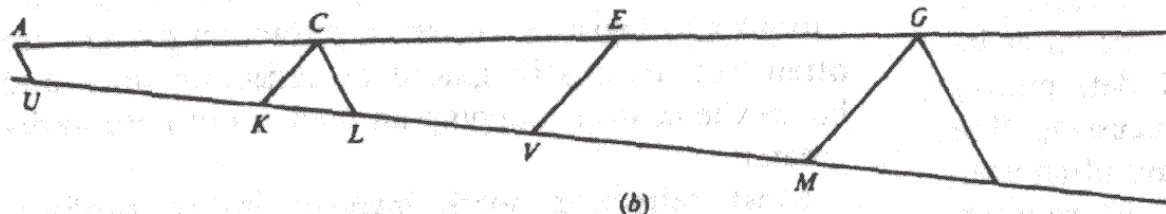
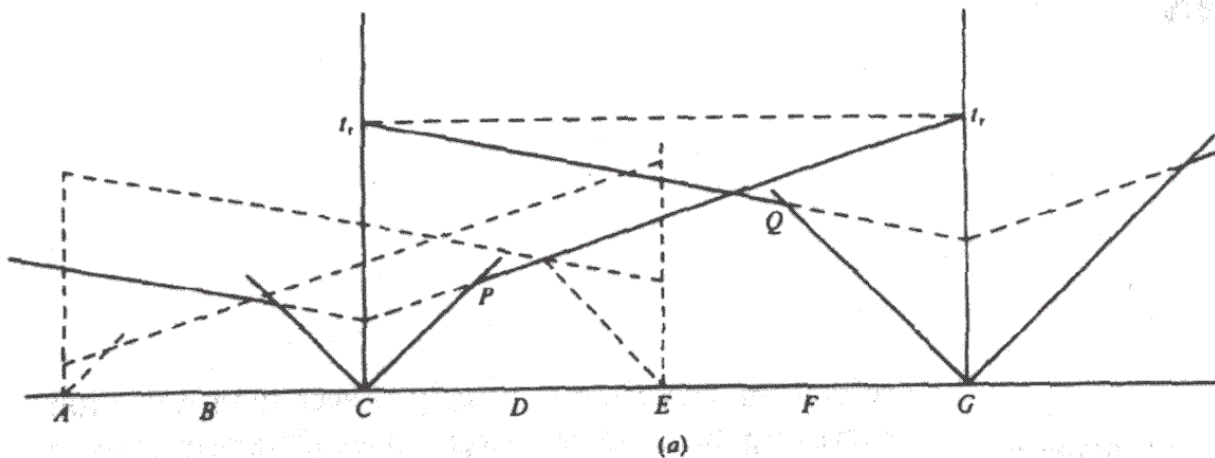


Refraction seismic Method

- Field techniques
- Inversion for refractor velocity, depth, and dip
- Delay time
- Interpretation
 - ◆ Basic-formula methods
 - ◆ Delay-time methods
 - ◆ Wavefront reconstruction methods
- Reading:
 - › Sheriff and Geldart, Chapter 11

Field techniques

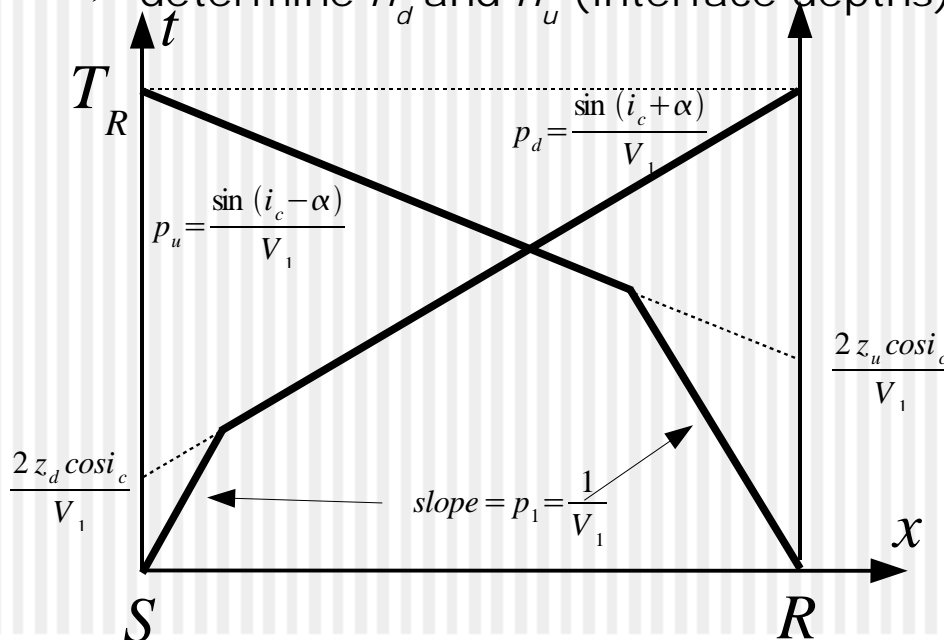
- In-line shooting
 - May shoot segments (e.g., C-D, D-E, E-F, etc. below) in order to economize
 - Depending on the target, longer or shorter profiles, with or without recording at shorter offsets



Refraction Interpretation

Reversed travel times

- One needs *reversed* recording (in opposite directions) for resolution of dips.
- The *reciprocal times*, T_R , must be the the same for reversed shots.
- Dipping refractor is indicated by:
 - ◆ Different *apparent velocities* ($=1/p$, TTC slopes) in the two directions;
 - determine V_2 and α (refractor velocity and dip).
 - ◆ Different *intercept times*.
 - determine h_d and h_u (interface depths).



Determination of Refractor Velocity and Dip

- *Apparent velocity* is $V_{app} = 1/p$, where p is the *ray parameter* (i.e., slope of the travel-time curve).

- ◆ Apparent velocities are measured directly from the observed TTCs;

- ◆ $V_{app} = V_{refractor}$ only in the case of a horizontal layering.

- ◆ For a dipping refractor:

- Down dip: $V_d = \frac{V_1}{\sin(i_c + \alpha)}$ (*slower than V_1*);

- Up-dip: $V_u = \frac{V_1}{\sin(i_c - \alpha)}$ (*faster*).

- From the two reversed apparent velocities, i_c and α are determined:

$$i_c + \alpha = \sin^{-1} \frac{V_1}{V_d}, \quad i_c - \alpha = \sin^{-1} \frac{V_1}{V_u}$$

$$i_c = \frac{1}{2} \left(\sin^{-1} \frac{V_1}{V_d} + \sin^{-1} \frac{V_1}{V_u} \right),$$

$$\alpha = \frac{1}{2} \left(\sin^{-1} \frac{V_1}{V_d} - \sin^{-1} \frac{V_1}{V_u} \right).$$

- From i_c , the refractor velocity is:

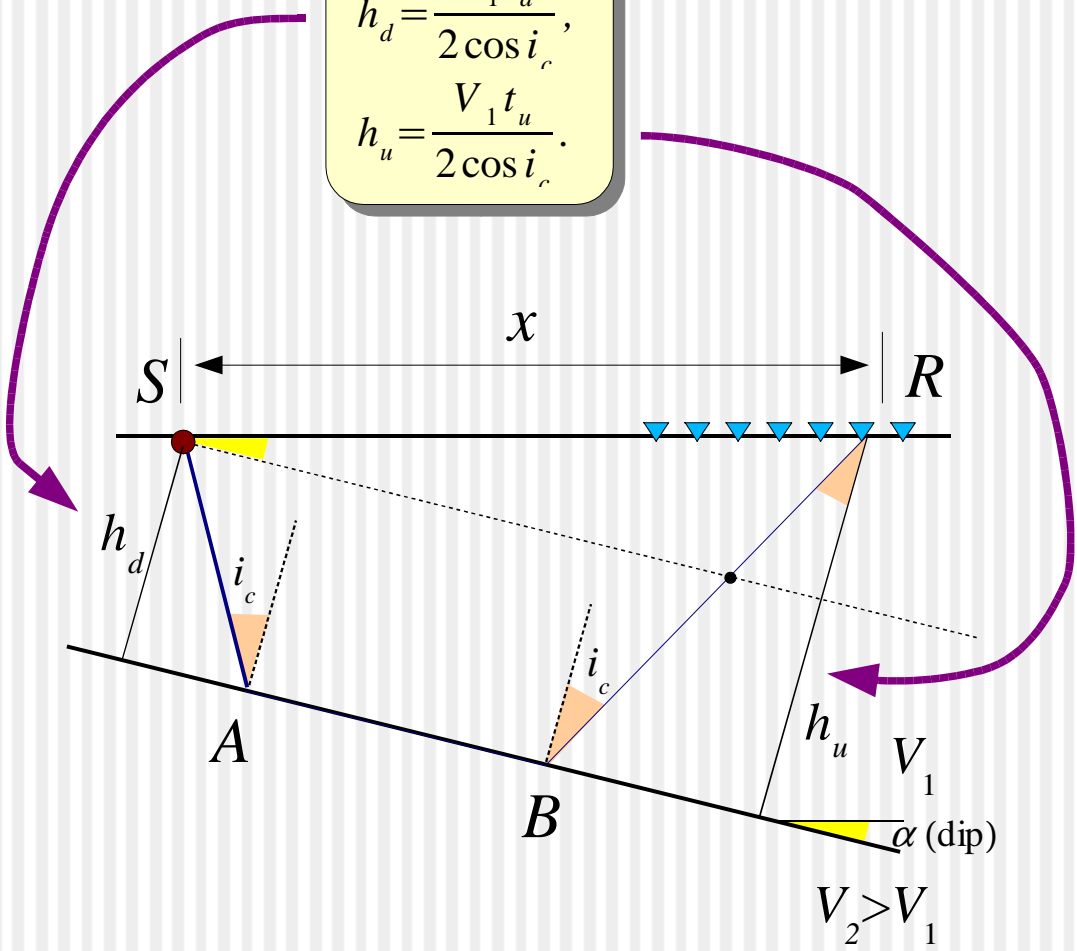
$$V_2 = \frac{V_1}{\sin i_c}.$$

Determination of Refractor Depth

- From the *intercept times*, t_d and t_u , *refractor depth* is determined:

$$h_d = \frac{V_1 t_d}{2 \cos i_c}$$

$$h_u = \frac{V_1 t_u}{2 \cos i_c}$$



Delay time

(the basis for most refraction interpretation techniques)

- Consider a nearly horizontal, shallow interface with strong velocity contrast (a typical case for *weathering layer*).
 - In this case, we can separate the times associated with the source and receiver vicinities: $t_{SR} = t_{SX} + t_{XR}$.

- Relate the time t_{SX} to a time along the refractor, t_{BX} :

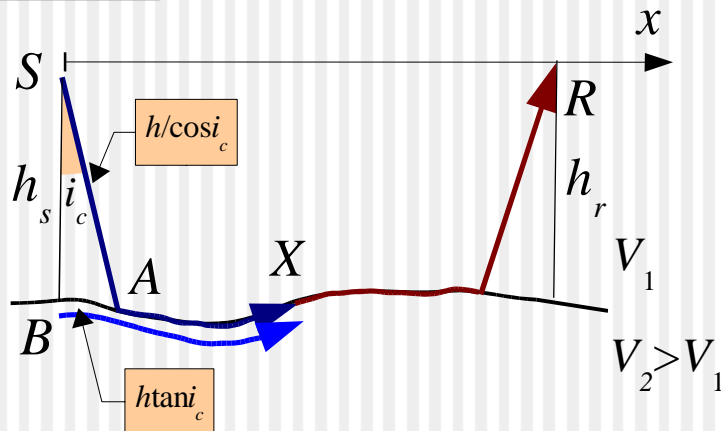
$$t_{SX} = t_{SA} - t_{BA} + t_{BX} = t_{S\text{Delay}} + x/V_2.$$

Note that $V_2 = V_1/\sin i_c$

$$t_{S\text{Delay}} = \frac{SA}{V_1} - \frac{BA}{V_2} = \frac{h_s}{V_1 \cos i_c} - \frac{h_s \tan i_c}{V_2} = \frac{h_s}{V_1 \cos i_c} (1 - \sin^2 i_c) = \frac{h_s \cos i_c}{V_1}$$

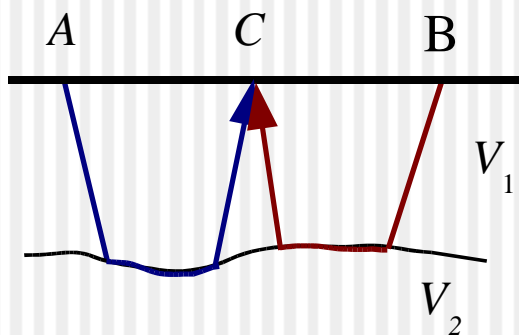
- Thus, the source and receiver *delay times* are:

$$t_{S,R\text{Delay}} = \frac{h_{s,r} \cos i_c}{V_1} \quad \text{and} \quad t_{SR} = t_{S\text{Delay}} + t_{R\text{Delay}} + \frac{SR}{V_2}.$$



Basic-formula interpretation (*The ABC method*)

- Combine the refraction times recorded along A-C, B-C, and A-B:



$$t_{AC} + t_{CB} - t_{AB} \approx 2t_{Delay(C)} = \frac{2h_c \cos i_c}{V_1}$$

- Therefore:

$$h_c \approx \frac{V_1}{2 \cos i_c} (t_{AC} + t_{CB} - t_{AB}).$$

- Note the typical time-to-depth conversion factor:

$$\frac{V_1}{\cos i_c} = \frac{V_1}{\sqrt{1 - \sin^2 i_c}} = \frac{V_1 V_2}{\sqrt{V_2^2 - V_1^2}}.$$

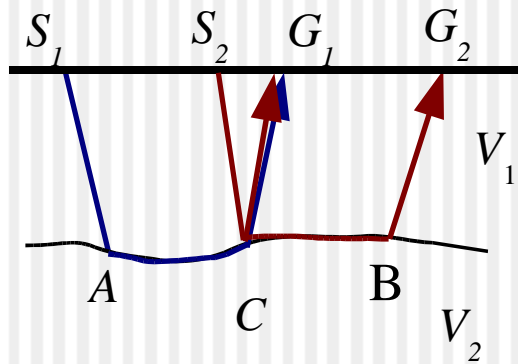
Delay-time methods

Barry's method

- Note that the ABC formula applies to the intercept times, with *any value* of V_2 assumed:

$$t^{\text{int}} = t - \frac{x}{V_2}$$

$$t_{AC}^{\text{int}} + t_{CB}^{\text{int}} - t_{AB}^{\text{int}} \approx 2 t_{\text{Delay}(C)} = \frac{2 h_C \cos i_c}{V_1}$$



- Thus the shot delay at C is:

$$t_{\text{Delay}(C)} \approx \frac{1}{2} (t_{CB}^{\text{int}} + t_{AC}^{\text{int}} - t_{AB}^{\text{int}})$$

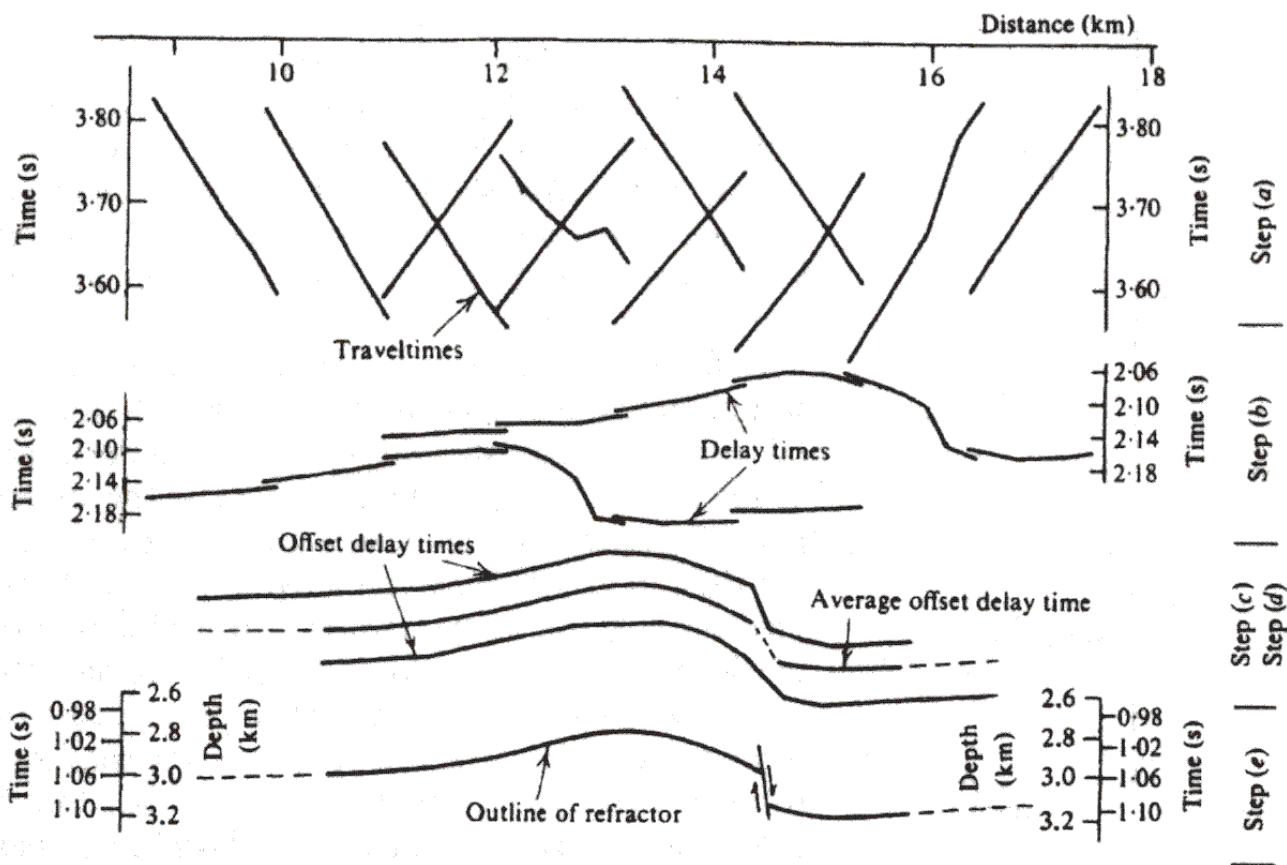
- And geophone delay at B:

$$t_{\text{Delay}(B)} = t_{\text{Delay}(CB)} - t_{\text{Delay}(C)} \approx \frac{1}{2} (t_{CB}^{\text{int}} - t_{AC}^{\text{int}} + t_{AB}^{\text{int}})$$

Delay-time methods

Barry's method

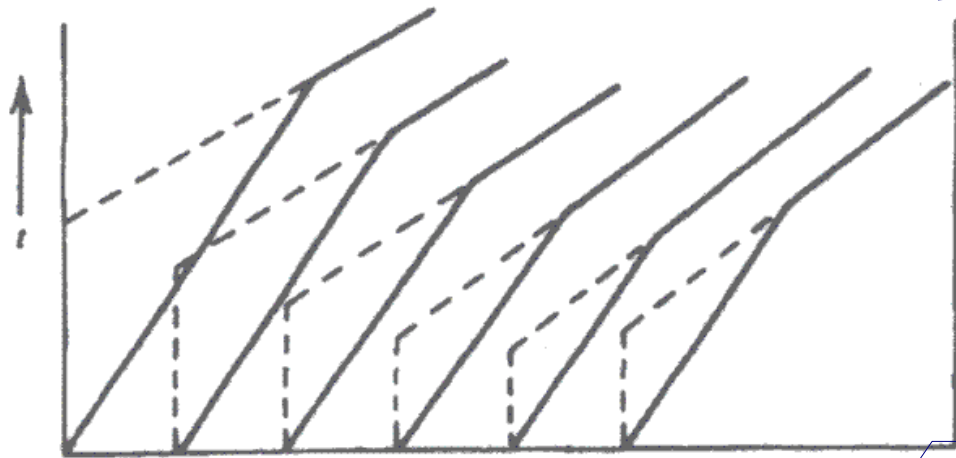
- 1) Plot the time-reduced travel times.
- 2) Calculate the geophone delay times.
- 3) Plot the delay times at the "offset geophone" positions.
- 4) Adjust V_2 until the lines from reversed profiles are parallel.



Delay-time methods

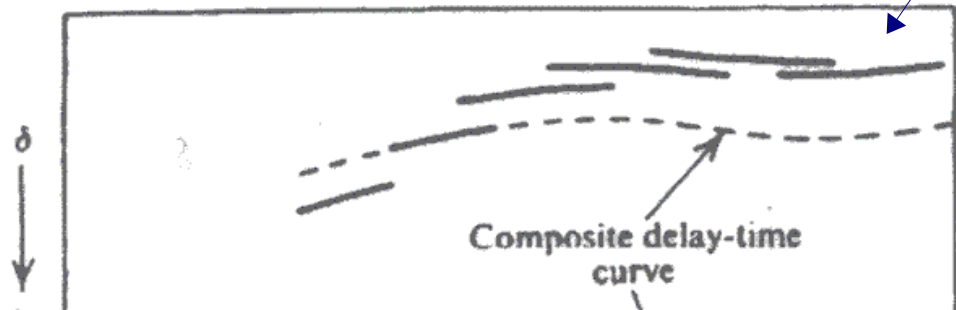
Wyrobek's method

A series of unreversed profiles is used



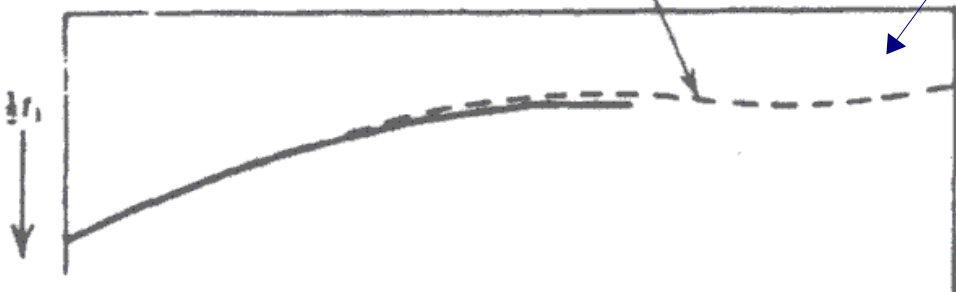
Step (a)
(travel times)

For each geophone the various shots form an equivalent of a reversed profile. The delay times are combined into a composite delay-time curve



Step (b)
(total delay times)

With properly adjusted V_2 , the composite delay times match the half-intercept times



Step (c)
(half-intercept times)

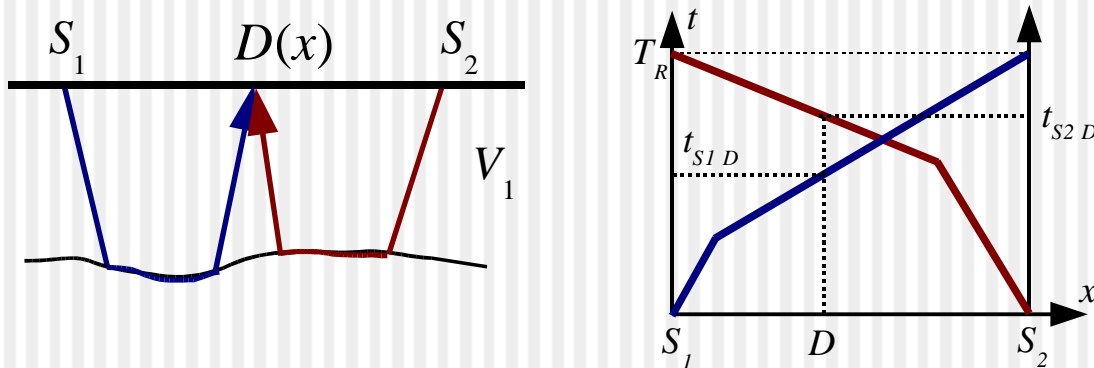


Step (d)
(depth)

Plus-Minus Method (Hagedoorn)

- Assume that we have recorded two headwaves in the opposite directions, and have estimated the velocity of the overburden, V_1 .

How can we map the refracting interface?



- Solution:

- Profile $S_1 \rightarrow S_2$: $t_{S_1 D} = \frac{x}{V_2} + t_{S_1} + t_D$;
- Profile $S_2 \rightarrow S_1$: $t_{S_2 D} = \frac{(S_1 S_2 - x)}{V_2} + t_{S_2} + t_D$.

Form PLUS travel-time:

$$t_{PLUS} = t_{S_1 D} + t_{S_2 D} = \frac{S_1 S_2}{V_2} + t_{S_1} + t_{S_2} + 2t_D = t_{S_1 S_2} + 2t_D.$$

Hence: $t_D = \frac{1}{2}(t_{PLUS} - t_{S_1 S_2})$.

- To determine i_c (and depth), still need to find V_2 .

Plus-Minus Method (Continued)

- To determine V_2 :

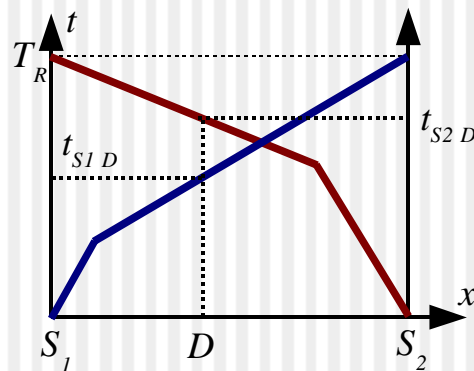
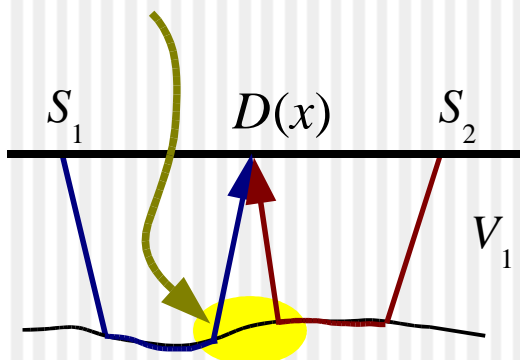
- ◆ Form MINUS travel-time:

this is a constant!

$$t_{MINUS} = t_{S_1 D} - t_{S_2 D} = \frac{2x}{V_2} - \left[\frac{S_1 S_2}{V_2} + t_{s_1} - t_{s_2} \right]$$

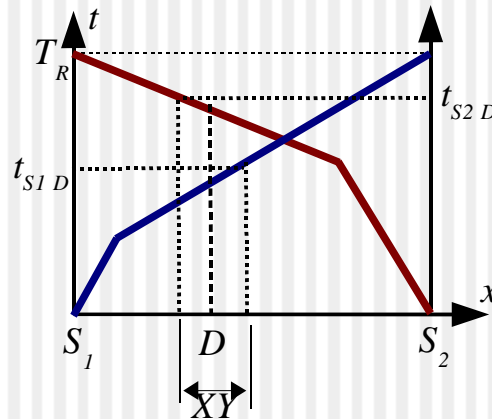
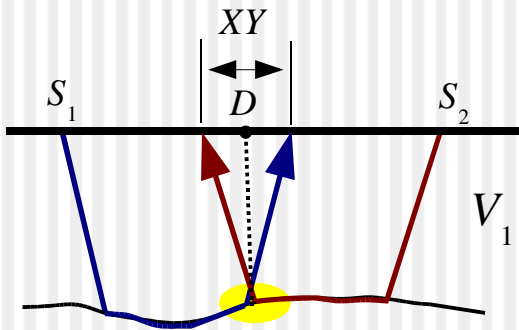
Hence: $slope [t_{MINUS}(x)] = \frac{2}{V_2}$.

- ◆ The slope is usually estimated by using the *Least Squares method*.
- Drawback of this method – averaging over the pre-critical region.



Generalized Reciprocal Method (GRM)

- Introduces offsets ('XY') in travel-time readings in the forward and reverse shots;
 - ◆ so that the imaging is targeted on a compact interface region.
- Proceeds as the plus-minus method;
- Determines the 'optimal' XY:
 - 1) Corresponding to the most linear *velocity analysis function*;
 - 2) Corresponding to the *most detail* of the refractor.



- The *velocity analysis function*:

$$t_V = \frac{1}{2}(t_{S_1D} - t_{S_2D} + t_{S_1S_2}),$$

should be linear, slope = $1/V_2$;

- The *time-depth function*:

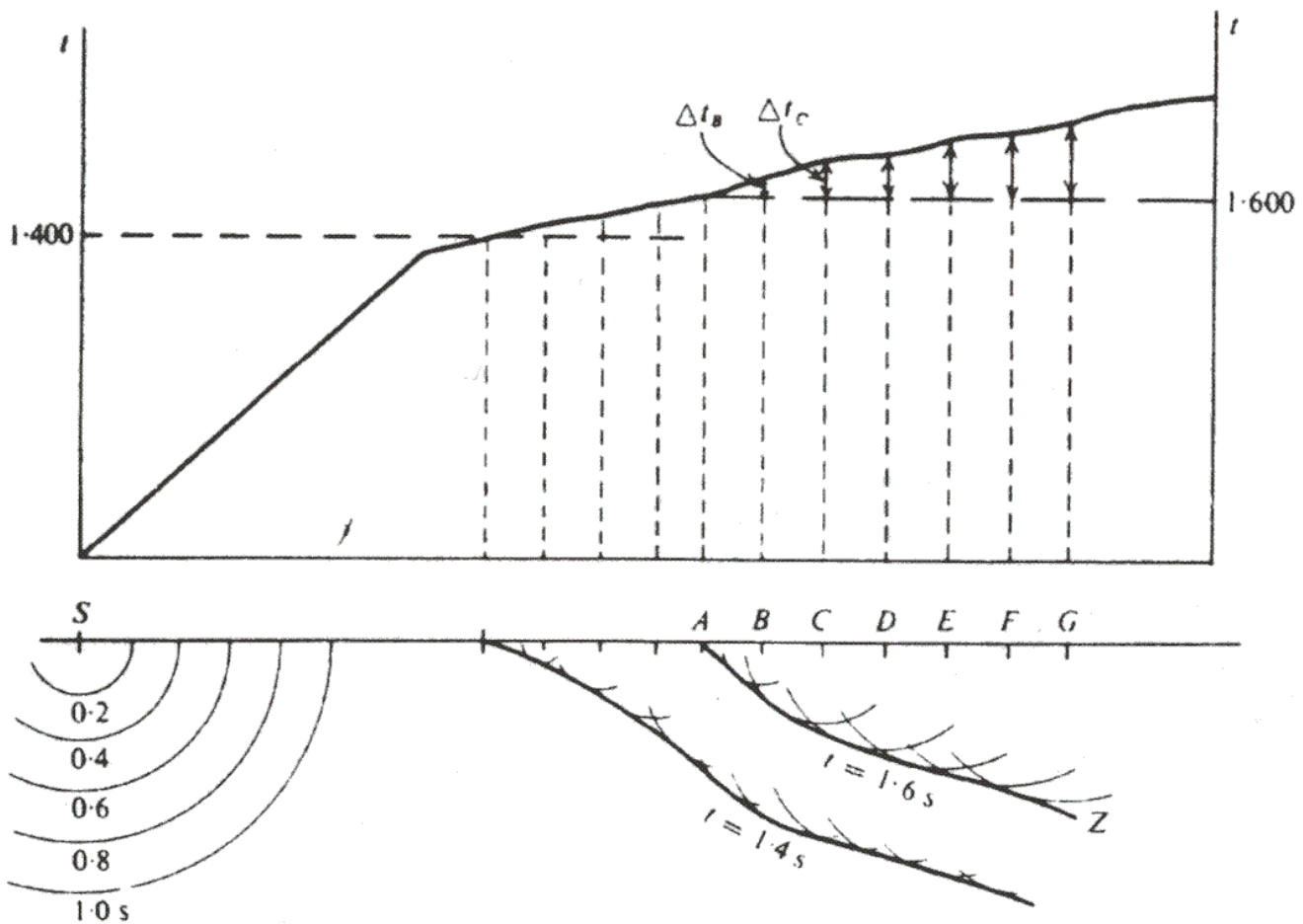
$$t_D = \frac{1}{2}(t_{S_1D} + t_{S_2D} - t_{S_1S_2} - \frac{XY}{V_2}).$$

this is related to the desired image:

$$h_D = \frac{t_D V_1 V_2}{\sqrt{V_2^2 - V_1^2}}$$

Wavefront reconstruction methods

- Head-wave wavefronts can be propagated back into the subsurface...



Wavefront reconstruction methods

- ... and combined to form an image of the refractor:
 - Refractor is the locus of (x, z) points such that:

$$t_{Forward}(x, z) + t_{Reversed}(x, z) = T_{Reciprocal}$$

- Note the similarity with the PLUS-MINUS method!

