Overview ta3520
Introduction to seismics

- Fourier Analysis
- Basic principles of the Seismic Method
- Interpretation of Raw Seismic Records
- Seismic Instrumentation
- Processing of Seismic Reflection Data
- Vertical Seismic Profiles

Practical:

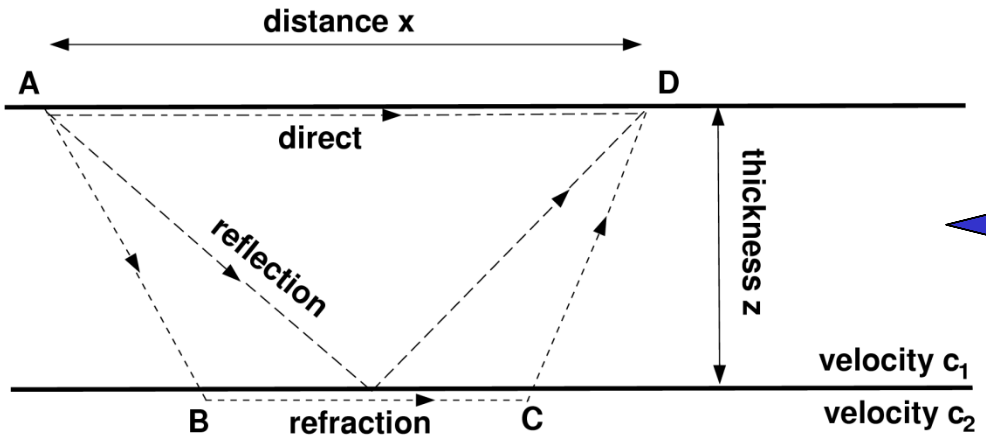
- Processing practical (with MATLAB)

Signal and Noise

Signal: desired
Noise: not desired

So for reflection seismology:
- Primary reflections are signal
- Everything else is noise!

Signal and Noise (2)

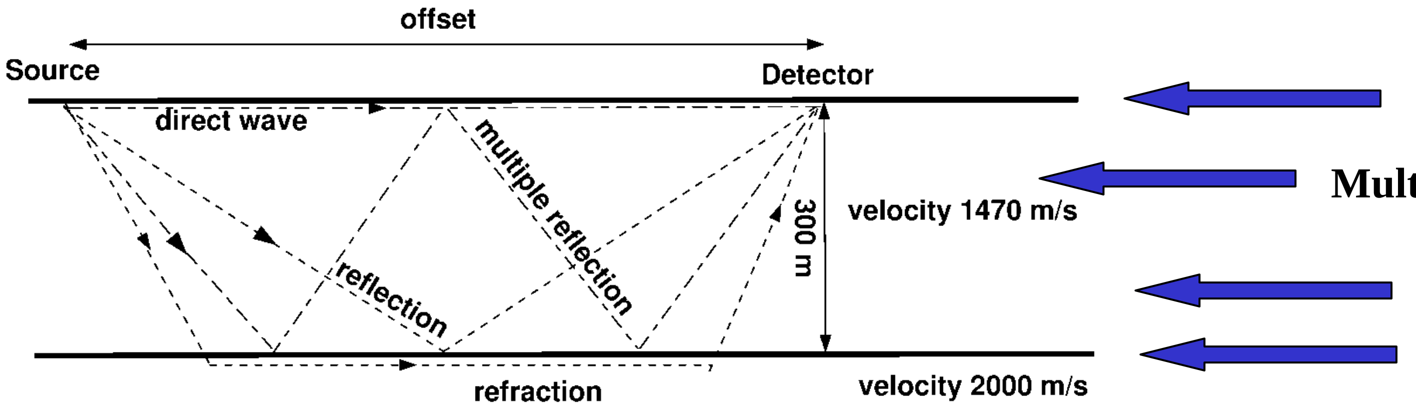


Direct wave: noise

Reflection: (desired) signal

Refraction: noise

Signal and Noise (3)



Direct wave: noise

Multiply reflected : noise

Reflection: signal

Refraction: noise

Signal and Noise for P-wave survey

Desired signal:

- primary reflected P-waves

Noise:

- direct wave through first layer
- direct air wave
- direct surface wave
- S-wave
- Multiply reflected wave
- Refraction / Head wave

Signal and Noise for P-wave survey

$$\frac{\text{Signal}}{\text{Noise}} = \frac{\text{Primary P-wave Reflected Energy}}{\text{All but Primary Reflection Energy}}$$

Goal of Processing:

Remove effects of All-but-Primary-Reflection Energy

Processing of Signal (Primary-reflected energy)

Goal of processing:

Focus energy to where it comes from

Understanding signal and noise: wave theory

Basic physics underlying signal is captured by wave equation

Ray theory: approximation of wave equation (“high-frequency”)
Resonances: modes expansion of wave equation

S-waves, P-waves: elastic form of wave equation

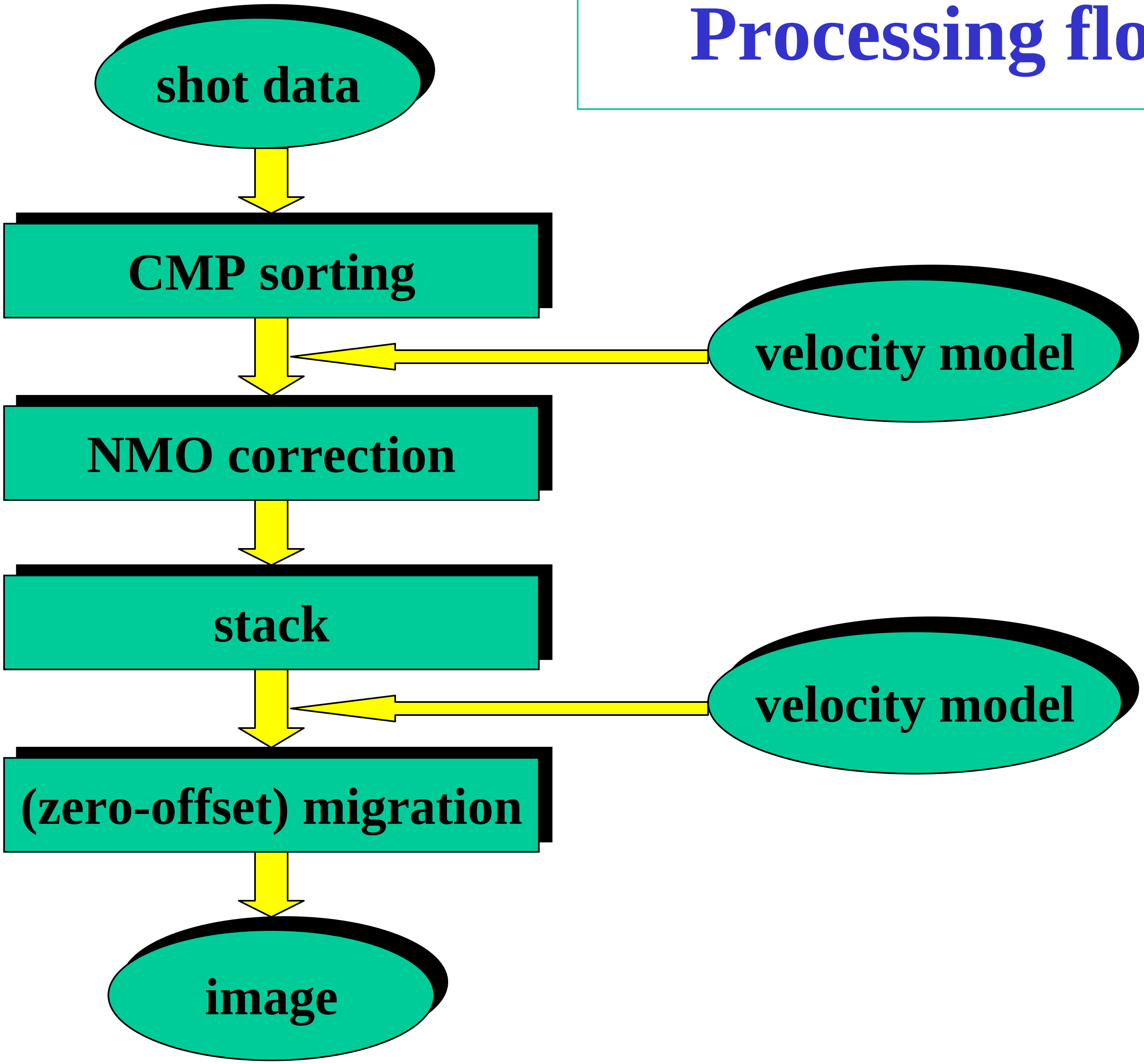
Seismic Processing

- Basic Reflection and Transmission
- Sorting of seismic data
- Normal Move-Out and Velocity Analysis
- Stacking
- (Zero-offset) migration
- Time-depth conversion

Basic Reflection and Transmission

(pdf-file with eqs)

Processing flow



shot data

CMP sorting

velocity model

NMO correction

stack

velocity model

(zero-offset) migration

image

Processing

Input: Multi-offset shot records

Results of processing:

1. Structural map of impedance contrasts

2. Velocity model

Sorting:
Common Shot gather

Seismic recording in the field:

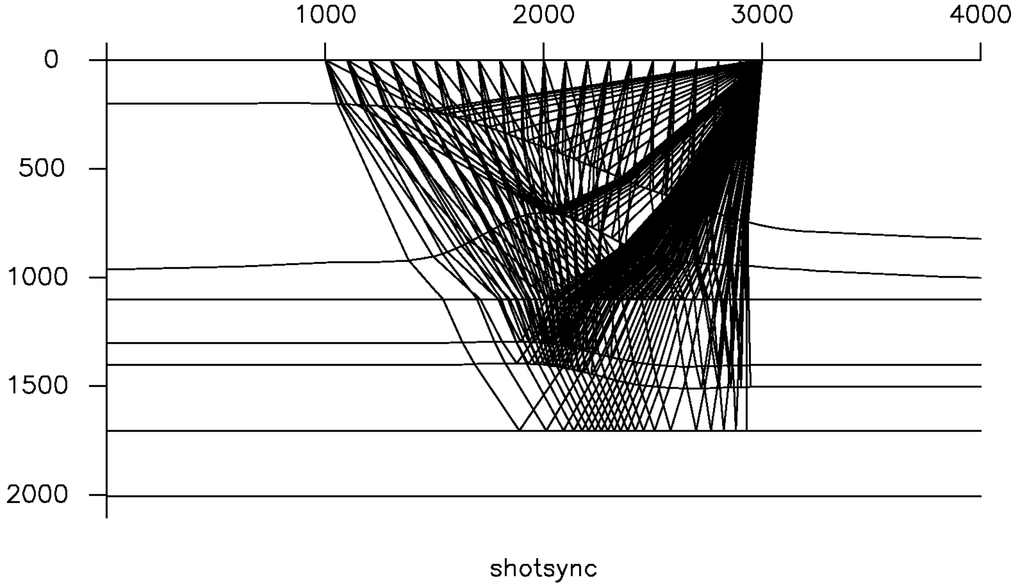
Common Shot data

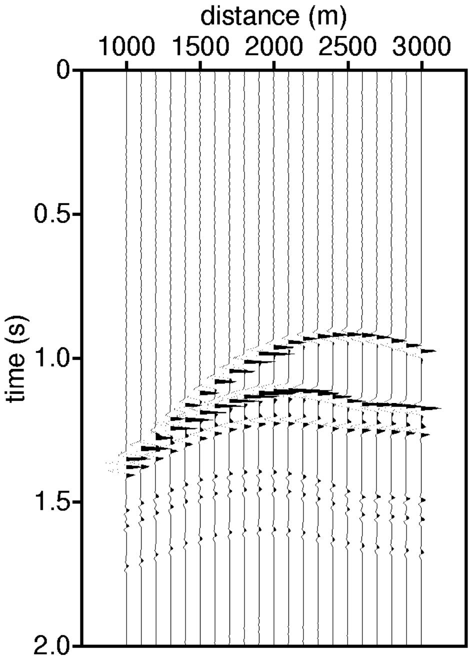
(Each shot is recorded sequentially)

Nomenclature:

- common-shot gather
- common-shot panel

Common Shot gather





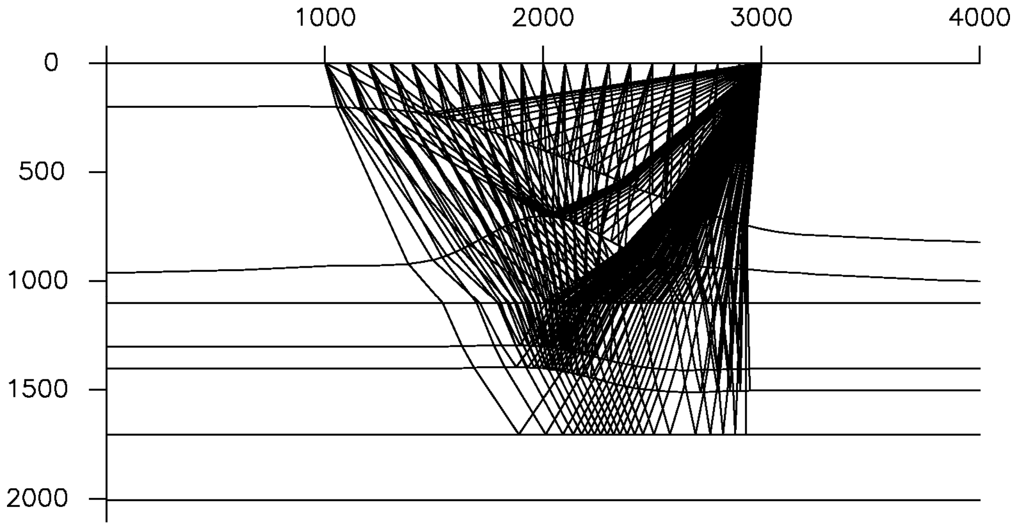
Sorting:
Common Receiver gather

Gather all shots belonging to one receiver position in the field

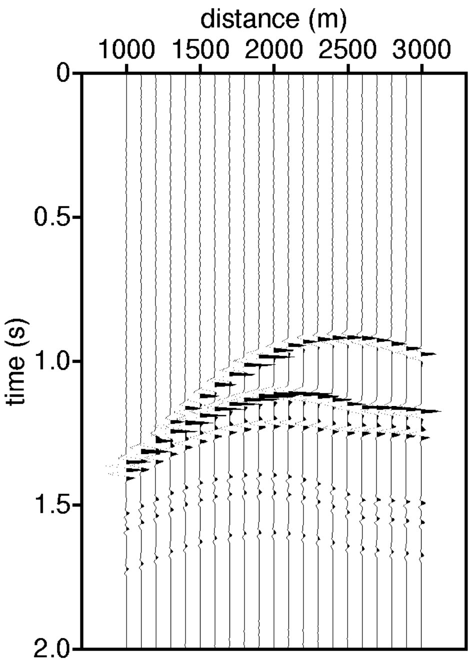
Analysis/Processing: shot variations
(e.g., different charge depths)

(Also in common-shot gathers: receiver variations, e.g.,
geophones placed at different heights)

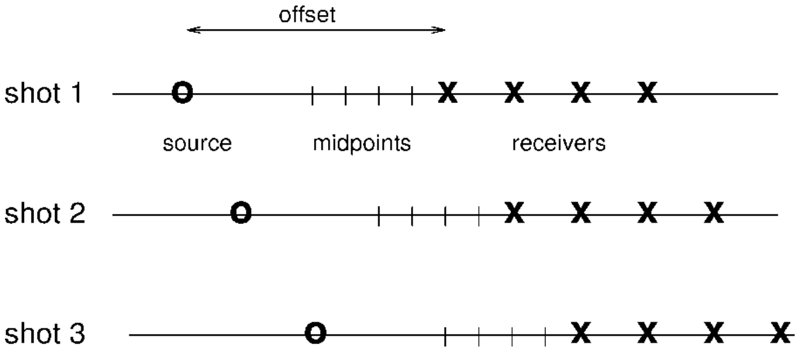
Common Receiver gather



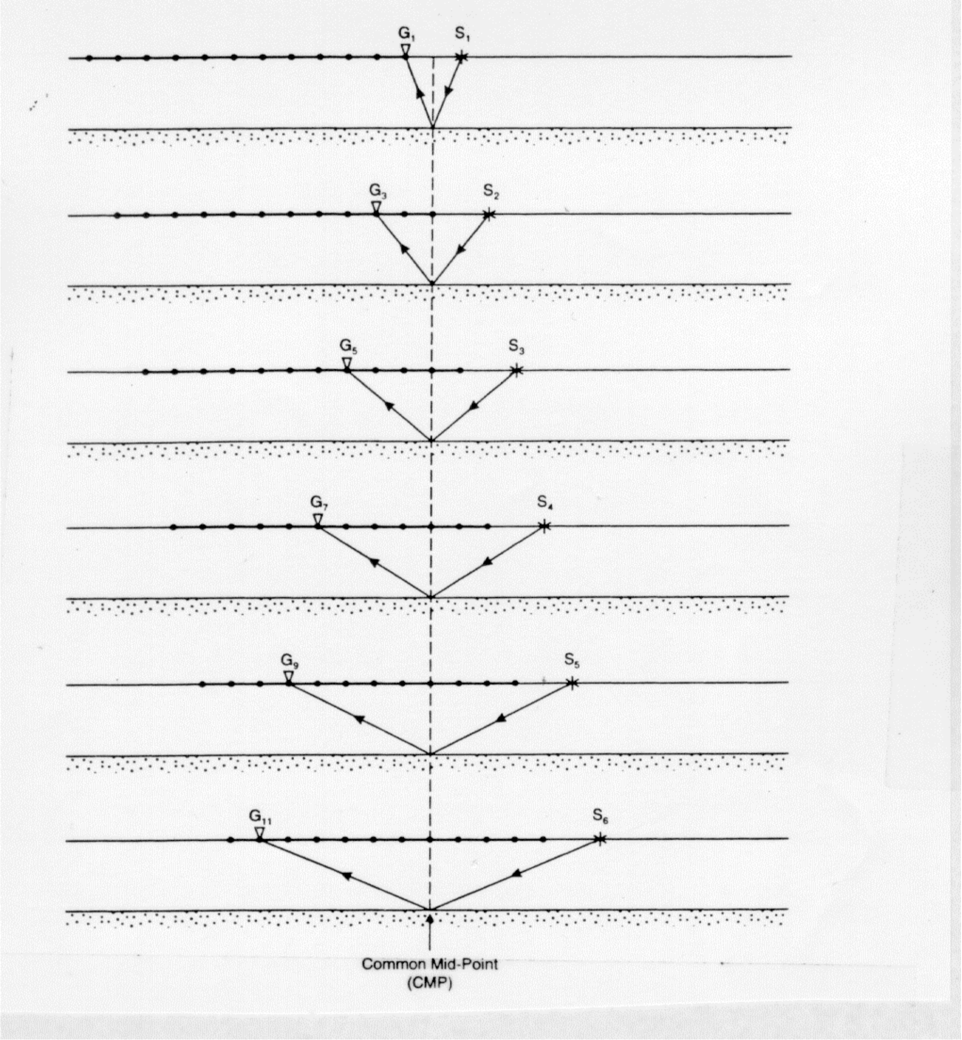
shotsync



Sorting



Sorting:
Common Mid-Point gather



Sorting:
Common Mid-Point gather

Mid-points defined as mid-points between source and receiver in horizontal plane

Since reflections are quasi-hyperbolic:

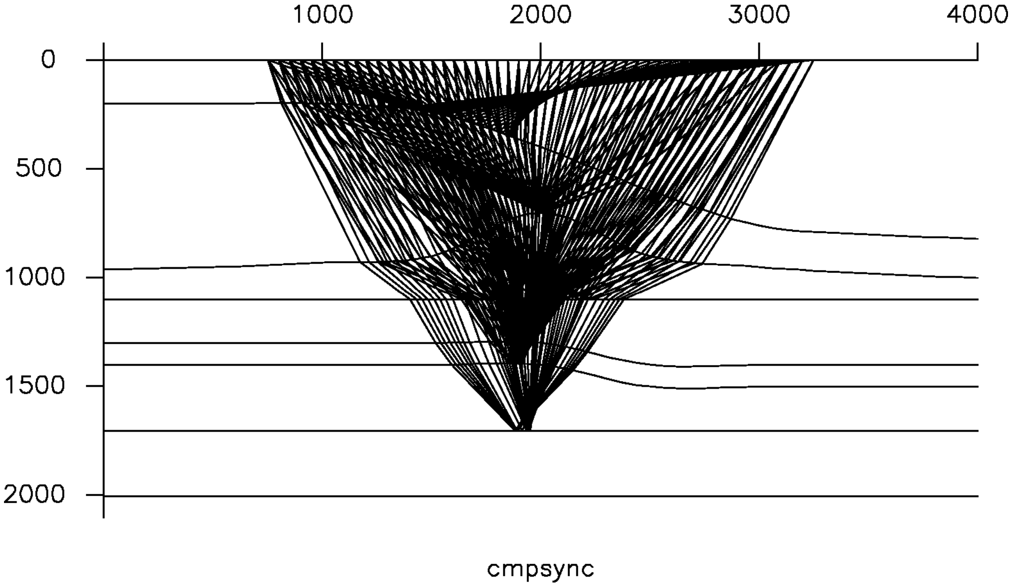
- Seismograms not so sensitive to laterally varying structures

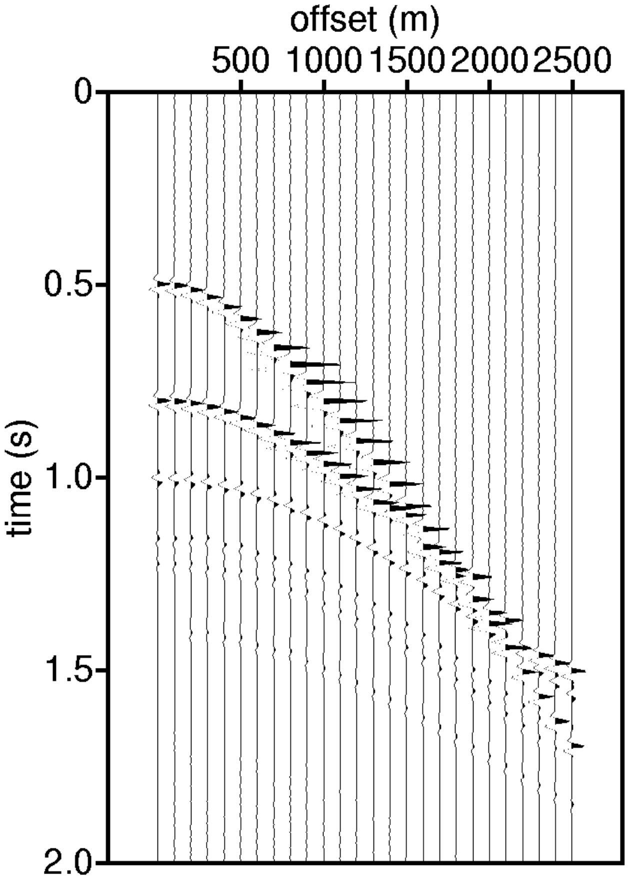
- Good for velocity analysis in depth

- Stacking successful (noise suppression)

In practice, not really a point but an interval: BIN

CMP gather over structure





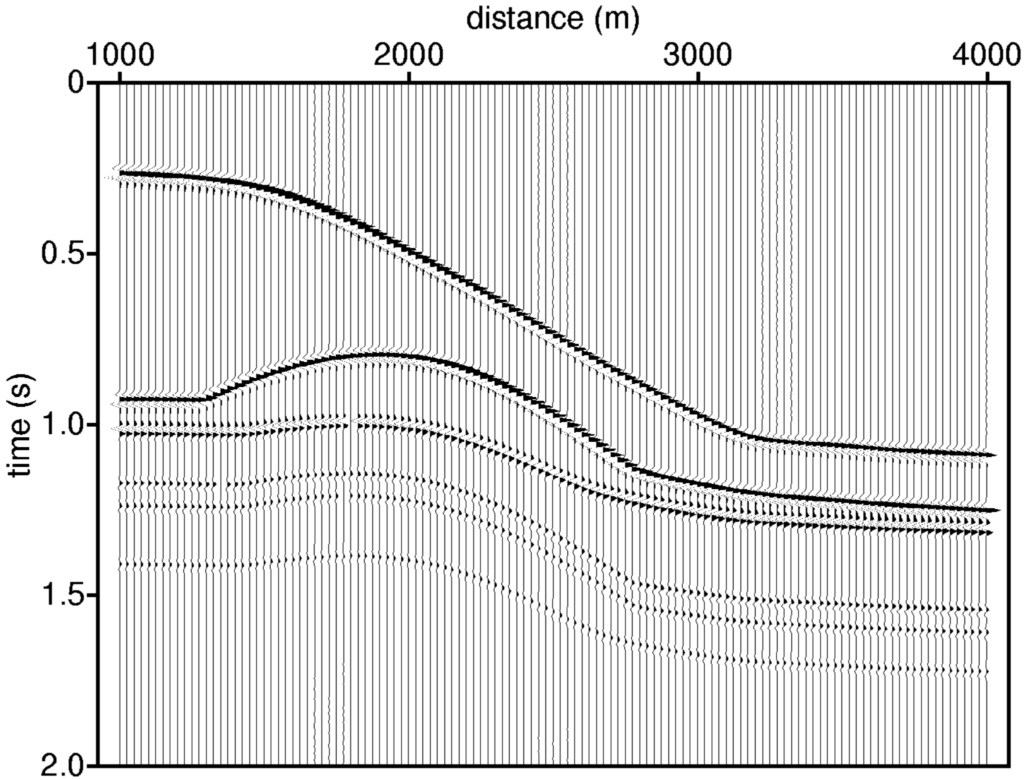
Sorting:
Common Offset gather

Purpose:

- Very irregular structures (in which stacking does not work)
- Application of Dip Move-Out (correction for dip of reflector)
- Checking on migration: small and large offsets should give the same picture : otherwise velocities are wrong

In practice, not really a point but an interval: BIN

Zero-offset gather over structure



Sorting

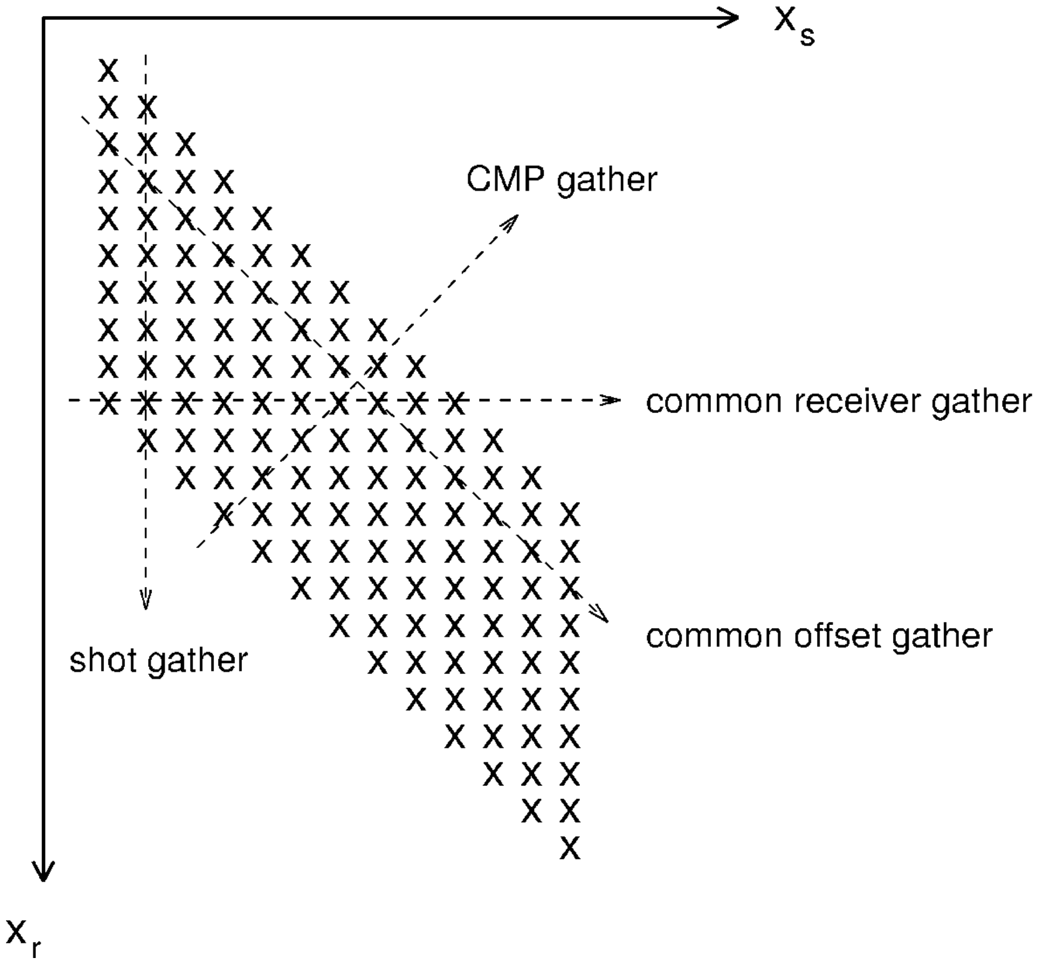
Common-Mid-Point (CMP) gathers: $x_s + x_r = constant$

Common-Offset gathers (COG): $x_s - x_r = constant$

Multiplicity = Fold: $$\frac{N_{rec}}{2\ \Delta x_s / \Delta x_r}$$

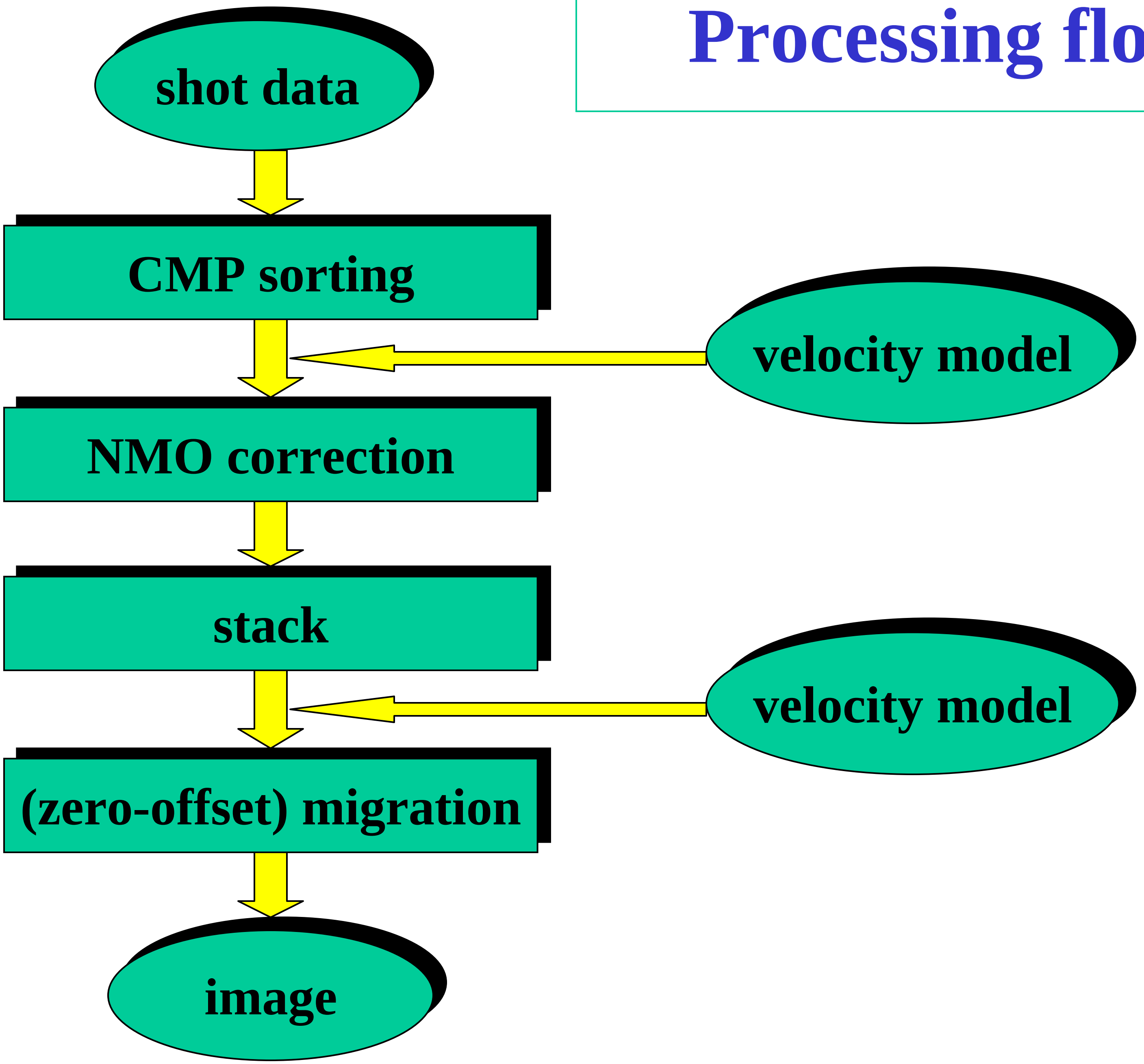
N_{rec} = Number of receivers
Δx_s = Spacing between subsequent shots
Δx_r = Spacing between subsequent receivers

Sorting



x_s
x_r
CMP gather
common receiver gather
common offset gather
shot gather

Processing flow



shot data

CMP sorting

velocity model

NMO correction

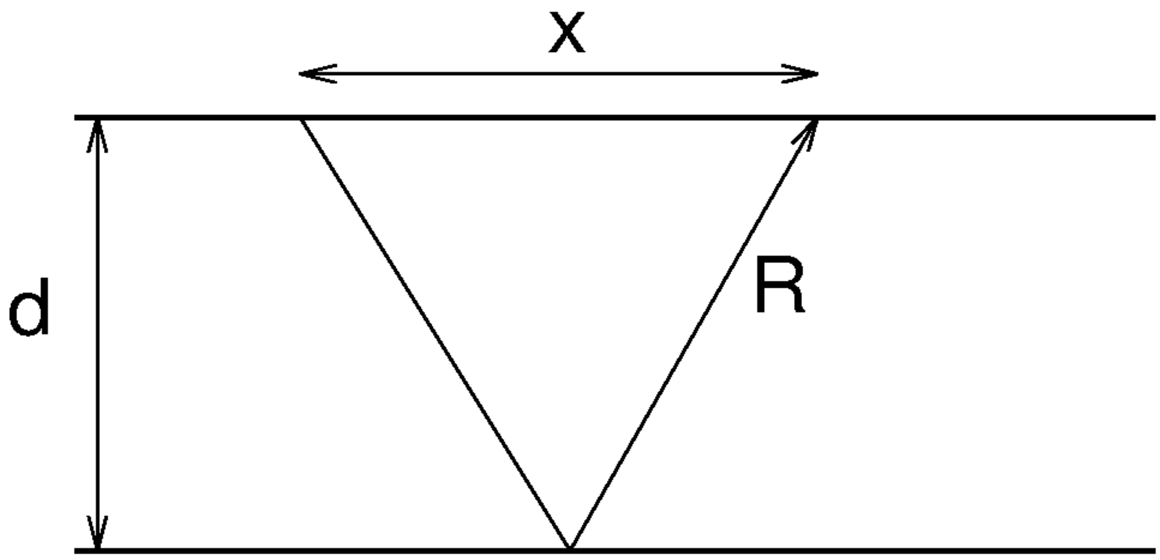
stack

velocity model

(zero-offset) migration

image

Reflection 1 boundary



Normal Move-Out: 1 reflector

$$T = \frac{R}{c} = \frac{(4d^2 + x^2)^{1/2}}{c}$$

x = source-receiver distance
R = total distance travelled by ray
d = thickness of layer
c = wave speed

We do not know distance, but we know time:

$$T = T_0 \left(1 + \frac{x^2}{c^2 T_0^2} \right)^{1/2}$$

where T_0 is zero-offset (x=0) traveltime: $T_0 = 2d/c$

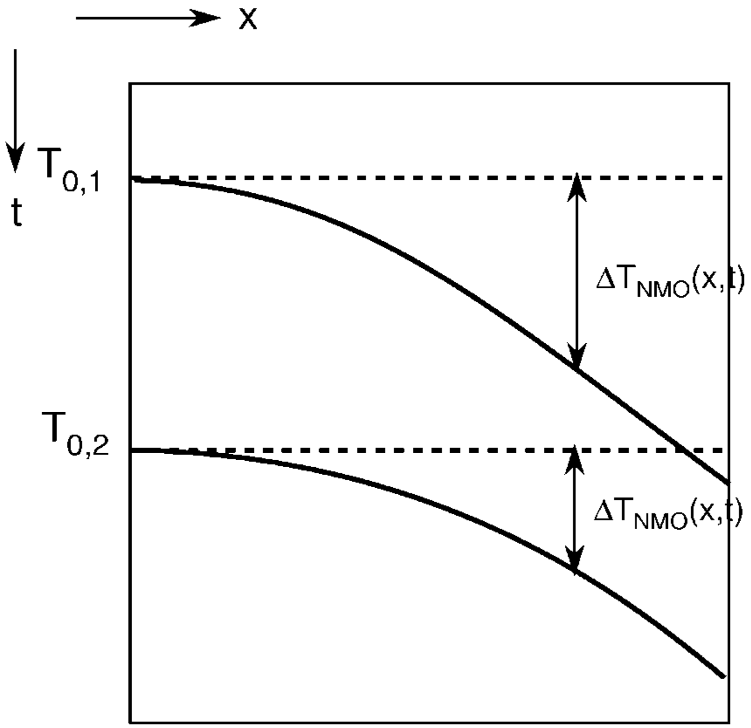
$$T = T_0 \left(1 + \frac{x^2}{c^2 T_0^2} \right)^{1/2}$$

Extra time shift compared to T_0 called:

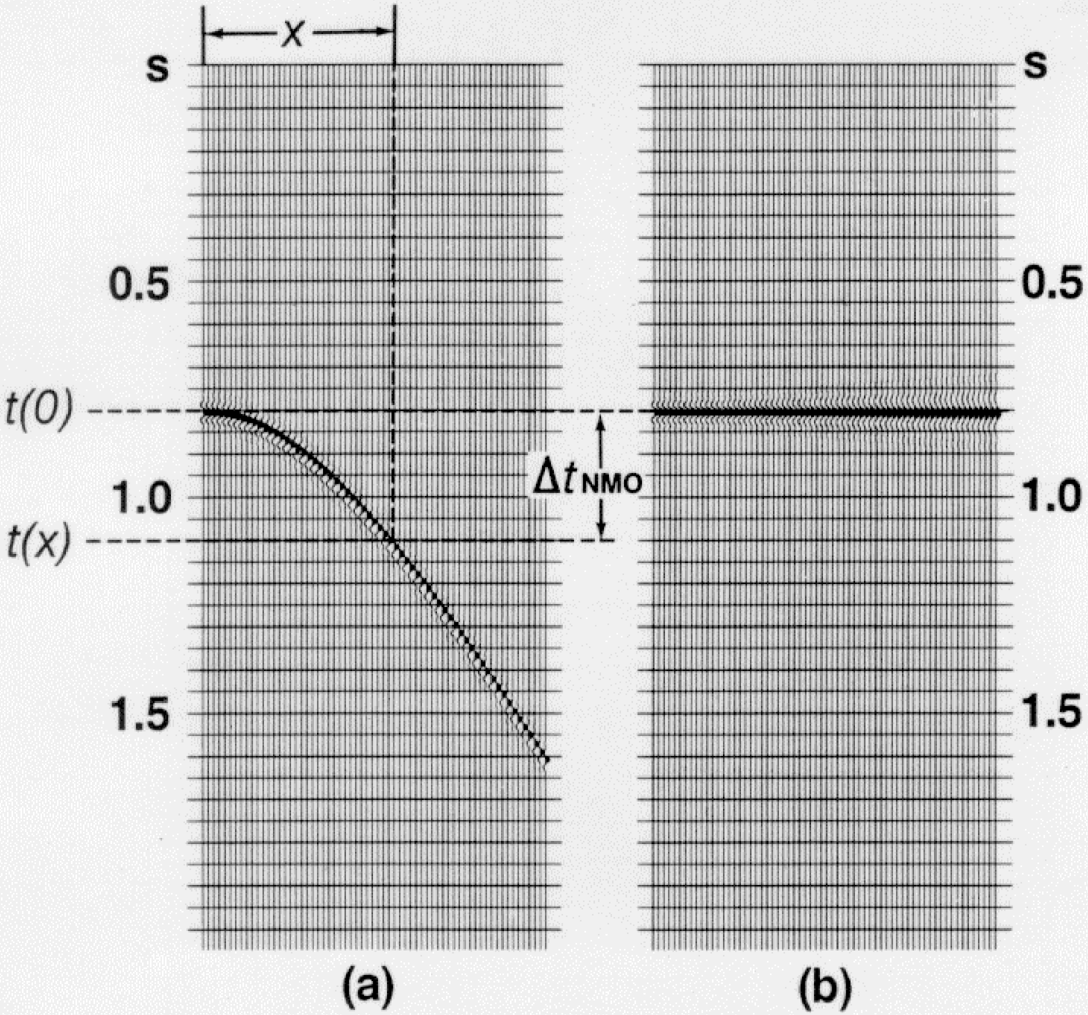
NMO- Normal Move-Out

$$\Delta T_{NMO} = T - T_0 = T_0 \left(1 + \frac{x^2}{c^2 T_0^2} \right)^{1/2} - T_0$$

Normal Move-Out (NMO)



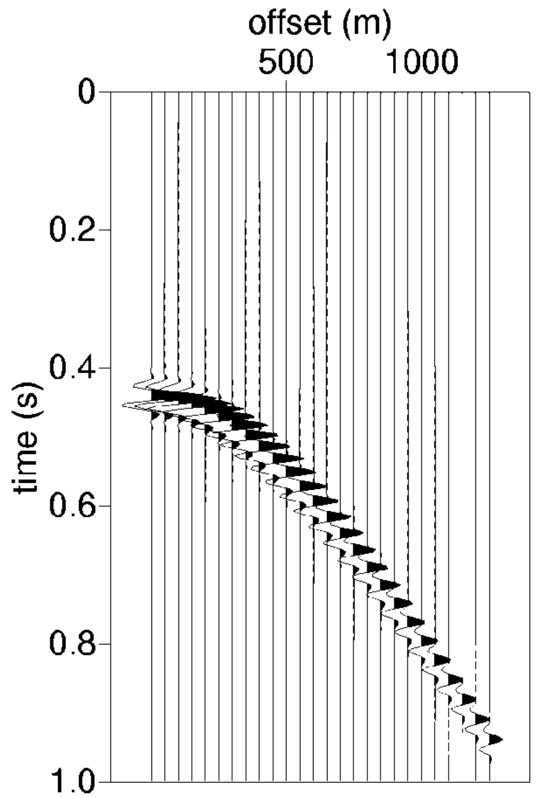
Normal Move-Out (NMO)



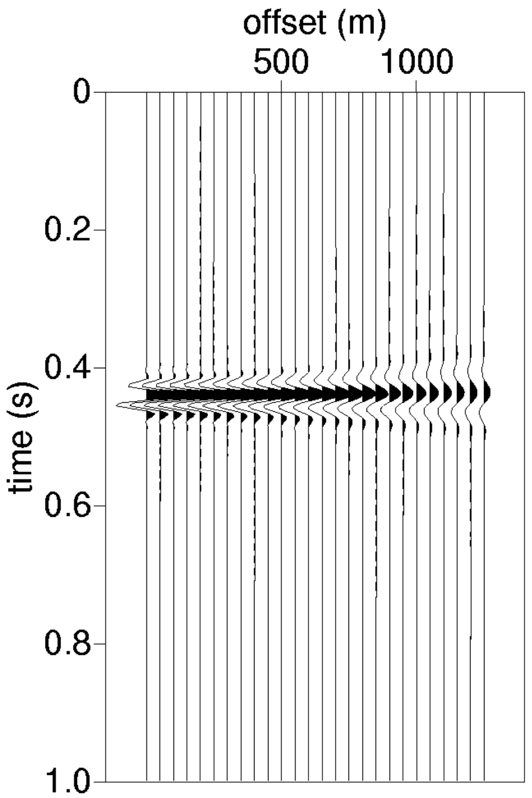
$$\Delta T_{NMO} = T - T_0 = T_0 \left(1 + \frac{x^2}{c^2 T_0{}^2} \right)^{1/2} - T_0$$

- Larger ΔT_{NMO} for larger offset
- Smaller ΔT_{NMO} for larger T_0
  (deeper layers have smaller move-out)
- Smaller ΔT_{NMO} for larger wave speed c
  (deeper layers usually larger velocities so smaller move-out)

Normal Move-Out (NMO)

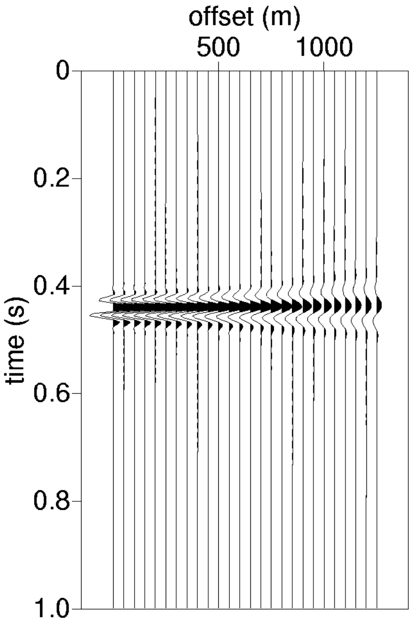


Input CMP-gather

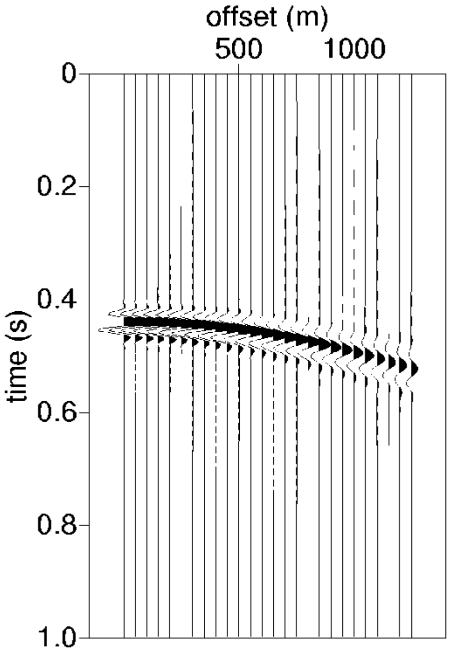


NMO-corrected CMP gather
(with right velocity)

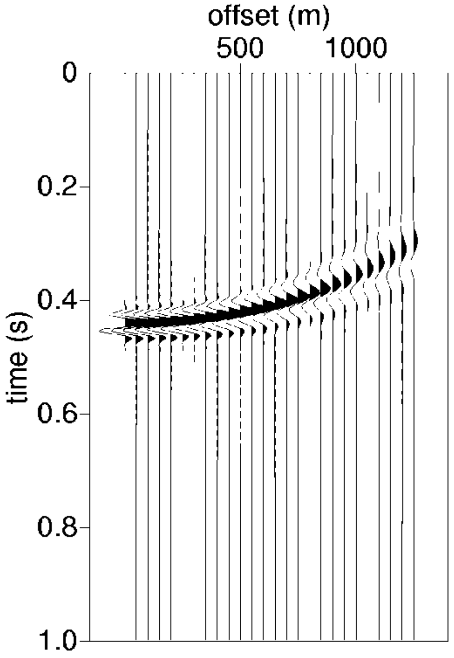
NMO: effect velocity



NMO with right velocity



NMO with too small correction: too high velocity



NMO with too large correction: too small velocity

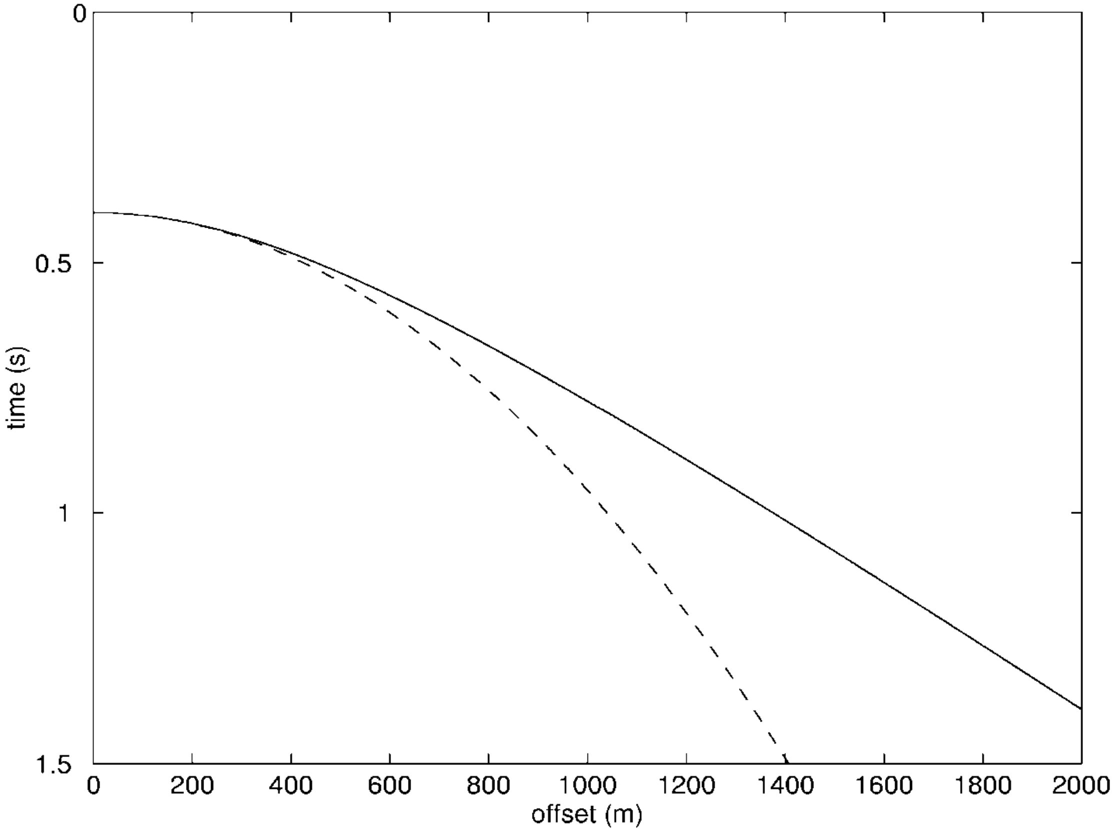
NMO: 1-layer approximation

$$\Delta T_{NMO} = T - T_0 = T_0 \left(1 + \frac{x^2}{c^2 T_0^2} \right)^{1/2} - T_0$$

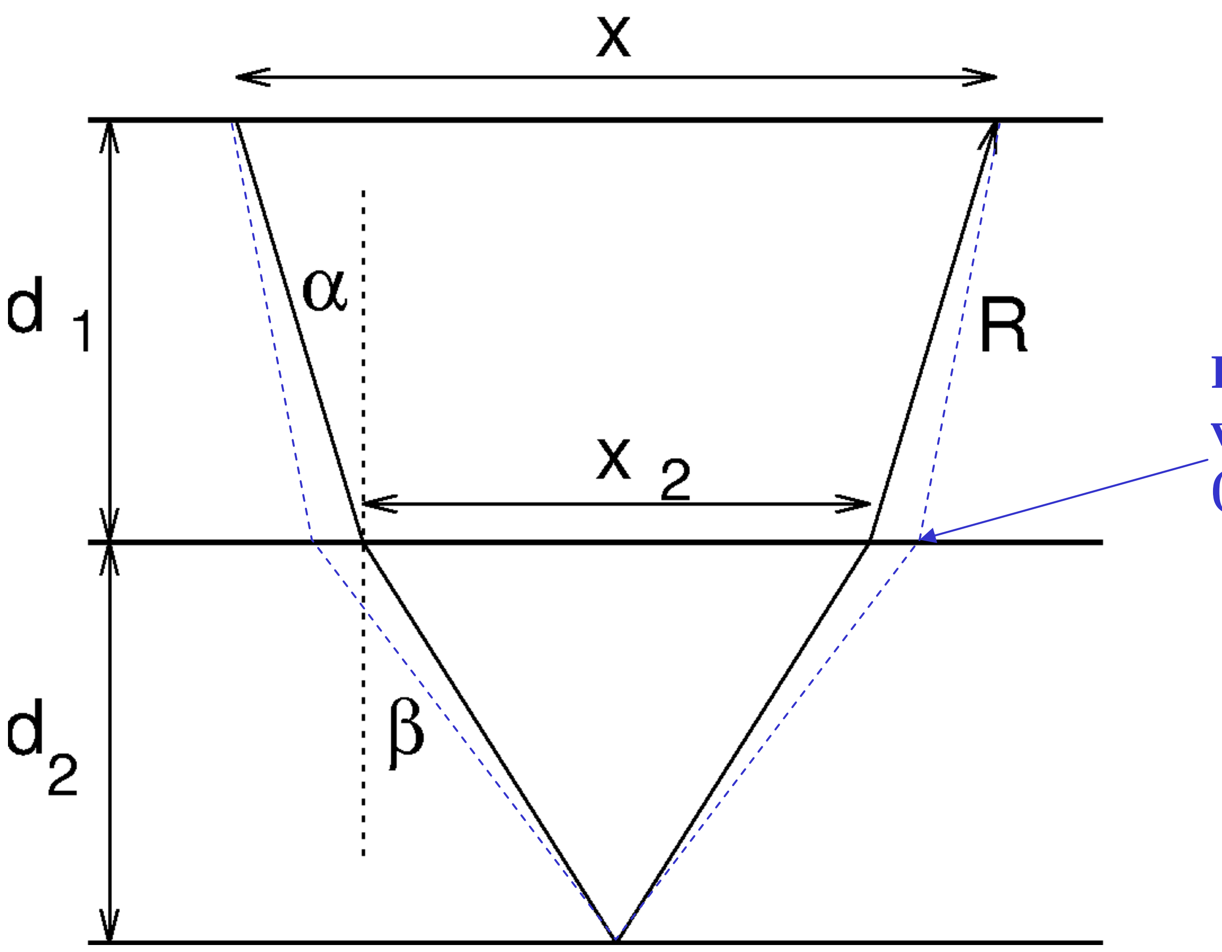
Use Taylor expansion of square root:

$$\Delta T_{NMO} = T - T_0 \approx T_0 \left(1 + \frac{x^2}{2 c^2 T_0^2} \right) - T_0 = \frac{x^2}{2 c^2 T_0}$$

NMO: 1-layer approximation



NMO: 2-layer

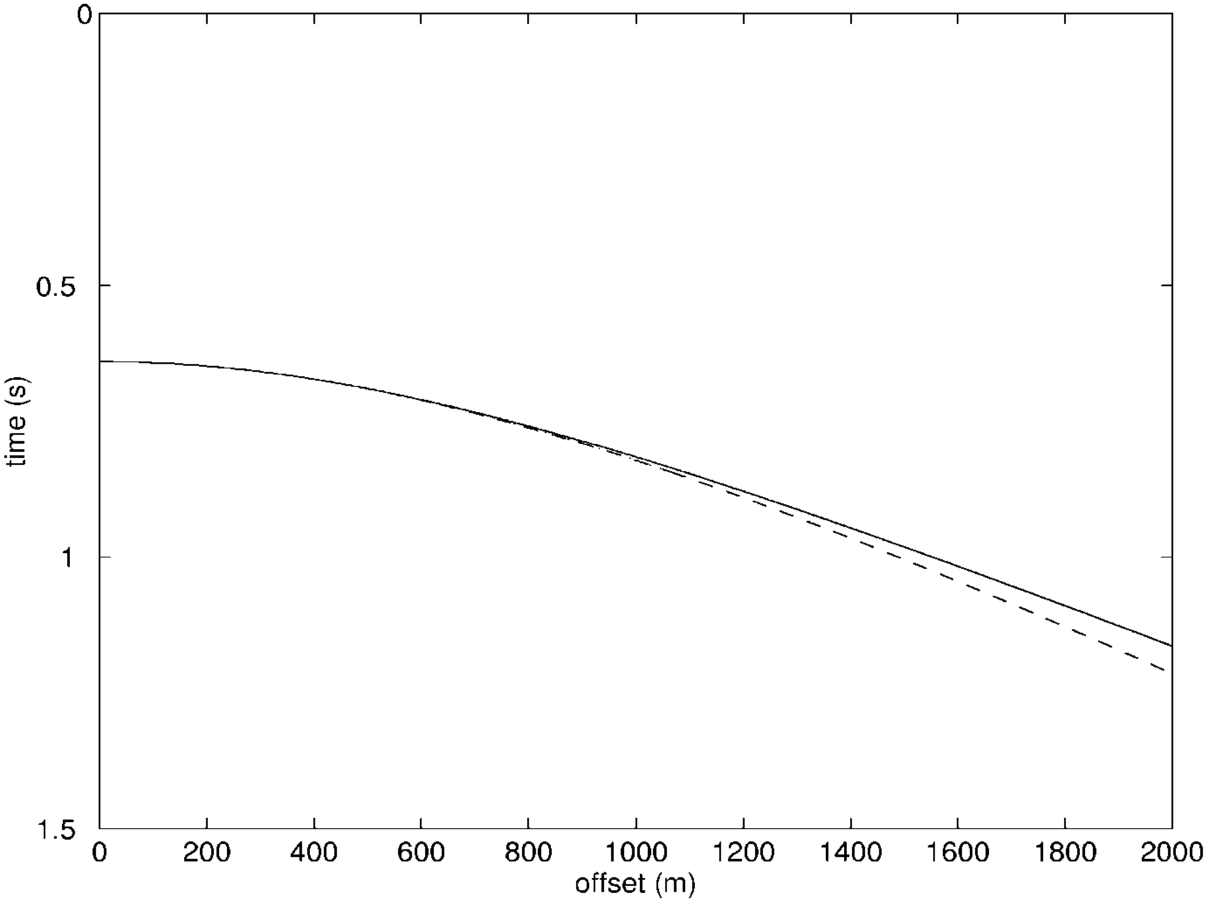


Position depends on velocities of layer 1 and 2 (via Snell's Law)

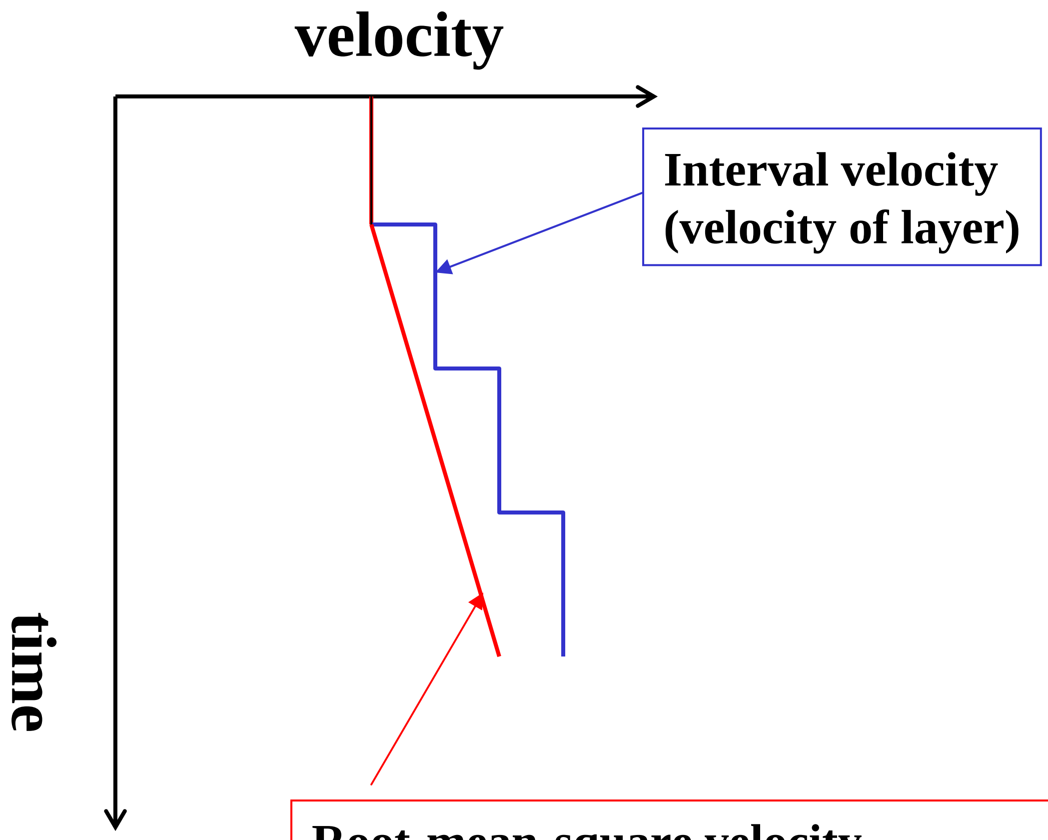
NMO: 2-layer

(pdf-eqs)

NMO: multi-layer approximation



Velocity model: RMS model



Interval velocity (velocity of layer)

Root-mean-square velocity (weighted-average velocity of layers above)

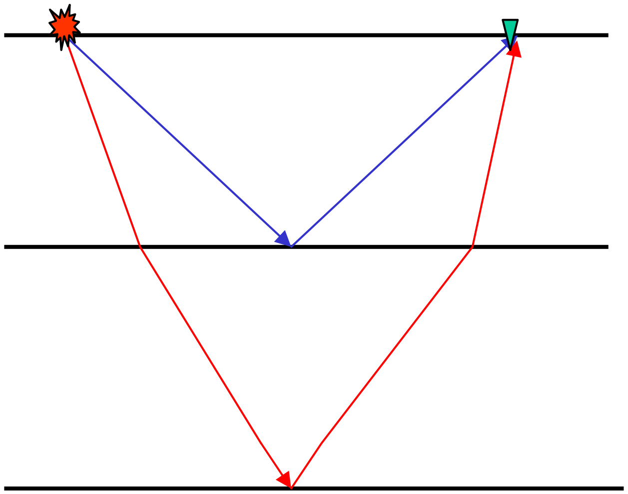
Velocity Analysis

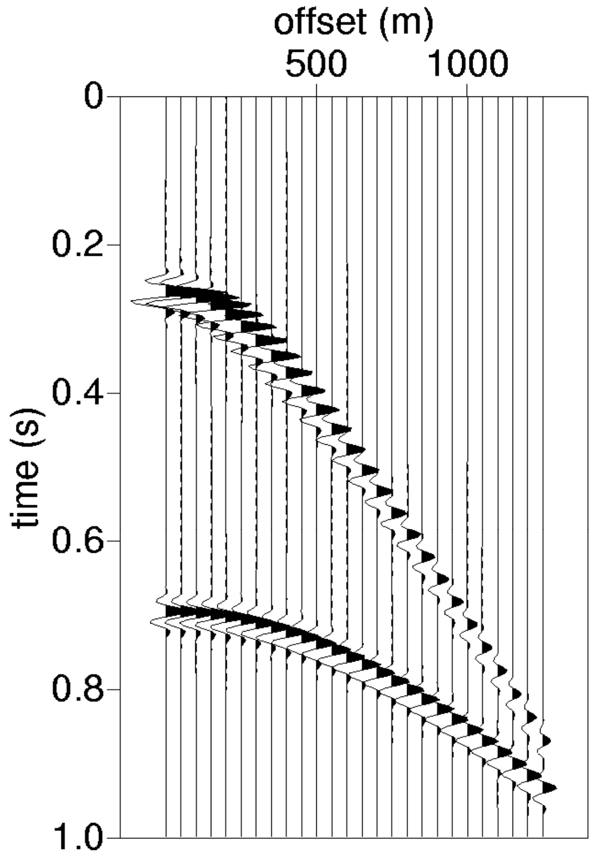
Approaches:

- **$T^2 - x^2$ analysis**
- **Alignment of reflectors: visually or mathematical expression of coherence**

With $T^2 - X^2$ analysis we depend on picking travel-times, and thus signal-to-noise ratio

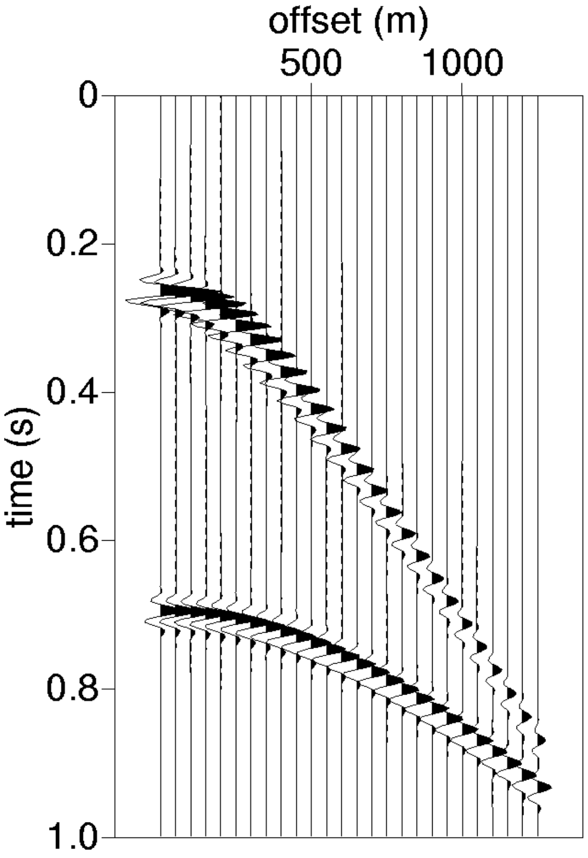
Velocity Analysis:
Original CMP gather

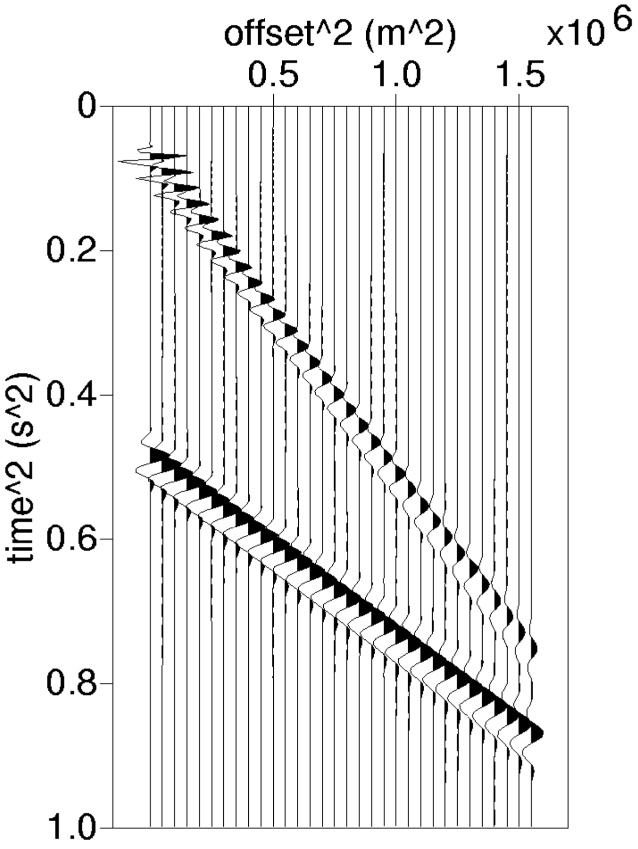




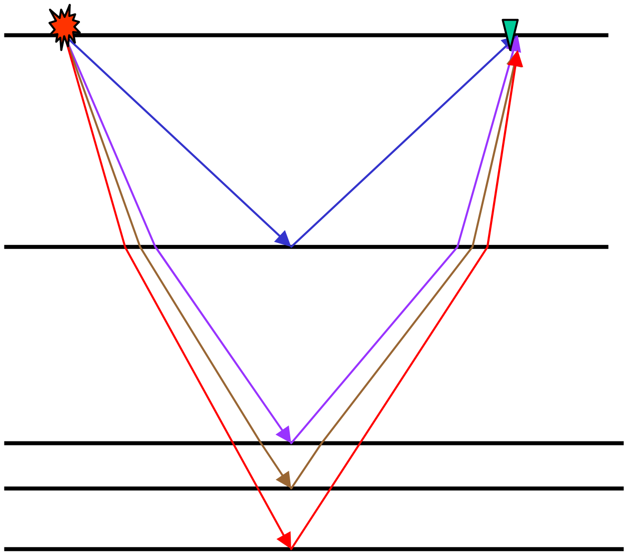
Starting CMP gather

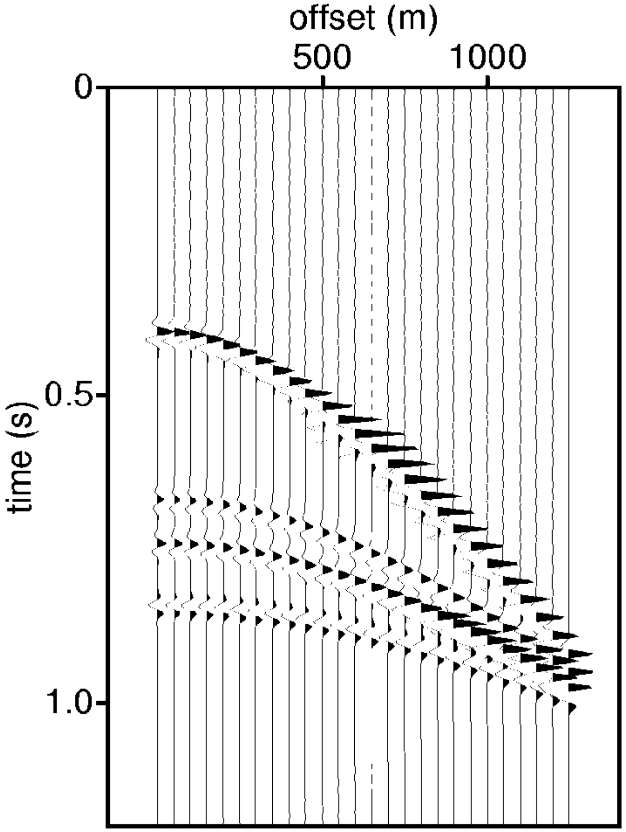
T^2-x^2 analysis





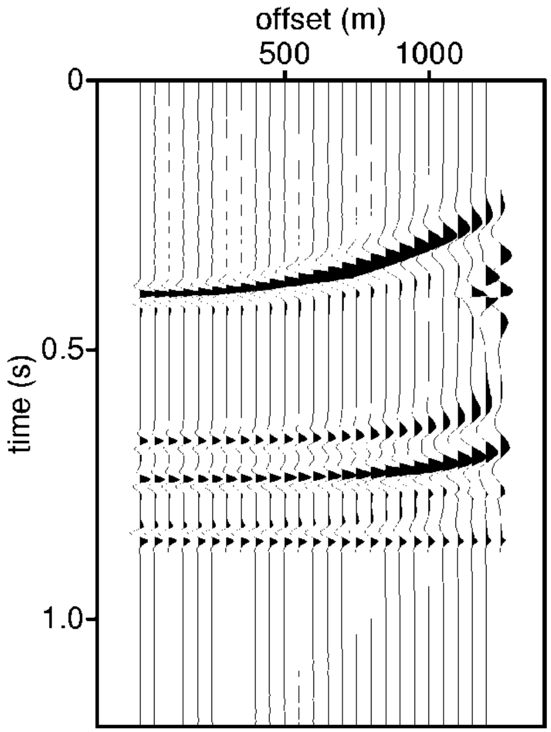
Velocity Analysis: aligning reflectors



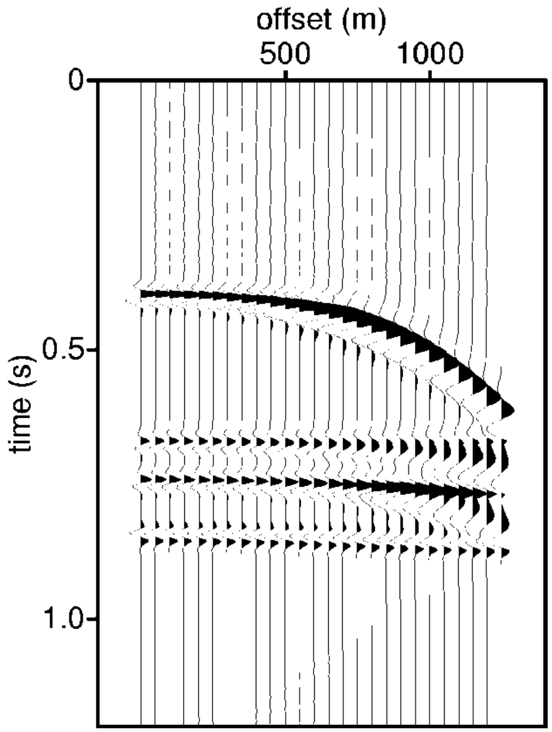


Starting CMP gather

Constant-velocity NMO

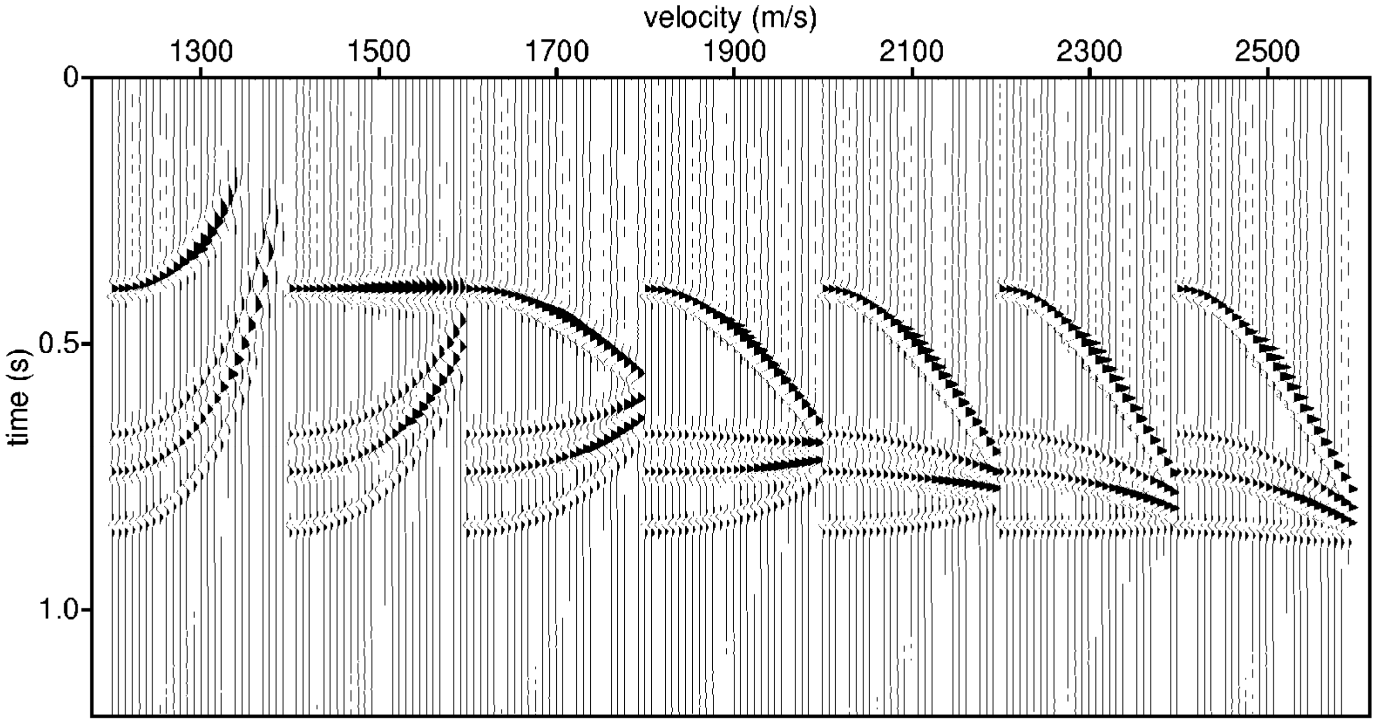


Velocity too low: correction too much



Velocity too high: correction too little

Velocity panels

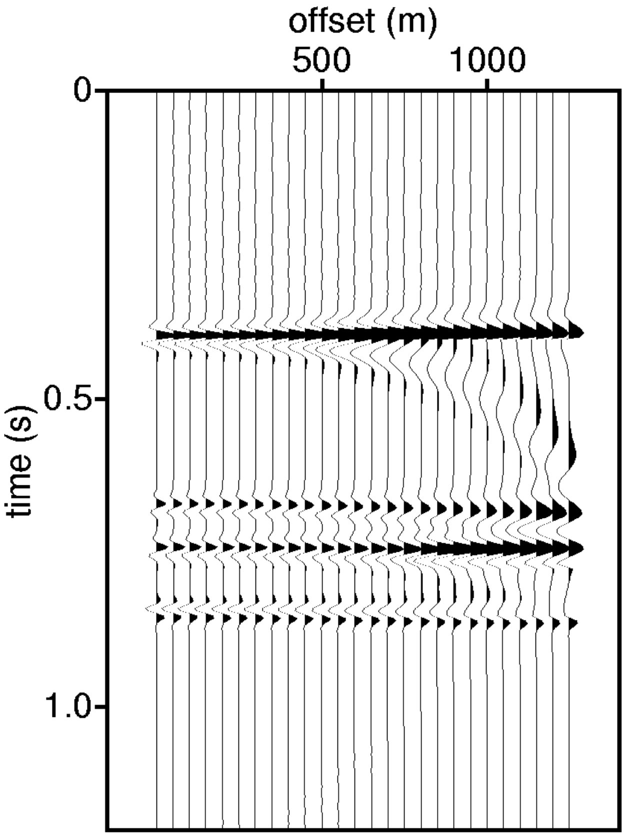


CMP gather with velocity 1300 m/s

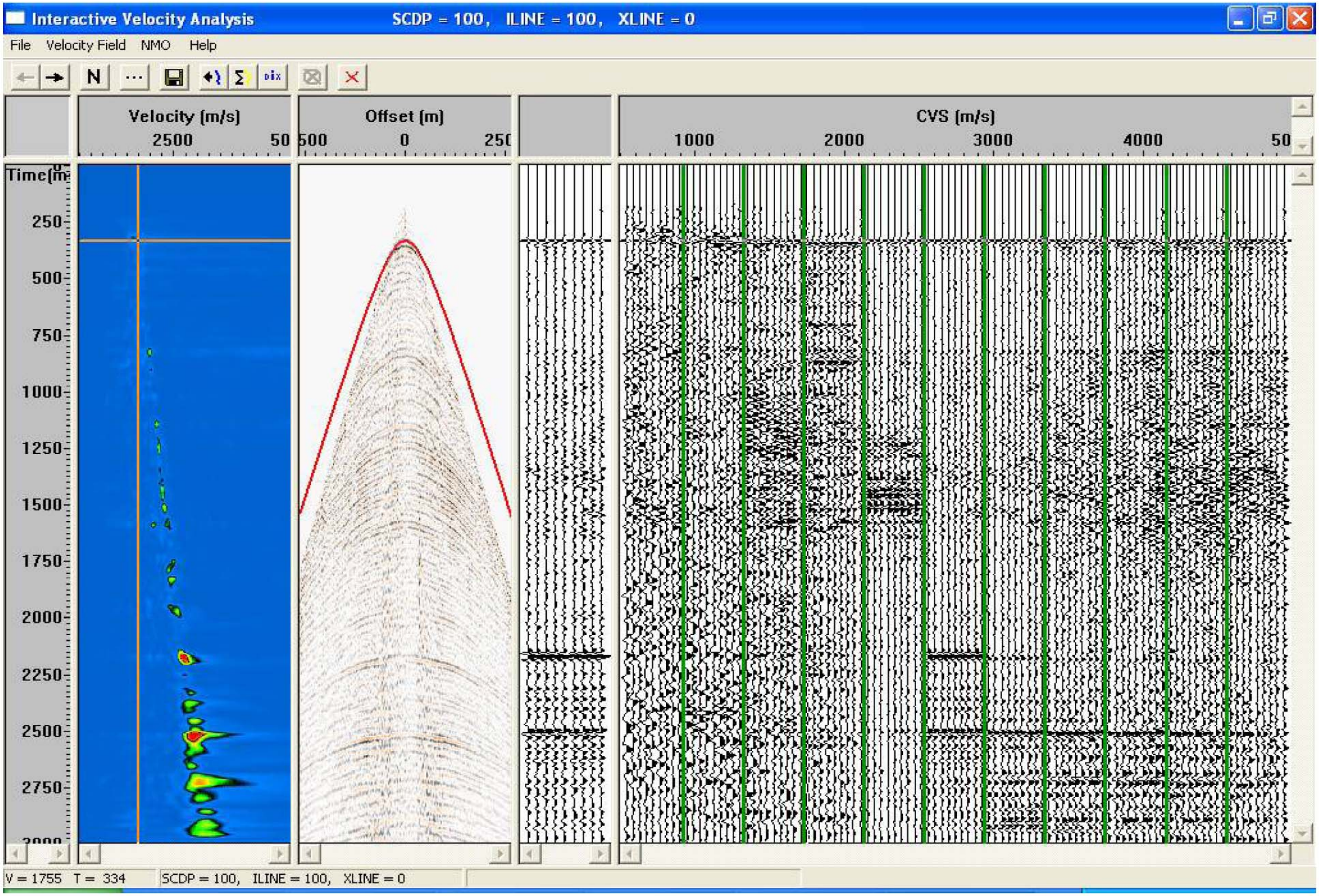
CMP gather with velocity 1700 m/s

CMP gather with velocity 2100 m/s

Velocity as function of time



Velocity panels:real data example



Coherence measures for velocity analysis

- **Stacked amplitude (normalized or not)**
- **Cross-correlation (normalized or not)**
- **Semblance:**

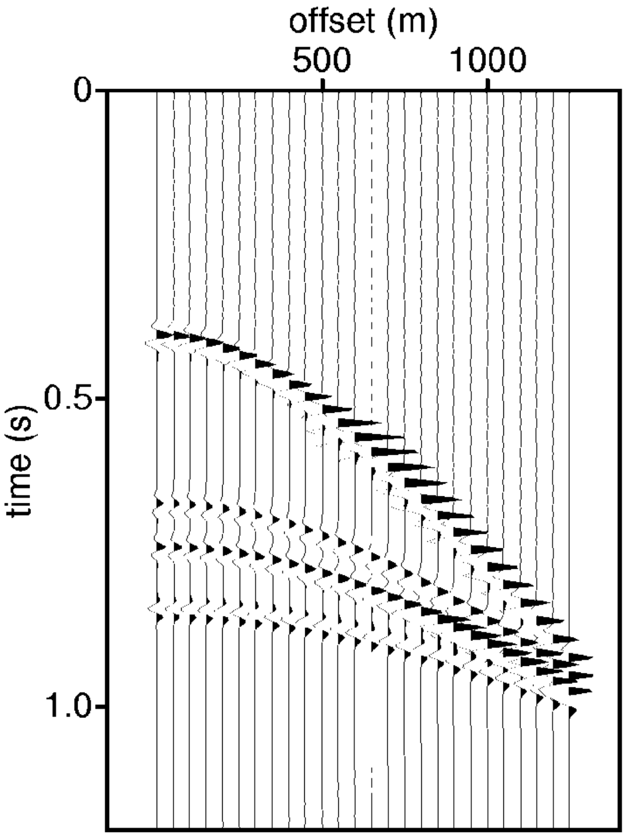
  related to cross-correlation

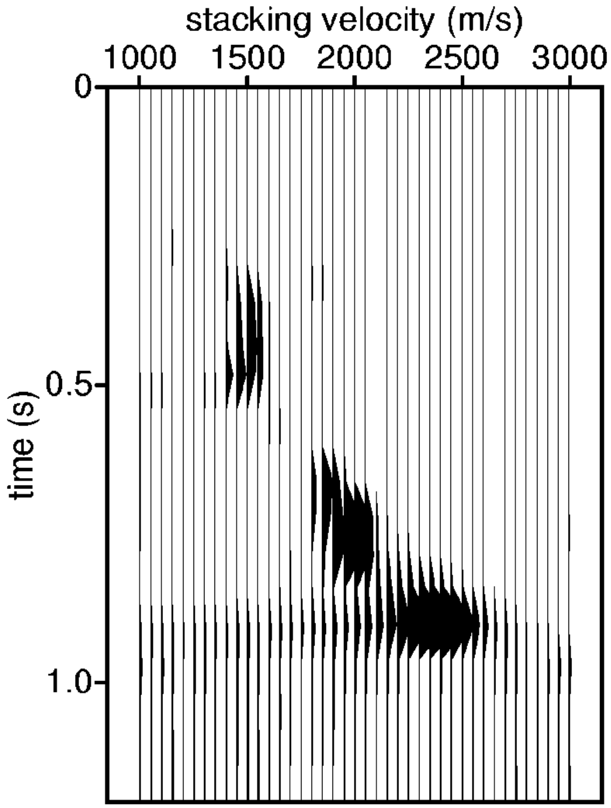
$$S(t, c) = \frac{1}{M} \frac{\left(\Sigma_m A(x_m, t, c) \right)^2}{\Sigma_m A^2(x_m, t, c)}$$

A = amplitude

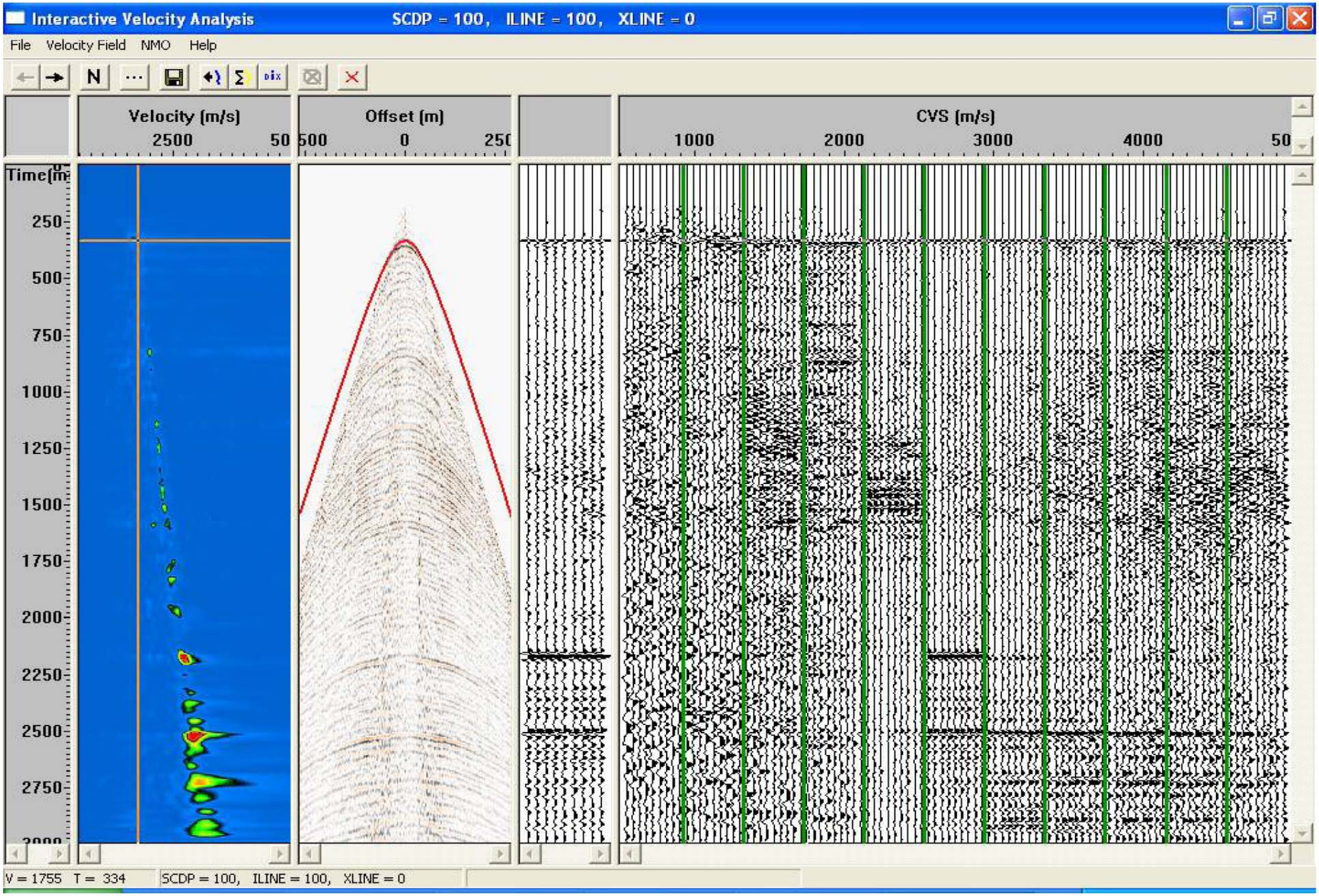
Sum Σ_m over traces m in CMP

Semblance for CMP gather





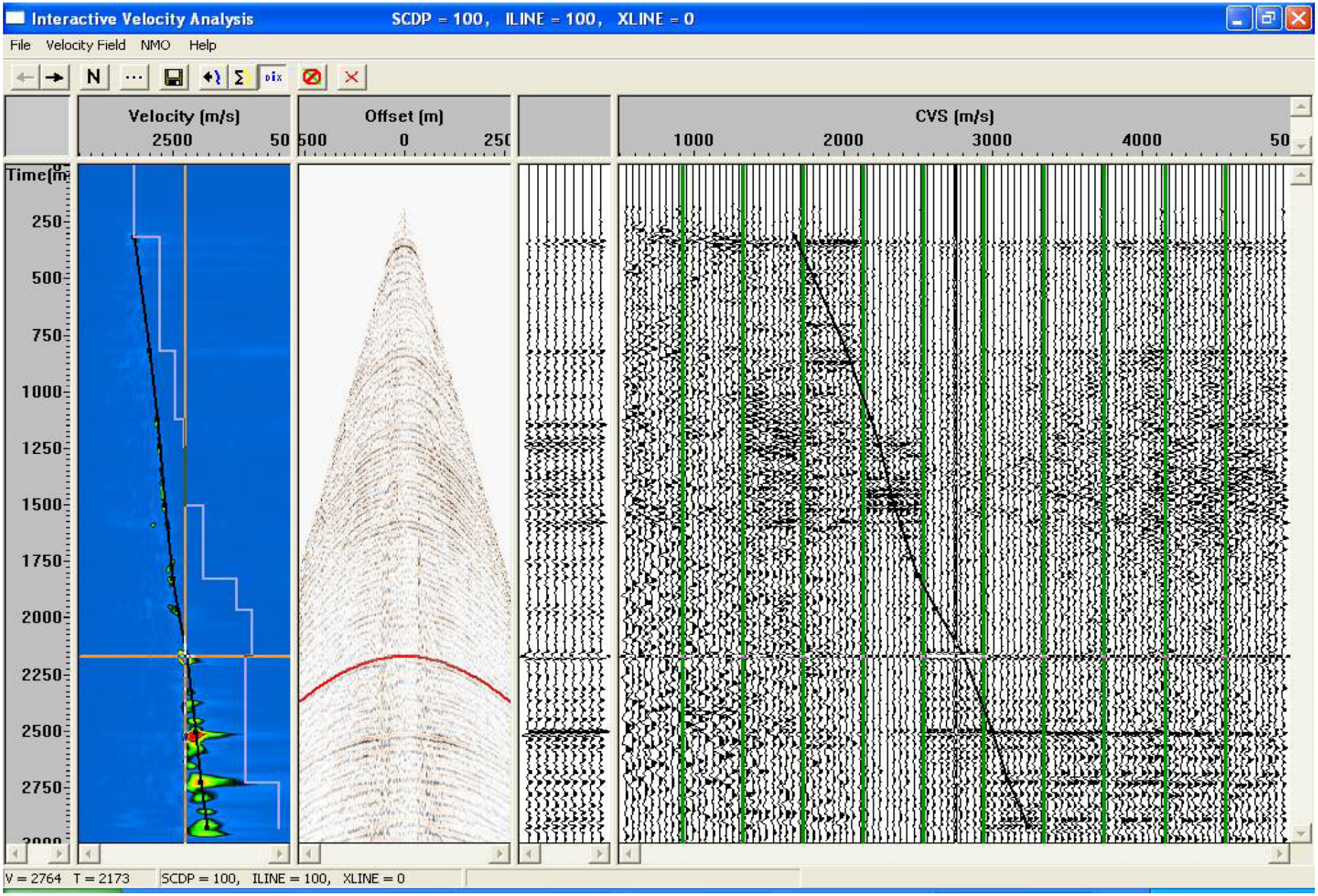
Velocity panels:real data example



SCDP = 100, ILINE = 100, XLINE = 0

V = 1755 T = 334 SCDP = 100, ILINE = 100, XLINE = 0

Velocity panels:real data example

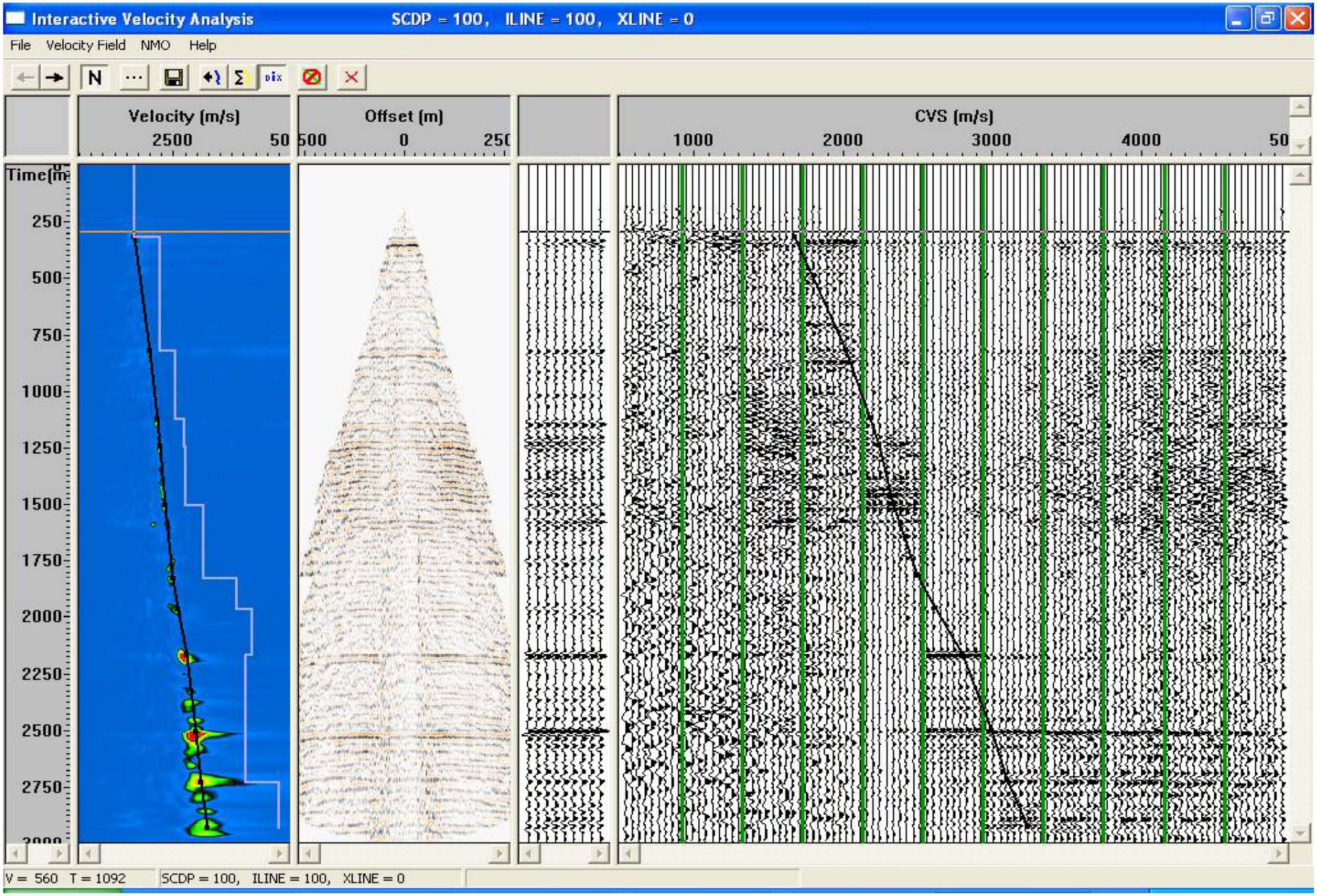


SCDP = 100, ILINE = 100, XLINE = 0

V = 2764 T = 2173

SCDP = 100, ILINE = 100, XLINE = 0

Velocity panels:real data example



Interactive Velocity Analysis SCDP = 100, ILINE = 100, XLINE = 0

V = 560 T = 1092 SCDP = 100, ILINE = 100, XLINE = 0

Factors affecting velocity estimation

(Yilmaz, 1988)

- **Spread length**
- **Stacking fold / Signal-to-Noise ratio**
  (fold = multiplicity in CMP)
- **Choice of coherence measure**
- **Departures from hyperbolic move-out**
- **NMO stretch**

Effect spread length on velocity estimation

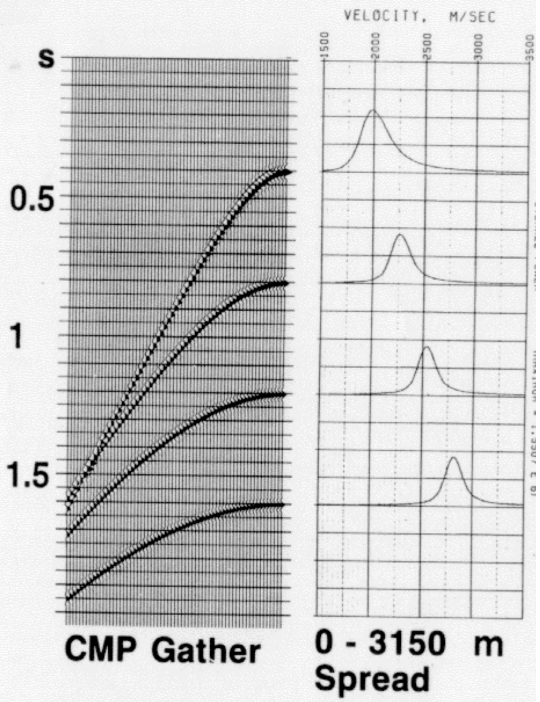


FIG. 3-32. Effect of spread length on velocity resolution. Lack of long offsets causes loss of resolution, especially at later times.

Effect spread length on velocity estimation

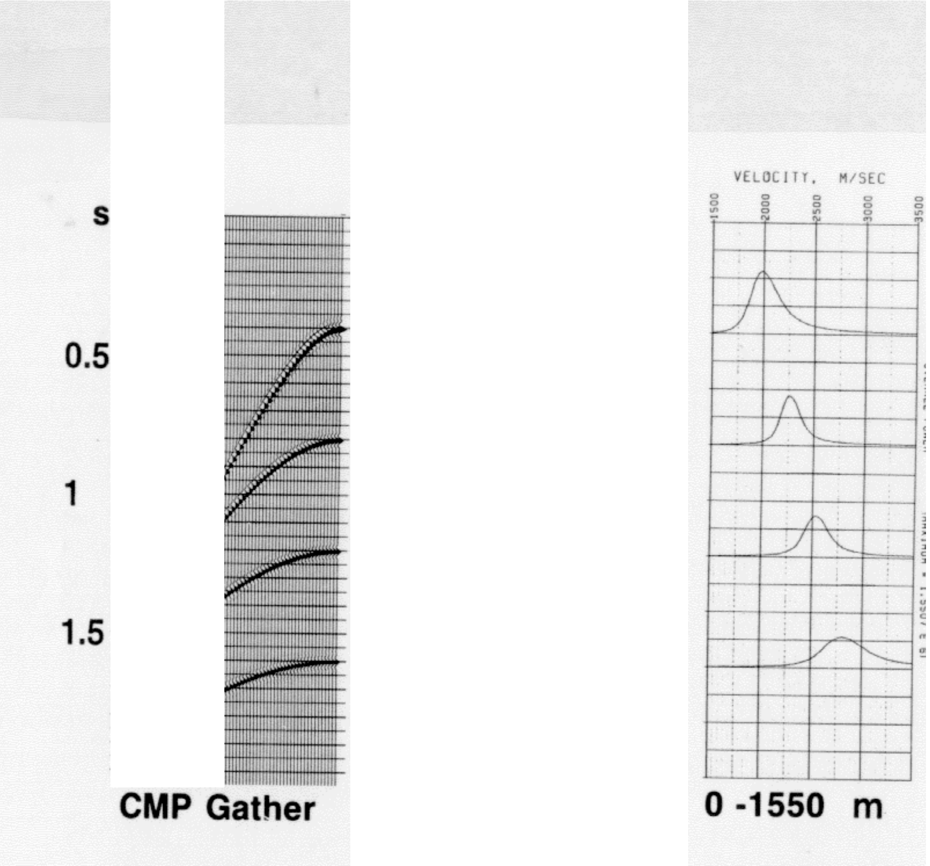


FIG. 3-32. Effect of spread length on velocity resolution. Lack of long offsets causes loss of resolution, especially at later times.

Effect spread length on velocity estimation

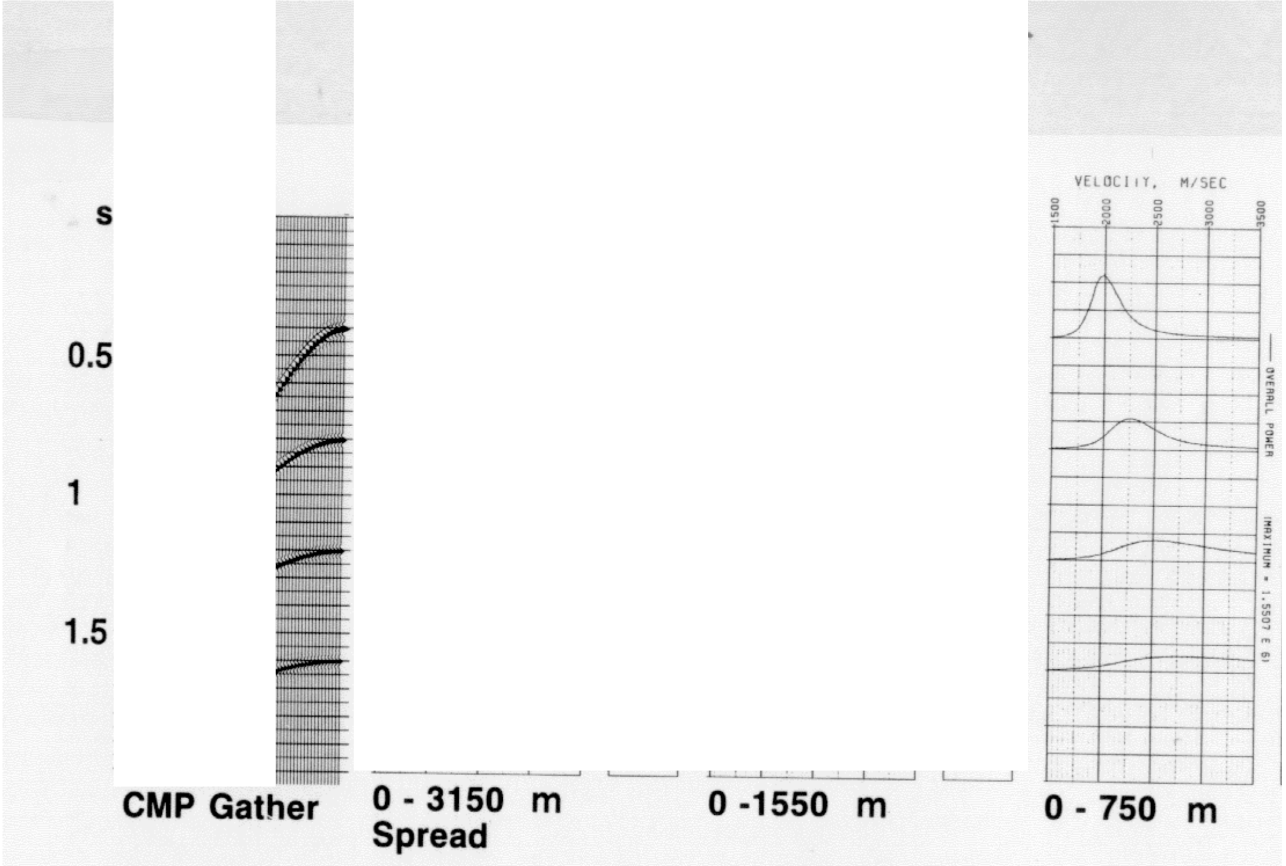
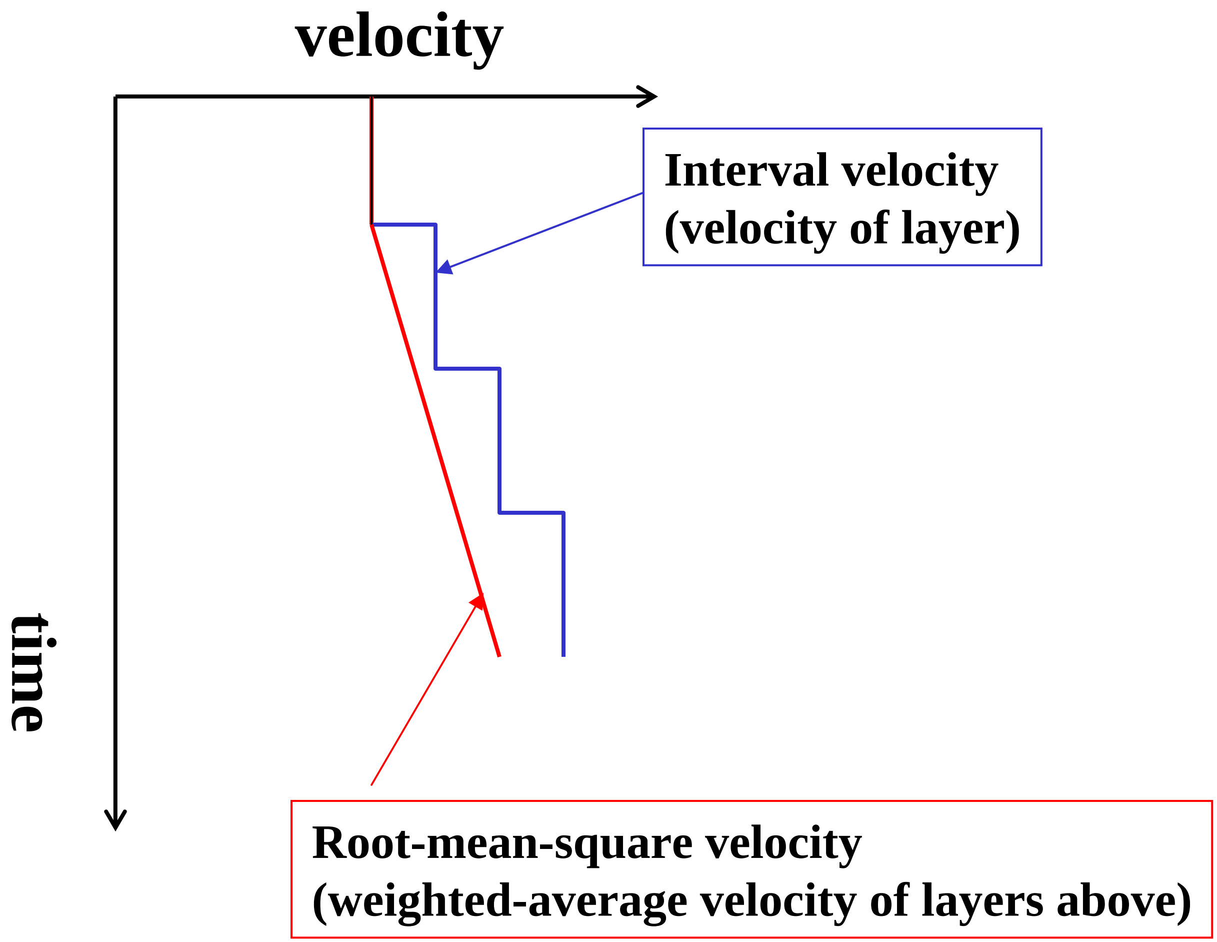


FIG. 3-32. Effect of spread length on velocity resolution. Lack of long offsets causes loss of resolution, especially at later times.

Effect spread length on velocity estimation

FIG. 3-32. Effect of spread length on velocity resolution. Lack of long offsets causes loss of resolution, especially at later times.

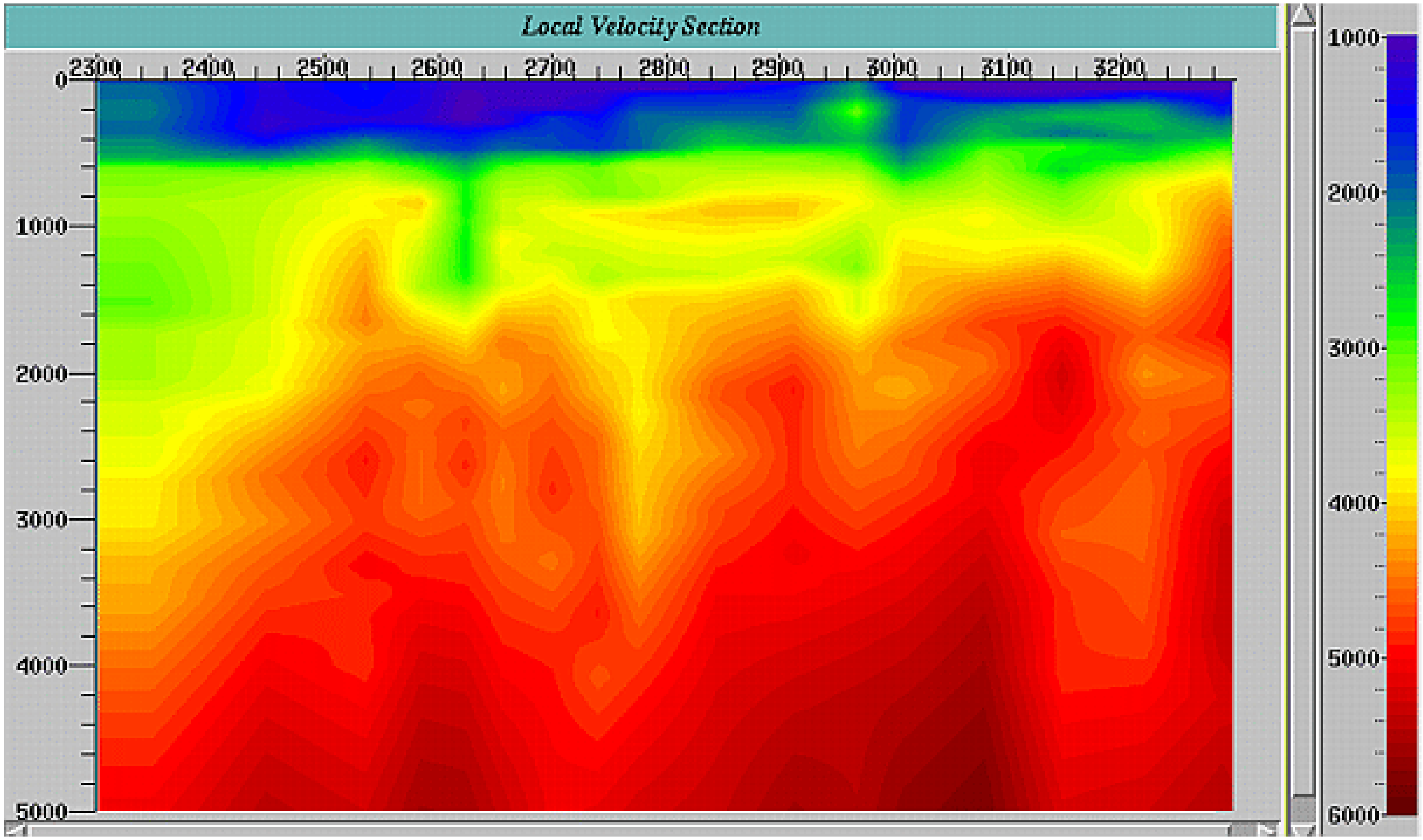
Velocity model: RMS model



Interval velocity (velocity of layer)

Root-mean-square velocity (weighted-average velocity of layers above)

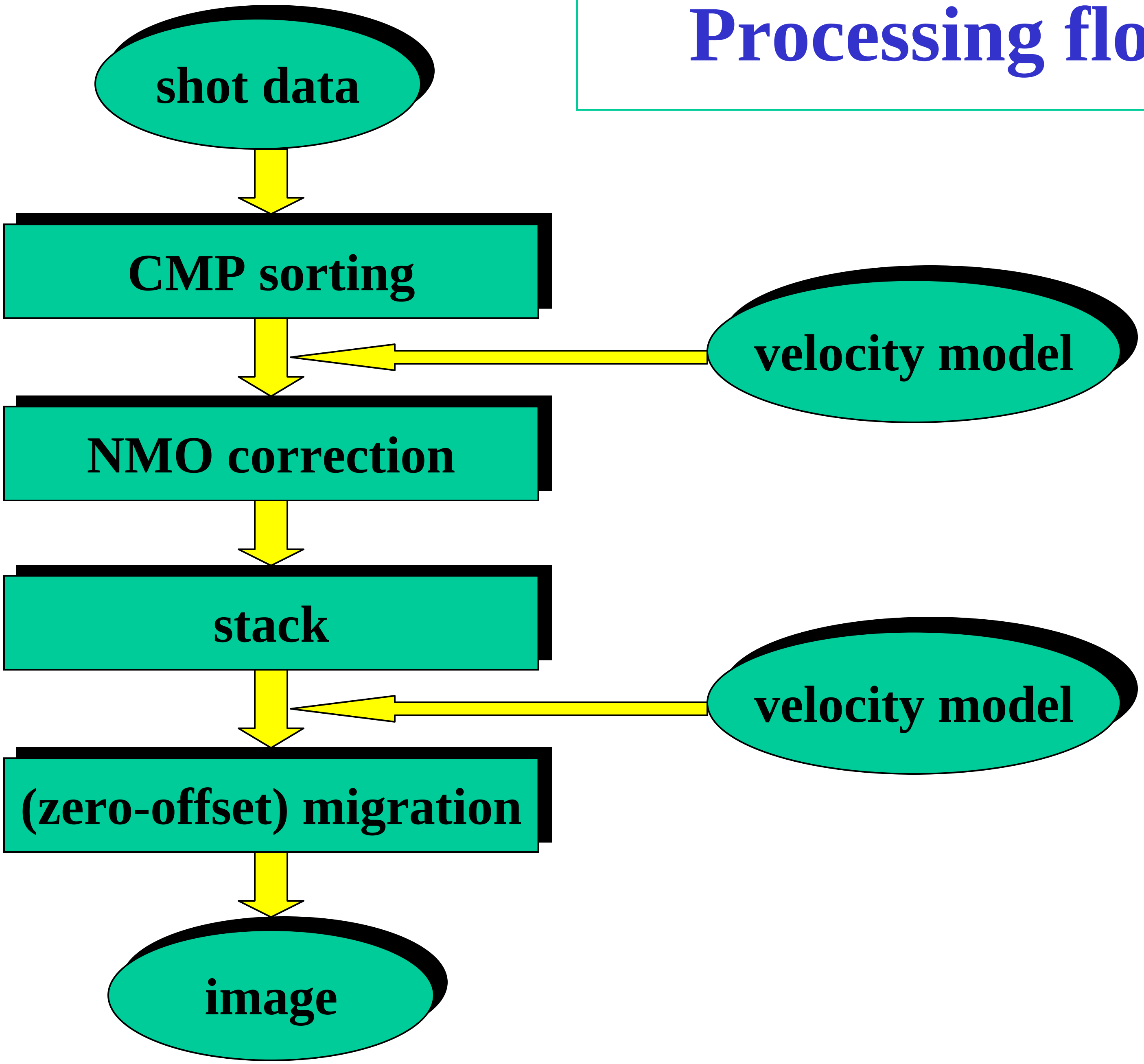
Velocity model: RMS model



Time (m-seconds)

CMP location

Processing flow


shot data

CMP sorting

velocity model

NMO correction

stack

velocity model

(zero-offset) migration

image

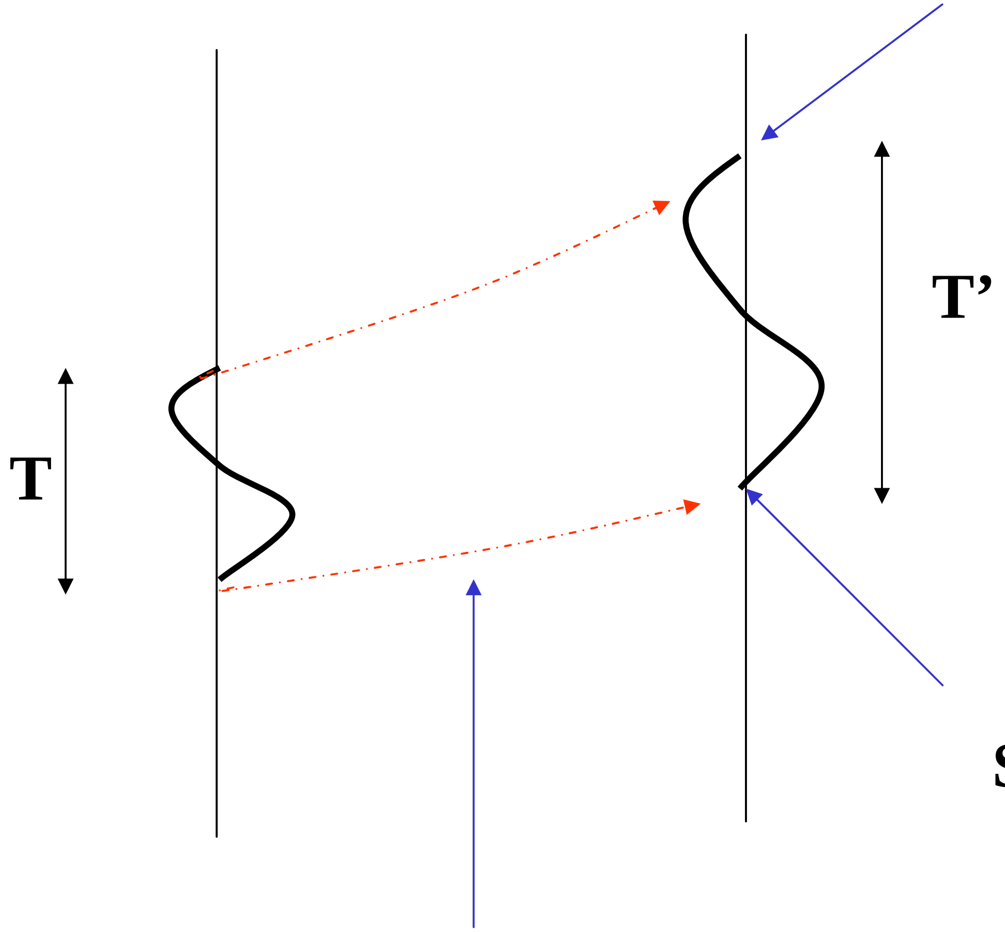
Applying NMO

Amount $x^2/(c^2 T_0^2)$ never exactly on a sample:

INTERPOLATION

NMO stretch

(via picture)



Since T_0 is smaller: shift is larger

Since T_0 is larger: shift is smaller

Hyperbolic shift

NMO stretch

(mathematically)

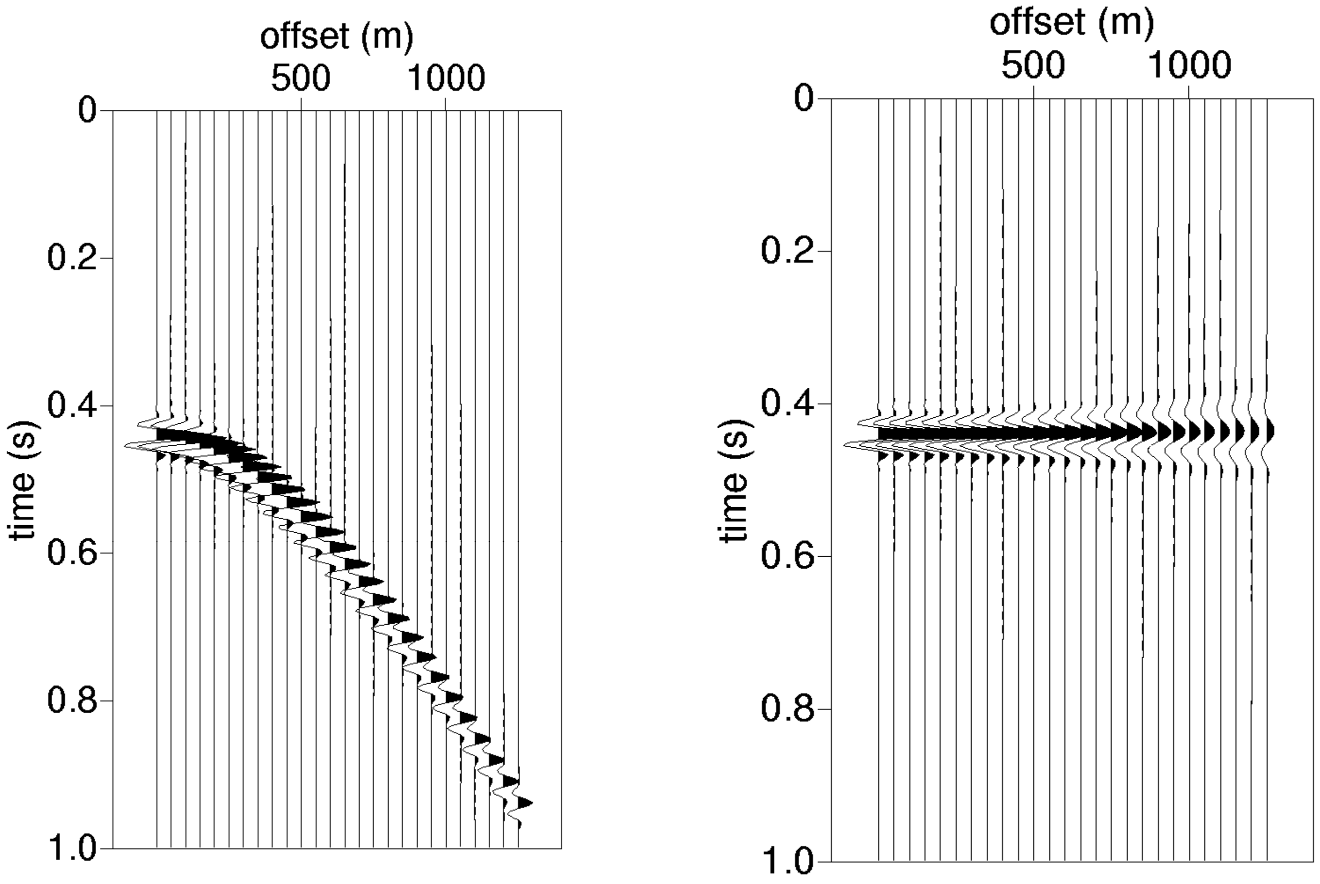
Due to differential working on T as function of T_0:

$$\frac{\partial}{\partial T_0} \Delta T_{NMO} = \frac{\partial}{\partial T_0} \frac{x^2}{2\, c^2\, T_0}$$

$$= - \frac{x^2}{2\, c^2\, T_0^2}$$

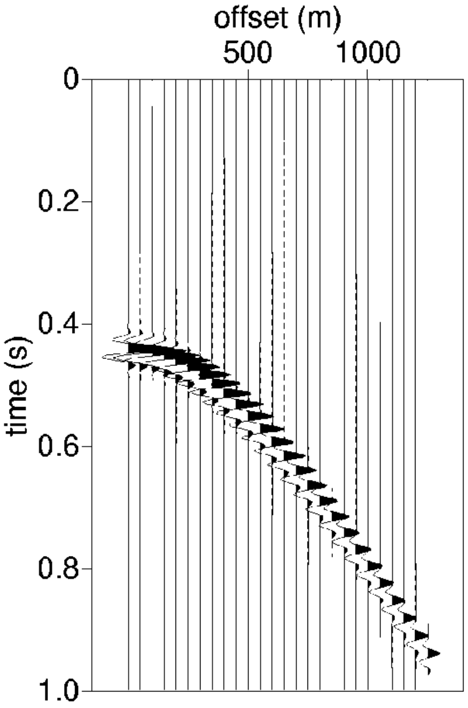
This is called NMO-stretch

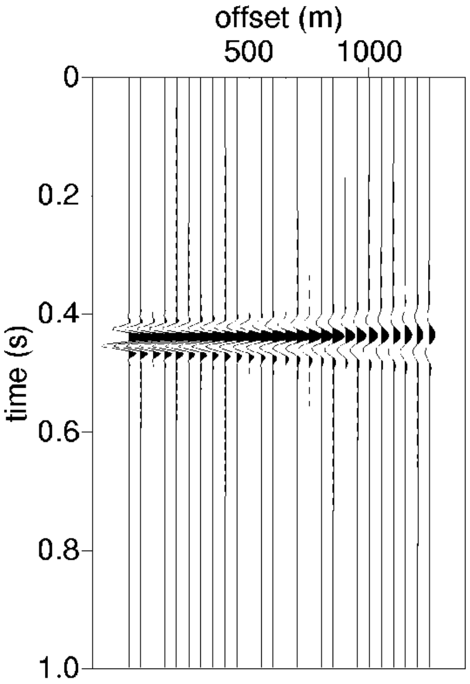
NMO stretch

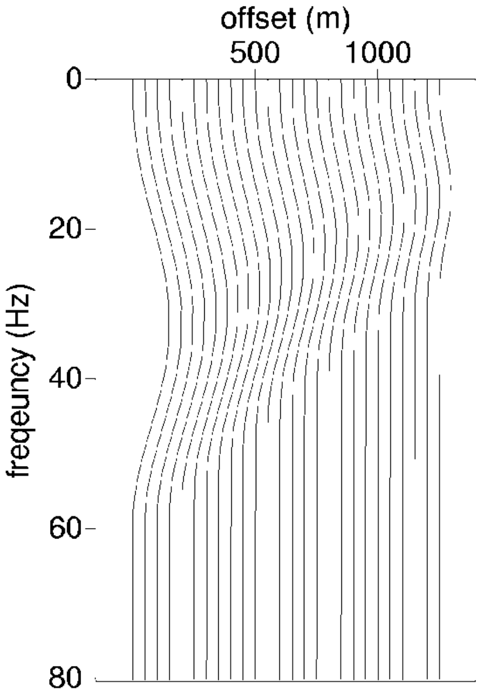


offset (m)
500
1000
0
0.2
0.4
0.6
0.8
1.0
time (s)
offset (m)
500
1000
0
0.2
0.4
0.6
0.8
1.0
time (s)

NMO stretch





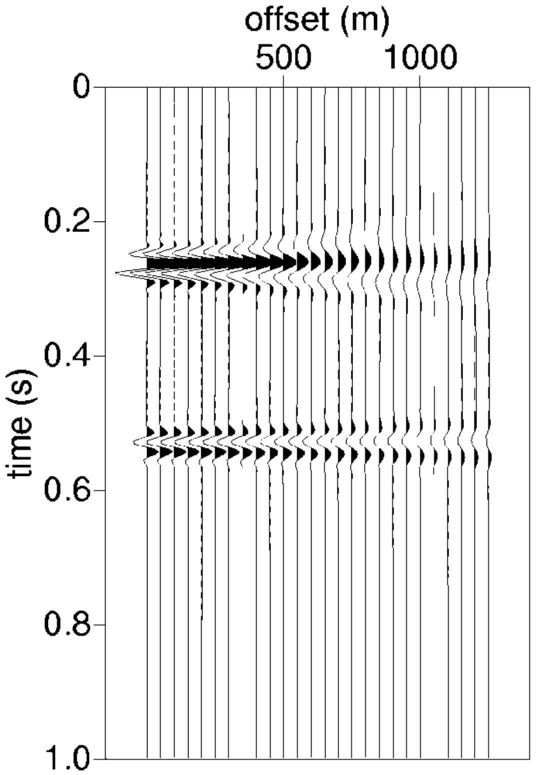


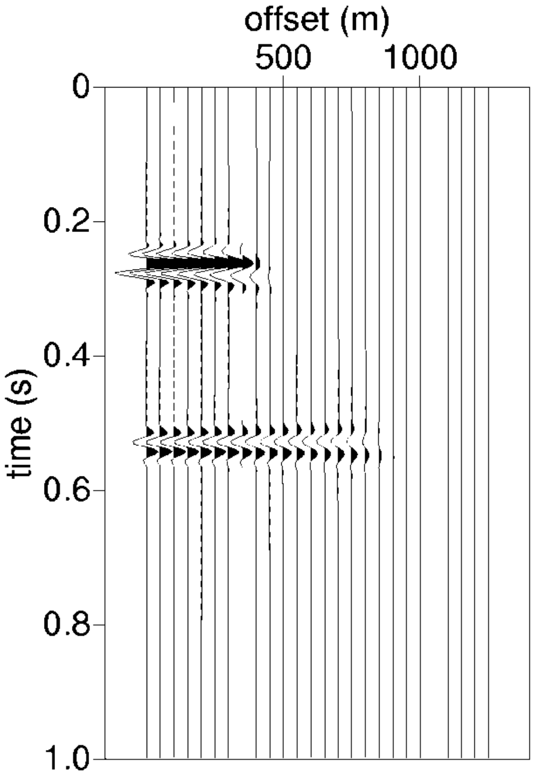
Amplitude spectra

Mute: too much NMO-stretch

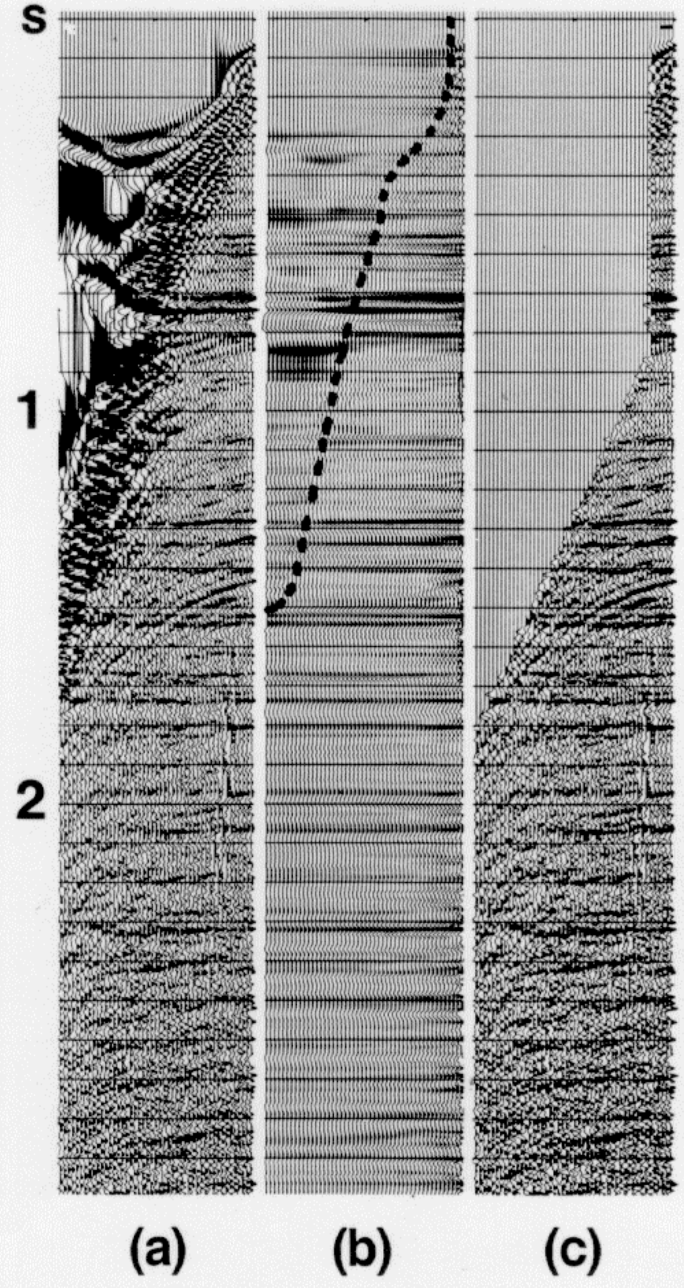
We do not want too much distortion: setting it zero.

This called muting

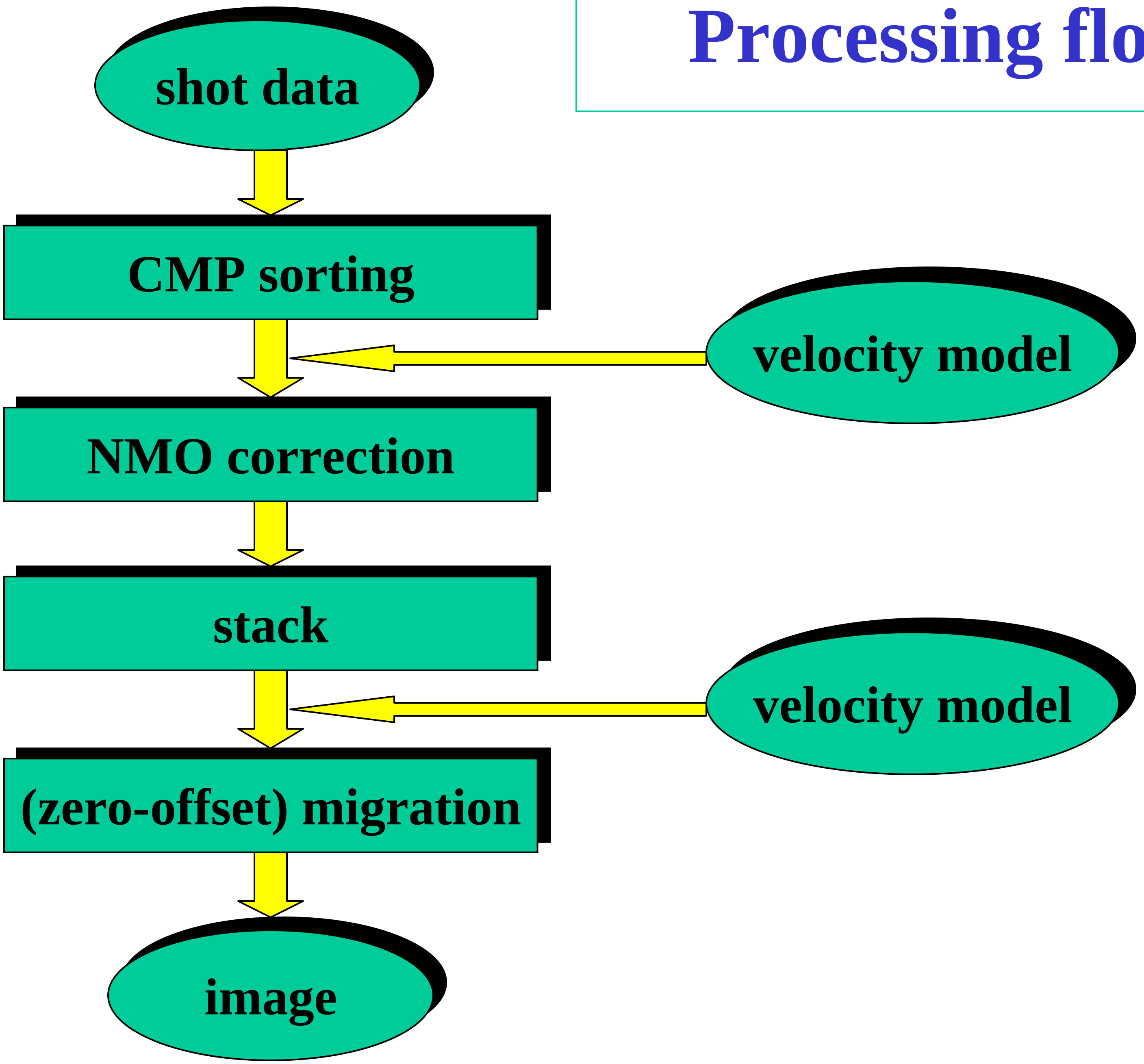




NMO-stretch on field data



Processing flow



shot data

CMP sorting

velocity model

NMO correction

stack

velocity model

(zero-offset) migration

image

Stacking

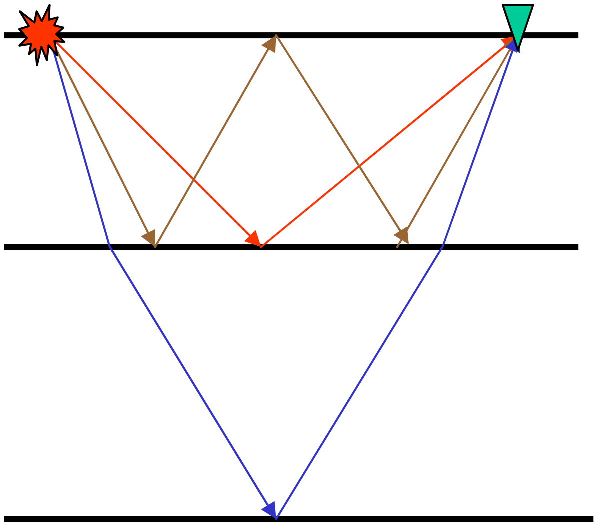
Add traces from NMO-corrected, CMP gather into ONE trace

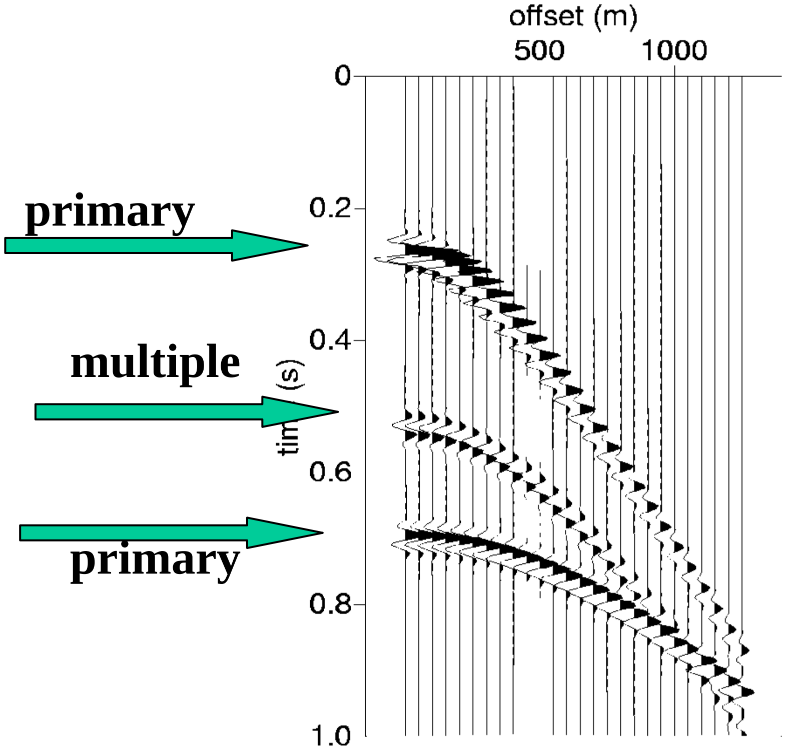
Number of traces = stack fold

Events that are not hyperbolic, do not add up nicely and destructively interfere

Goal of stacking : to increase signal-to-noise ratio

Primaries and multiple





primary

multiple

primary