Introduction to Geophysics:

Seismic Exploration

Reflection

What causes seismic reflection?

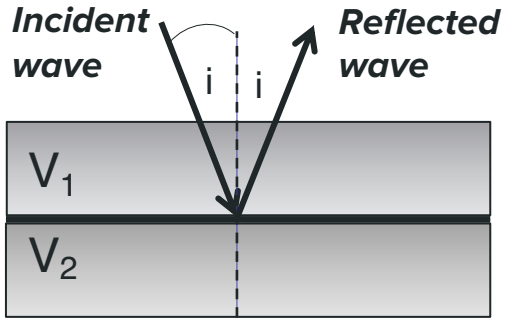
Seismic reflection occurs when seismic waves encounter **boundaries** between layers of different rock types or materials, causing part of the energy to bounce back toward the surface. The difference in density and elasticity between the layers causes varying degrees of reflection, which can be detected by seismic sensors.

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

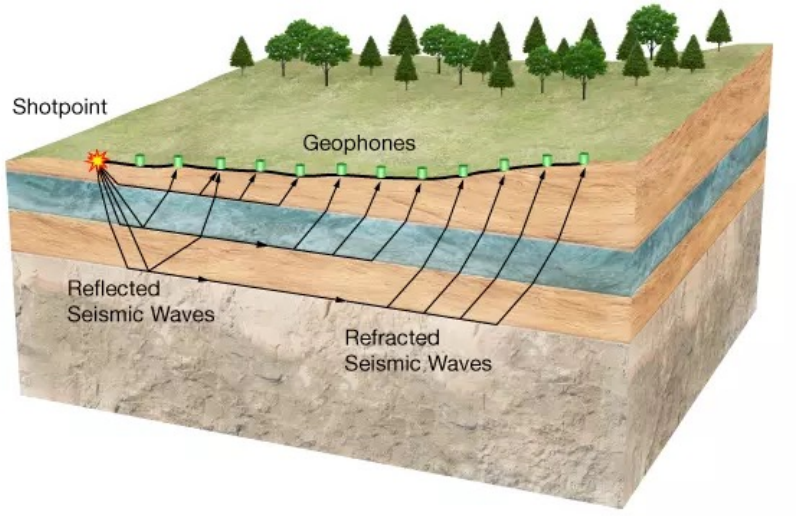
$$\textbf{Velocity} = \frac{\textbf{Distance}}{\textbf{Time}}$$

$$\textbf{Velocity} = \sqrt{\frac{\textbf{Stiffness}}{\textbf{Density}}}$$



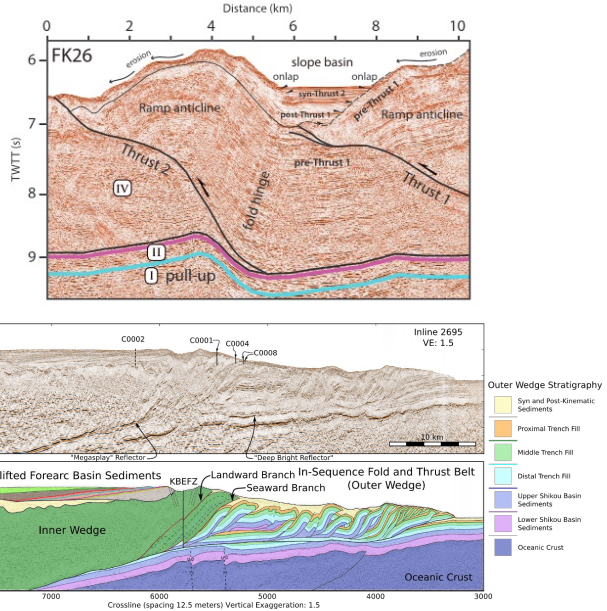
Reflection Seismology

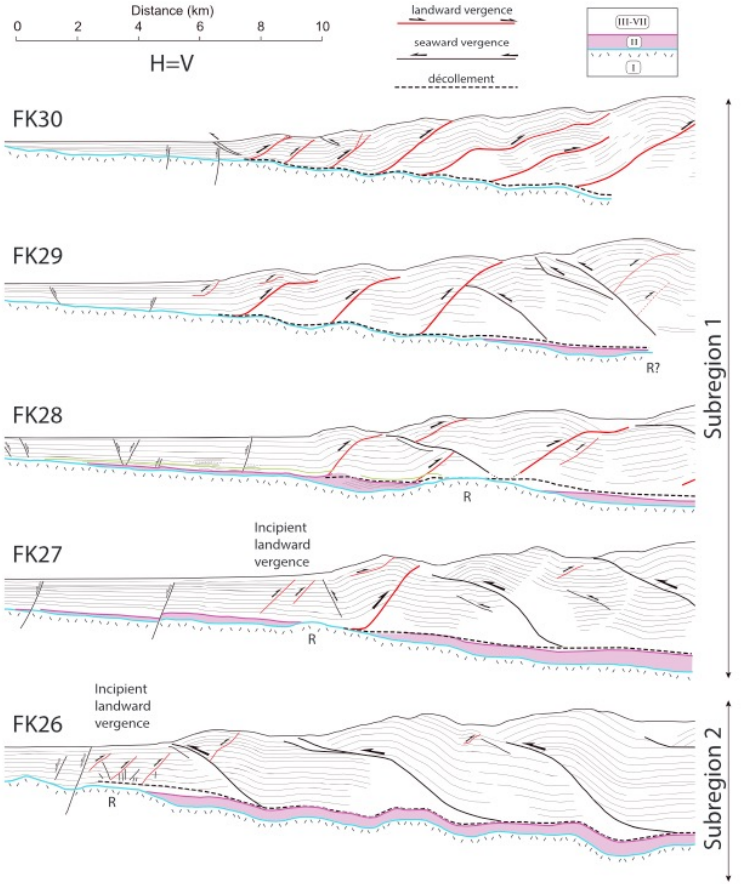
Reflection seismology is a geophysical method used to study the Earth's subsurface by sending seismic waves into the ground and analyzing the waves that are reflected back from geological layers. This technique helps in mapping and identifying different rock formations, fault lines, and oil or gas reservoirs.



Reflection Seismology: Study of Geological features

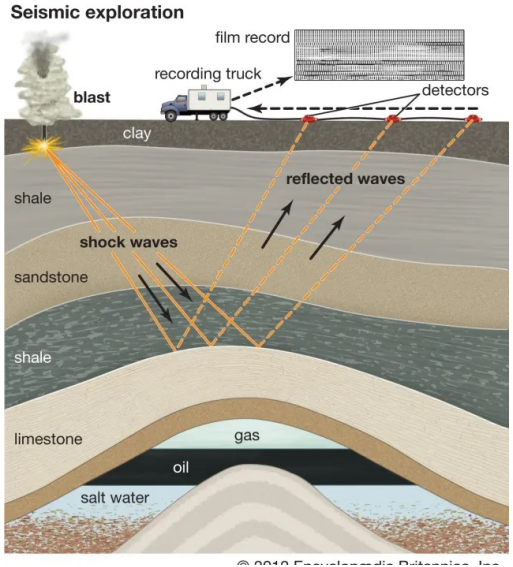
Uses body-waves usually P-waves.
Sensitive to impedance contrasts
Result is a velocity model and a reflection stack
Requires a lot of data processing!

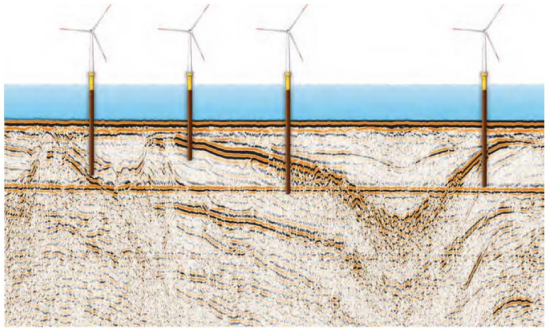


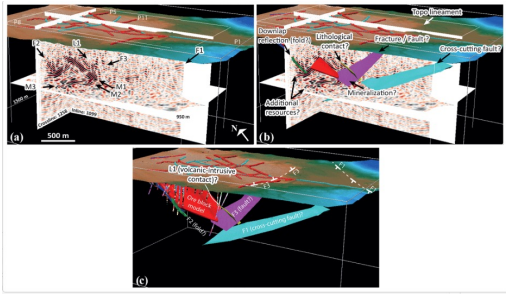


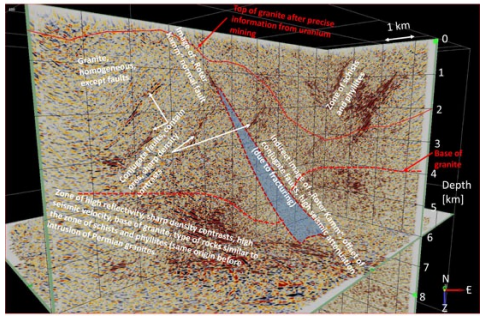
Reflection Seismology: Other uses

Oil and gas – find it and develop it (4D)
Carbon capture and storage – find it and monitor it
Geothermal exploitation
Groundwater aquifers
Mining
Windfarm placement
Earth structure/properties









Seismic Sources

Reflection (and refraction) methods need a source of seismic waves, such as an earthquake or human-made source. Examples of human-made sources are:

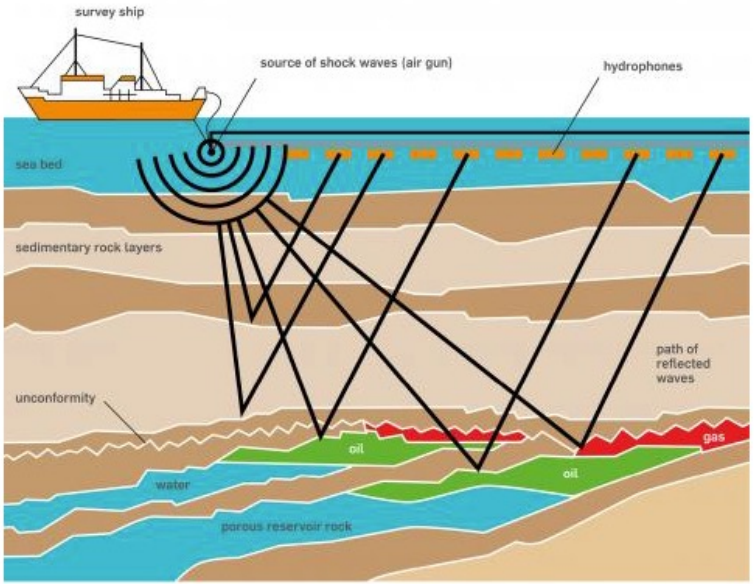
Hammer on plate
Explosion
Vibroseis
Weight drop
Airgun (marine)

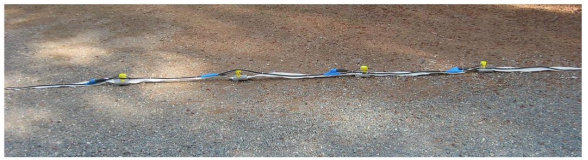
How do you choose a seismic source?

The seismic source is chosen based on **terrain**, **cost** and the **depth** of interest (bigger source goes deeper into ground).
e.g. for a hammer and plate, the maximum depth is about 15-20m.

Seismic Receivers

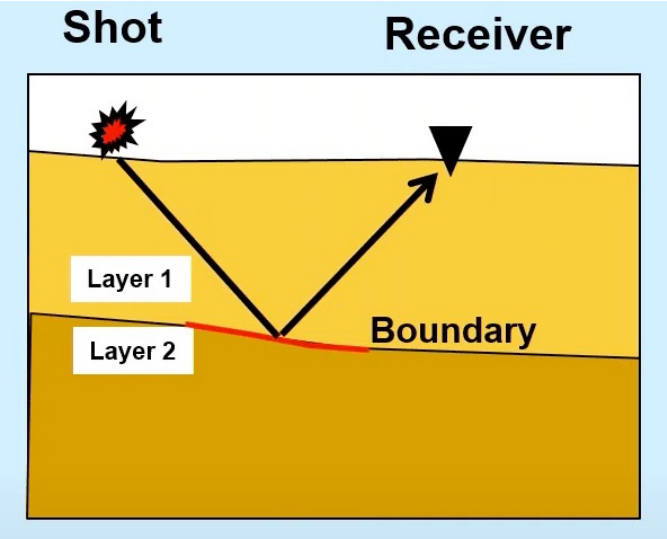
Geophones and hydrophones are used to listen to the sound reflected and refracted from the source.





Seismic Impedance

Different layers have different acoustic properties
Reflected waves are sensitive to changes in velocity/density
Seismic amplitudes are determined by seismic impedance (an acoustic property)



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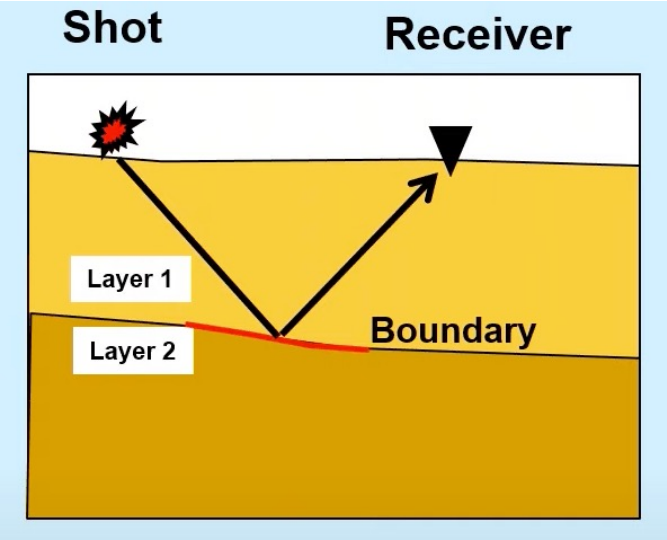

Impedance (I) = velocity x density

The proportion of energy reflected is governed by the reflection coefficient R

$$R = \frac{I_2 - I_1}{I_2 + I_1}$$

If $I_2 > I_1$, R will be positive

If $I_1 > I_2$, R will be negative

Question:

How much energy do you think gets reflected? Comment on the impedance of the layers (low or high impedance) and how it affects the seismic wave reflection.

Impedance (I) = velocity x density

Velocity = 1500 m/s
Density = 2000 kg/m^3

Velocity = 2000 m/s
Density = 2200 kg/m^3

$$R = \frac{I_2 - I_1}{I_2 + I_1}$$

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$$R = \frac{I_2 - I_1}{I_2 + I_1}$$

Velocity = 2000 m/s
Density = 2200 kg/m^3

About 18.9% is reflected, 81.1% gets transmitted.
Low Impedance contrast causing weak reflection

Question:

How much energy do you think gets reflected? Comment on the impedance of the layers (low or high impedance) and how it affects the seismic wave reflection.

Impedance (I) = velocity x density

Velocity = 1500 m/s
Density = 2000 kg/m^3

Velocity = 3500 m/s
Density = 2700 kg/m^3

$$R = \frac{I_2 - I_1}{I_2 + I_1}$$

Question:

How much energy do you think gets reflected? Comment on the impedance of the layers (low or high impedance) and how it affects the seismic wave reflection.

Impedance (I) = velocity x density

Velocity = 1500 m/s
Density = 2000 kg/m^3

$$R = \frac{I_2 - I_1}{I_2 + I_1}$$

Velocity = 3500 m/s
Density = 2700 kg/m^3

About 51.8% is reflected, 48.2% gets transmitted. High Impedance contrast causing strong reflection

Question:

Which of the following combinations of materials would produce the strongest seismic wave reflection?

a) Water over sandstone
b) Clay over granite
c) Sandstone over shale
d) Water over shale

Question:

Which of the following combinations of materials would produce the strongest seismic wave reflection?

a) Water (low impedance) over sandstone (low impedance)
b) Clay (low impedance) over granite (high impedance)
c) Sandstone (low impedance) over shale (low impedance)
d) Water (low impedance) over shale (low impedance)

Question:

Which of the following combinations of materials would produce the strongest seismic wave reflection?
a) Water (low impedance) over sandstone (low impedance)
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c) Sandstone (low impedance) over shale (low impedance)
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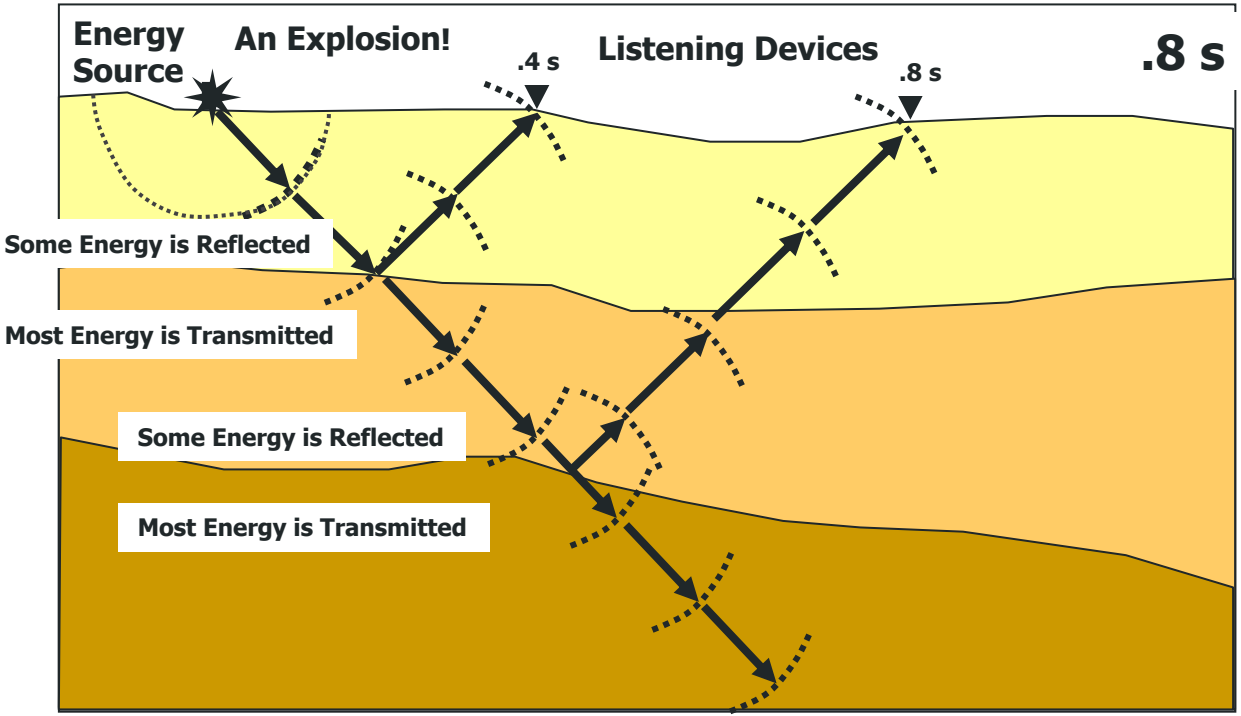
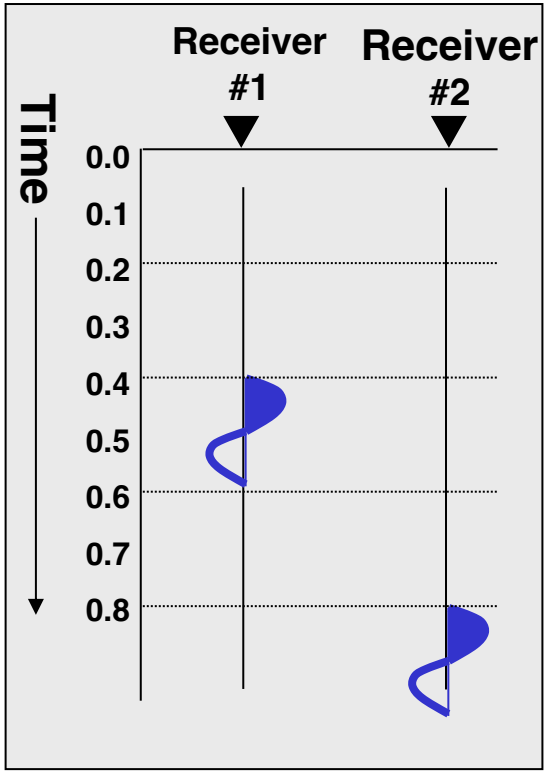
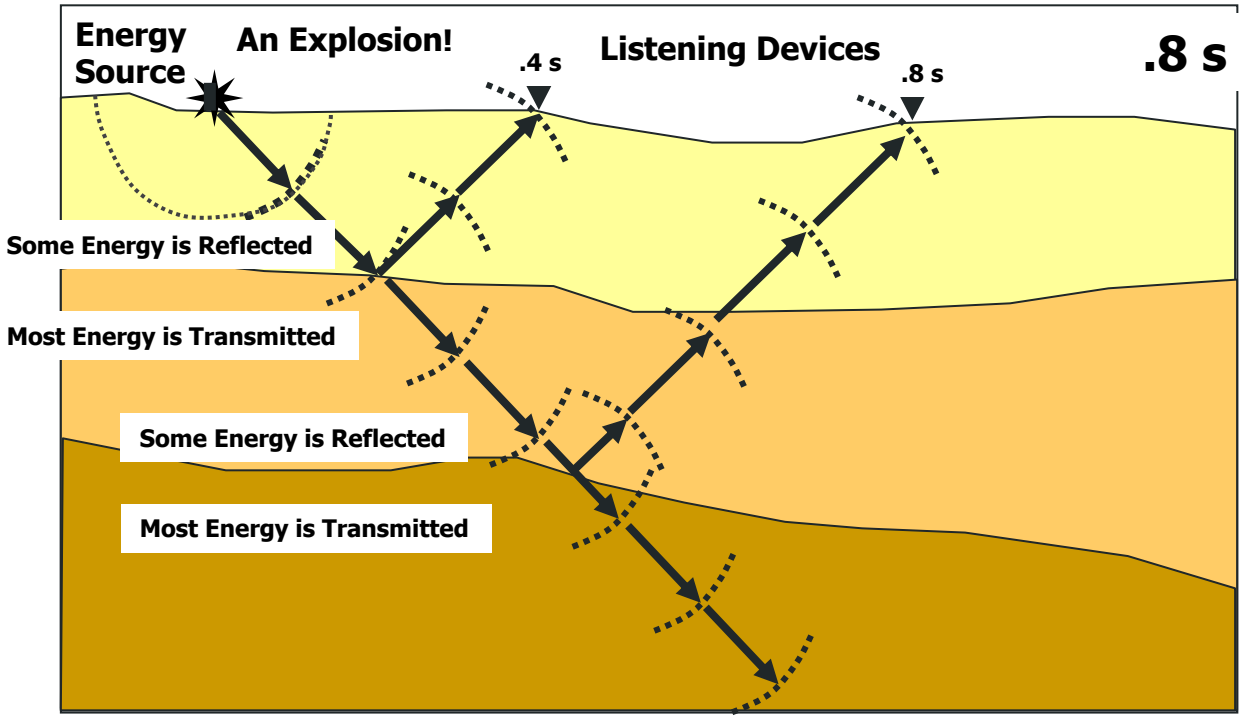
How does this work?



How does this work?

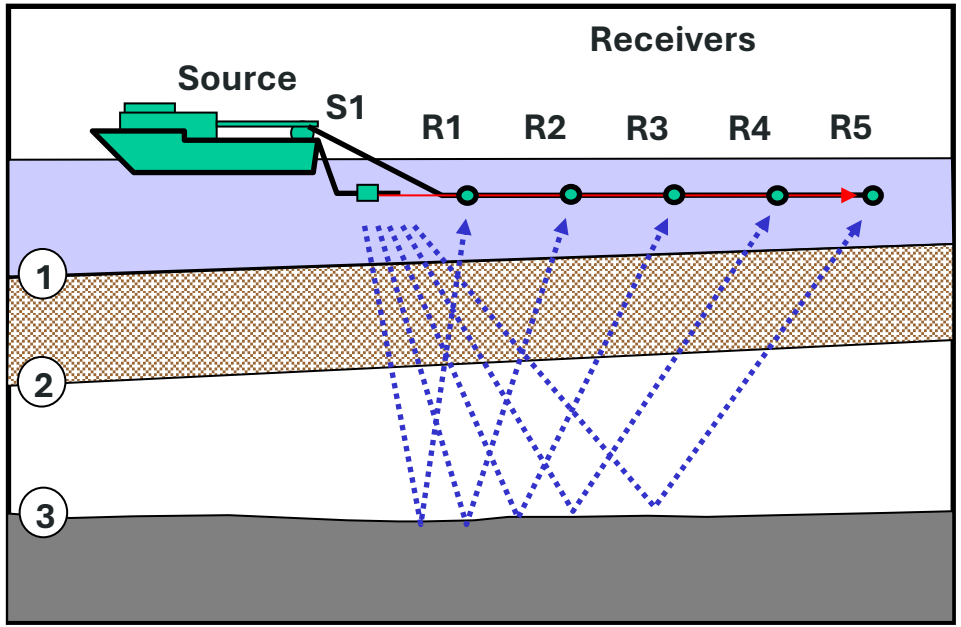




Travel times of reflected waves is curved in a TX plot

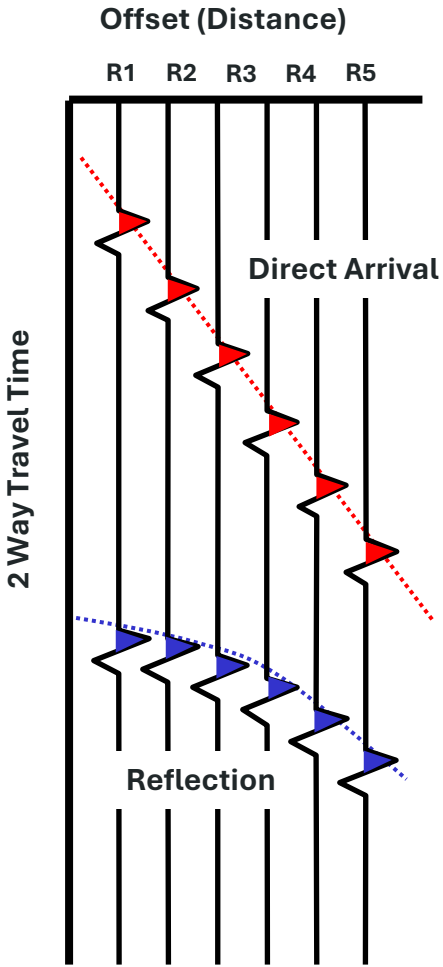
There are 5 ‘bounce’ points along interface 3

Reflected Wave – curved
Direct and refracted waves – straight line



Red rays are Direct Arrival

Blue rays are reflections



Travel times of reflected waves is curved in a TX plot

$$t_0 = \frac{2h}{V_1}$$

$$T(x)^2 = t_0^2 + \frac{x^2}{V_1^2}$$

Rearranging

$$T(x)^2 = t_0^2 + \frac{x^2}{V_1^2}$$

gives:

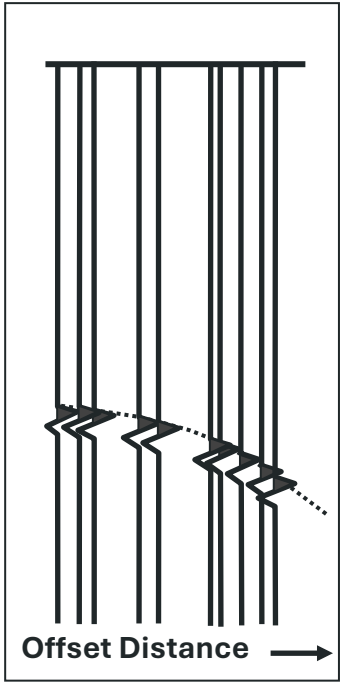
$$\frac{T^2}{t_0^2} - \frac{x^2}{V_1^2 t_0^2} = 1$$

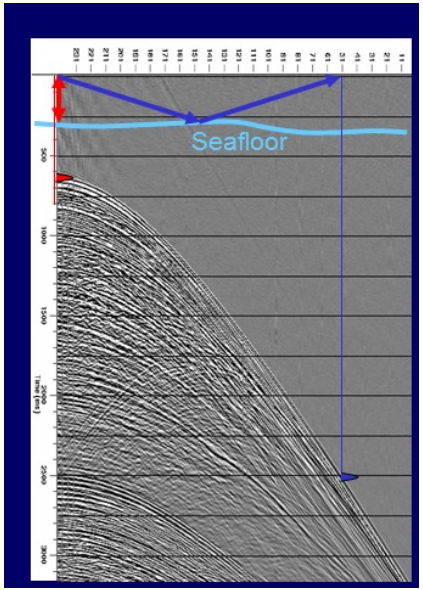
Equation of a hyperbola:

$$\frac{y^2}{b^2} - \frac{x^2}{a^2} = 1$$

Reflected Wave – hyperbolic travel time vs distance shape

Direct and refracted waves – linear travel time vs distance shape



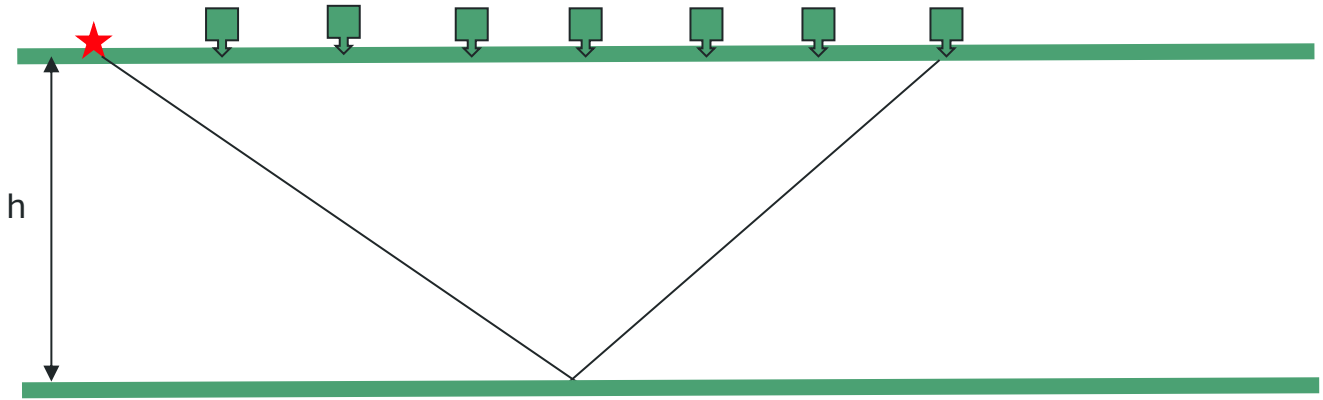


The curvature of this hyperbola is a function of the average velocity down to the depth of the reflection

Reflection Seismology: Survey Design

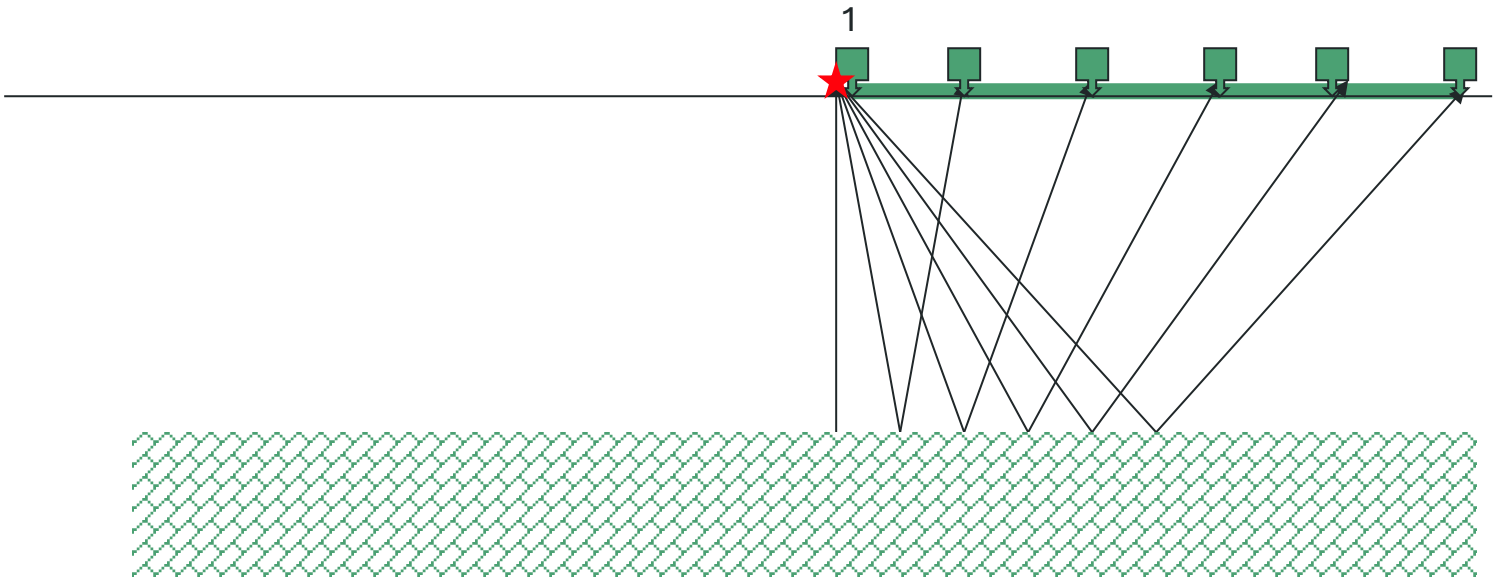
Important questions to ask before proceeding with survey design:

1. What is my depth of interest (h)?
   maximum source-receiver offset = 2h
2. How many geophones do I have? How much detail do I want in the image?



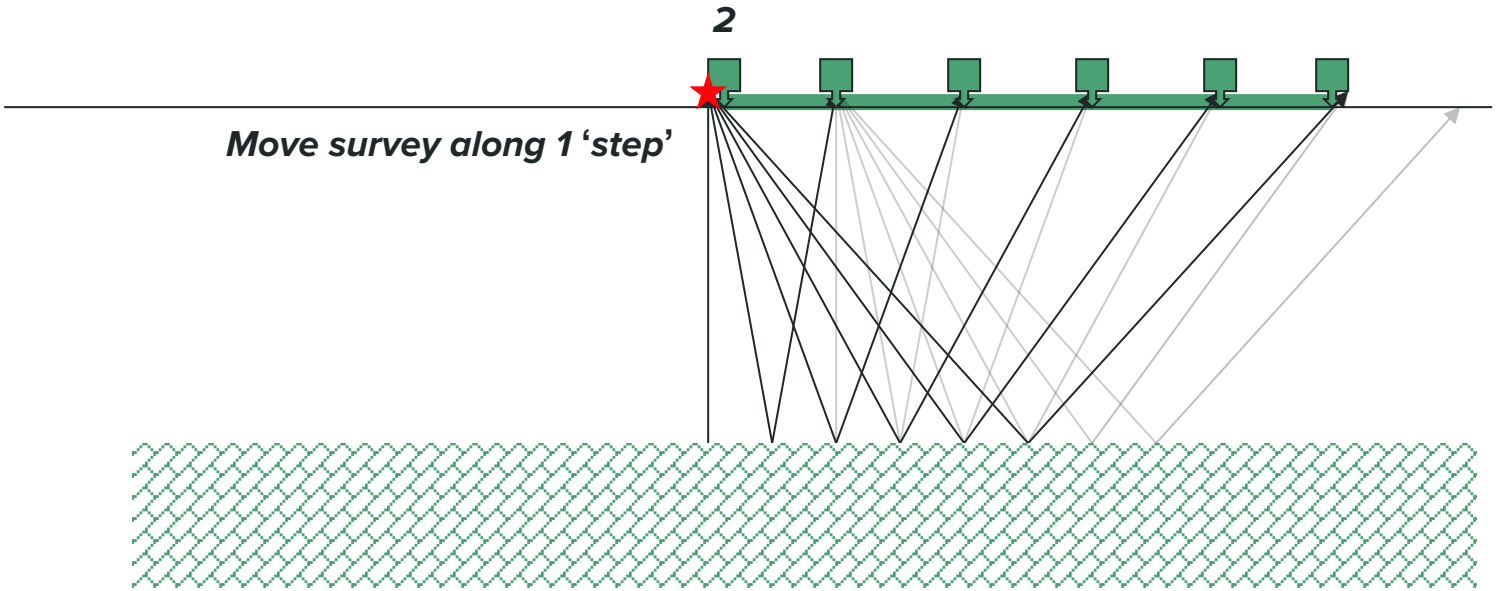
Reflection Seismology: Survey Design

First shot, into 6 receivers ....

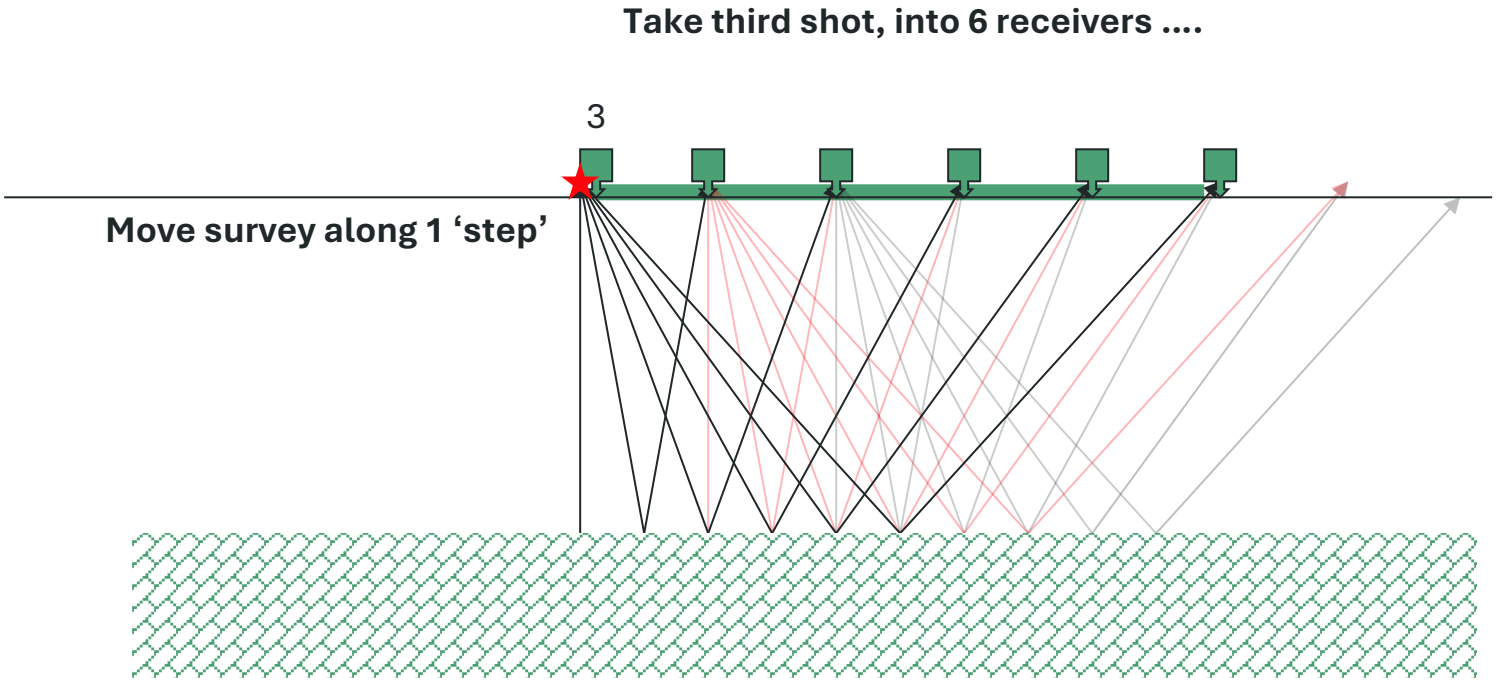


Reflection Seismology: Survey Design

Take second shot, into 6 receivers ....

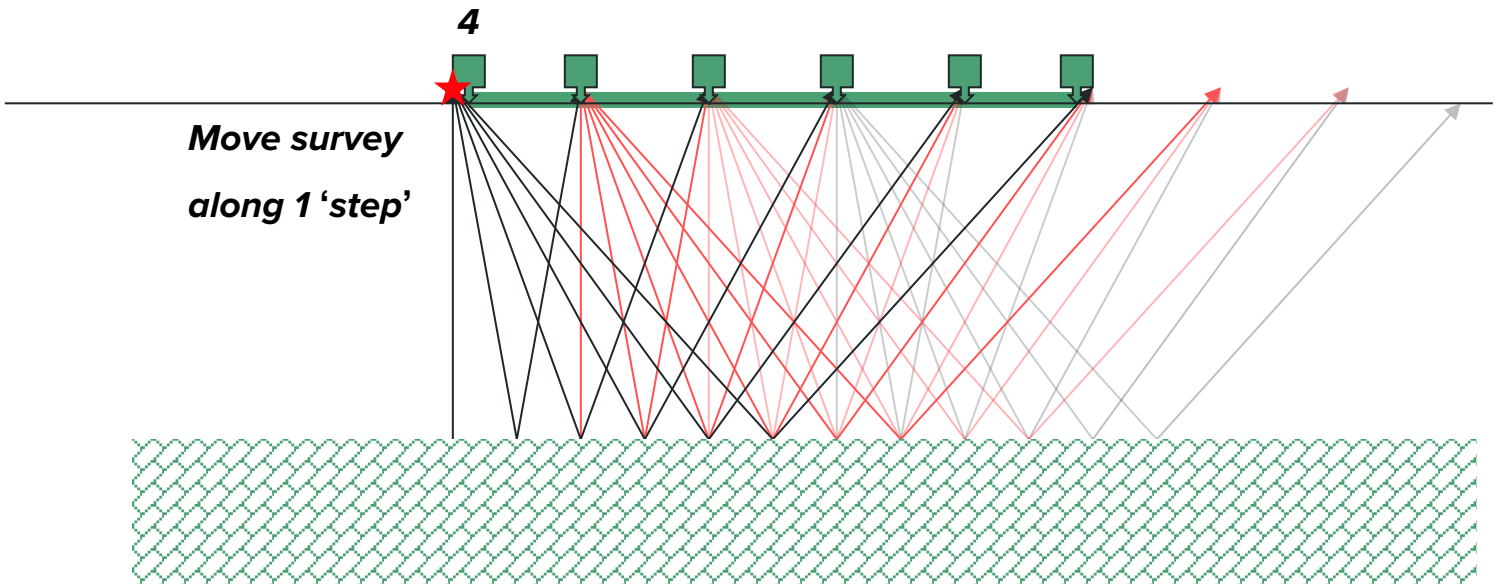


Reflection Seismology: Survey Design

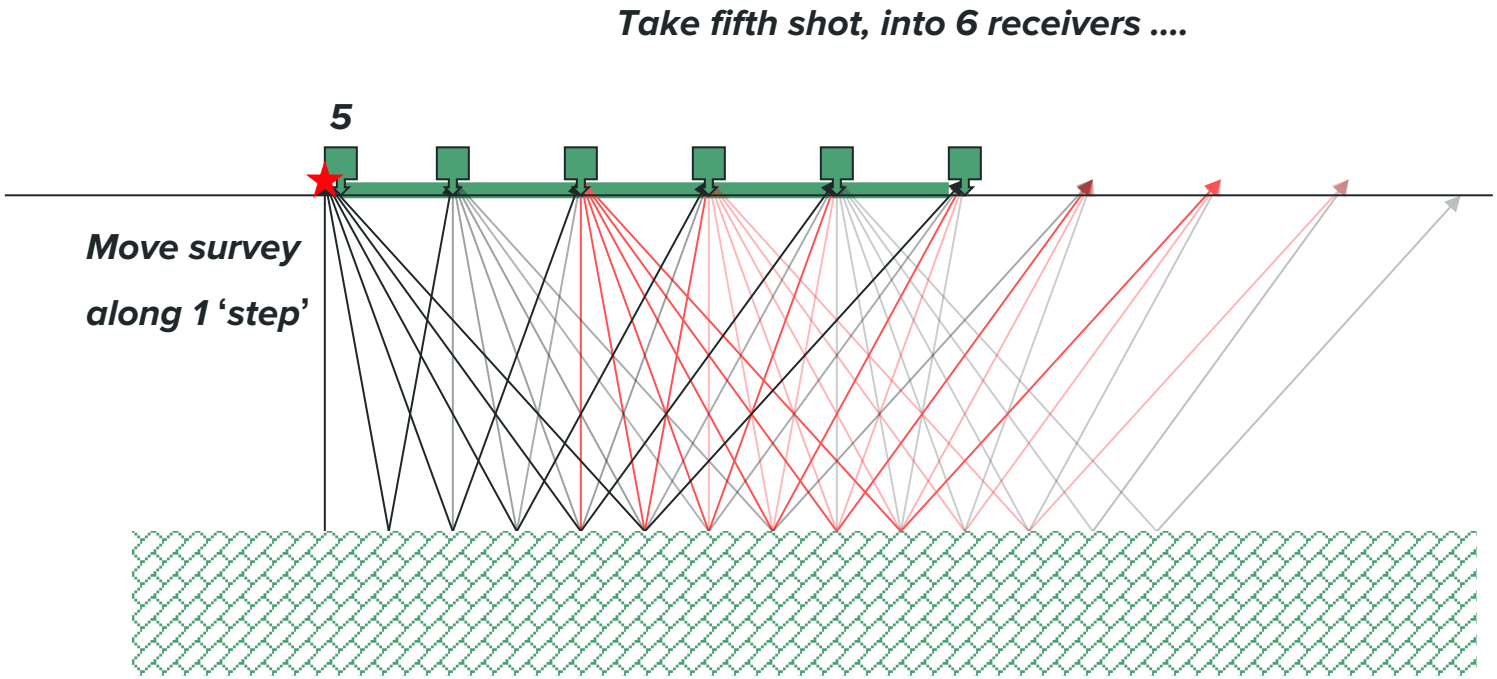


Reflection Seismology: Survey Design

Take fourth shot, into 6 receivers ....



Reflection Seismology: Survey Design



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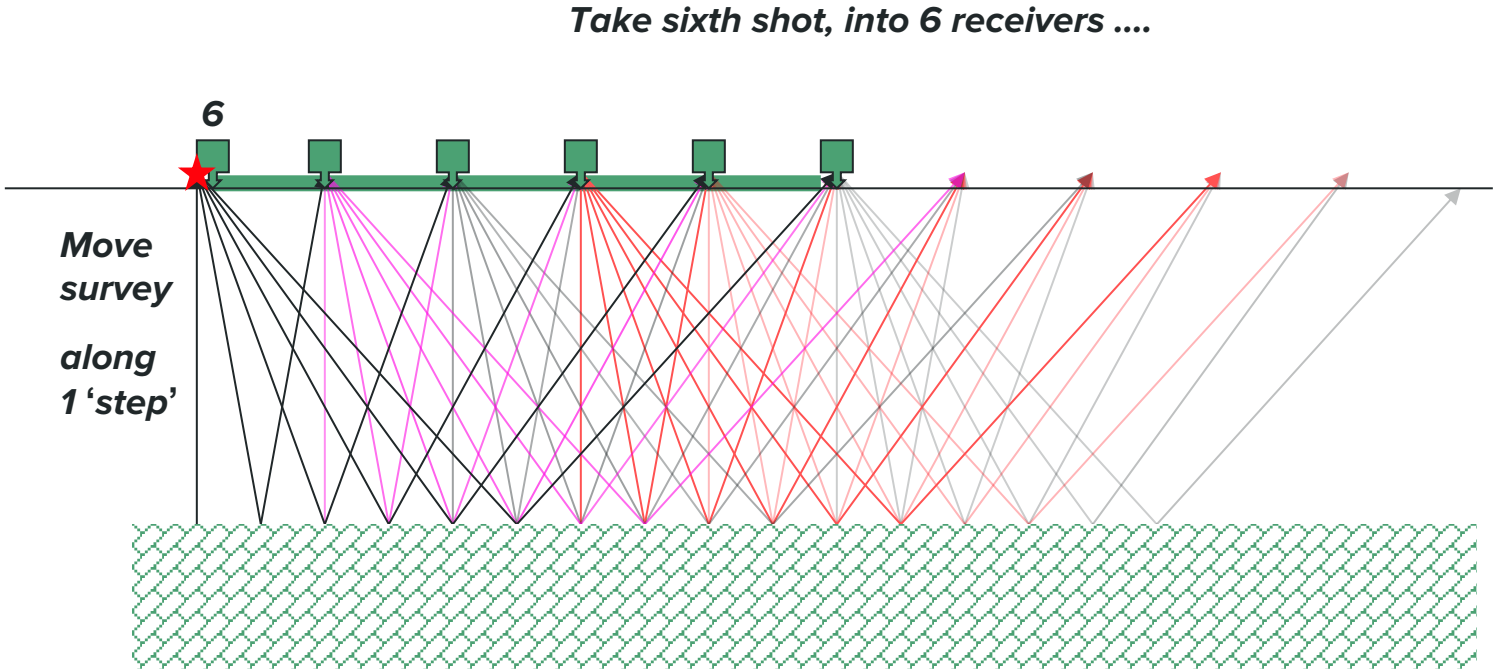

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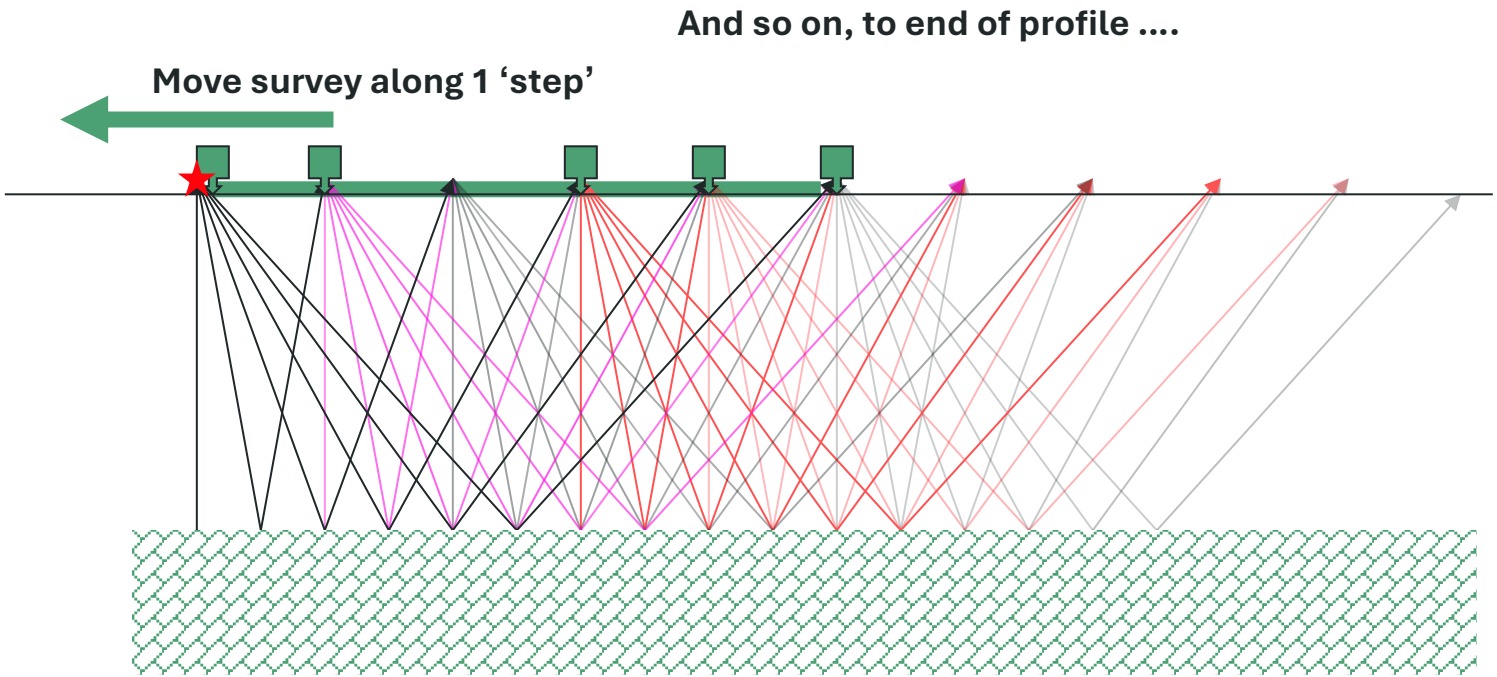
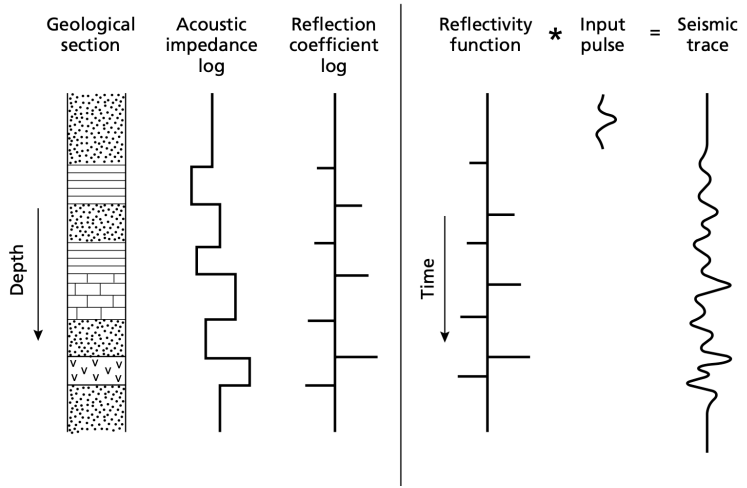
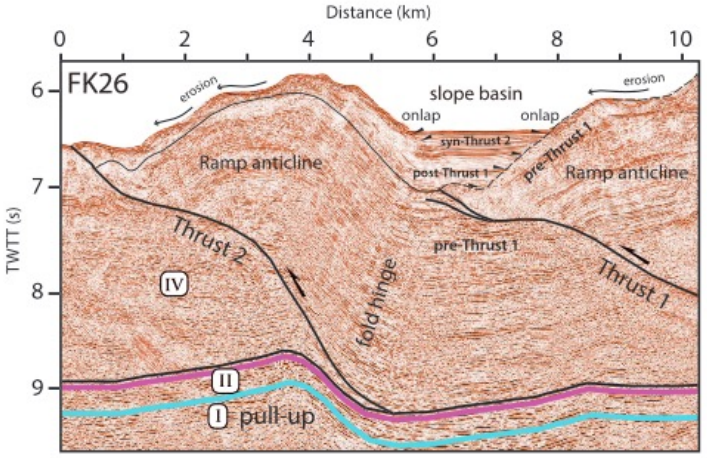


Reflection Seismology

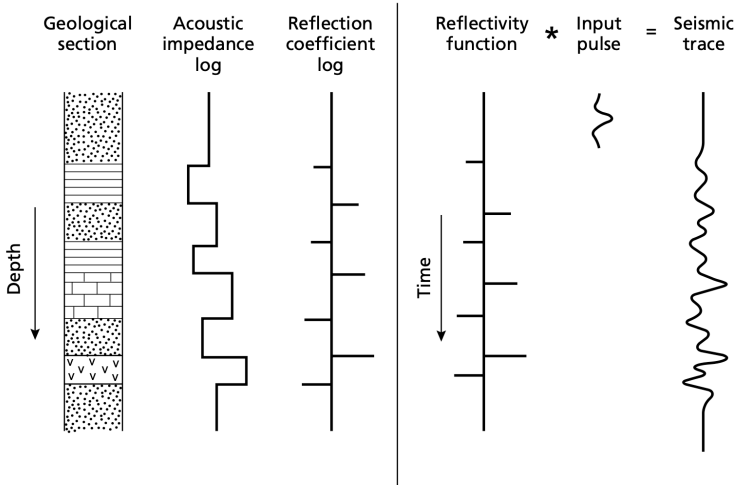
Going from a seismic trace to an image of the subsurface requires various steps from data acquisition to data processing!

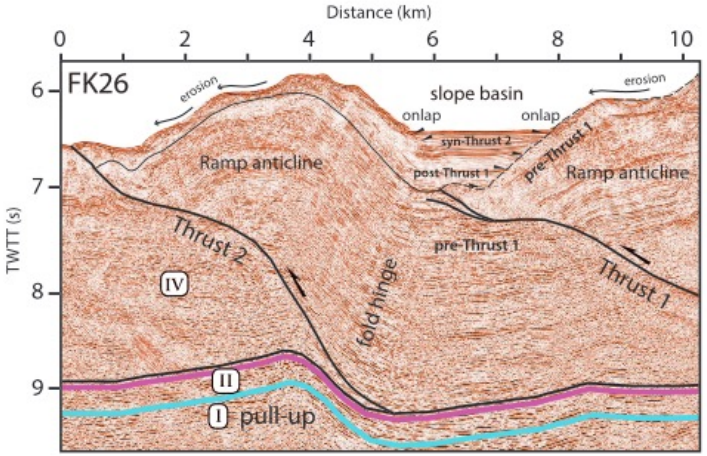




Basic Processing Steps to a reflection image

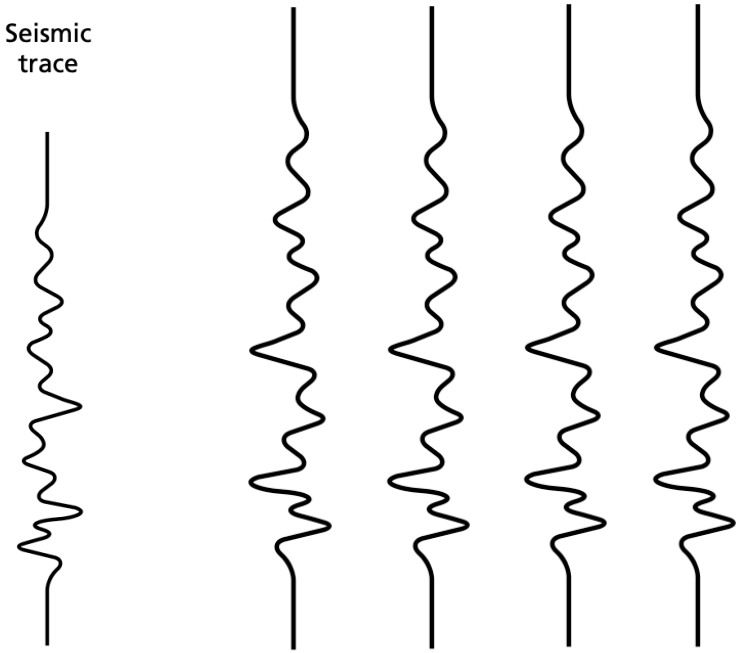
Sort to CMP gather
Correct for changes in the moveout
Stack all traces to get one trace at each CMP
Plot all stacked traces at their CMP location

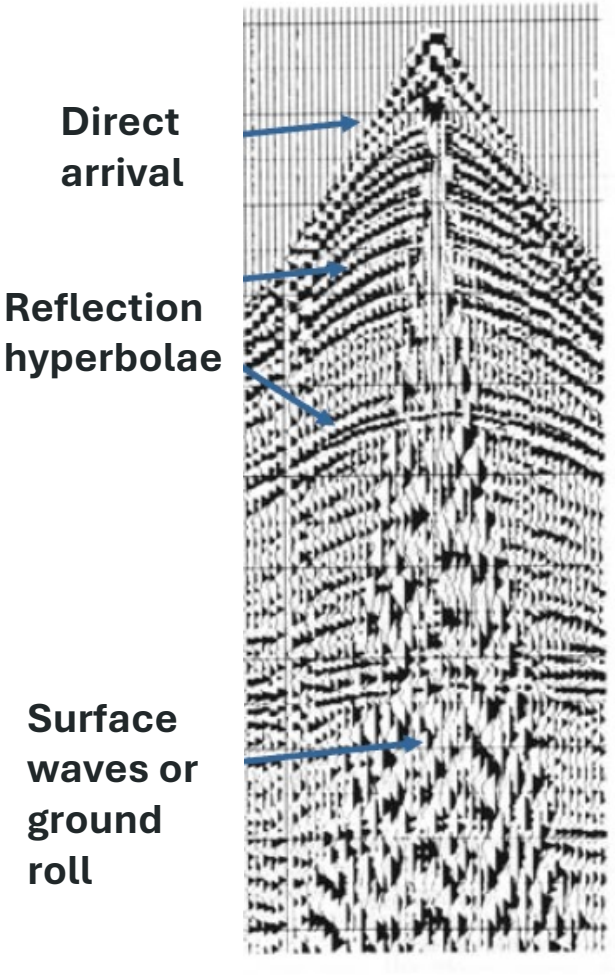




Reflection Seismology: Shot Gathers

A gather is a collection of traces (seismograms) with a common parameter. In this case, the traces recorded during a shot is called a shot gather





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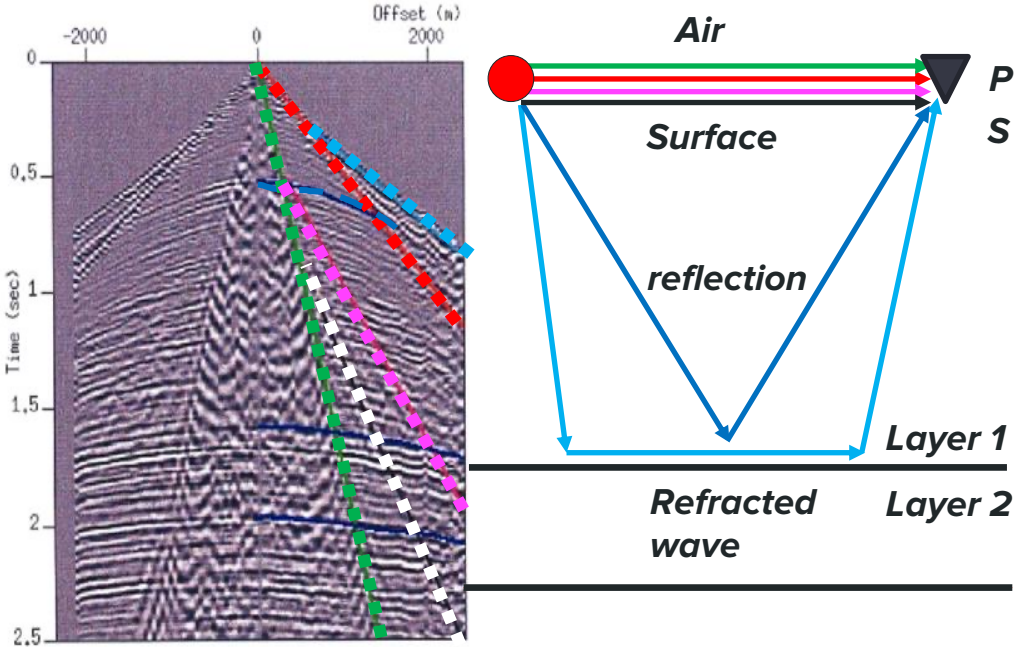
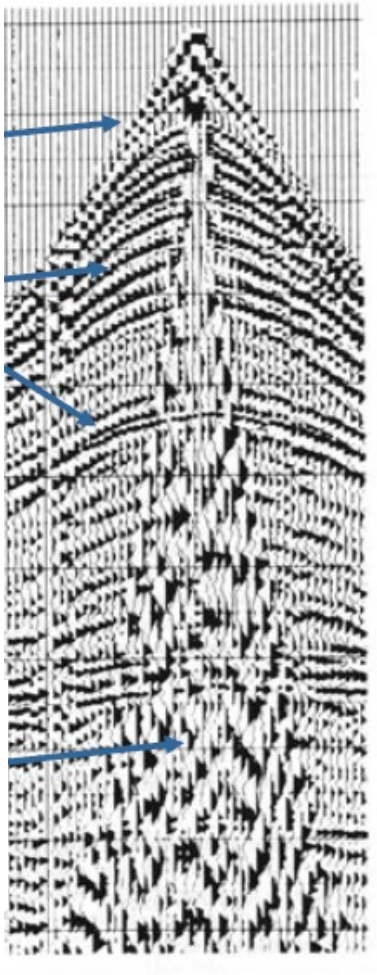


Direct arrival

Reflection hyperbolae

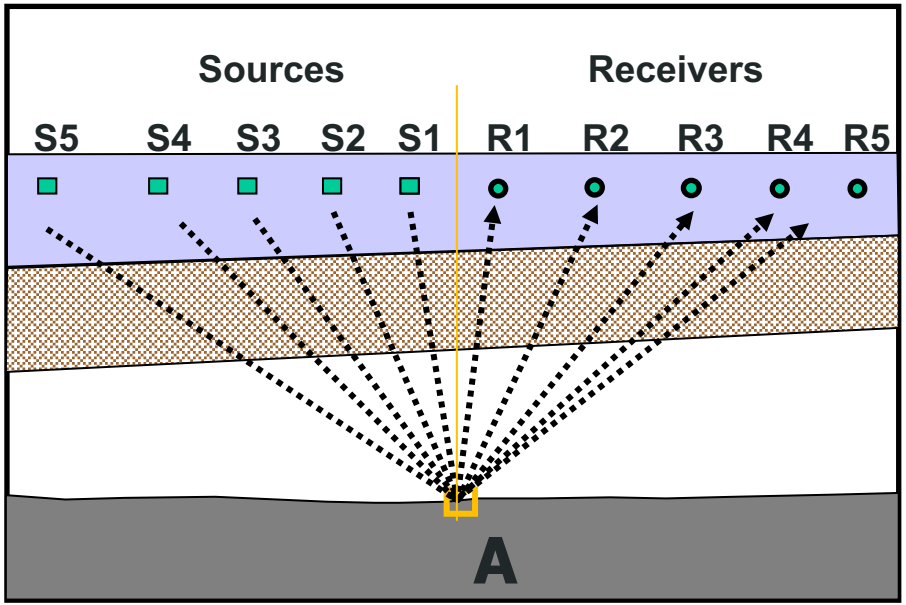
Surface waves or ground roll

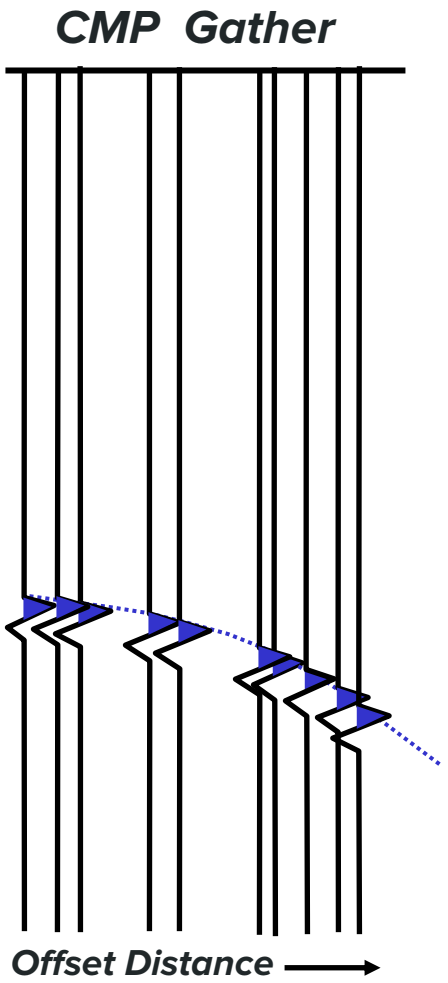


Reflection Seismology: Common Midpoint Gather (CMP)

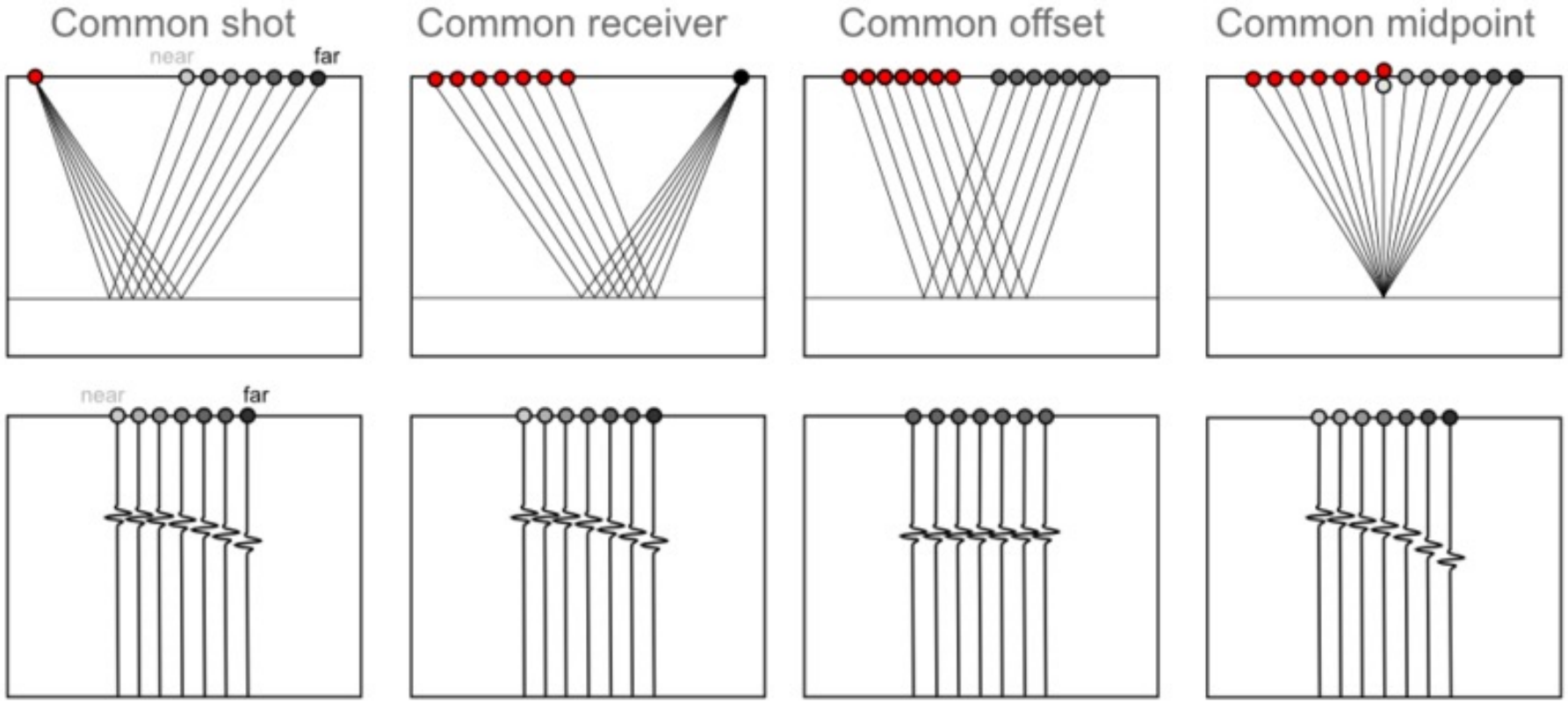
Group all source-receiver pairs that sample the same CMP.
WHY? We want to do this so we can stack data from more than one shot, which enhances the signal.

We sort the shot-receiver pairs so that data from the same 'bounce' point (e.g., at 'A') is captured





We can re-organize the data in other ways



Sample Exam Question

1. What is the difference between a shot gather and a CMP gather?

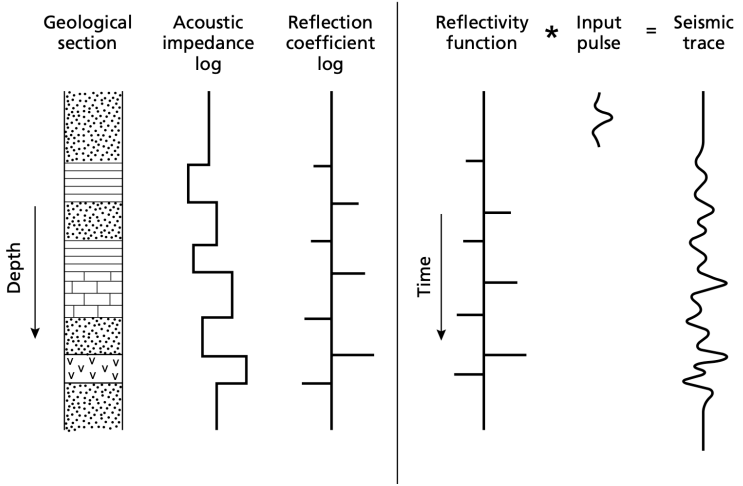
Sample Exam Question

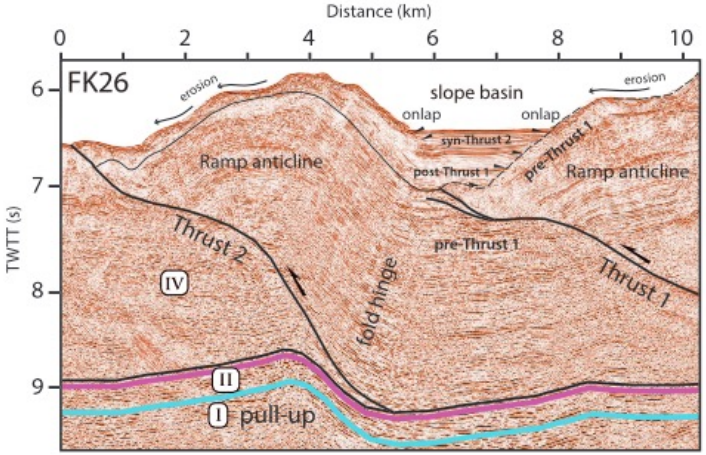
What is the difference between a shot gather and a CMP gather?

A "shot gather" refers to a collection of seismic traces recorded from a single shot location with multiple receivers, while a "CMP gather" (Common Midpoint gather) is a collection of traces from different shot-receiver combinations that all share a common reflection point in the subsurface, essentially combining data from multiple shots to improve signal quality by focusing on a single point of reflection; meaning a CMP gather is a more refined data set compared to a single shot gather.

Basic Processing Steps to a reflection image

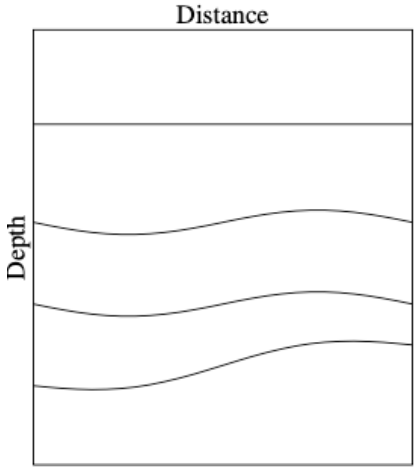
Sort to CMP gather
Correct for changes in the moveout
Stack all traces to get one trace at each CMP
Plot all stacked traces at their CMP

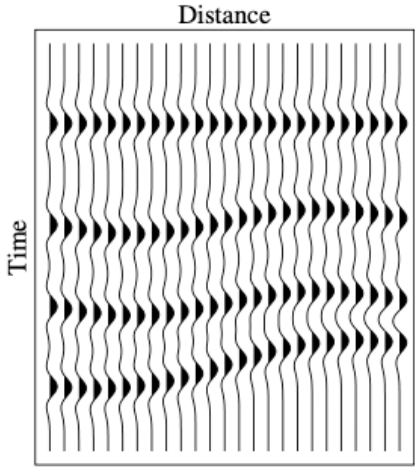


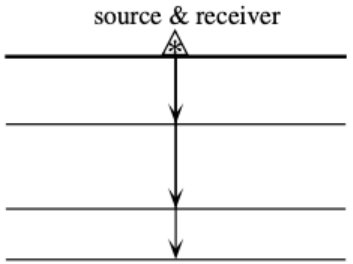


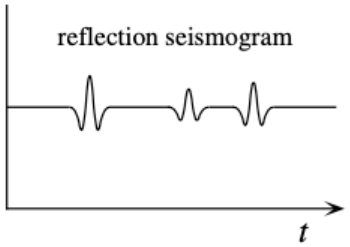
Zero-offset

Offset refers to the distance between the source and receiver.
When the source and the receiver are co-located, you get zero-offset section



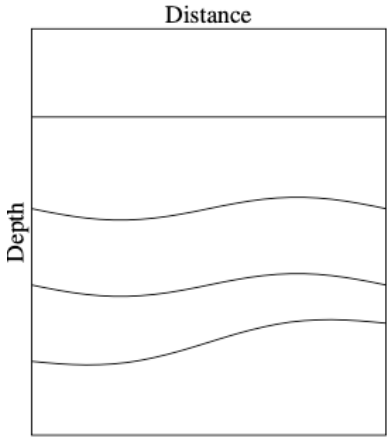


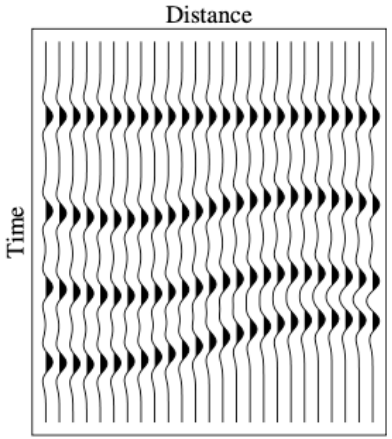


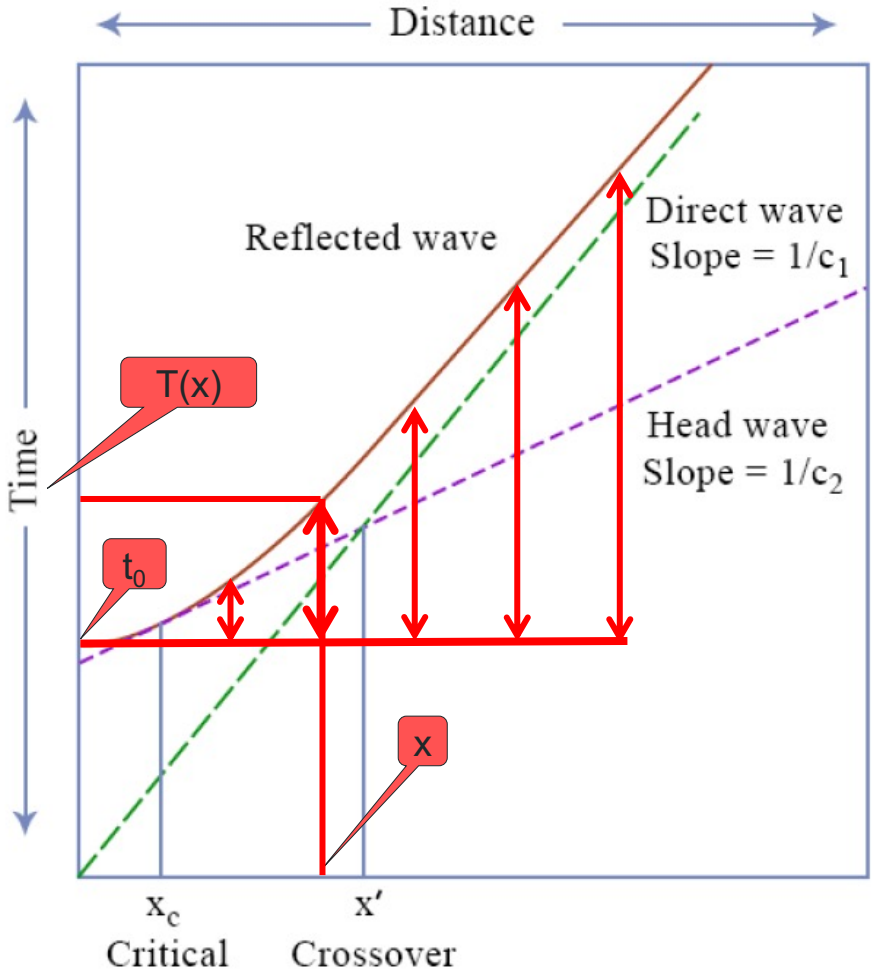


Normal Move Out

The difference between travel time at x=0, "t0", and the travel time at any other distance x, is called the Normal MoveOut (NMO) time tNMO







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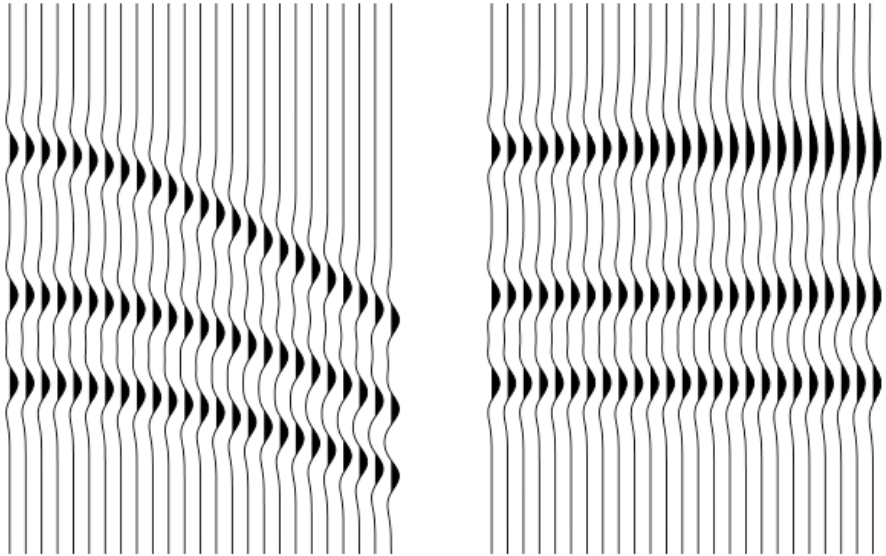
$$tNMO = T(x) - t0$$

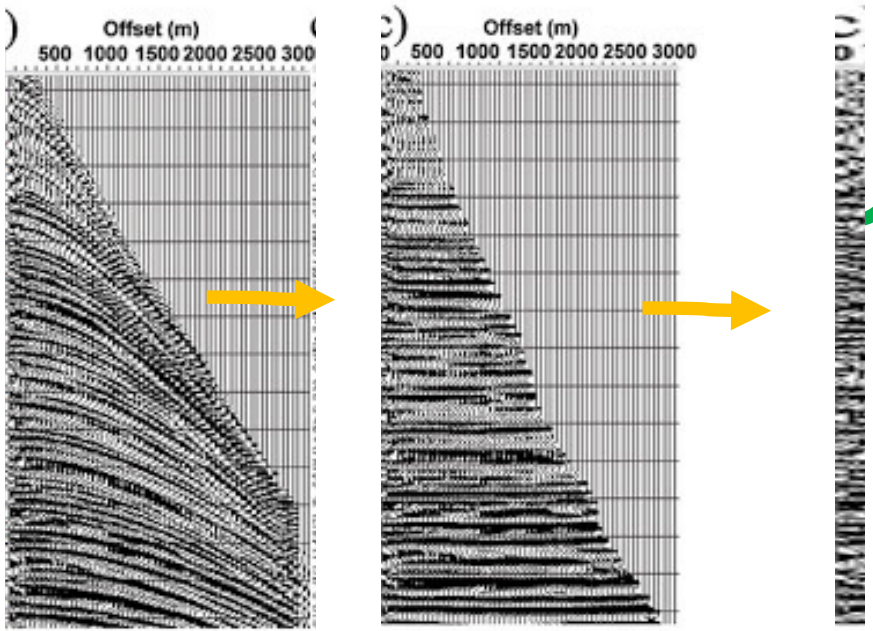
The curvature of a reflection on a T-X plot is controlled by the velocity above it



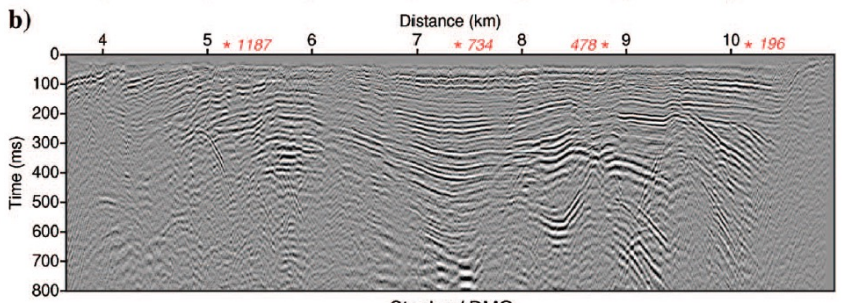
The NMO corrected records can then be stacked to produce a single composite zero-offset record.

Basic Processing Steps to a reflection image

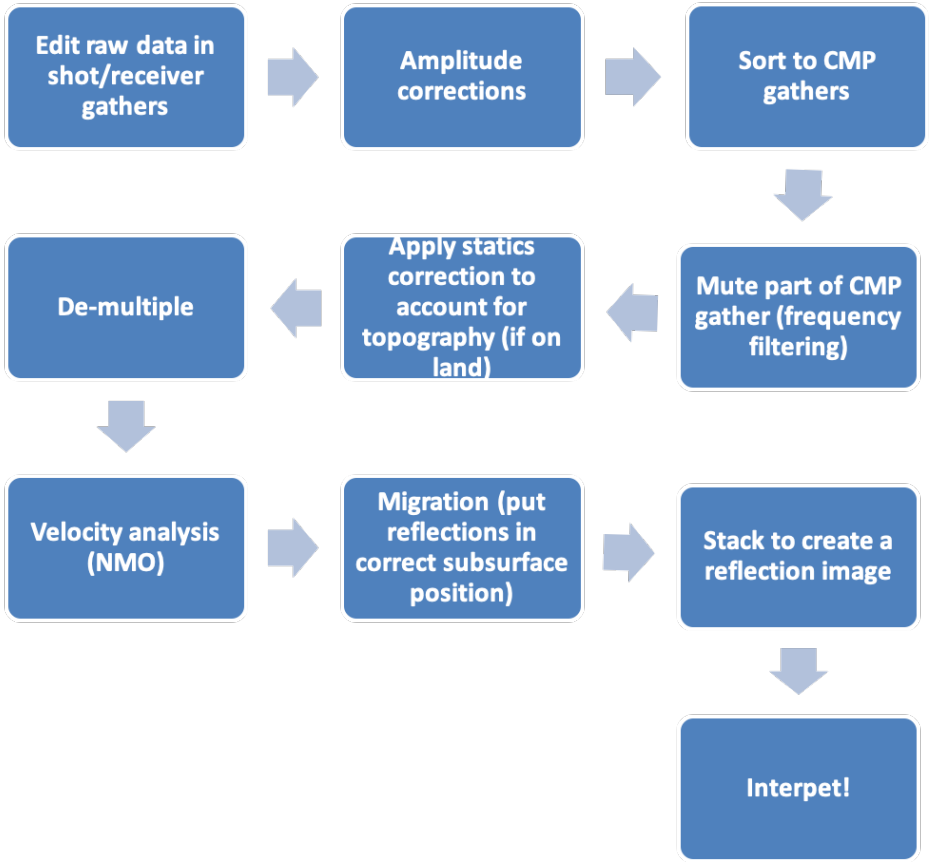
Sort to CMP gather
Correct for changes in the moveout
Stack all traces to get one trace at each CMP
Plot all stacked traces at their CMP location



Stacking implies summation. Signals are coherent while noise is not, so the signal to noise ratio improves when there is constructive addition (signals).



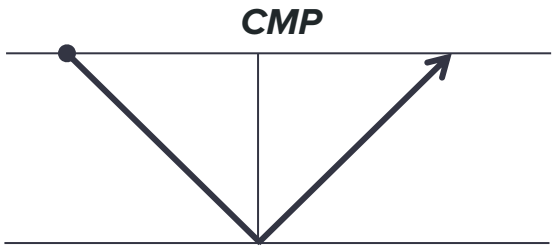
A typical reflection processing sequence

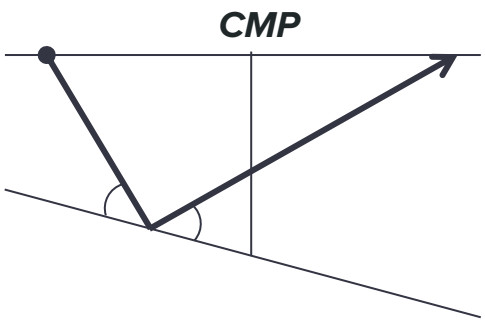


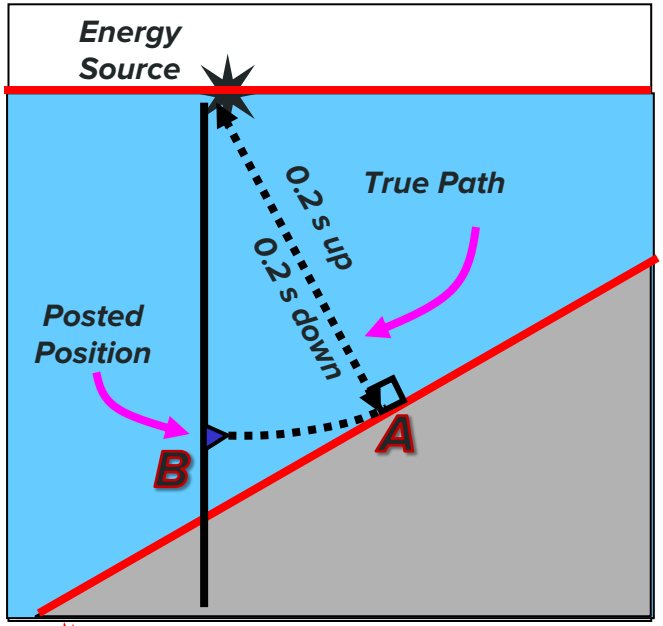
Things can get complicated.. If the layers aren't horizontal

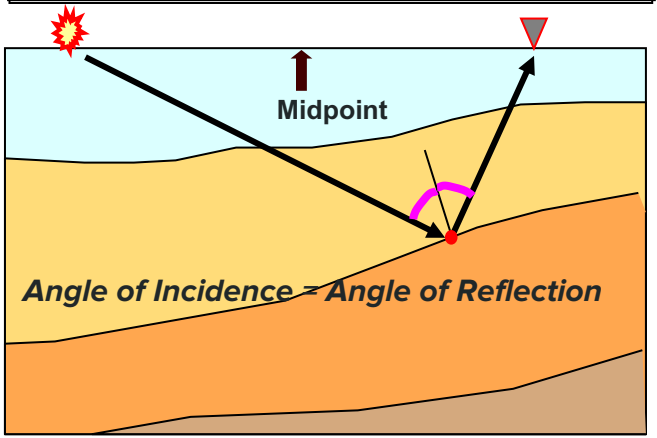
For horizontal layers, the reflection point comes from below the CMP.

For dipping layers though, the reflection point is actually up-dip from the CMP, so travel time sections show a reduced dip.









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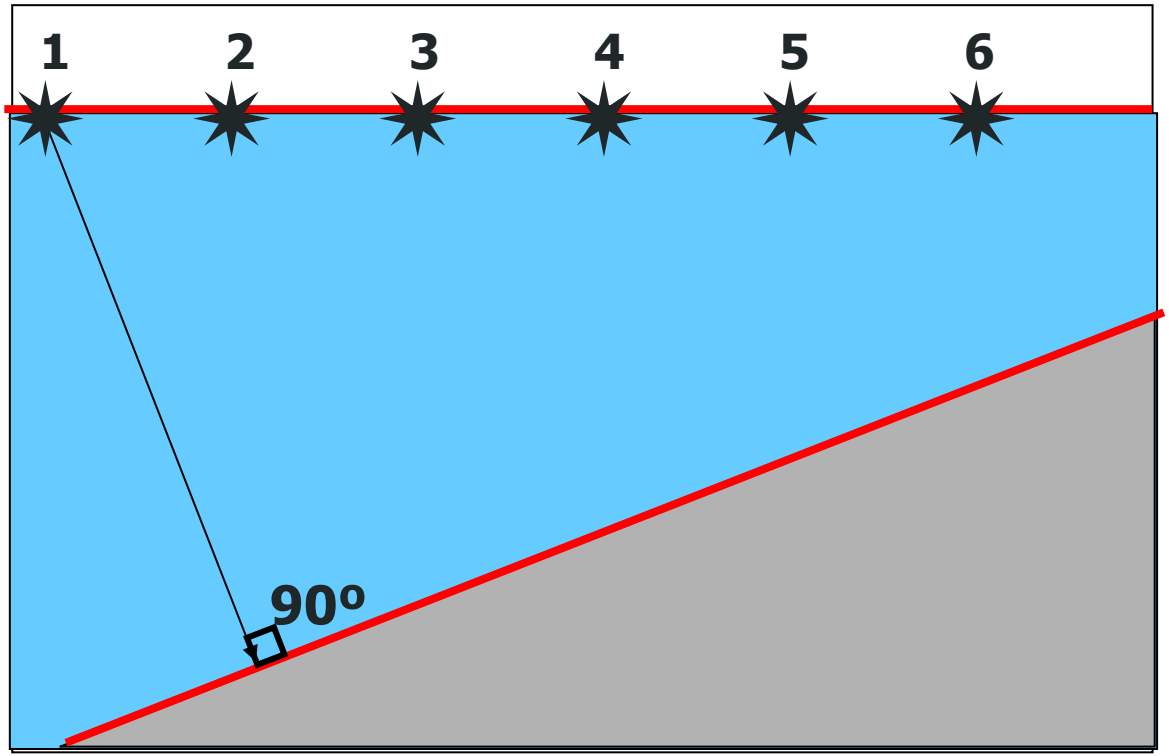
Where would the reflection lie?



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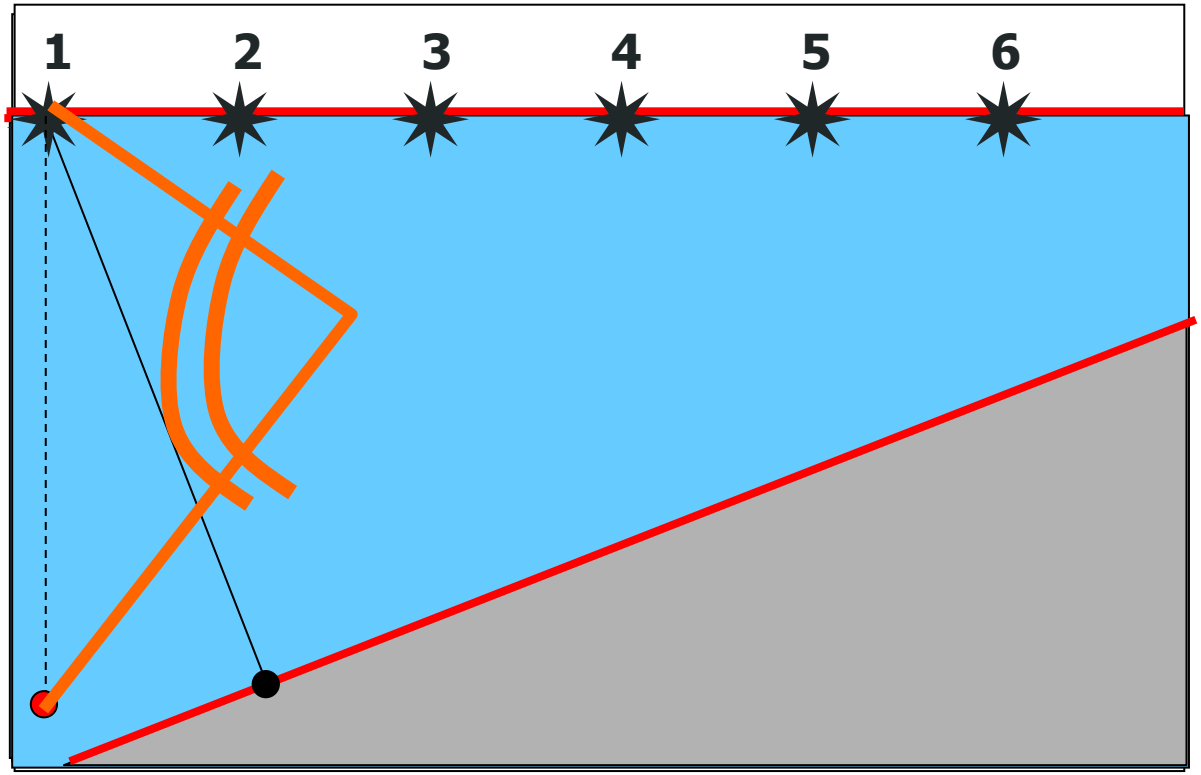

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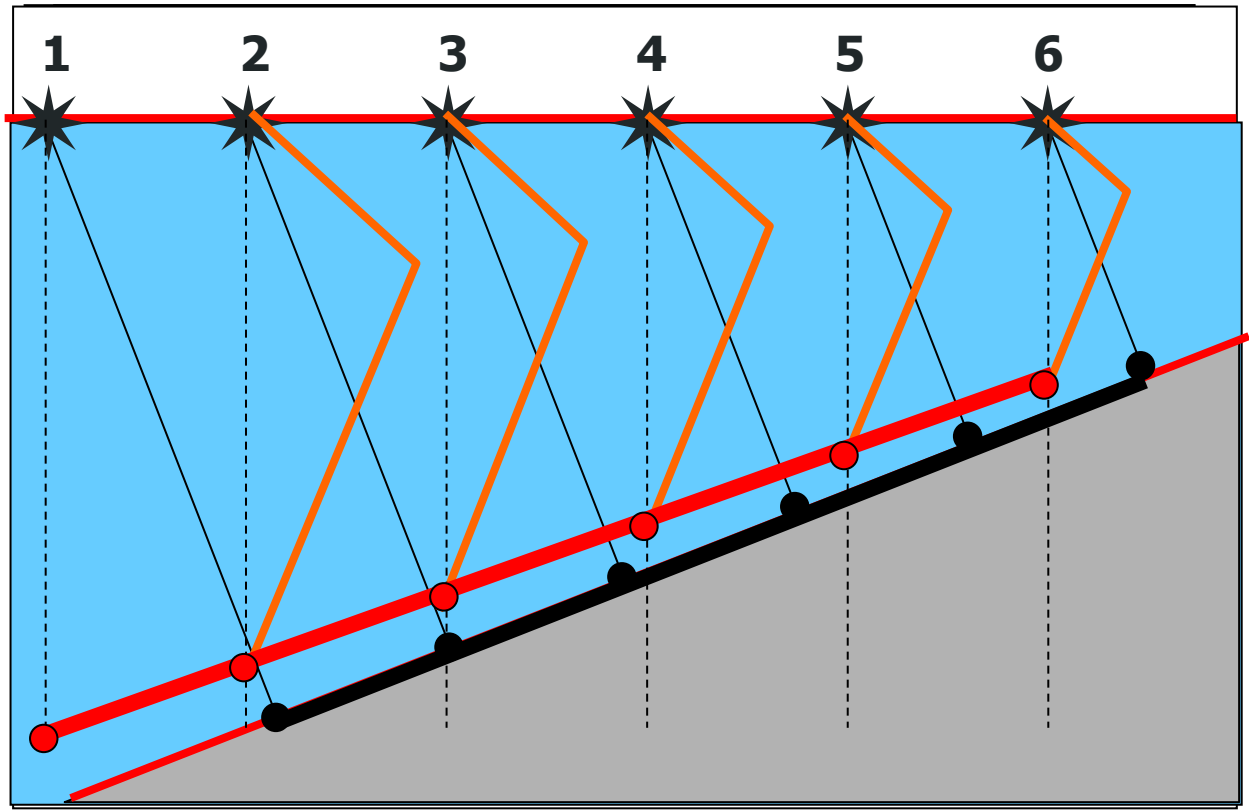
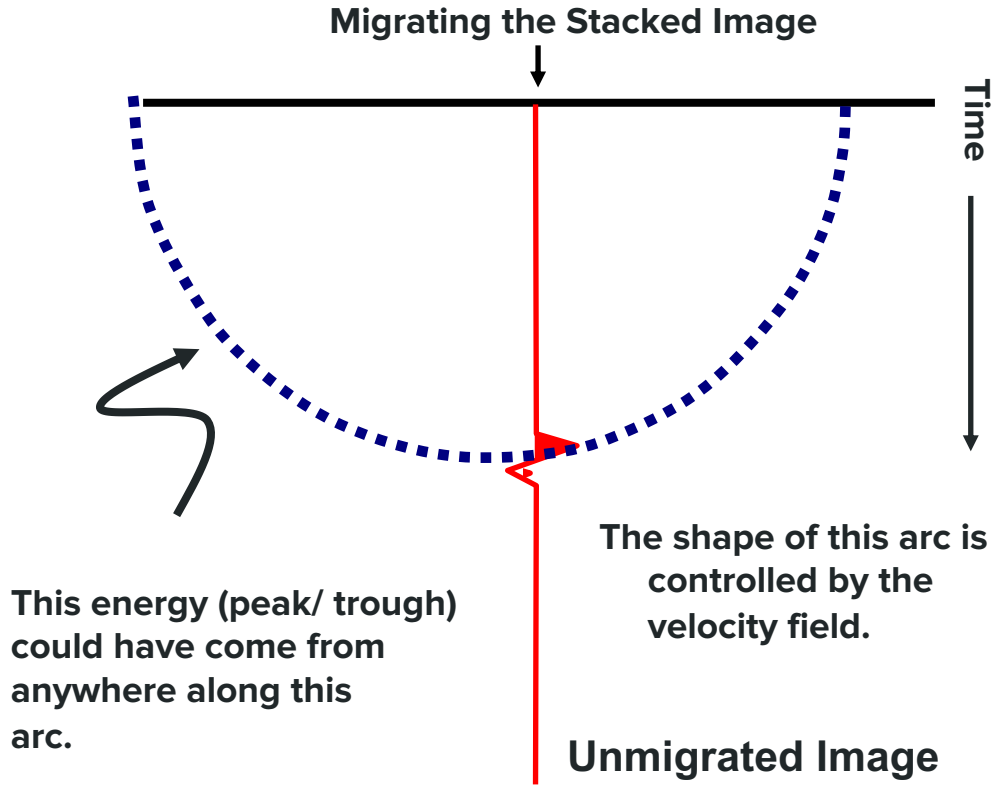
The reflection is positioned downdip and has less dip than the interface



Things can get complicated.. If the layers aren't horizontal.. But we can do something about it.

Migration is the process that fixes a lot of our reflection mispositioning problems.

We refer to the seismic data that has not been migrated as **unmigrated** data. An unmigrated seismic line would be like the red line for the sea floor that we constructed earlier!



Migration to fix mispositioning problems

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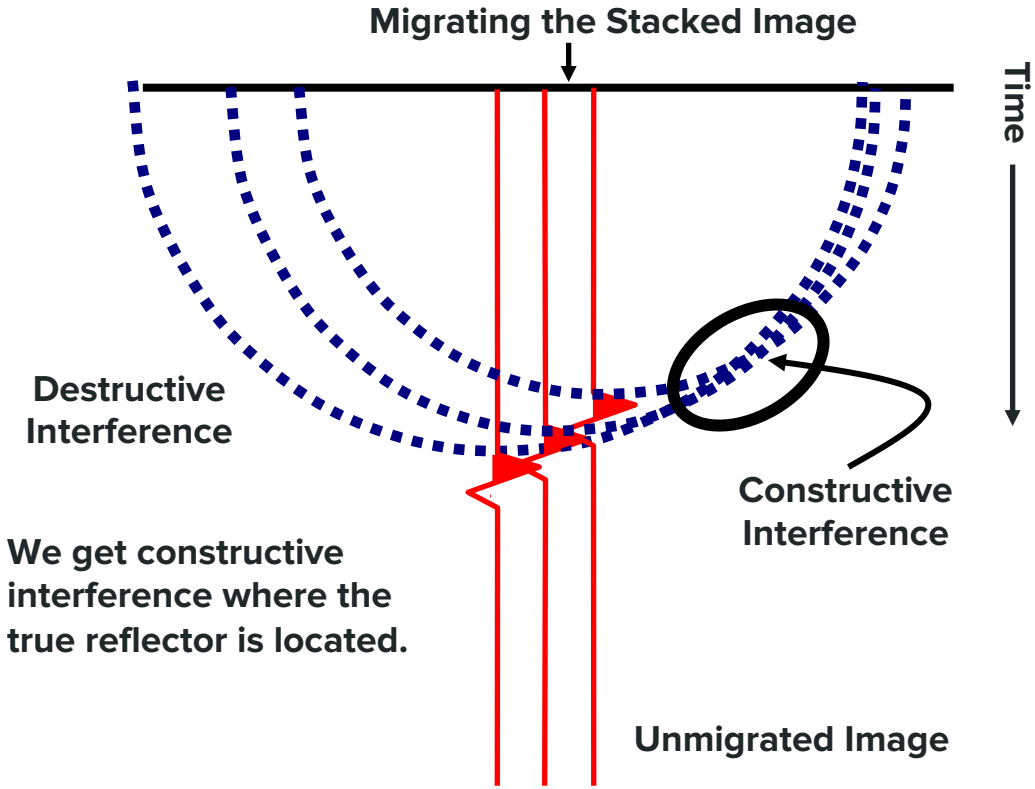

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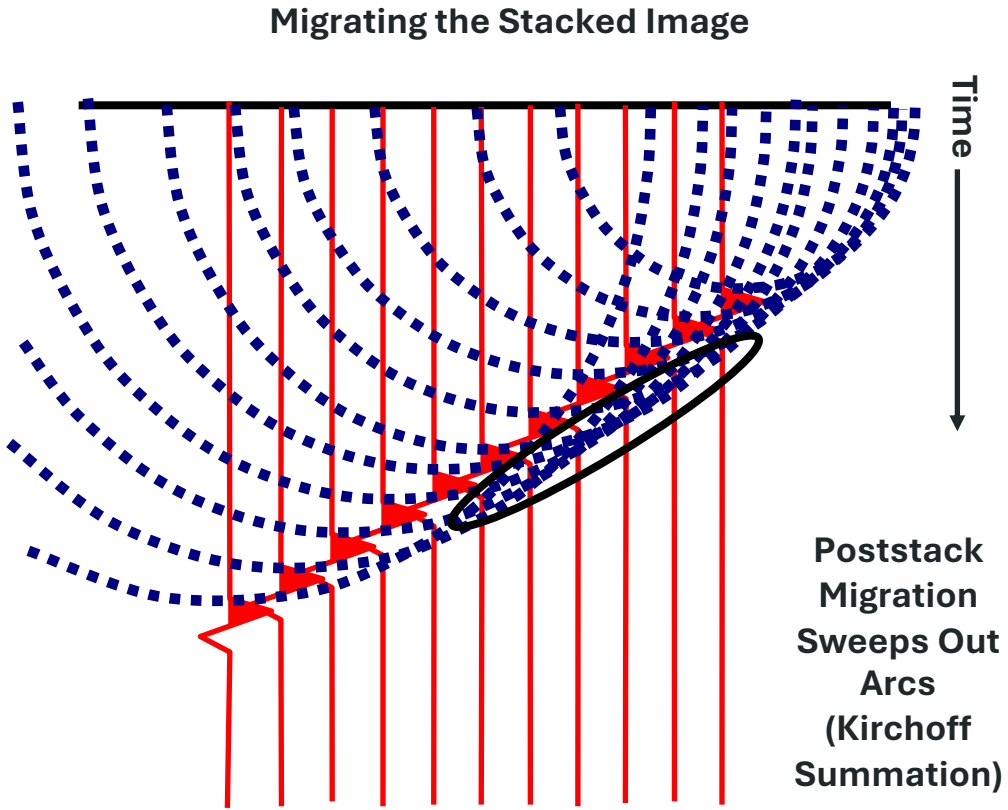

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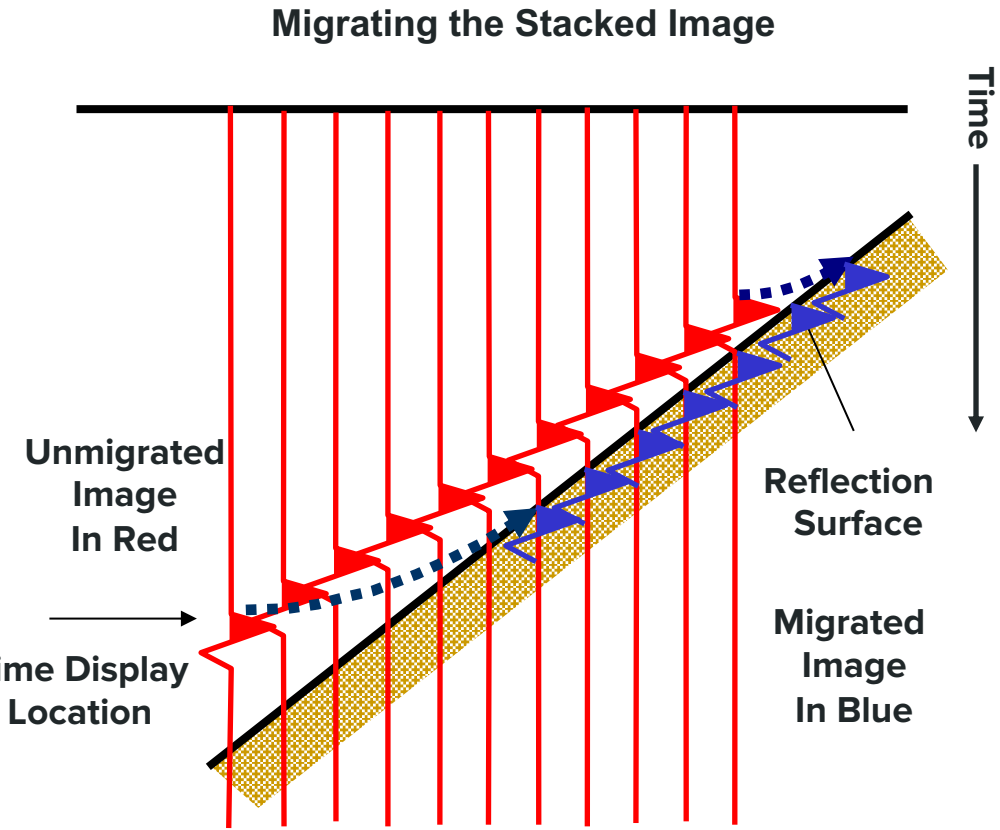
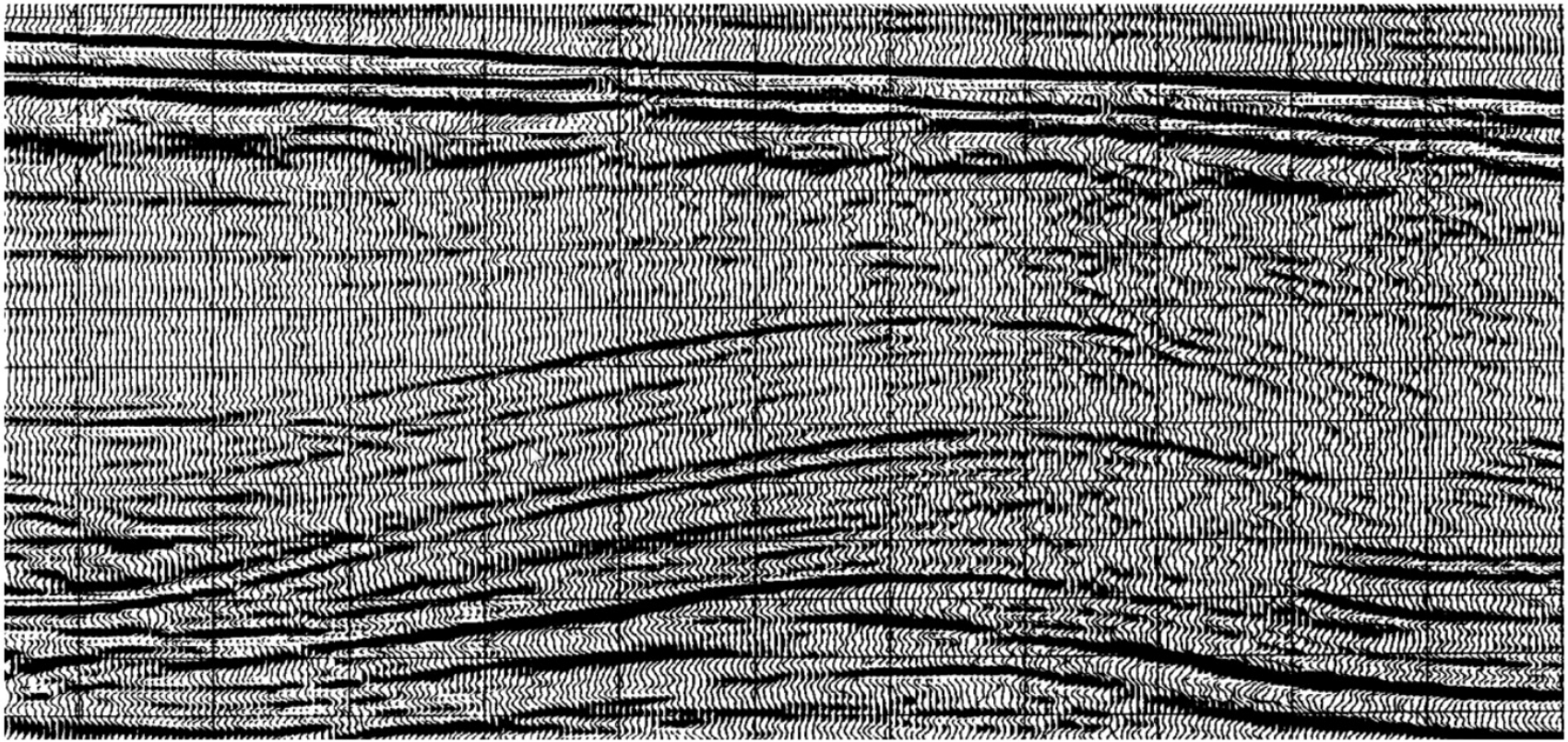
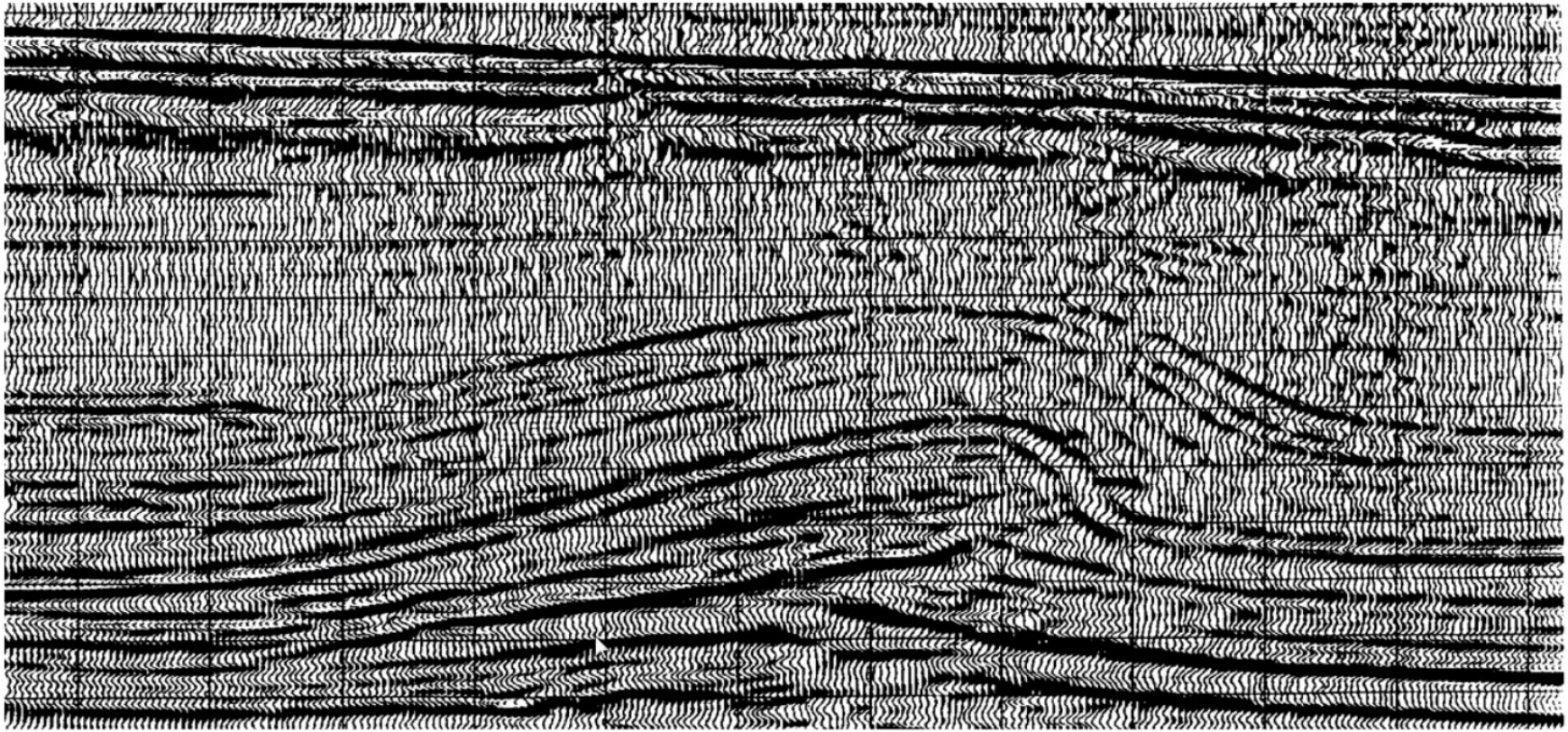


Example for seismic migration

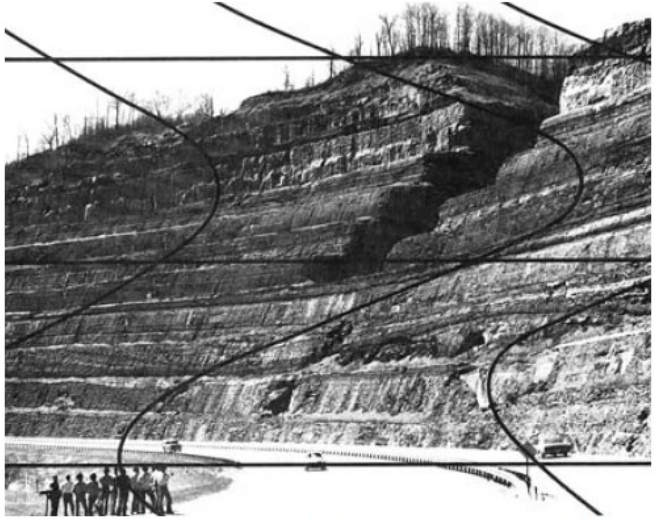


Example for seismic migration

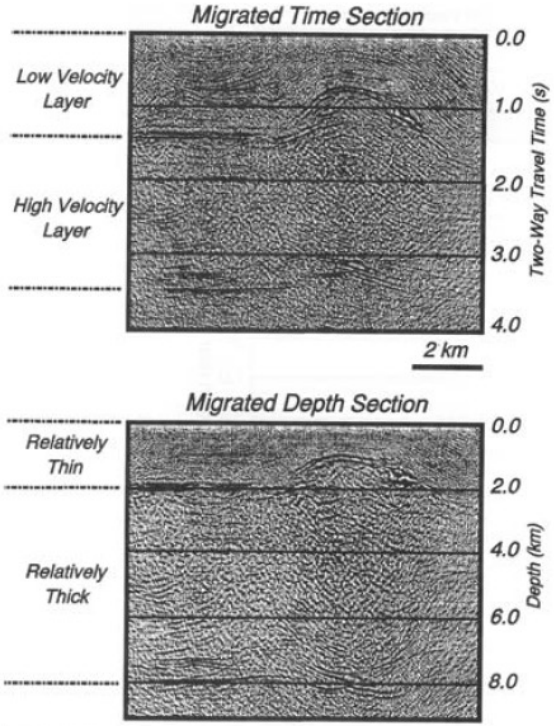


Some pitfalls when interpreting data

Resolution of the seismic data: the seismic data never has outcrop scale resolution. Remember that high frequencies attenuate faster than lower ones, so wavelength increases with depth!

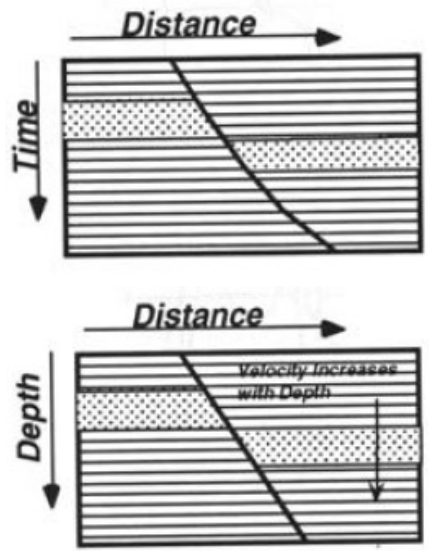


Depth migration can output a true depth section. Relative thicknesses of units from time images to depth images will likely change, maybe a lot!

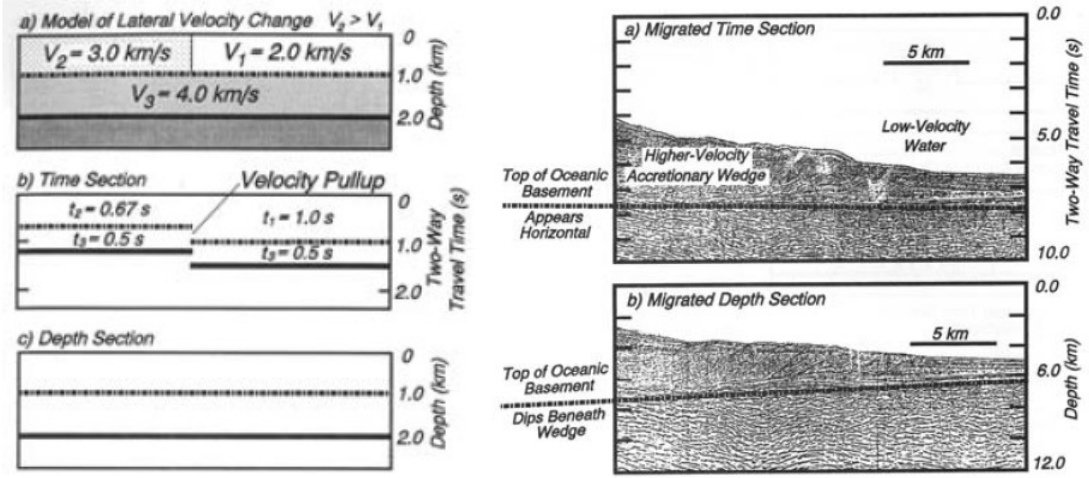


Some pitfalls when interpreting data

Fault geometry can be distorted with depth. Many “listric” faults mapped in seismic are because of this.



Lateral velocity variations produce pull-ups and pull-downs that may not be apparent in time sections.



Sample Exam question

List the differences between reflection and refraction methods.

Questions

Refraction	Reflection
Uses refracted waves	Uses reflected waves
Uses travel times	Uses travel times and amplitude
Results in a velocity model	Results in a velocity model and reflection stack
Only applicable where velocity increases with depth	Applicable even if low velocity layers
Typically used for mapping bedrock depths	Typically used for deeper targets (>100m to <8km)
Coarser resolution	Higher resolution – can obtain detailed geological information

More sample exam questions

1. What does applying a normal move out do to a seismic trace physically?
2. You have two reflectors – one shallow at 0.5s and one deep at 3 s. At the same offset, which shows more moveout and why?
3. Explain from first principles why stacking improves SNR.
4. Trace the journey of a seismic reflection from raw field record to a migrated section.
5. A seismic section (raw data that is stacked) shows a reflection that appears to come from directly beneath a river valley. Your geologist colleague is excited and says there must be a deep structure there. What caution would you raise before they get too excited?