Reflection Seismology

The Seismic Reflection Method:

A dynamic geophysical technique of generating a sound wave at a source and recording the time it takes for components of that seismic energy to return to the surface and be recorded by receivers

Ground Penetrating Radar:

Utilizes similar theory, but the source is electromagnetic waves

Seismic Reflection

- Things to know before we start…
  - Seismic reflection is the single most important technique for seeing into the Earth.
    - It is useful for shallow and deep depths
    - Massively used by the oil and gas industry
    - It can detect:
      - Stratigraphy
      - Faults
      - Folds
      - Oil & Gas Reservoirs
      - Groundwater Resources
  - Why so popular?
    - Produces results that actually look a lot like an actual geologic cross section!!

Reflection Seismology

- 1920's - 1930's, seismic reflection developed for oil/gas exploration in sedimentary basins.
- Since 1970's, valuable in understanding structure of mid-lower crust.
- Popular for three main reasons:
  - Reflection data is commonly portrayed as profile resembling "geologic cross sections".
  - Offers high resolution of subsurface data.
  - Cheaper than blindly drilling

Dr. A. BALUKKARASU

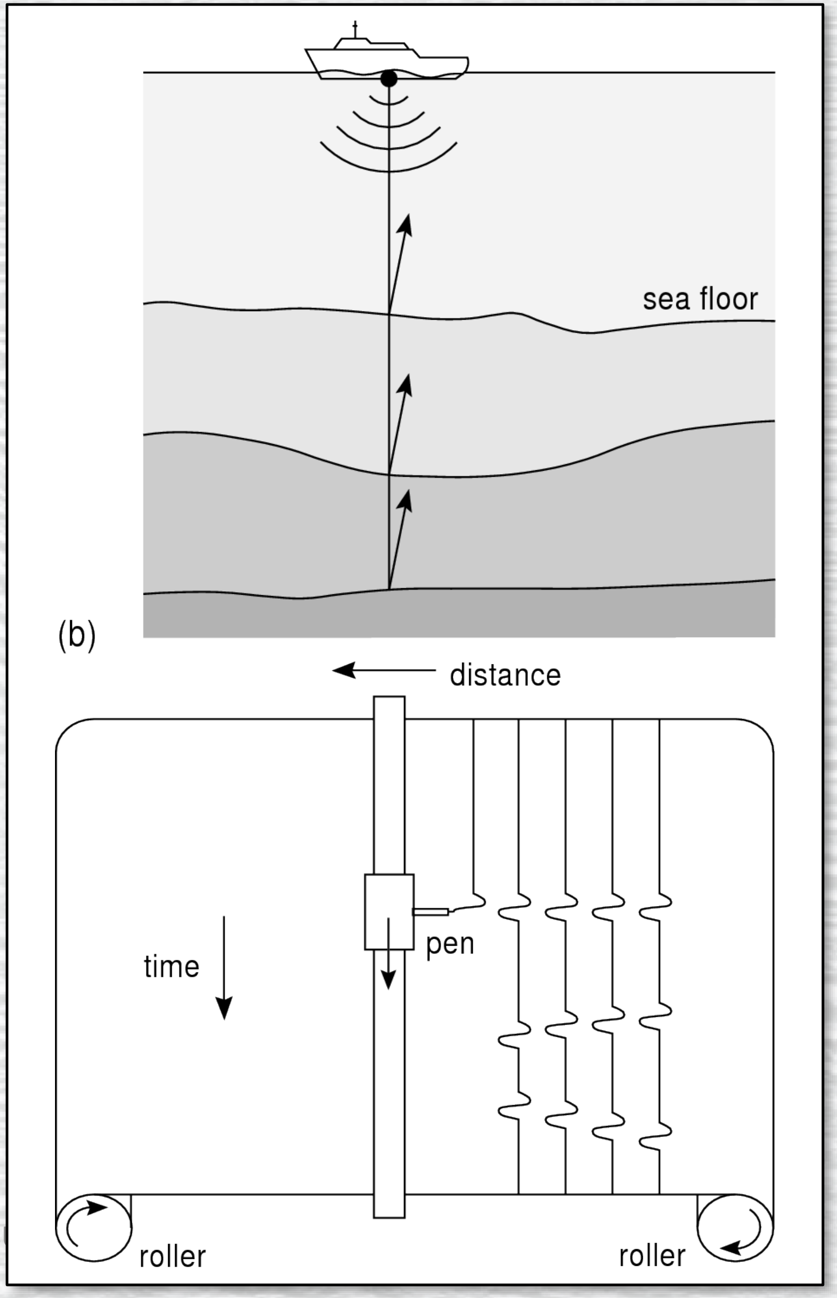
Refraction vs. Reflection

- So, what are the main take-home differences between these two seismic techniques?

Refraction	Reflection
Resolves gross crustal velocities	Resolves fine subsurface details
critical refraction requires large v gradient	requires a change in v or density
X=5-10x the depth of interest	X=1x the depth of interest
Processing is relatively easy	Processing can be very CPU intensive

Seismic Reflection :: The Basics

- In the simplest sense seismic reflection is echo sounding.
  - Echoes come from layers in the Earth, not fish or the sea floor
- E.g. a ship sends out a seismic pulse
  - The pulse is reflected back to a receiver on the ship's bottom after some time has passed
  - The various arrivals can be used to map out subsurface "reflectors" or layers

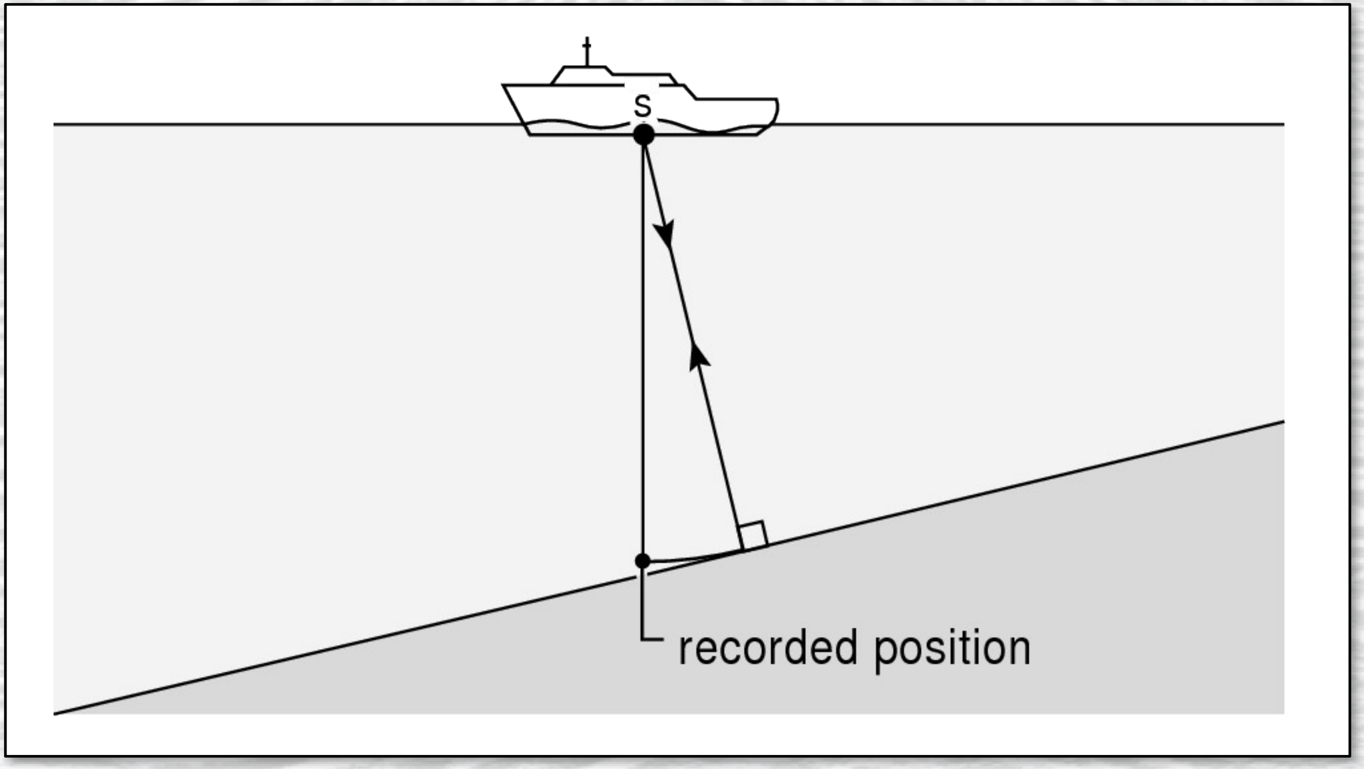


Seismic Reflection Caveats

1. The vertical scale on seismic reflection profiles is time, not depth
   - Velocity varies with depth, so time cannot be easily converted to depth
2. Reflections may not come from directly below the source
   - Reflections occur perpendicular to the interface. Receivers / Geophones / Seismometers cannot directly detect this.
3. There may be multiple reflections off of single interfaces
   - Called multiples
4. There are other caveats, but we'll deal with these later

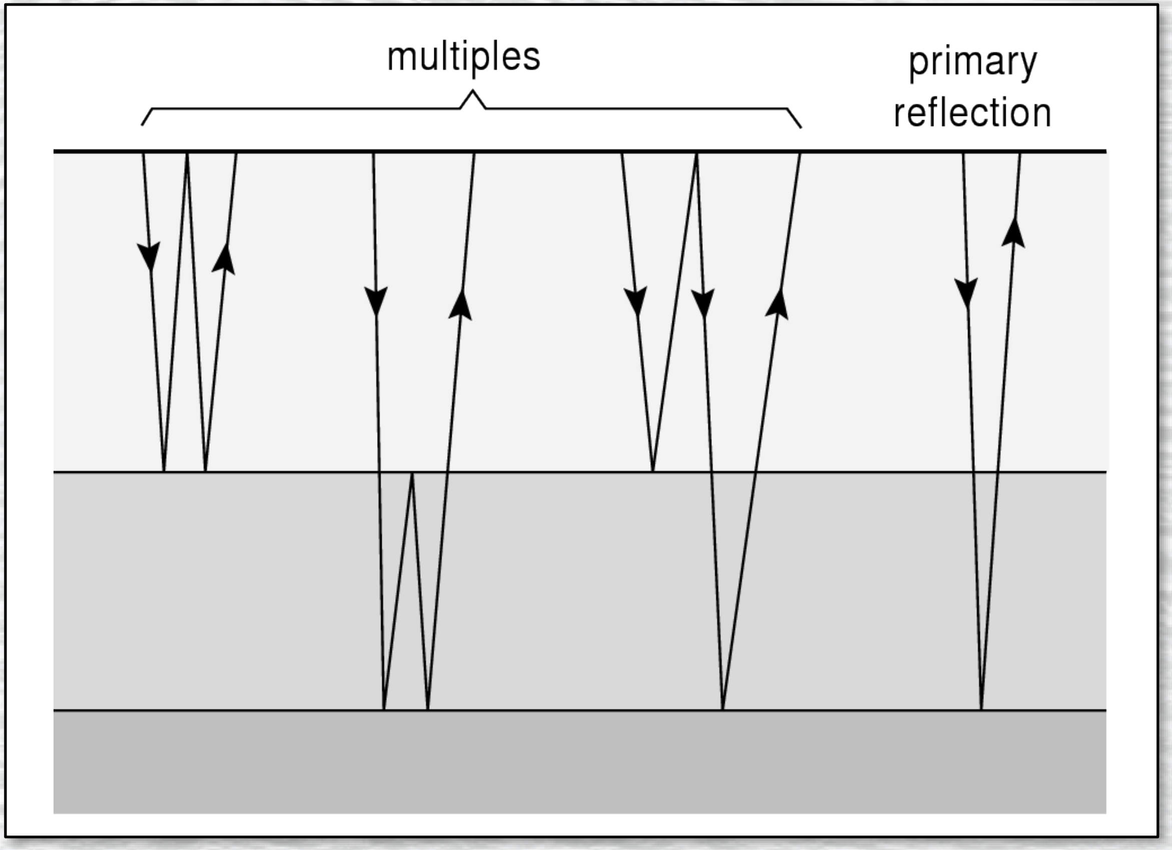
Non-Vertical Reflection

- Reflected rays travel back to the source following a path perpendicular to the interface
  - The receiver will record an arrival time that is too short and a dip that is too shallow
  - We'll talk more about this later…

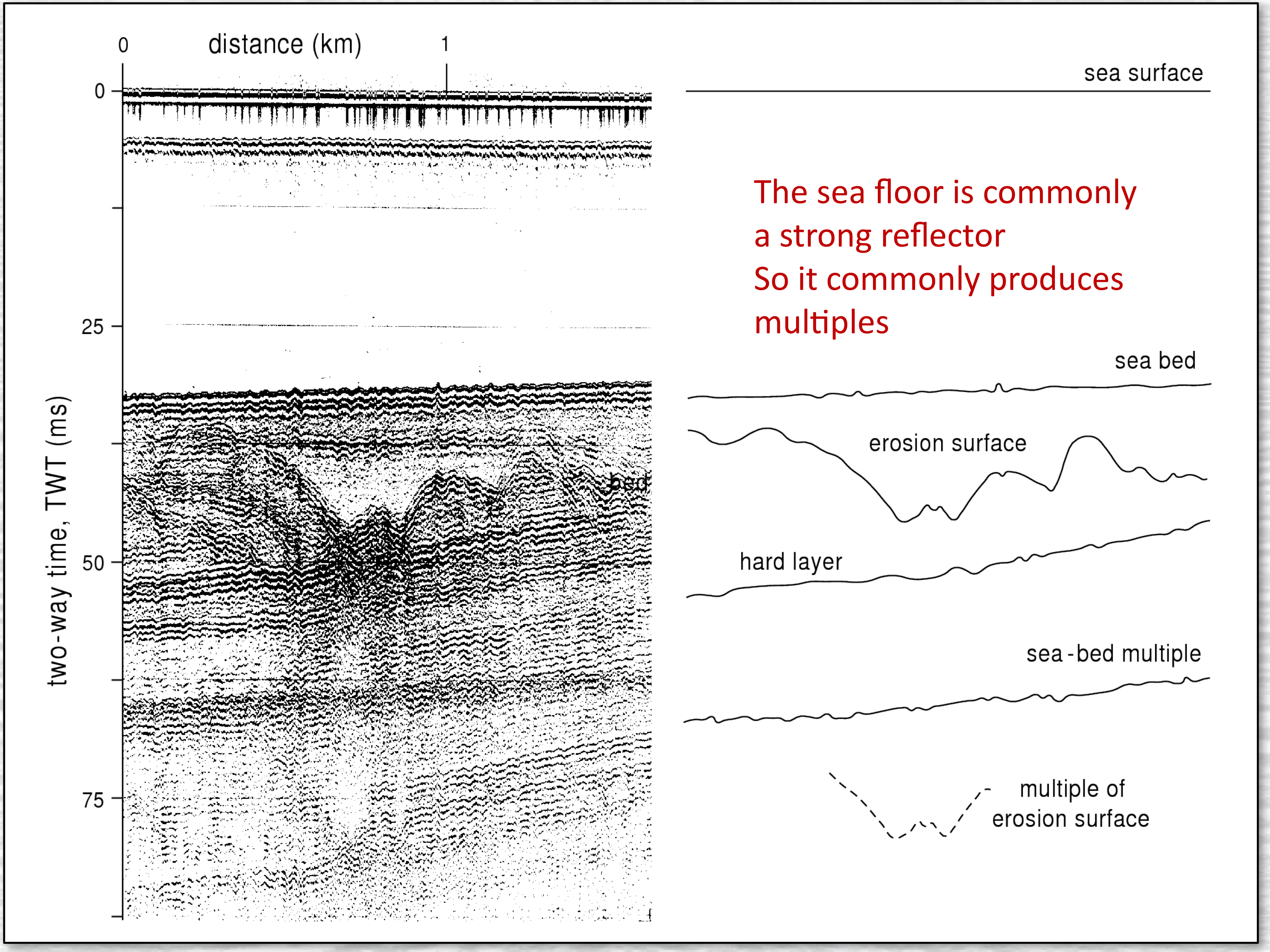


Multiples

- On their return to the surface…
  - Reflected rays can also reflect back down and then later be reflected back up
- This causes a single reflector to potentially produce several "multiples"
- Short path (less reflections) multiples are usually stronger
- These artifacts can be removed by migration
  - We'll talk about migration later…



Multiples in a Seismic Section



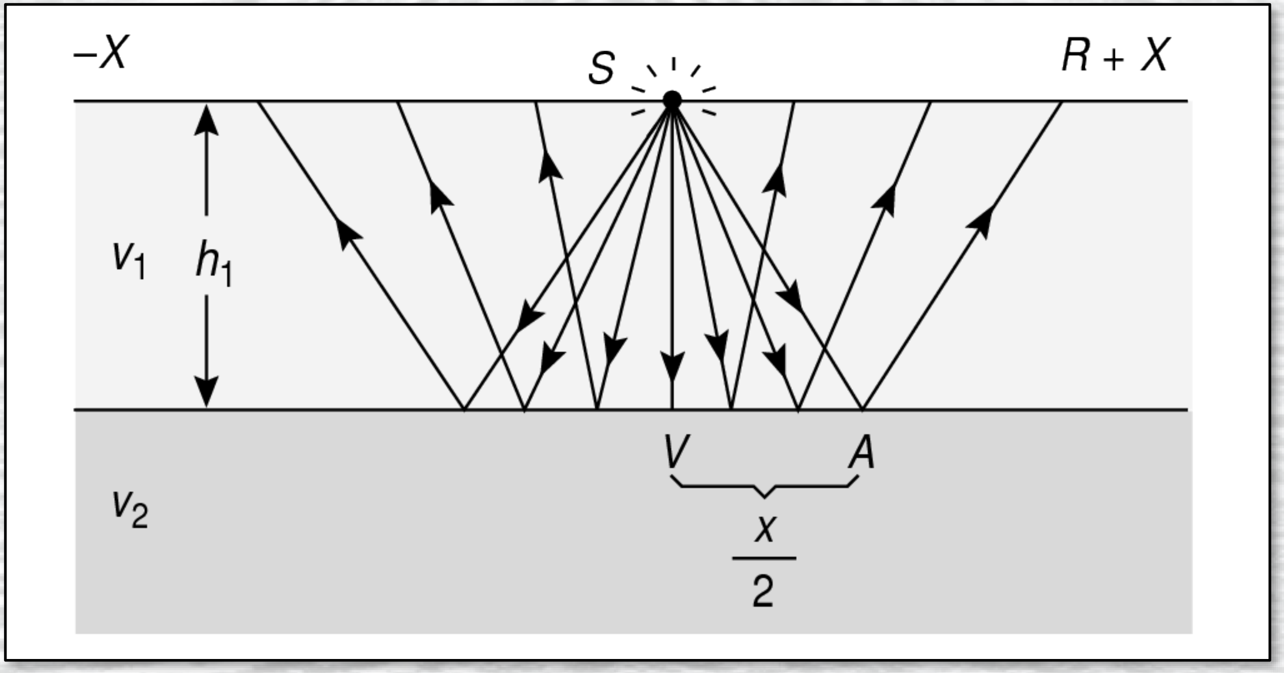
The sea floor is commonly a strong reflector
So it commonly produces multiples

Velocity Determination Using Normal Move out

- To deduce the velocity structure, multiple receivers are needed so that most rays do not travel vertically
- For a **horizontal reflector…**
  - The shortest path is the vertical one
  - Rays that reach receivers to each side travel increasingly longer distances

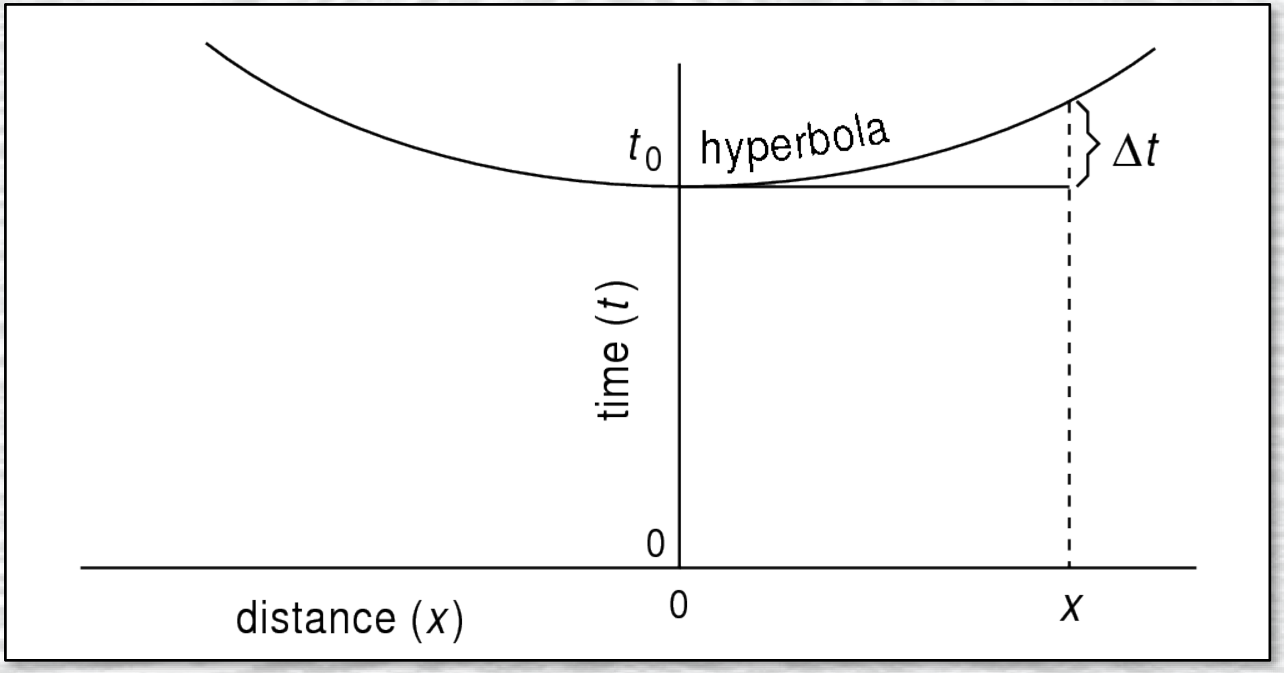
This is the **Fixed Source Method**

There are also other methods: e.g. the **Common Midpoint Method**



Velocity Determination Using Normal Move out

- Normal Moveout = The later time of arrival of the reflected rays at receivers offset from the source **for a horizontal reflector**.
- On a t-x diagram, the Normal Moveout (NMO) produces a hyperbola.



Velocity Determination Using Normal Move out

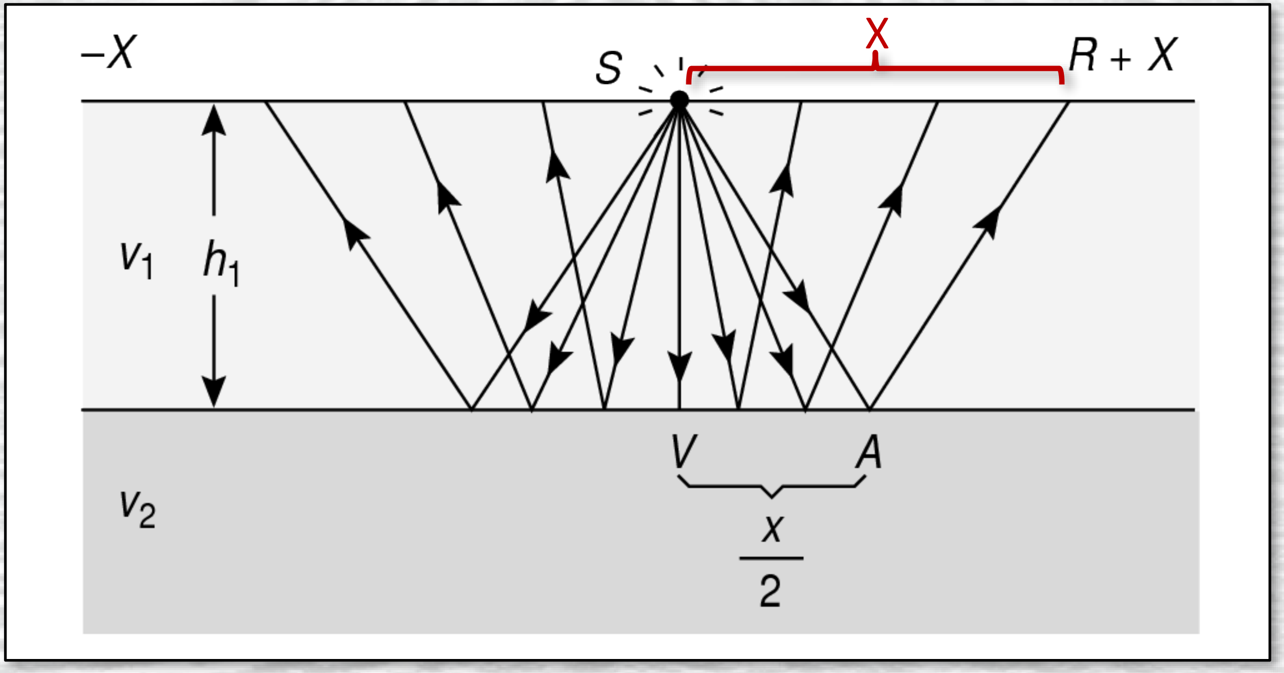
- Using the Fixed Source Method, we can estimate seismic velocity

$$t^2 = t_0^2 + \frac{x^2}{v_1^2}$$

  - These parameters are read off of the t-x diagram
  - If layer thickness is large compared to receiver offset…

$$v_1 \approx \frac{x}{\sqrt{2t_0 \Delta t}}$$

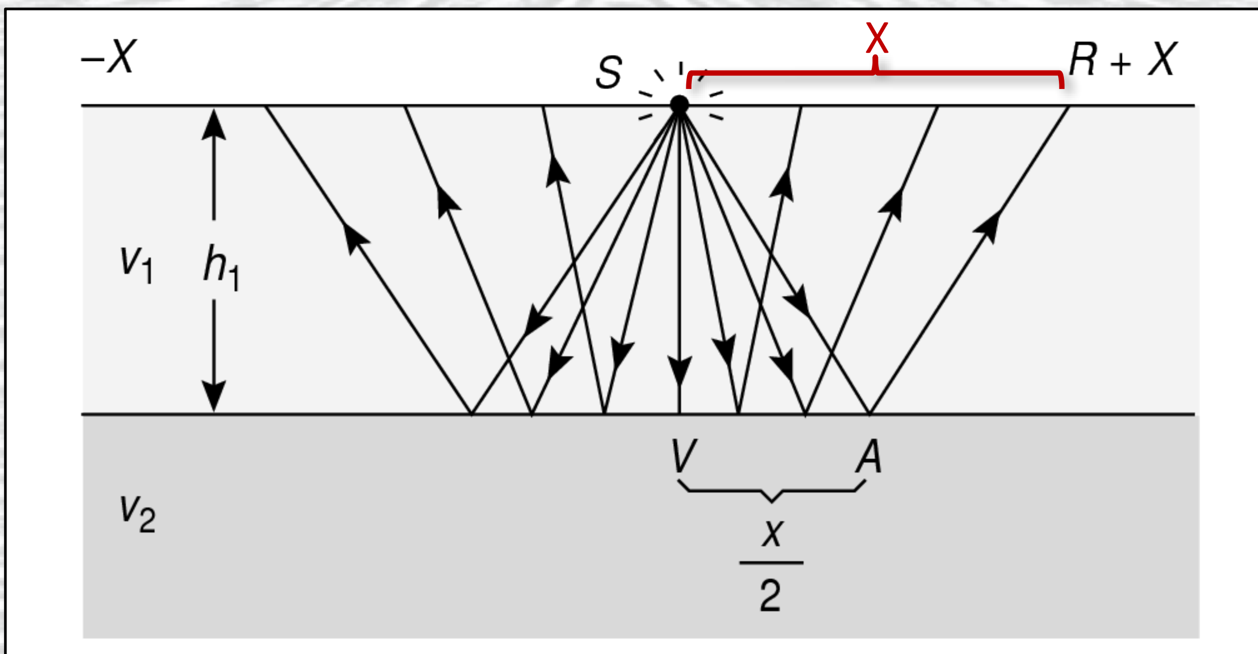
But where does this come from??



Velocity Determination Using Normal Move out

("TWTT")

- t_0 = vertical "two-way travel time" (book calls it "TWT")
  - Measured along SV $\boxed{t_0 = \frac{2h_1}{v_1}}$
- t = total two-way travel time to receiver R (at distance = X)
  - Use triangle SVA: $\boxed{t = (t_0 + \Delta t) = \frac{2}{v_1}\sqrt{h_1^2 + \left(\frac{x}{2}\right)^2}}$
    - Travel time, t, is $2*SA/v_1$



This isn't helpful because we don't know v_1 or h_1

Velocities From Normal Move out

- Given some basic geometry and data from the t-x diagram, we can do some mathematical magic…
  - Given:

$$t = \left(t_0 + \Delta t\right) = \frac{2}{v_1}\sqrt{h_1^2 + \left(\frac{x}{2}\right)^2}$$

  - Square both sides:

$$t^2 = \left(t_0 + \Delta t\right)^2 = \frac{4}{v_1^2}\left(h_1^2 + \left(\frac{x}{2}\right)^2\right) = \frac{4}{v_1^2}\left(h_1^2 + \frac{x^2}{4}\right)$$

  - Do some algebra…

Replace $2h_1/v_1$ with t_0

$$\cancel{t^2} = \left(t_0 + \Delta t\right)^2 = \frac{4h_1^2}{v_1^2} + \frac{4x^2}{4v_1^2} = \frac{4h_1^2}{v_1^2} + \frac{x^2}{v_1^2} = \left(\frac{2h_1}{v_1}\right)^2 + \frac{x^2}{v_1^2} = t_0^{\,2} + \frac{x^2}{v_1^2}$$

  - Expand

$$\cancel{t_0^2} + 2t_0\Delta t + \Delta t^2 = \cancel{t_0^2} + \frac{x^2}{v_1^2}$$

Almost there…

Now we know all of these terms from t-x graph except v_1, so we can solve this!!

Velocities From Normal Moveout

- From previous page…

$$2t_0\Delta t + \cancel{\Delta t^2} = \frac{x^2}{v_1^2}$$

- If the receiver offsets are small compared to the layer thickness (this is common)
  - Then Δt will be small…and thus $\Delta t^2 \approx 0$

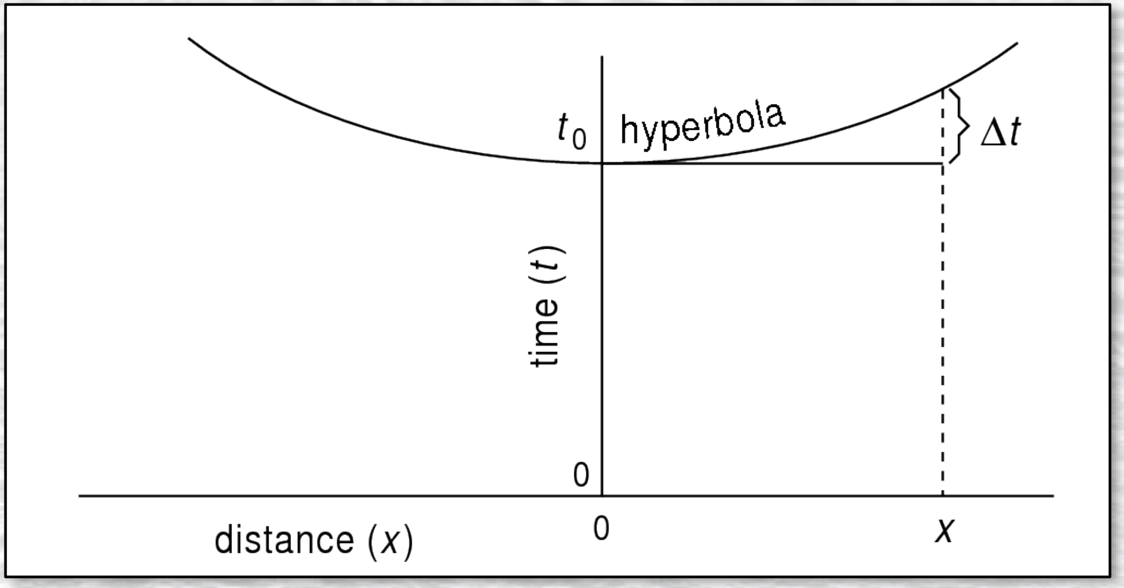
$$\Delta t = t - t_0 \approx \frac{x^2}{2v_1^2 t_0}$$

- Rearrange to solve for v_1

$$v_1 \approx \frac{x}{\sqrt{2t_0\Delta t}}$$

Look at the t-x diagram. This makes sense right?

*The bad news…
This process is only for the first layer / topmost reflector.
We must account for refraction in the subsequent layers…

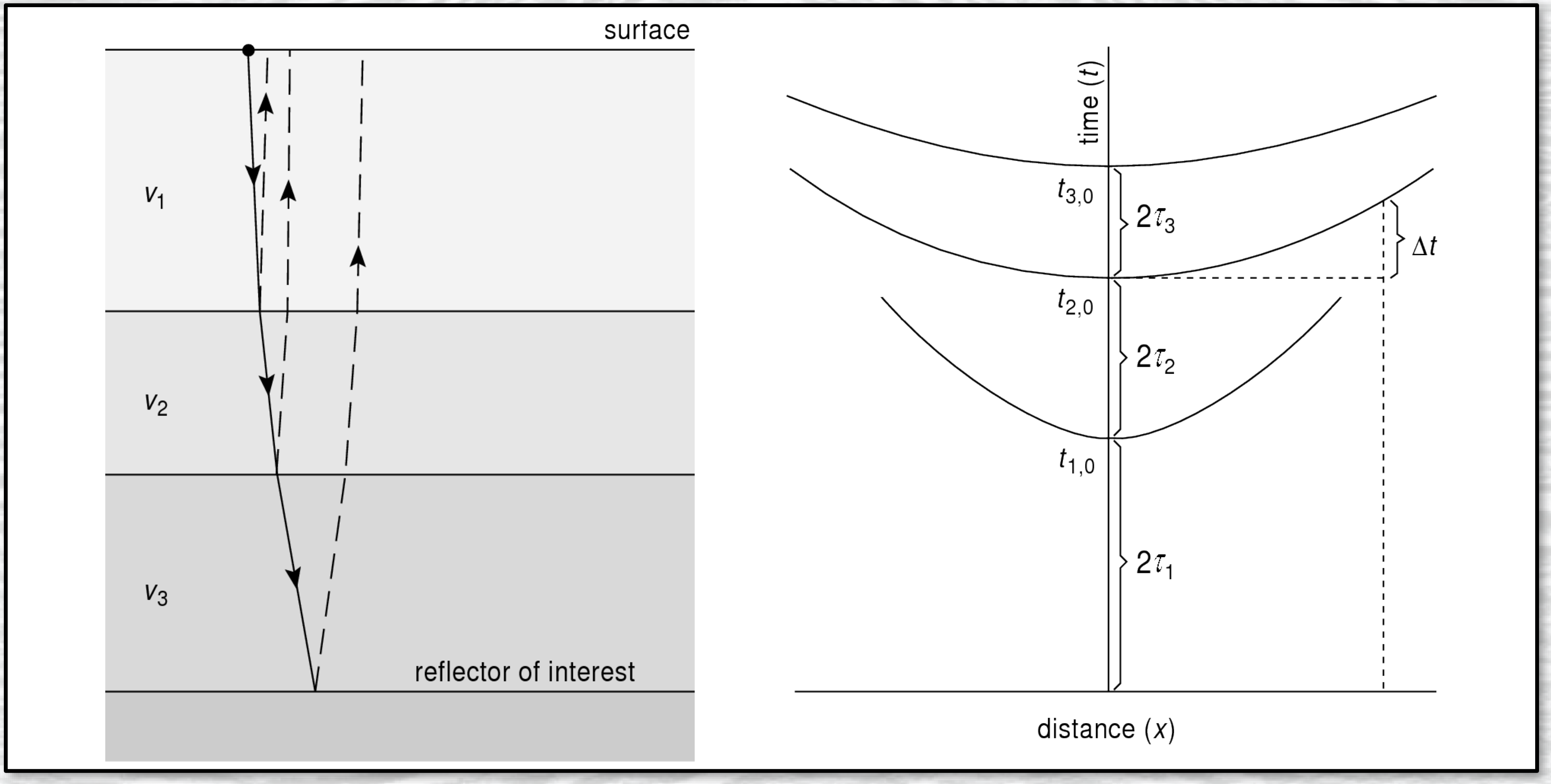


Multiple Horizontal Layers

- If multiple reflectors are encountered
  - This is almost always the case
- The preceding formulas still work, however:
  - We must keep track of the t-axis intercepts ($t_{1,0}$, $t_{2,0}$, etc…) for each interface
  - We must also account for refraction through the various interfaces
- If we do this, we can still use the previous process
  - The previous equations will then yield RMS velocities.
    - What are RMS velocities?
      - We'll look at this later…

Multiple Horizontal Layers

- When multiple reflectors are encountered, multiple NMO hyperbolas are produced
  - The shallowest reflector arrives first at $t_{1,0}$
  - Each reflector's TWTT for vertical reflection ($t_{1,0}$, $t_{2,0}$, $t_{3,0}$, etc…) and NMO (Δt) can be read off of the graph.
    - We can then easily calculate the one-way travel times in each layer, τ_n



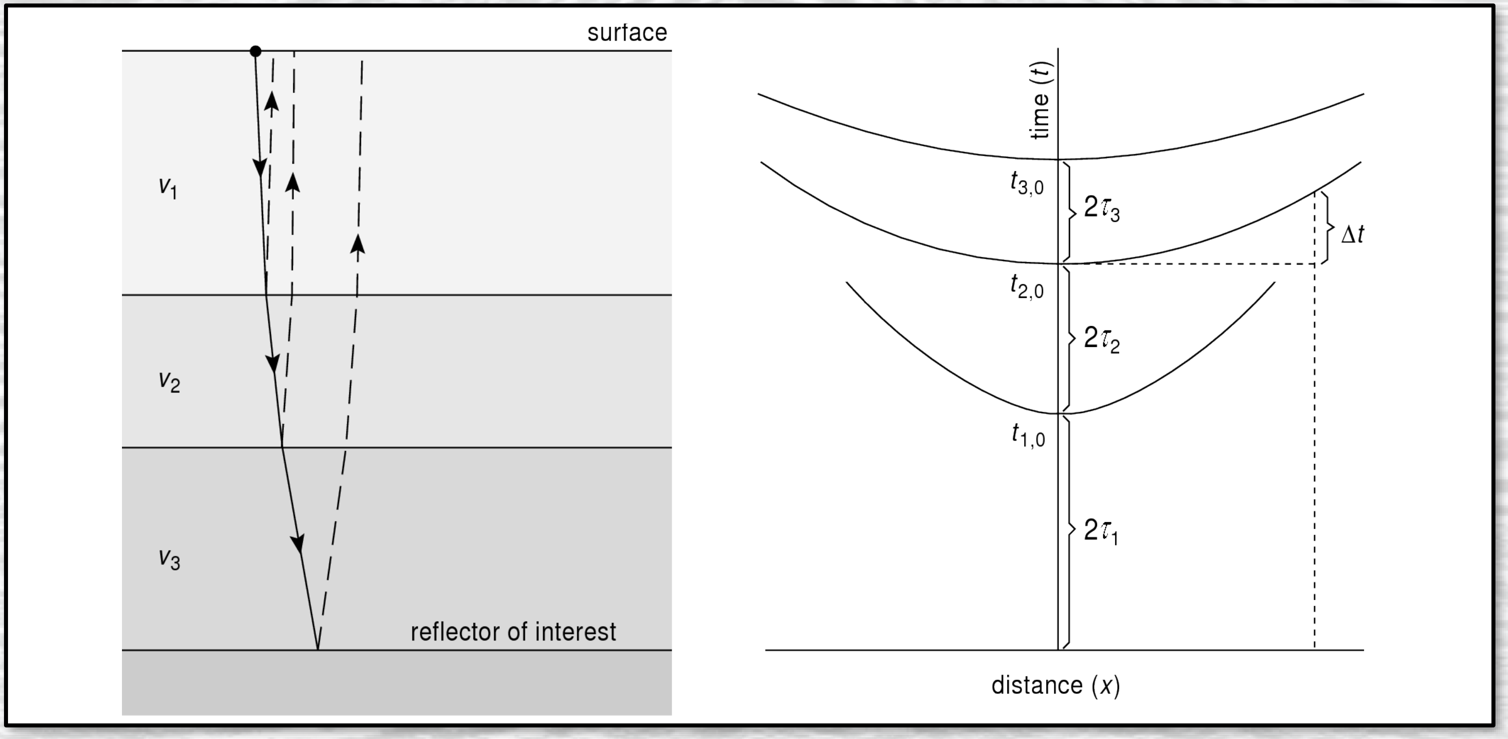
RMS Velocity

- Root-Mean-Square (RMS) Velocity: A weighted average across n-layers that factors out the differences in travel time spent in layers of differing velocity

$$v_{rms} = \sqrt{\frac{\sum_{i=1}^{n} v_i^2 \tau_i}{\sum_{i=1}^{n} \tau_i}}$$

τ_i = the one-way travel time for vertical reflection in i^{th} layer

v_i = the interlayer velocity of the i^{th} layer



Two-Layer Example

For a simple two layer model…

- Get velocity of first layer using NMO equations
- Get RMS Velocity down to 2nd layer from NMO eq's
- Solve for the second interlayer velocity
- Use the various $t_{n,o}$ values

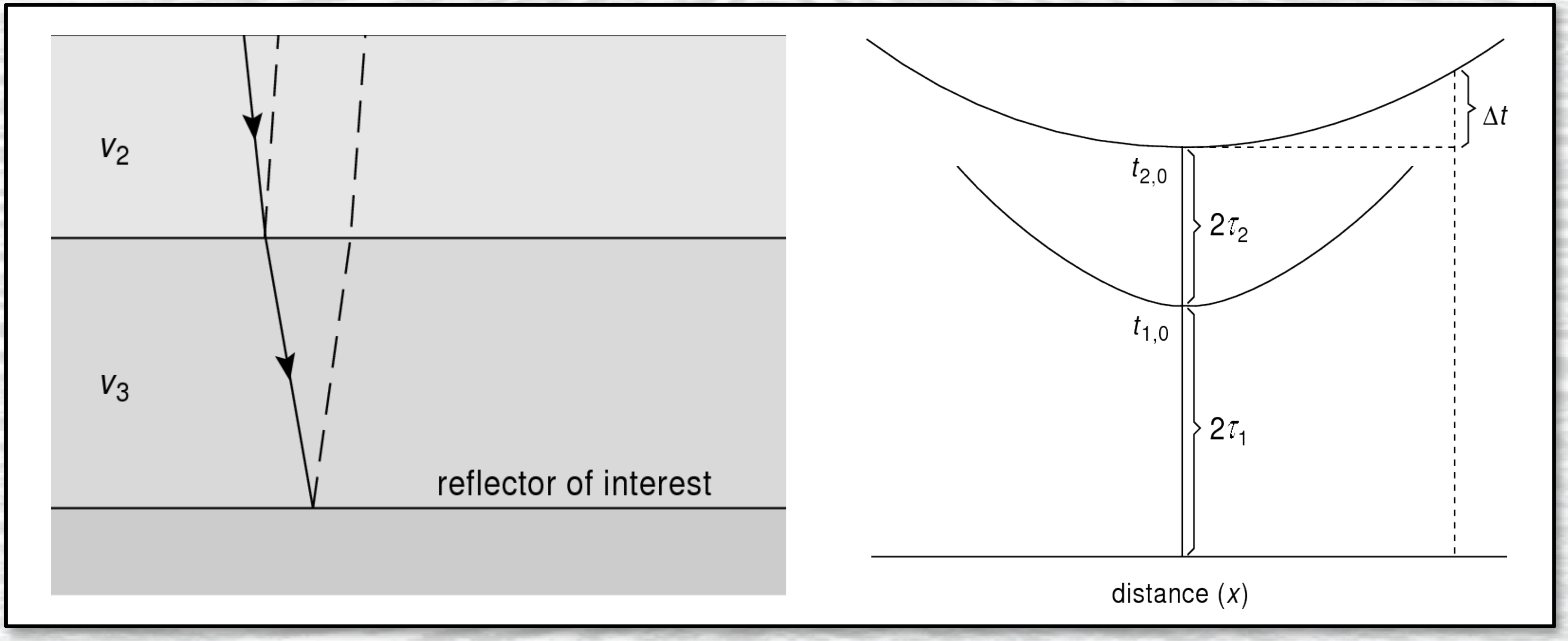
To get thicknesses

$$v_1 \approx \frac{x}{\sqrt{2t_{1,0}\Delta t}}$$

$$v_{rms} \approx \frac{x}{\sqrt{2t_{2,0}\Delta t}}$$

$$v_{rms} = \sqrt{\frac{\sum_{i=1}^{n} v_i^2 \tau_i}{\sum_{i=1}^{n} \tau_i}} = \sqrt{\frac{\left(v_1^2\tau_1 + v_2^2\tau_2\right)}{\left(\tau_1 + \tau_2\right)}}$$

$$t_{n,0} - t_{n-1,0} = \frac{2h_n}{v_n}$$



N-Layer Example

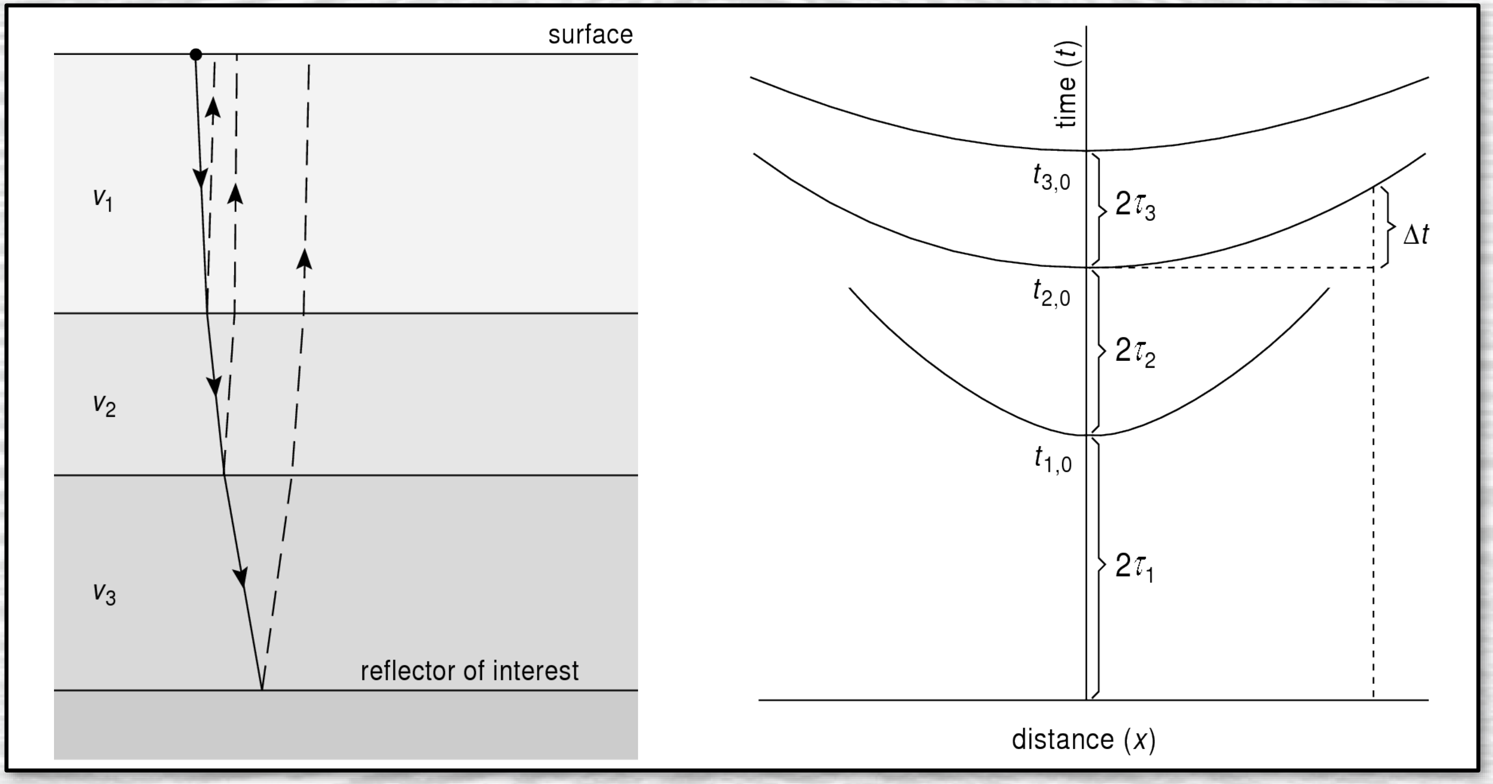
For an n-layer model…

- You could follow the previous procedure for each layer
- If you only want to know a certain interlayer velocity
  - Only need to know the information for the reflectors directly above and below the layer of interest.
  - Dix Formula ::

$$v_{layer} = \sqrt{\frac{\left(v_{rms.B}^2 t_n - v_{rms.T}^2 t_{n-1}\right)}{\left(t_B + t_T\right)}}$$

t_B = the TWTT to the deeper (bottom) reflector

t_T = the TWTT to the shallower (top) reflector



N-Layer Example

$$t_{n,0} - t_{n-1,0} = \frac{2h_n}{v_n}$$

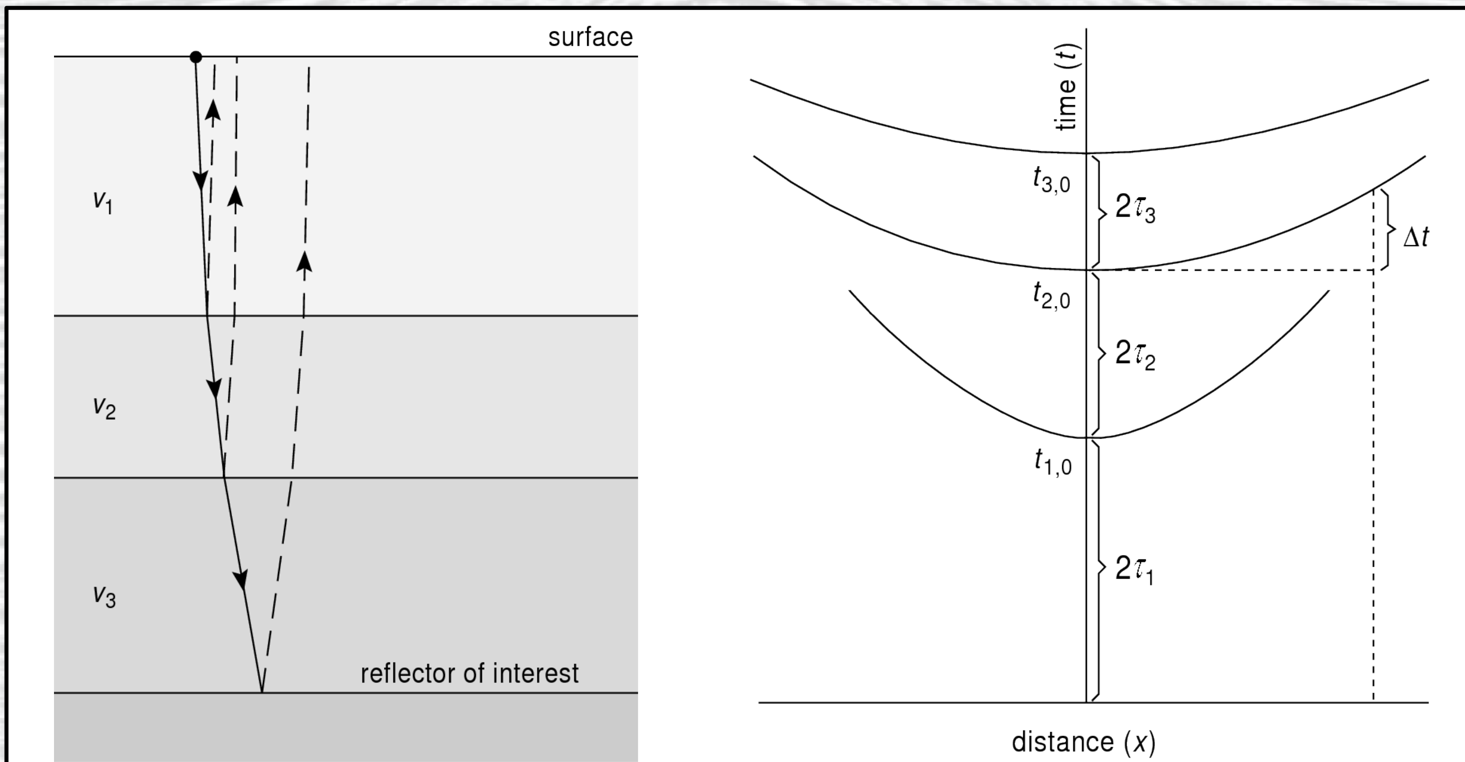
To Find Layer Thicknesses…

- Use the intercepts and calculated velocities to calculate thicknesses of each layer

Rearrange and solve for h_n

$$h_n = v_{layer}\left(\frac{t_{n,0} - t_{n-1,0}}{2}\right)$$

Warning! Your book says $\cancel{h_n = v_{layer}\left(\frac{\tau_B - \tau_T}{2}\right)}$

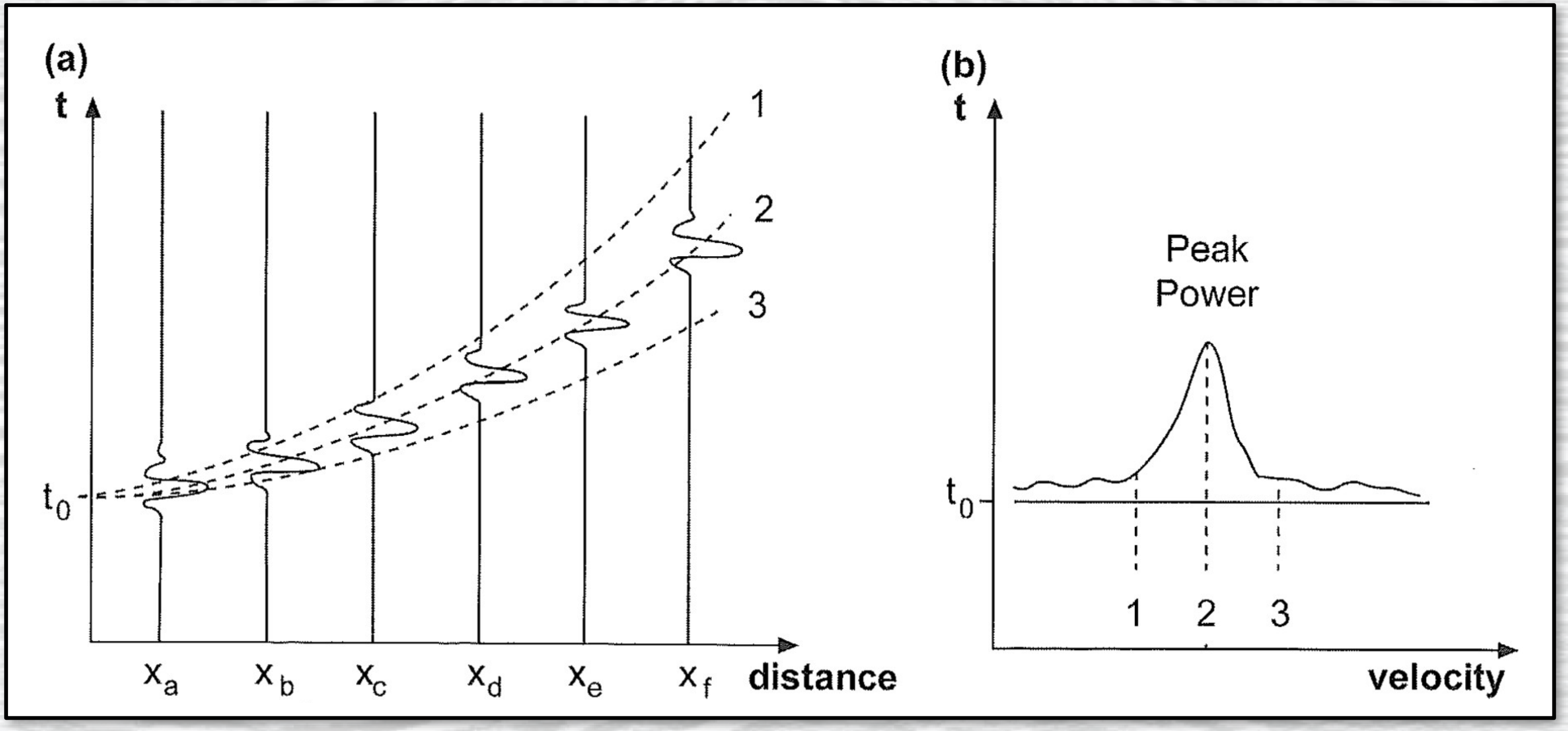


Stacking

- Often reflections are weak, particularly from deep interfaces
  - The downgoing pulse loses energy
    - As the wave front spreads out
    - Each reflection removes some energy
- Noise is therefore an issue
  - Stacking increases the signal to noise ratio
    - In refraction seismology: repeat the shot and stack the results
    - In reflection seismology: The records of the line of receivers from a single shot are used
      - First, the line of receivers must be corrected for moveout. This turns hyperbolas into lines.
      - Because moveout is difficult to calculate with weak arrivals, finding velocities and stacking are done together…

Stacking and Determination of Velocity

- In practice, the interlayer velocities are guessed
  - If the guess is bad, the stacked records will show a weak or no clear arrival
  - If the guess is good, the stacked records will show a strong arrival
    - Much stronger than the raw data

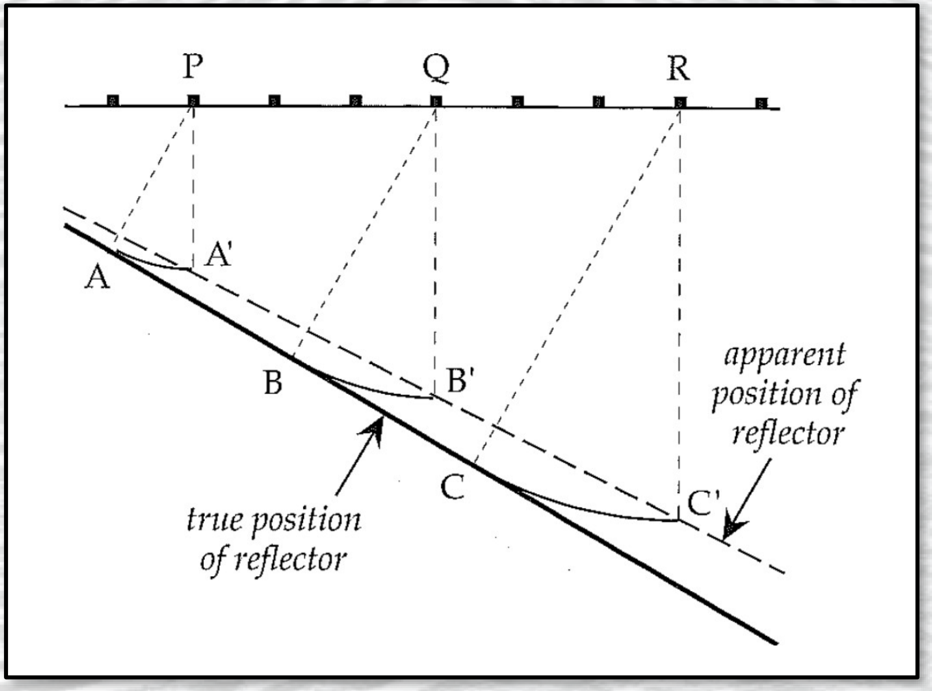


Dipping Reflectors

If a reflector is dipping…

- Both its position and dip on a raw seismic section are incorrect
  - The receiver (geophone) records the arrival and assumes that the reflection came from straight below.
  - As a result, the interface will appear less steep, shallower, and offset down-dip from its actual location

Given the single receiver system shown here, we cannot correct for this…

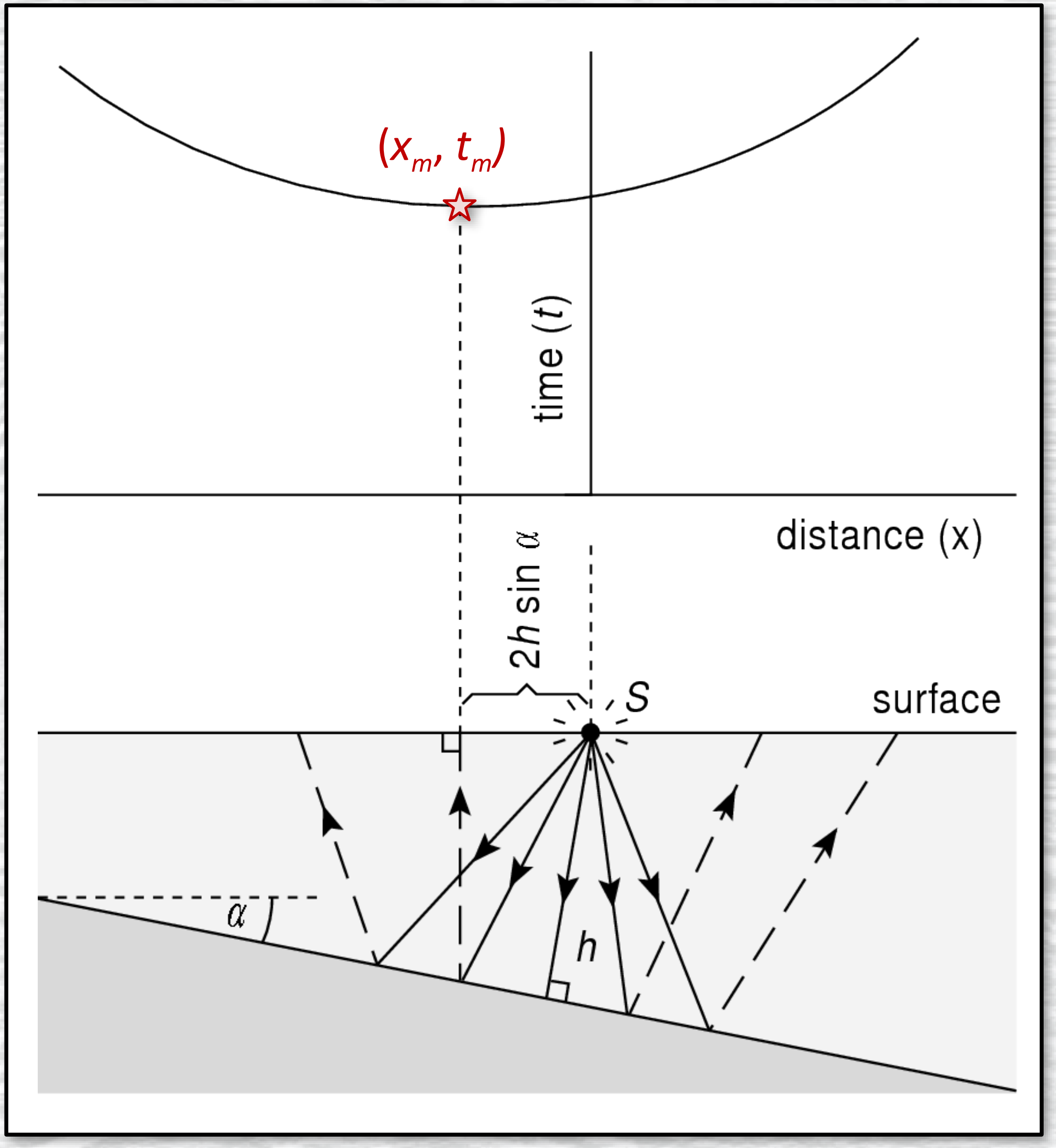


However, a line of receivers offset from the shot point, can detect and correct for this…

Dipping Reflectors

- When a multi-receiver system is used…
- The moveout hyperbola is offset for dipping layers
  - The coordinates of the minimum TWTT, (x_m, t_m)

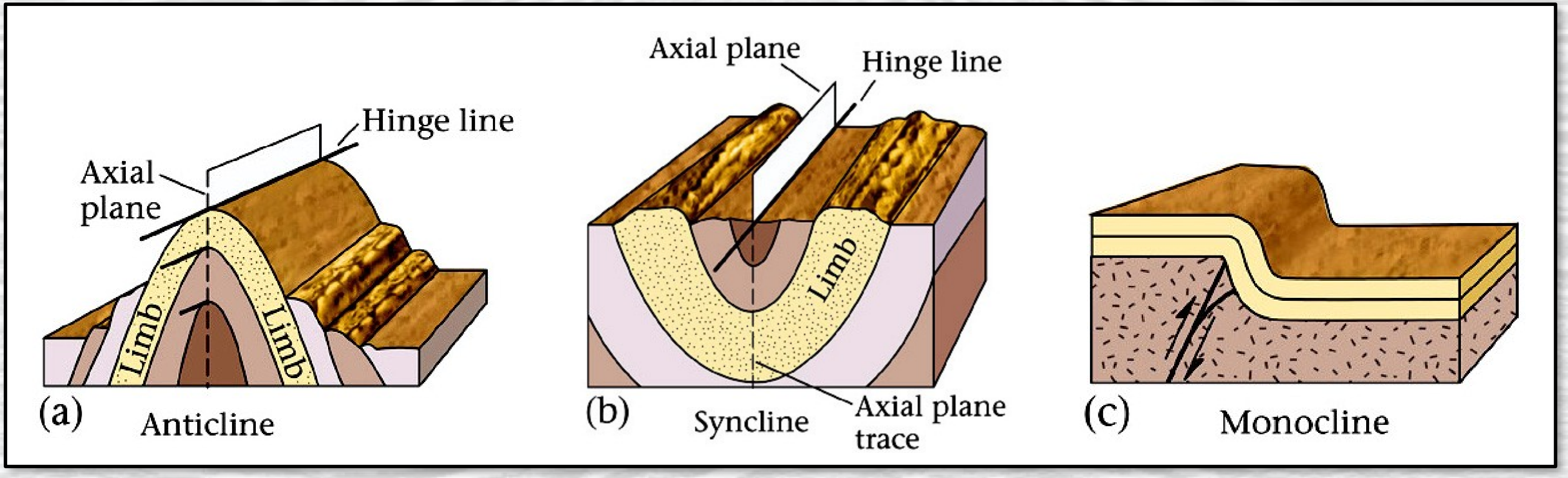
$$\boxed{\begin{aligned} x_m &= 2h(\sin\alpha) \\ t_m &= \frac{2h\cos\alpha}{v} \end{aligned}}$$

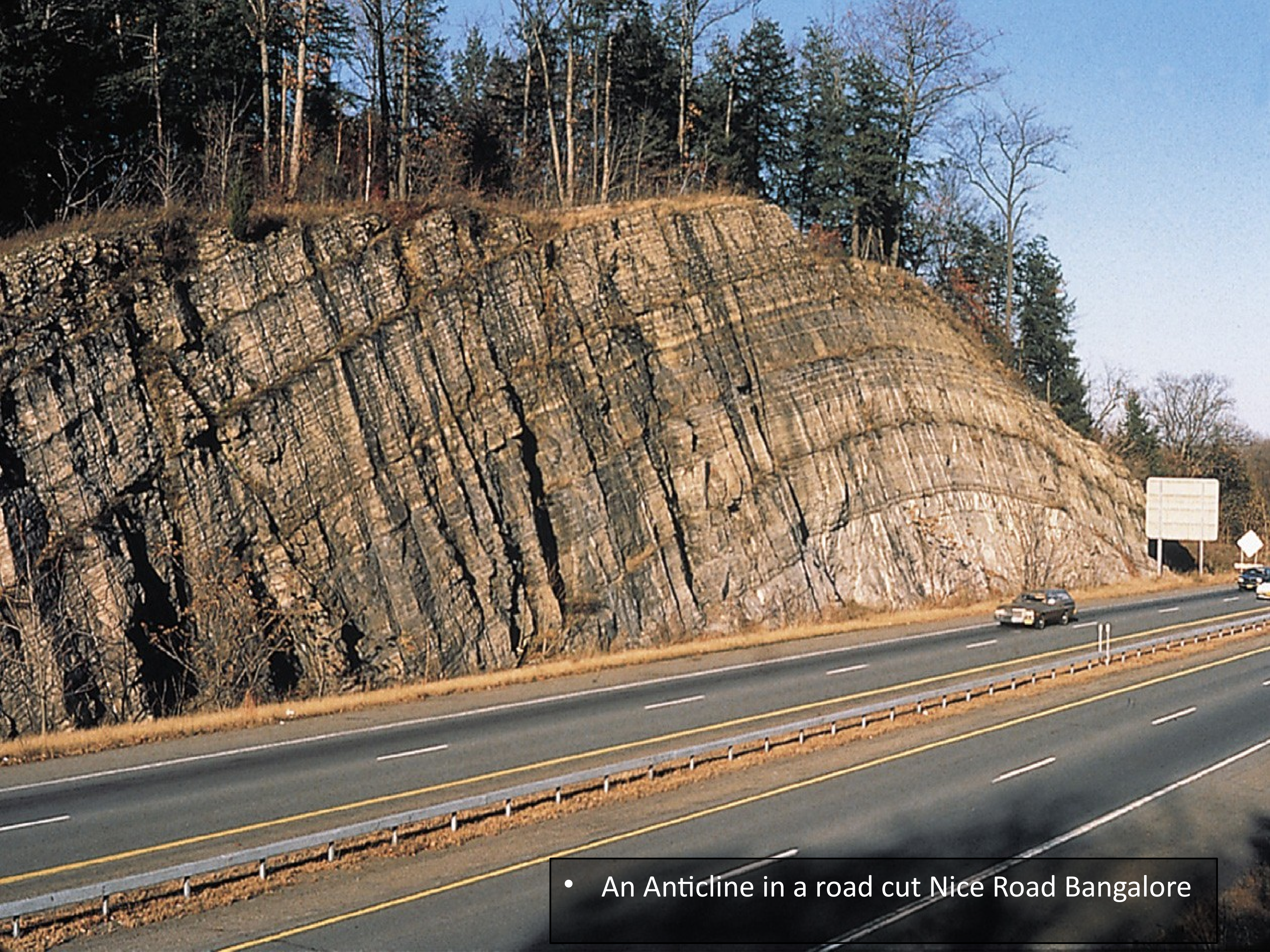


Curved Reflectors

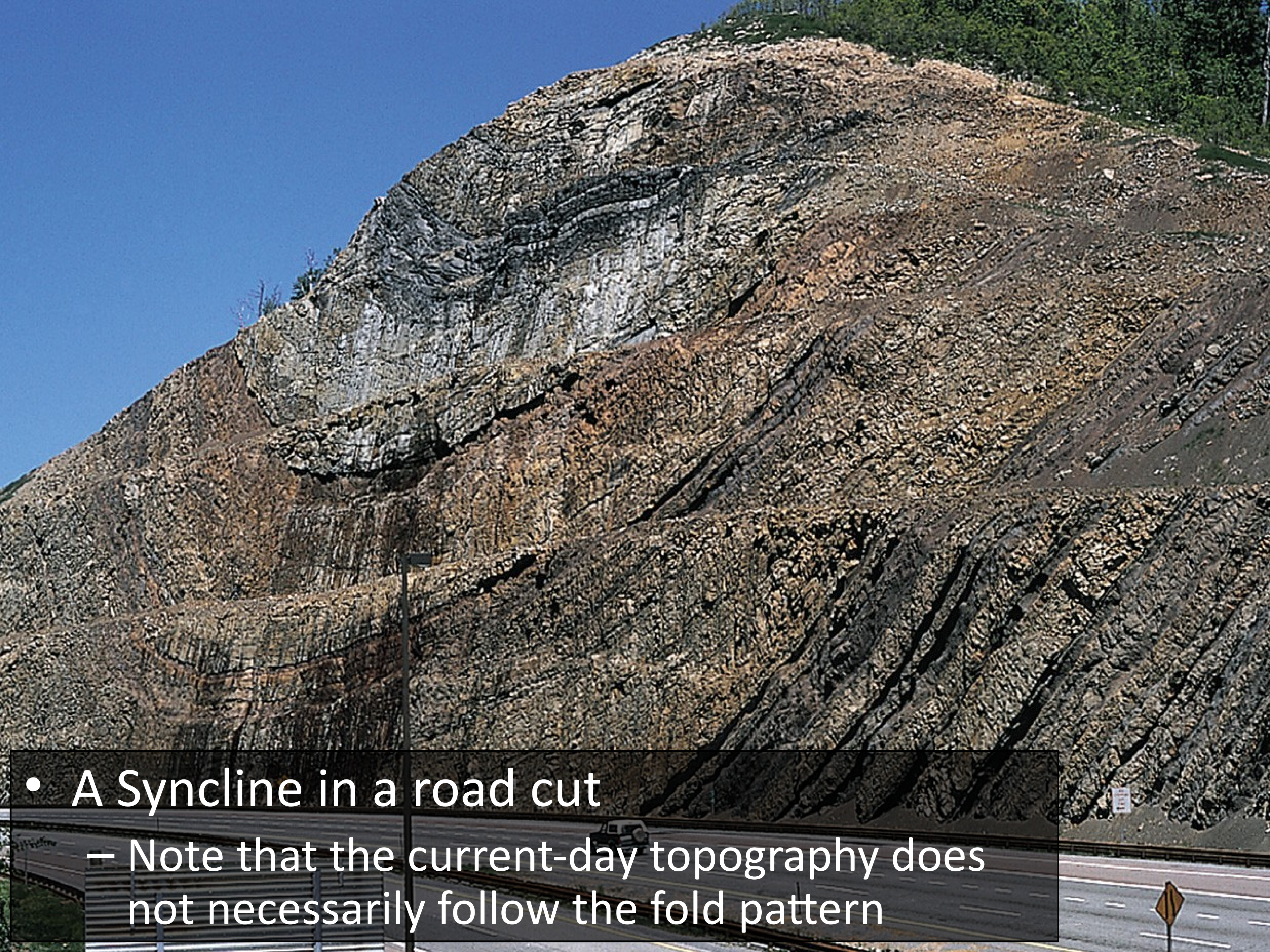
- If the reflector is curved, distortions may be more complex
  - There may be many paths between the reflector and receiver

- Because the pre-requisites for this course are just one intro-level GLY course, we should do a quick review of the basic fold types…
  - Be sure to know the following terms: anticline, syncline, monocline, fold train…



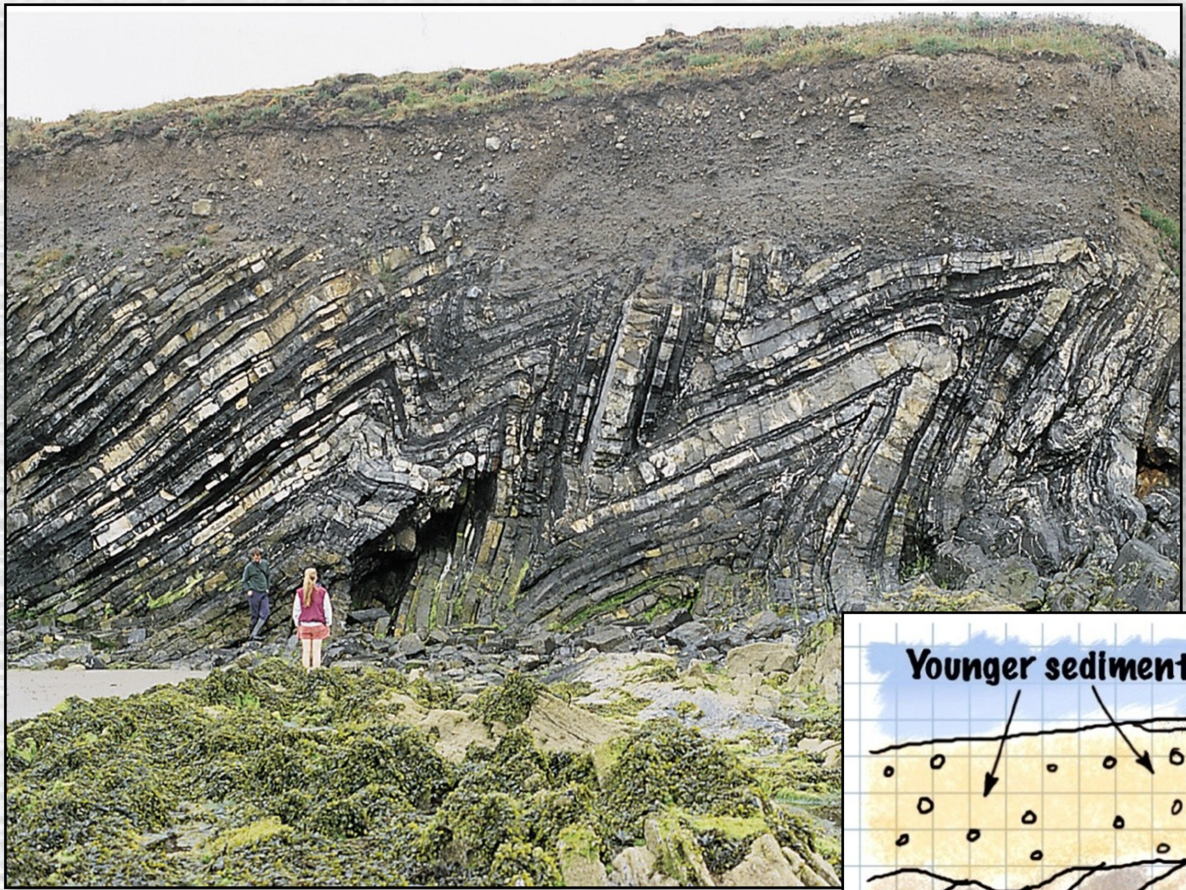


- An Anticline in a road cut Nice Road Bangalore

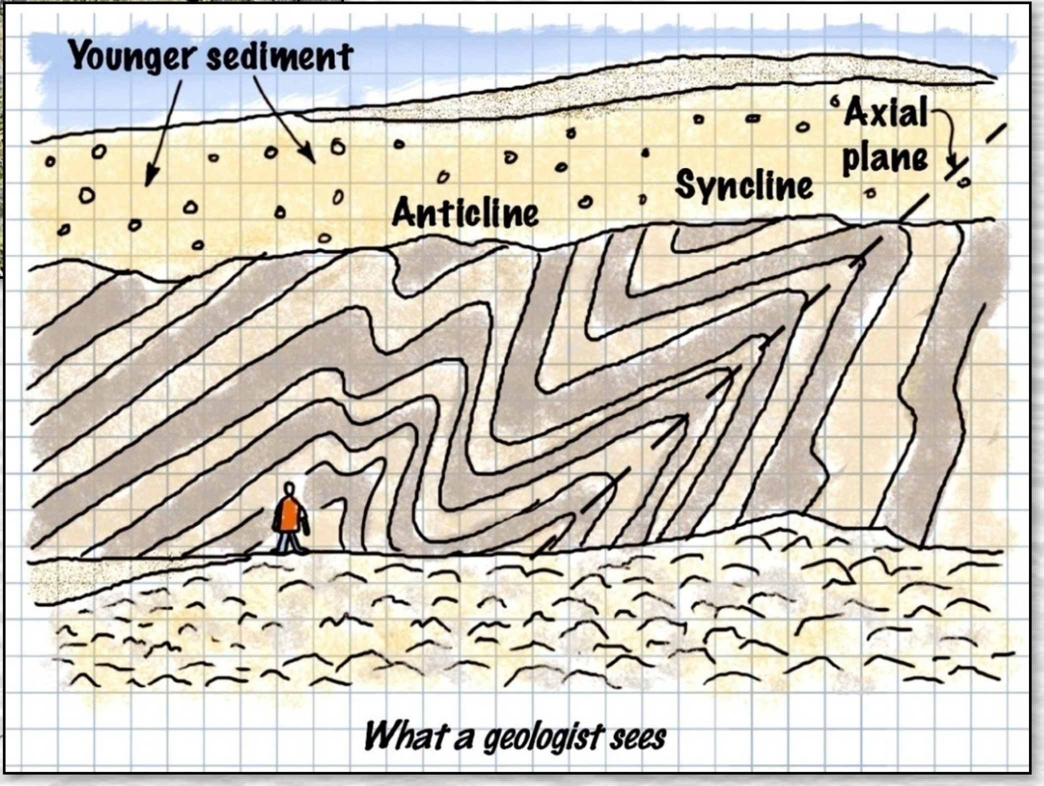


- A Syncline in a road cut
  - Note that the current-day topography does not necessarily follow the fold pattern

Fold Trains



- Folds exposed along a cliff in eastern Ireland

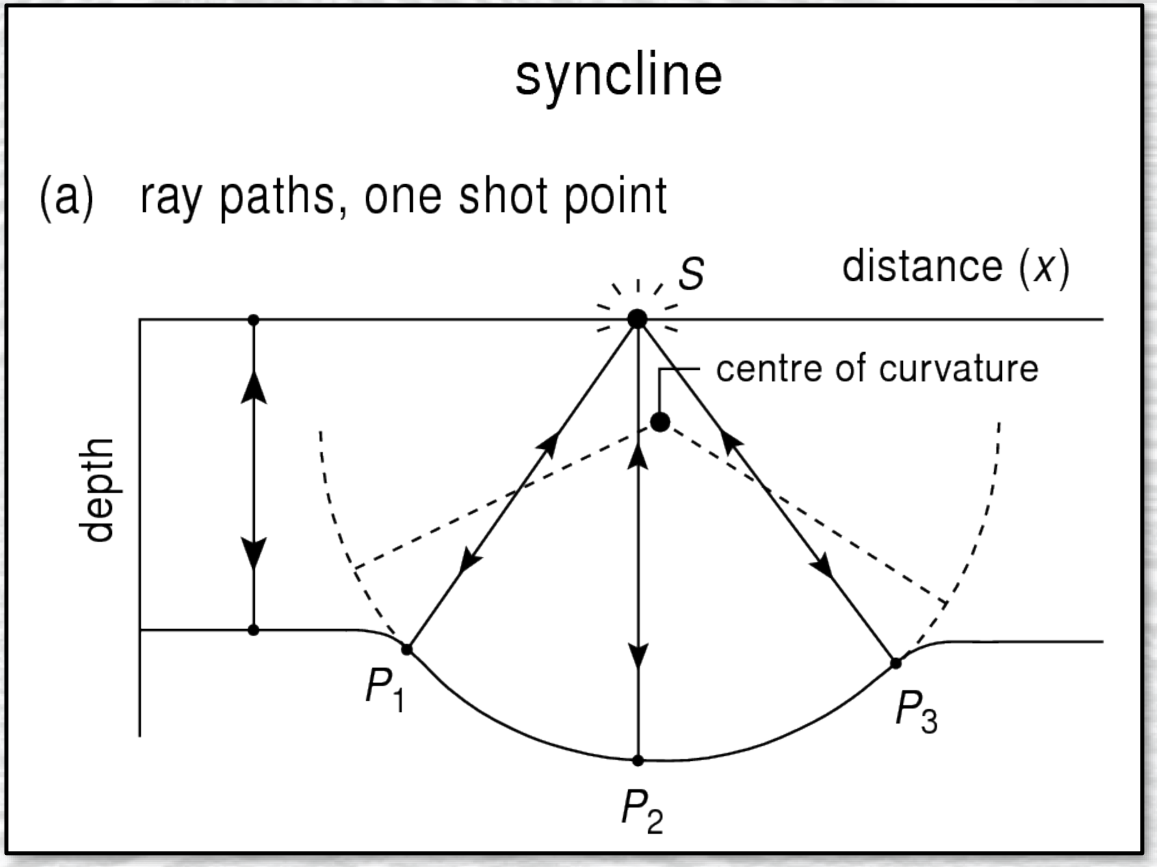


- Anticlines and synclines are commonly found together in trains of folds.
- Note that in these particular folds, the fold axes are not vertical.

Curved Reflectors

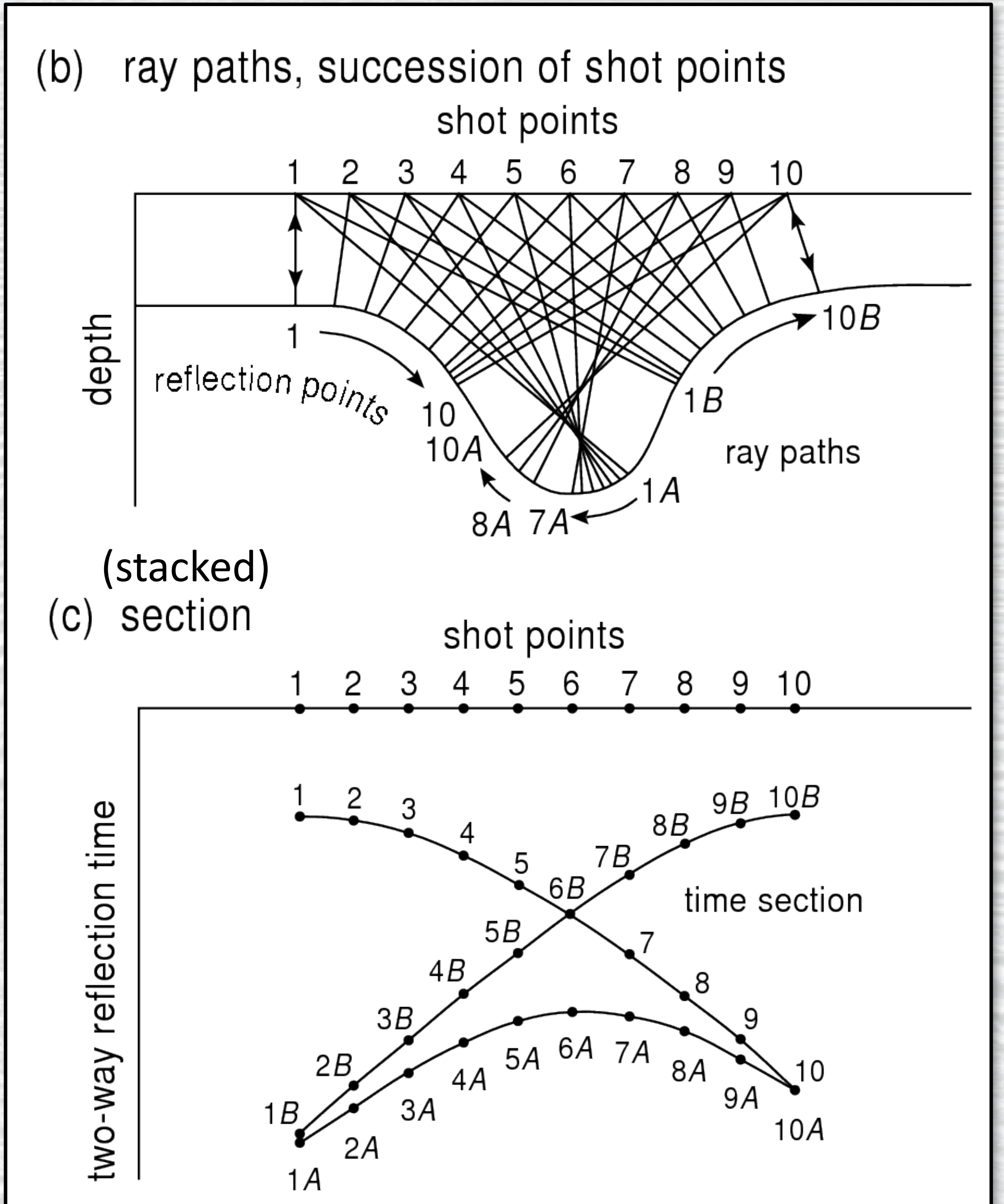
- If the reflector is curved, distortions may be more complex
  - There may be many paths between the reflector and receiver

- The vertical ray is generally not first to arrive
  - Only true if the center of curvature is below surface of earth
  - Common for tight folds
  - Open folds don't usually produce multiple arrivals



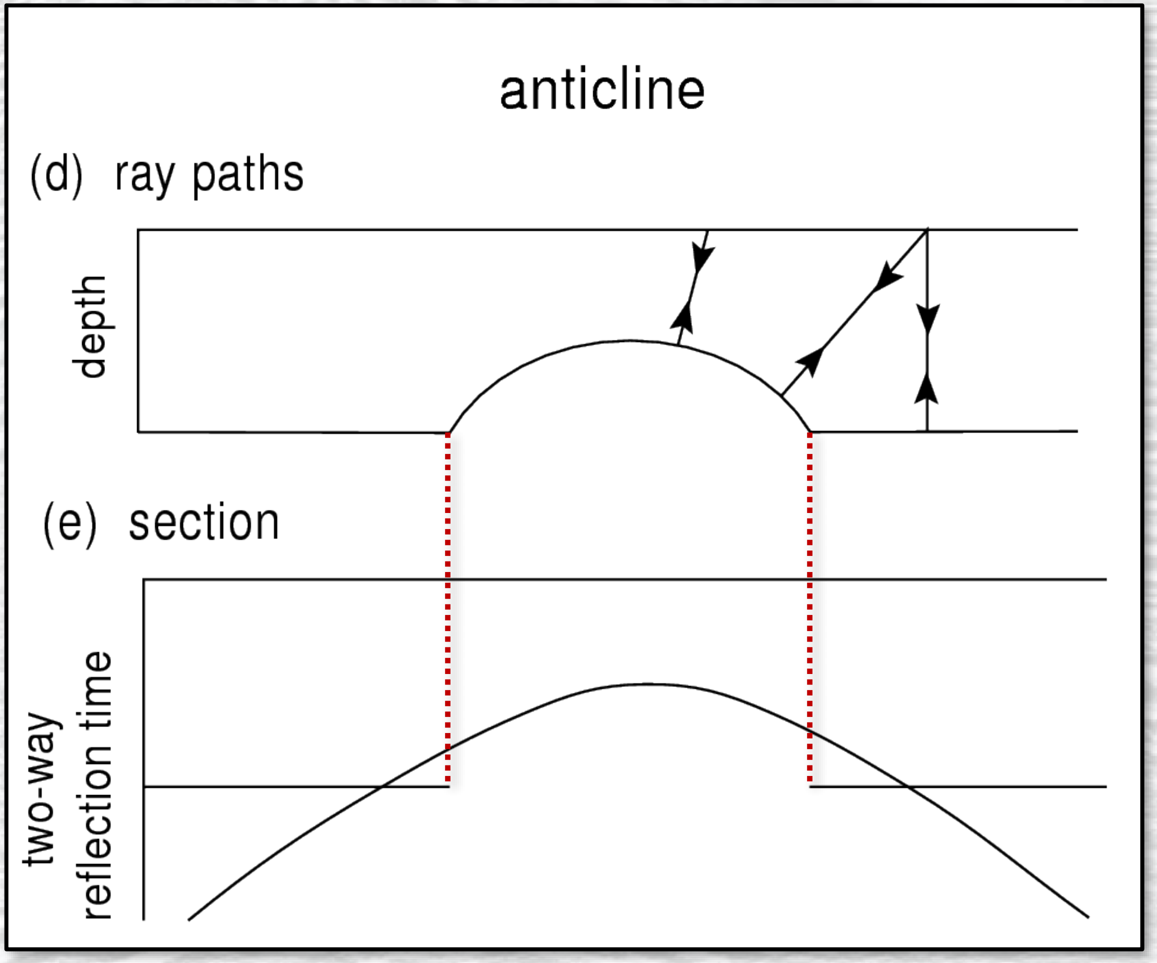
Synclines

- Raw data from a multi-shot reflection survey produce…
- A "bow tie" pattern for synclines
- If center of curvature is above the surface…
  - A narrowed syncline is produced



Anticlines

- For subsurface anticlines…
- A broadened or widened anticline pattern with multiples near the anticline margins



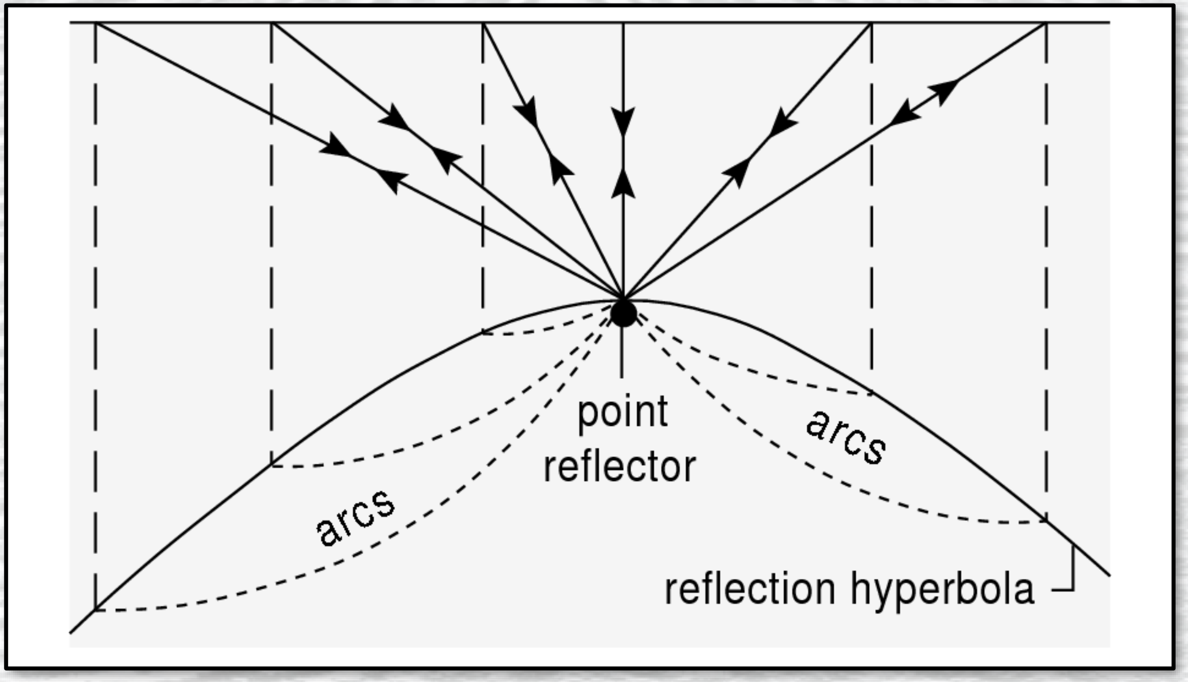
Migration

- Migration: Correcting for the displacement of position and the shape of a non-horizontal reflector
  - Also includes several other geometric corrections
  - So, the previous examples were examples of migration!
- Extremely complicated process
  - This is the main reason why ~30% of the world's CPU time is spent on seismic reflection
  - Requires sophisticated numerical routines to detect and correct these patterns.
  - Sometimes reflection profiles are left "unmigrated"
    - Saves time and money
    - Reflection seismology experts can look at unmigrated sections and immediately see the migrated image in their head.

Diffraction

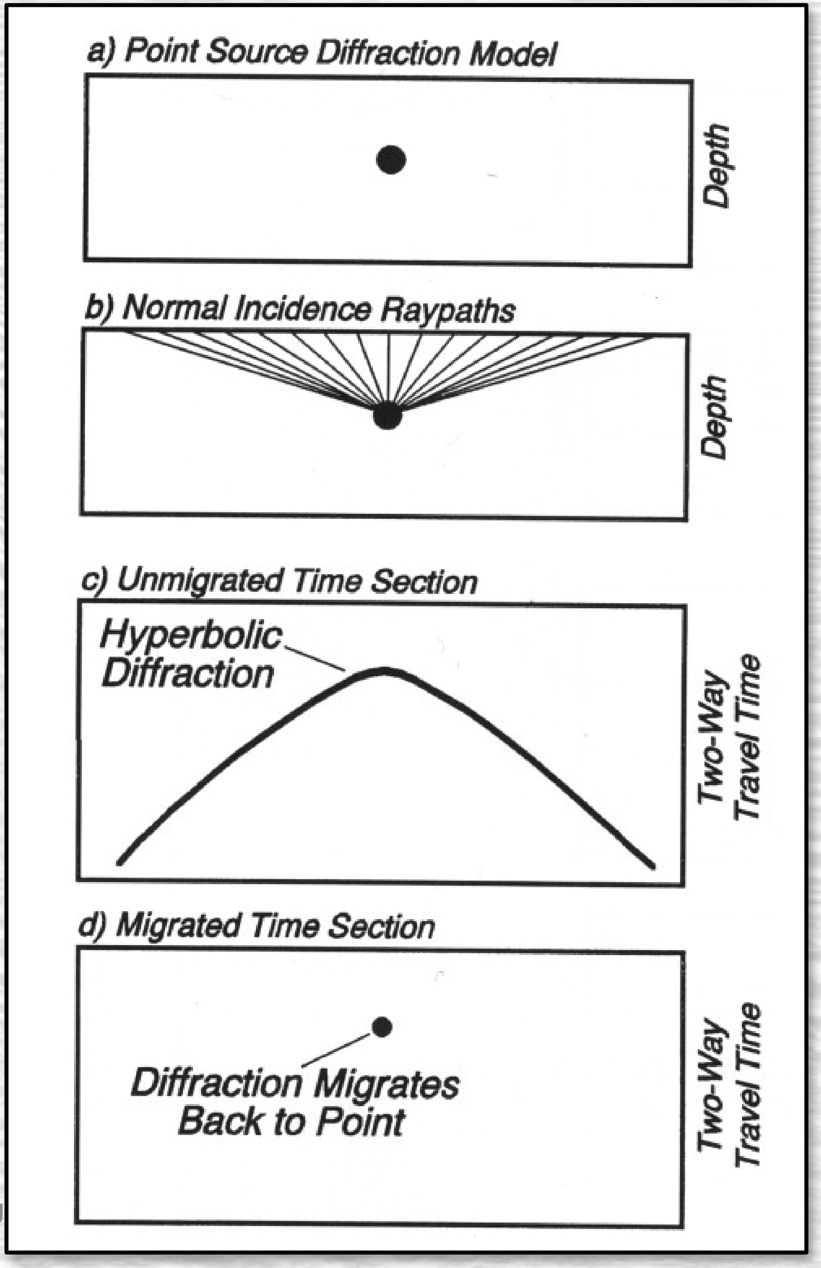
- Although many reflectors are laterally continuous, often discontinuous reflectors are encountered
  - Discontinuous reflectors produce diffracted waves
    - Remember Huygen's Wavelets?
    - Three main causes of diffraction…
      - Faulted rock layers
      - Pinchouts (a stratigraphic layer that thins to nothing)
      - Point sources (usually non-geologic)

Migration also corrects these artifacts!

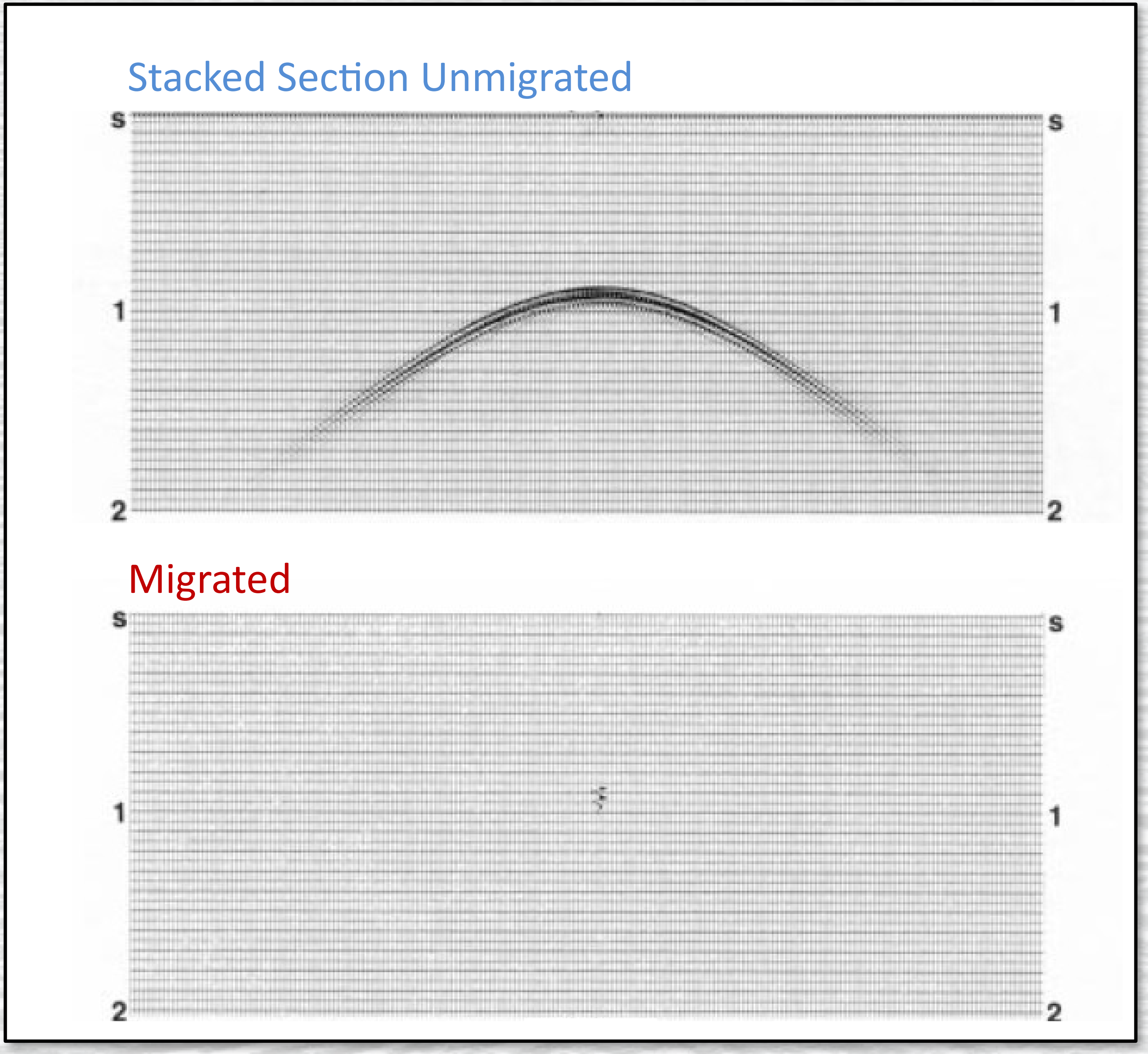


Point-Source Diffraction and Migration

- Although point sources are geologically uncommon…
  - They are common in environmental or civil engineering surveys
    - E.g. Buried pipes / wires
- Reflection of energy from a small sphere produces diffracted waves
- An unmigrated point source produces a hyperbolic pattern.
- Migration collapses the hyperbola back into a point.

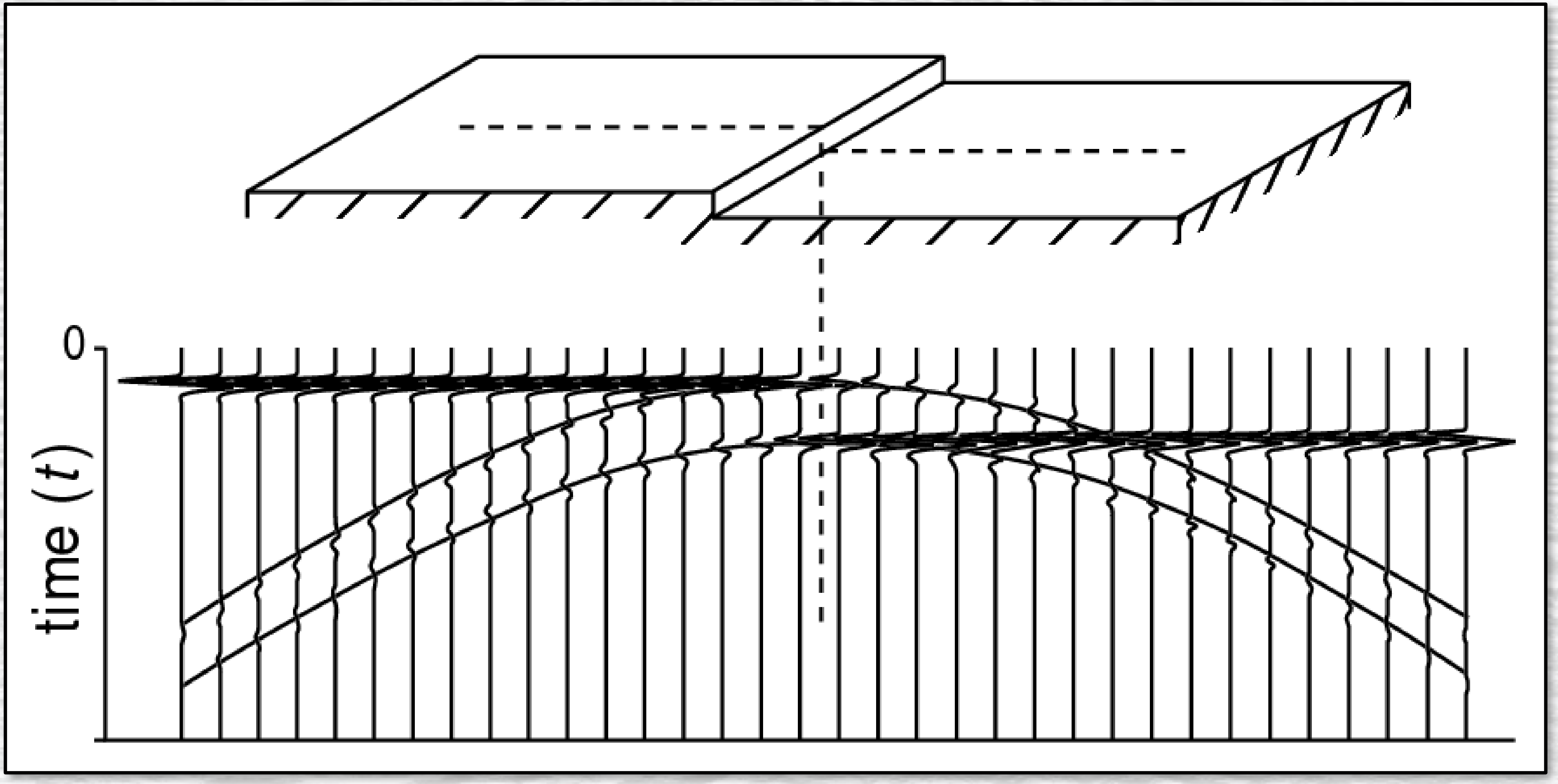


Point-Source Diffraction and Migration



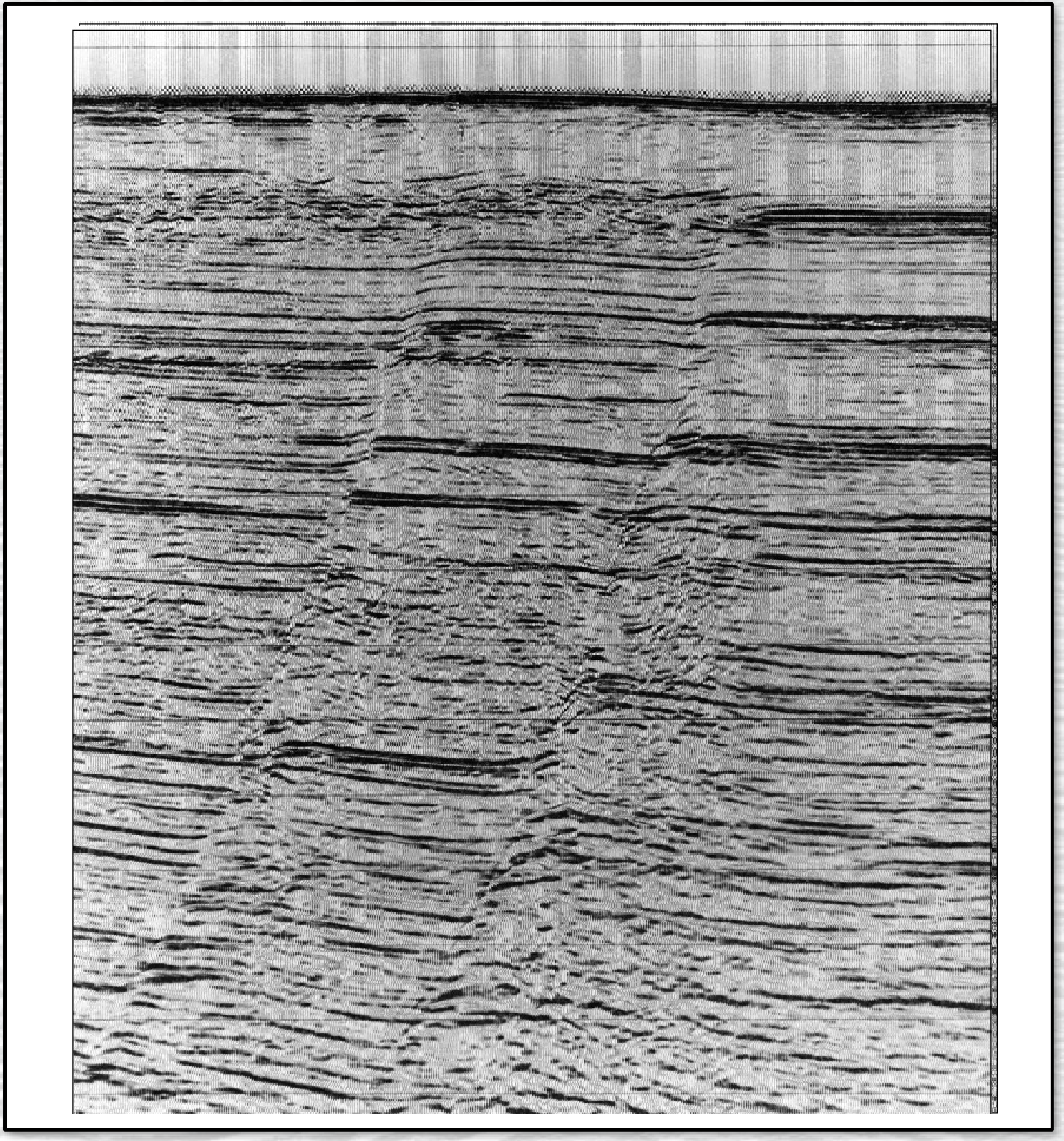
Faulted Reflectors: Diffraction

- Discontinuous layers also produce diffracted waves
  - Due to faulting or pinchouts
  - Edges act like point sources



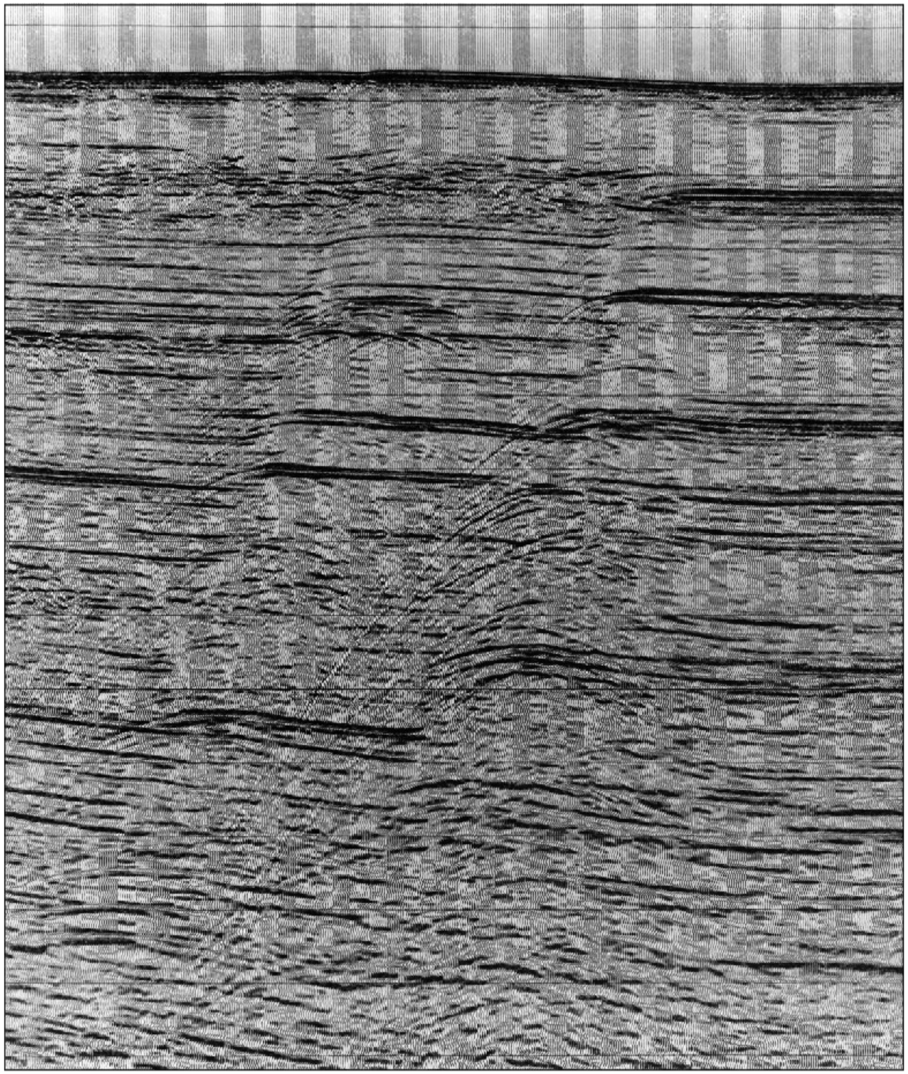
Unmigrated

Migrated

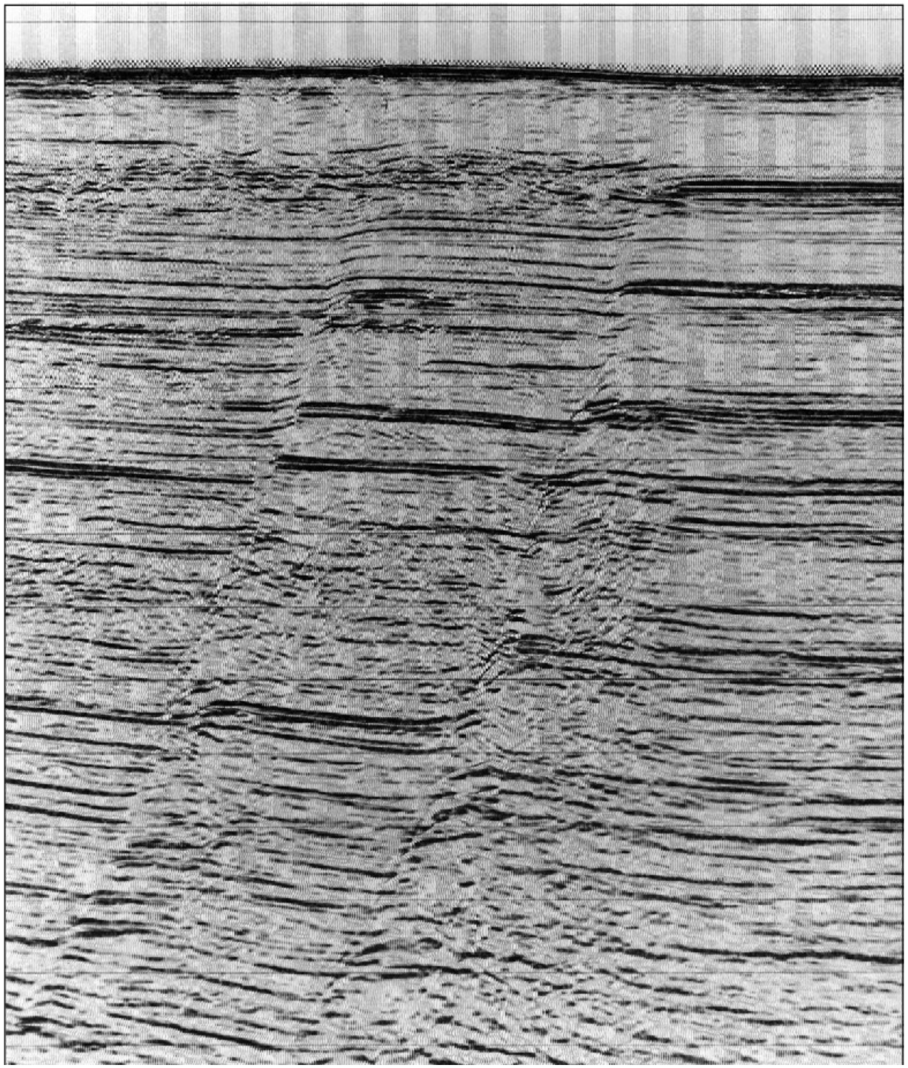


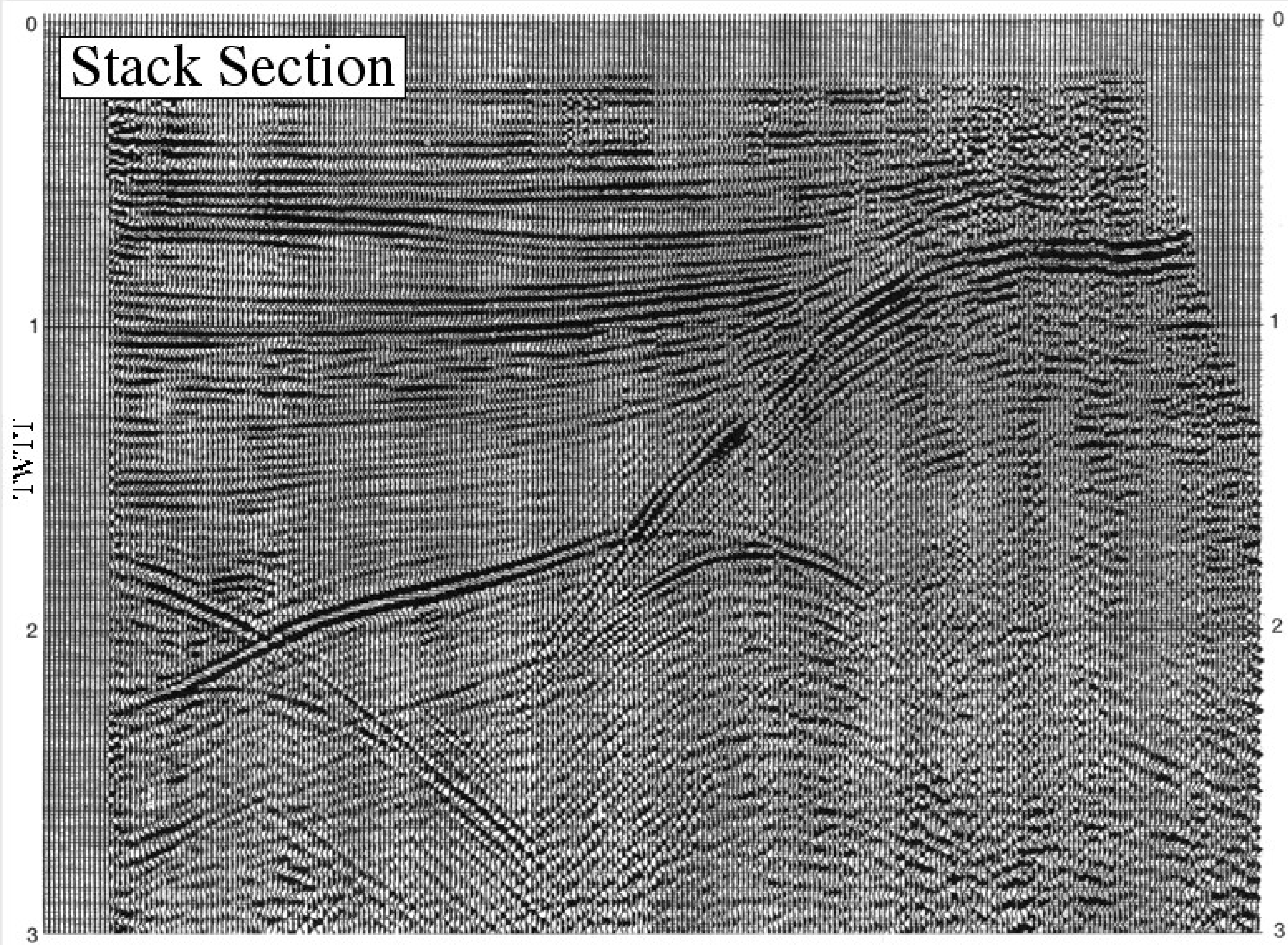
Migration Example

Unmigrated

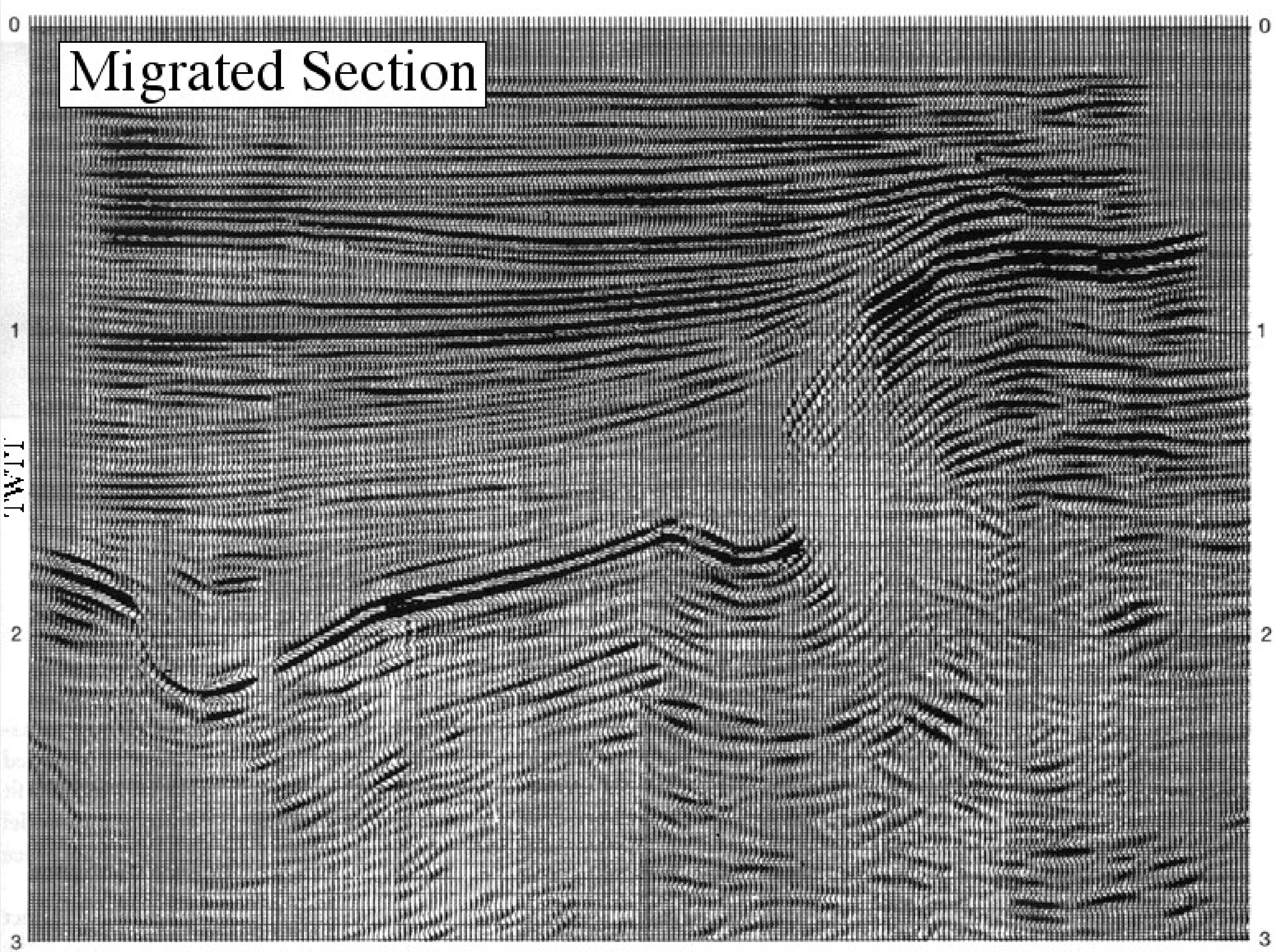


Migrated



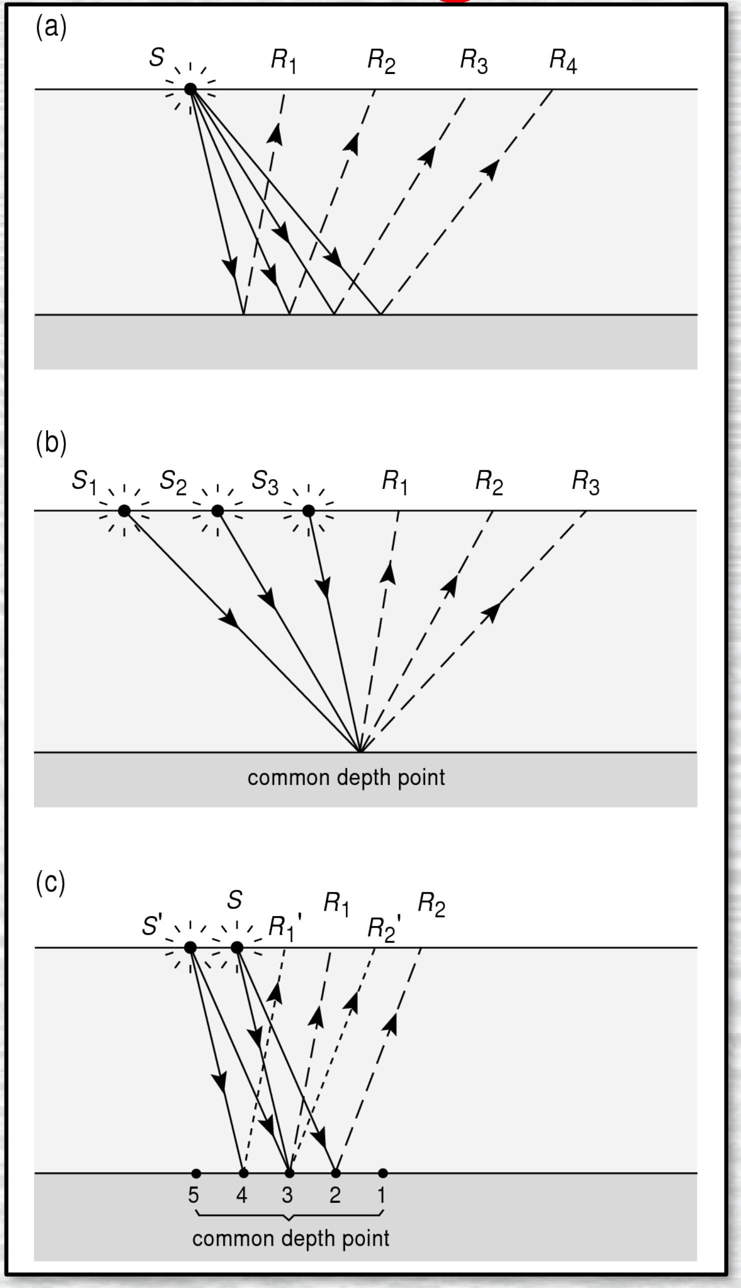


Stack Section
T.W.T.
0
1
2
3


Migrated Section
T.W.T.
0
1
2
3
0
1
2
3

Common Depth Point Stacking

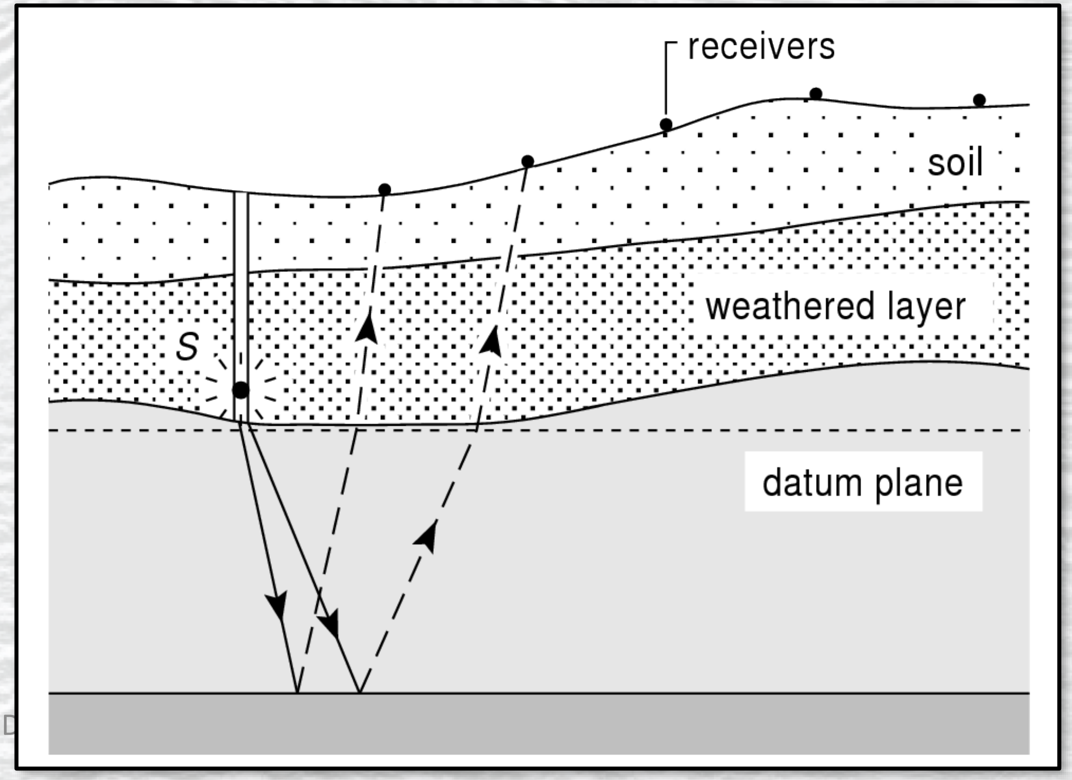
- We'll skip this…
- Basically…CDP stacking is a way to get a greater signal to noise ratio and determine the velocity structure all in one step.



Static Correction

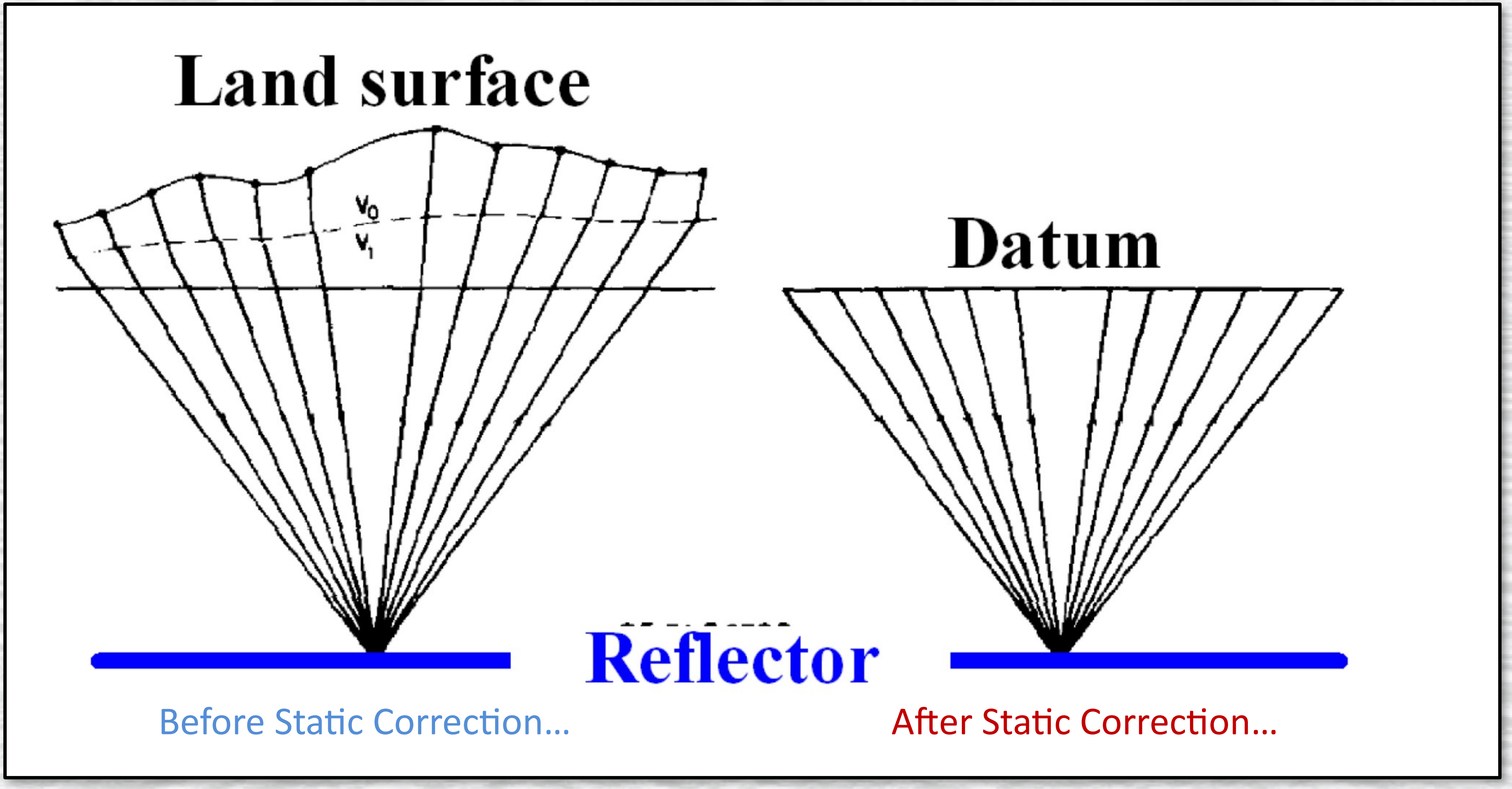
In land surveys…

- Geophones may be at different elevations
- Near-surface weathered layers (low velocity) may produce artifacts in data
  - Time spent in these shallow layers may be interpreted as thicker layers at depth.
- Static corrections make the data appear as if it were collected at some convenient constant elevation (i.e. horizontal) datum
- Why are static corrections not needed in marine surveys?



Static Correction

- …a simpler view



Types of Surveys

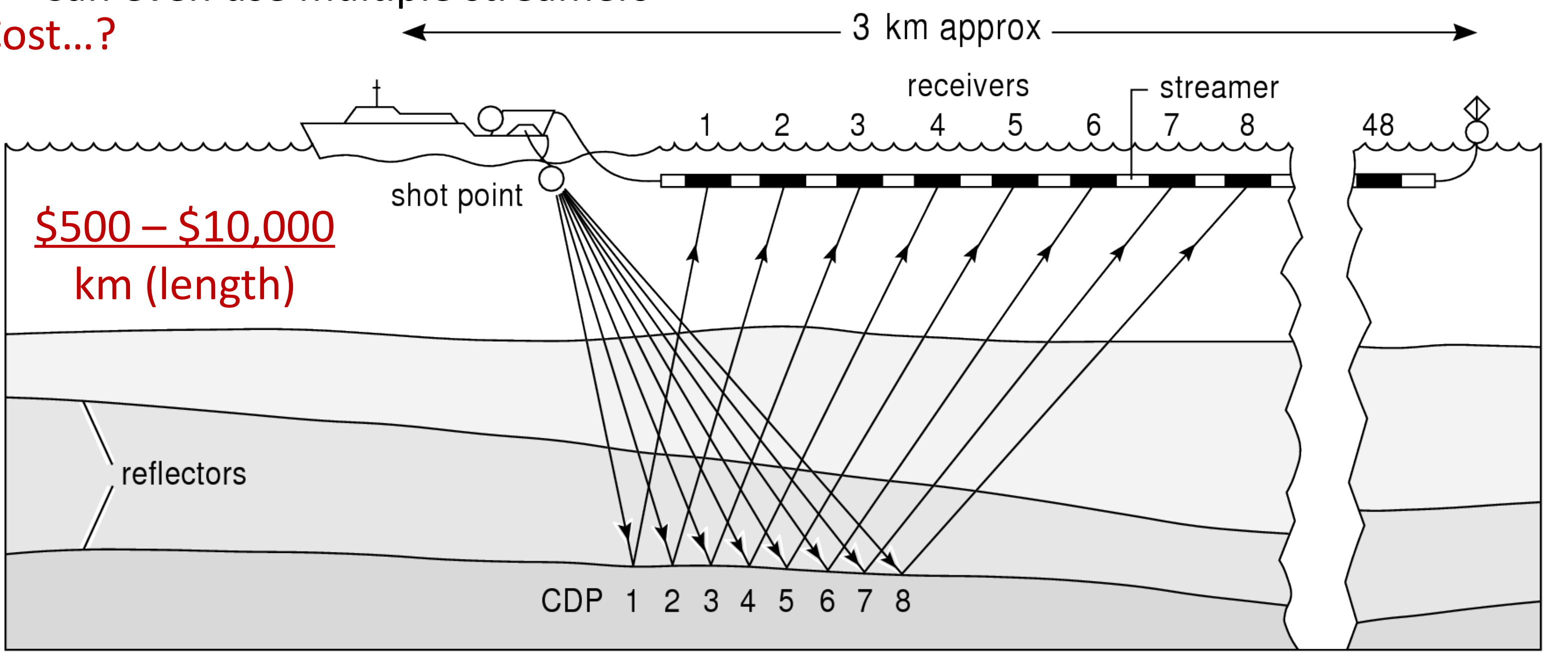
- Seismic Reflection is commonly done both on land and at sea
- Land surveys use geophones
  - Measure ground motion
- Marine surveys use hydrophones
  - Measure pressure changes in the water

Marine Surveys

- Use a variety of sources
  - Air Gun: Generates a high pressure air burst (> 100 atm)
  - Sparker: Generates a high voltage charge
  - Water Gun: Pulse of high pressure water
  - Aquapulse: Exposion of a mixture of gas and water
- The source type is unimportant, what is key is that the source can be repeated easily
- Hydrophones are floated behind the ship connected by streamers
  - Can even use multiple streamers

Cost…?

<u>$500 – $10,000</u>
km (length)



Land Surveys

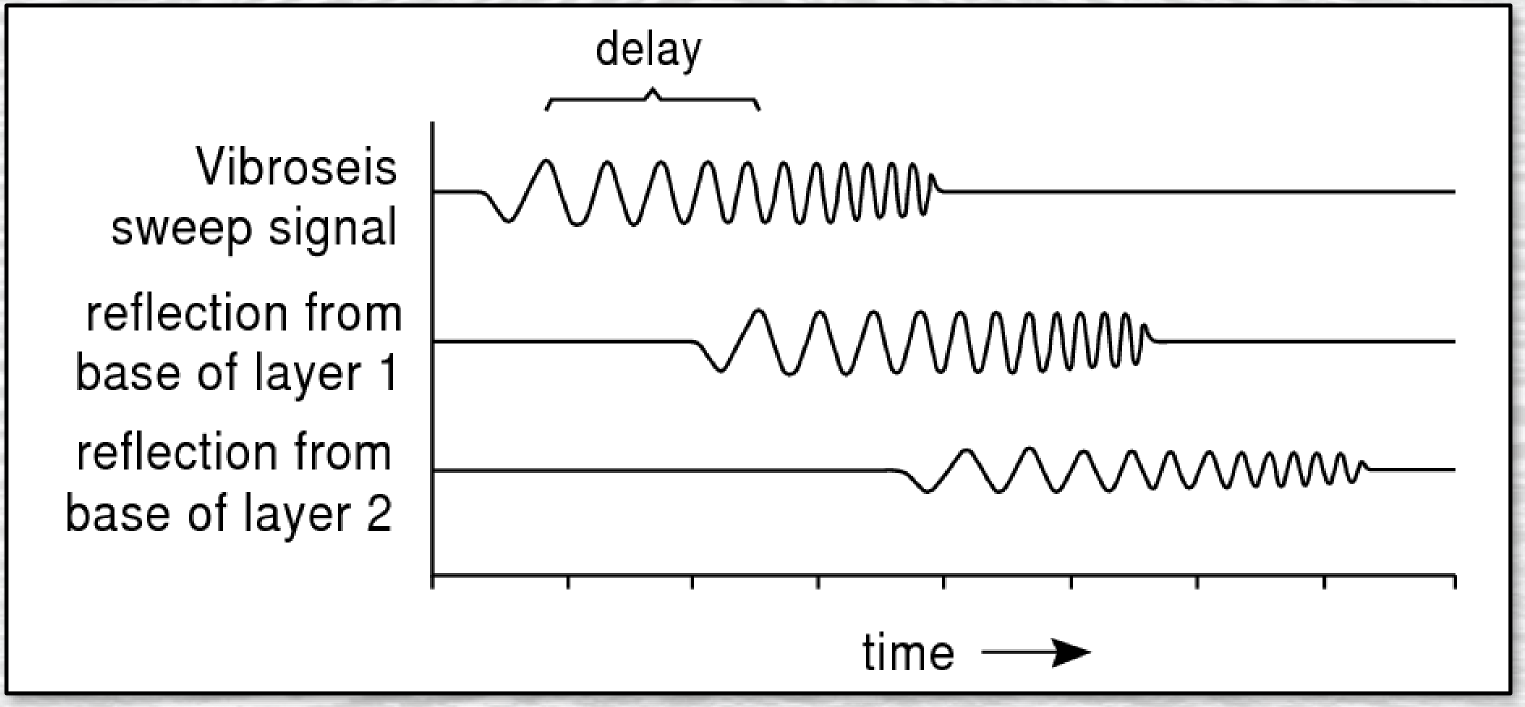
- Use a variety of sources
  - Impulsive
    - Explosives: Shallow-buried explosives (Boom!)
    - Dropping a large weight:
      - Usually ~ a few tons
  - Non-impulsive
    - Vibroseis
- Data recorded by geophones
  - Often clusters of geophones are used for each location to stack the data
- Moving the system is difficult
  - cost is ~ 10x of marine survey

Vibroseis

- Instead of a short pulse (impulsive) Vibroseis relies on a continuous train of waves with a changing frequency (non-impulsive)
- Generated by a large truck with vibrating plate

Vibroseis

- The source "sweep signal" is known & controlled
  - Commonly 1-100 Hz; up to 30 seconds
  - Low amplitude (compared to impulsive sources)
    - Can use multiple trucks vibrating the same sweep signal to increase strength
      - Has been known to get Moho reflections!
  - Can easily identify the arrival on seismograms
    - Match multiple troughs and peaks
    - High signal to noise ratio
    - Is successful in noisy environments

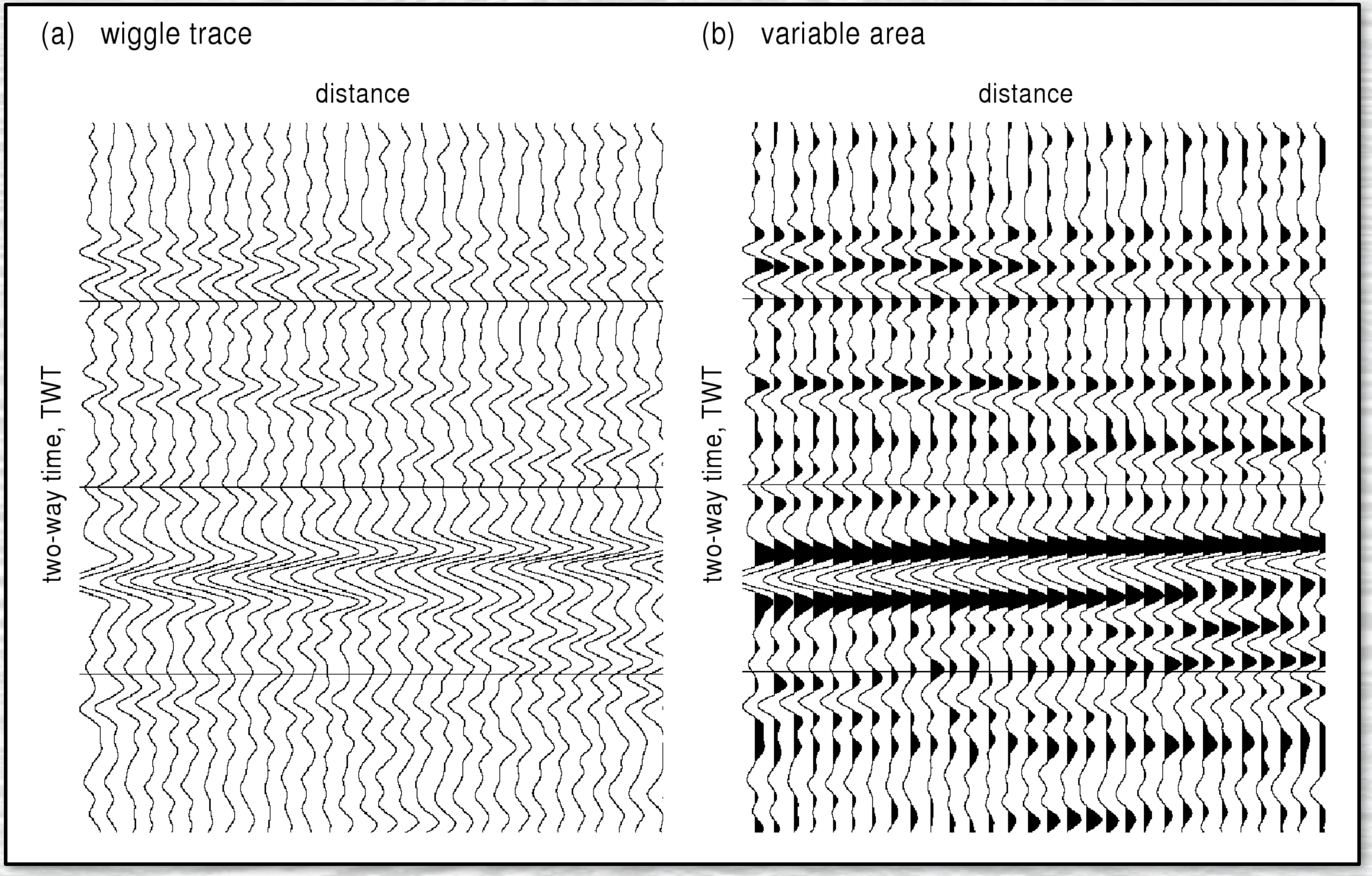


Vibroseis

http://www.voyageuroil.com/WhatsNew.aspx

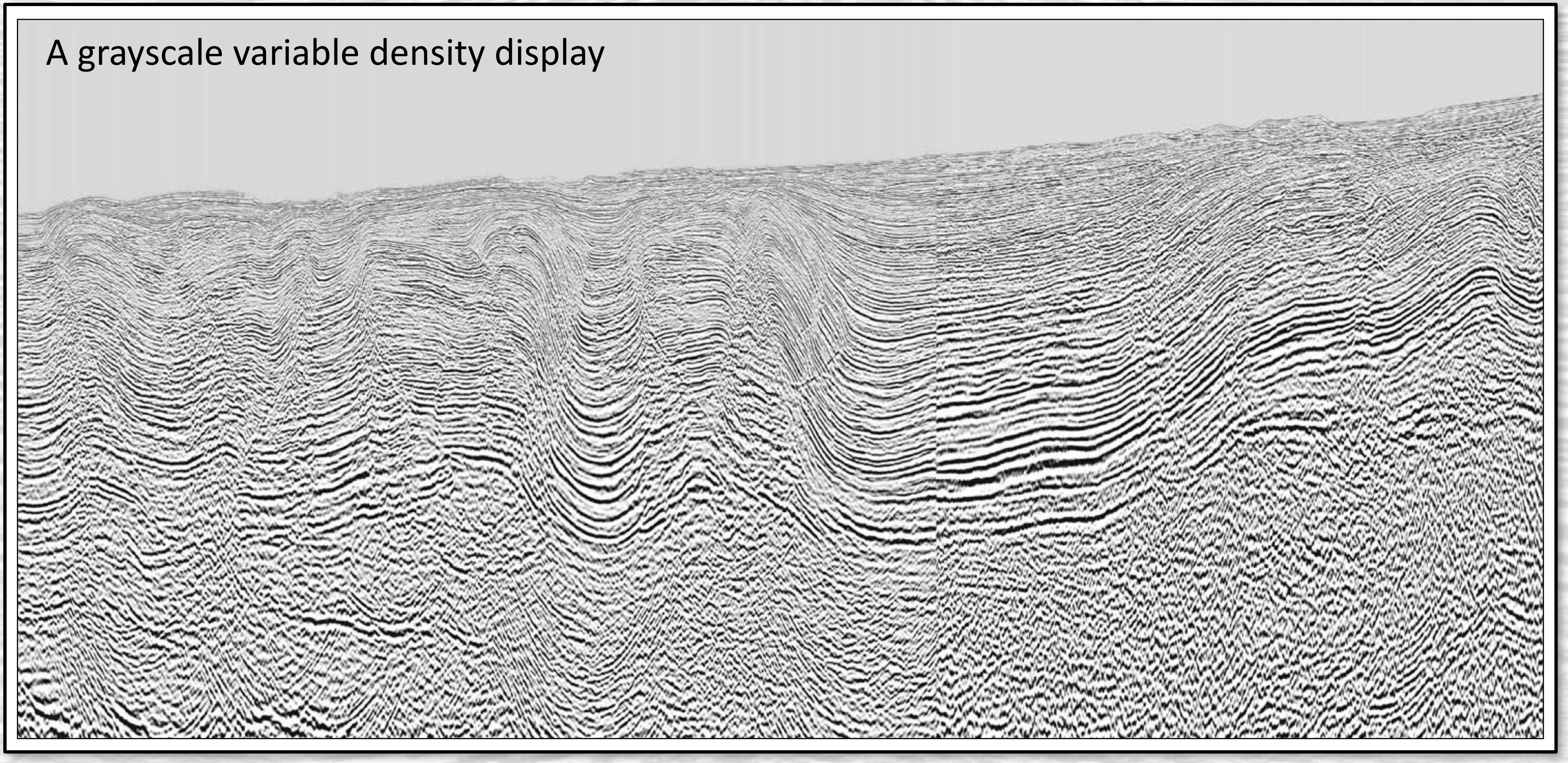
Display of Seismic Reflection Data

- Seismic data is almost never plotted as raw wiggle traces.
- Plotted as either **variable area** or **variable density**
  - Variable area: shades peaks but not troughs



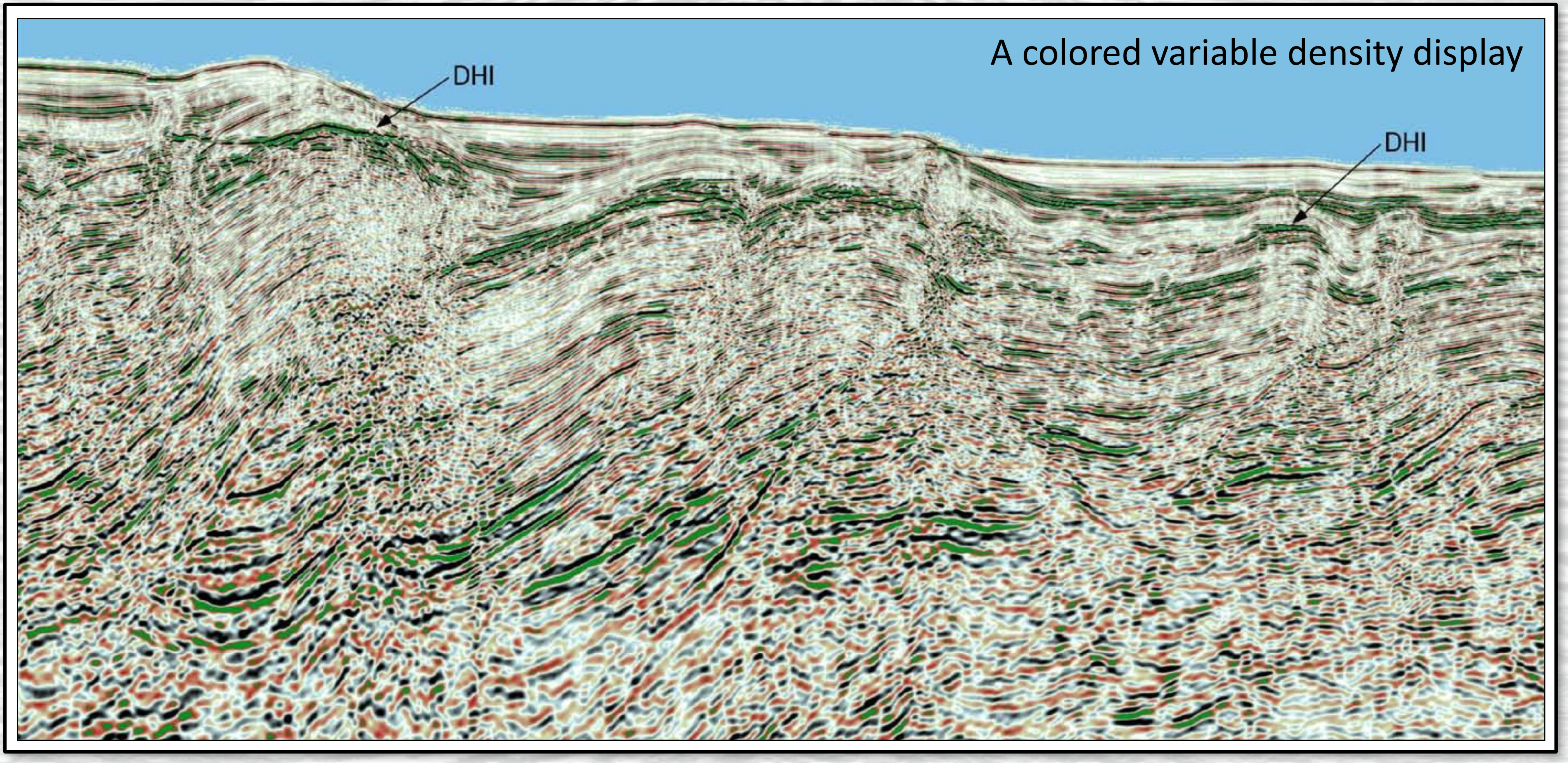
Display of Seismic Reflection Data

- **Variable Density:** the photographic intensity (i.e., gray value; color) is proportional to the amplitude



Display of Seismic Reflection Data

- **Variable Density**: the photographic intensity (i.e., gray value; color) is proportional to the amplitude



What is a Reflector?

- **Critical Reflection:** When 100% of a ray is reflected
  - Happens at angles greater than the critical angle
- **Sub-critical reflection**: Part of the total ray energy is reflected at angles less than the critical angle.
- The amount of an incident ray that is reflected depends on the **acoustic impedance**

  Acoustic Impedance $= \rho v$

  - **So both density and velocity matter!**
- **Reflection Coefficient:** ratio of reflected to incident amplitudes

$$\boxed{R = \frac{a_{refl}}{a_{incid}} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}}$$

Warning!! Only true if the incident ray is nearly normal to the interface

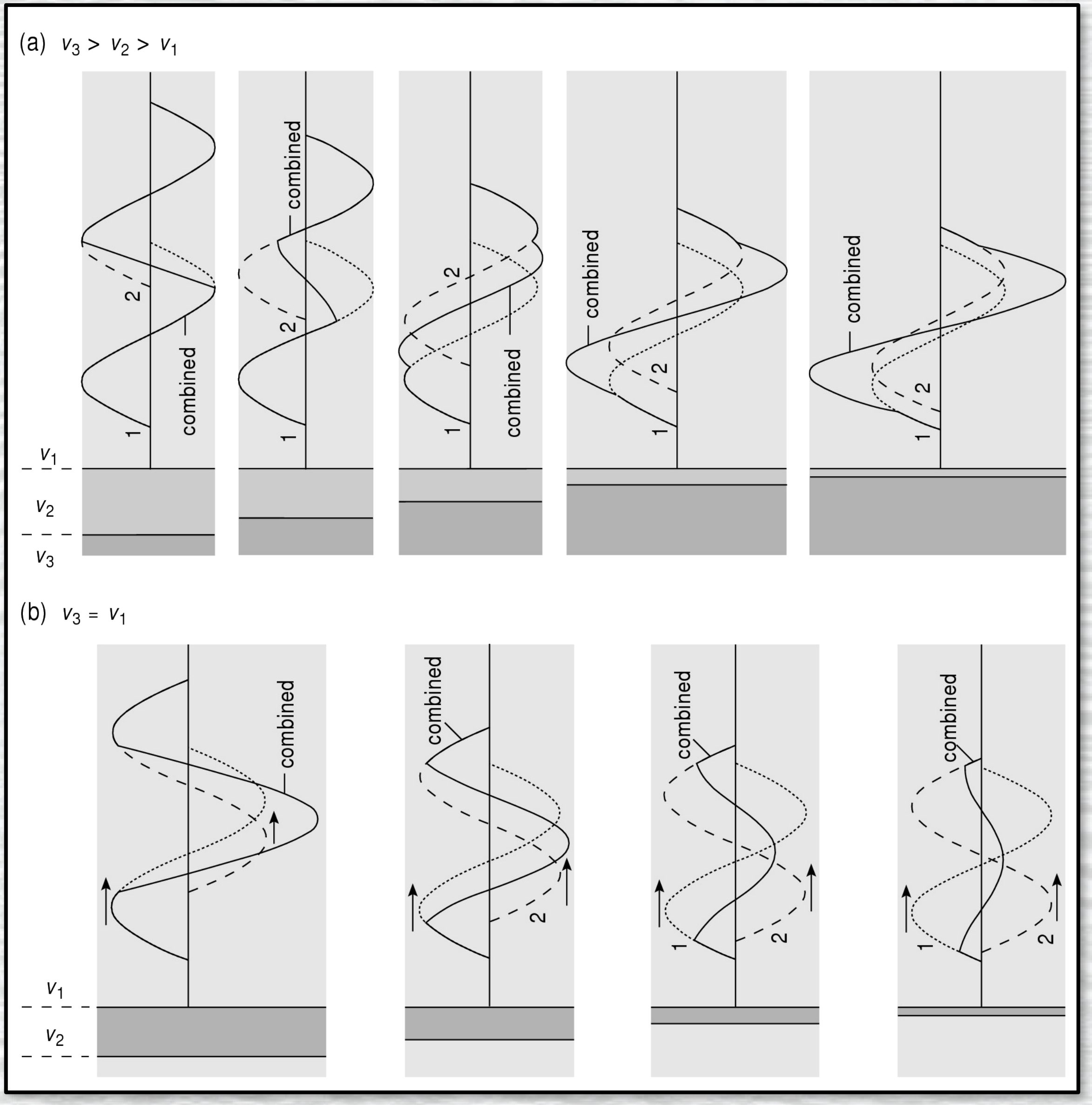
- **Transmission Coefficient:** ratio of transmitted to indecent amplitudes

$$\boxed{T = \frac{a_{trans}}{a_{incid}} = \frac{2\rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}}$$

Interference

The equation for reflectance can produce negative values…

- This means that the reflected pulse will be out of phase or have troughs where the incident pulse had peaks
- Certain reflector geometries can cause either constructive interference or destructive interference
- Interference causes the vertical resolution to be *~1/4 λ*



Vertical Resolution

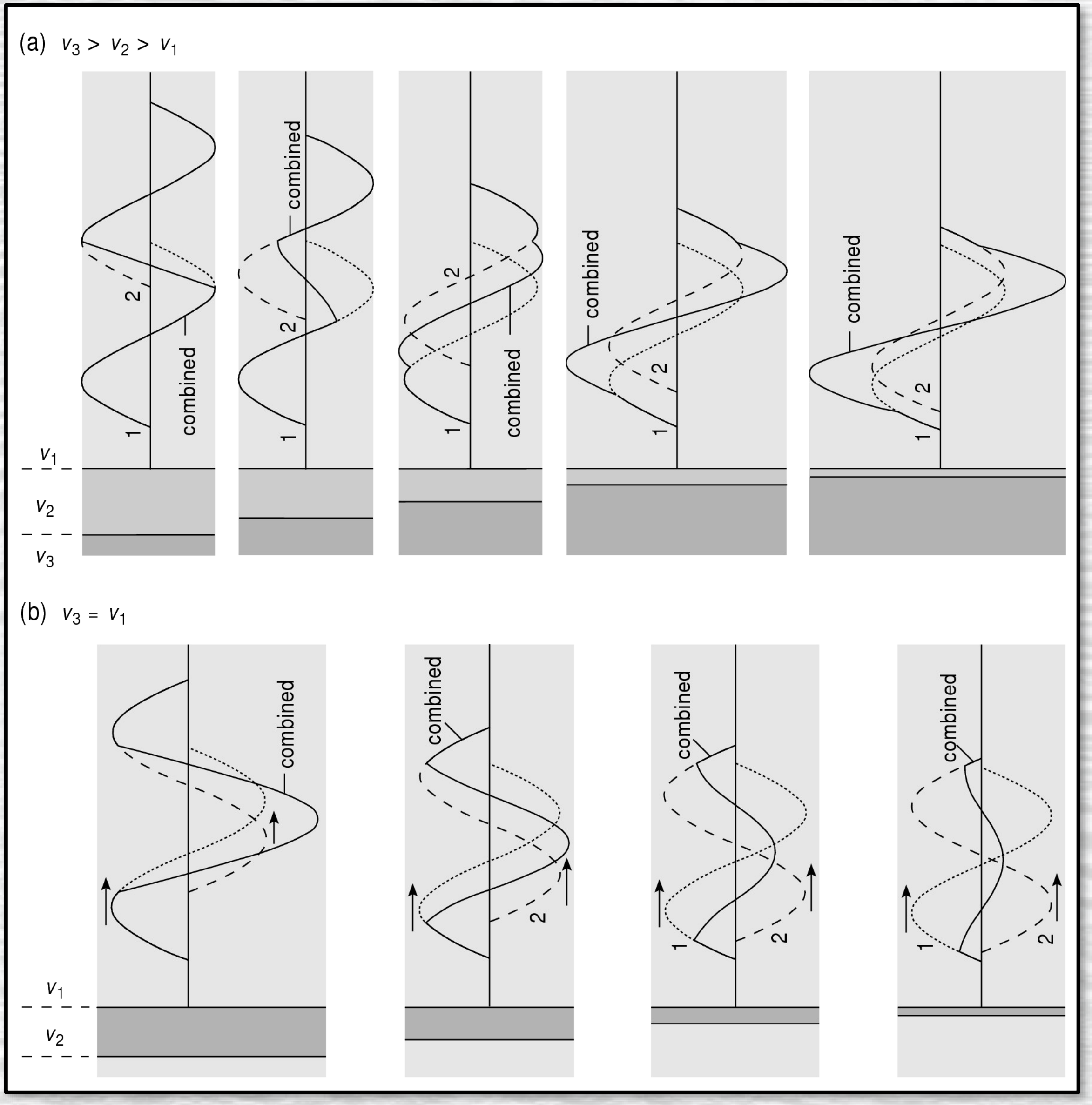
Interference with reflected waves affects the resolution…

- Vertical resolution is ~*1/4 λ*

- Want more detail?
  - Higher frequency source
  - Limited depth penetration

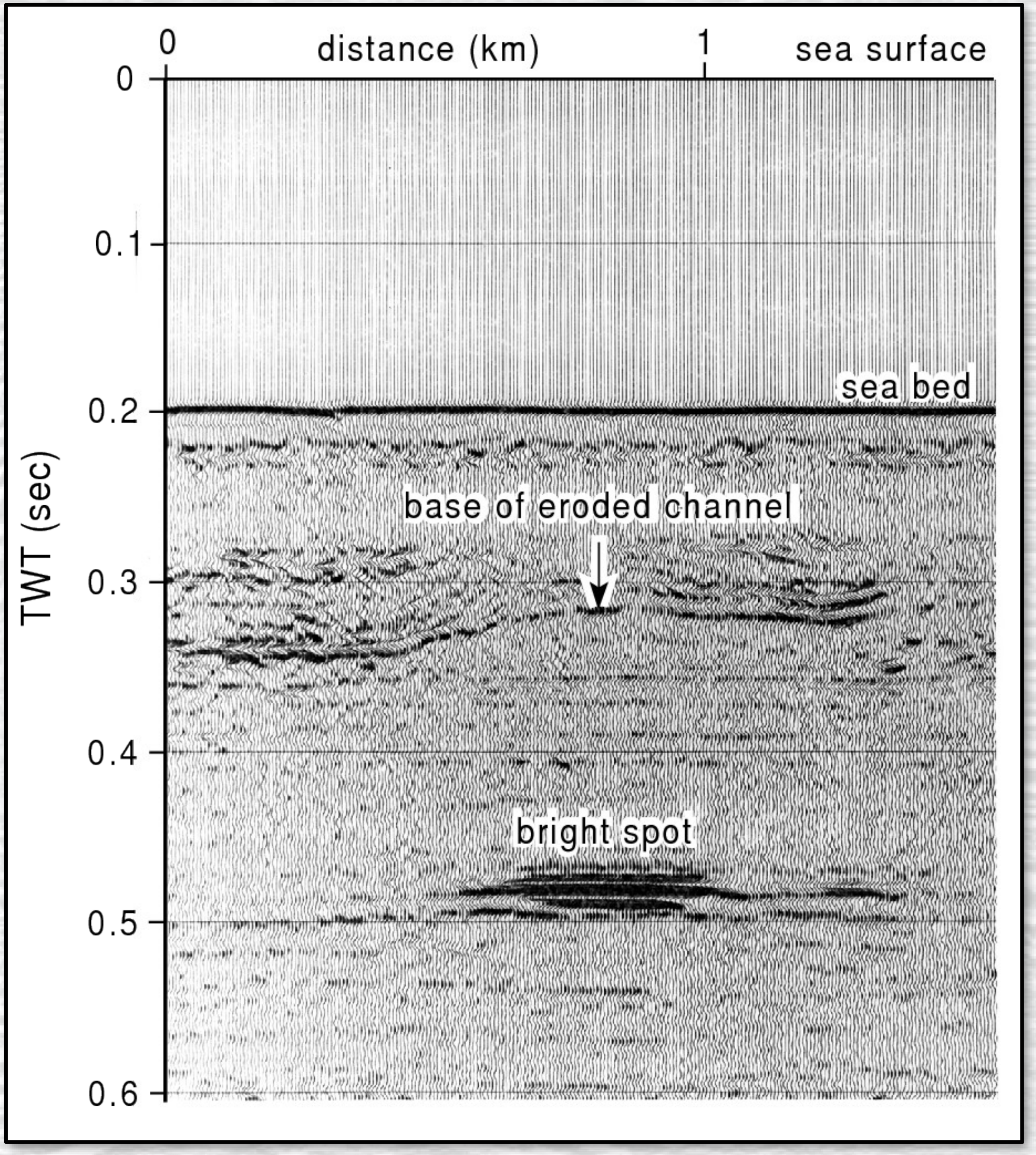
- Want greater depth penetration?
  - Lower frequency source
  - Lower vertical resolution

- Same is true for GPR



Bright Spots

- Because of large contrasts in acoustic impedance…
  - Oil and gas reservoirs produce strong reflections
  - Called “bright spots”
- No (or weak) reflections?
  - Gradational boundaries
  - Steeply dipping or vertical layers



Seismic Hazards

- Seismic reflection data are also used to help identify active faults, define their geometries, and slip histories, for the characterization of earthquake hazards.

Puente Hills thrust, LA basin