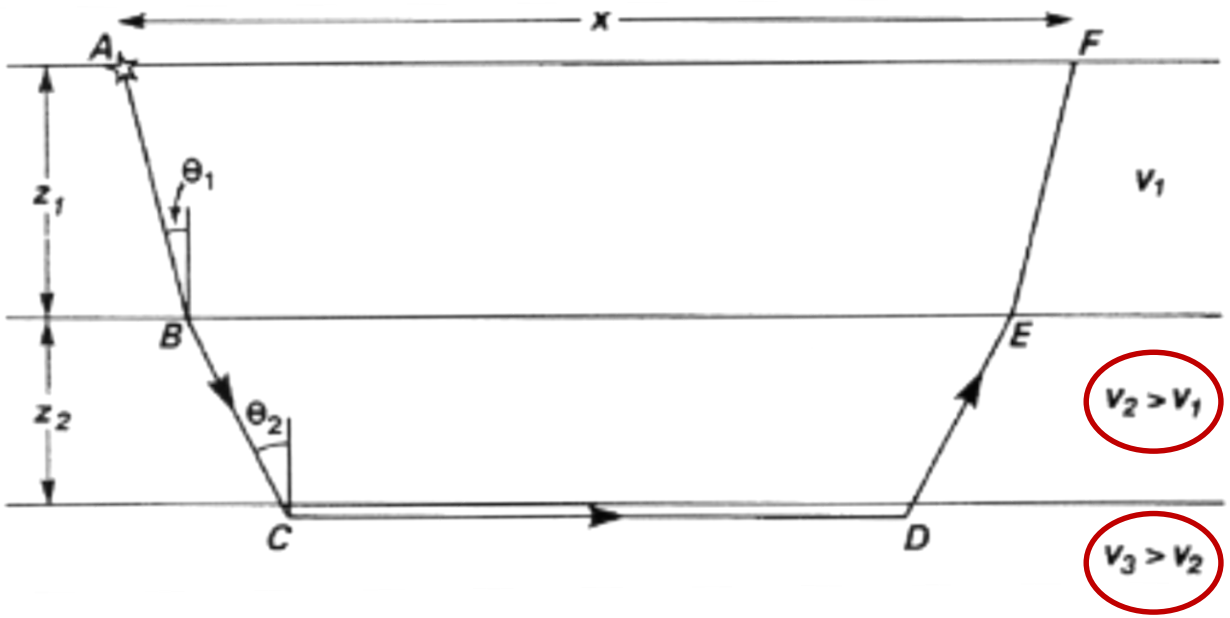
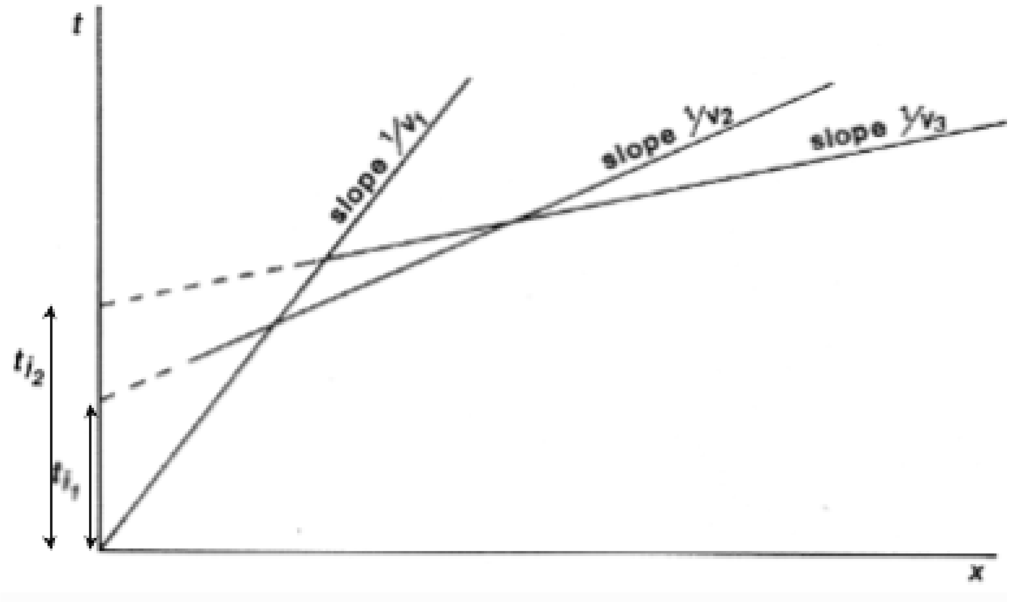
From last time

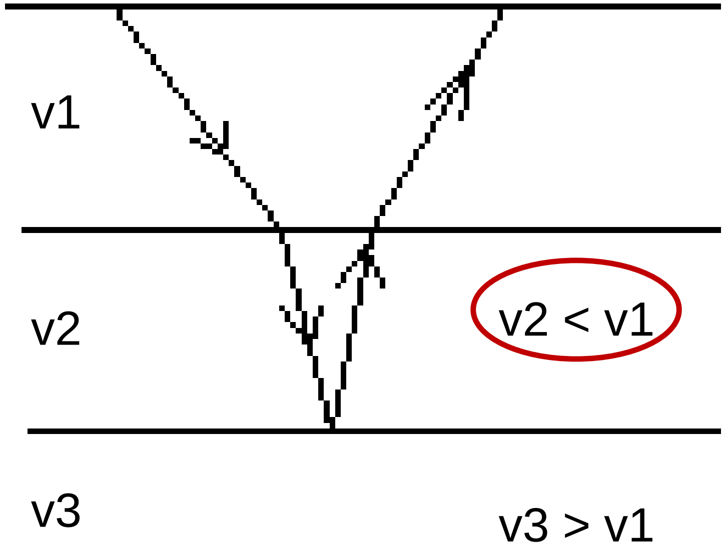
- Refraction survey works best when:
  - Velocity increases with depth
  - Layers are sufficiently thick



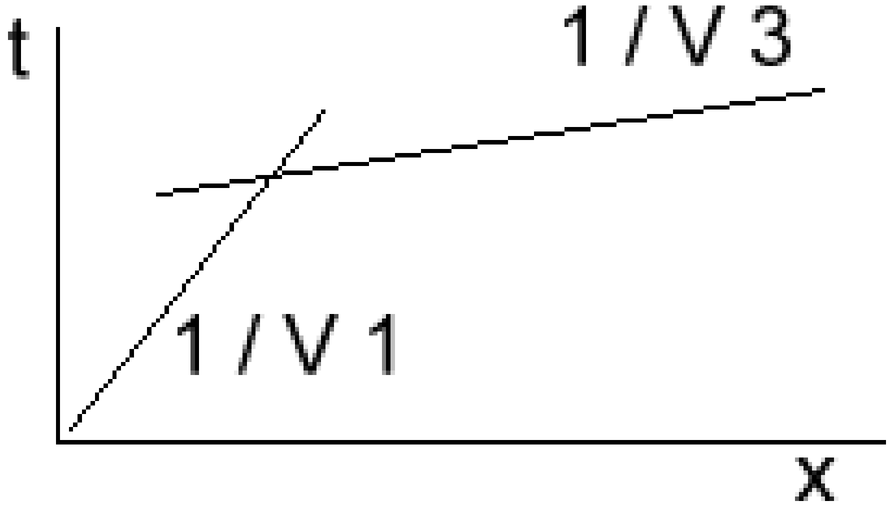


From last time

- No critical refraction at interface with low velocity zone
  → No refracted signal from layer 2
  → Low velocity zone "invisible"



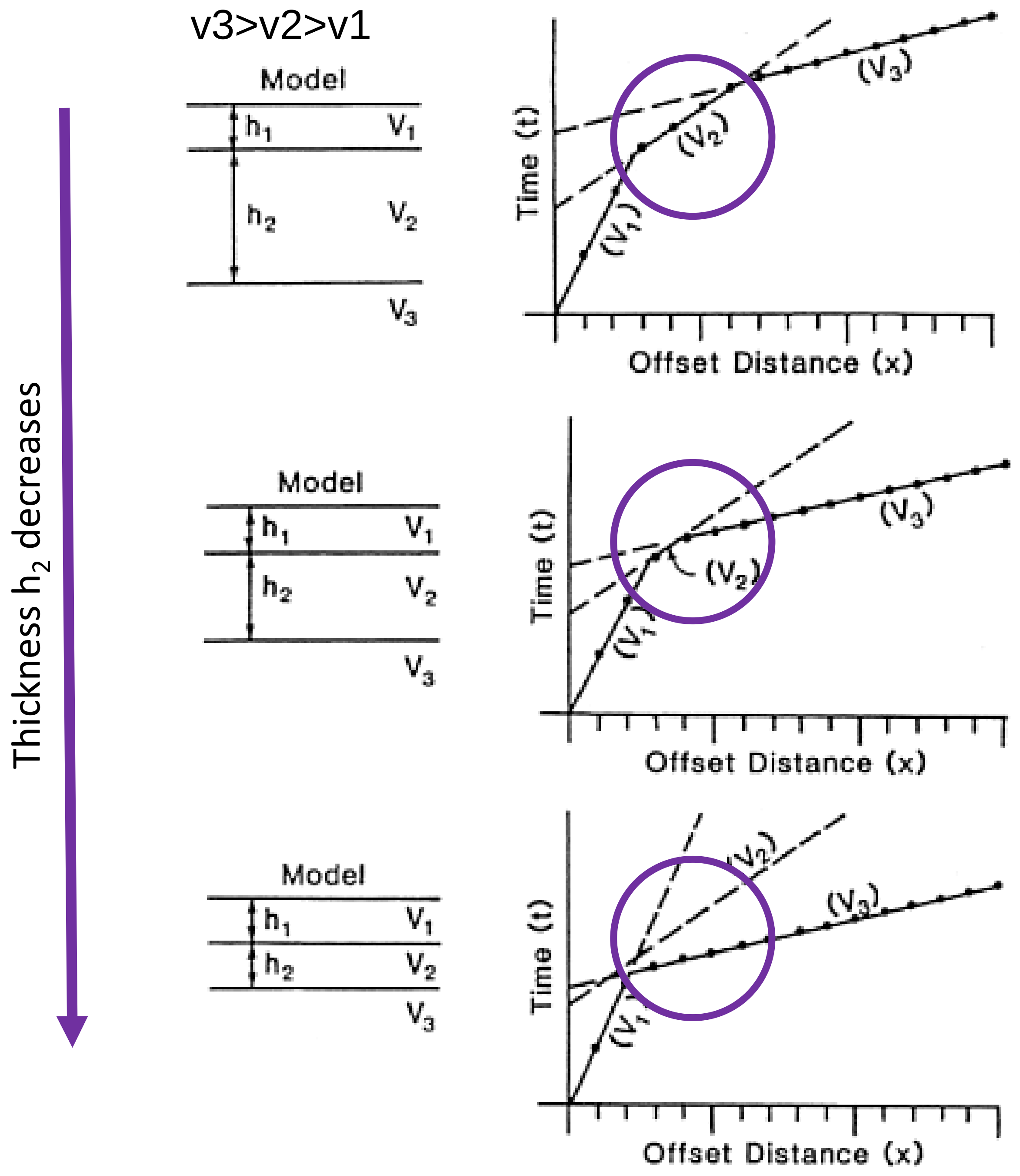
$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$$



From last time

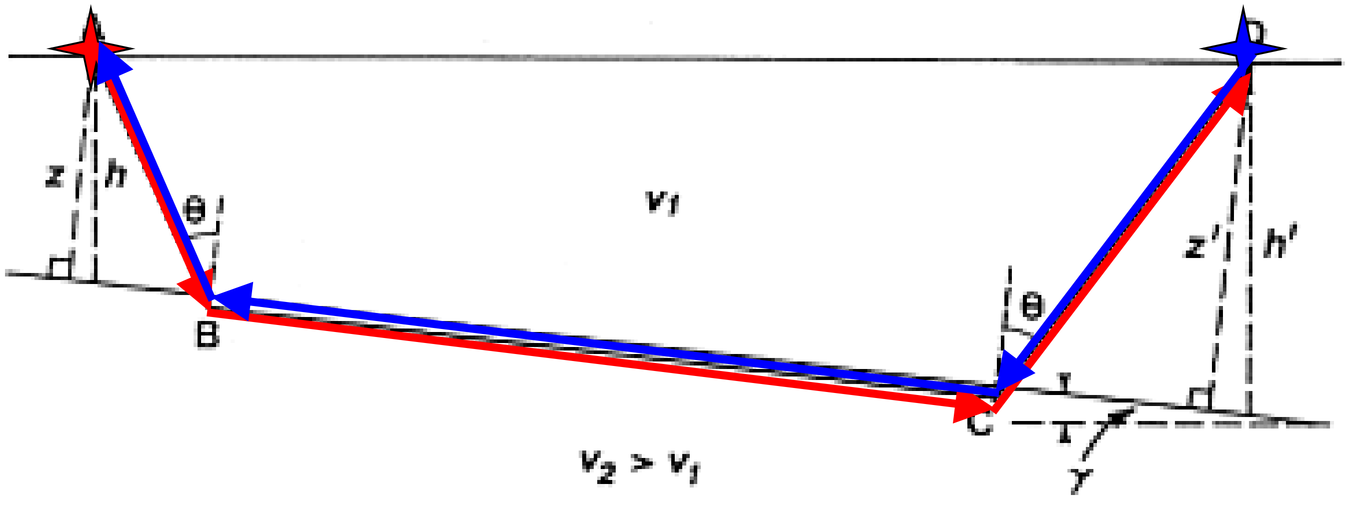
- Layers that are too thin may not be seen

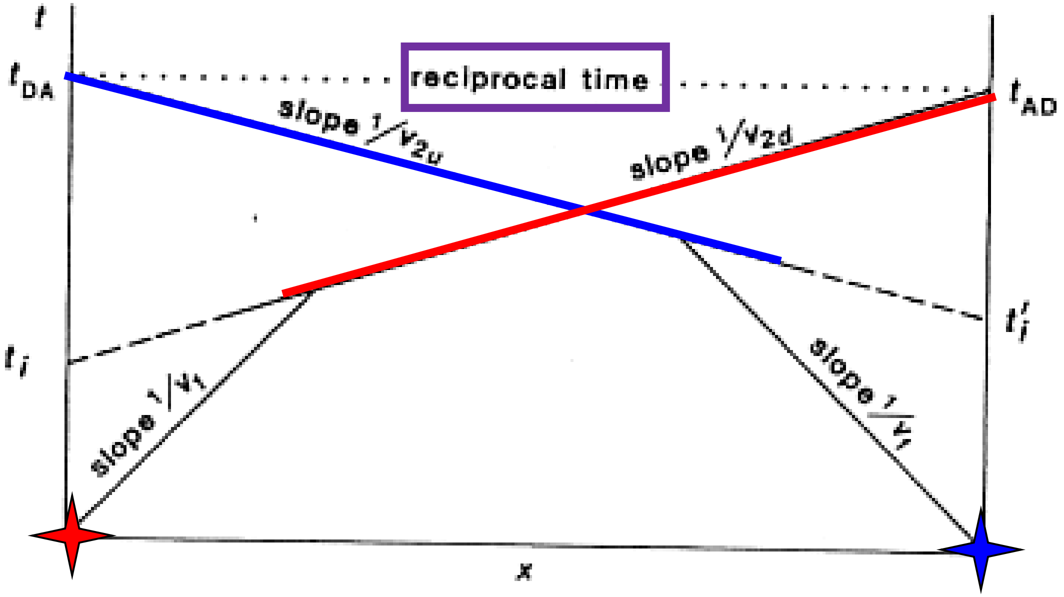
- Arrival from layer 3 beats that from layer 2



From last time

- Requires **TWO** shots to be able to interpret





- Travel time in down-dip direction

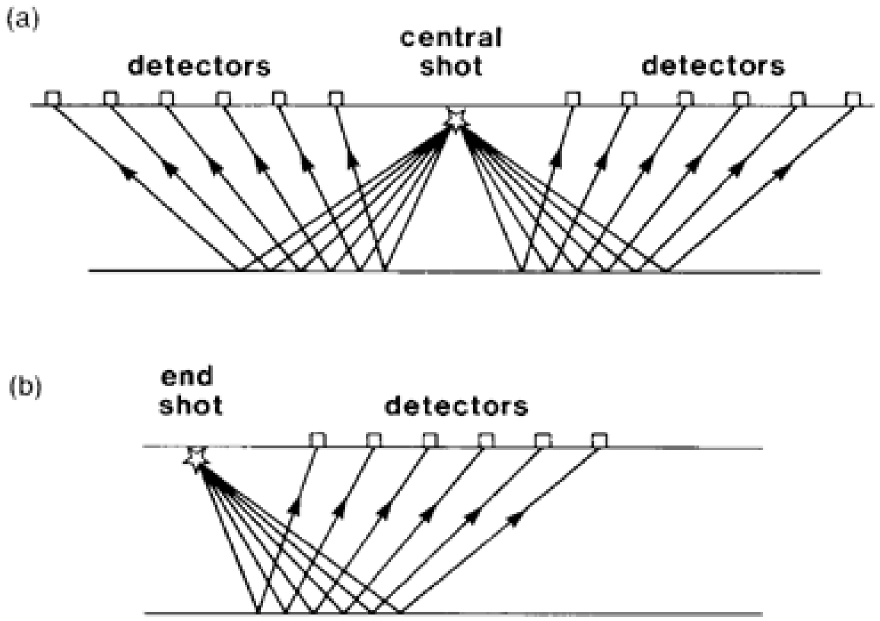
$$t_2 = \frac{x\sin(\theta+\gamma)}{v_1} + \frac{2z\cos\theta}{v_1} = \frac{x}{v_{2d}} + t_i$$

- Travel time in up-dip direction

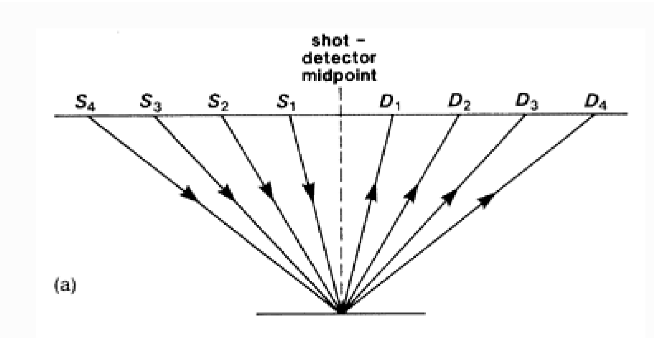
$$t_2' = \frac{x\sin(\theta-\gamma)}{v_1} + \frac{2z'\cos\theta}{v_1} = \frac{x}{v_{2u}} + t_i'$$

From last time: Reflection Surveys

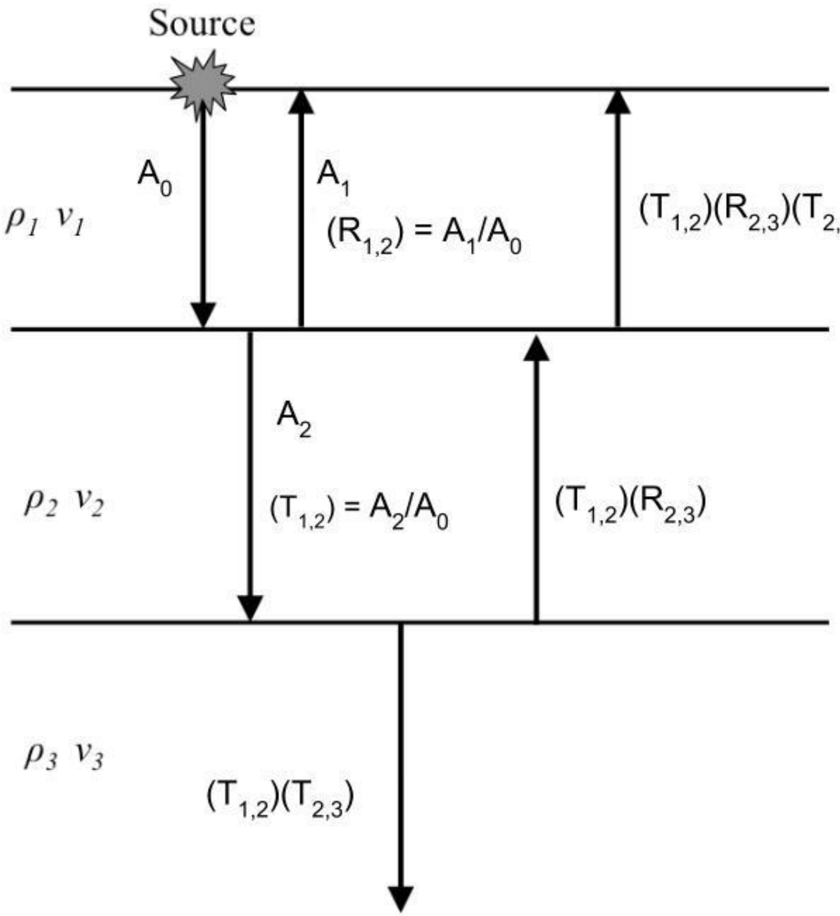
Many different reflected signals measured



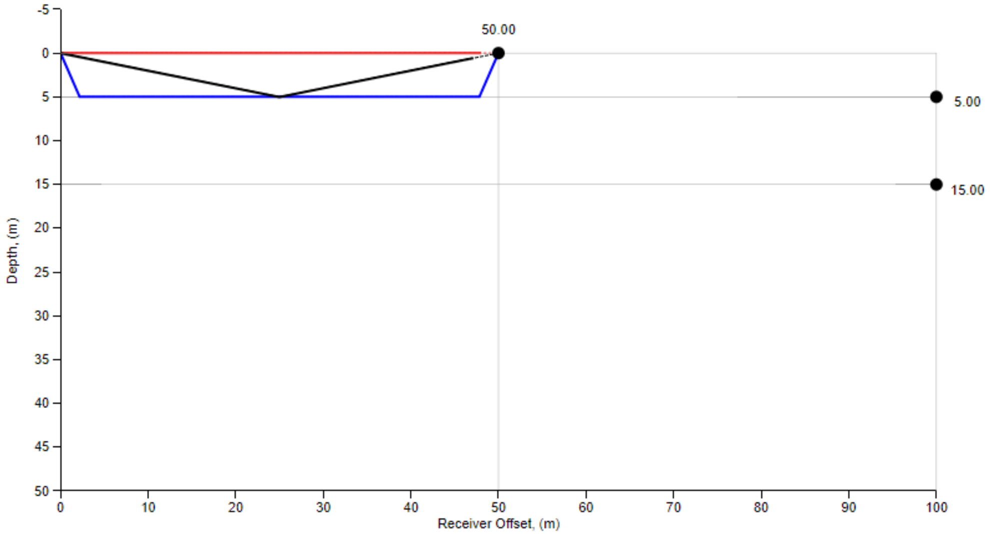
Some reflections from same spot



Impedances impact returning signal amplitudes

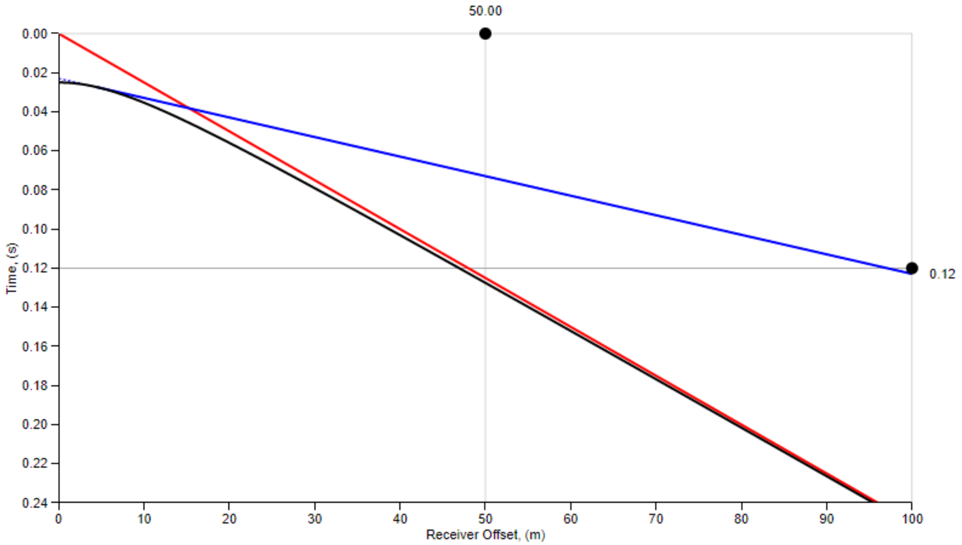


Reflection Surveys: Travel time



- Recall that travel time for a reflected wave is

$$t_{refl} = \frac{\sqrt{x^2 + 4h^2}}{v_1}$$



- Which is a hyperbola

Today's Topics

- Motivation and fundamental procedure

- Processing and Interpretation (Reflection)
  - Normal move out correction
  - Migration
  - Travel time to depth
  - Resolution

- Processing and Interpretation (MASW)

Motivation

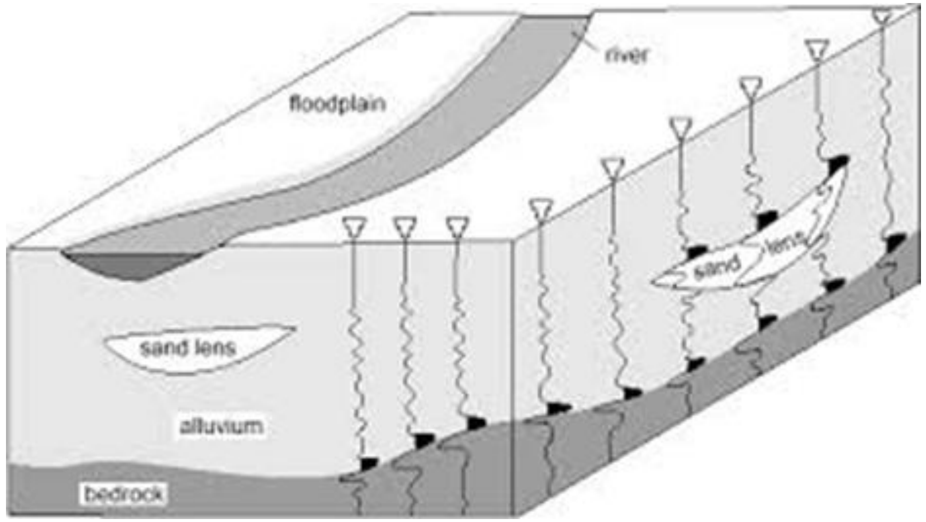
Motivation

- Seismic refraction was effective for finding interfaces and velocities
  - As long as velocity increased with depth
  - Only the first arrivals were used

- What if we want to image something much more complicated?

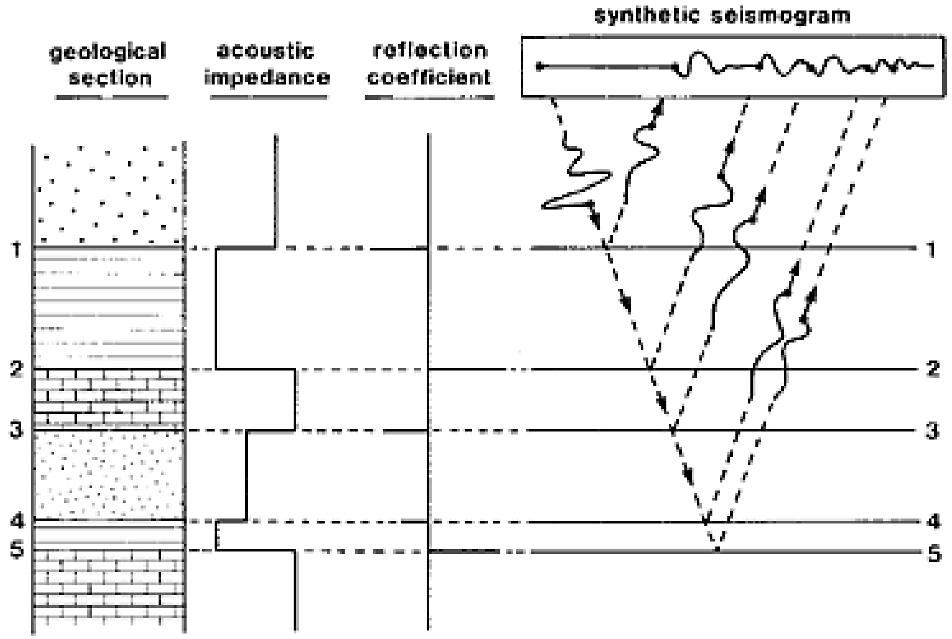
- Impedance contrasts gives reflections

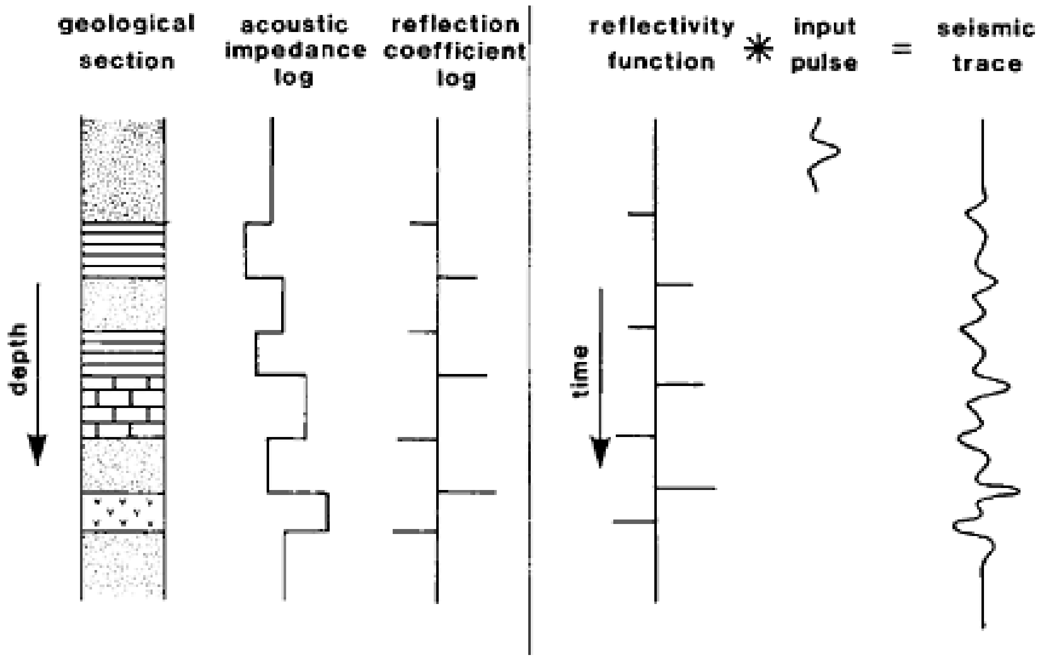
- Generate an image made from normal incidence seismograms



Ideal Scenario

- Assume:
  - Ray travels straight down and back up.
  - 0m offset and normal incidence
  - Layered Earth
- Could find depth to reflectors easily from single shot

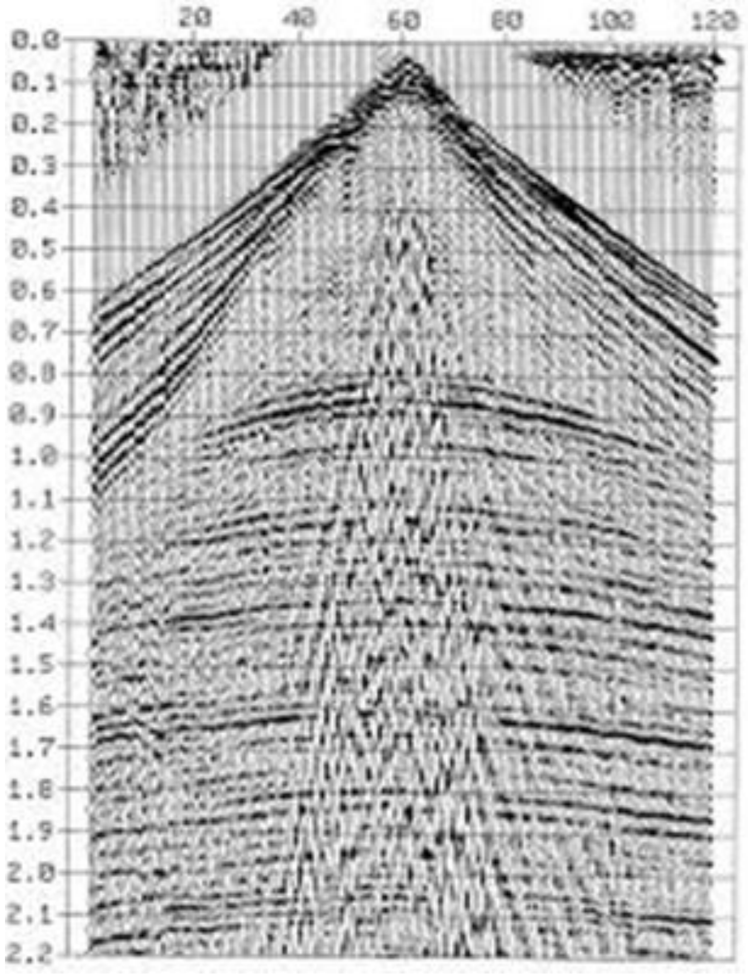




Reality

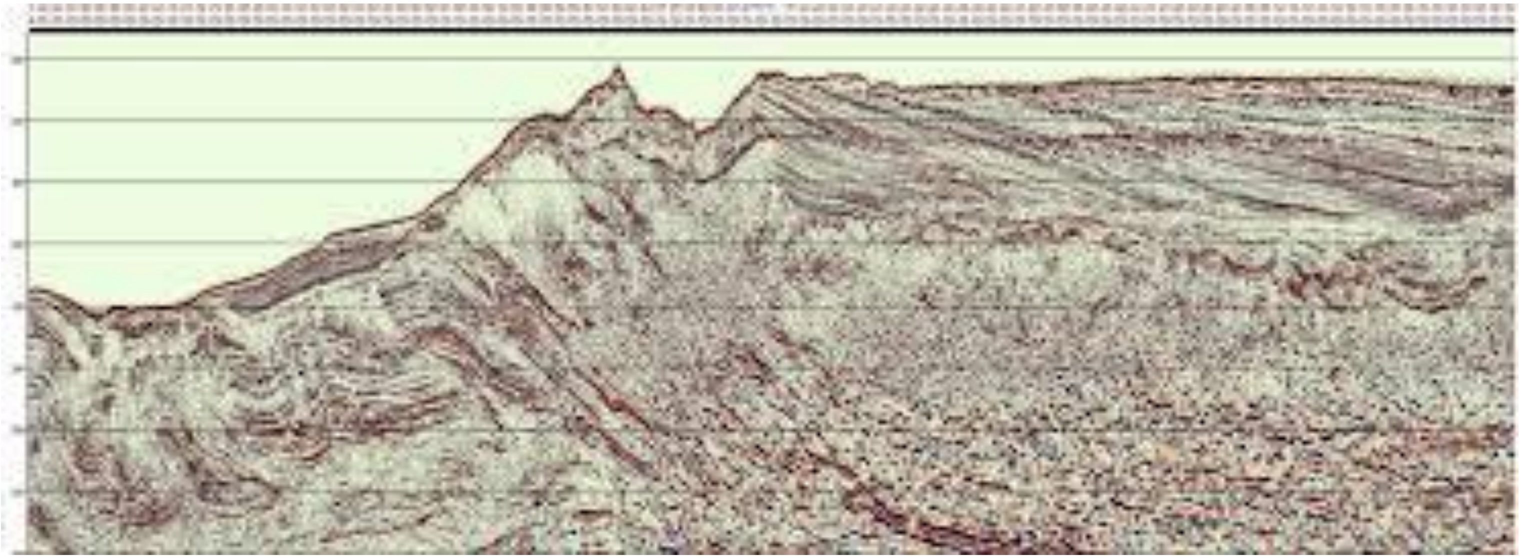
- Geologies can be complex
- Seismic surveys consist of many shots
- Need to convert data to a set of “ideal” traces
  → ideal seismogram

Single common shot gather



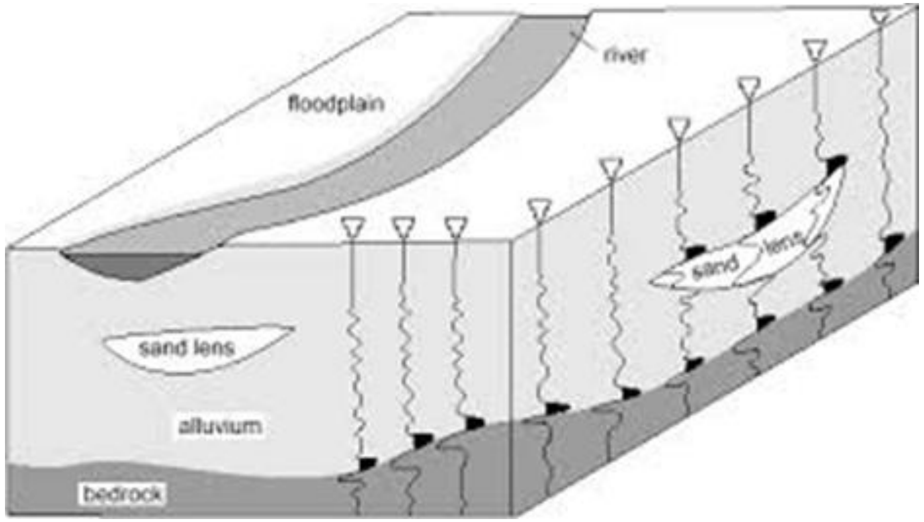
If processing successful

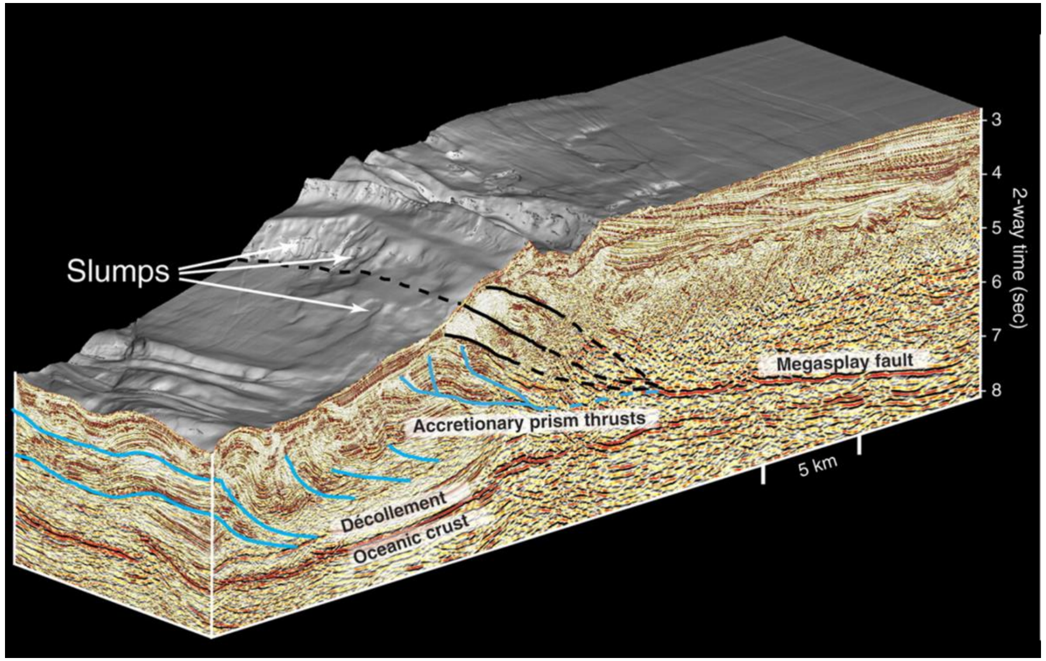
- Each trace is an ideal reflection seismogram of a wave that …
  - Travels vertically downward
  - Reflects off of boundaries
  - And arrives back at the surface along the same vertical path
- Plotting many such traces yields an image in which structure can be observed



Goal of processing reflection data

- Collect seismic data → Processing → Something we can interpret





Fundamental Procedure

We have gathered data with many sources and receivers. The fundamental procedure is:

1) Collect a set of common shot gathers (CSG)

2) Extract and organize common the mid point (CMP) traces
   (all source-receiver pairs that share same mid point)

3) Apply normal move out (NMO) correction and stack the traces for each set of CMP traces

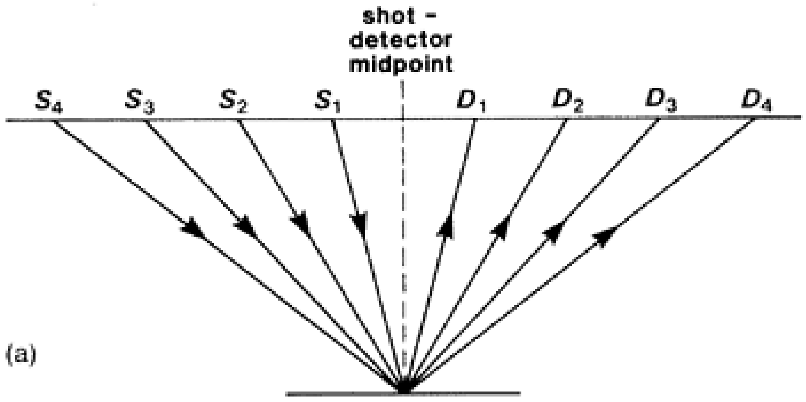
4) Combine the set of stacked traces to create a cross-section of the Earth

5) Interpretation

Normal Move Out (NMO) Correction

General Idea

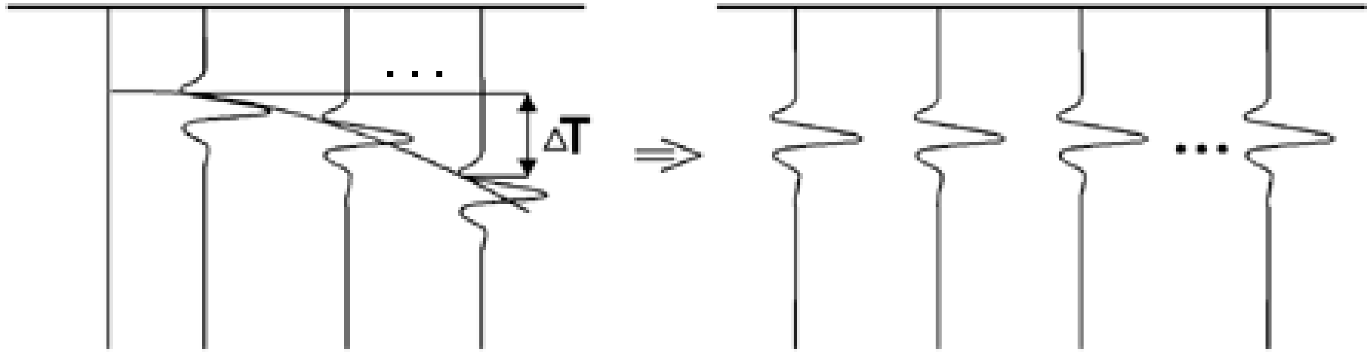
- For each common mid point gather…



what would the traces **from a single reflective event** look like if the source and receiver were over the reflector?

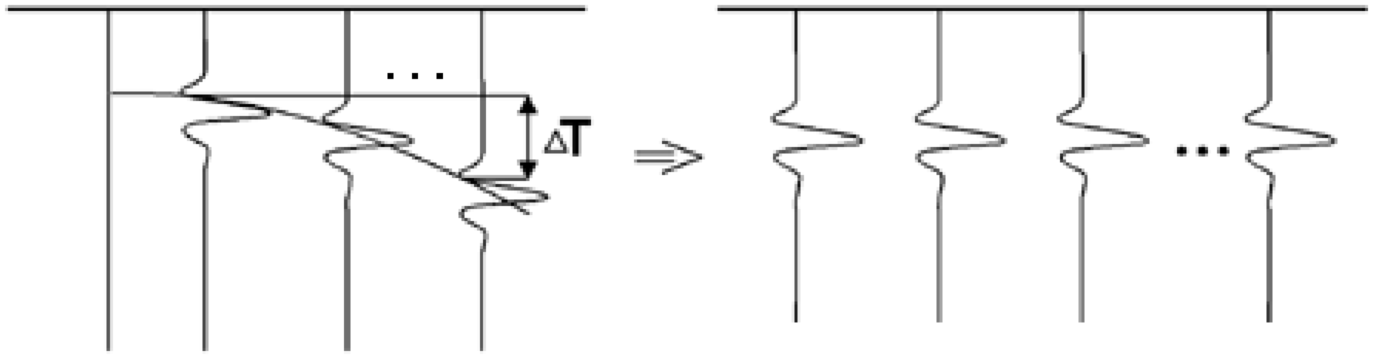
→ apply a correction

$$\triangle t = t - t_0$$



General Idea

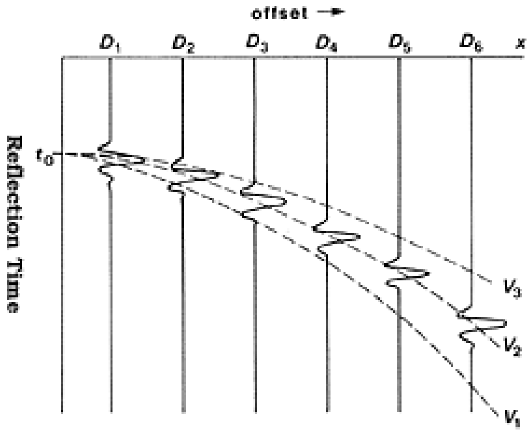
- If the reflective interface is horizontal
  → turn a parabolic feature to a flat one

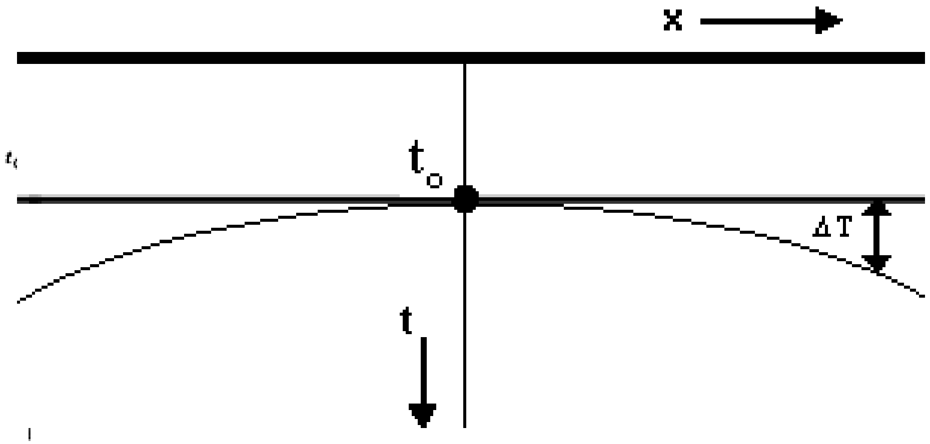


- NMO can highlight non-flat interfaces better than parabola
  → Dipping layers
  → Faults

Step 1: Estimate t_0 and v_{st} for a reflector

- Travel time for reflector can be expressed as: $t^2(x) = t_0^2 + \frac{x^2}{v_{st}^2}$

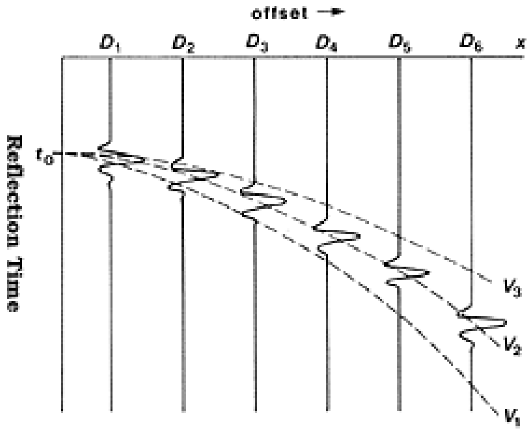


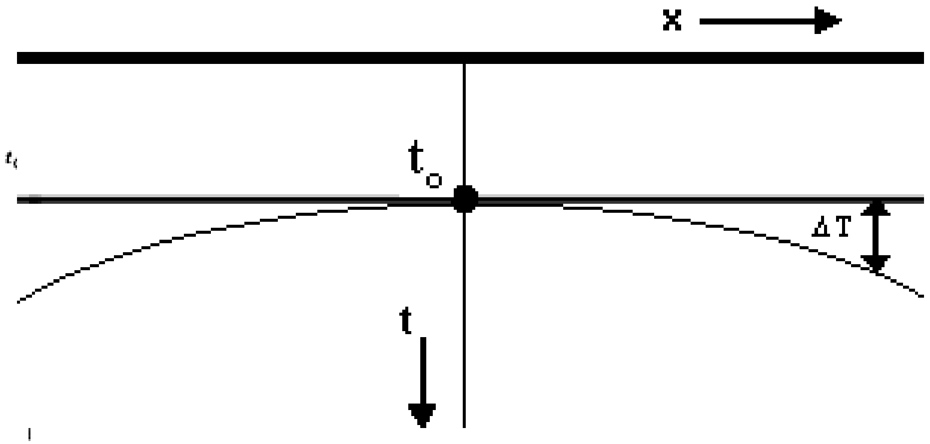


- t_0 is travel time for zero-offset trace
- v_{st} is stacking velocity
- Could use curve fitting to estimate

Step 2: normal move out Δt for the reflector

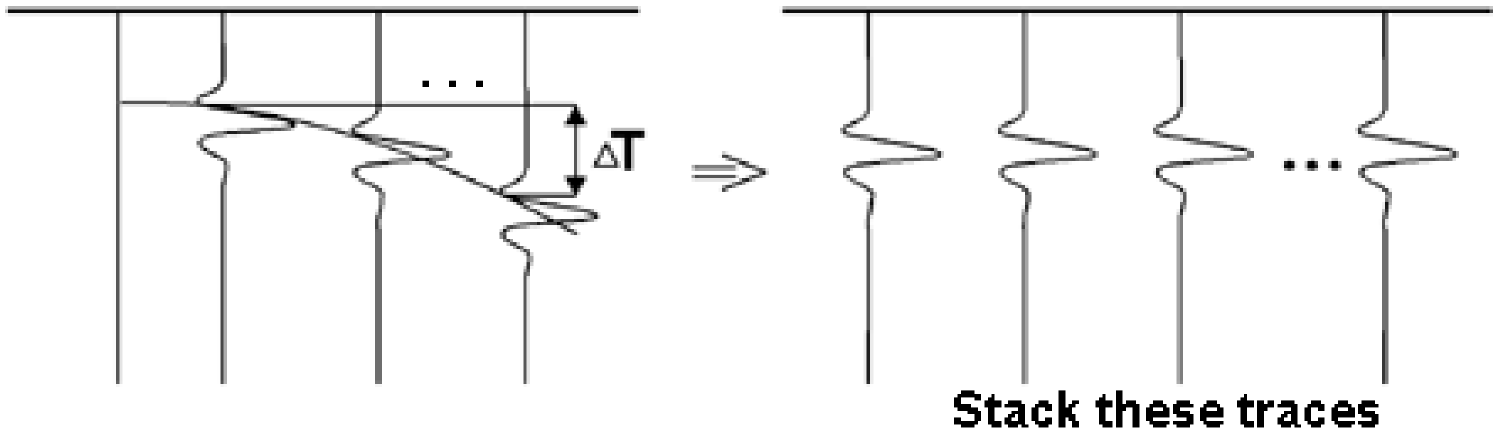
- For each trace, subtract normal move out Δt for observed time





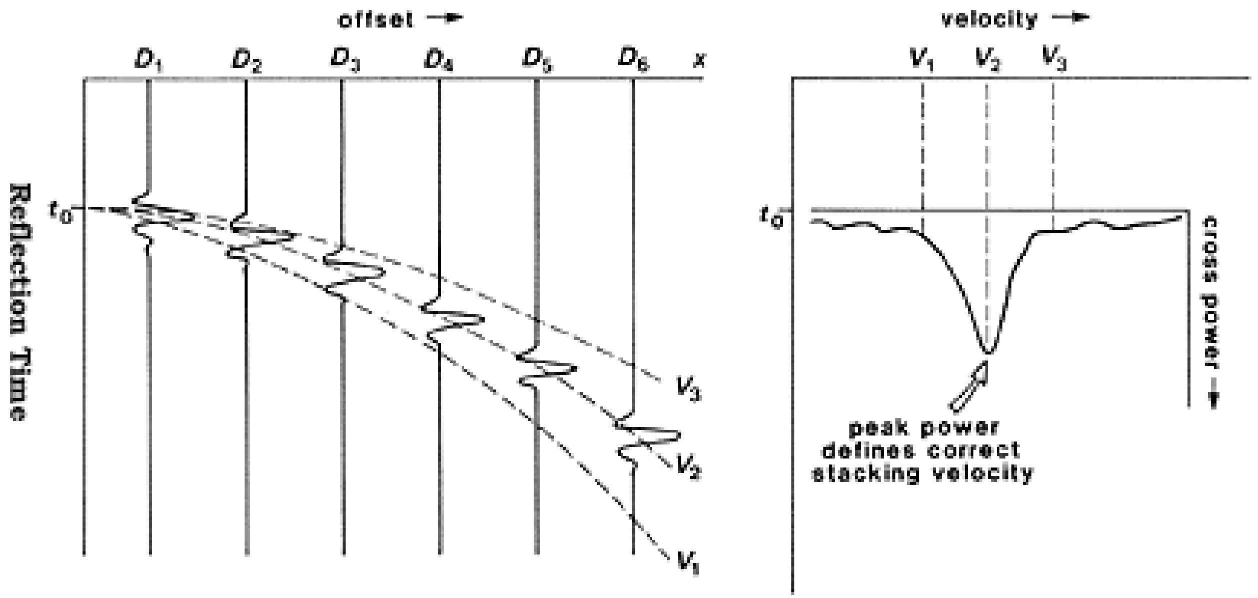
$$\Delta t = \sqrt{{t_0}^2 + \left(\frac{x}{v_{st}}\right)^2} - t_0$$

Step 3: Stack the NMO corrected traces



- Should result in a set of similar traces
- These can be stacked to obtain a single trace for the reflector

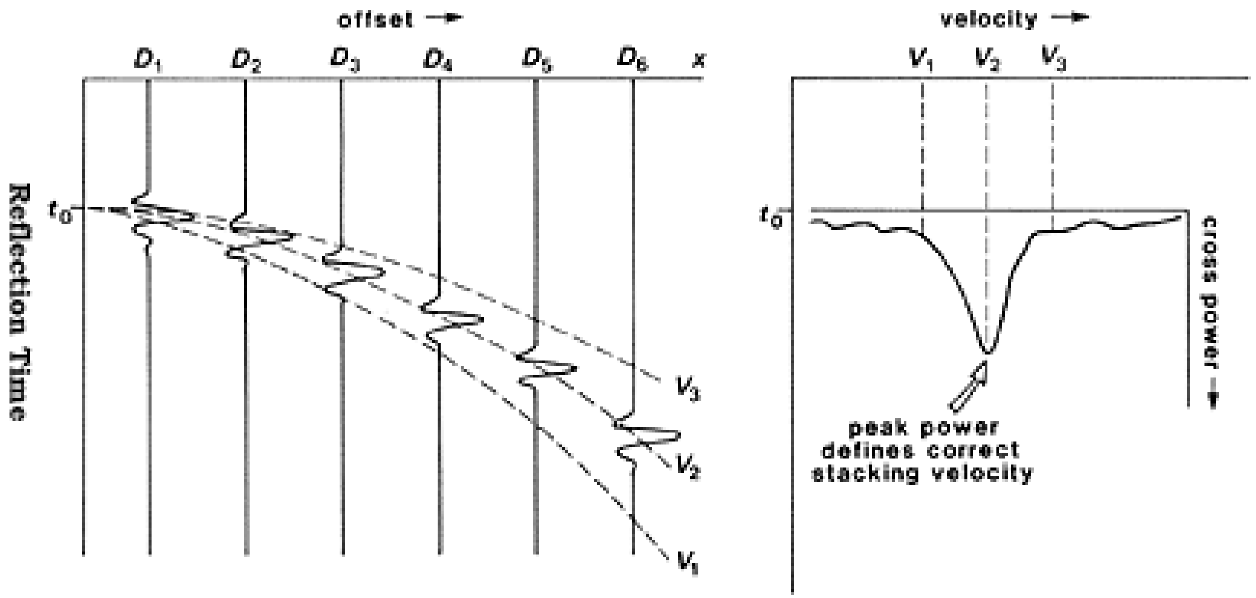
Step 4: Verify NMO correction



- Sum energy of the traces after NMO correction
- If t_0 and v_{st} correct, you will have largest energy

Multiple Reflectors/Layers

- For each reflection event, perform velocity analysis to find v_{st}
  - Estimate t_0 and v_{st}
  - Apply correction to traces
  - Stack NMO corrected traces
  - Compute energy of stacked traces
  - Repeat until you have result that yields max energy

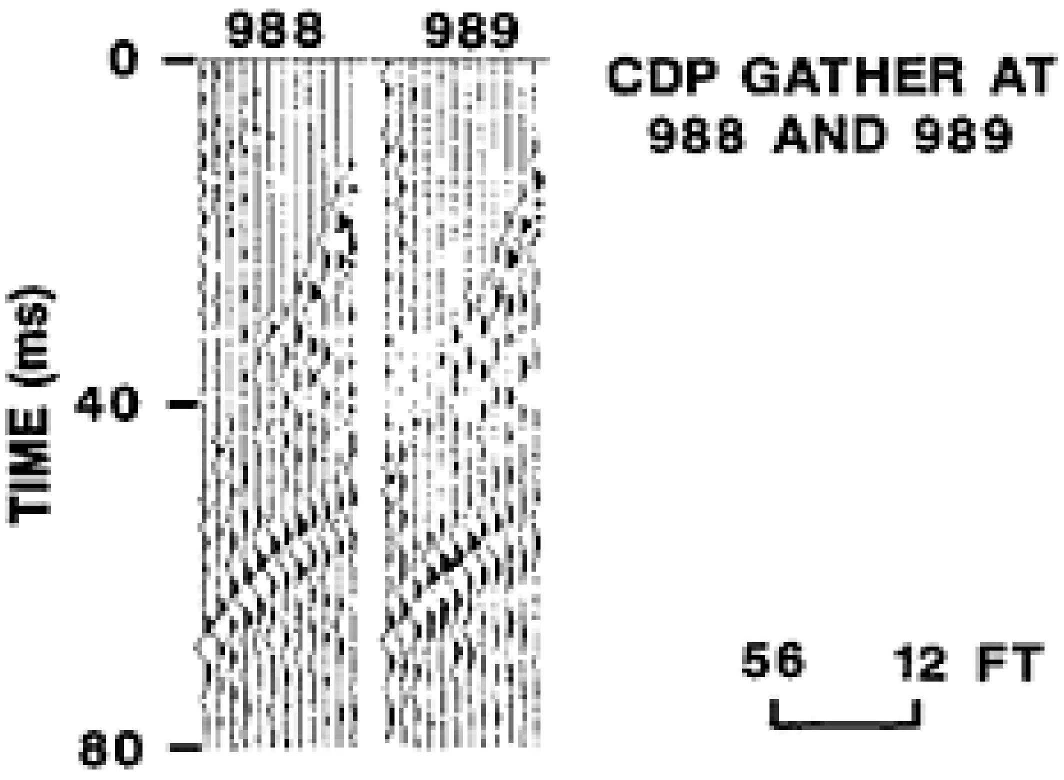


Multiple Reflectors/Layers

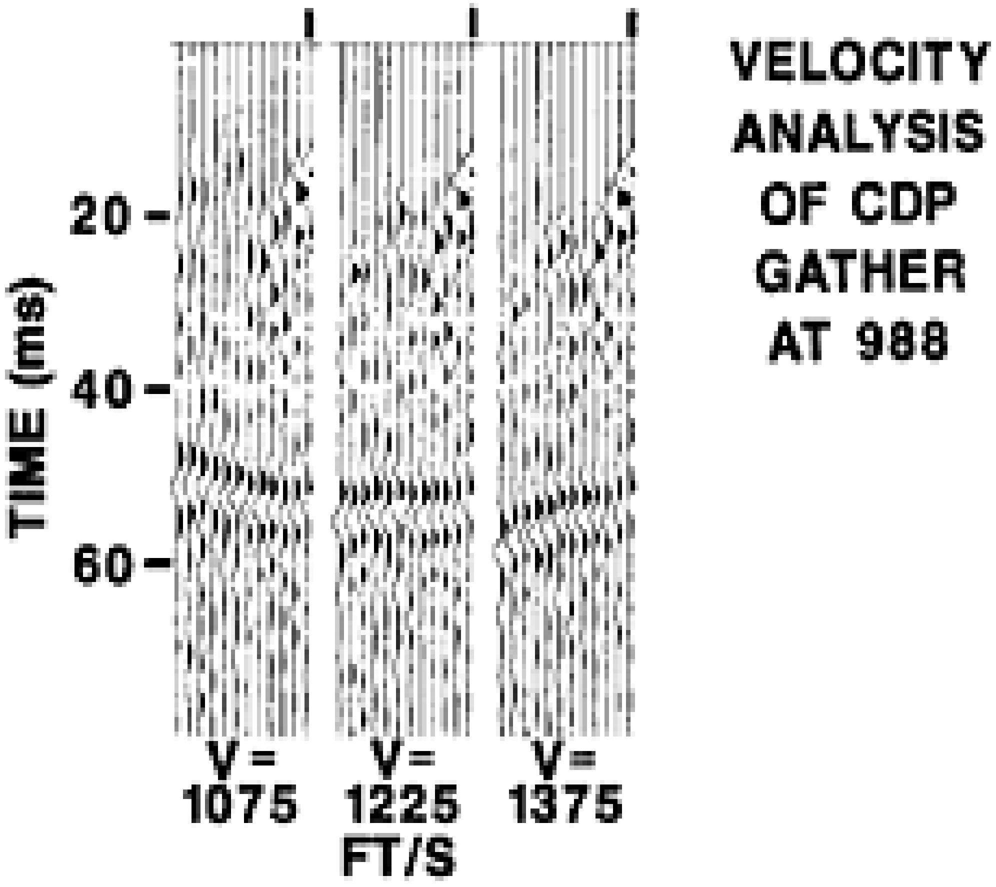
- Reflections are impacted by overlying structures

- NMO correction cannot be used as successfully to interpret deeper structures

Example with several stacking velocities

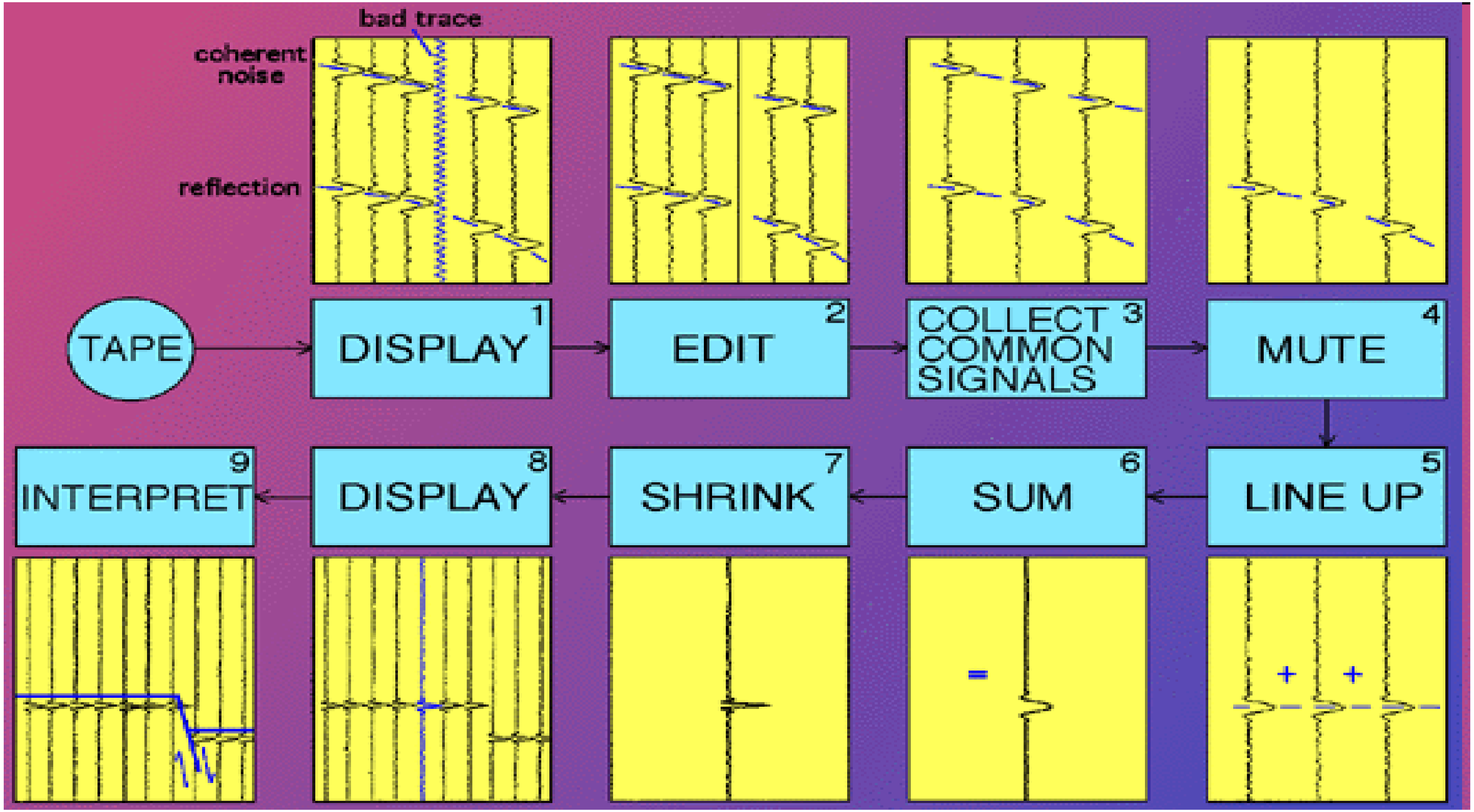


NMO correction for 988

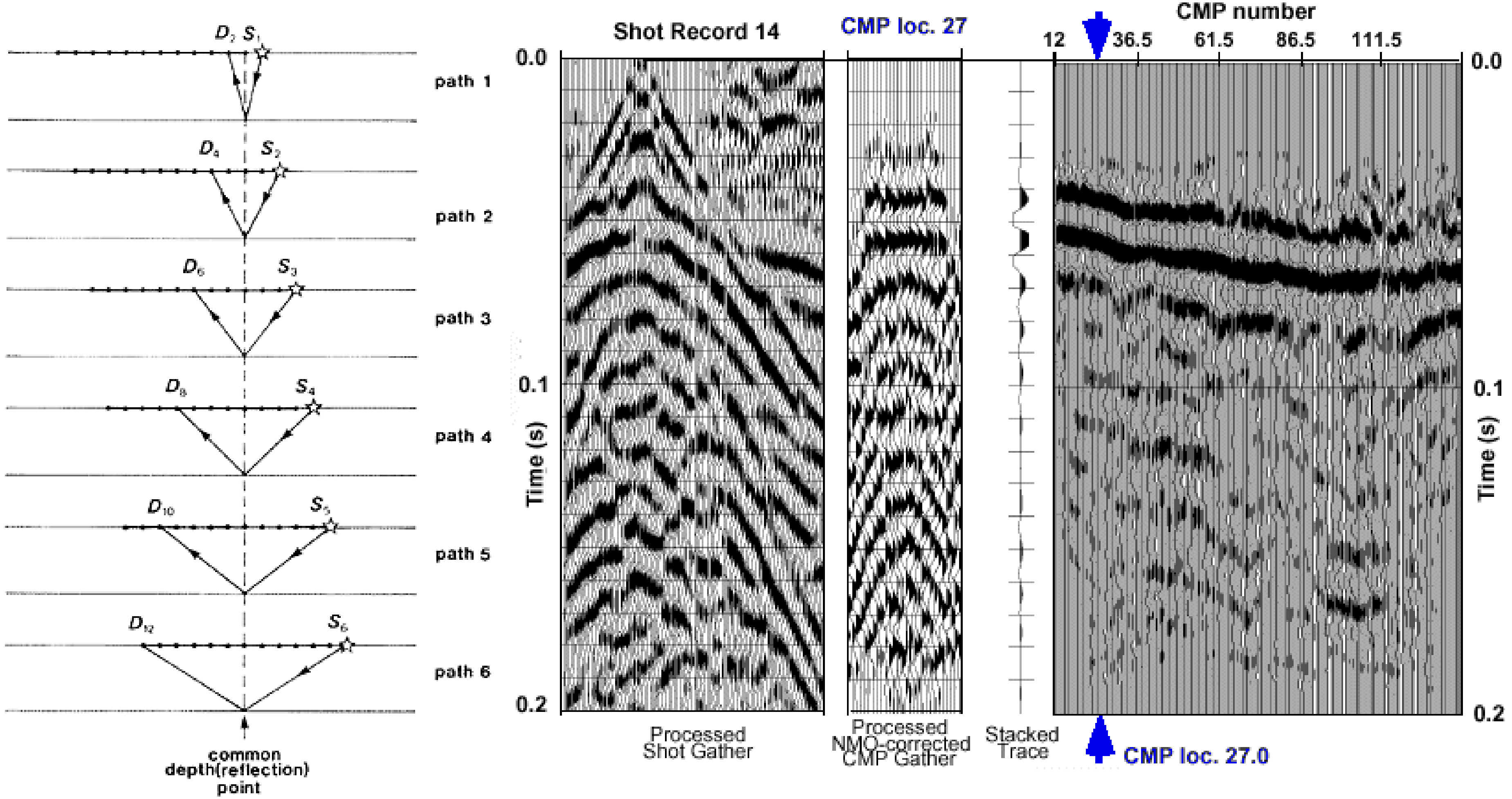


- Stacking these signals will produce a high quality reflection signal

Summary of CMP processing



Recap



CSG = common shot gather
CMP = common midpoint gather

Migration

What is migration?

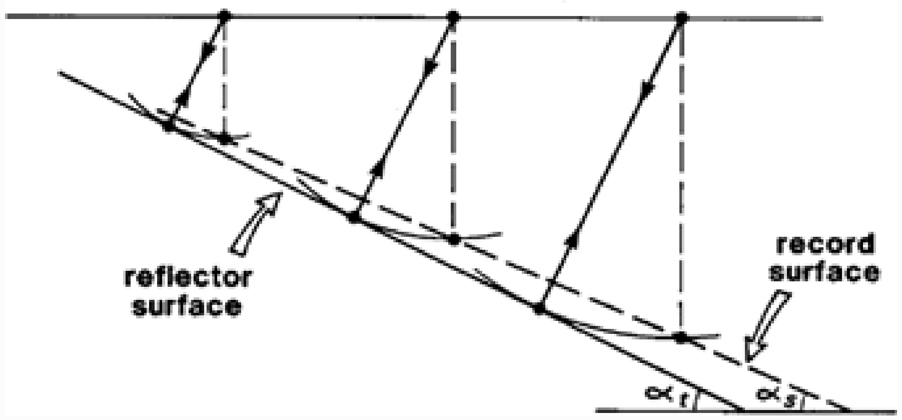
- Reconstruct seismic section so reflection events are shown at correct horizontal location and travel time.

- Migration is used to:
  - Make dipping structure have correct dip angle
  - Remove “bow-tie” features from synclines
  - Collapse hyperbolic feature from diffraction to a point
  - Shorten anticlines

Migration: Dipping reflector

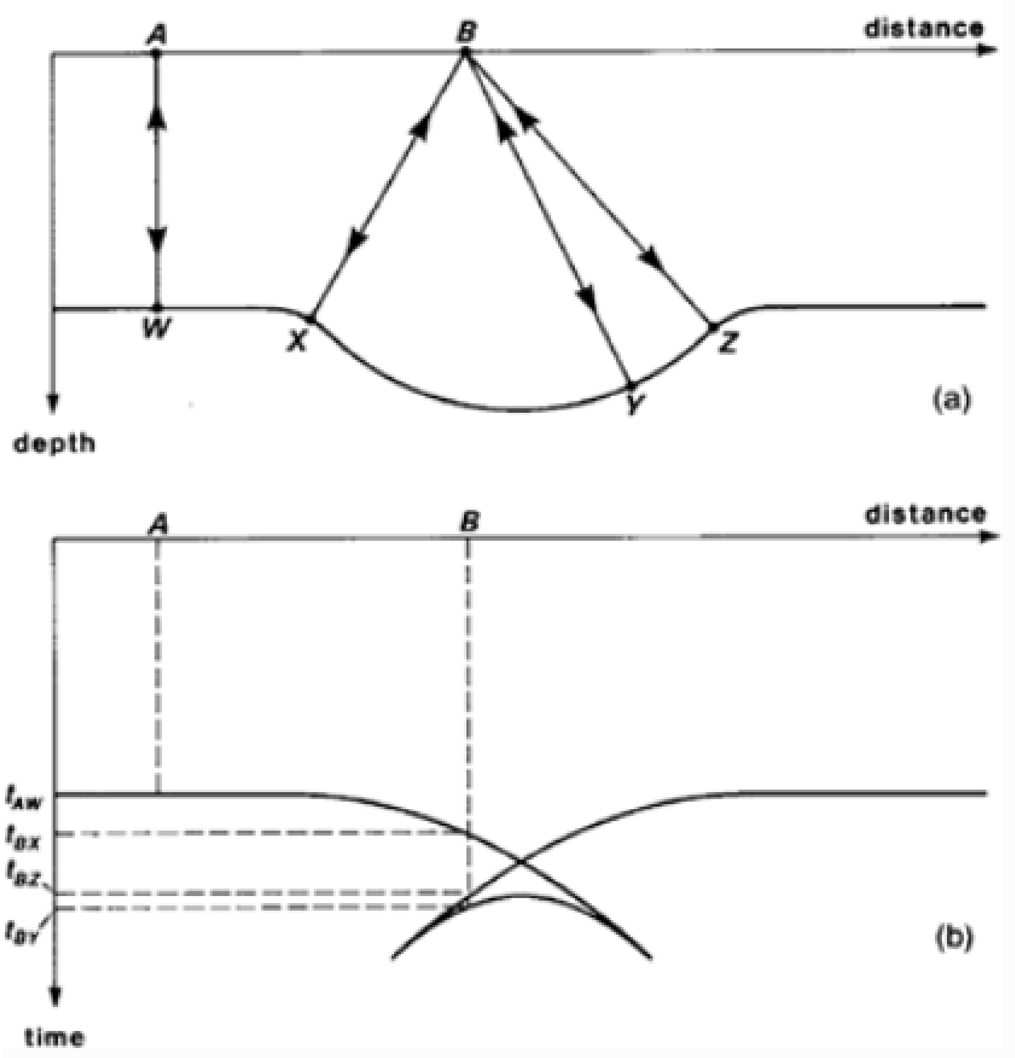
- Reflection does not follow vertical path
- Assuming leads to:
  → underestimating dip angle
  → underestimating depth to reflector
- Migration uses angle on seismogram to infer true dip angle

$$sin(\alpha_t) = tan(\alpha_s)$$



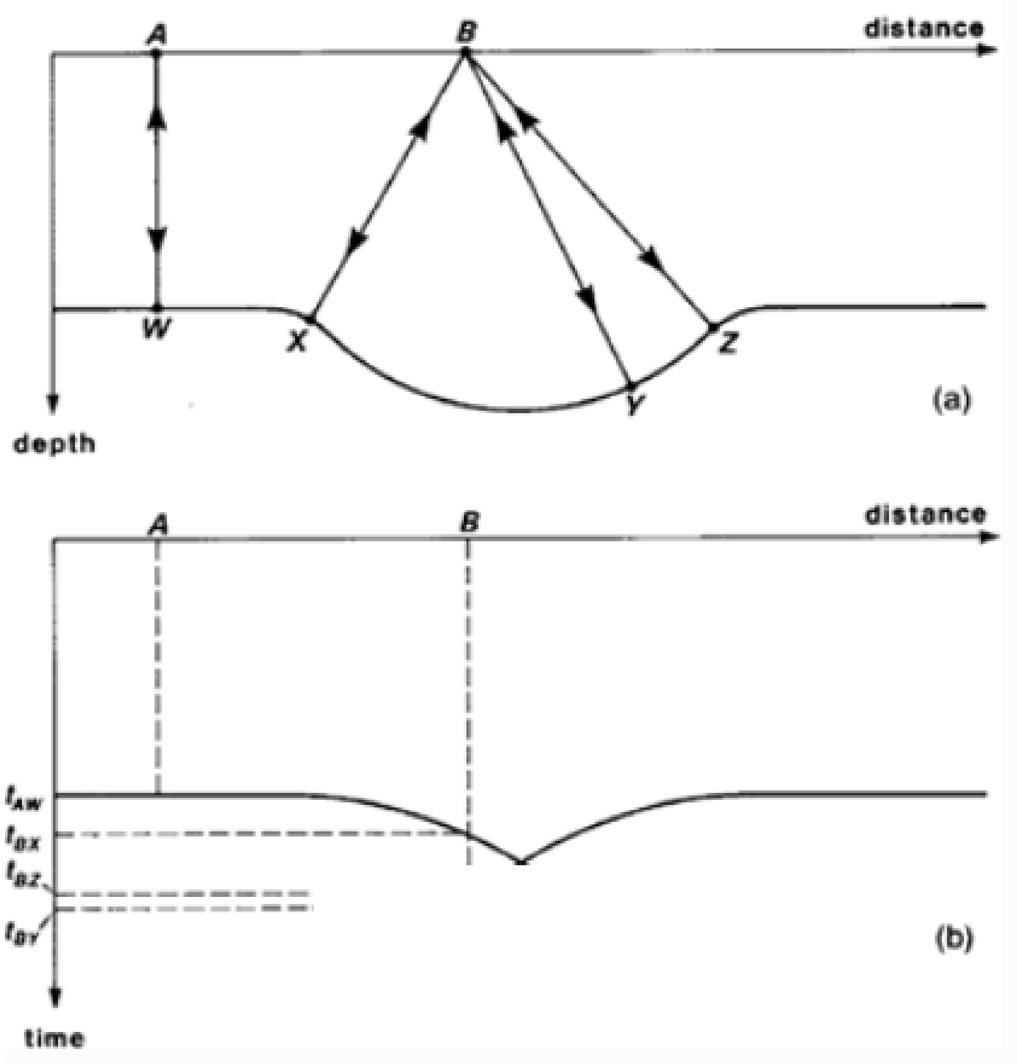
Migration: Syncline Reflector

- Assume above layer velocity homogeneous
- Multiple reflections from same interface
- Leads to “bow-tie” features



Migration: Syncline Reflector

- Assume above layer velocity homogeneous
- Multiple reflections from same interface
- Leads to “bow-tie” features
- Migration removes bowtie so syncline more easy to interpret



Migration: Syncline Reflector

- Assume above layer velocity homogeneous
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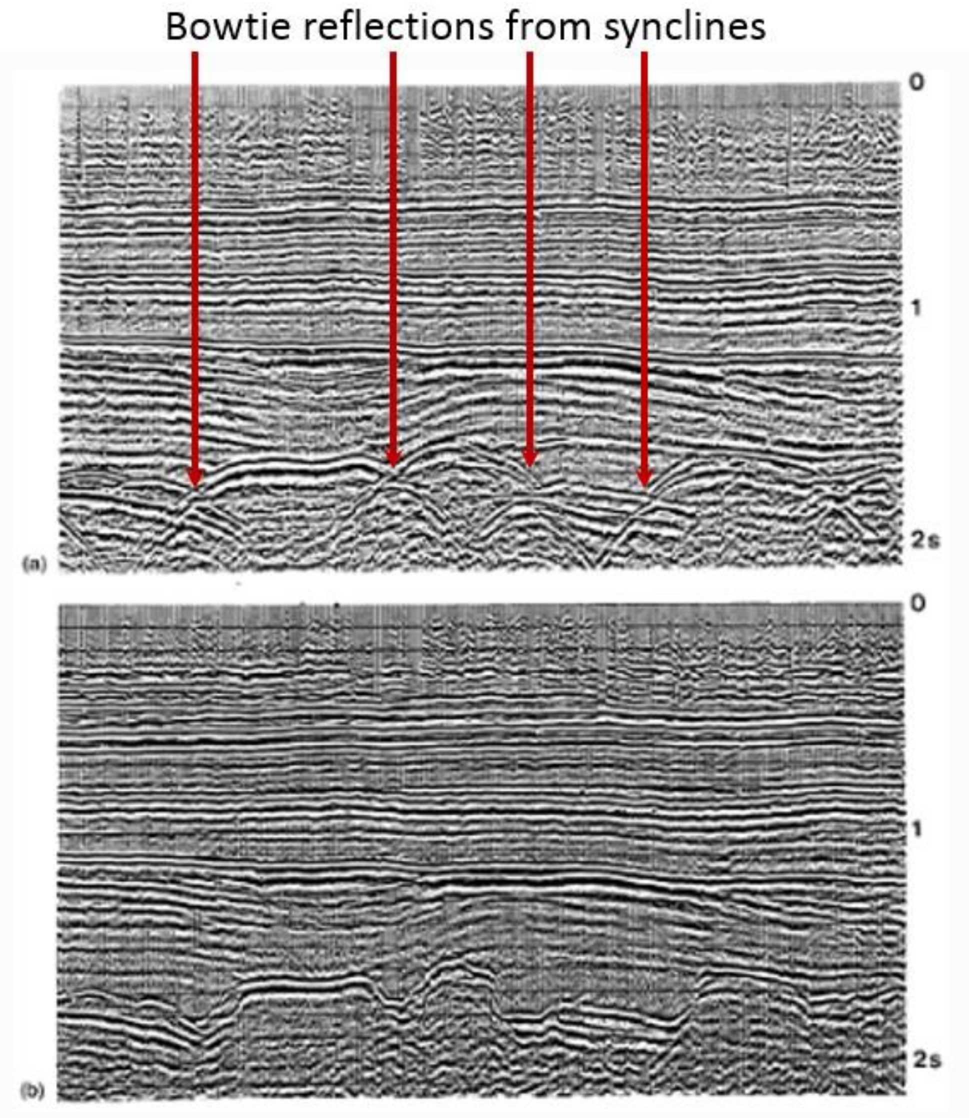
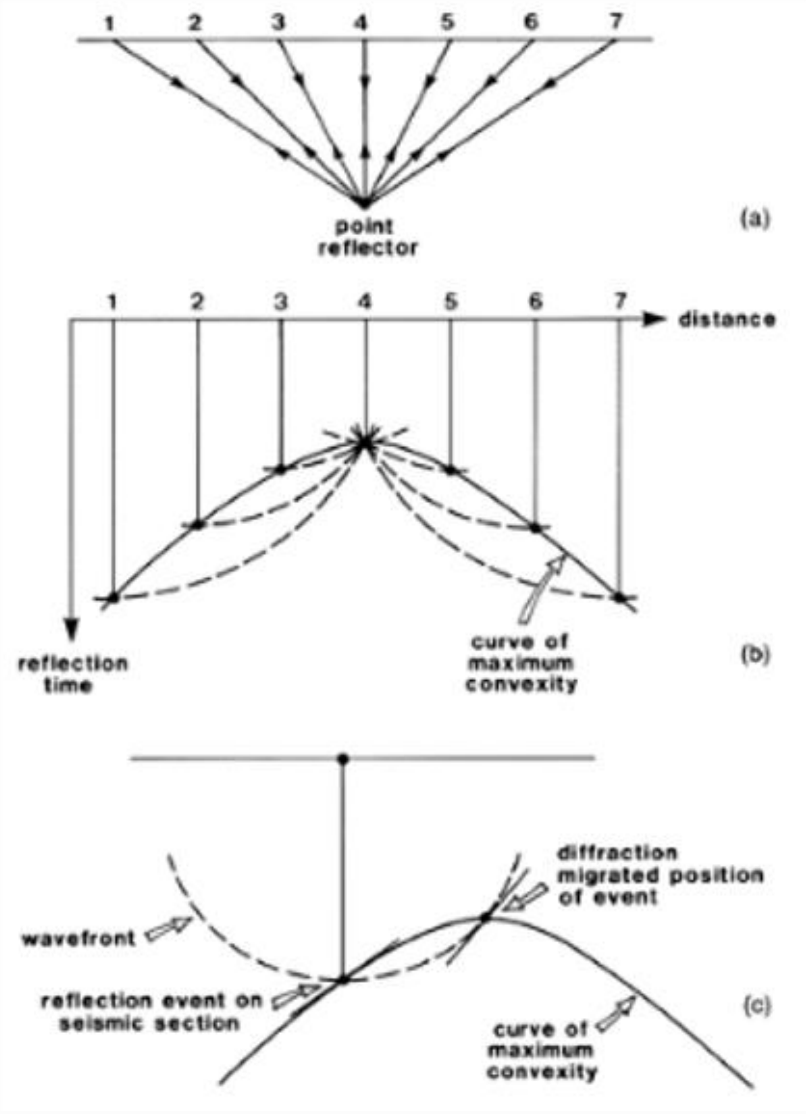


Migration: Point Reflector



- Many reflected signals from common mid point gathers from same point
- Results in hyperbolic feature
- Use hyperbola to determine location of point reflector
- Collapse hyperbolic feature to a point

Processed CMP section (Depth converted)

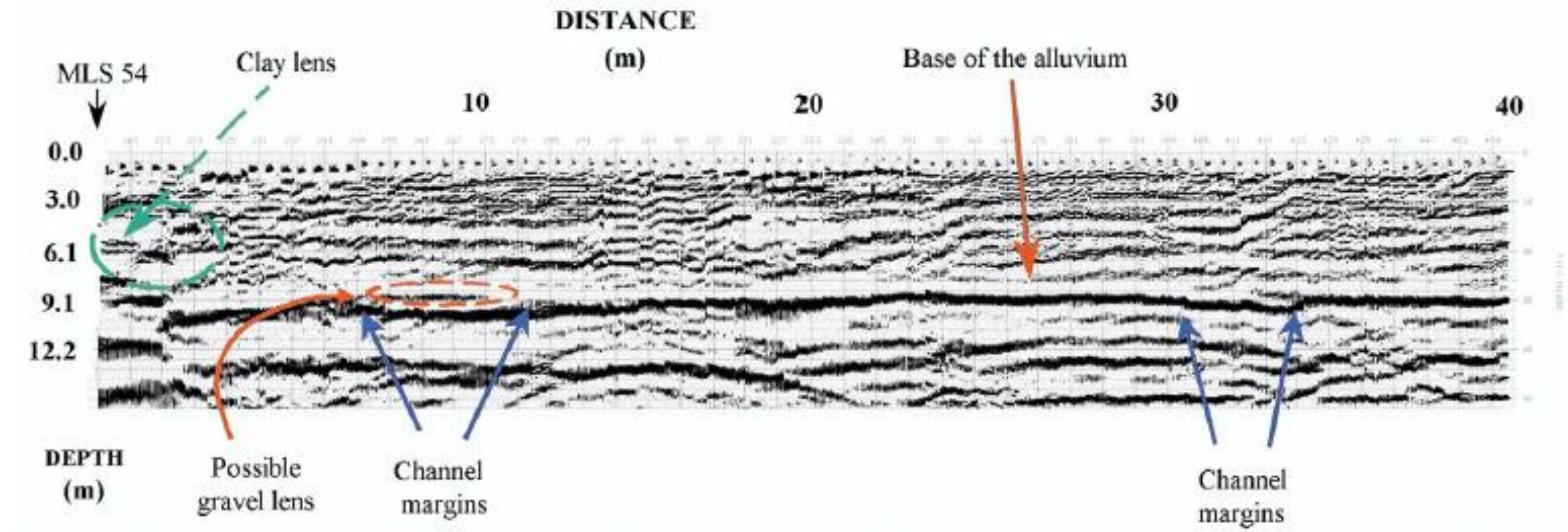
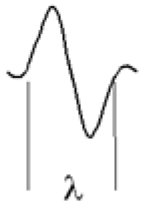


Figure 10. Depth-converted *SH*-wave, stacked section. The top of the shale at a depth of approximately 9 m is very clear cut. Depressions in the top of the shale are interpreted to be channels, possibly filled with a gravel lens (CMP 255-275). Reflections from a depth of 6 m correlate with the presence of clay lenses in borehole MLS 54.

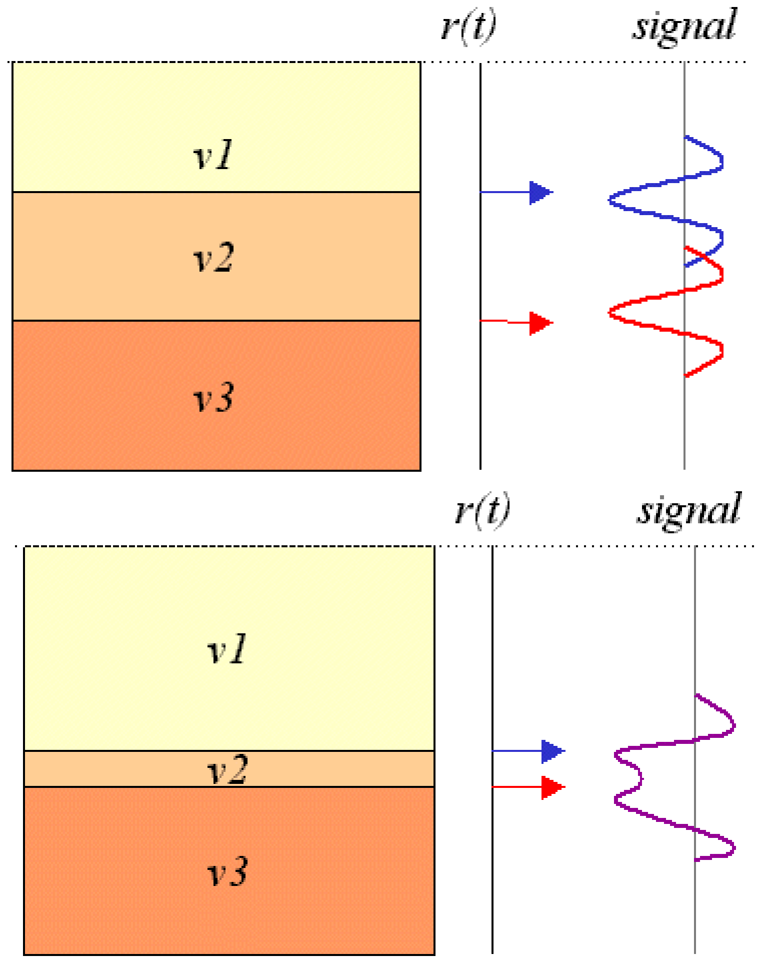
- Conversion of time to depth:
  - Requires an average velocity
  - Obtained from stacking velocity used to perform NMO correction

Vertical resolution

$$\lambda = vT = \frac{v}{f}$$



- Rayleigh resolution criterion: peak separation of at least peak-trough distance ($\lambda/2$).
- Account for 2-way travel time through layer
- Vertical resolution = $\lambda/4$



seismic wavelength, metres

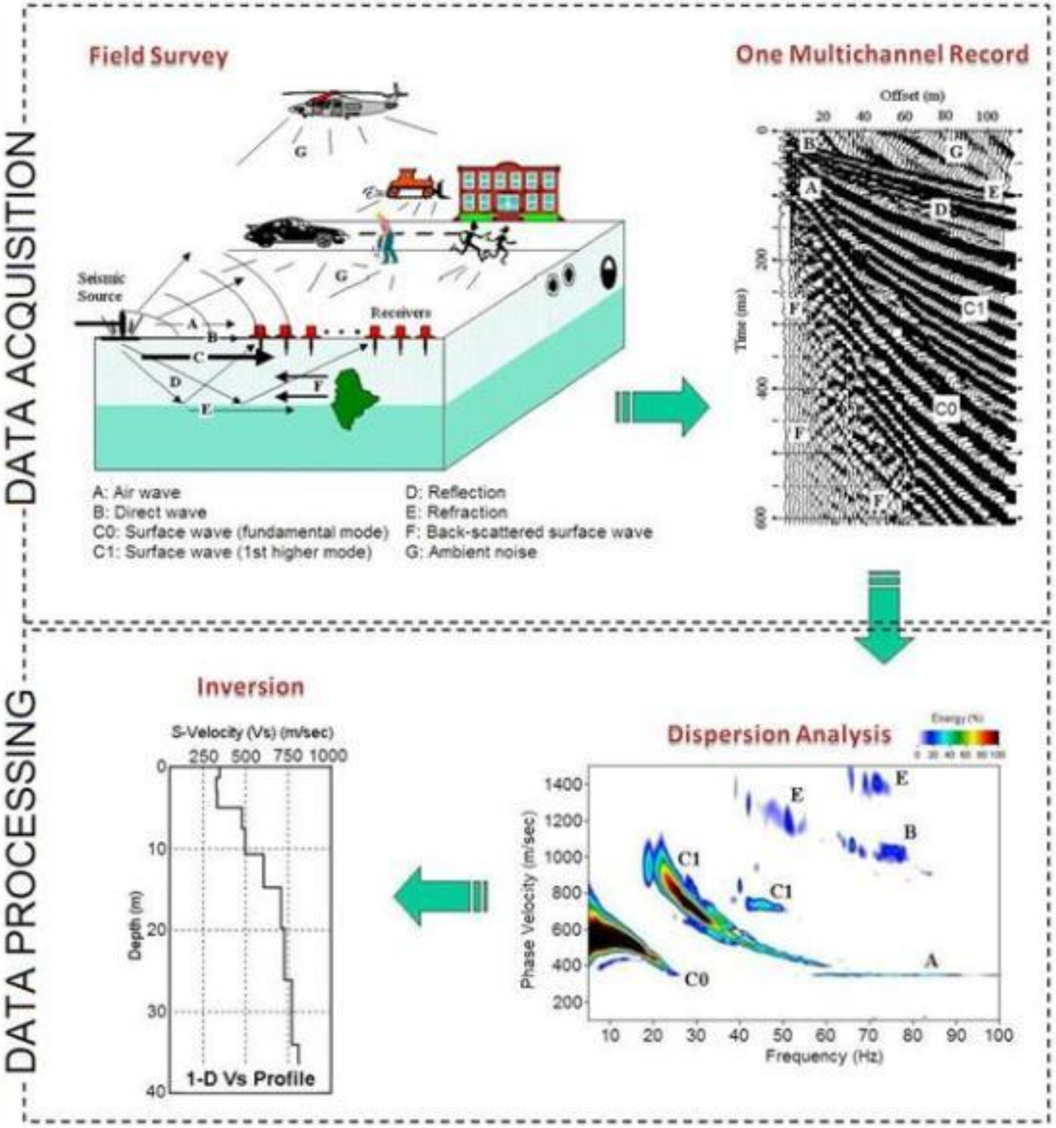
f, Hz	T, sec	V, m/sec					
		330	500	1000	1500	2000	4000
10	0.1	33	50	100	150	200	400
100	0.01	3.3	5	10	15	20	40
1000	0.001	0.33	0.5	1	1.5	2	4

MASW

Reading on the GPG:

https://gpg.geosci.xyz/content/seismic/seismic_reflection_processing.html

Multichannel Analysis of Surface Waves



- www.masw.com
- Uses surface waves to study the propagation of shear waves in the subsurface
- Compared to reflection and refraction techniques, it's quite new and mostly used for geotechnical work.

Data Acquisition

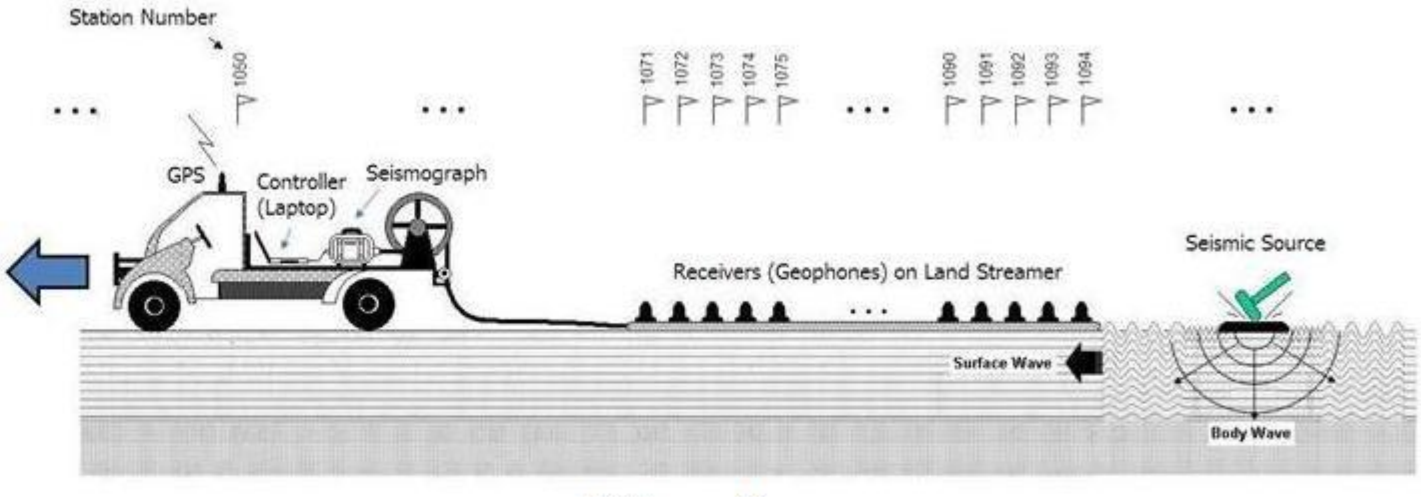
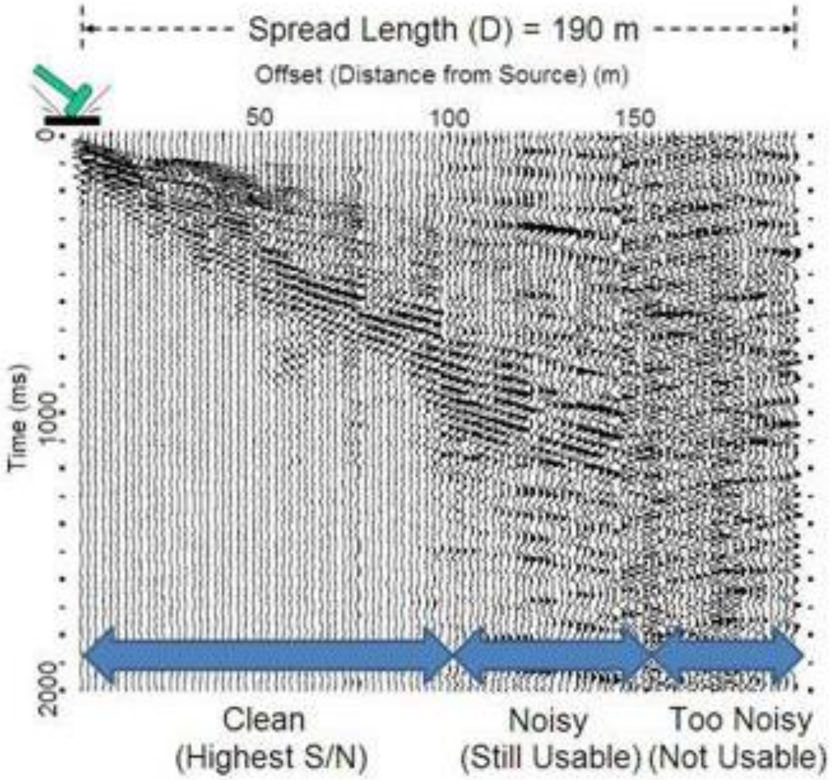
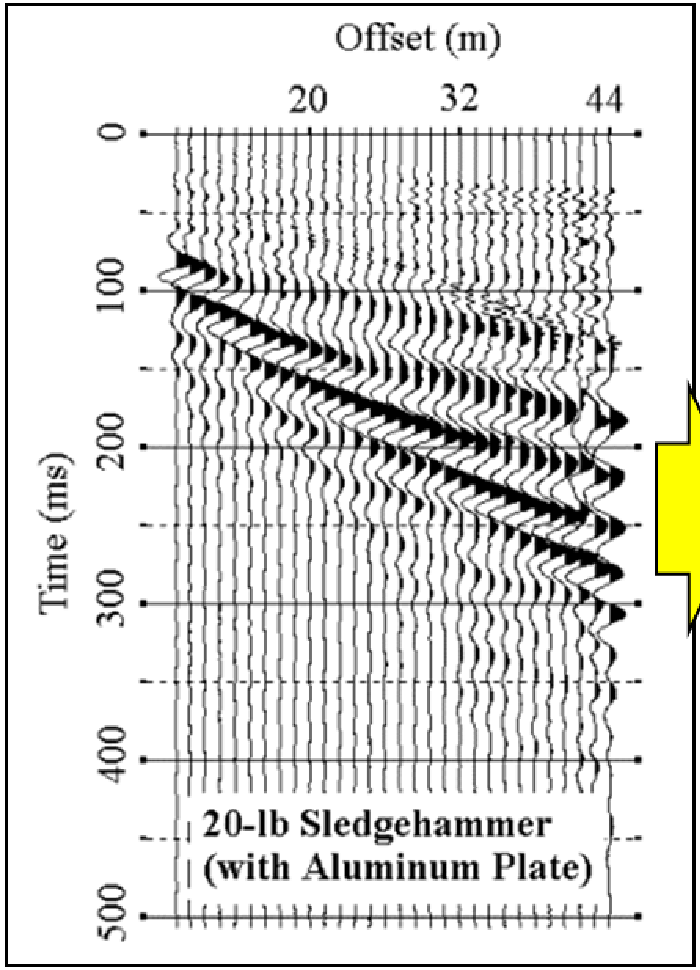


Fig. 4. A field record illustrating usable offset range.

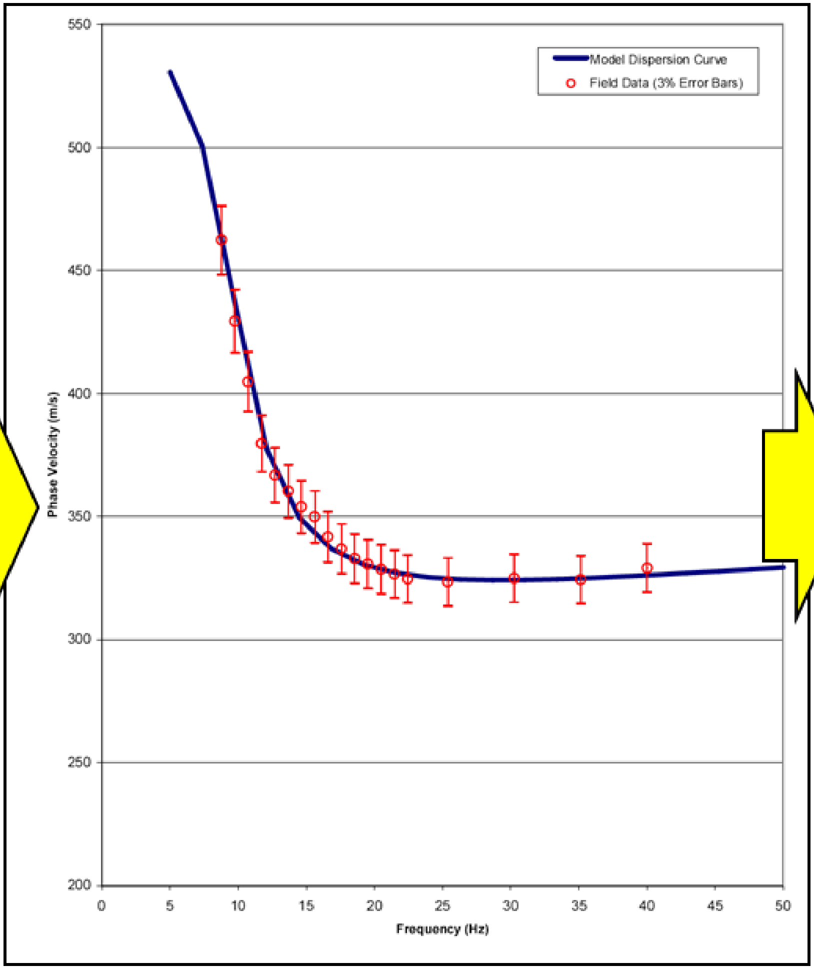


Processing

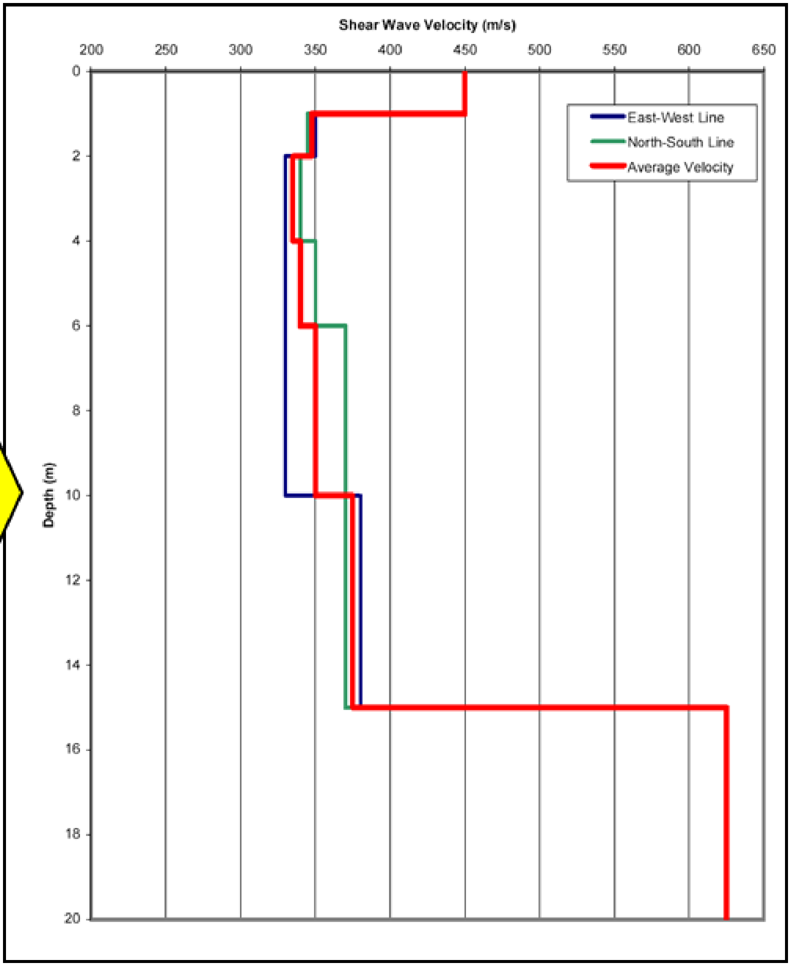
Single common shot gather



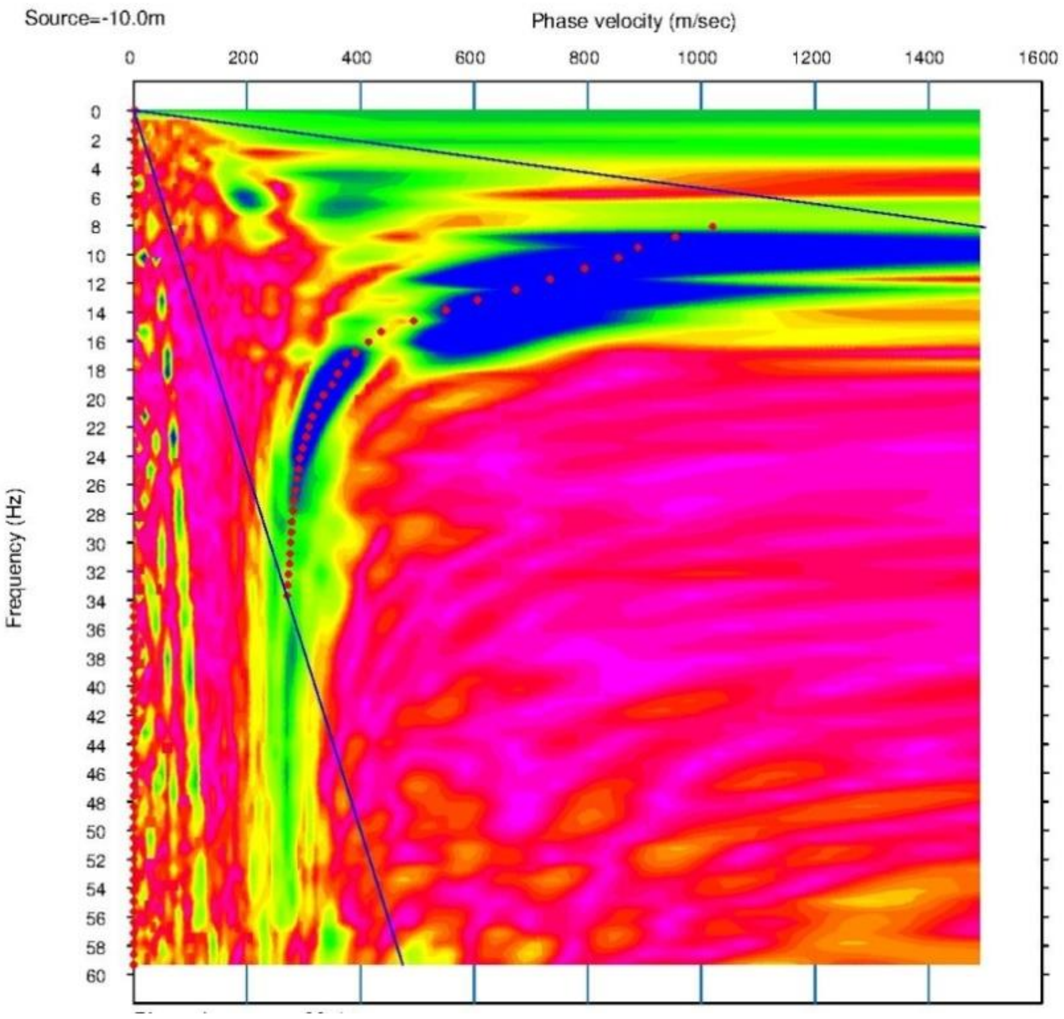
Frequency vs. phase velocity



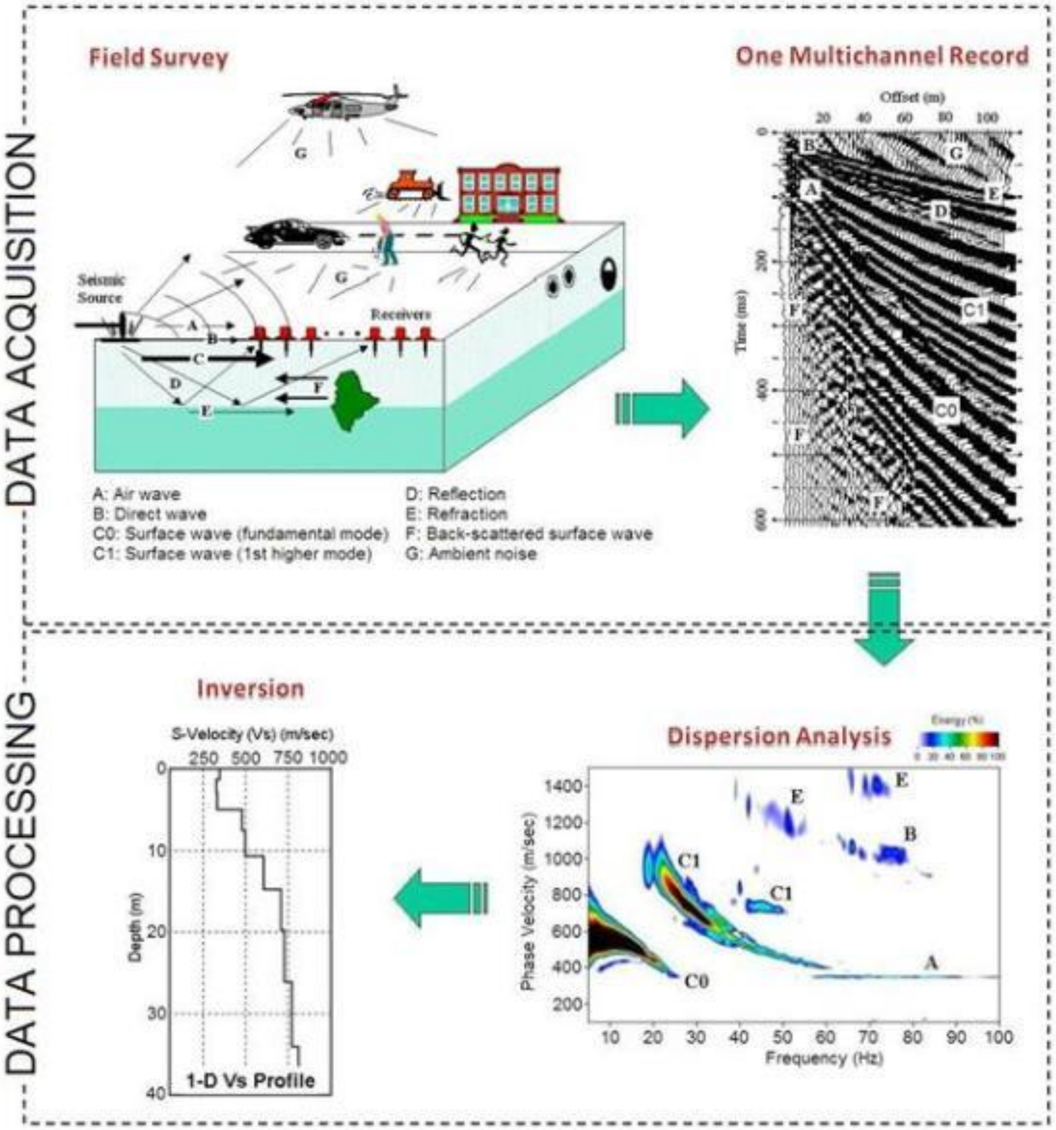
1D inversion



Processing: Finding Curve



All together

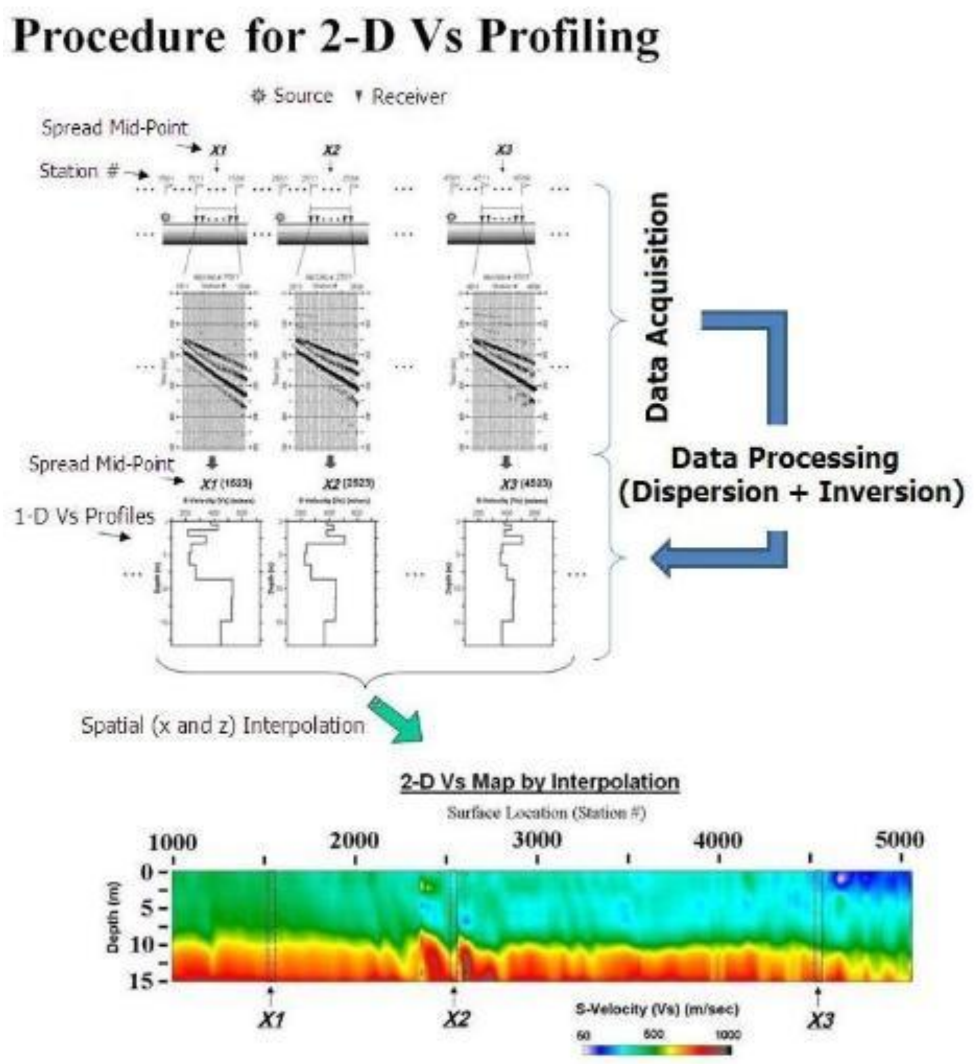


For a common shot gather:

1. Record
2. Dispersion analysis
3. Extract freq. vs. phase velocity
4. 1D inversion to get vs profile

MASW in 2D

- Do 1D procedure for many shots
- Create 2D map of v-shear through interpolation

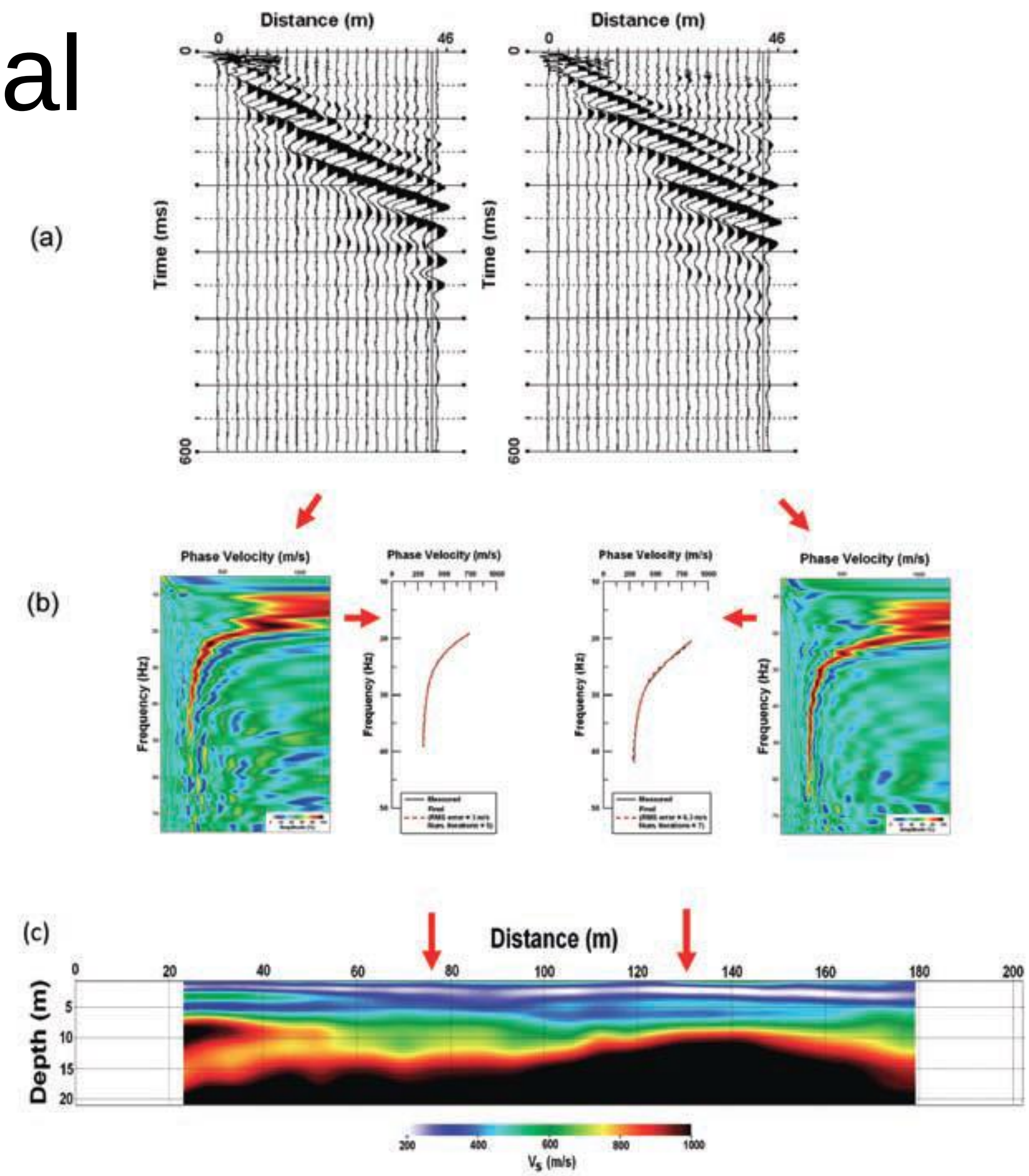


Case history: Hodgson et al

- Setup
  - City of Dublin is underlain by Dublin Boulder Clay (DBC).
  - Hard lodgement till with high stiffness and low permeability.
  - Large cobbles and boulders above DBC.
- Properties
  - Elastic parameters, stiffness is related to shear velocity
- Survey
  - Seismic, MASW
- Data Acquisition
  - Roll-along survey
  - Land streamer 24 plated-coupled 4.5Hz geophones
  - Tractor-mounted weight drop with shots every 6m

Case history: Hodgson et al

- Analysis
  - Dispersion curve analysis of surface waves
  - Invert to obtain Vs
  - Generate a 2D profile.
- Interpretation
  - Low Vs (200-700 m/s) associated with glacial till (0-10m thickness)
  - High velocity material (Vs>900 m/s) at depth
- Synthesis
  - Borehole verified the high velocity material as limestone bedrock
  - The depth is variable.



Unit Activities

- **Labs: (Seismic I)**
  - Monday, September 30th
  - Tuesday, October 1st

- **Labs: (Seismic II)**
  - Monday, October 7th
  - Tuesday, October 8th

- **TBL:**
  - Monday, October 7th

- **Quiz:**
  - Monday, October 7th