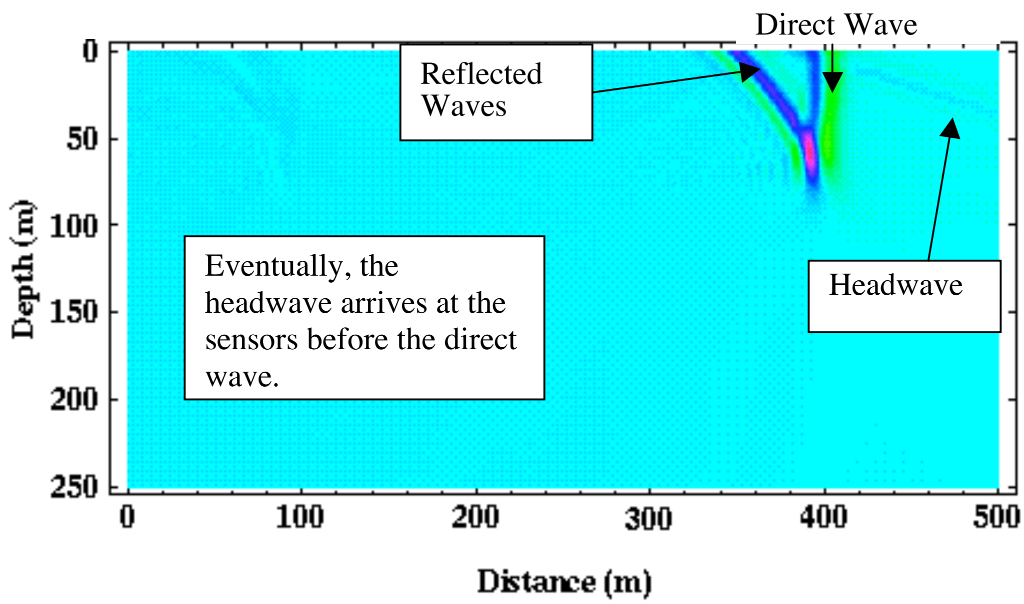
Why does the data look the way it does? To help you understand the data we have just looked at, lets look at a mathematical model of waves traveling in the earth. Show the series of gifs in the powerpoint. On the next two pages, several key images from the powerpoint have been annotated for you.

E. Taxonomy	*Question*	*Answer*
Knowledge	What is a model?	
Knowledge	Show the first image of the power point. Is this a photograph of the inside of the earth? Does this model actually exist?	No. It is a hypothetical description of a complex entity or process. In this case it shows wavefronts traveling through two different mediums where the bottom medium allows the seismic waves to travel faster. No. This is a model created in the computer.




Source
Direct Wave
The wavefront encounters a boundary. In this case the refracted wave travels faster than the direct wave
Refracted Wave
Depth (m)
0
50
100
150
200
250
0
100
200
300
400
500
Distance (m)


Reflected waves
Source
Direct Wave
Headwave
The energy striking the boundary at the critical angle travels along the boundary between the two layers generating a headwave as a result of Huygen's principle.
Refracted Wave
Depth (m)
50
100
150
200
250
0
100
200
300
400
500
Distance (m)



You will probably need to step through the powerpoint many times to help students visualize this. Once students begin to grasp the concept, begin referring back to the data to help them transition between a graph and what the graph actually means "in the ground."

E. Taxonomy	*Question*	*Answer*
Application	Where is the headwave in our graph?	The second velocity on the graph is the headwave arriving before the direct wave.
Synthesis	Now that you have seen the data and the model, suppose that you got some weird data back from somewhere in the field. Do you think the model could be helpful?	Accept all answers, but lead students to see that you could alter the model until you got something that matched the strange data. It is also important to point out to them that just because the model matches the data does not necessarily mean that it is the only correct interpretation.

Once you feel students are comfortable with the concept introduce them to the equation they will need to help the school district find the depth of the bedrock. Students should then complete the rest of Student Handout #3. (The solutions are on page 5.)

***R**eflect – 20 Minutes*

R. Taxonomy	*Question*	*Answer*
Prior to this exercise we learned about waves using light, however as you have seen today, all the same basic principles apply to this new geophysics example. Distribute Student Handout #4.		
Application	You will have 10 minutes to add the following terms to the diagram below. There is no single correct placement for each term, so you must be able to justify the placement of the term; Angle of reflection, Angle of refraction, Headwave, Direct wave,	There is no single correct answer. Students should be able to use correct logic to place each term on the diagram. Review students responses on the overhead as a class and allow students to determine if they agree or disagree with each terms placement and the students justification.

	Huygen’s principle, Normal, Critical angle, Snell’s Law	

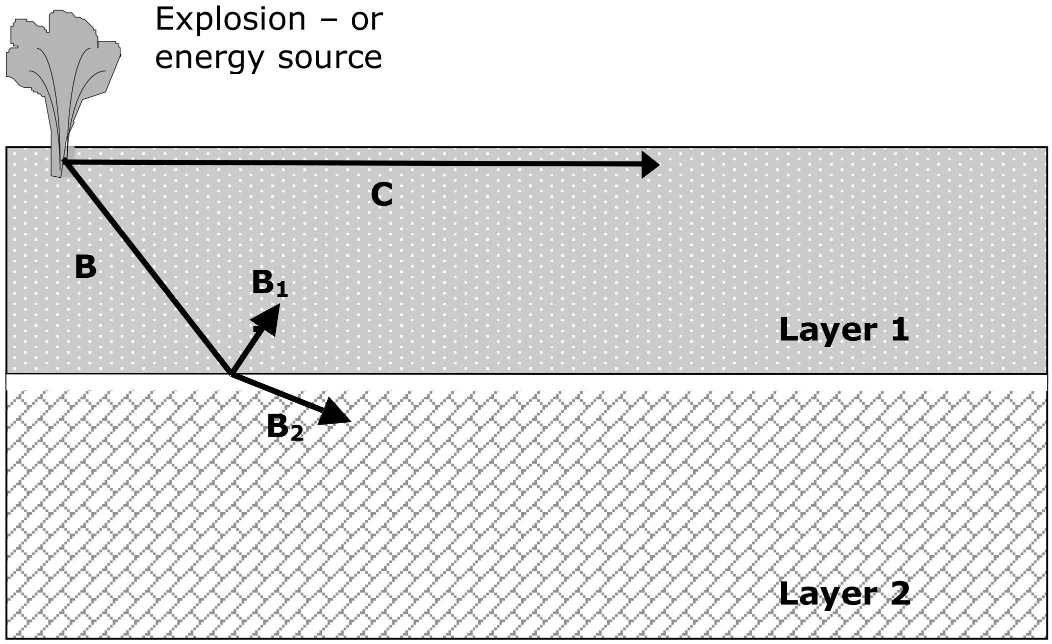
Apply – Assign Homework See Appendix XXX

Appendix A: Student Worksheet(s)& Homework

Student Handout #1

WHAT DO YOU KNOW?

Directions: Based on your prior knowledge, please answer the following questions regarding the diagram.



2. Which letter indicates the reflected ray?

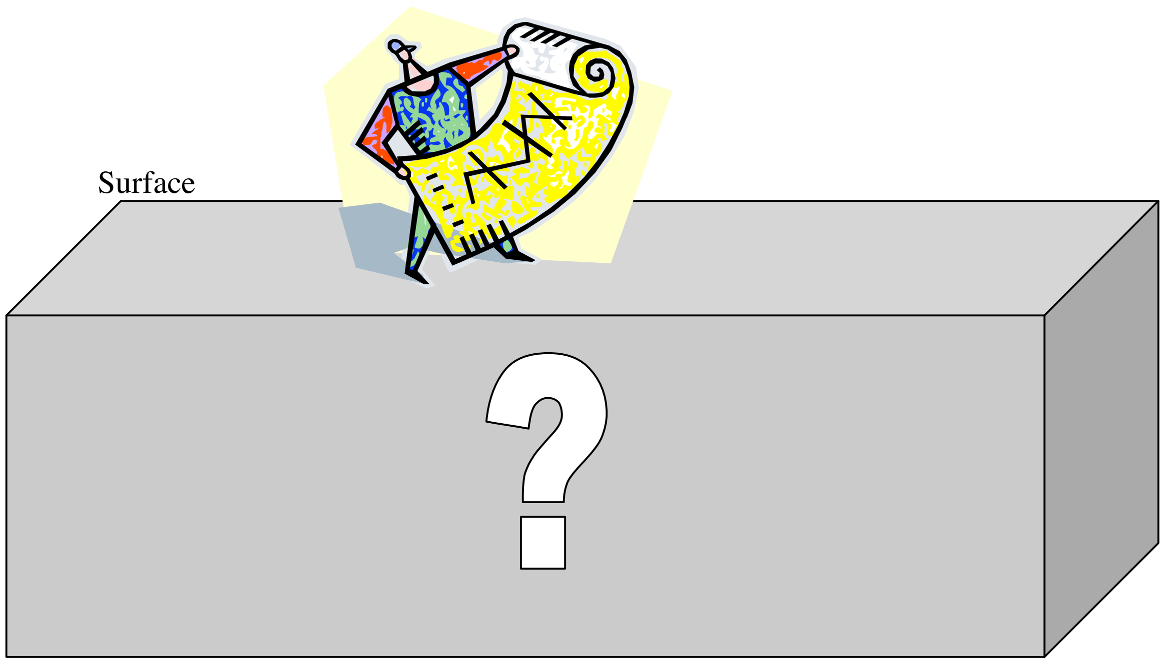
3. Which letter indicates the refracted ray?

4. In which layer does the energy travel the fastest? How do you know this?

Student Handout #2

Name:____________________________

Direction(s): The school district is planning construction of a new elementary school. To plan the work necessary to begin construction, they have asked our physics class to help them find out what is underneath the playground, and how far it is from the surface to the bedrock.



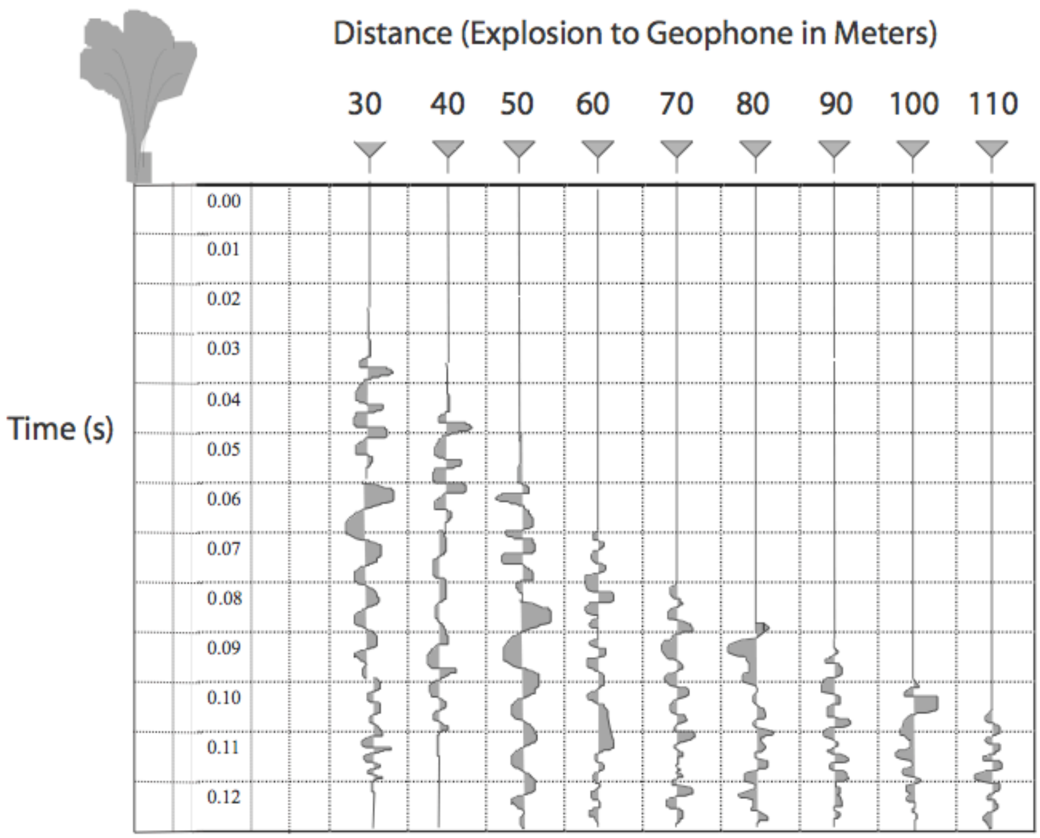
1. Based on our previous discussion and human simulation, what two components will we need collect information about what is below the surface without digging?

2. Draw the components you listed above on the diagram in a position or geometry that would provide us with enough information to help the school district.

Student Handout #3

Name:_________________________________

Directions: The survey we designed as a class has been carried out by a local geophysics consulting firm and the results are in. Below is a printout of the data. Time is the time since the explosion. Please study the data and answer the questions below.



Notes:

Equation:

Questions:
1. Calculate the depth to the bedrock from the data above?

Material	VP (m/s)	Material	VP (m/s)
Granite	5000 - 6000	Marble	3700 - 7000
Diorite	5780	Sandstone	1400 - 4300
Gabbro	6450	Limestone	5900 - 6100
Basalt	5400 - 6400	Anhydrite	4100
Dunite	6800 - 8640	Shale	2100 - 3400
Gneiss	3500 - 7500		

Table 2.1. P- -wave speeds for some rock material, from Dobrin (1976).

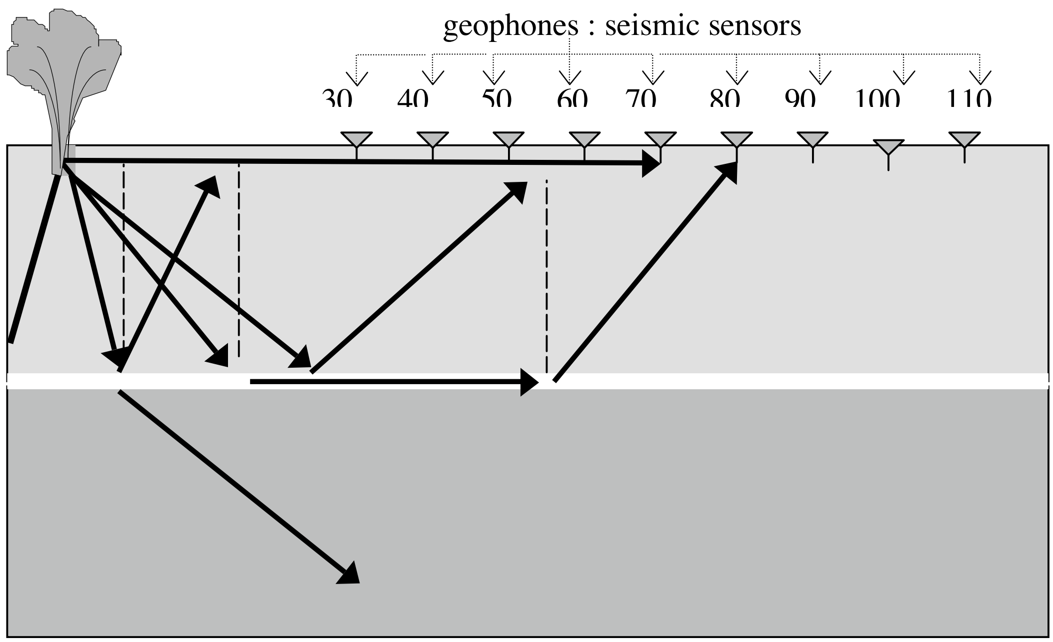
2. Using the table above and your calculations from the first page, what type of rock will the elementary school be built?

Student Handout #4

Name: ____

Directions: Add the following terms to the diagram below. There is no single correct placement for each term, so you must be able to justify the placement of the term;

Angle of reflection, Angle of refraction, Headwave, Direct wave, Huygen's principle, Normal, Critical angle, Snell's Law

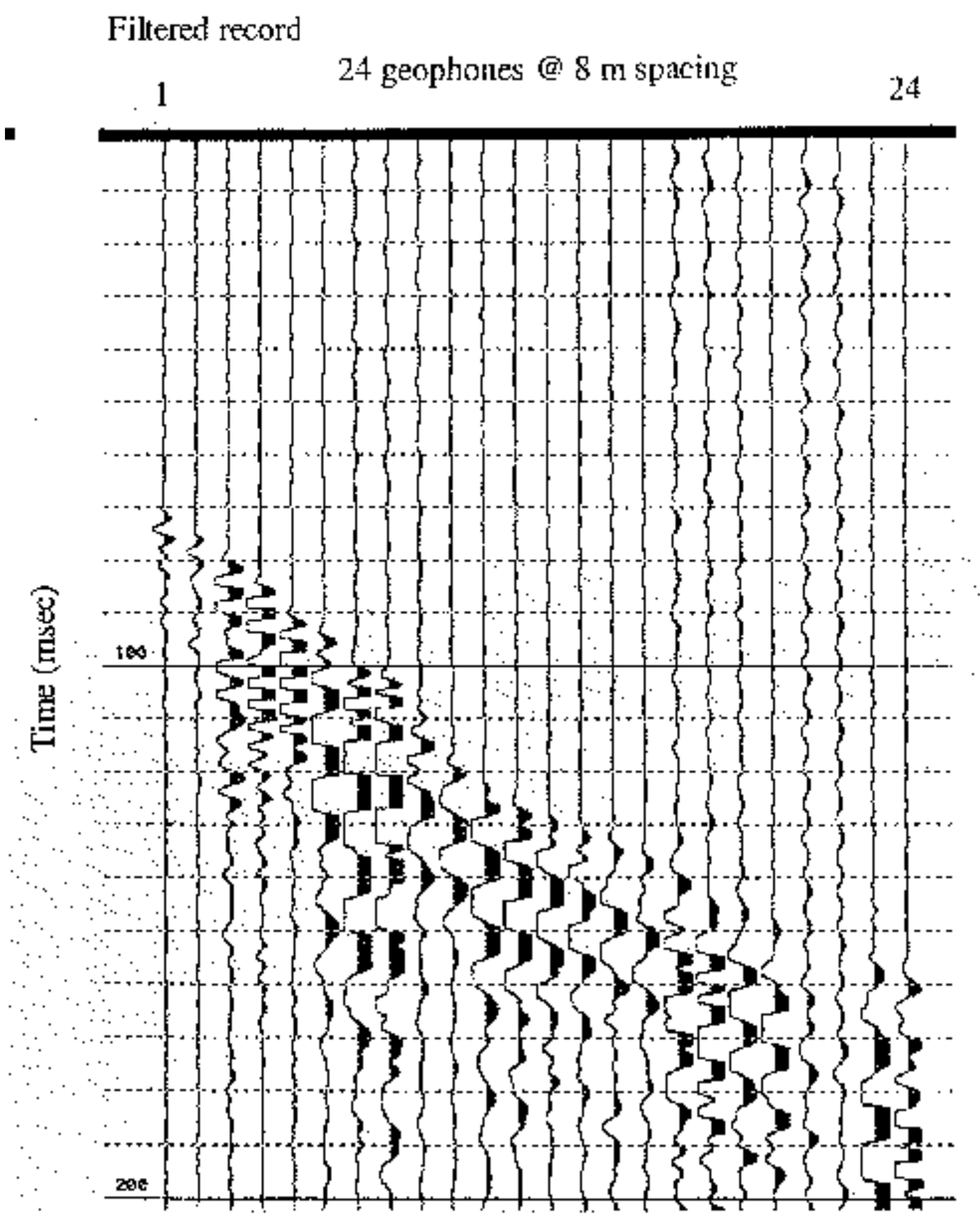


HOMEWORK

Analysis of real data

Based on your success with the previous data set, the local geophysics team has decided to hire you as a summer intern. They have recently gotten back from the field in New Zealand where they collected this seismic record from a region called Wainuiomata. Write up a lab report that includes your interpretation of the data as a potential building site. (Note: You will want to do some internet research on what makes a good building site)

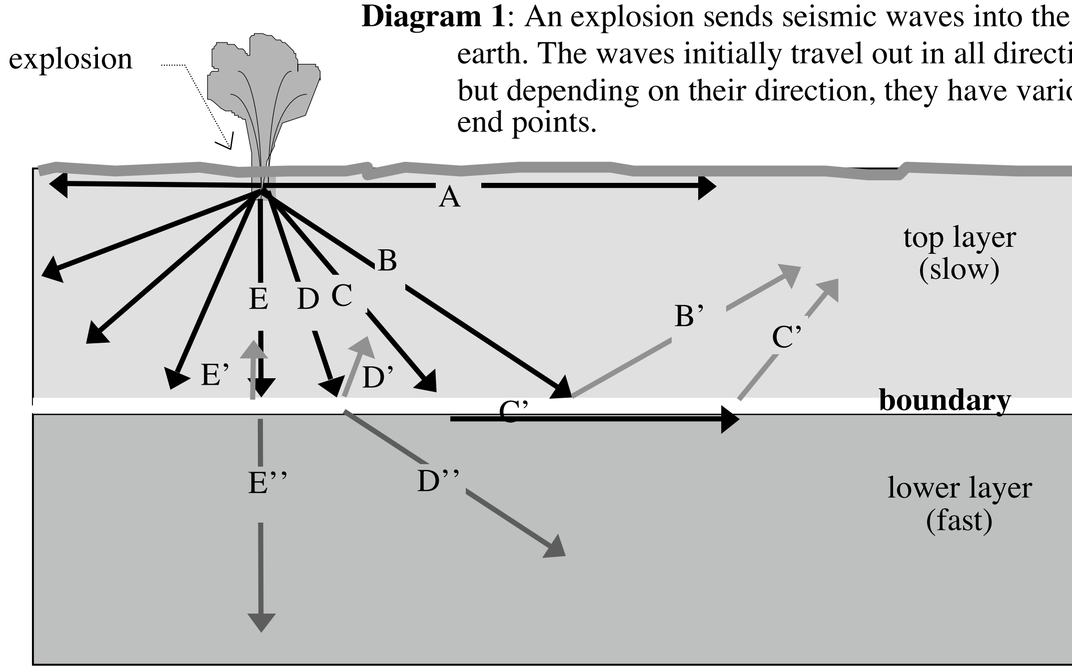
Geophone 1 (first vertical line on the left) was 100 m from the explosion and the geophones are 8 m apart, so the last geophone (number 24) was 184 m from the explosion. The vertical time scale is in milliseconds, starting from 0 (the time of the explosion) at the dark line at the top of the plot to 200 milliseconds at the bottom of the plot.



Appendix B: Teacher Background Discussion

Energy travels through the Earth in seismic waves. As a seismic wave travels it causes the particles in the Earth to oscillate. These oscillations are related to the 'rock stiffness' or rigidity of the rock. Eventually seismic waves dissipate their energy to the earth and lose amplitude. Like other waves, seismic waves obey the laws of physics. For example, seismic waves have difficulty passing from one medium into another, hence they reflect (partially) from such a boundary. Waves also have different speeds in different media because each medium has its own rigidity. Different speeds give rise to refraction effects, including critical angle.

Diagram 1: An explosion sends seismic waves into the earth. The waves initially travel out in all directions but depending on their direction, they have various end points.



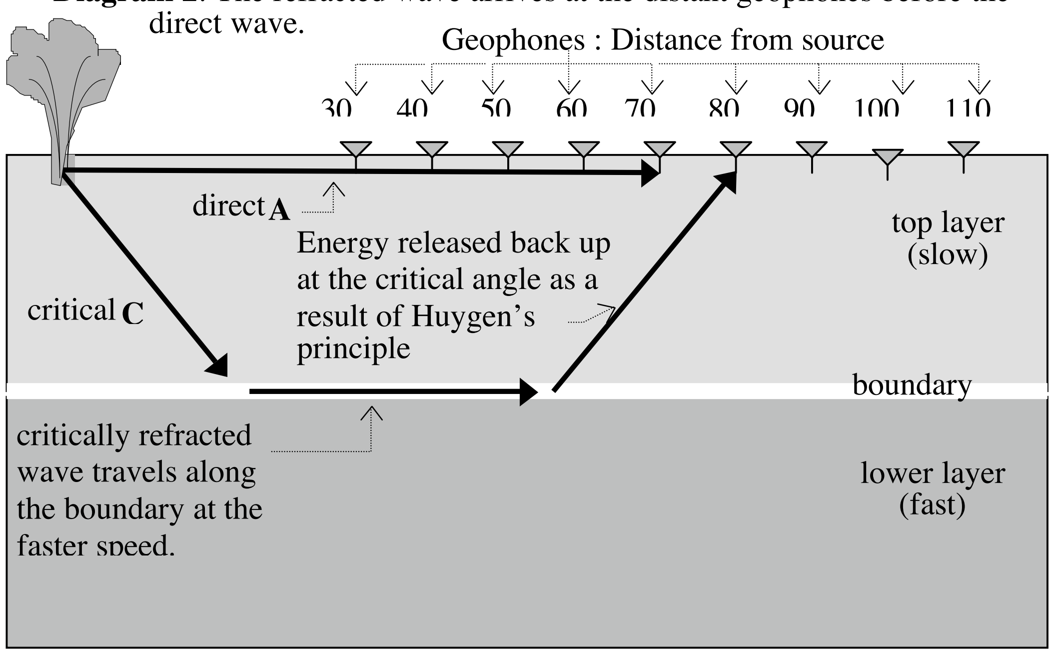
Wave path	Wave propagation in the upper medium		What happens at the boundary
A	Direct wave - along the surface		(doesn’t get to the boundary)
B	Super-critical wave - down & along at an angle greater than the critical angle	**B’**	The wave is totally reflected back up to the surface (at an equal angle)
C	Critical wave - down & along at the critical angle	**C’**	refracted so much by the lower medium that it travels along the boundary ...
		C’’	and refracts back up towards the surface at the critical angle.

D	sub-critical wave - down & along at an angle less than the critical angle	**D'**	some of the energy is reflected back to the surface at an equal angle.
		D''	while the rest of the waves energy is transmitted into the lower medium but at a new, refracted angle.
E	Vertical wave - straight down perpendicular to the boundary	**E'**	a small part of the waves energy is reflected straight back up
		E''	while most is transmitted. The direction does not change but the speed does.

How do we use this to learn about what is under the ground?
We can calculate the seismic wave velocities in both layers and the depth to the boundary. We determine the 2 velocities using the time it takes for the seismic waves to travel to recorders on the surface. Usually, seismic waves travel slowly in the top layer and faster in the lower layer (the lower layer is more rigid). Going on to **Diagram 2**. below...

The direct wave (A) travels slowly toward the geophones (on the right).
The critical wave (C) starts by traveling slowly down and across the top layer at the critical angle. When it gets to the boundary it refracts and travels along the boundary at the faster speed of the lower layer. At points along the boundary it refracts up toward the surface, again, at the critical angle as a result of Huygen's Principle. Huygen's principle says that each point on a wave front is considered to be the source of a wavelet. The line tangent to all these wavelets defines a new position of a wavefront. For geophones nearer the left hand side of the diagram, the direct wave will arrive first. For geophones nearer the right hand side of the diagram, the refracted wave will arrive before the direct wave because it has traveled much of its path at the faster speed. The geophones are linked together and all start recording at the instant of the explosion.

Diagram 2: The refracted wave arrives at the distant geophones before the direct wave.



Geophone records show the times that the first (& also later) seismic wave arrived at each geophone. The first seismic wave to arrive at the close geophones is the direct wave. However, more distant geophones record the refracted wave first. For the close geophones the time difference between consecutive geophone arrivals is related to the speed of the direct wave and, of course, the distance between the geophones.

However, the difference in arrival times for two consecutive distant geophones is related to the speed of the refracted wave as it was traveling along the boundary (at the faster speed). Can you explain why? (The actual arrival time is related to the whole wave path - going down, going across, going back up. Thus, the only difference in the path traveled for waves arriving at 2 adjacent stations is the section of the path along the lower boundary. The time difference in the arrival at the 2 stations is the time it takes the wave to travel the distance between the 2 stations, but along the lower boundary.)

Finding the velocities.
When viewing the geophone records in **Diagram 3** it is important to keep in mind that these are a series of seismograms situated next to one another. Positioned this way, the seismograms line up to create a simple distance versus time graph. While graph is conceptually simple, students often have difficulty interpreting graphs so the presence of seismograms may cause them difficulty at first. When working with students it is important to keep in mind that many students interpret distance/time graphs as the paths of actual journeys (Kerslake, 1981).

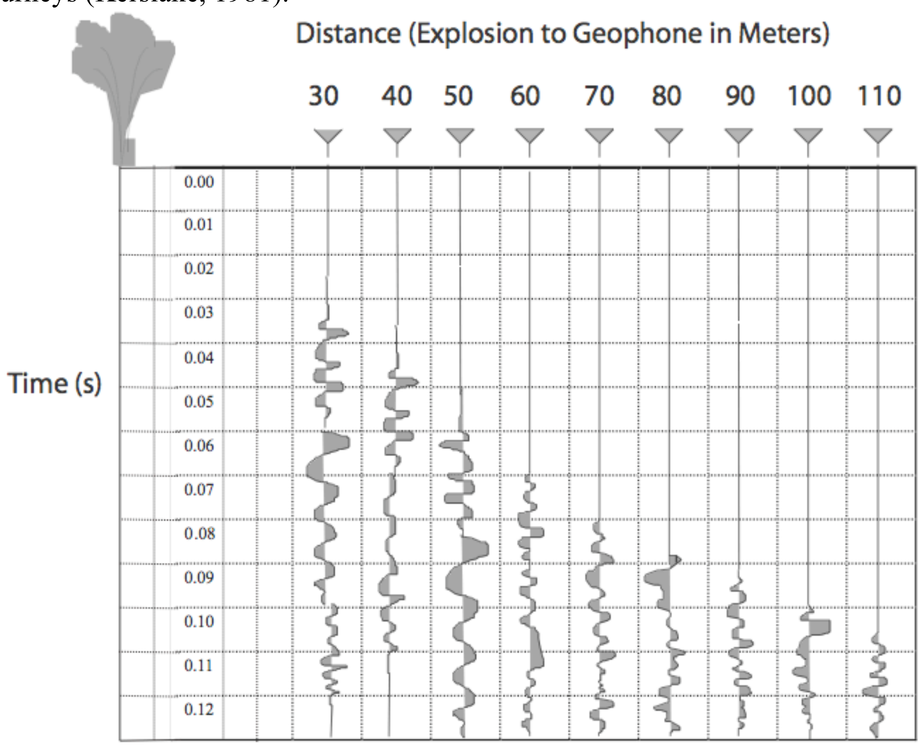


Diagram 3. Geophone records plotted with respect to distance.

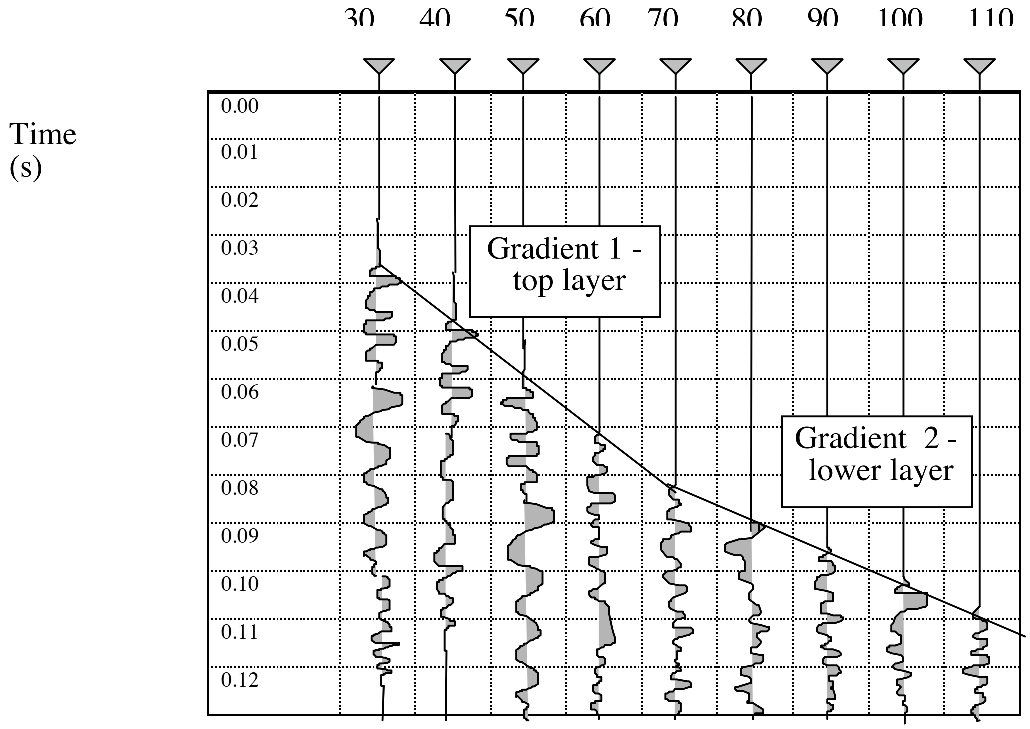


Diagram 4. Connecting the 1st arrival times to find the velocity of the layers. We use the gradients of these 2 lines to calculate the velocities.

The velocity in the top layer (**Diagram 4**) is found by taking the inverse of the first (steeper) gradient, and the speed of the lower layer is found by taking the inverse of the second (shallower) gradient. Students often confuse the slope of a graph with the maximum or the minimum value and do not know that the slope of a graph is a measure of rate so extra care must be taken when exploring these concepts with students (McDermott et al., 1987; Clement, 1989).

Finally, we can calculate the depth, *z*, to the boundary using this formula ... $z = 0.5\sqrt{\frac{v_2 - v_1}{v_2 + v_1}}.X_{cross}$

{where X_{cross} is the distance from the source where the two gradient lines cross over.}

In this example ...

The top layer velocity, $v_{TL} = \frac{1}{0.001176} = 850\text{ms}^{-1}$

the lower layer velocity $v_L = \frac{1}{0.000658} = 1520\text{ms}^{-1}$

and the depth to the boundary, $z = 0.5\sqrt{\frac{(1520 - 850)}{(1520 + 850)}} \times 67 = 18$ m

Appendix C: Alignment with Standards

Reinforces - By the end of 8th Grade
4.F. Motion
Vibrations in materials set up wavelike disturbances that spread away from the source. Sound and earthquake waves are examples. These and other waves move at different speeds in different materials.

4.C. Processes that Shape the Earth
Thousands of layers of sedimentary rock confirm the long history of the changing surface of the earth and the changing life forms whose remains are found in successive layers. The youngest layers are not always found on top, because of folding, breaking, and uplift of layers.

9. B. Symbolic Relationships
Graphs can show a variety of possible relationships between two variables. As one variable increases uniformly, the other may do one of the following: increase or decrease steadily, increase or decrease faster and faster, get closer and closer to some limiting value, reach some intermediate maximum or minimum, alternately increase and decrease indefinitely, increase or decrease in steps, or do something different from any of these.

Supports - By the end of 12th Grade
4.F. Motion
Waves can superpose on one another, bend around corners, reflect off surfaces, be absorbed by materials they enter, and change direction when entering a new material. All these effects vary with wavelength. The energy of waves (like any form of energy) can be changed into other forms of energy.

Appendix D: References

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Many thanks to Tom Boyd, Colorado School of Mines from whom the wavefront gifs originated.