Lab 5: Seismic Reflections

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Due: Before your next lab session

Overview

When reflection seismic data are collected, geophones are laid out, and a source (such as dynamite or a vibroseis truck) sends a wavelet (ie, a shot) into the subsurface. The wavelet reflects off of interfaces separating units with different impedances. A reflection seismic survey will consist of multiple shots over the survey area. For this lab, we will consider a 2D seismic line, where sources and receivers are positioned along a straight line.

Reflection seismology is the workhorse geophysical technique for oil and gas exploration. Seismic sections or volumes, such as the one shown in Figure 1, are interpreted for geologic structure and other geologic features. Each of the traces composing the volume is an ideal *Normal Incidence Reflection Seismogram*. In this lab, we will be investigating geologic factors that impact the character of a seismogram and walk through how a seismogram is generated from the collected data.

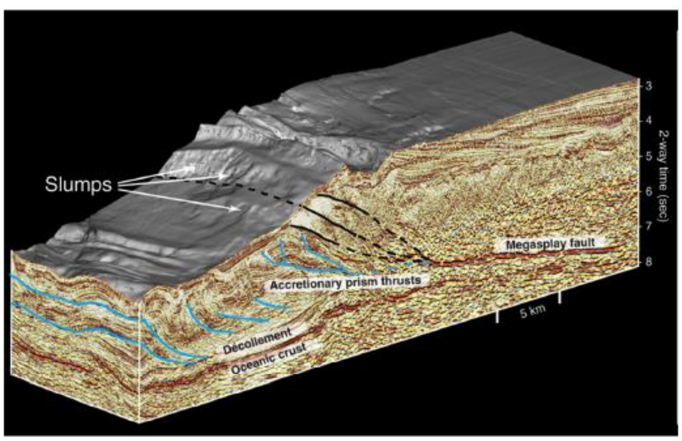


Figure 1: 3D seismic volume.

Resources

- GPG: https://gpg.geosci.xyz/content/seismic/basic_principles.html
- Lab 5 Python Notebook: GPGlabs Seis_Reflection.ipynb

Normal Incidence Seismogram

A **normal incidence seismic trace** simulates the time series you would observe if the source and receiver were coincident. For horizontal layers, it simulates the response you would expect for a signal that travels vertically and is reflected off of the various interfaces it encounters.

The arrival time and amplitude of the signal depend on the density (ρ) and seismic velocity (v) of the layers it travels through. Using the Seismic Reflection notebook, we will walk through how to construct a normal incidence seismogram.

Reflection coefficient and reflectivity

- The **reflection coefficient** is dependent upon the change in the acoustic impedance at an interface.
- The **reflectivity** is the amplitude of the wave (at the earth's surface) that has been reflected from that interface. That is, it incorporates transmission losses that the wave incurs as it travels from the source, to the reflecting interface, and back to the surface.

Answer the following questions related to acoustic impedance, reflection coefficients, and reflectivity. Use section 1.1 in the notebook.

Q1. Using the notebook, start with uniform density ($\rho_1 = \rho_2 = \rho_3$) for all layers and adjust the velocity (v_1, v_2, v_3) of the layers.
What is required for the reflection coefficients to be positive?

What is required for the reflection coefficients to be negative?

What is required to have two reflection coefficients of opposite sign?

Q2. Using the notebook, pick a constant velocity ($v_1 = v_2 = v_3 = 2150\,\frac{m}{s}$) and adjust the density of the layers.
What is required for the reflection coefficients to be positive?

What is required for the reflection coefficients to be negative?

What is required to have two reflection coefficients of opposite sign?

Q3. Consider Figure 1 in the notebook. Assuming that the input amplitude is 1, use the equations provided in the notebook to calculate the reflected and transmitted amplitudes. Use $\rho_1 = \rho_2 = 2000\frac{kg}{m^3}, v_1 = 500\frac{m}{s}, v_2 = 1000\frac{m}{s}$.

Q4. Consider Figure 2 in the notebook, which shows the reflection from the second interface. Specifying the input amplitude as 1, is the reflected amplitude from the second interface received at the surface greater or smaller than the reflection coefficient ($r_{2,3}$) at this interface?

Q5. Using Section 1.1 in the notebook, we explore the effect of transmission coefficients to reflectivity at the second interface. Turning on the "usingT" toggle in the notebook incorporates transmission coefficients (to yield reflectivity), and turning it off will show only the reflection coefficients. From default parameters, set $v_2 = 300\frac{m}{s}, v_3 = 4000\frac{m}{s}$. Try turning on and off "usingT". Do you recognize any difference? Then increase v_2 to $2800\frac{m}{s}$; can you recognize the difference?

Q6. When do you think that considering transmission coefficients are important? Try a few more examples and justify your answer.

Depth to time conversion

We now have a series of reflectivity that tells us the amplitudes measured at the surface from reflections off of particular interfaces at depth. However, the signal we input and the data we measure are in time. Knowing the layer thicknesses and velocities, we can map from depth to time. We will use section 1.2 in the notebook.

First set the parameters of the notebook to reproduce the model in Figure 2 below.

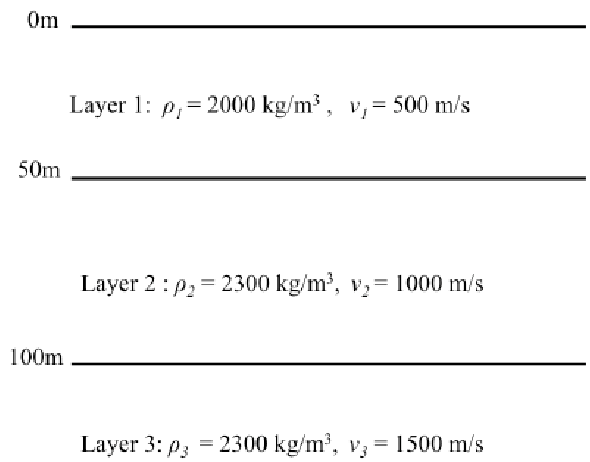


Figure 2

Answer the following questions related to depth to time conversion.

Q7. Compute the two-way travel time for the two reflection events shown in the left panel of the notebook (section 1.2). Show how you computed those times. Does it agree with reflection events shown in the right panel?

Q8. Using the notebook, observe changes in the left and right panels while you are increasing v_1 from 500 to 1900 m/s. Make the changes slowly when you increase velocity so that you can observe them.

Do the location of the reflection events in the left panel change?

Do the location of the reflection events in the right panel change?

What insight do you obtain from these experiments?

Modeling the ideal seismogram

By using the depth-time conversion, we can describe the reflectivity series in time. We input a source wavelet and record a seismogram in time, which is the convolution of the wavelet and the reflectivity series. Execute section 1.3 in the notebook to define a wavelet and convolve it with the reflectivity series to construct a seismogram. For this problem, we use the same model as shown in Figure 2 above.

Q9. Adjust the amplitude (wavA) of the input pulse. How does it affect the resulting seismogram?

Q10. Adjust the frequency (wavf) of the input pulse. How does the width of the wavelet change as the frequency is changed?

Q11. The SEG Wiki: Ricket Wavelet webpage gives a good description of how to measure the period. Then, use the notebook to adjust the frequency of the wavelet to those listed in the table below. For each frequency, measure the dominant period of the wavelet off of the notebook and compare it with the theoretical value $T = \frac{1}{f}$.

Frequency (f, in Hz)	Period (T, in s)	Theoretical period
5		
20		
50		

Vertical resolution

Run the notebook for section 1.4. Here we will investigate the impact of the wavelet frequency on seismic resolution. One question that is always of interest is “how thick must a layer be before it is detectable?”

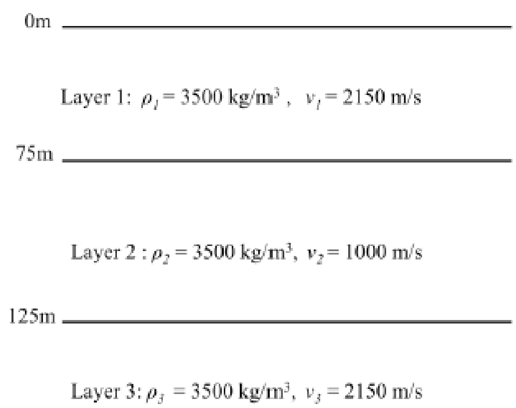


Figure 3: Three layer model.

Q12. Using the model in Figure 3 as a starting point, we will fill in the following table. Adjust the thickness of layer 2 (h_2) by adjusting the depth to the top of layer 3 (d_3). For each of the frequencies (wavf) listed, record the minimum h_2 for which evidence of the top and bottom of the layer are visible in the seismogram.

f (Hz)	Minimum h_2 (clean)	Minimum h_2 (noisy)
20		
50		
100		

Construction a Normal Incidence Seismic trace from CMP gather data

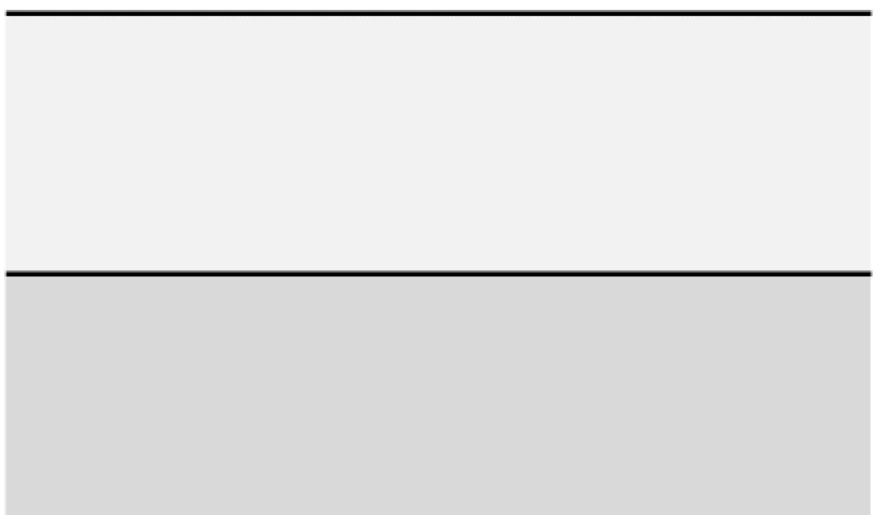
Now that we have investigated the impact of geologic factors on an ideal normal incidence seismogram, we will examine how such a trace is extracted from the seismic data.

There are multiple ways to sort seismic data: common shot gather and common midpoint gather.

- A **common shot gather** consists of the time-series recorded by the geophones for a single shot. The recorded time series are usually plotted with time on the y-axis and location on the x-axis.
- A **common midpoint gather** consists of the collection of traces that share the same midpoint between the source and receiver.

Q13. On the figure below, sketch 4 reflection ray paths, from source to receiver, for a **common shot gather**.

Q14. On the figure below, sketch the ray paths for the reflections recorded for 4 source-receiver pairs for a **common midpoint gather.**



From CMP gather to a seismic trace

Here, we will walk through how to construct a normal incidence seismogram from a CMP gather. We have two data sets: see Step 1 in Section 2.2 in the notebook. One is a clean data set, and other is noisy.

To estimate the geologic model and interpret structure from the seismic data, we want a single, normal incidence trace. There are two challenges that must be considered when doing this from a CMP gather:

- For different source-receiver offsets, the arrival times of the reflection event will be different.
- The data are usually contaminated with noise.

Challenge 1 will the be tackled using a Normal Moveout (NMO) correction. The second challenge will be addressed by stacking the NMO corrected traces to reduce the impact of random noise. If performed properly, the result will be a single normal incidence trace.

The arrival time of a reflection event as a function of source-receiver offset is described by a hyperbola.

$$t(x) = \sqrt{\frac{x^2}{v^2} + t_0^2}, \qquad t_0 = \sqrt{\frac{4d^2}{v^2}}$$

The offset (x) is known for each trace, but we do not know the velocity (v) or thickness (d) of the first layer, so both v and t_o must be estimated.

Q15. Use Step 2 in Section 2.2 in the notebook. By adjusting the intercept time t_o and velocity v, fit a hyperbola to the reflection even in the CMP gather. The middle panels show the NMO corrected data (that is, the data flattened on the hyperbola). What is the intercept time and velocity for the hyperbola you fit?

Q16. What happens to the NMO corrected reflection event when use a velocity that is too small? What if the velocity is too large?

Q17. Compute the depth to the reflector.

Now let's look at the noisy data set. Because the data set is so noisy, we provide a hyperbola for you to fit a reflection event: $t_0 = 0.5\ s, v = 1000\frac{m}{s}$.

Q18. Use the given parameters to fit the reflection event in the noisy data in Step 3 in Section 2.2 of the notebook. Look at the stacked trace (right panel) and find the reflector of interest. What is the depth to this reflector?

Q19. Now run the second app in Step 3. This generates three stacked traces with the same intercept time as above but three different velocities: $v - 200, v, v + 200$. Can you recognize the reflected arrival in the stacked trace:

- On the left?
- In the middle?
- On the right?

What does this tell you about choosing velocities for NMO correction of noisy data?

Finding the best hyperbole: semblance analysis

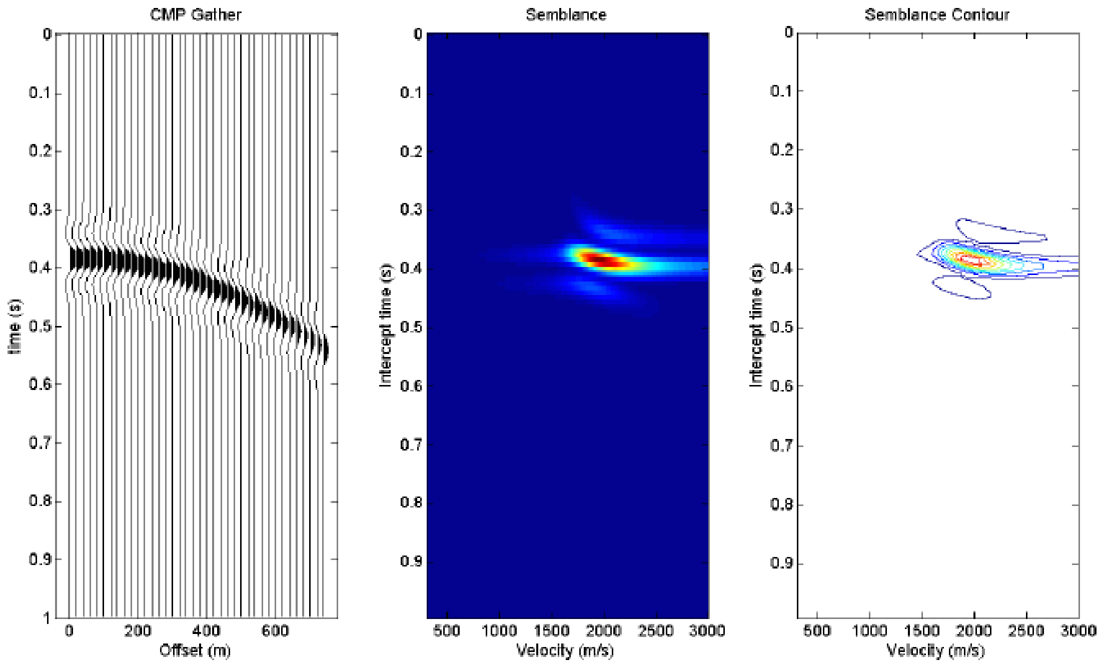
One approach to estimating the hyperbolas corresponding to the reflection events is to use a semblance analysis. To do this, we select a number of hyperbolas, with intercept time t_0 (y-axis on the semblance panels) and velocity v (x-axis on the semblance panels, and sum up the coherent energy in a window along that hyperbola (color for the semblance panels). The figures (on the next page) show the semblance images for the clean and noisy data.

Q20. Which values of t_0 and v correspond to the reflection events?

- Clean data:
- Noisy data:

Q21: Do these agree with the values you estimated (for clean data) or were given (for noisy data) in the previous questions?

Clean data:



Noisy data: