Reflection Seismic Method

- Reflection images
- Zero-Offset reflection section
- Seismic Impedance
- Depth and horizontal resolution
- 2-D field acquisition geometries
- Noise (wave) tests
- Data and Image sort orders
- Common mid-point (CMP) binning and “fold”
- Stacking charts
- Normal Moveout (NMO) and correction for it
- Stacking
- Migration
- Tying reflections to well logs

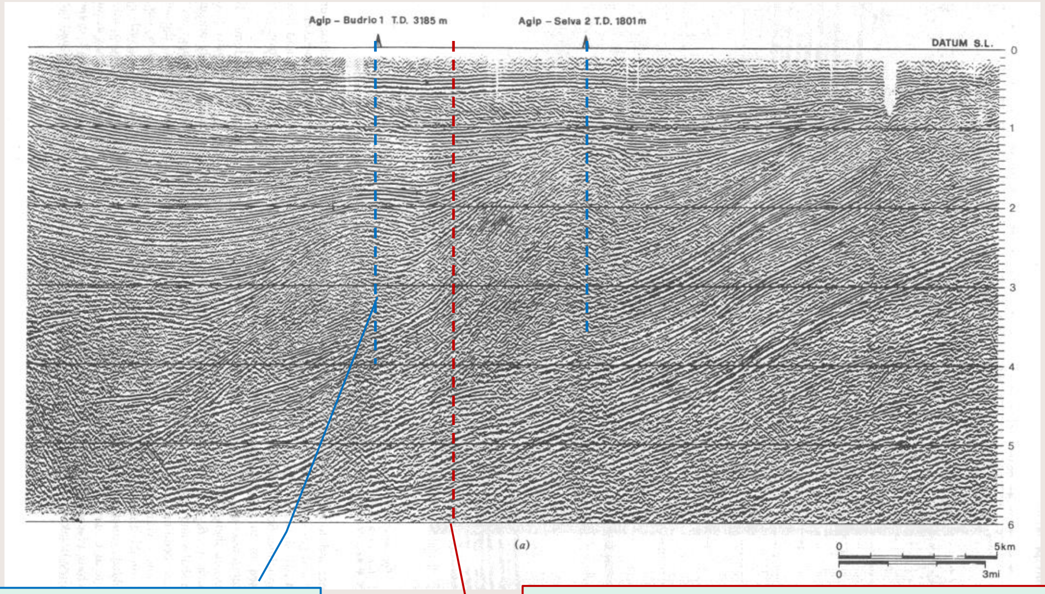
- <u>Reading:</u>
  - Reynolds, Chapter 6
  - Shearer, 7.1-7.5
  - Telford *et al*., Sections 4.3, 4.7, 4.8, 4.10

Reflection seismic imaging

- The goal of reflection seismic work consists in obtaining (distance, depth) or (distance, time) (or similar 3D) images like shown below
- The procedure for obtaining such images involves numerous transformations and filtering operations
- <u>Key concepts involved in these transformations</u> are discussed in the following slides

Distance or 2D coordinates on the surface

Two-way reflection time or depth



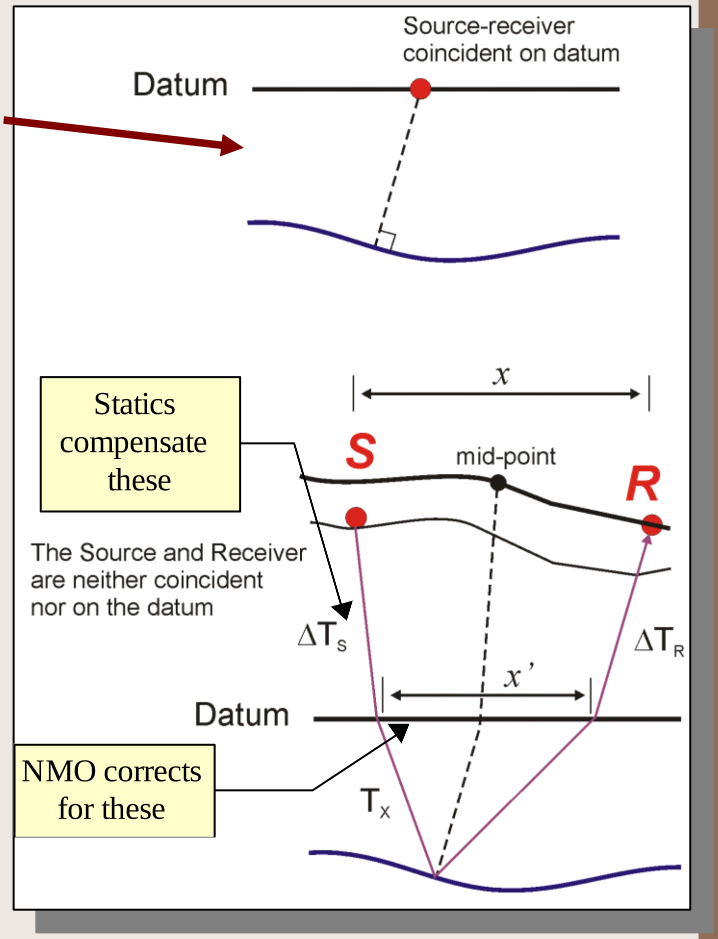
Well logs provide **ground truth** for interpreting seismic reflections

Each vertical line in this plot is a **graph of variations of reflectivity**, usually sampled at ~2 ms of reflection time

Zero-Offset Section

(*The goal of reflection seismic imaging*)

- **The "ideal" case of reflection imaging** consists in *sources* and receivers *collocated* on a flat horizontal surface (called "*datum*")



- However, in reality, we have to record at *source-receiver offsets*, and over complex *surface topography*

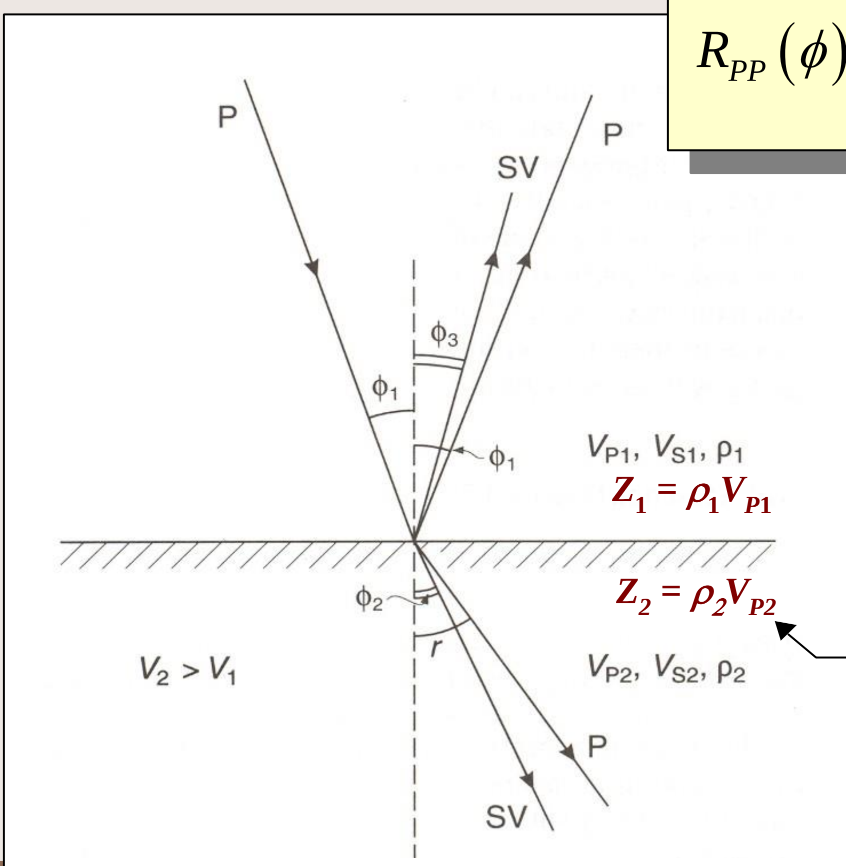
- **Two types of data transformations** are applied to compensate for these factors:
  - Statics "place" sources and receivers onto the datum;
  - Normal Moveout Corrections "transform" the records into as if they were recorded at collocated sources and receivers.

Reflection coefficient

Physical property imaged in reflection sections

- At *near-normal* incidence:
  - *P*-to-*S*-wave conversions are negligible
  - *P*-wave reflection and transmission *amplitudes* are determined by the contrast in *acoustic impedance* $Z=\rho V$ (see next page)
- *P*- and *S*-wave *reflection* amplitudes usually *vary with incidence angles*

$$R_{PP}(\phi) = \frac{A_{P_{\text{reflected}}}(\phi)}{A_{P_{\text{incident}}}(\phi)}$$



Acoustic Impedance

- Reflection-coefficient relations follow from physical reasons:
  1) continuity of displacement, and
  2) conservation of energy upon wave reflection or transmission
- Acoustic impedance measures the energy flux within the wave:

$$E_{flux} = VE_{density} = V\frac{\rho}{2}(\omega A)^2 = \frac{\omega^2}{2}\boxed{\rho V}A^2$$

Kinetic energy

Z

P-wave Reflection Coefficient

$$R_{PP} = \frac{A_{P_{\text{reflected}}}}{A_{P_{\text{incident}}}} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Note: if $Z_2 < Z_1$, $R<0$.
This means *polarity reversal* upon reflection

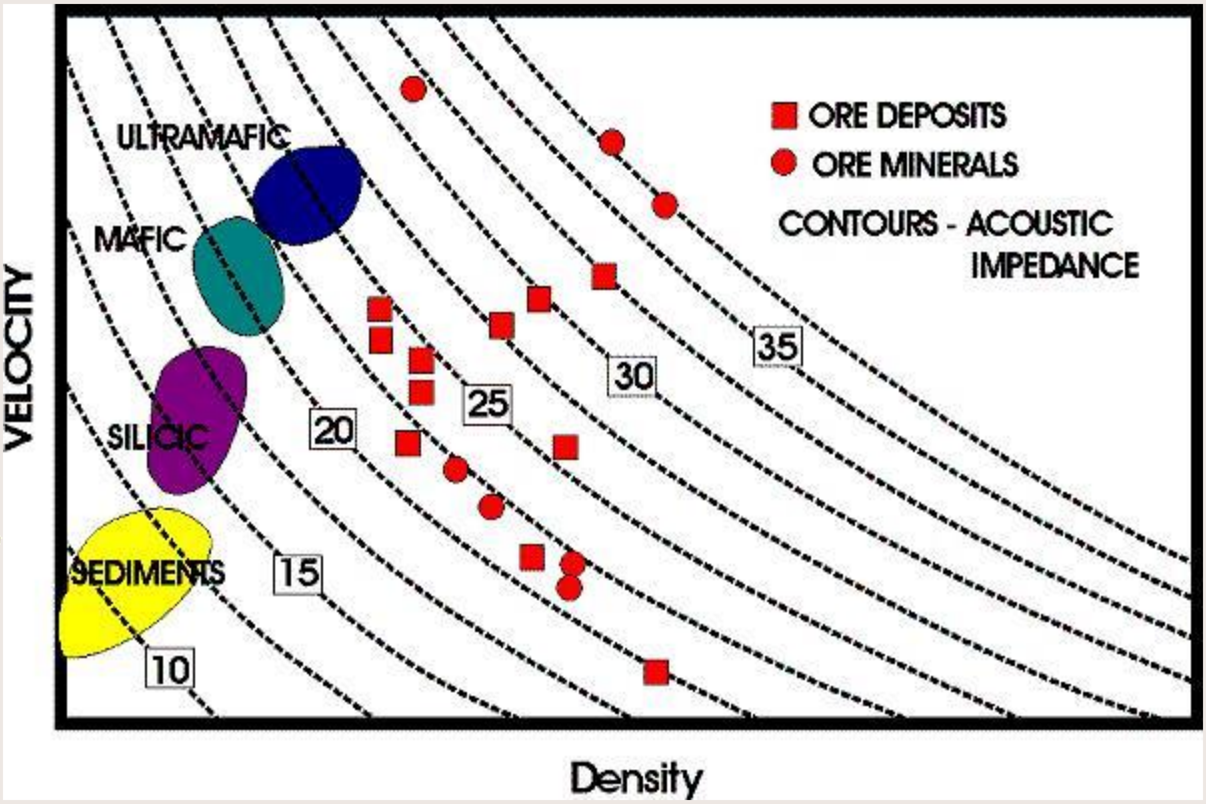
P-wave Transmission Coefficient

$$T_{PP} = 1 - R_{PP} = \frac{2Z_1}{Z_1 + Z_2}$$

This follows from the continuity of displacement across the boundary

Acoustic Impedance

Typical values for rocks



From Salisbury, 1996

Impedance units in boxes are rather peculiar but convenient:

$$[\text{Impedance}] = \left[\frac{\text{g}}{\text{cm}^3}\right]\left[\frac{\text{km}}{\text{s}}\right]$$

$$Z \qquad \rho \qquad V$$

Spatial resolution of reflectors

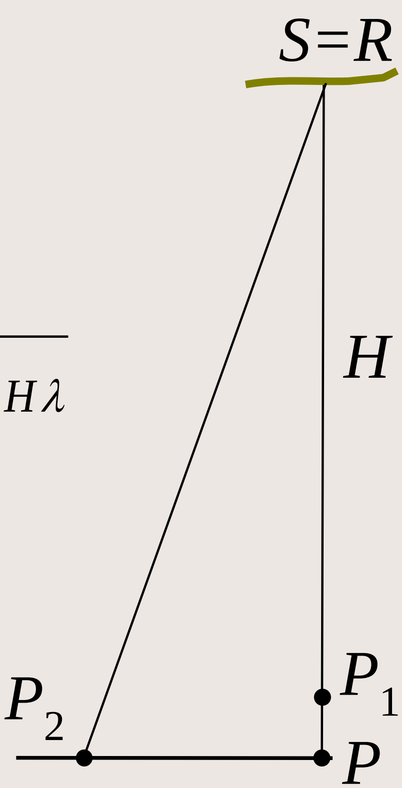
- Two points are considered *unresolvable* when their reflection travel times are separated by less than *half the dominant period* of the signal: $\delta t < T/2$.
- Therefore,
  - vertical resolution:

$$\delta z = PP_1 = \frac{\lambda}{4}$$

  - horizontal resolution:

$$\delta x = PP_2 = \sqrt{\left(H + \frac{\lambda}{4}\right)^2 - H^2} \approx \sqrt{\frac{1}{2} H \lambda}$$

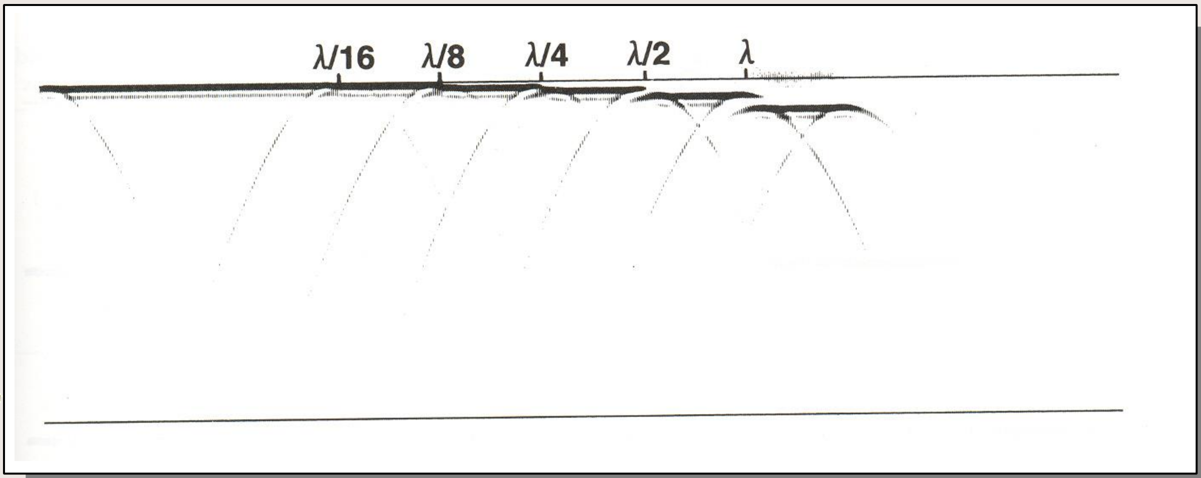
This is called *Fresnel Zone* radius



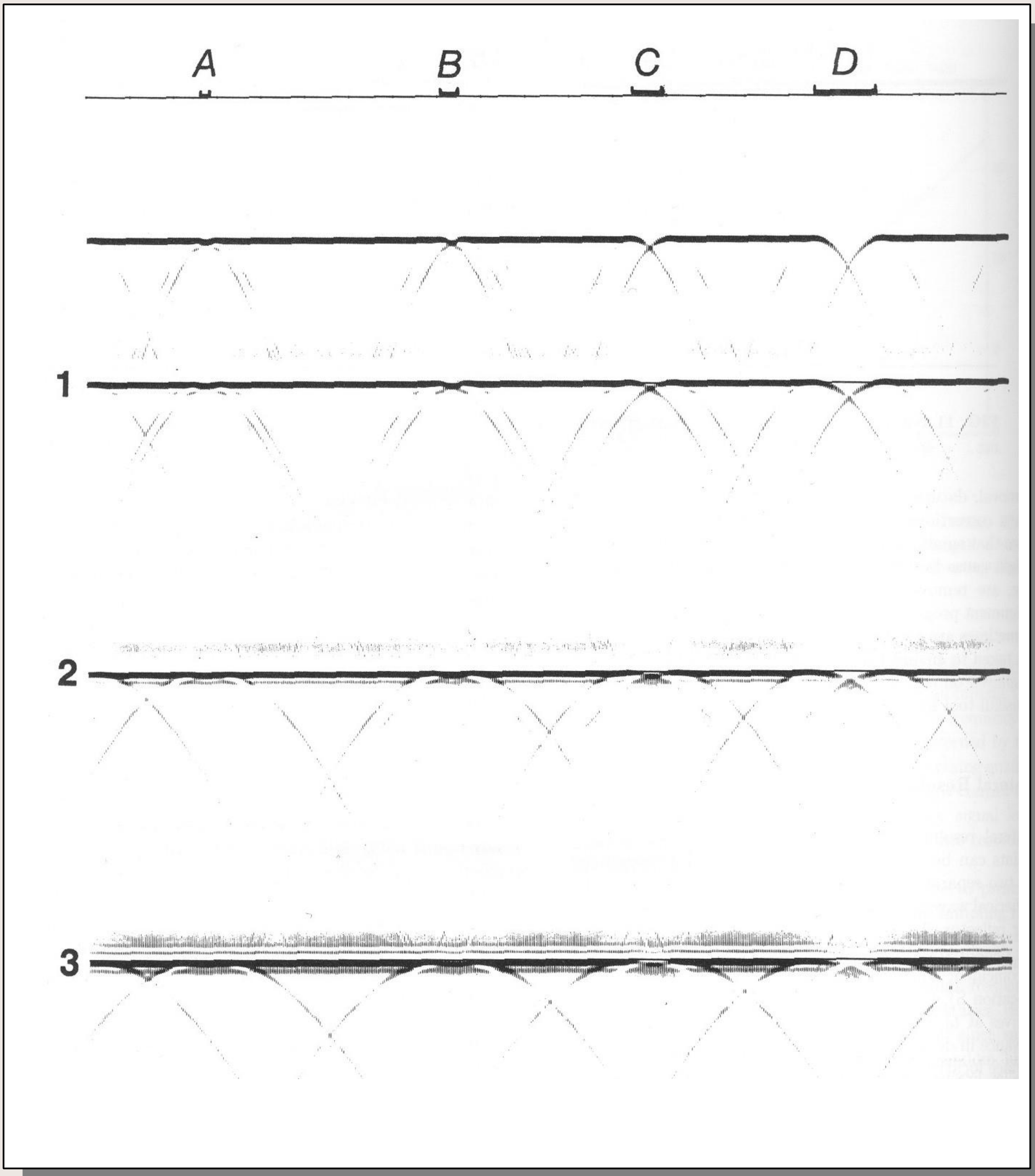
- Note that *horizontal resolution decreases with depth.*

Vertical resolution example

- Faults with different amounts of vertical throws, compared to the dominant wavelength:

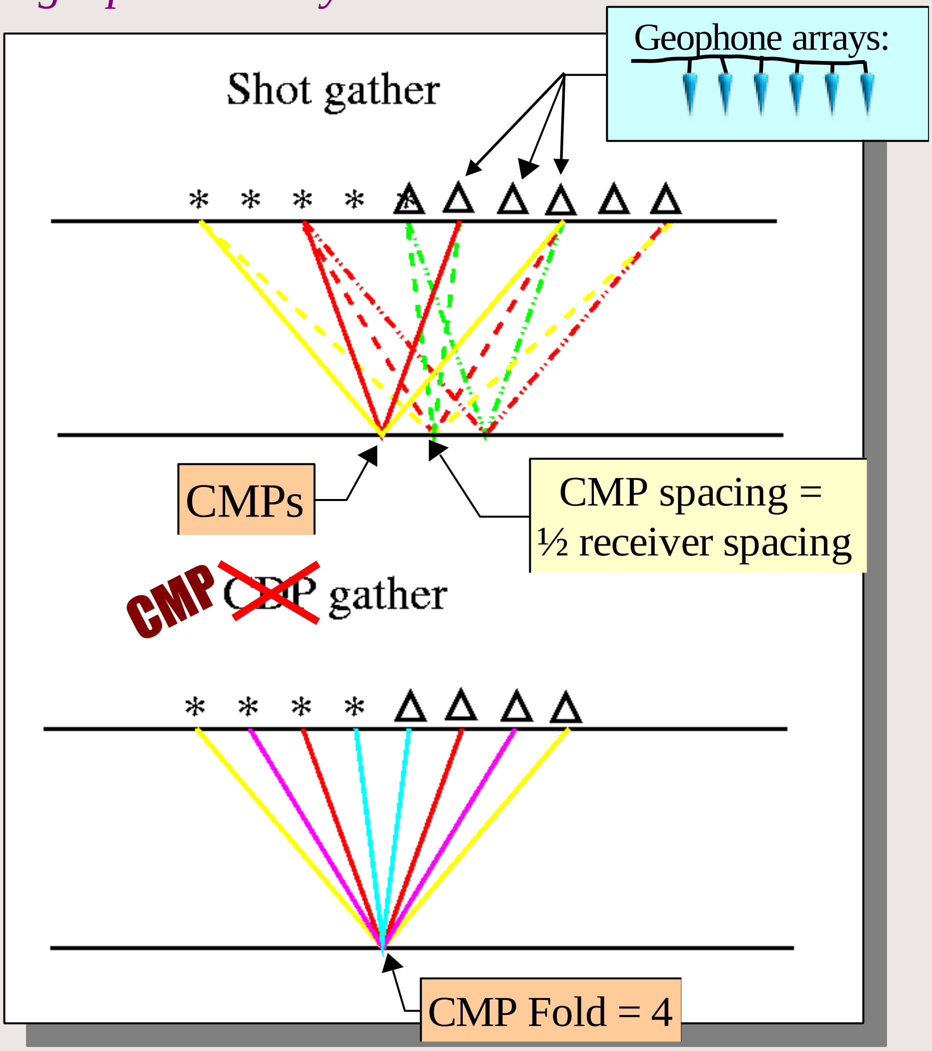


Horizontal resolution example



Shot (field) and Common-Midpoint (image) data sort orders

- Common-Midpoint survey:
  - Helps in reduction of random noise and multiples via *redundant coverage* of the subsurface;
  - Ground roll is attenuated through the use of *geophone arrays*.

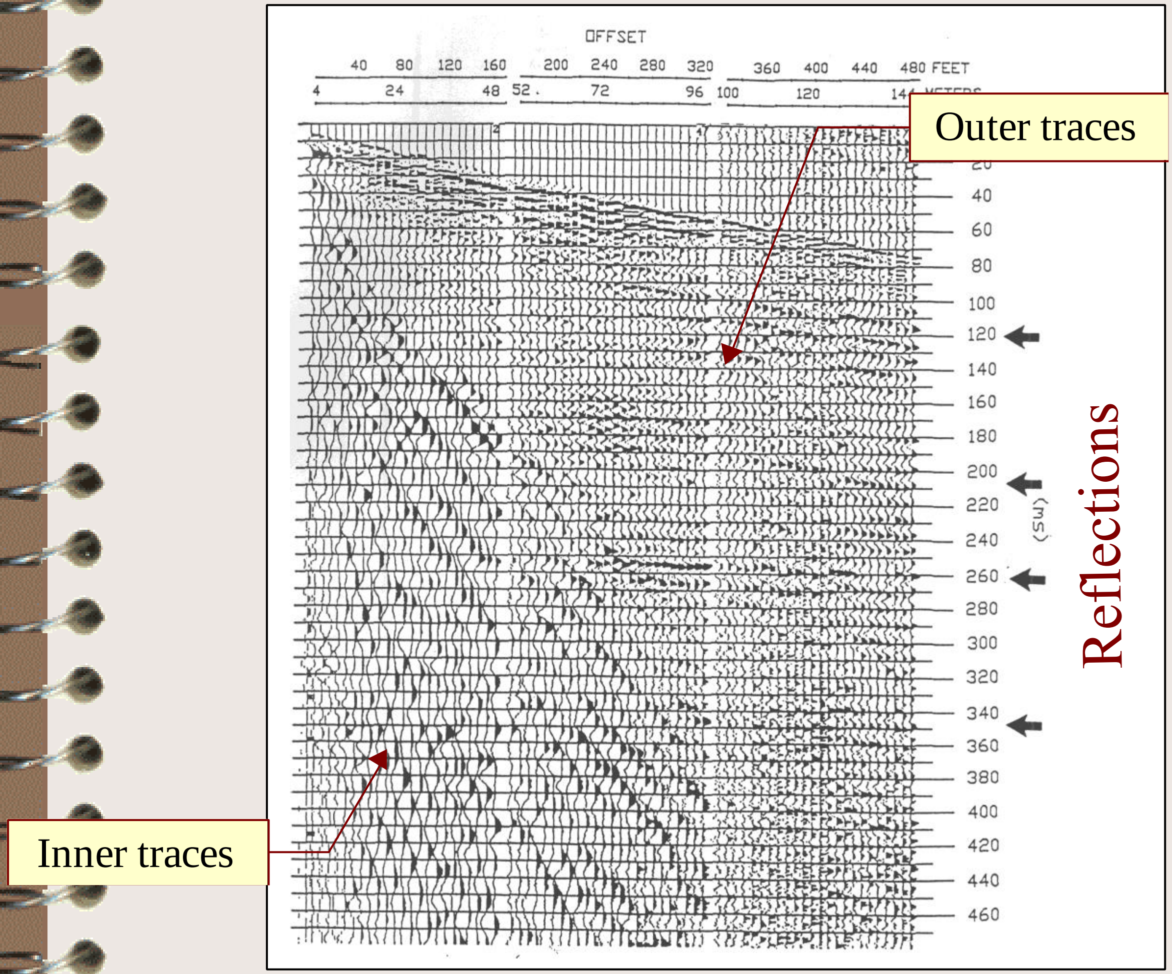


Field geometry
survey and observer's logs, “chaining notes”

- Survey file
  - Produced by surveyors (usually comes out of GPS unit);
- Observer's Notes
  - A record of shooting and recording sequence
    - Lists shot positions, record (“field file”) numbers (FFIDs), spread positions (“first live station”);
    - Records weather, interruptions, usual and unusual noise, state of recording system.

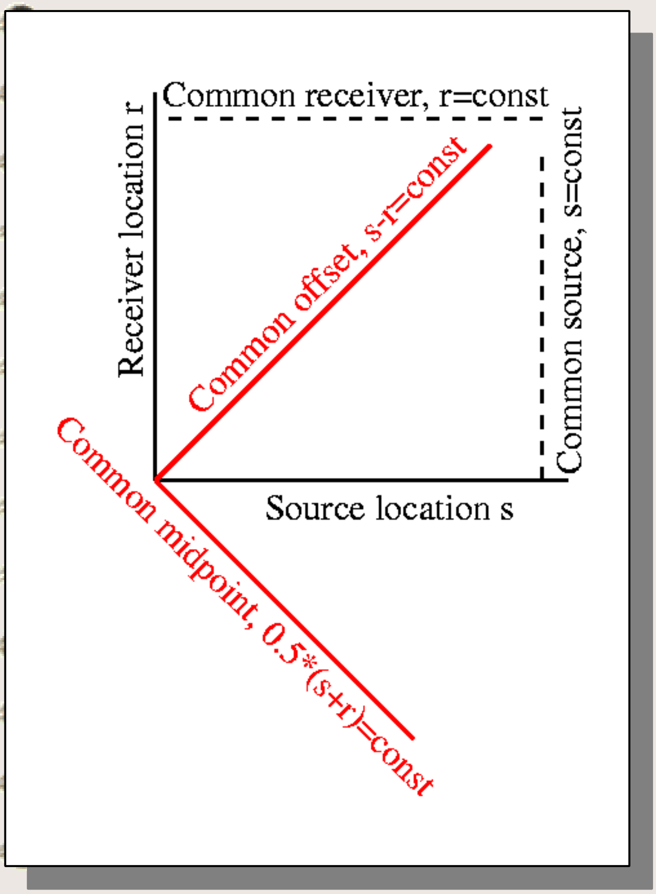
Noise (Wave) Test

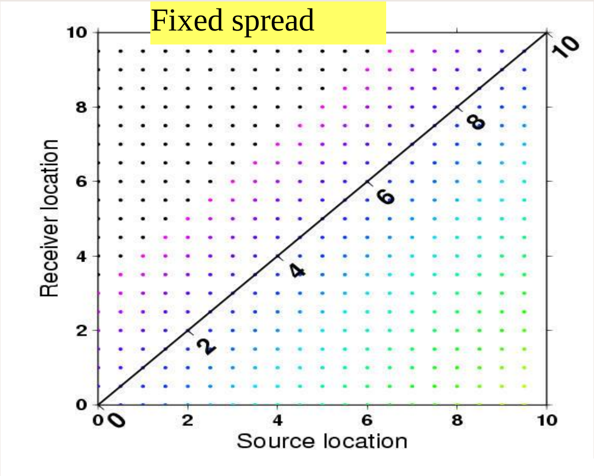
- Conducted prior to the acquisition in order to evaluate the appropriate survey design
  - Offset range;
  - Noise (ground roll, airwave) characteristics;
  - Offset range for useful reflections.

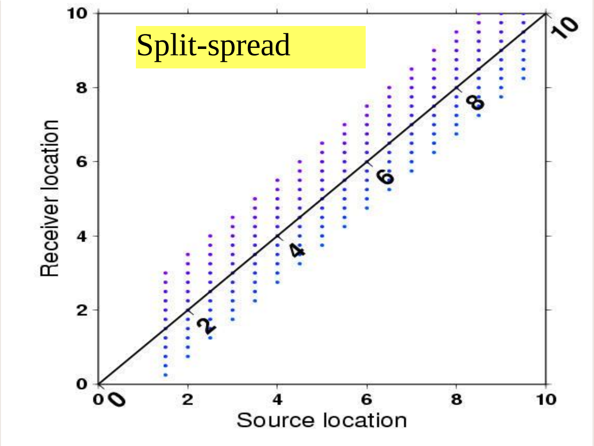


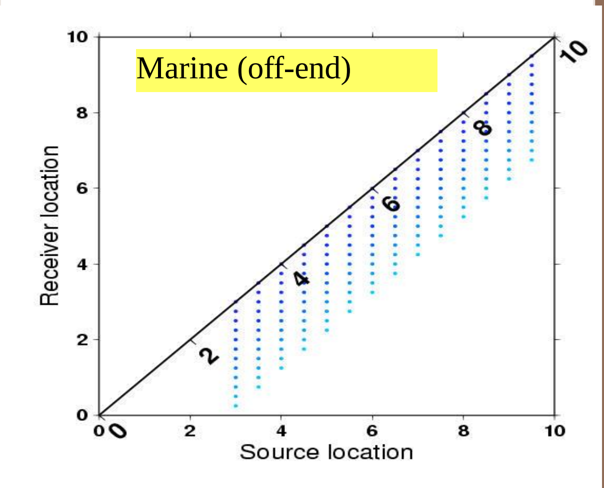
Stacking chart

- Visualization of mutual positions of sources and receivers





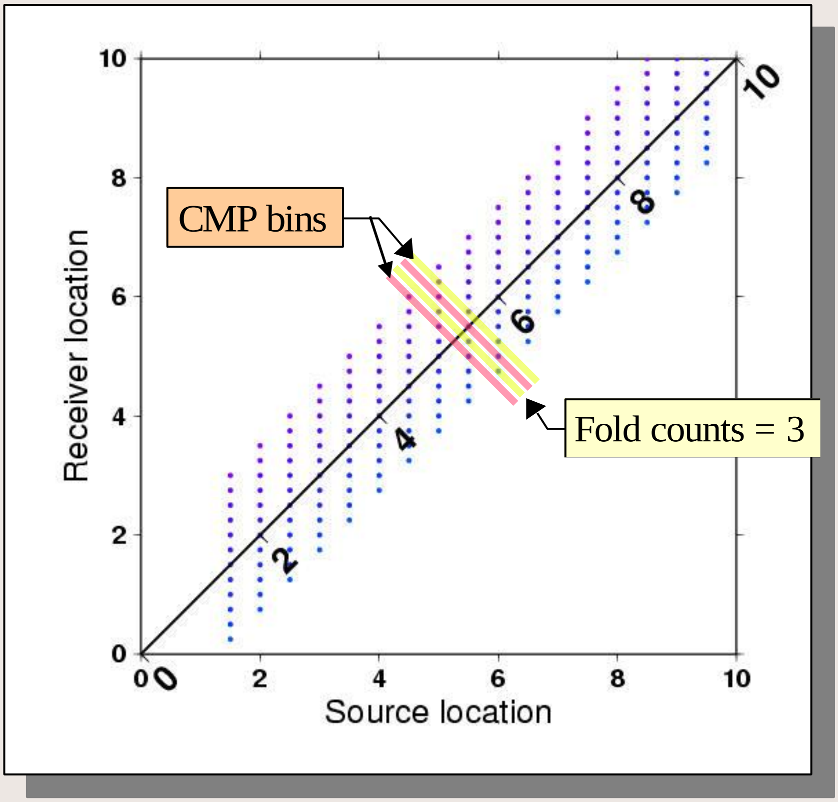




CMP Fold number

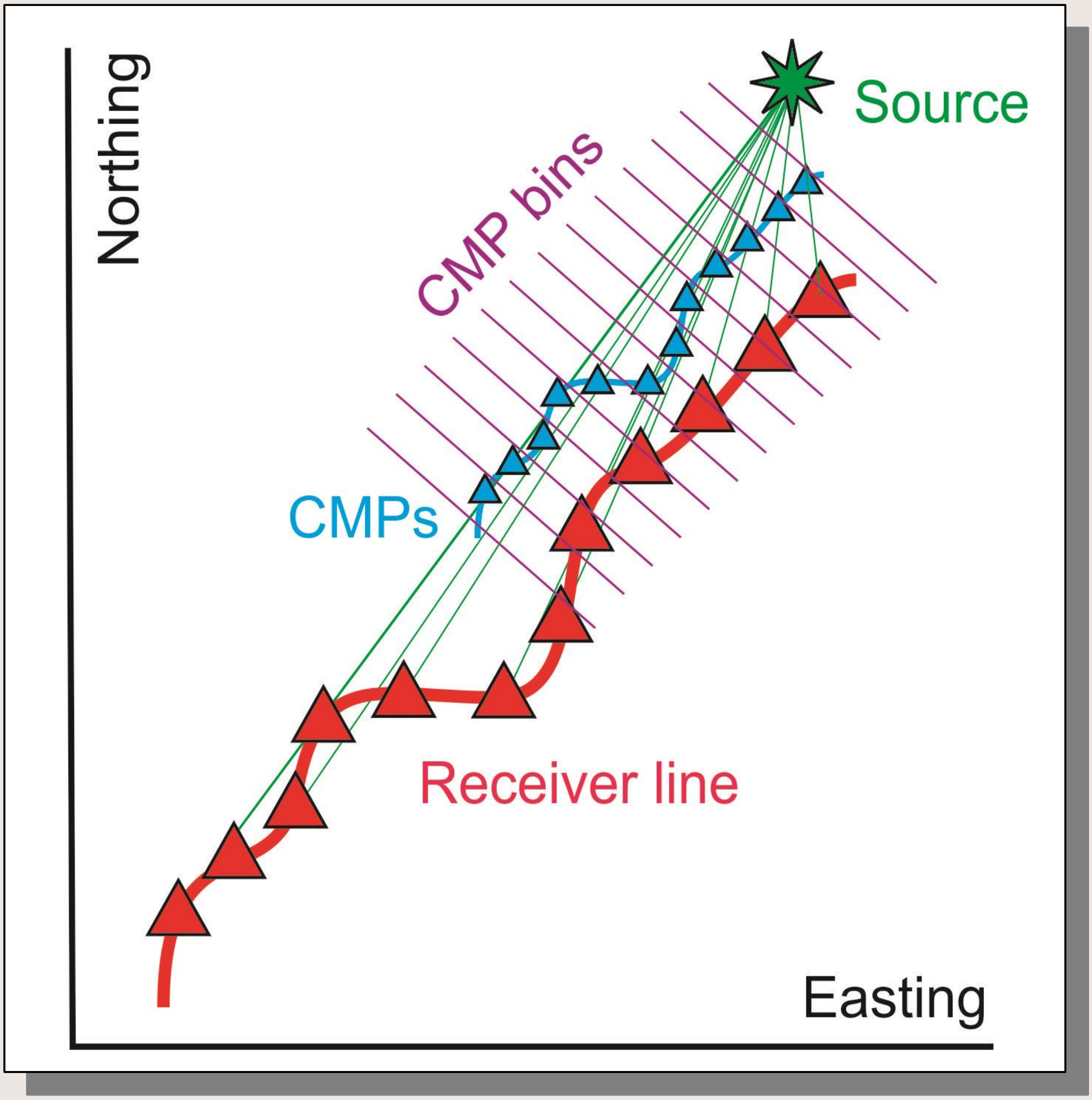
- "Fold" is the Number of records per CMP
  - Should be optimal (typically, 10-40);
- Should be uniform (this is particularly an issue with 3D).

$$Fold = \frac{\text{Number of recording channels}}{2\left(\text{Number of Shot point advances by Receiver spacing}\right)}$$



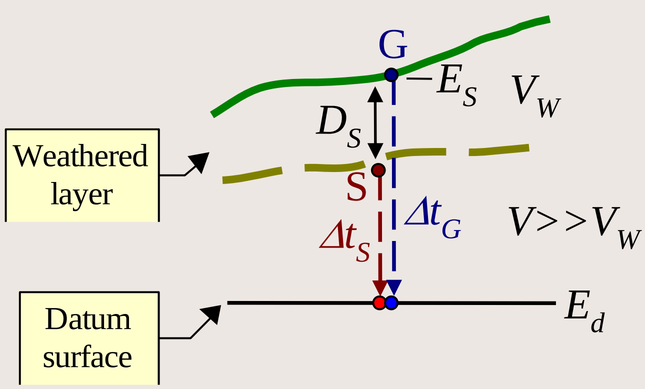
Crooked-line binning

- Real seismic lines are often “crooked”
- CMP bins are then defined for an averaged, smooth line of midpoints



Statics

- Statics are time shifts associated with source (Δt_S) and receiver (Δt_R) positions
  - When subtracted ('*applied*') from the travel-times, place the source and receiver on a common datum.
- (*Field statics*) = (*Elevation Correction*) + (*Weathering Correction*);
  - Elevation correction 'moves' the source and geophone to a common datum surface;
  - Weathering correction removes the effect of slow (~600 m/s) unconsolidated layer.
    - Obtained from *first arrivals*, using the plus-minus, GRM, or similar methods.
- Where field statics are not accurate enough, *residual statics* are also applied.



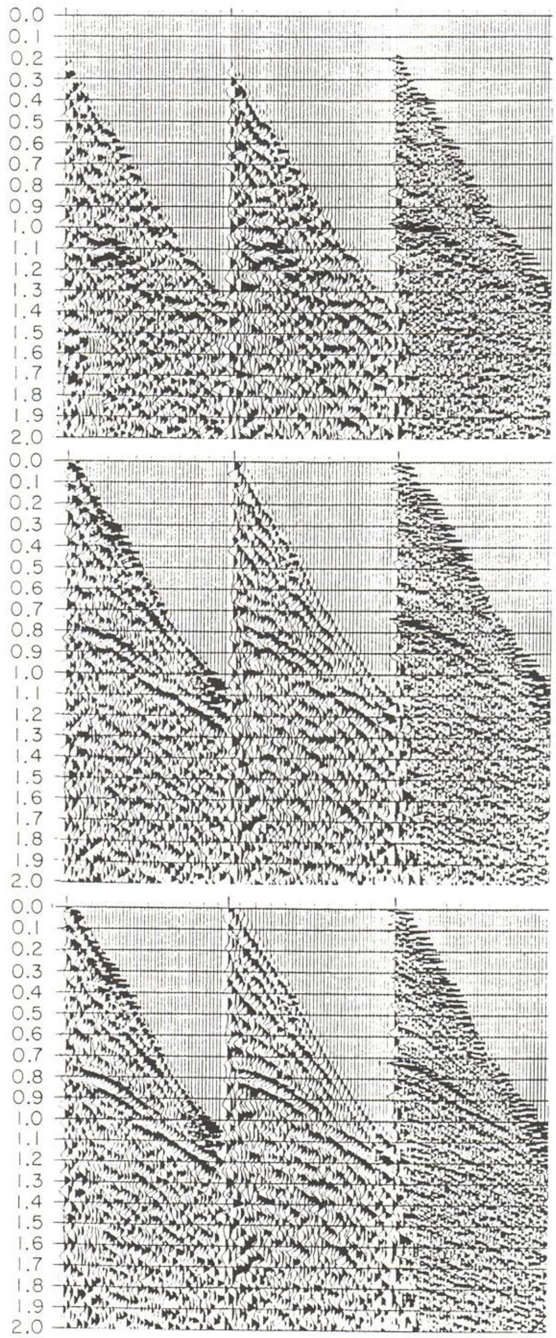
Elevation statics:

$$\Delta t_S = \frac{E_S - D_S - E_d}{V}$$

$$\Delta t_G = \Delta t_S + t_{uphole}$$

Effects of statics in shot gathers

- Note that good static corrections are VERY important for producing good reflection images

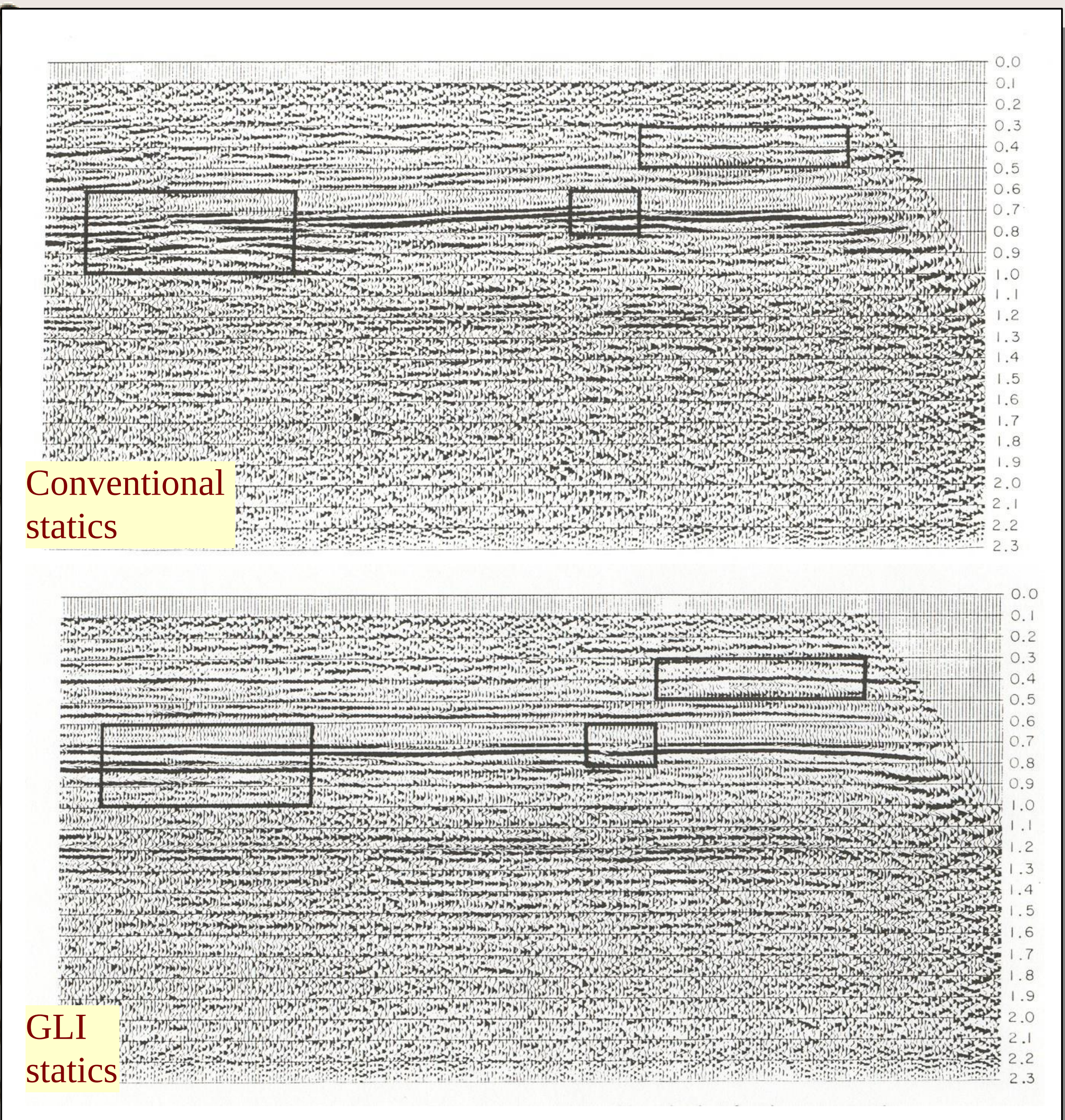


No static corrections applied

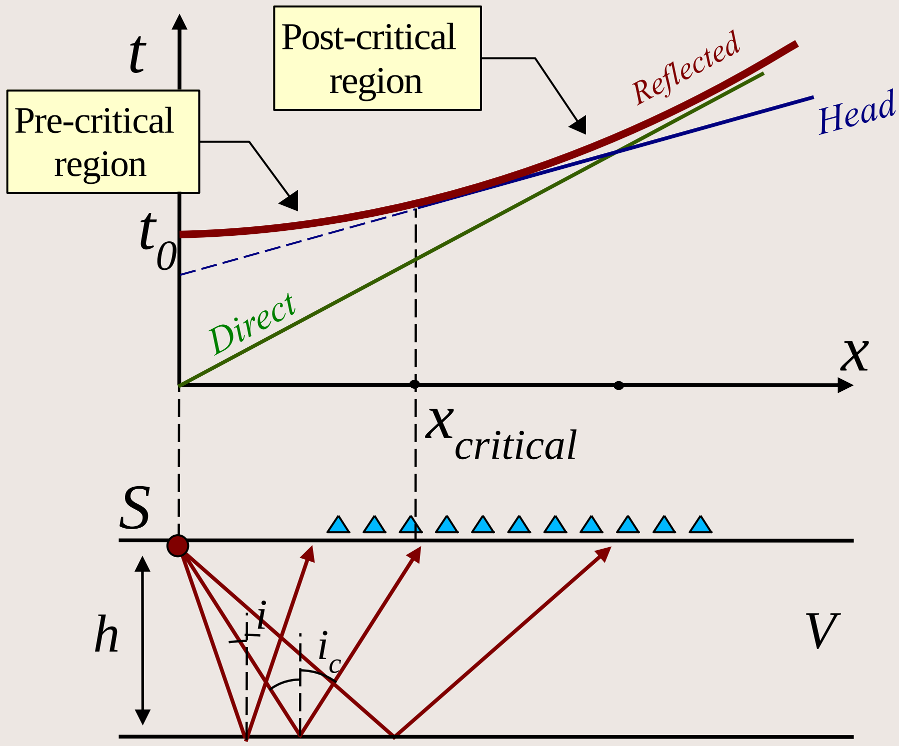
Conventional statics

GLI (tomography) statics

Effects of statics in stacked image



Reflection travel times
(*Single layer*)



$$t(x)=\frac{\sqrt{4h^2+x^2}}{V}=\sqrt{\left(2\frac{h}{V}\right)^2+\left(\frac{x}{V}\right)^2}=\sqrt{t_0^2+\left(\frac{x}{V}\right)^2}$$

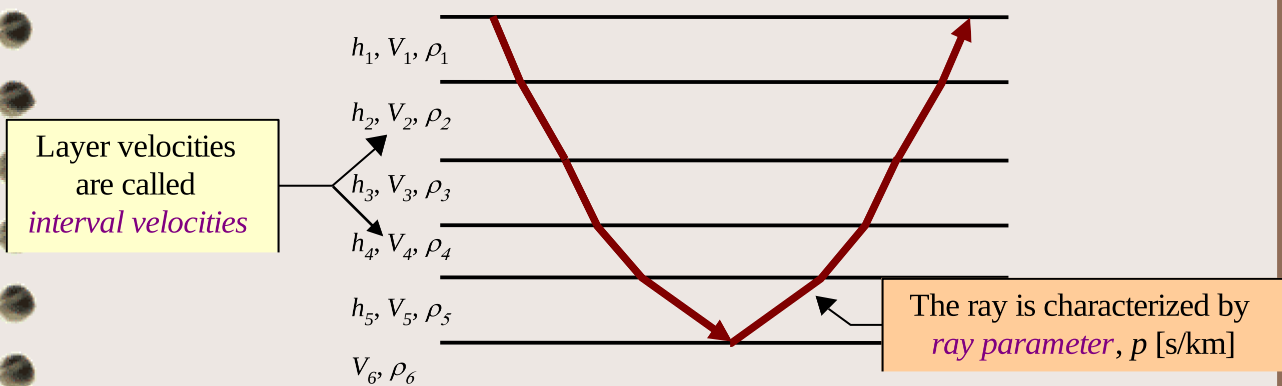
- *t*(*x*) is called (hyperbolic) Normal reflection Moveout (NMO)
  - Approximation for $x \ll h$ (parabolic):

$$t(x)\approx t_0+\frac{1}{2t_0}\left(\frac{x}{V}\right)^2$$

Note that deeper reflections in faster layers have smaller moveouts

Reflection travel times
(*Multiple layers*)

- For multiple layers, $t(x)$ is no longer hyperbolic:



- For practical applications (near-vertical incidence, pV_i<<1), $t(x)$ still can be approximated as:

$$x_n(p) = \sum_{i=1}^{n} \frac{h_i p V_i}{\sqrt{1-(pV_i)^2}} \approx p \sum_{i=1}^{n} h_i V_i \left[1 + \frac{1}{2}(pV_i)^2\right] \approx p \sum_{i=1}^{n} h_i V_i$$

hence: $p = \dfrac{x_n}{\sum_{i=1}^{n} h_i V_i}$

$$t_n(p) = \sum_{i=1}^{n} \frac{h_i}{V_i \sqrt{1-(pV_i)^2}} \approx \sum_{i=1}^{n} \frac{h_i}{V_i}\left[1 + \frac{1}{2}(pV_i)^2\right] = t_0 + \frac{1}{2} p^2 \sum_{i=1}^{n} h_i V_i$$

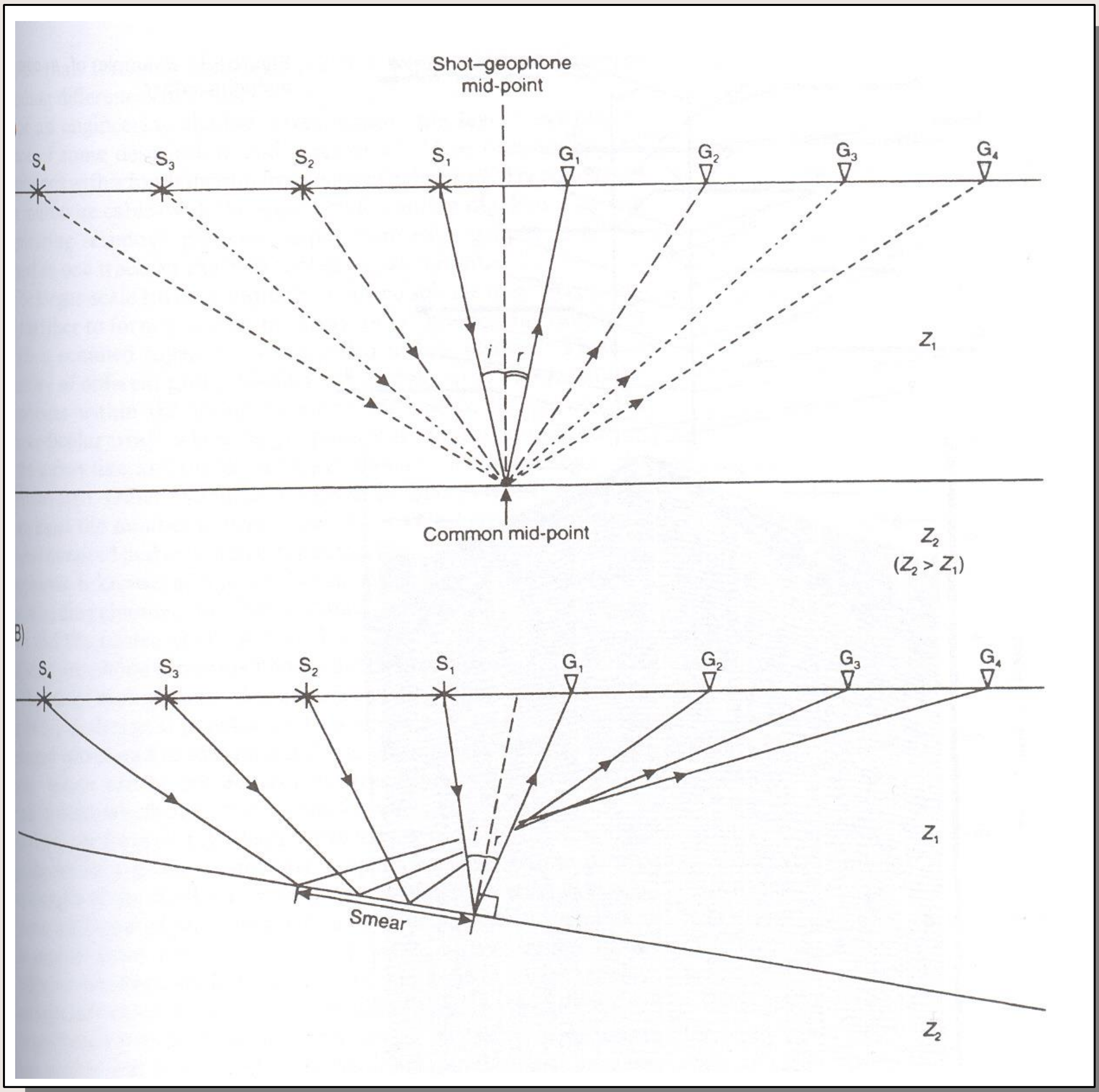
$$t_n(x) \approx t_0 + \frac{1}{2t_0}\left(\frac{x}{V_{RMS}}\right)^2$$

- where V_{RMS} is the RMS (root-mean-square) velocity:

$$V_{RMS} = \sqrt{\frac{\sum_{i=1}^{n} h_i V_i}{t_0}} = \sqrt{\frac{\sum_{i=1}^{n} t_i V_i^2}{\sum_{i=1}^{n} t_i}}$$

Dipping reflector

- For a dipping reflector, the image is *smeared up-dip* and the stacking velocity is *over-estimated*.

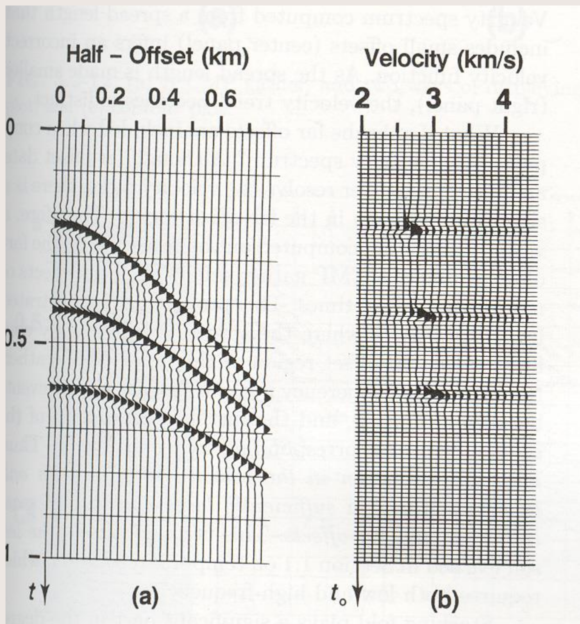


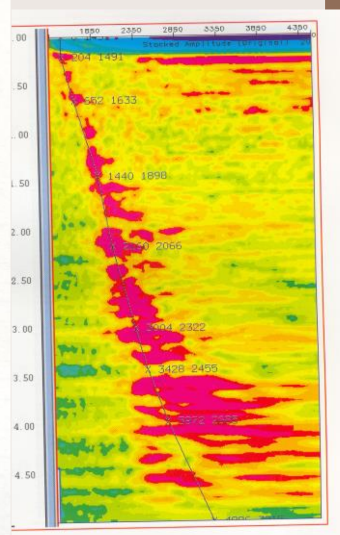
Measurement of velocities
(*Velocity analysis*)

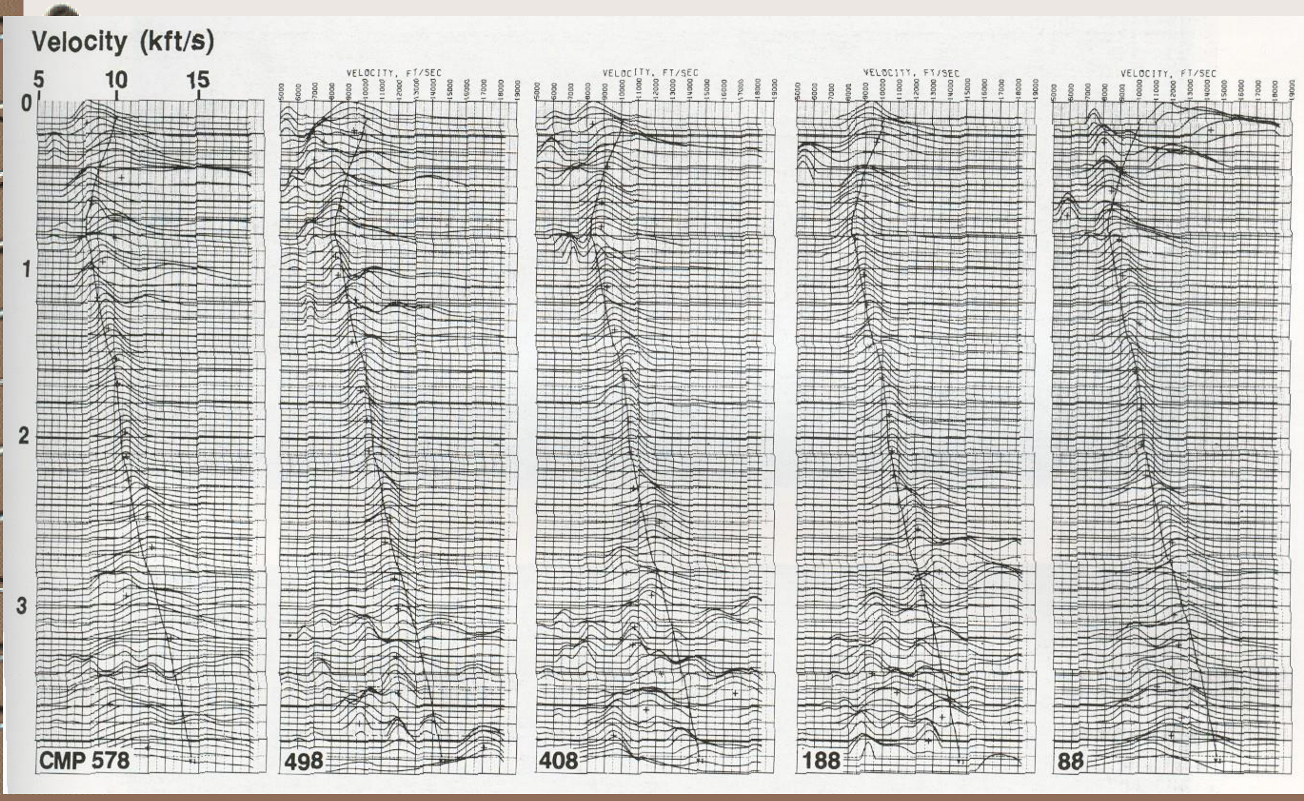
- Reflection (*stacking*) velocity analysis is usually performed in CMP gathers
  - because they pertain to specific locations within the subsurface.
- Travel-time approach - T^2-X^2 method: $t^2(x^2)$ is a linear function. Slope of the graph in $t^2(x^2)$ diagram is $(1/V_{Stacking})^2$.
- Waveform approach (*velocity spectrum* and *common velocity stacks (CVS)*)
  - stack the records along trial reflection hyperbolas;
  - plot the resulting amplitude in a (*time*, V_{trial}) diagram;
  - pick amplitude peaks - this results in a $V(time)$ profile.

Velocity Spectra

CMP gathers are stacked along trial velocities and presented in time-velocity diagrams.

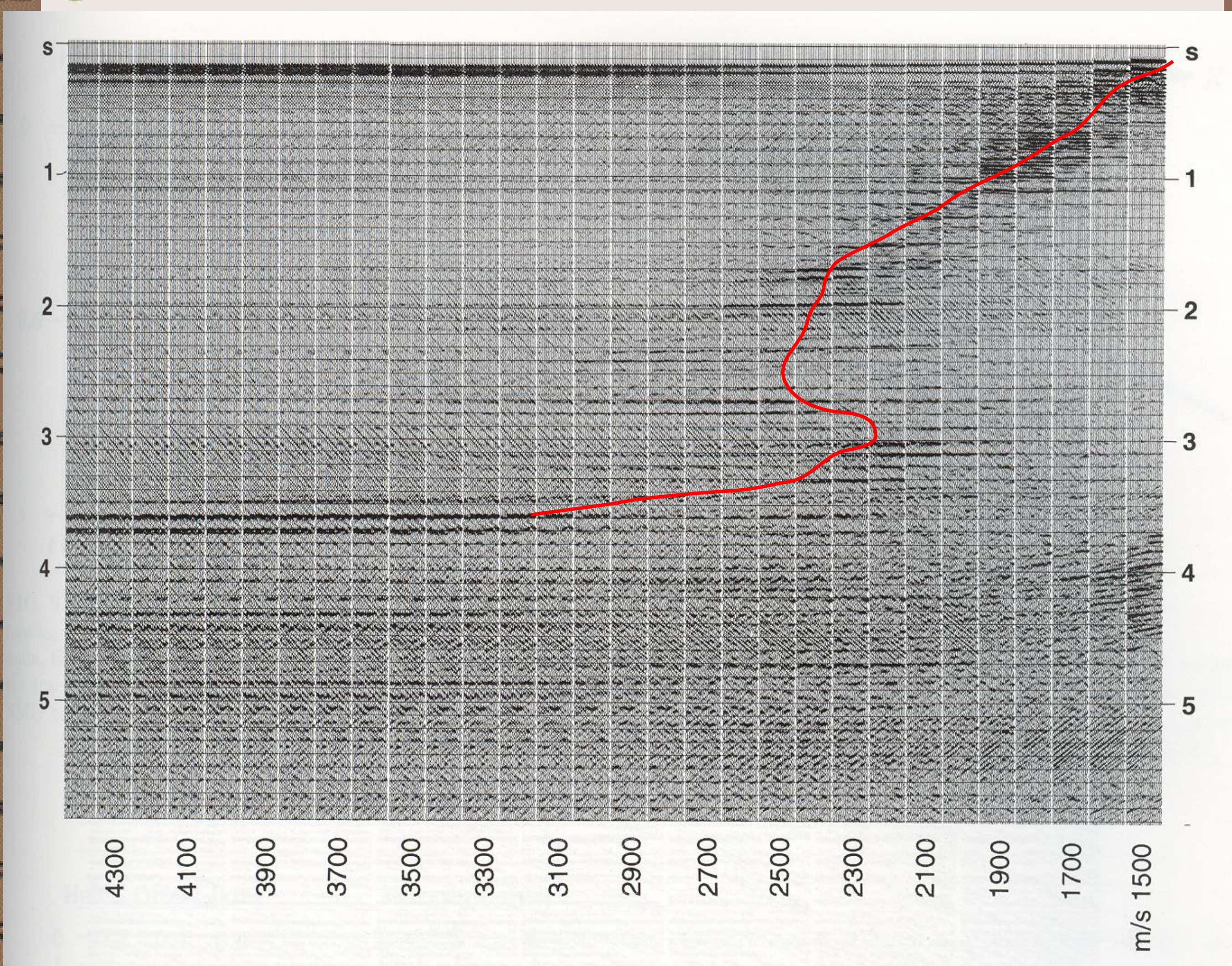






Common-Velocity Stacks
(*Velocity analysis*)

- CMP gathers are NMO-corrected (hyperbolas flattened) using a range of trial velocities and stacked.
- Velocities are picked at the amplitude peaks and best resolution in the stacks.



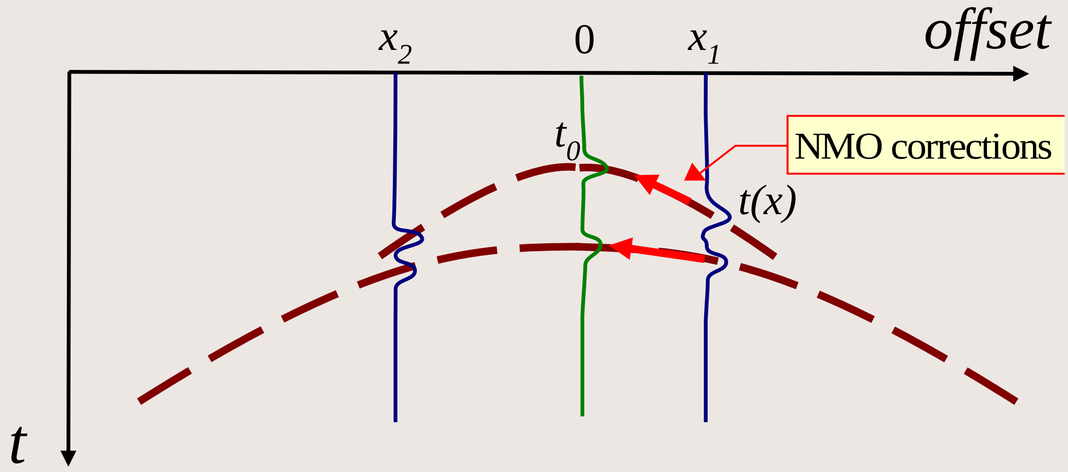
Normal Moveout (NMO) correction

- NMO correction transforms a reflection record at offset *x* into a normal-incidence (*x* = 0) record:

$$t(x) \to t_0 = t(x) - \delta t_{NMO}$$

$$\delta t_{NMO} = \sqrt{t^2 - \left(\frac{x}{V}\right)^2} - t_0 \approx \frac{1}{2t}\left(\frac{x}{V}\right)^2$$

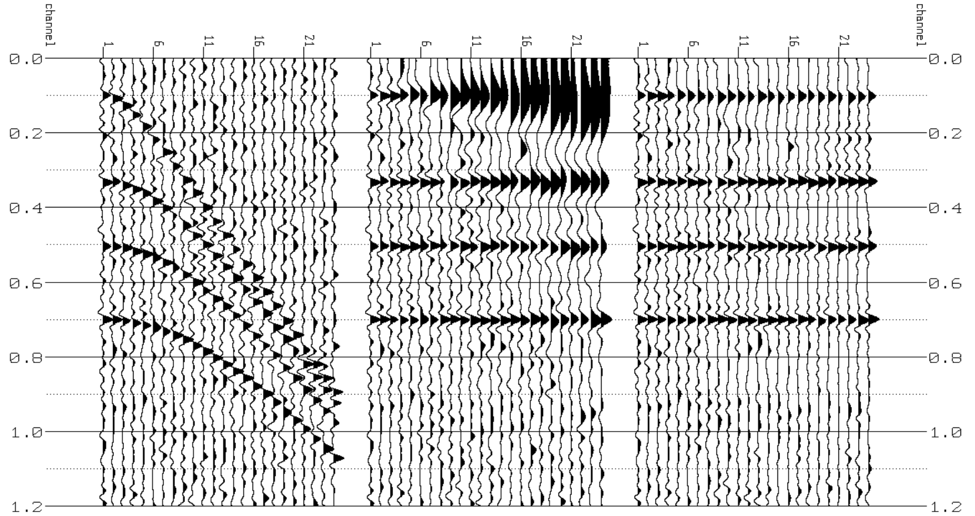
"Stacking velocity"



- *Stacking velocity* is determined from the data, as a parameter of reflection hyperbola which is best aligned with the observed reflection

NMO stretching

- NMO correction affects the shallower and slower reflections stronger
  - This is called "*NMO stretch*"
  - There is a considerable effort in creating "non-stretching" NMO algorithms



Raw

NMO corrected

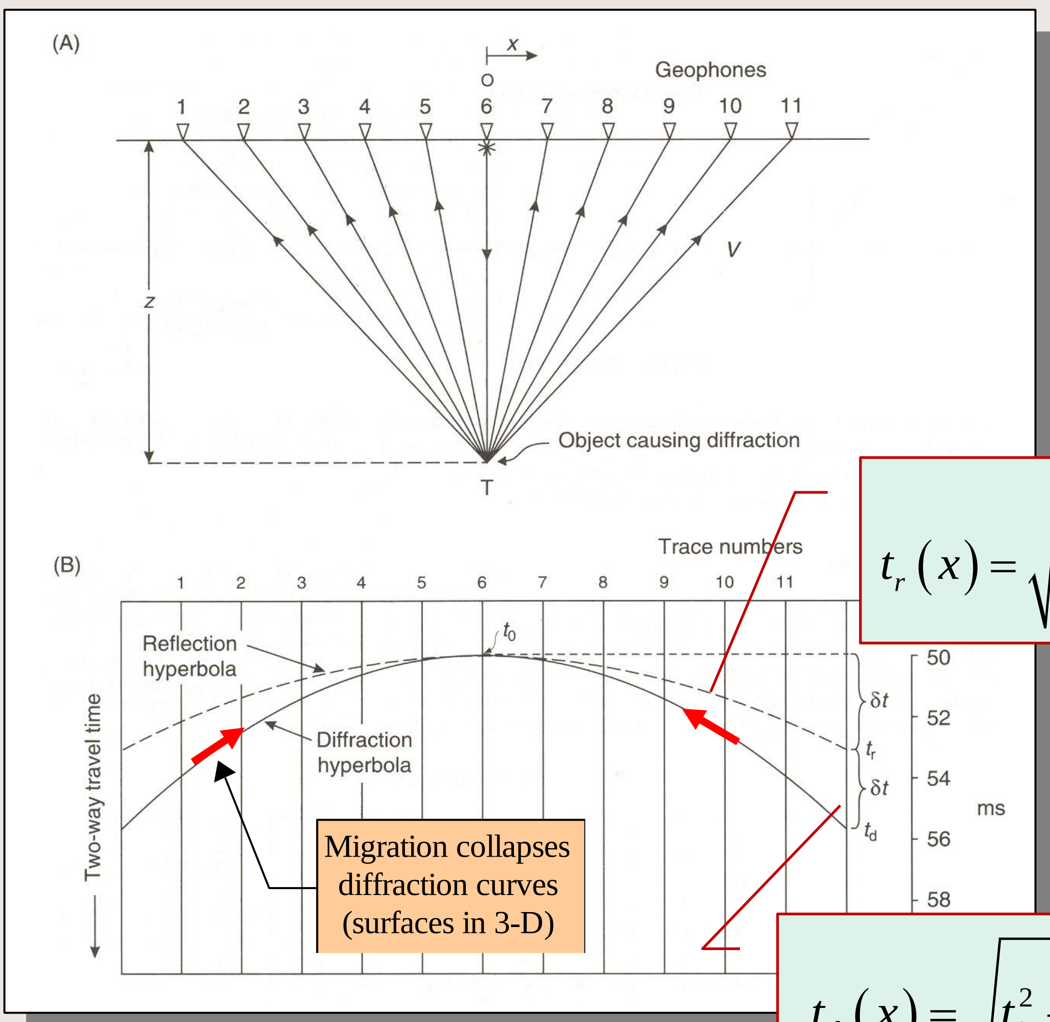
Non-stretching NMO corrected

Exercise: derive the sensitivities of NMO correction to δt, δV, and δx:

$$\partial\left(\delta t_{NMO}\right)/\partial t,\quad \partial\left(\delta t_{NMO}\right)/\partial V,\quad \partial\left(\delta t_{NMO}\right)/\partial x.$$

Migration

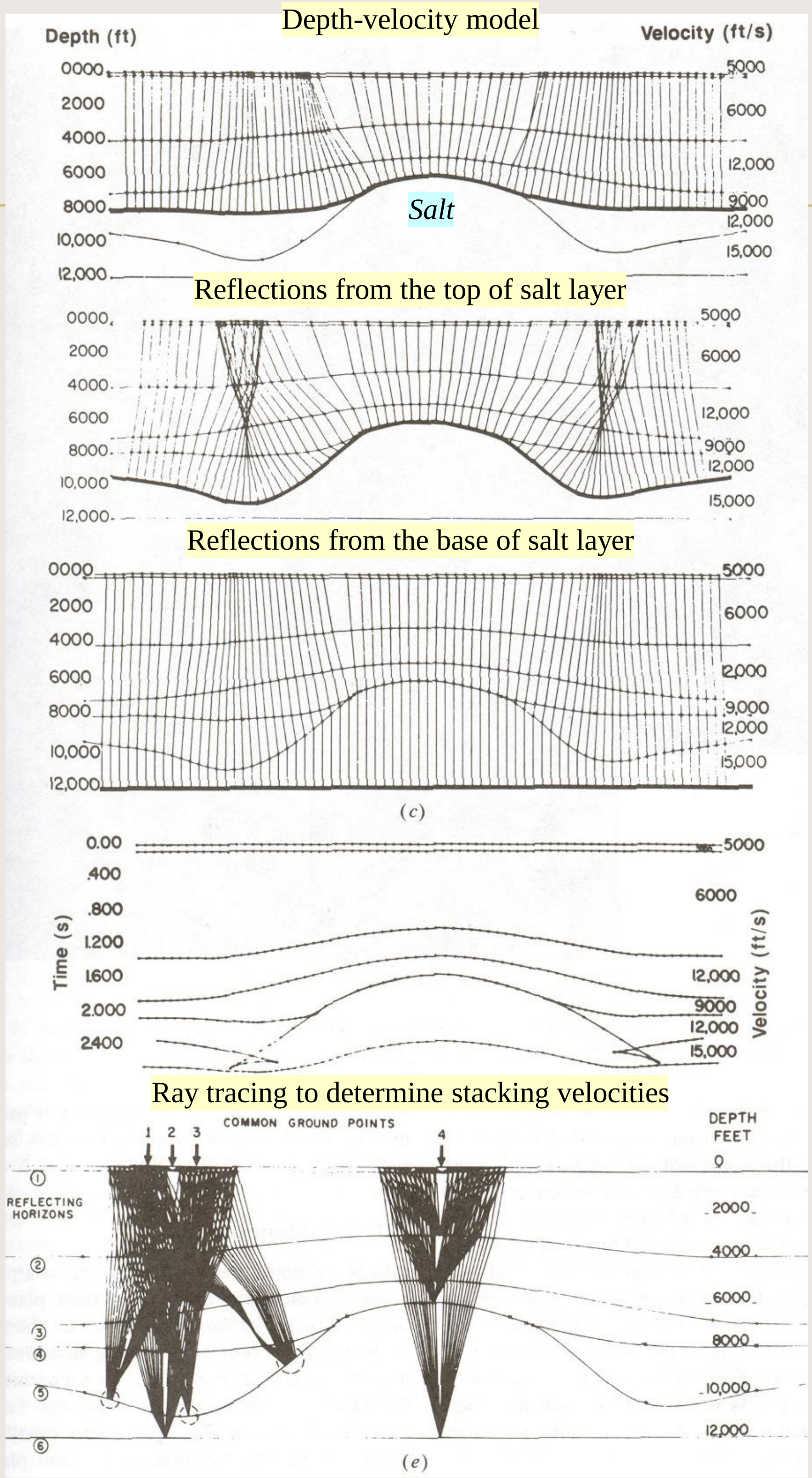
- A simplified variant of '*inversion*'
  - Transforms the 'time section' into true 'depth image'
- Establishes true positions and dips of reflectors
- Collapses diffractions



$$t_r(x) = \sqrt{t_0^2 + \left(\frac{x}{V}\right)^2}$$

$$t_d(x) = \sqrt{t_0^2 + \left(\frac{2x}{V}\right)^2}$$

Use of modeling



Use of synthetic seismograms

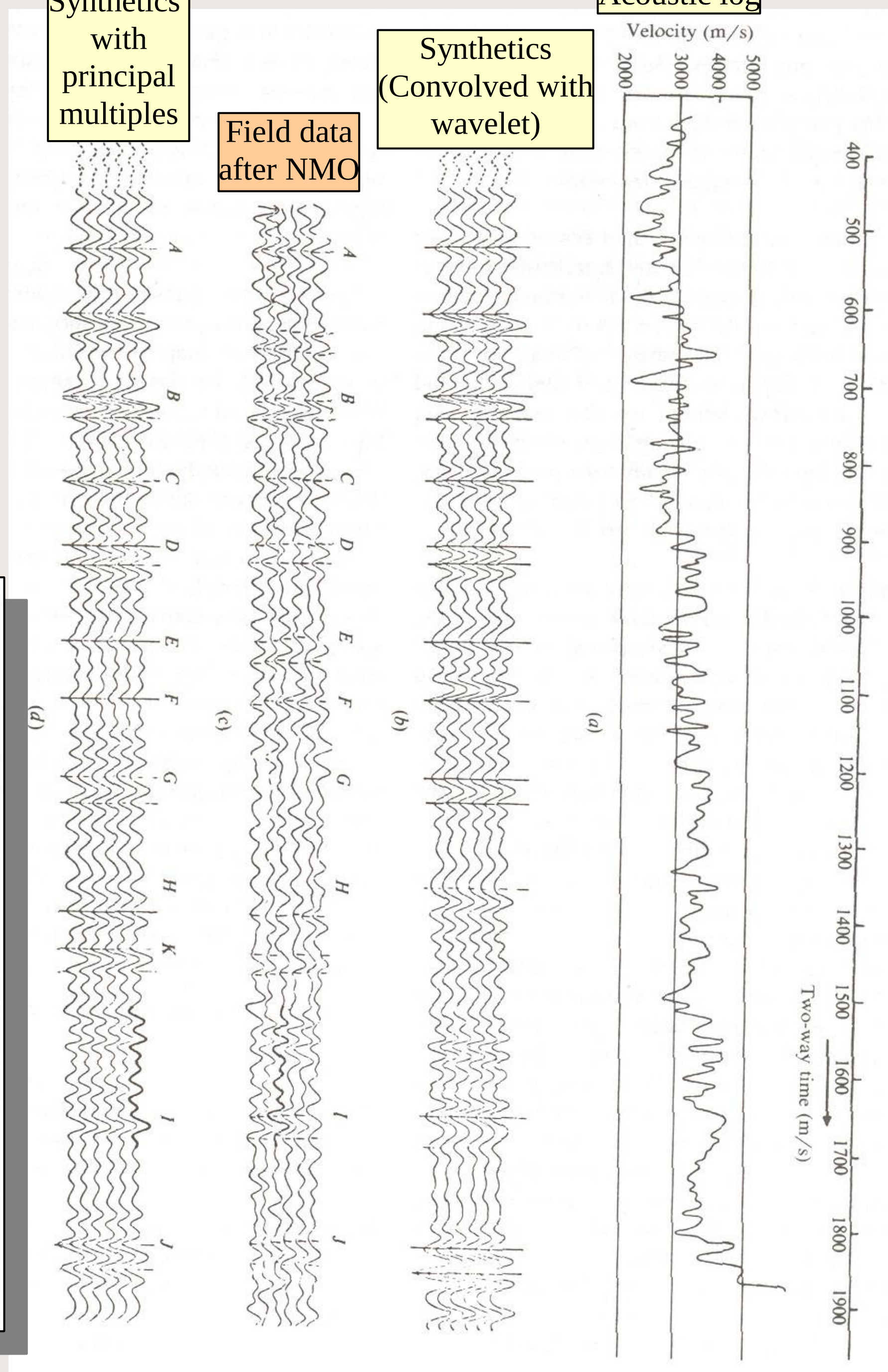
Proceed

Acoustic log

Synthetics (Convolved with wavelet)

Field data after NMO

Synthetics with principal multiples



Synthetics is spliced into CMP section for comparison