Reflection seismic Method - 2D

- Acoustic Impedance
- Seismic events
- Wavelets and wavelet “phase” New!
- Convolutional model
- Resolution
- Stacking and Signal/Noise
- Subsurface sampling New!

Reading:

Sheriff and Geldart, Chapters 6, 8

Acoustic Impedance

What we image in reflection sections

- From previous lectutres, we know that at *near-vertical* incidence:
  - *P*-to-*S*-wave conversions are negligible;
  - *P*-wave reflection and transmission *amplitudes* are sensitive to *acoustic impedance* ($Z=\rho V$) contrasts:

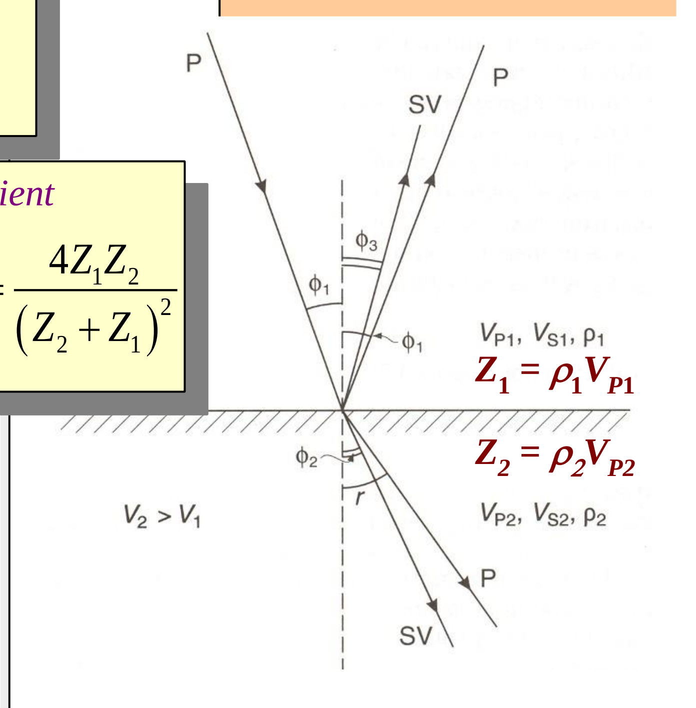
P-wave Reflection Coefficient

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

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

P-wave Transmission Coefficient

$$T_{PP}^2 \equiv \left(\frac{A_{P_{refracted}}}{A_{P_{incident}}}\right)^2 = 1 - R_{PP}^2 = \frac{4Z_1Z_2}{\left(Z_2+Z_1\right)^2}$$



P- and *S*-wave *reflection* amplitudes *increase with incidence angle.*

Reflection imaging

- **CMP Stacking:**
  - Multi-offset data are transformed into a *zero-offset section* (ZOS):
    - Statics place sources and receivers on a flat reference (datum) surface
    - Deconvolution compresses the wavelet into a "spike", "zero-phase", or "minimum-phase" shapes and attenuates "short-period" multiples
    - NMO corrections and stacking produces the ZOS
  - "Post-stack" *migration* transforms the zero-offset section into a depth image
- **Pre-stack imaging:**
  - Velocity models are inverted for
  - Multi-offset reflection amplitudes data are directly mapped (migrated, or "inverted") into the depth image

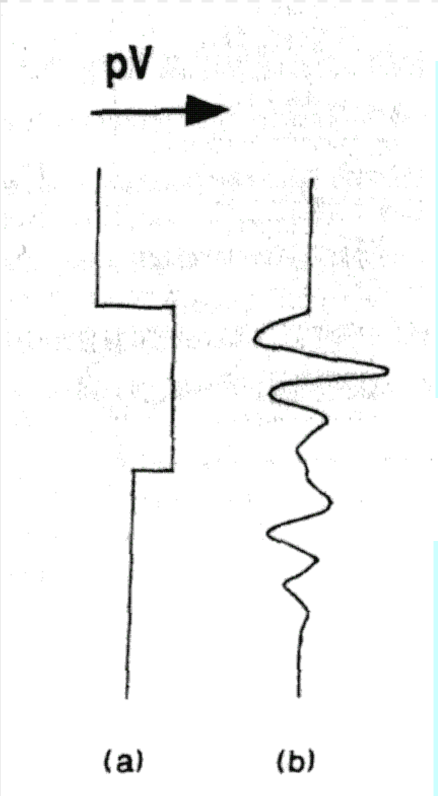
- In both cases, various types of filtering attenuates noise and other multiples, improve the quality of images (smoothness of reflectors, resolution of faults, etc.)

New!

Wavelets

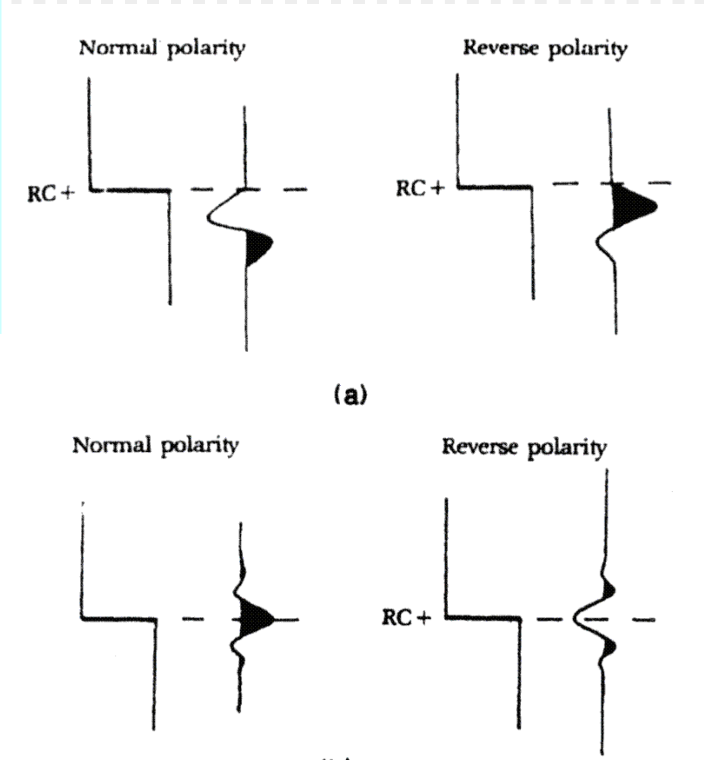
- Impedance contrasts are assumed to be sharp, but the source waveform always imposes its signature on the record (plot on the left)

Standard convention for reflection polarity is related to reflection from a positive impedance contrast:



"Minimum-phase" wavelet

"Zero-phase" wavelet



New!

Wavelet “phase”
key properties

- For any waveform, an infinite number of other waveforms can be obtained by changing the Fourier phase spectrum while keeping the amplitude spectrum fixed
- All these waveforms (wavelets) are separated by the specific property of their “phase”:
  - “Minimum-phase” (or minimum-delay) – waveforms with the steepest rise at the beginning
  - “Maximum-phase” – opposite to the above
  - Zero-phase – waveforms symmetric in time (Fourier phase equals zero at all frequencies)
  - “Mixed-phase” – all other wavelets
- Minimum- (maximum-) phase wavelets have the fastest (slowest) rate of energy build-up with time:

$$E(t_k) = \frac{1}{2}\sum_{i=0}^{k} w^2(t_i)$$

  - This curve $E(t)$ lies above all others for minimum-phase wavelets and below all others for maximum-phase

- Minimum-phase wavelets are associated with *causal* physical processes, such as an explosion or impact

New!

Wavelet "phase"
Definition

- Consider a wavelet consisting of two spikes: $w=(1,a)$:

  For $|a| < 1$, this wavelet is called *minimum-phase*;

  For $|a| > 1$, it is called *maximum-phase*;

  Note that its *z*-transform is $W(z)=1+az$, *and* $1/W(z)$ represents a convergent series near $z=0$. This means that there exists a filter that could convert the wavelet into a spike.

- A convolution of all minimum- (maximum-) phase wavelets is also a minimum- (maximum-) phase wavelet:

$$W(z)=\prod_{i=0}^{N}(1+a_i z)$$

- When minimum- and maximum-phase factors are intermixed in the convolution, the wavelet is called *mixed-phase*

New!

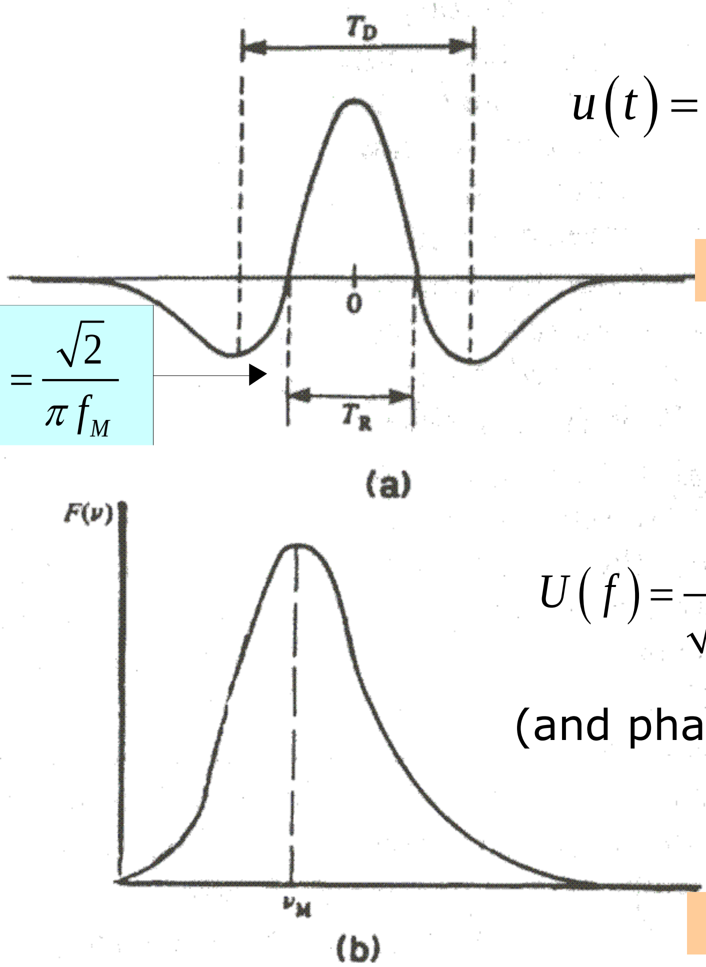
Ricker wavelet

- The most broadly used zero-phase wavelet was proposed by Ricker:
    - Described by a single parameter, such as duration or f_M - the *peak frequency*

$$u(t) = \left(1 - 2\pi^2 f_M^2 t^2\right) e^{-(\pi f_M t)^2}$$

Time-domain form

$$T_R = \frac{\sqrt{2}}{\pi f_M}$$



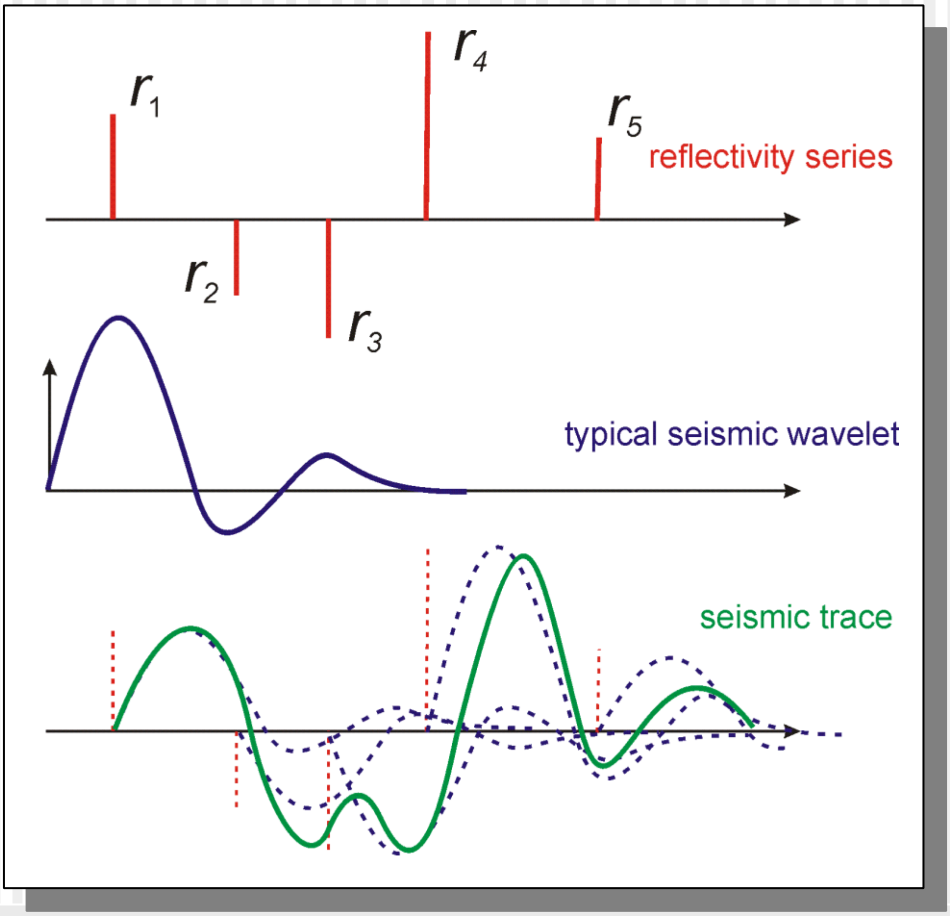
$$U(f) = \frac{2 f^2}{\sqrt{\pi} f_M^2} e^{-\left(\frac{f}{f_M}\right)^2}$$

(and phase=0)

Frequency-domain

Convolutional model of seismic reflections

- Reflection seismic trace is a convolution of the source wavelet with the Earth's ‘reflectivity series’
- The reflectivity series includes:
  - primary reflections;
  - multiples.



Convolution

- Mathematically, convolution of two time series, u_i, and w_i, denoted $u*w$, is:

$$(u*w)_k = \sum_i u_{k-i} w_i$$

- In *Z* or *frequency* domains, convolution becomes simple multiplication of polynomial functions or complex-valued spectra (show this!):

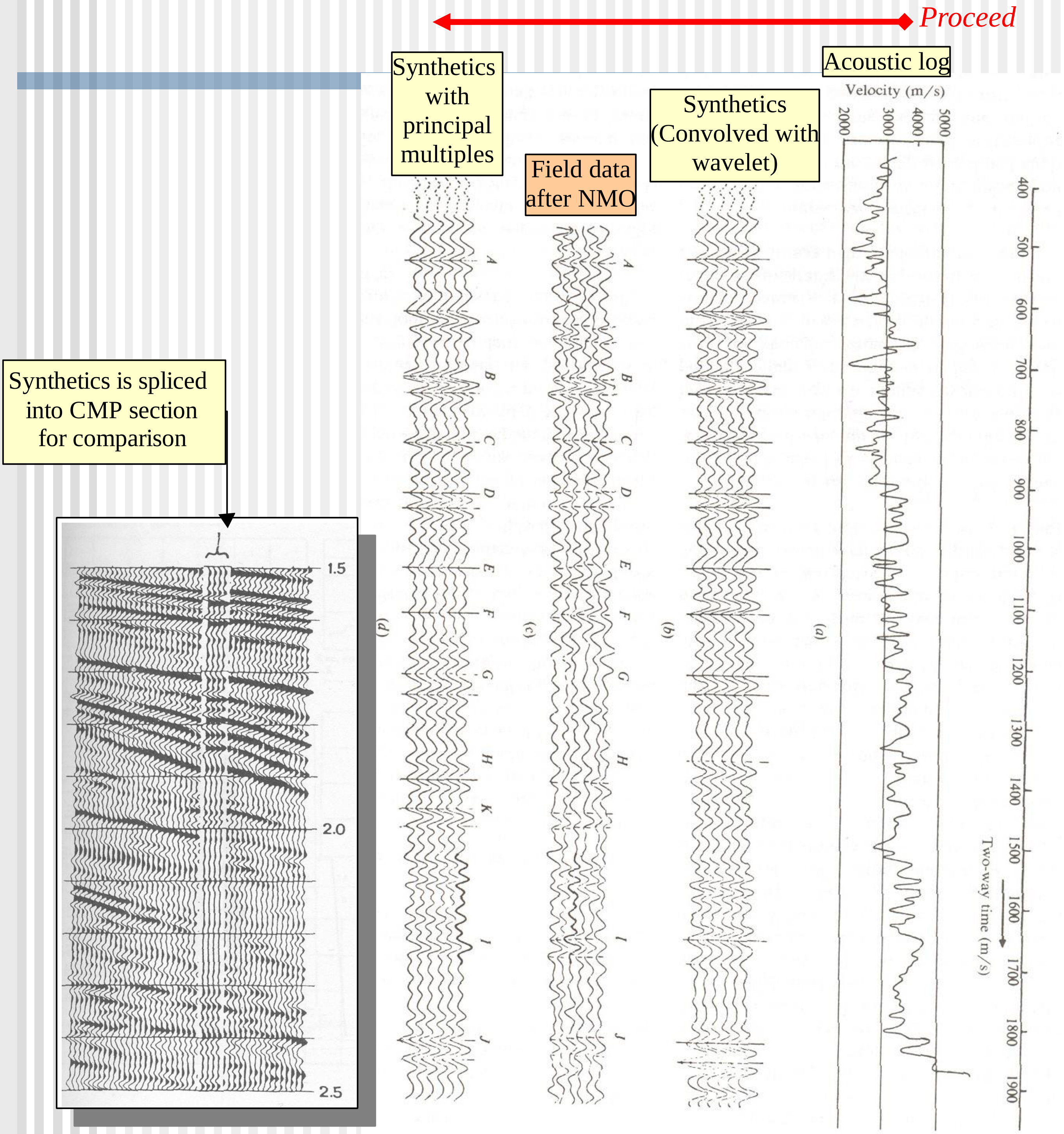
$$u*w \leftrightarrow U(z)W(z) \leftrightarrow U(f)W(f)$$

- This property of convolution is key for facilitating efficient digital filtering.
- Also as multiplication, convolution is symmetric (commutative):

$$u*w = w*u$$

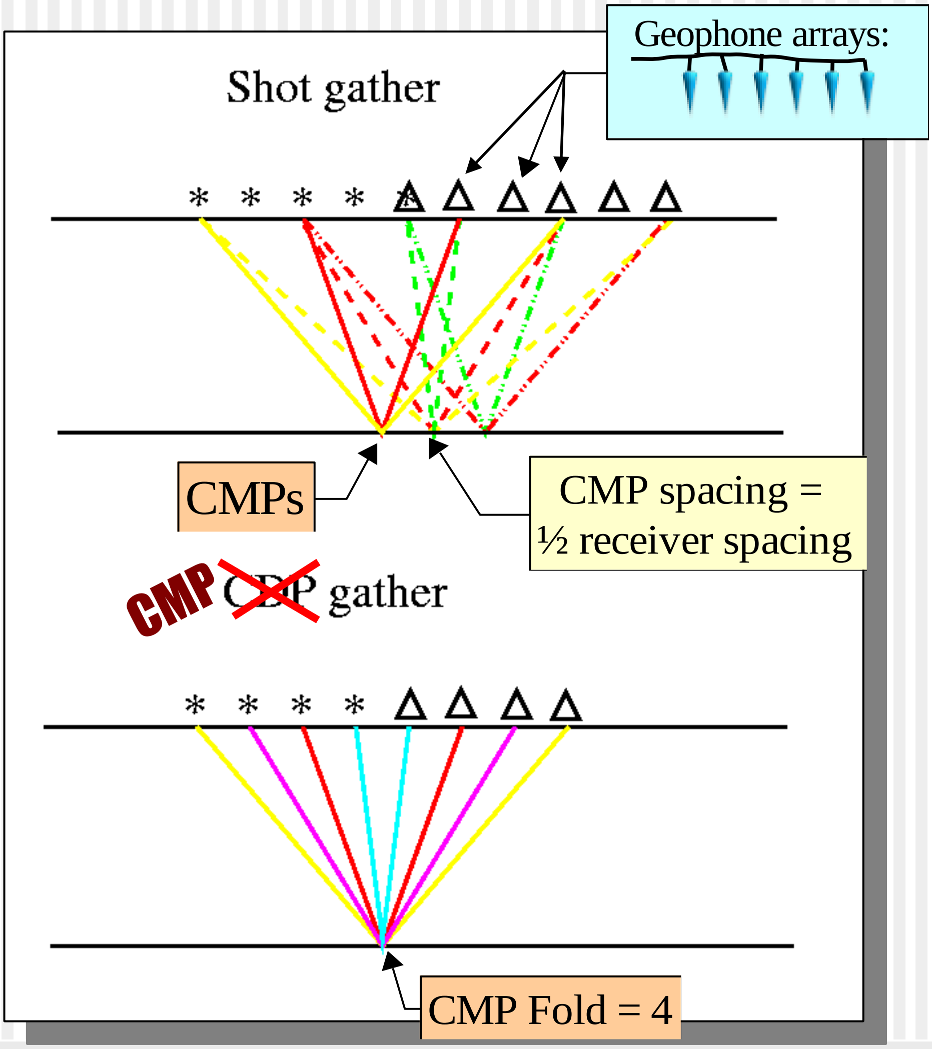
Convolutional model

Calibration of reflection seismic sections using well logs



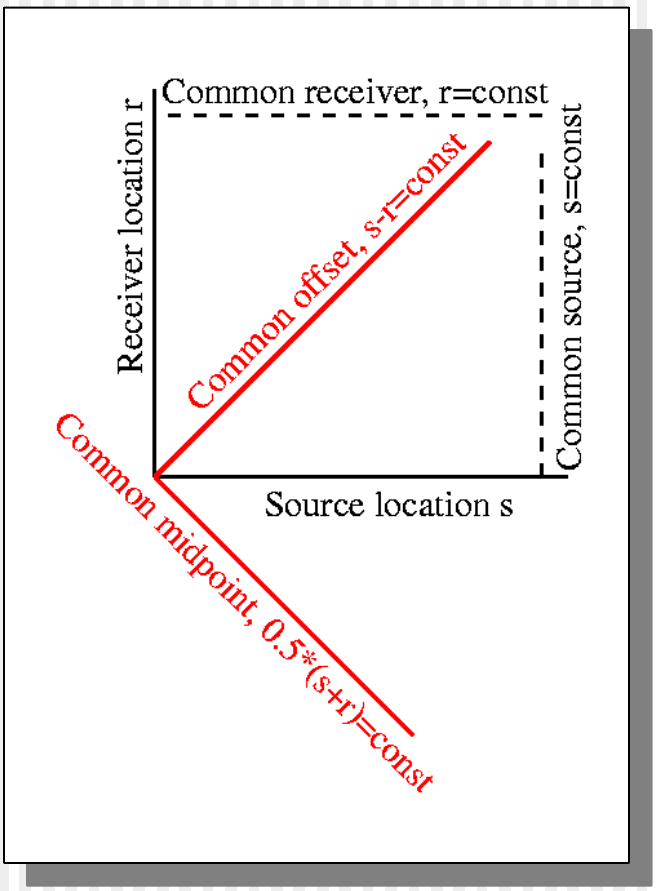
Data sort orders:
Shot (field) and Common-Midpoint (image)

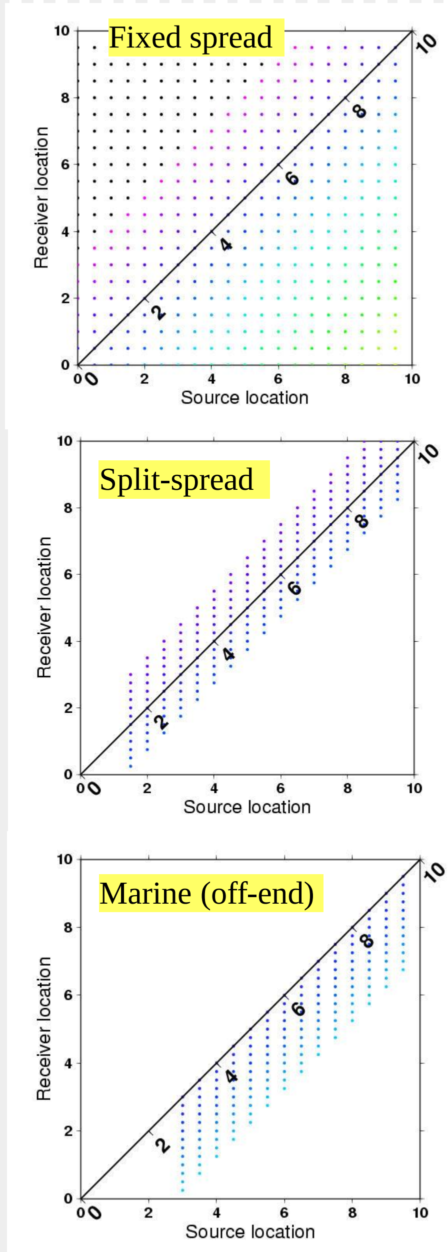
- Common-Midpoint reflection imaging:
  - Helps to reduce the effect of random noise and multiples via *redundant coverage* of the subsurface;
  - Provides offset coverage for Amplitude-vs. Offset (AVO) analysis



Stacking chart

- Visualization of 2D source-receiver geometry



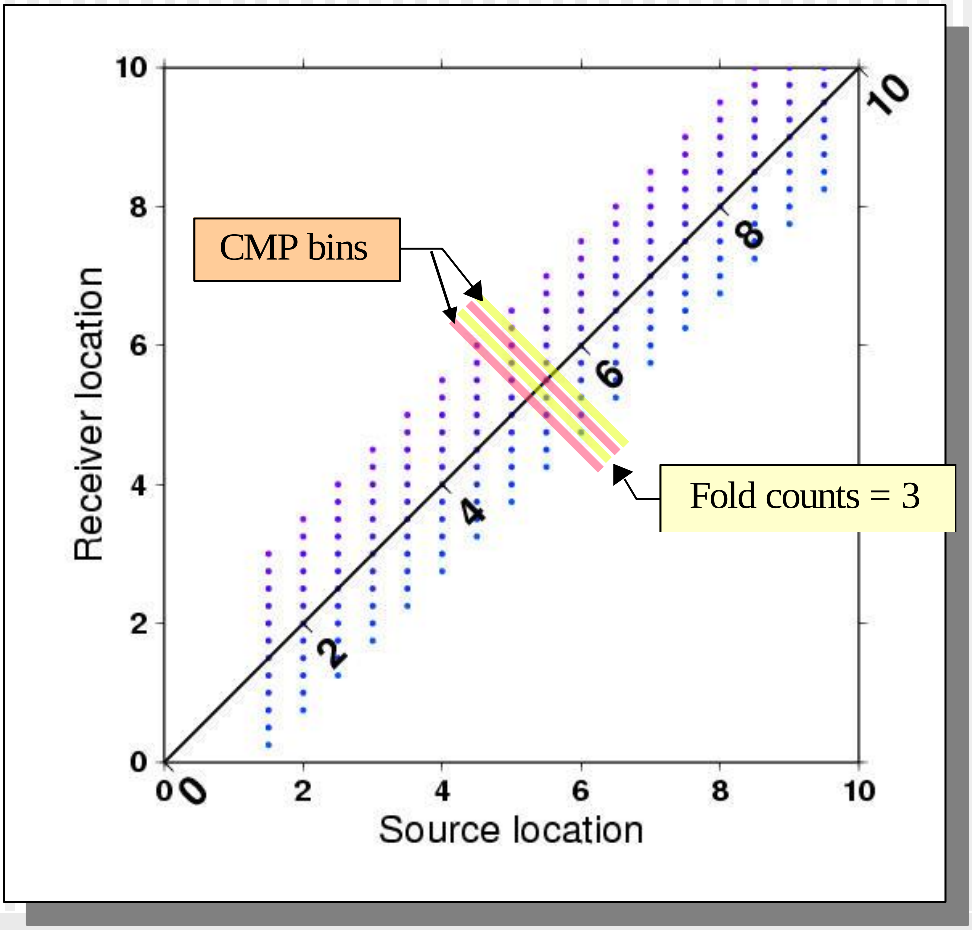


CMP Fold

CMP Fold is the number of records in the given CMP

- Should be optimal (typically, 10-40);
- Should be uniform (this is particularly an issue with 3D).

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



Stacking

- In order to suppress *incoherent noise*, stacking is commonly employed
  - *Vertical stacking* – summation of the records from multiple shots at the same locations.
  - *CMP stacking* – summation of multiple NMO-corrected records corresponding to the same midpoint.

$$u_i = S + n_i$$

Mean noise power (variance)

$$\sum u_i = NS + \sum n_i$$

$$Noise^2 = \left(\sum u_i^2 - NS\right)^2 = \left(\sum n_i\right)^2 = \sum_i \sum_j n_i n_j = \sum_i n_i^2 = N\sigma_n^2$$

- Thus, stacking of *N* traces reduces the incoherent noise by factor $\sqrt{N}$:

$$\frac{\text{Stacked signal}}{\text{Stacked noise}} = \frac{NS}{\sqrt{N\sigma_n^2}} = \sqrt{N}\frac{S}{\sigma_n}$$

Spatial resolution of reflectors

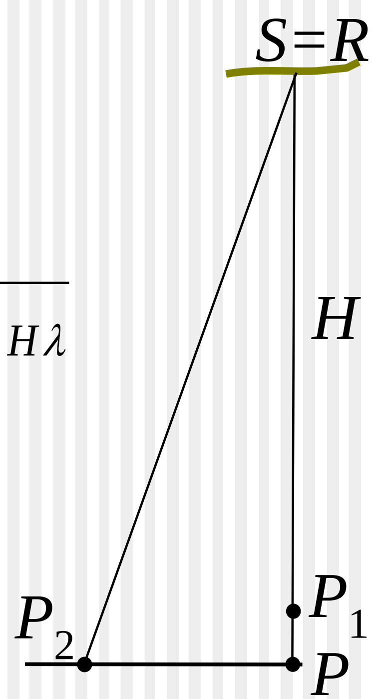
- Resolution is limited by the dominant wavelength of reflected signal.
- Two points are considered *unresolvable* when their reflection travel times are separated by less than *half the dominant period* of the signal: $\delta t < T/2$.
- Therefore,
  - vertical resolution limit:

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

  - horizontal resolution:

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

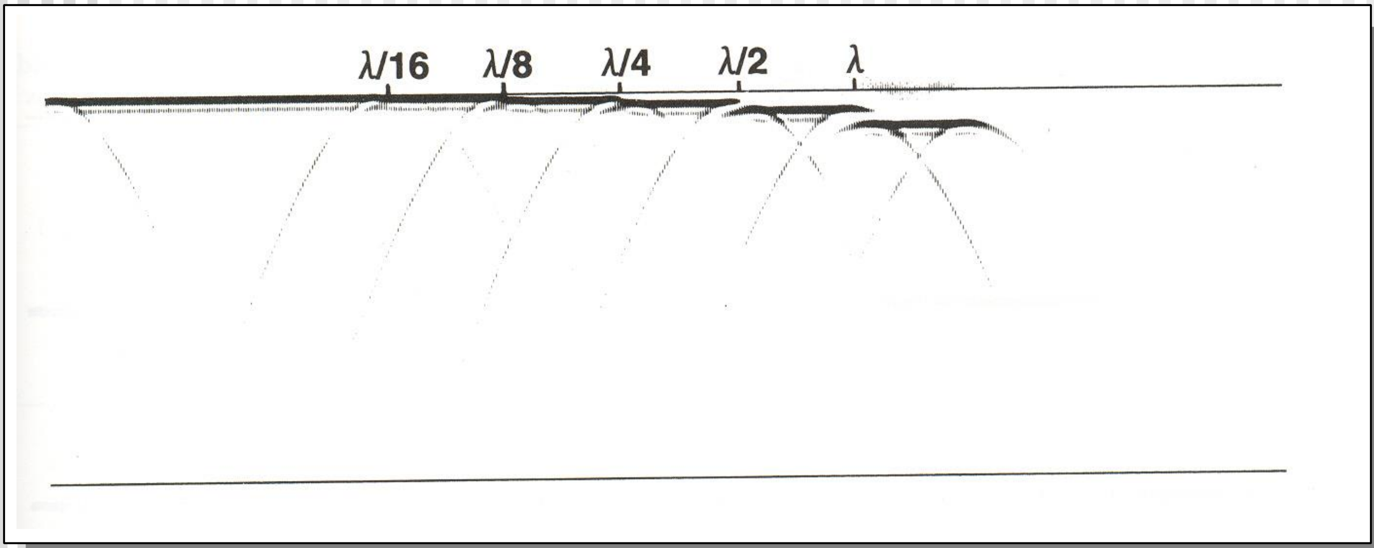
This is called the *Fresnel Zone* radius



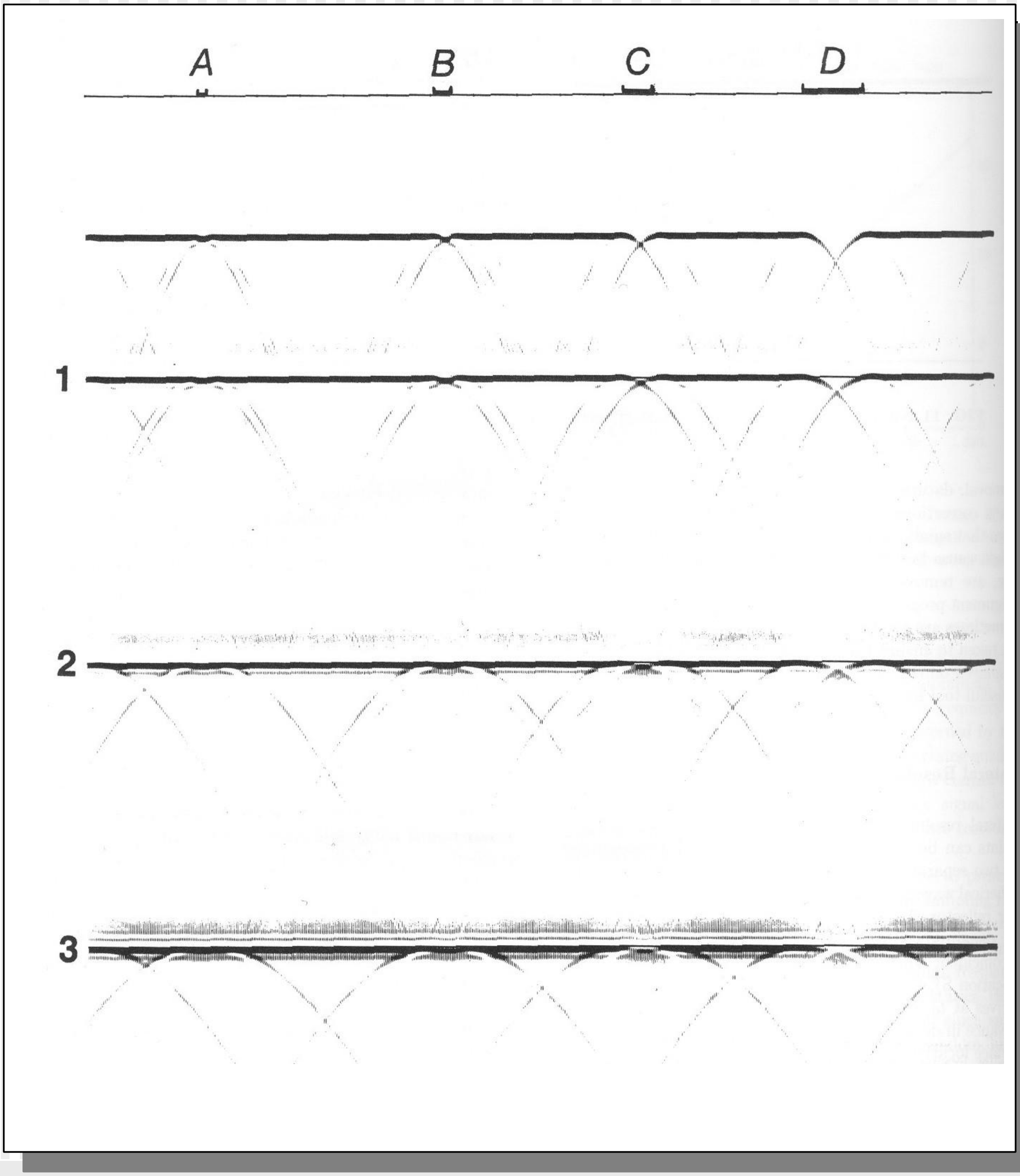
- Note that the *resolution decreases with depth* as a result of 1) increasing *H*; 2) attenuation

Vertical resolution

- $\lambda/4$ is generally considered as the vertical resolution limit
- Example: Faults with different amounts of vertical throws, compared to the dominant wavelength:



Horizontal resolution



New!

Subsurface sampling

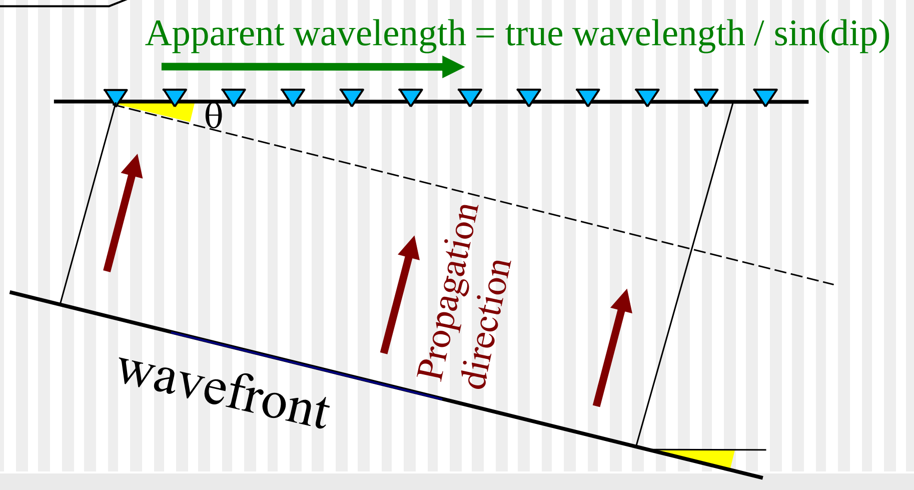
- How to select geophone spacing for a reflection survey?
- Seismic surreys are designed with some knowledge of geology and with specific targets in mind:
  - Limiting factors: velocities, depths, frequencies (thin beds), dips.
- Maximum allowable geophone spacing in order to record reflections from dipping interfaces

$$\left(\text{Geophone Spacing}\right)_{\substack{\max\\ \text{allowed}}} < \frac{\lambda_{apparent}}{2} = \frac{\lambda_{\min}}{2\sin\theta} = \frac{V_{\min}}{2 f_{\max}\sin\theta}$$

- The same, in terms of moveout dt/dx ($\sin\theta = \tan(moveout)$):

$$\left(\text{Geophone Spacing}\right)_{\max} < \frac{1}{2 f_{\max}\frac{dt}{dx}}$$

More conservatively, this factor is usually taken = 4



New!

Voxel
(Elementary cell of seismic volume)

- “Voxel” is determined by the spatial and time sampling of the data
  - For a typical time sampling of 2 ms (3 m two-way at 3000 m/s), it is typically 3 by 15 m^2 in 2D;
  - 3 by 15 by 25 m^3 in 3D
- For a properly designed survey, voxel represents the smallest potentially resolvable volume
  - Note that the Fresnel zone limitation is partially removed by *migration* where sufficiently broad reflection aperture is available
  - Migration is essentially summation of the amplitudes over the Fresnel zones. This summation collapses diffraction hyperbolas laterally
  - Migration is particularly important and successful in 3D