Seismic Reflection Method

I. Introduction and General considerations

- Seismic reflection is the most widely used geophysical technique. It can be used to derive important details about the geometry of structures and their physical properties.

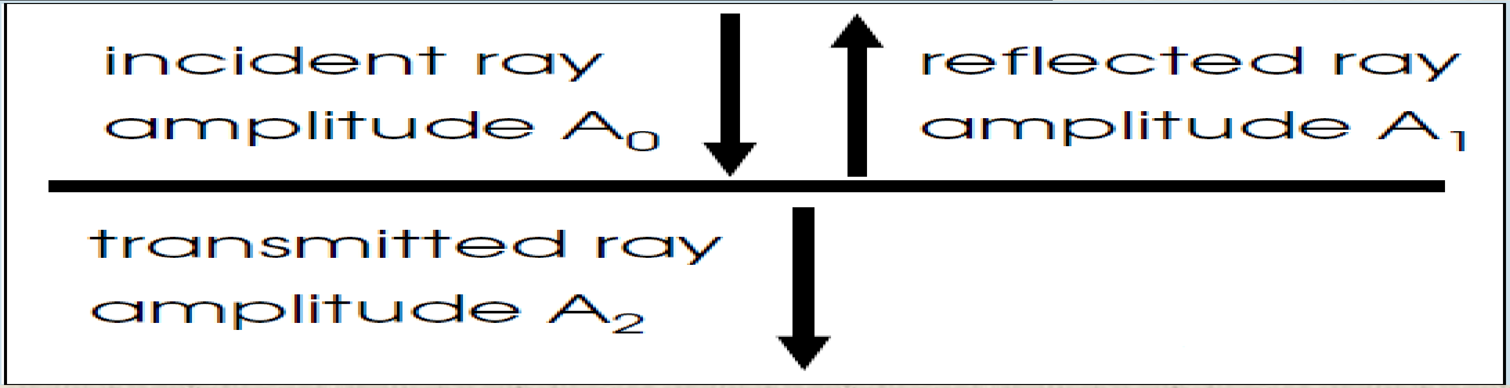
- Major fields of application of Seismic reflection include:
  - ✓ hydrocarbon exploration,
  - ✓ research into crustal structure with several kilometers of depths of penetration,
  - ✓ Engineering and environmental investigations (depth <200m),
  - ✓ mapping structural features such as shallow faults, buried valleys and Quaternary deposits,
  - ✓ Hydrological studies of aquifers.

- The basic principle of the seismic reflection technique application is to measure the time taken for a seismic wave that travels from a source down into the ground where it is reflected back to the surface where it can be detected by a receiver (geophone):

  - The measured time is known as the two way time (TWT).
  - The basic issue in seismic reflection interpretation is the conversion of the measured two way time into depth. Although the two way time (TWT) is known (measured), still there are two unknown parameters; these are: depth and velocity. Velocity is considered as the parameter that most affects the conversion of the two way time into depth.

II. Reflection and Transmission of seismic waves in layered media

- At an interface between two rock layers there is generally a change in propagation velocity resulting from difference in physical properties of the two layers. At such an interface, the energy within an incident seismic wave is partitioned into transmitted and reflected waves.
- The relative amplitudes of the transmitted and reflected waves depend on: the velocities (V), densities (ρ) and the angle of incidence.
- The total energy of the transmitted and reflected waves must be equal to the energy of the incident ray.



- The amount of energy transmitted through the interface is <u>inversely</u> proportional to the acoustic impedance defined by:

$$Z = \rho V \qquad = \text{acoustic impedance}$$

Where:
Z: acoustic impedance
V: velocity
ρ: density

This means that the smaller the contrast in acoustic impedance across the rock interface the greater is the portion of the transmitted energy.

- The more energy is reflected, the greater is the contrast. This is expressed by the Reflection Coefficient, R, given by:

$$R = A_1 / A_0$$

$$R = \frac{(\rho_2 v_2 - \rho_1 v_1)}{(\rho_2 v_2 + \rho_1 v_1)} = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)} \qquad -1 < R < 1$$

Where:

R: reflection coefficient

A_1: amplitude of the reflected wave

A_0: amplitude of the incident wave

Z: acoustic impedance

V: velocity

ρ: density

Negative values of the reflection coefficient indicate a phase change of 180° in the reflected wave.

- The transmission coefficient, T, is given by:

$$T = A_2 / A_0$$

$$T = 2 \frac{Z_1}{(Z_2 + Z_1)}$$

Where:

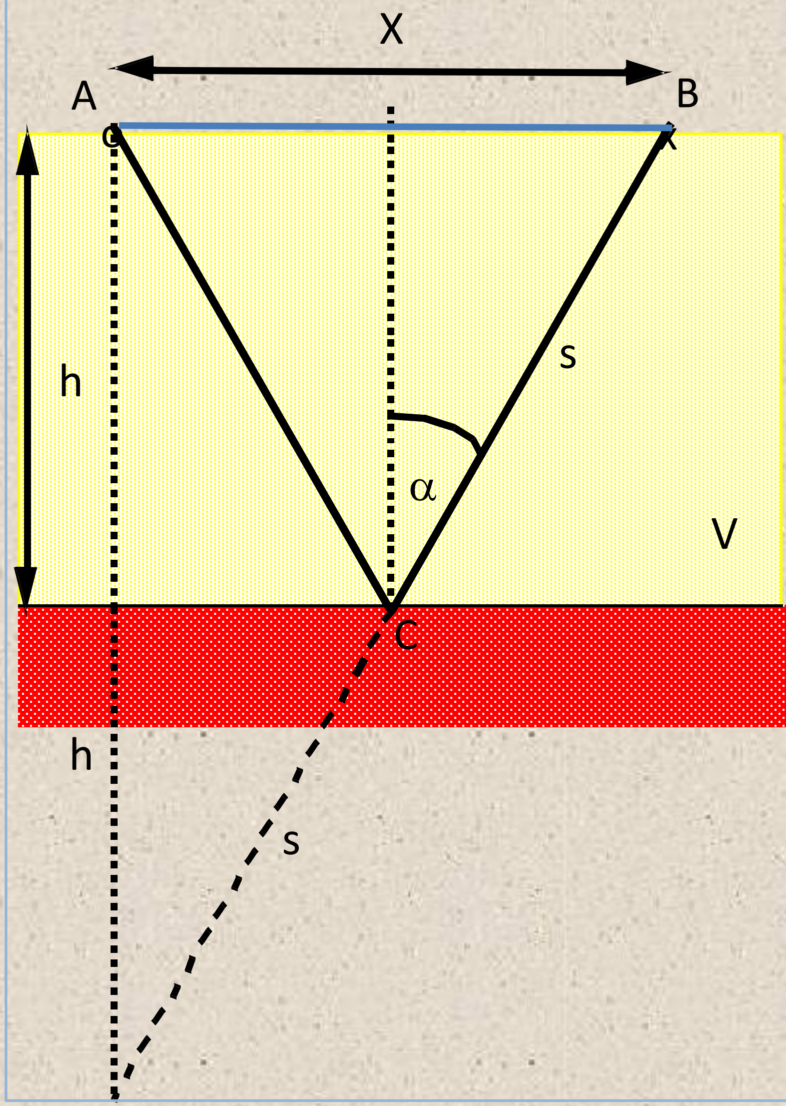
T: transmission coefficient

A_2: amplitude of the transmitted wave

A_0: amplitude of the incident wave

Z: acoustic impedance

III. The Case of Single Horizontal Reflector



The travel time equation of a reflected wave from a shot point to a receiver (geophone) located at a horizontal offset X can be derived as follows:

$$4S^2 = 4h^2+x^2 = t^2v^2$$

$$t^2=(4h^2+x^2)/v^2$$

$$\mathbf{t = (4h^2+X^2)^{1/2}/V} \quad ....(1)$$

There are two unknown parameters in the above equation, these are: Velocity (V) and depth (h).

Now, Eq. 1 can be written in the form:

$$\frac{t^2v^2}{4h^2} - \frac{x^2}{4h^2} = 1$$

Hyperbola

The Intercept Time

By measuring many reflection times, t, at different offsets, x, it will be possible to calculate the depth, h, and the velocity, V (See the figure below).

By substituting X= 0 in Eq. 1:

$$t = (4h^2+X^2)^{1/2}/V \text{ ....(1)}$$

we obtain:

$$t_\circ = 2h/V \text{ ....(2)}$$

Eq. 2 is the travel time equation of a vertically reflected wave (intercept on the time axis of the time – distance curve).

By squaring Eq. 1 and substituting Eq. 2 in Eq. 1, we obtain: Velocity can be determined using Eq. 3.

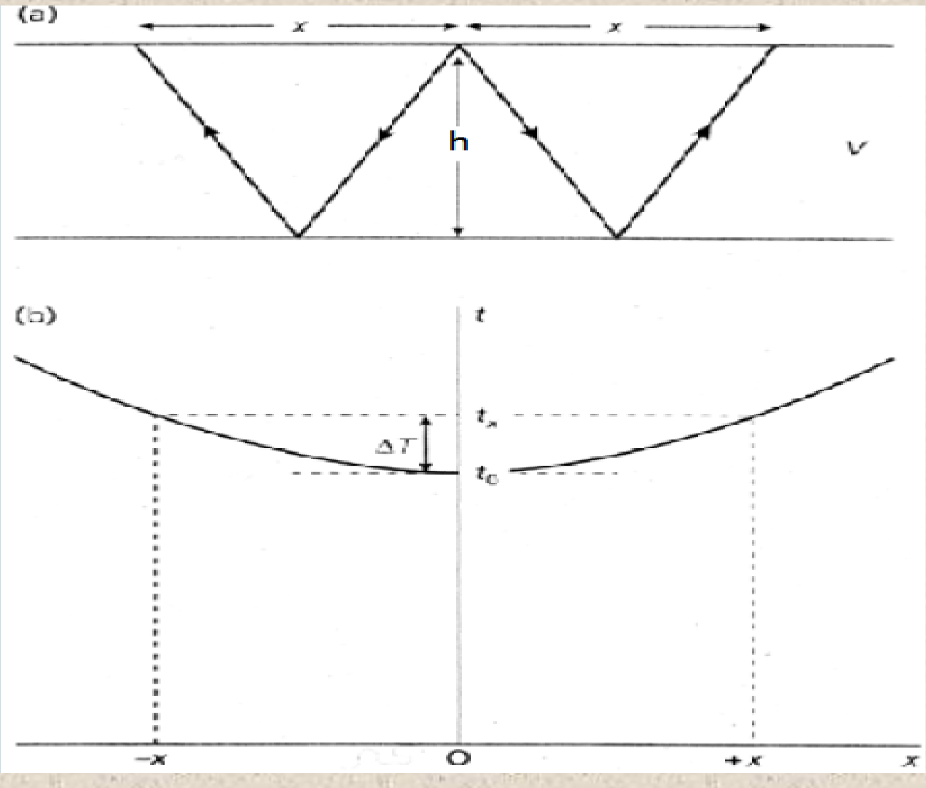


Fig. : (a) Section through a single horizontal layer showing the geometry of reflected ray paths and (b) time-distance curve for reflected rays from a horizontal reflector.
ΔT= normal moveout (NMO).

By squaring Eq. 1 and substituting Eq. 2 in Eq. 1, we obtain:

$$t^2 = 4h^2/ V^2 + X^2/V^2$$

$$t^2 = t_\circ^2 + X^2/V^2 \quad \textbf{................(3)}$$

<u>Velocity can be determined using Eq. 3.</u>

CALCULATION OF THE VELOCITY

- Plot t^2 against x^2

The graph will produce a straight line of slope $1/v^2$. The intercept on the time axis will give the vertical two way travel time, t_0 , from which the depth to the reflector can be found.

This method is unsatisfactory, since the values of x are restricted.

- A much better method of determining velocity is by considering the increase of reflected travel time with offset distance, the moveout.

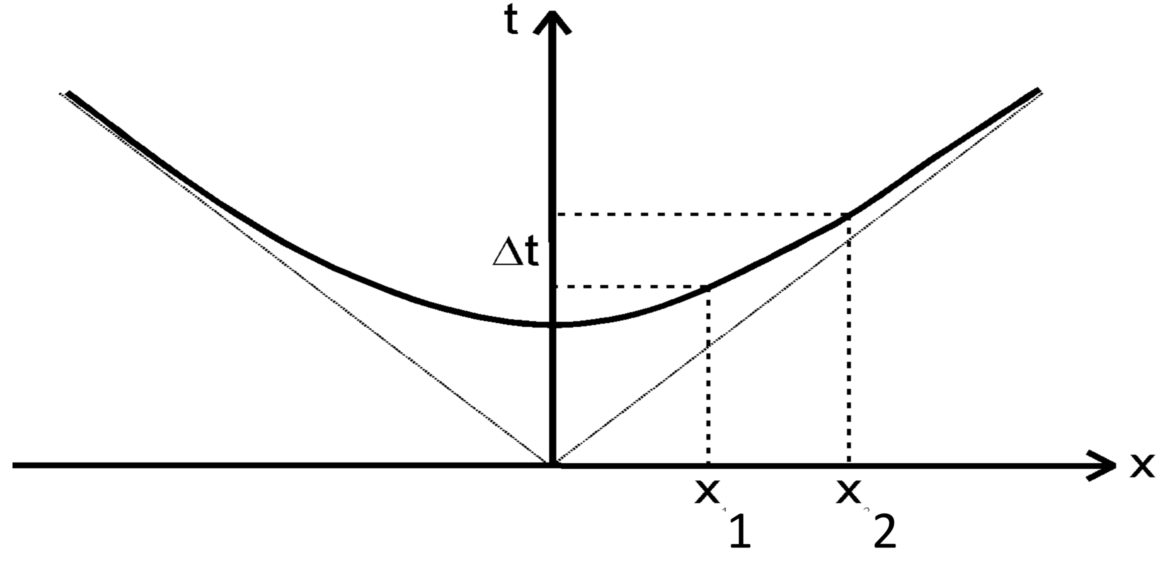
MOVEOUT

- Moveout is defined as the difference between travel times t_1 and t_2 of reflected-ray arrivals recorded at two offset distances x_1 and x_2.

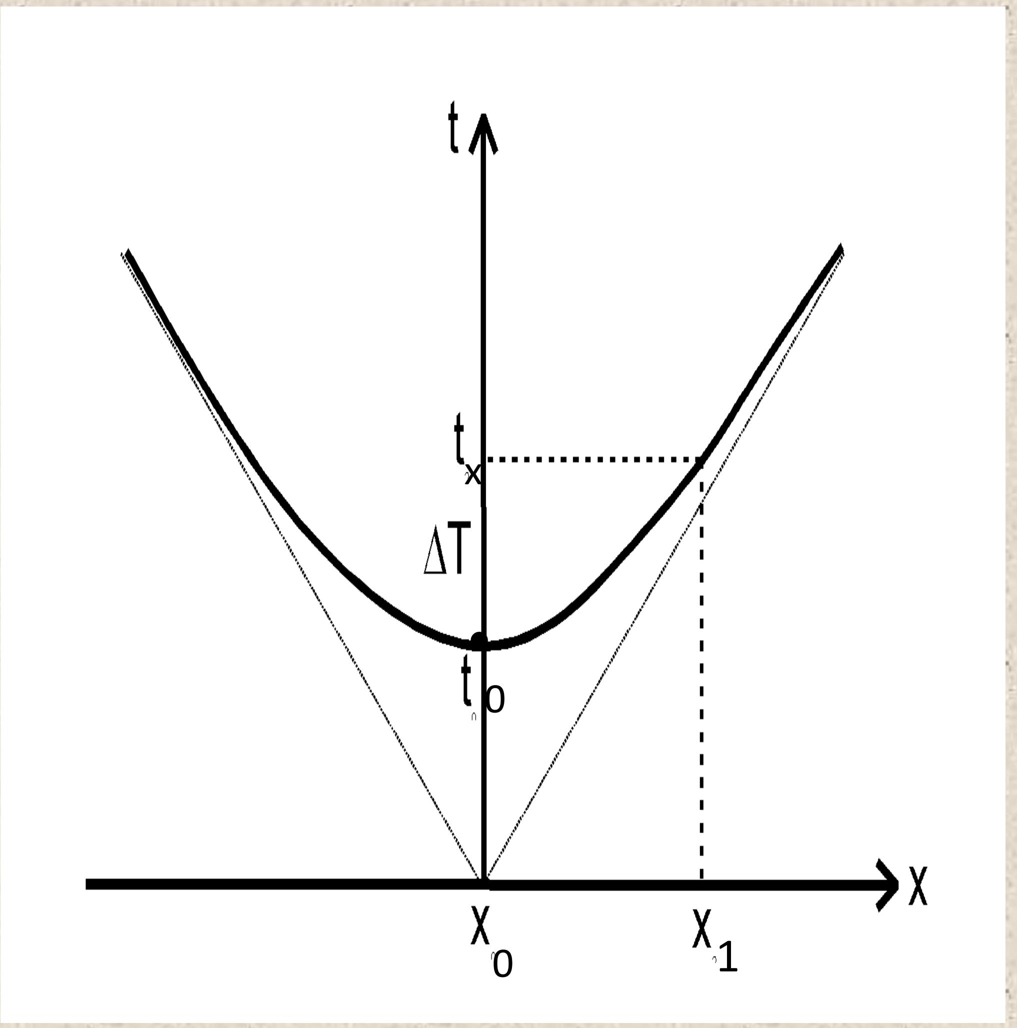
$$t_2 - t_1 = \frac{x_2^2 - x_1^2}{2 v^2 t_0}$$

- Normal moveout (NMO) at an offset distance x is the difference in travel time ΔT between reflected arrivals at x and at zero offset. (see Figure)

$$\Delta T = t_x - t_0 \approx \frac{x^2}{2 v^2 t_0} \Rightarrow v = \frac{x}{(2 t_0 \Delta T)^{1/2}}$$



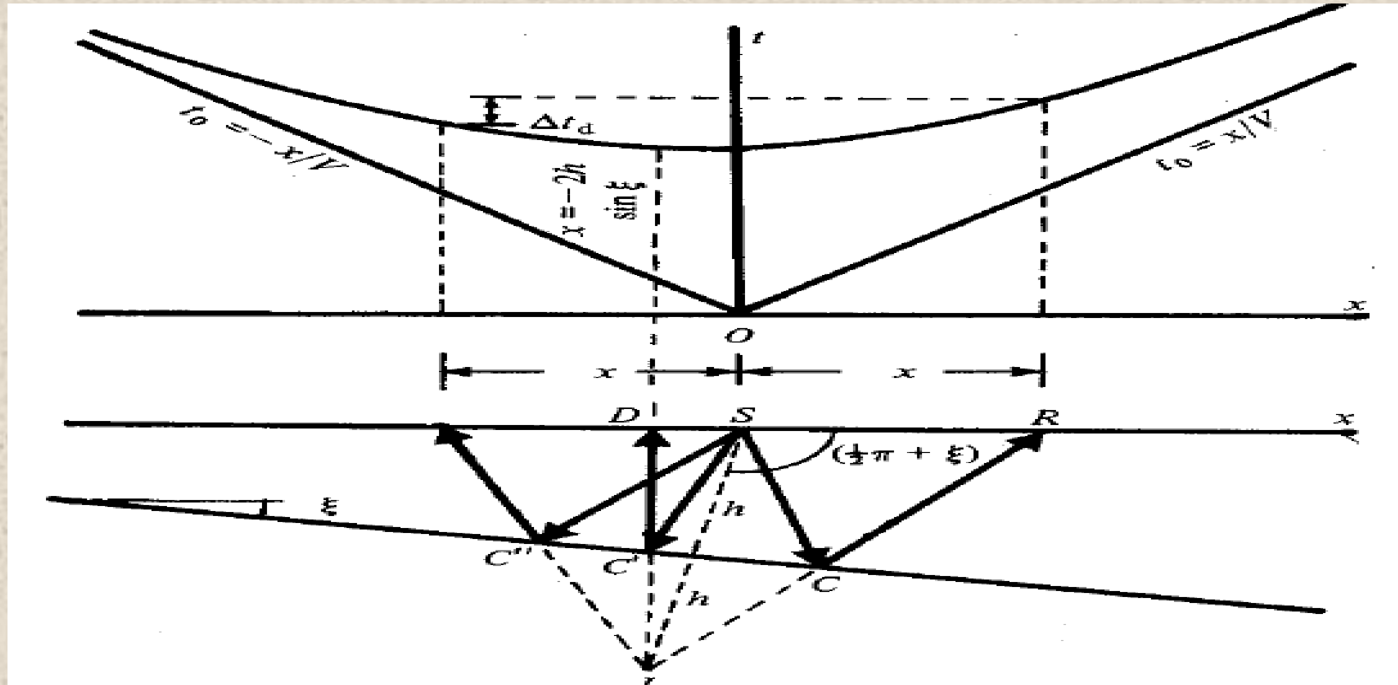
MOVE OUT: Difference in travel time $t(x_1)$ and $t(x_2)$: $t_2 - t_1 \approx \frac{x_2^2 - x_1^2}{2v^2 t_0}$



Normal Moveout: Difference in travel time t_0 and t(x): $\Delta T = t_x - t_0 \approx \frac{x^2}{2v^2 t_0}$

Travel Time for Single Plane Dipping Layer

The length of the reflection path, SCR, from Source to Receiver is the same as path IR, from an imaginary source, I, obtained by reflecting the surface source, S, in the interface.



The Cosine rule in the triangle IRS gives the travel time, T, as VT, which is the distance travelled by the seismic reflection:

$$\cos(90+\xi) = -\sin\xi$$

$$c^2 = a^2 + b^2 - 2ab\cos(C)$$

$$(IR)^2 = V^2T^2 = x^2 + 4h^2 - 4hx\cos(90+\xi)$$
$$= x^2 + 4h^2 + 4hx\sin\xi$$

By combining X terms using the complete square rule, we obtain:

$$V^2T^2 = (x + 2h\sin\xi)^2 + 4h^2 - 4h^2\sin^2\xi$$

$$V^2T^2 = (x + 2h\sin\xi)^2 + 4h^2\cos^2\xi$$

$$\frac{V^2T^2}{(2h\cos\xi)^2} - \frac{(x + 2h\sin\xi)^2}{(2h\cos\xi)^2} = 1$$ **..Eq. (1)**

Equation 1 represents a asymmetrical (not symmetrical) hyperbola with it's apex shifted from X = 0. Apex is displaced towards UPDIP direction to:

X = - $2h\sin\xi$

Estimation of Reflector Dip

By measuring travel times at two locations offset by same distance ΔX to either side of the source, an estimation for the dip can be obtained by:

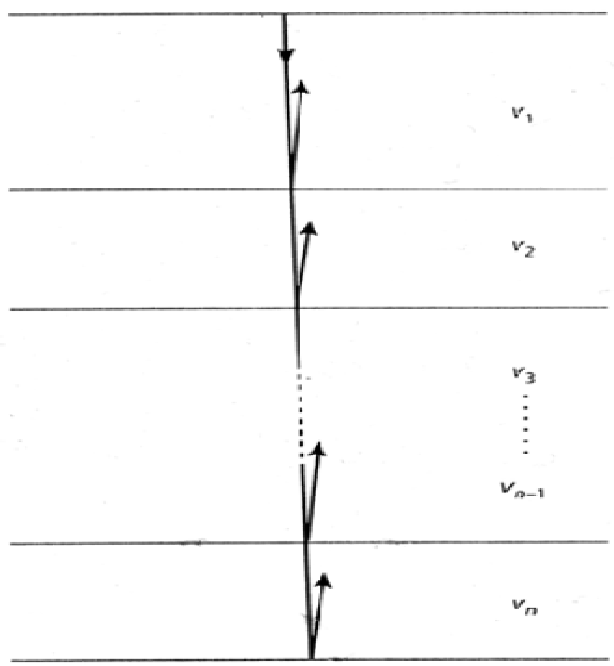
$$\sin \xi \approx \frac{1}{2} V \frac{\Delta t_d}{\Delta x}$$

Where:

Δt_d is the difference in observed travel times.

TYPES OF VELOCITIES

I. Interval Velocity:



$\mathbf{v_i}$ = interval velocity
$\mathbf{z_i}$ = thickness of the interval
τ_i = one way travel time

$$\mathbf{v}_i = \frac{\mathbf{z}_i}{\tau_i}$$

II. Average Velocity:

The interval velocity may be averaged over several depth intervals to yield an average velocity $\bar{v}$.

$$\bar{v} = \frac{\sum_{i=1}^{n} z_i}{\sum_{i=1}^{n} \tau_i} = \frac{\sum_{i=1}^{n} v_i \tau_i}{\sum_{i=1}^{n} \tau_i} \qquad \text{or} \qquad \bar{v} = \frac{Z_n}{T_n}$$

Z_n = total thickness of the top n layers
T_n = total one way travel time through the n layers

III. ROOT MEAN SQUARE (rms) Velocity:

$$V_{rms} = \left[\frac{\sum_{i=1}^{n} V_i^2 t_i}{\sum_{i=1}^{n} t_i} \right]^{\frac{1}{2}}$$

Where:

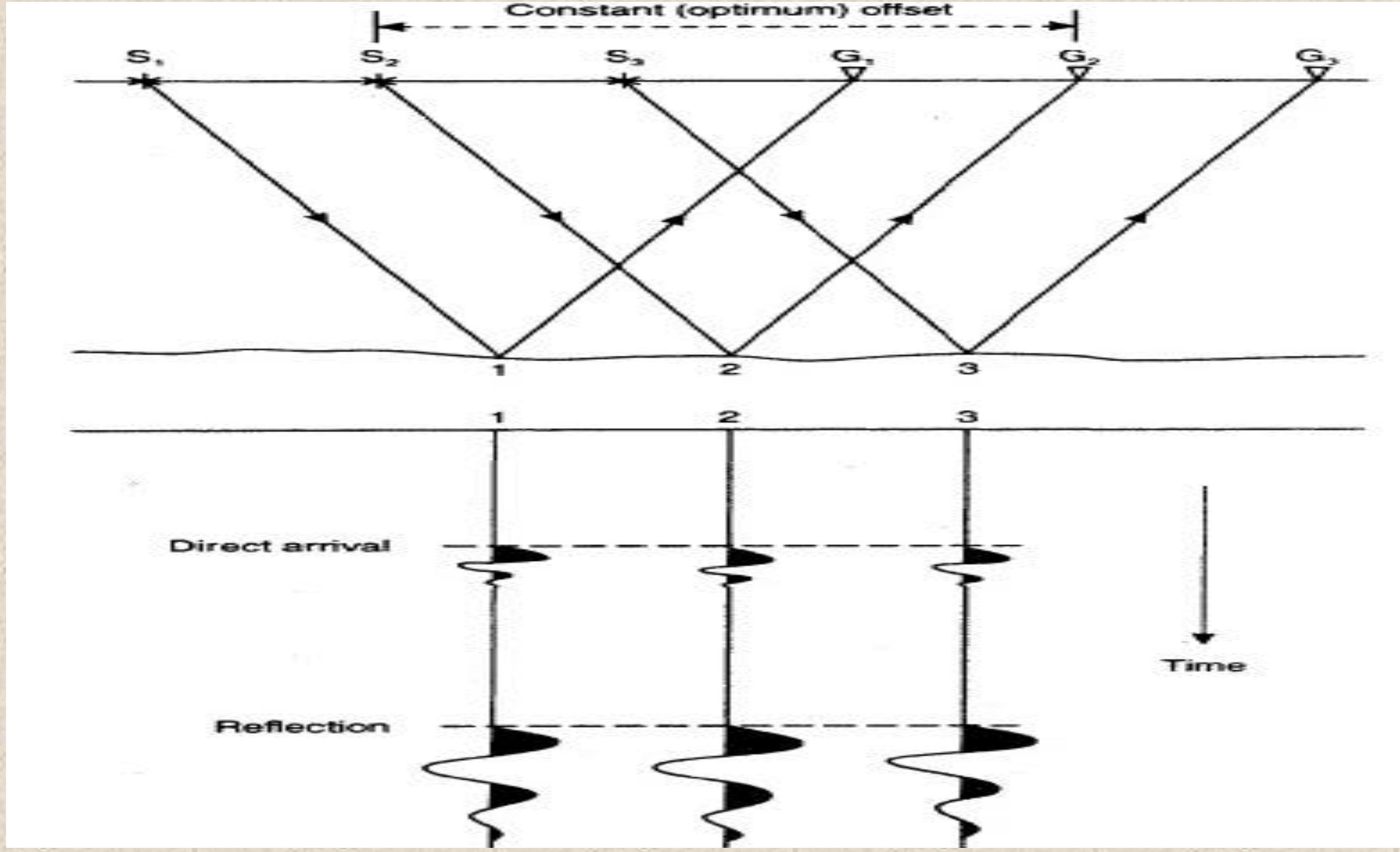
$t_i = 2 Z_i / V_i$ → the vertical travel time in the *i* th layer

V_i = interval velocity

SEISMIC REFLECTION FIELD PROCEDURES & DATA ACQUISITION

I. Field Procedures

Seismic reflection profiling obtains a cross-section through subsurface by recording data continuously along a surface profile.



- *Single-channel Seismic Profiling (constant offset)*: In case of shallow reflection profiles, the simplest survey is to use a source and a single geophone (receiver). In this procedure:
    - source and receiver are both moved along profile by same amount between shots
    - plotting successive shots side by side creates a reflection profile of the subsurface.
    - used in engineering and hydrogeological surveys.

- *Multichannel Seismic Profiling (single fold)*:

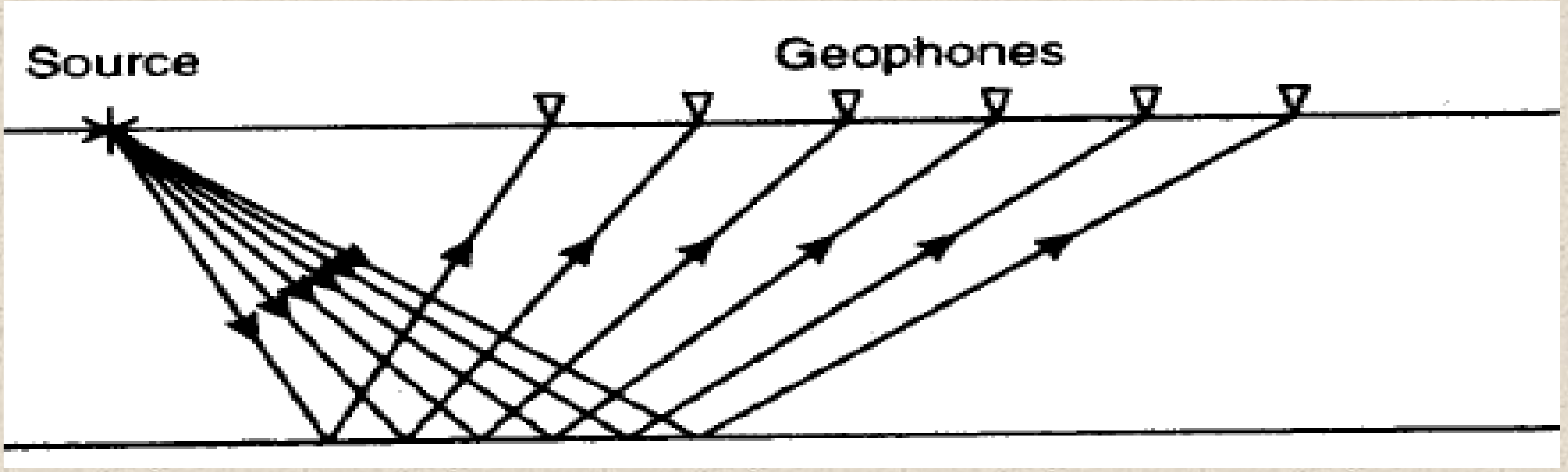
Multichannel Recording: Single-Channel reflection surveys are subject to noise. Combining multiple reflections from single subsurface location allows attenuation of this noise.

II. Gathering of Seismic Data

Large volume of seismic data can be recorded and be organized in different ways. A GATHER is the name for a collection of seismic traces.

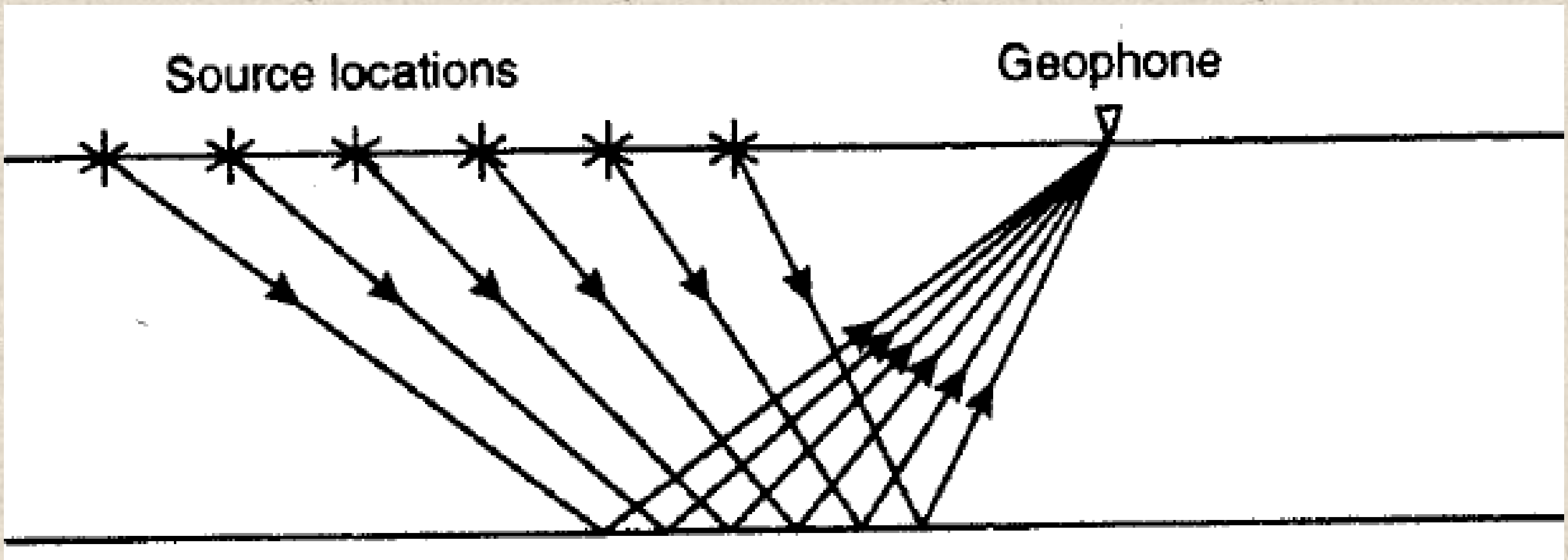
There are several trace gathers, these are:

- ***Common Shot Gather***: a collection of seismic traces recorded at several receivers (geophones) from single shot. This is the configuration in which seismic data are acquired in the field.



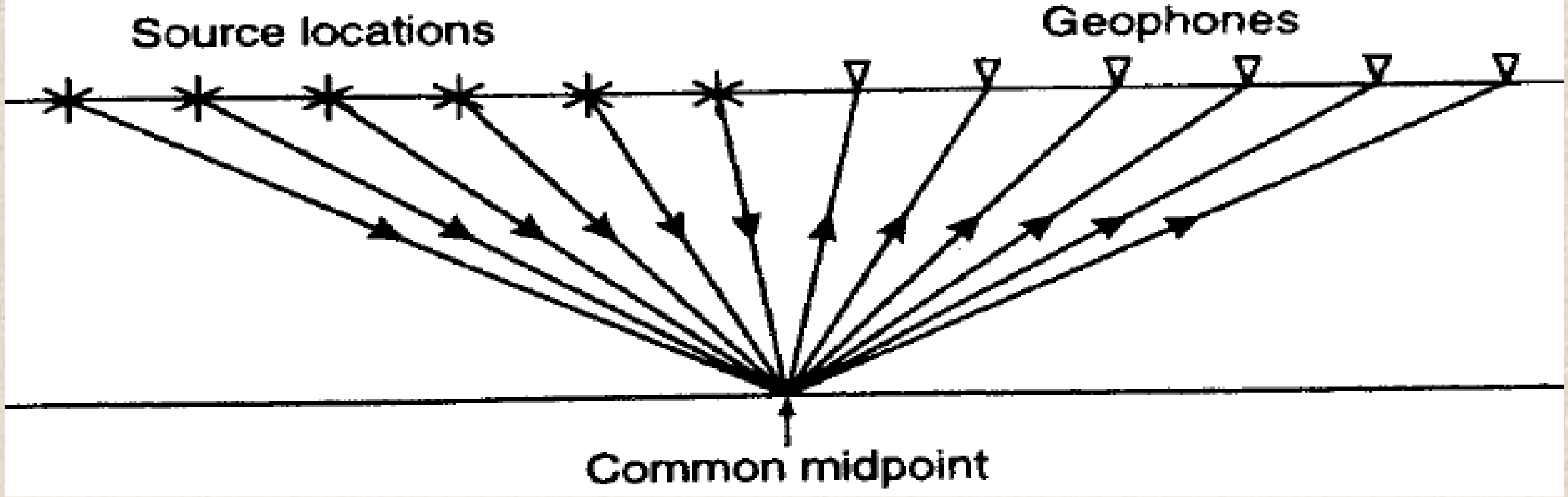
❑ ***Common Receiver Gather***:

A collection of seismic traces corresponding to several shots recorded at a single receivers (geophone).



❑ ***Common Midpoint (CMP) Gather***:

A collection of seismic traces in which the shot and the receiver are symmetrically distributed about the same midpoint location.



The *common Depth Point (CDP)* is the point on a plane horizontal interface from which all the reflections in a *Common Midpoint (CMP) Gather* are generated.

➢ **The *Common Midpoint (CMP) Gather* is fundamental in seismic reflection data processing for two reasons:**

1) The variation of travel time with offset, the moveout will depend only on the velocity of the subsurface layers (horizontal uniform layers).

➔ The subsurface velocity can be derived.

2) The reflected seismic energy is usually very weak. It is imperative to increase the signal-noise ratio of most data.

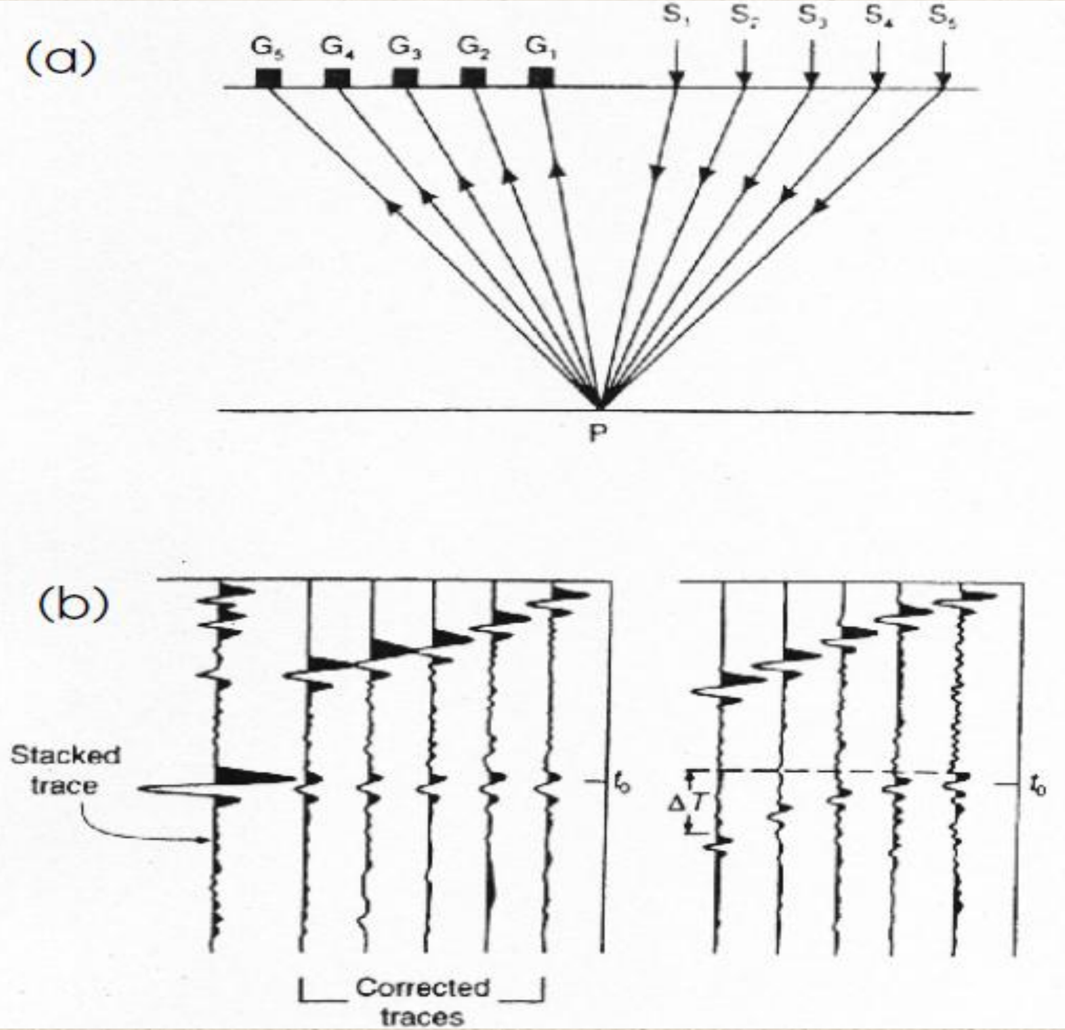
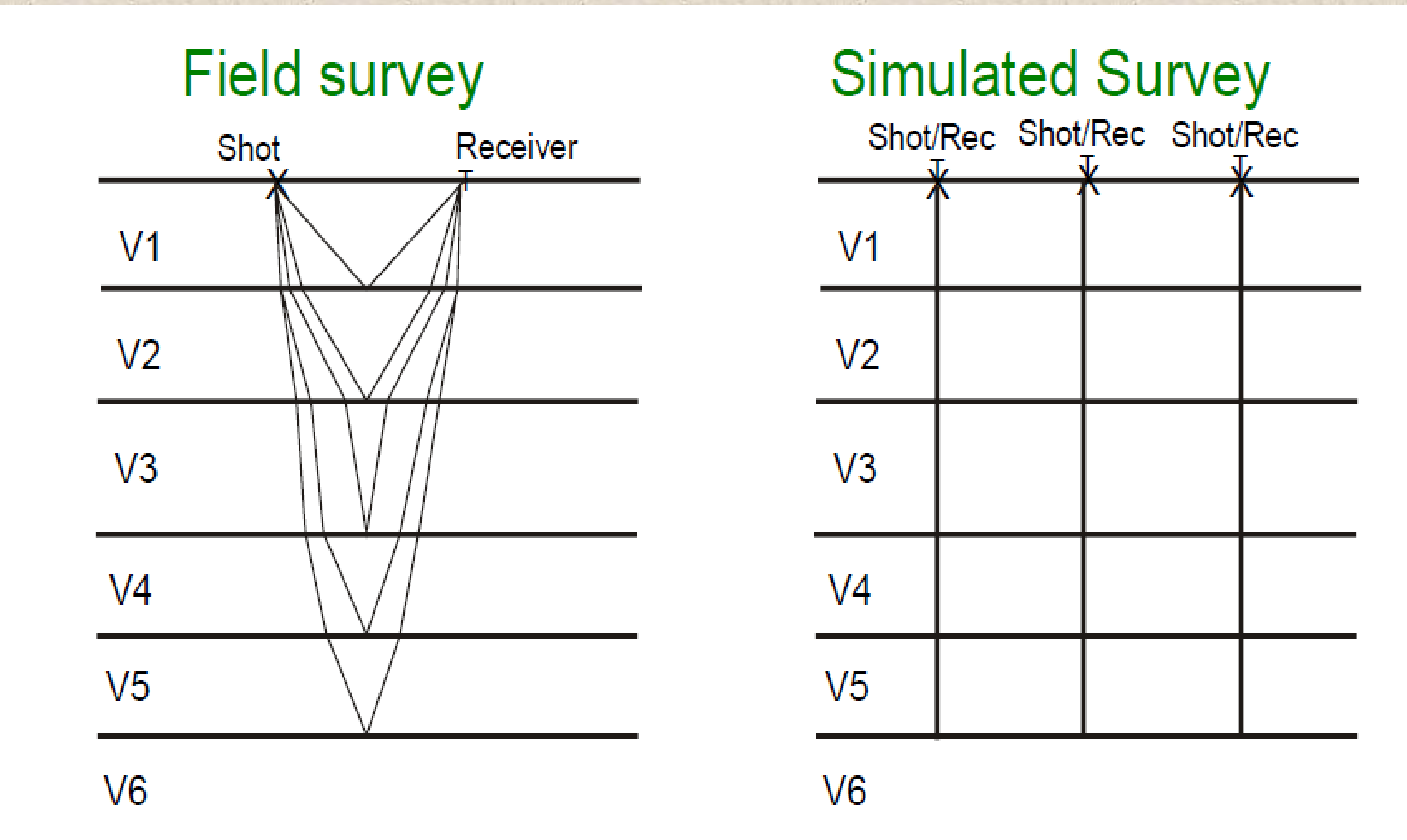
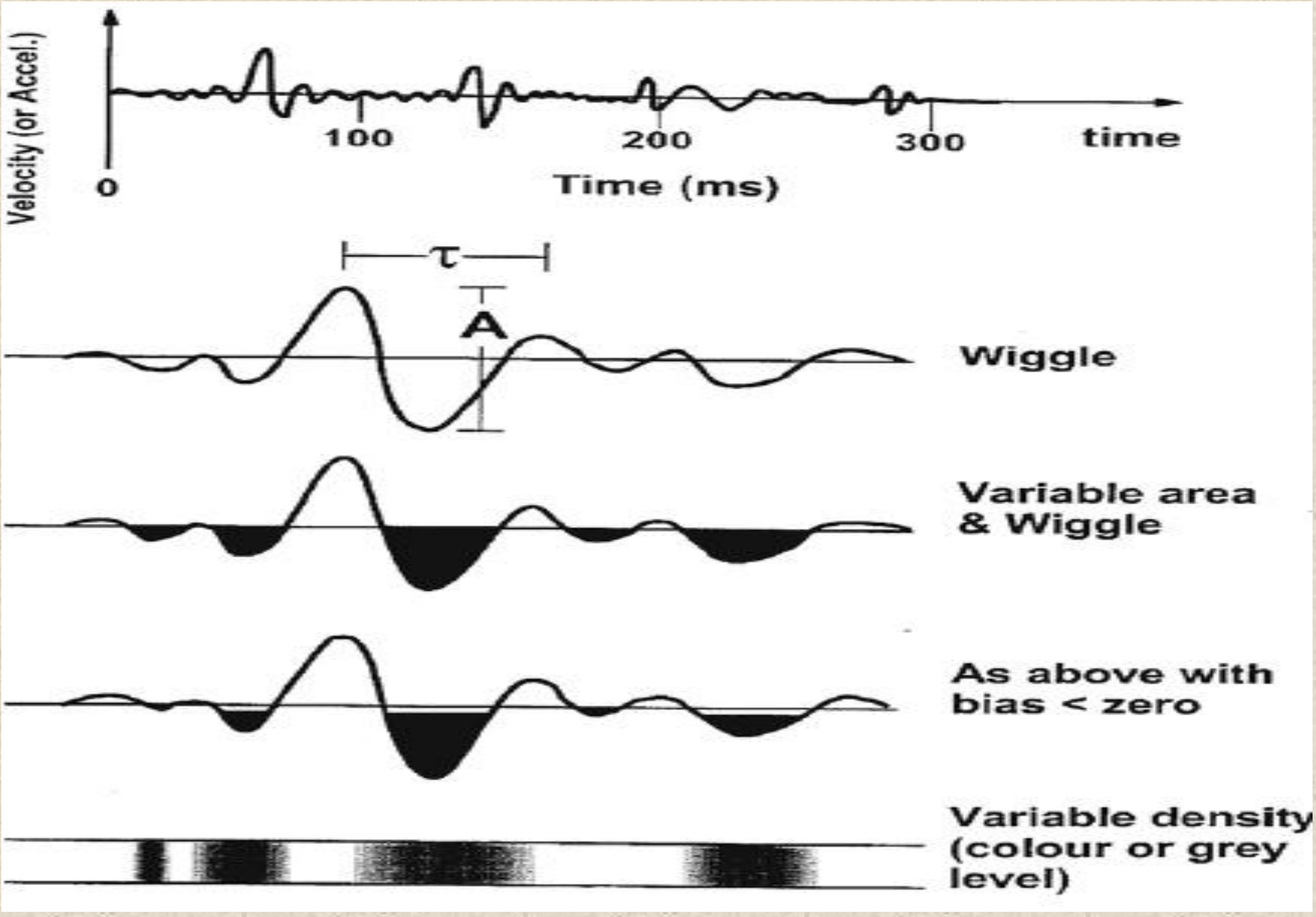


Fig. : Given the source-receiver layout and corresponding ray-paths for a common depth point spread, shown in (a), the resulting seismic traces are illustrated in (b), uncorrected (on the right), (corrected on the left) – note how the reflection events are aligned – and the final stacked trace.

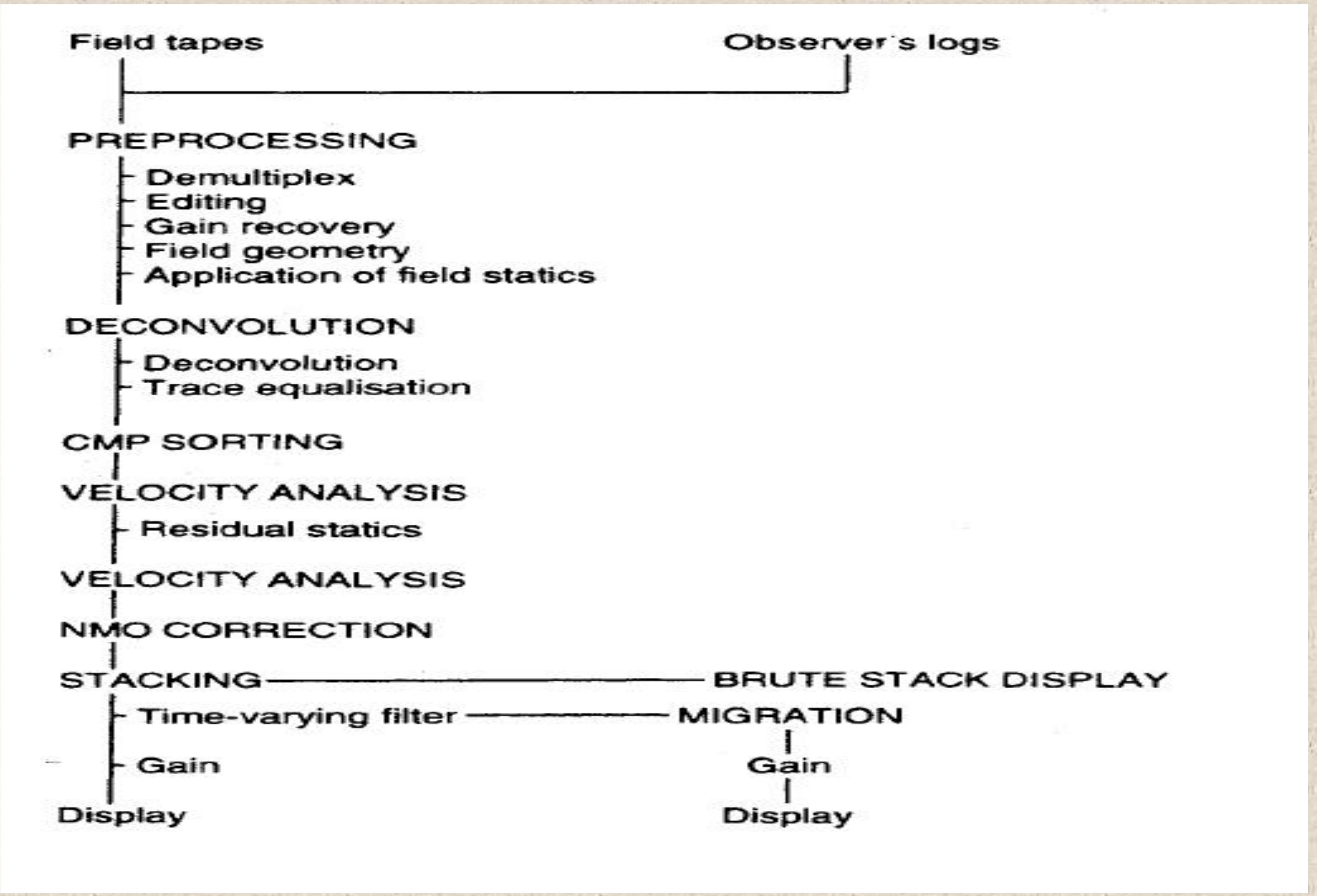
Display & Processing of Seismic Reflection Data


Field survey
Shot
Receiver
V1
V2
V3
V4
V5
V6
Simulated Survey
Shot/Rec
Shot/Rec
Shot/Rec
V1
V2
V3
V4
V5
V6

❑ Seismograms can be displayed is various ways:



PROCESSING OF SEISMIC DATA



PRE-PROCESSING OF REFLECTION DATA

I. Demultiplexing

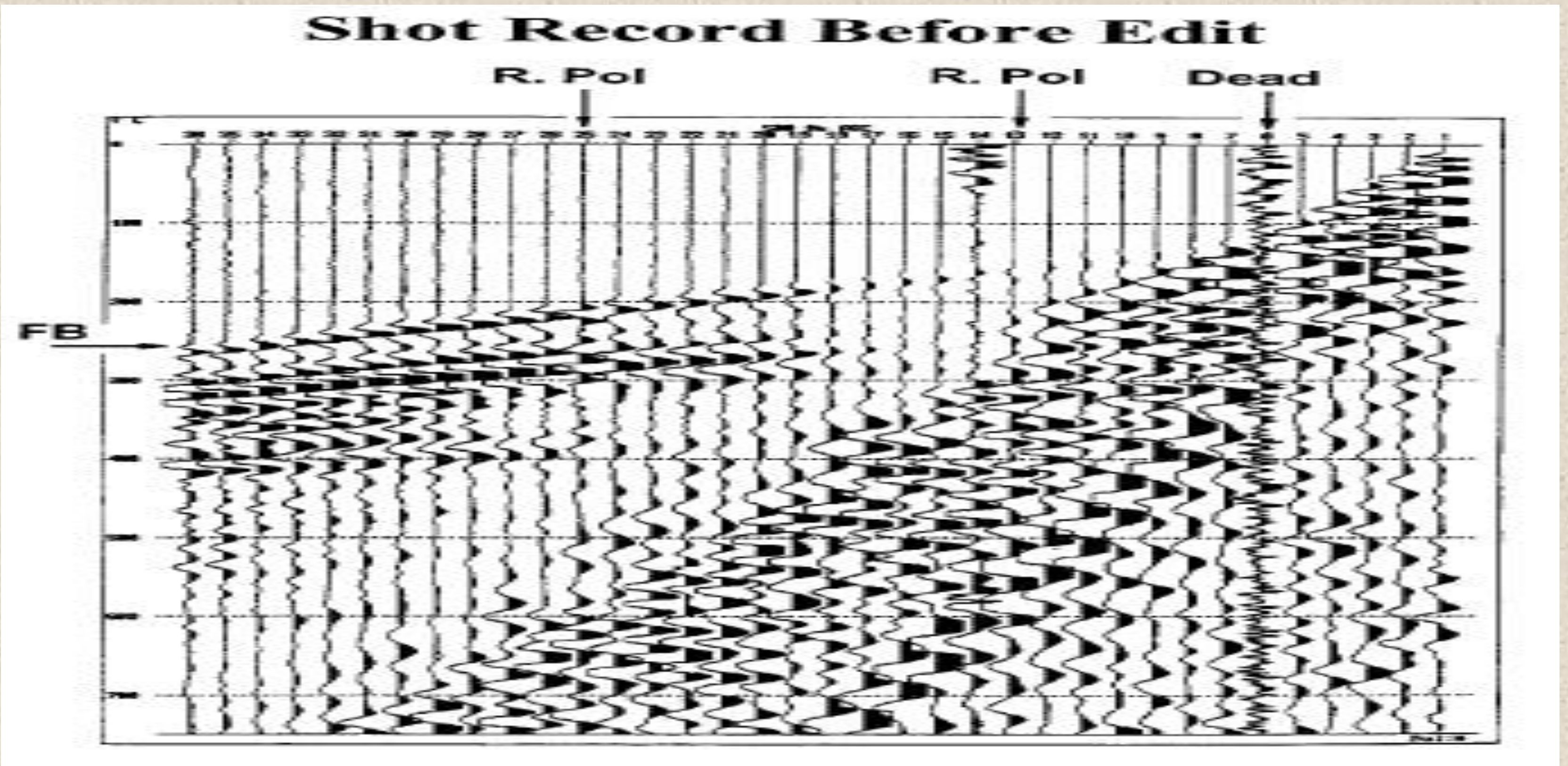
Prior to mid-1980s, a shot gather was recorded *multiplexed* → adjacent samples came from adjacent traces at the same time.

Demultiplexing means reorganizing the data such that successive samples on tape represent successive time samples for each seismogram.

Now most oil industry seismic data is recorded demultiplexed.

	Sample 1	Sample 2	Sample 3		Sample 4
Channel 1	a_1	a_2	a_3	$\cdots$	a_n
Channel 2	b_1	b_2	b_3	$\cdots$	b_n
Channel k	k_1	k_2	k_3	$\cdots$	k_n

II. Trace Editing

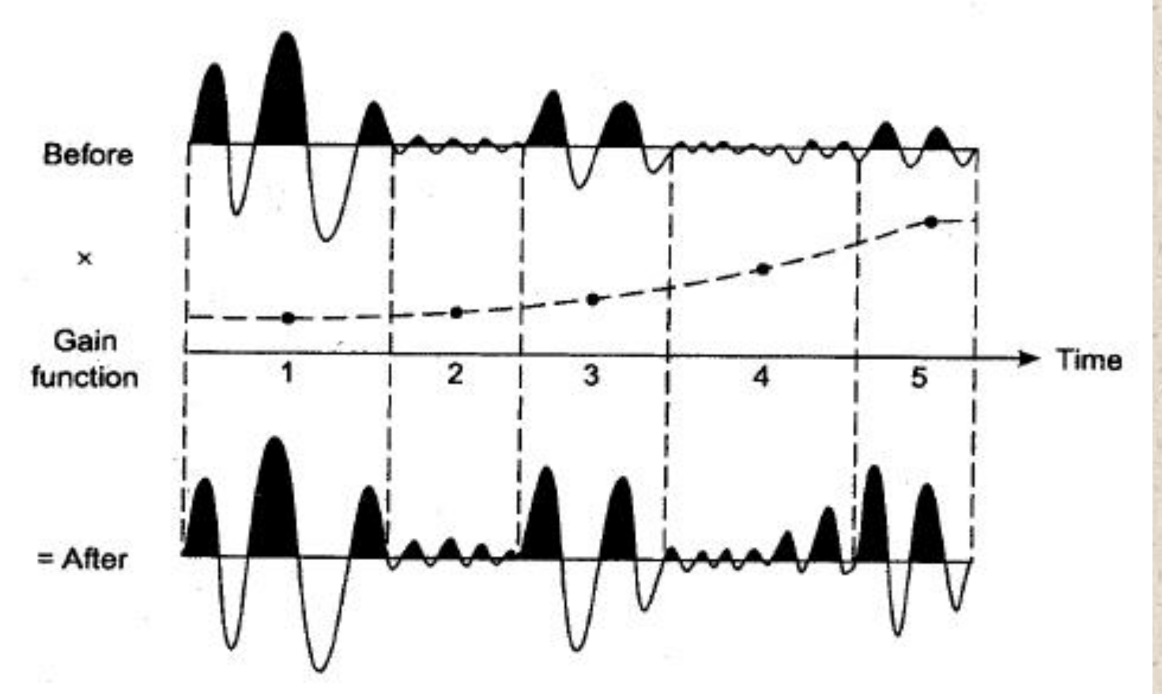


Removal of traces contaminated with high amplitude noise, e.g. due to geophones close to machinery, or that did not record data.

III. Gain Recovery

Seismic waves decrease in amplitude as they propagate further into the Earth:

Reflections recorded at late times have lower amplitude than those at early times.



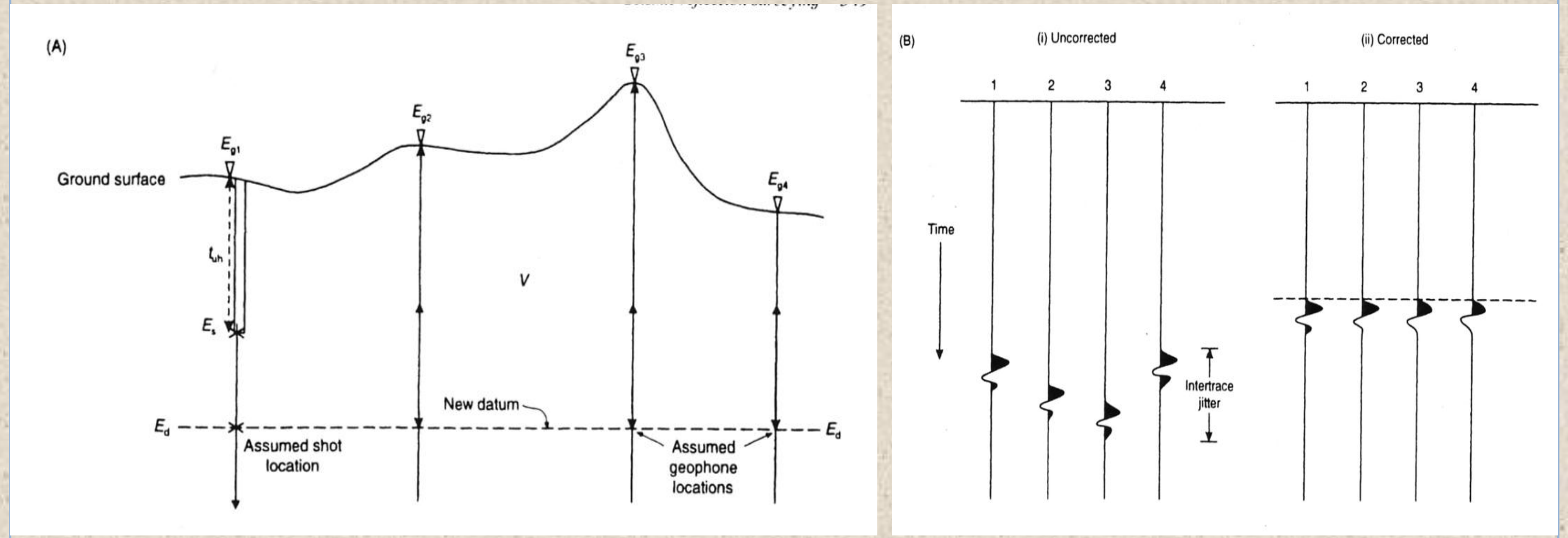
IV. Elevation Statics

Vertical travel time through the near-surface layer varies due to changes in elevation of shot or receiver; it causes:

- misalignment of reflections
- after NMO correction, reflections do not stack correctly.

Statics

- The time shift is added to a trace to correct it to a recording made with source and receiver at a specified datum elevation.
- It is constant for each trace.



VIII. Stacking:

Stacking

Each CMP gather contains several traces corresponding to a single position on a subsurface interface (assuming horizontal layers).

In CMP gathers, many seismic arrivals appear approximately hyperbolic with their apex at zero offset

Stacking Velocity

The stacking velocity of an arrival is the velocity value that characterises the hyperbola that is the best fit to the arrival

Creating a Reflection Profile

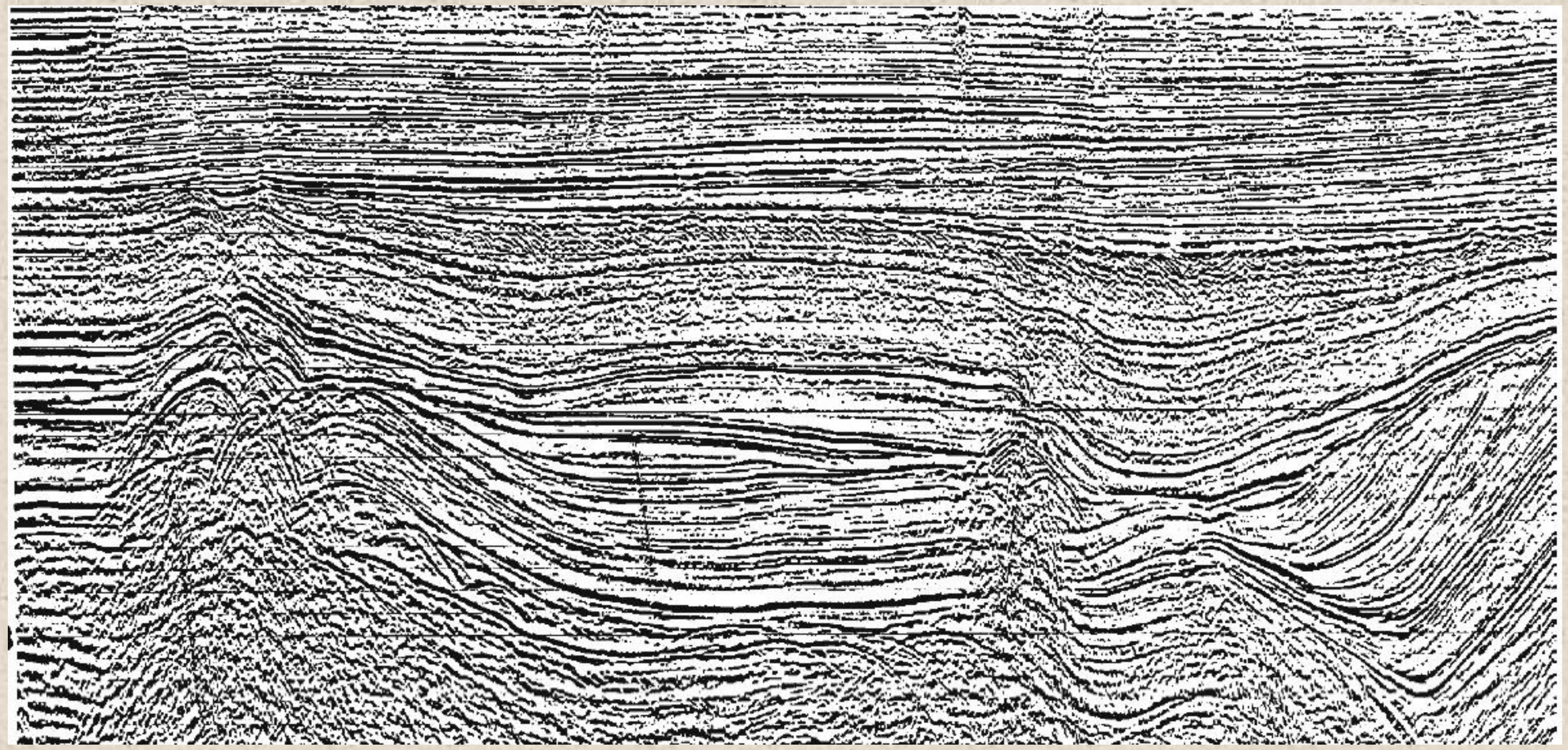
The traces in each CMP gather are combined in a 3-stage process to produce a single trace that represents the reflections recorded at that CMP position.

- NMO Correction: Aligns each primary reflection at its zero-offset reflection time using primary reflection stacking velocities
- Muting: Parts of traces stretched greatly by NMO correction are muted, i.e. set to zero
- Stacking: All traces in a CMP gather are summed to create a single seismogram that simulates a recording made with a coincident source and receiver at the CMP location

Stacking enhances primary reflections and suppresses random noise and unaligned coherent arrivals such as multiples.

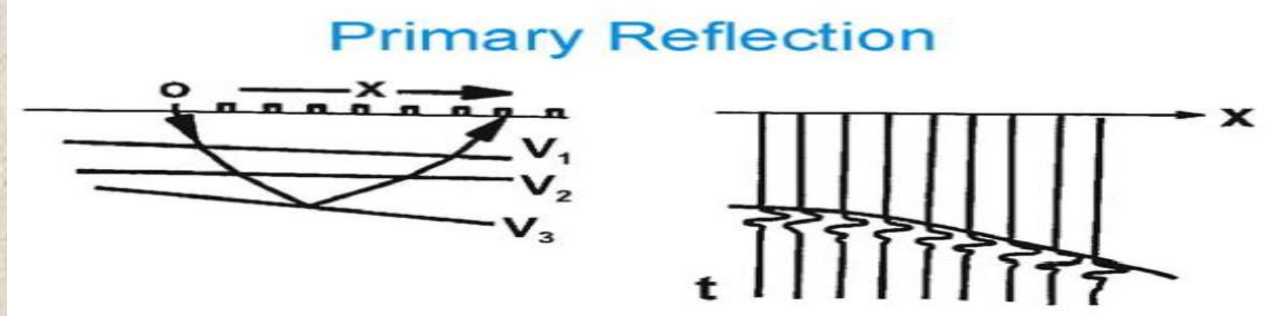
Stacked Reflection Profile

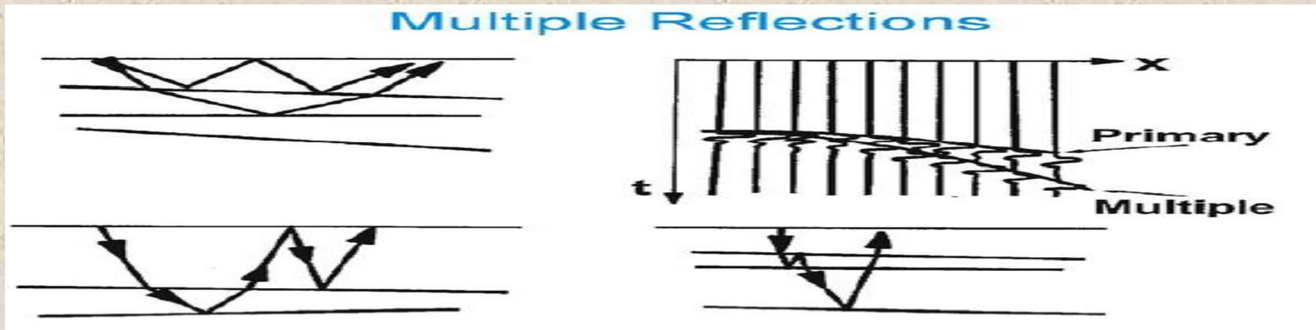
A seismic reflection profile is created by plotting side-by-side each stacked trace from the CMP gathers along a seismic profile.



Stacking Suppresses Multiples

- **Primary Reflection:** Wave that travels directly down to an interface, is reflected, and then travels directly back to surface
- **Multiple Reflection:** Wave that is reflected more than once, and so has two or more up and downgoing legs





X. Migration:

- A dipping reflection is NOT at its true subsurface position.
- Migration moves reflections on a stacked seismic section to their true subsurface position

A reflection is in its true subsurface position when the angle between the normal incidence raypath and reflector is 90°.

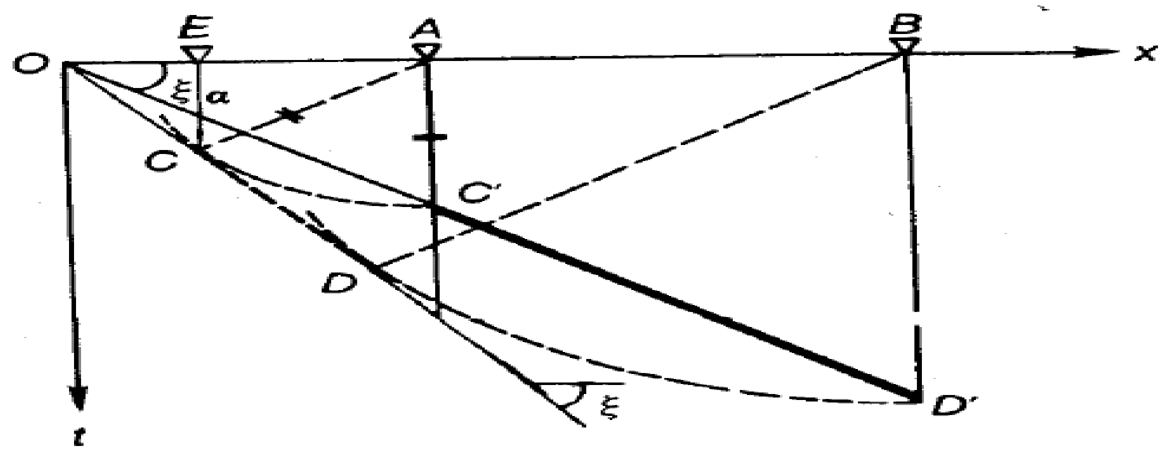


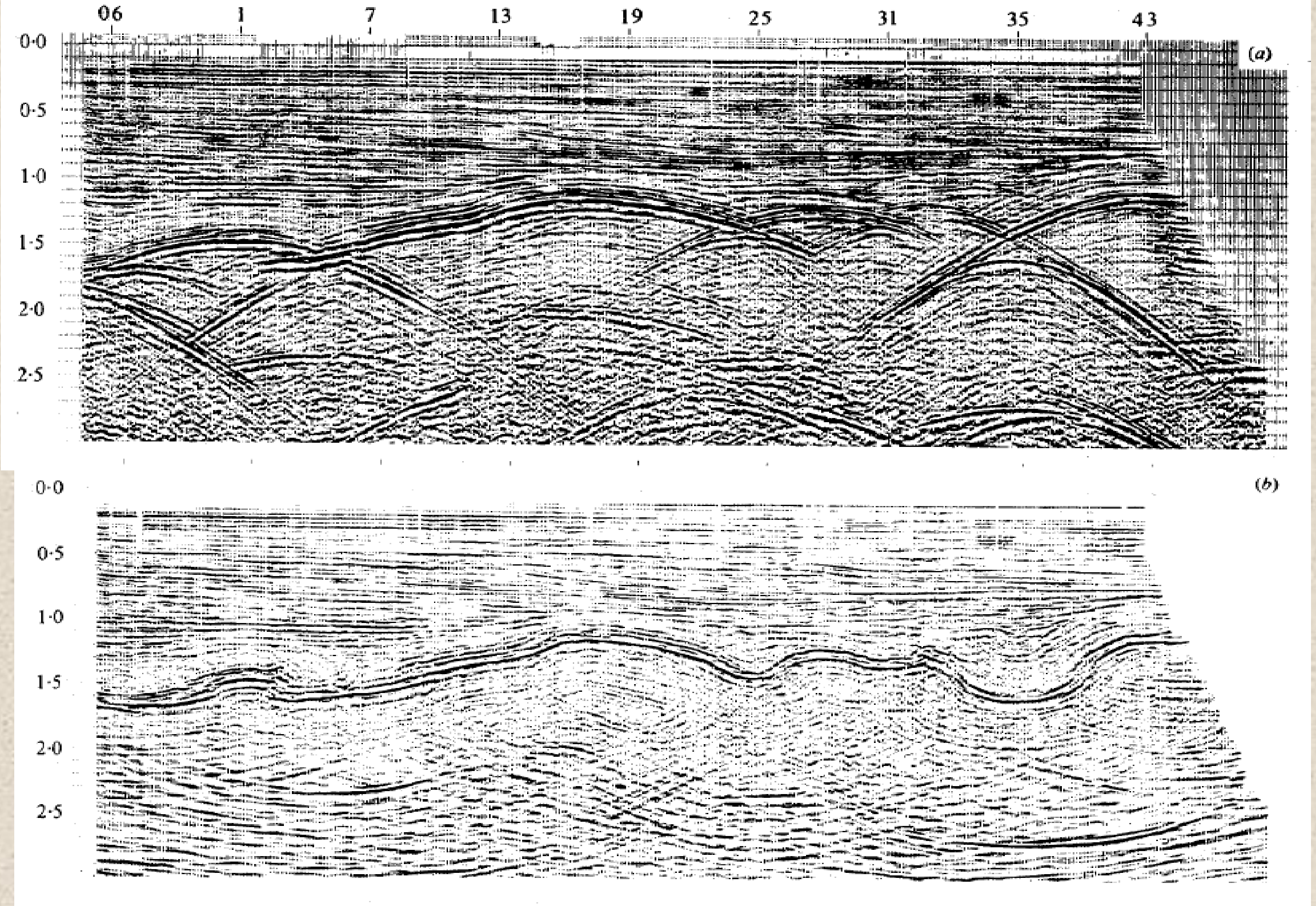
Fig. Migration principle. Migration of segment $C'D'$ into CD increases the dip from ξ_a to ξ.

$$\sin\xi = \frac{BD}{OB} = \frac{BD'}{OB} = \tan\xi_a$$

The true position of a dipping reflection is updip at shallower time.

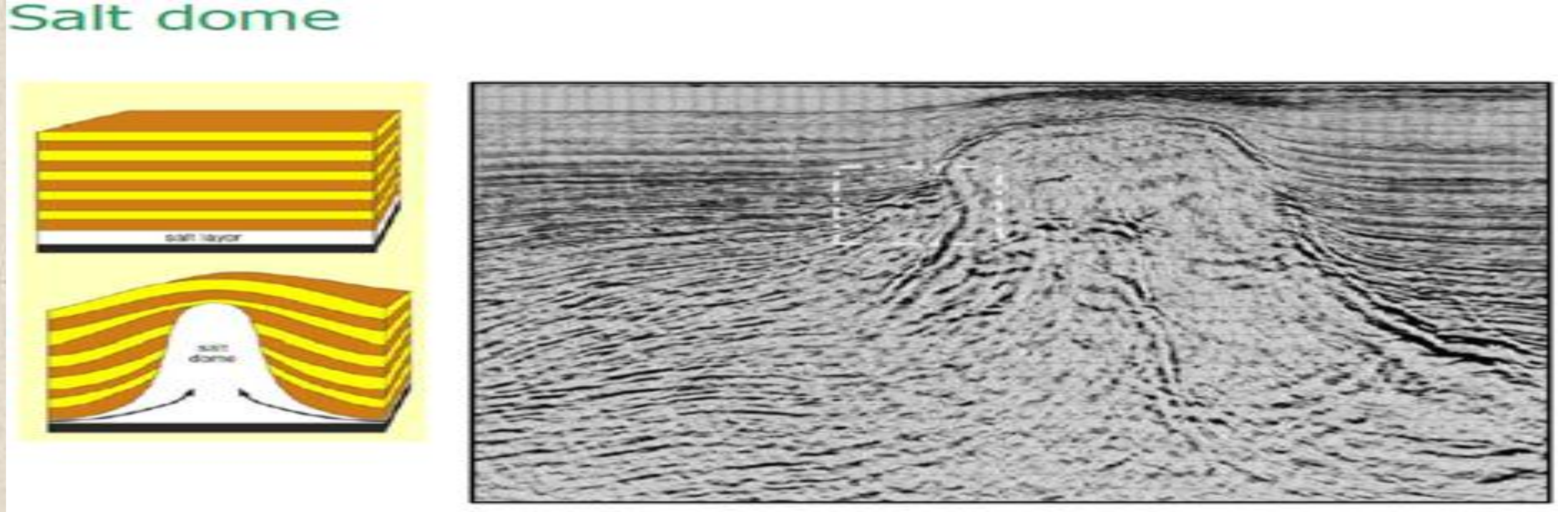
Maximum dip on unmigrated section is 45°.

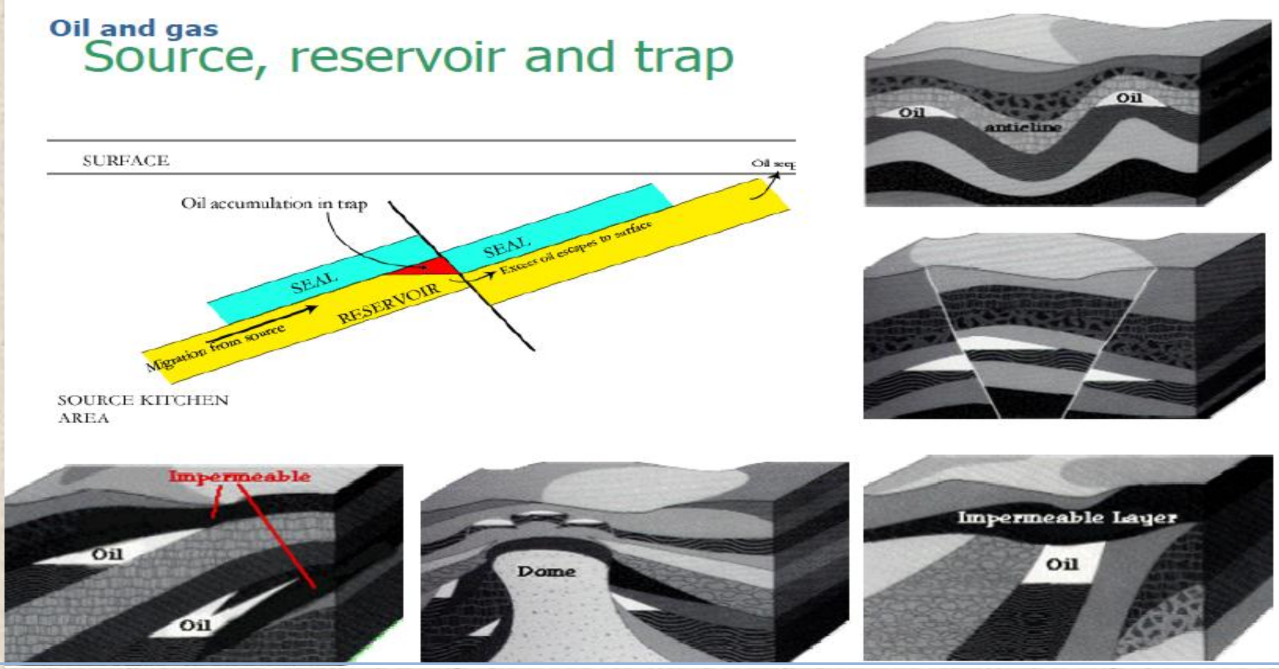
Example: Migration of reflection from a rugged interface



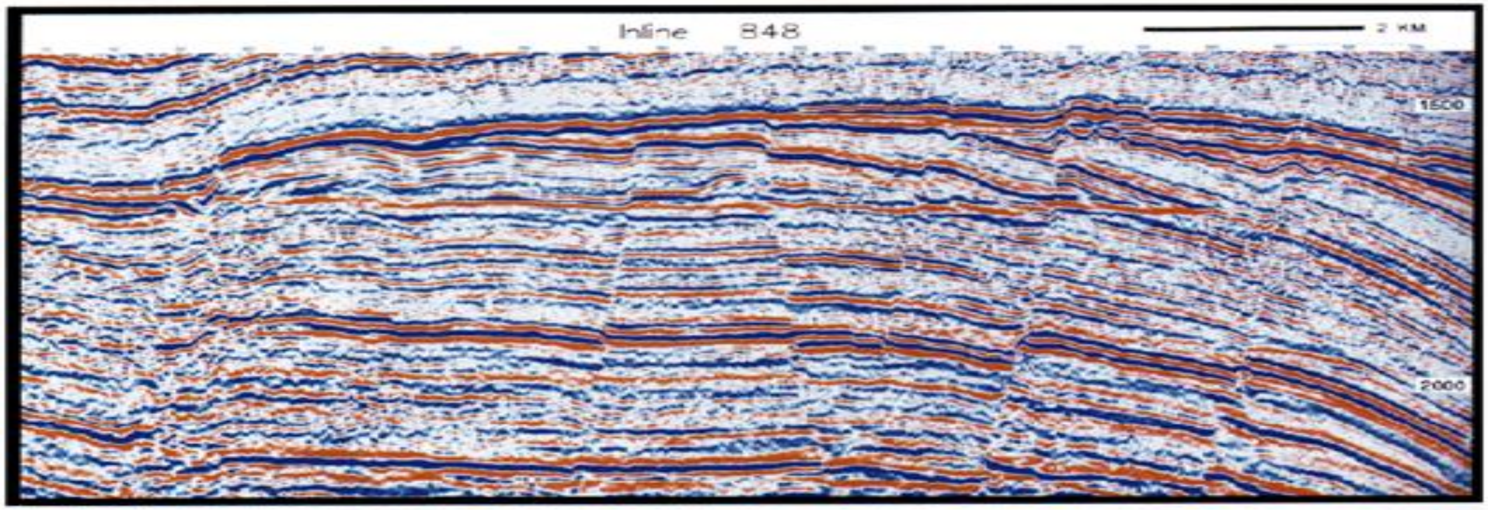
(a) Unmigrated section; (b) Migrated section.

Examples of Structural Features Responses





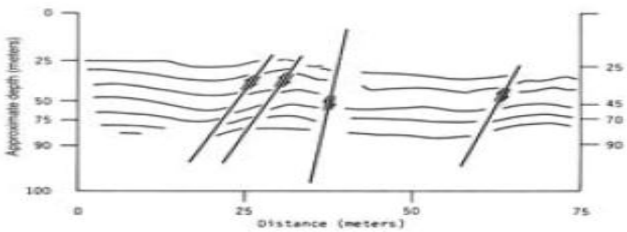
Faults

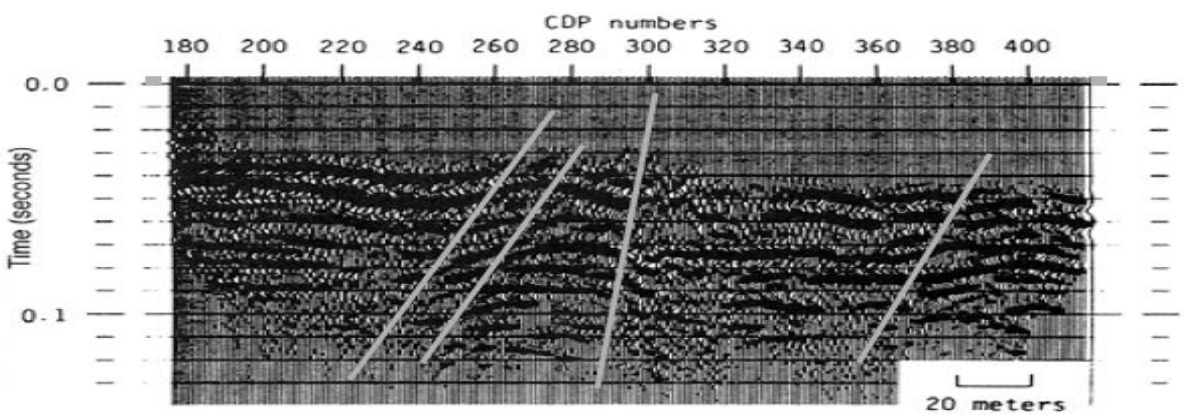


Locating faults

- ➔ **Migrating fluids**
- ➔ **Seismic hazard**

Identified as discontinuities in reflection surfaces





None of these faults visible at the surface – suggests recent inactivity