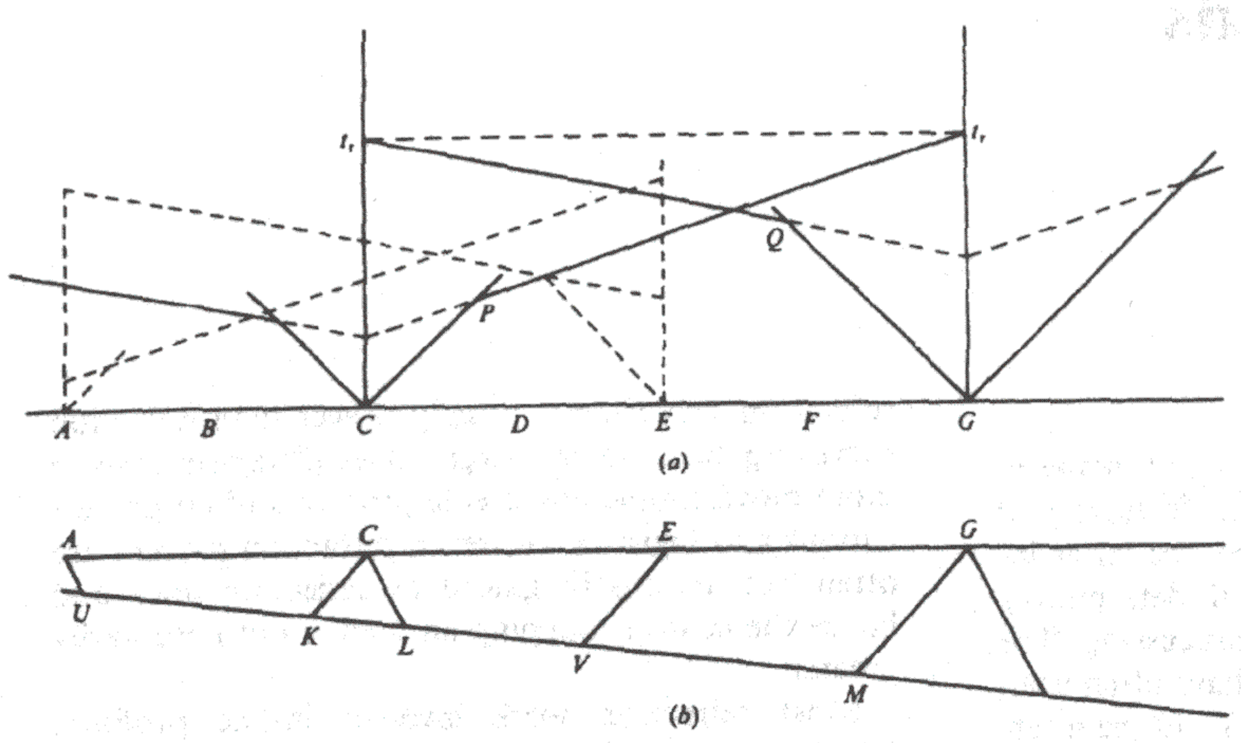
Refraction seismic Method

- Field survey planning
- 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

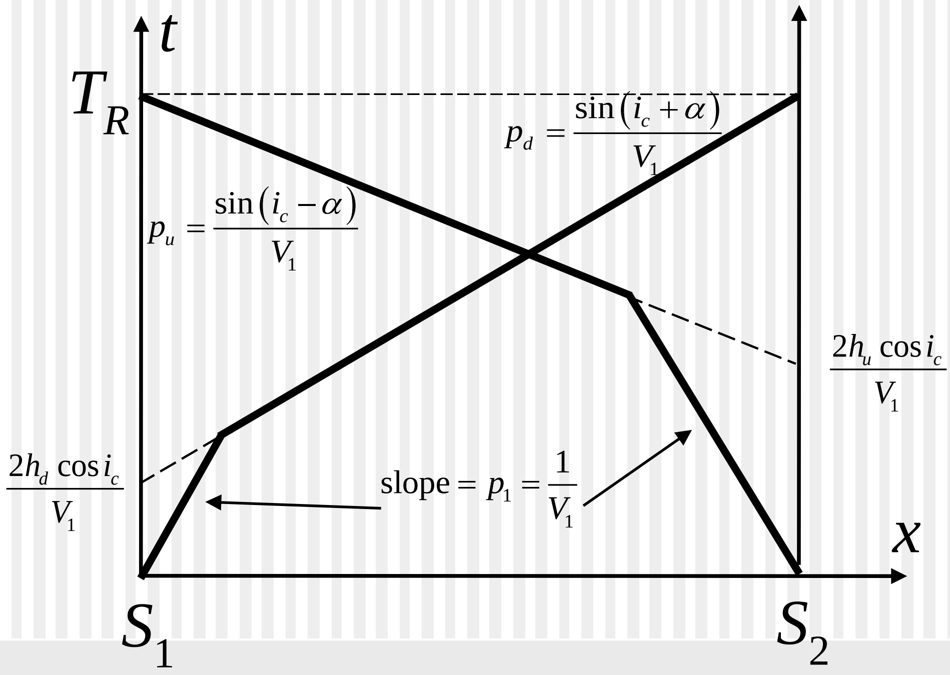
Field survey planning

- Usually in-line shooting (making a 2-D section)
  - In designing the experiment, the goal is to cover the direct-wave intervals, cross-over points, and head-wave segments
    - Reversed shooting is usually preferred
  - 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 (refracting boundary depths)



Determination of Refractor Velocity and Dip

- *Apparent velocity* is $V_{\text{app}} = 1/p$, where p is the *ray parameter (*i.e., slope of the travel-time curve).
  - Apparent velocities are measured directly from the observed TTCs;
  - $V_{\text{app}} = V_{\text{refractor}}$ 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:

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

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

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

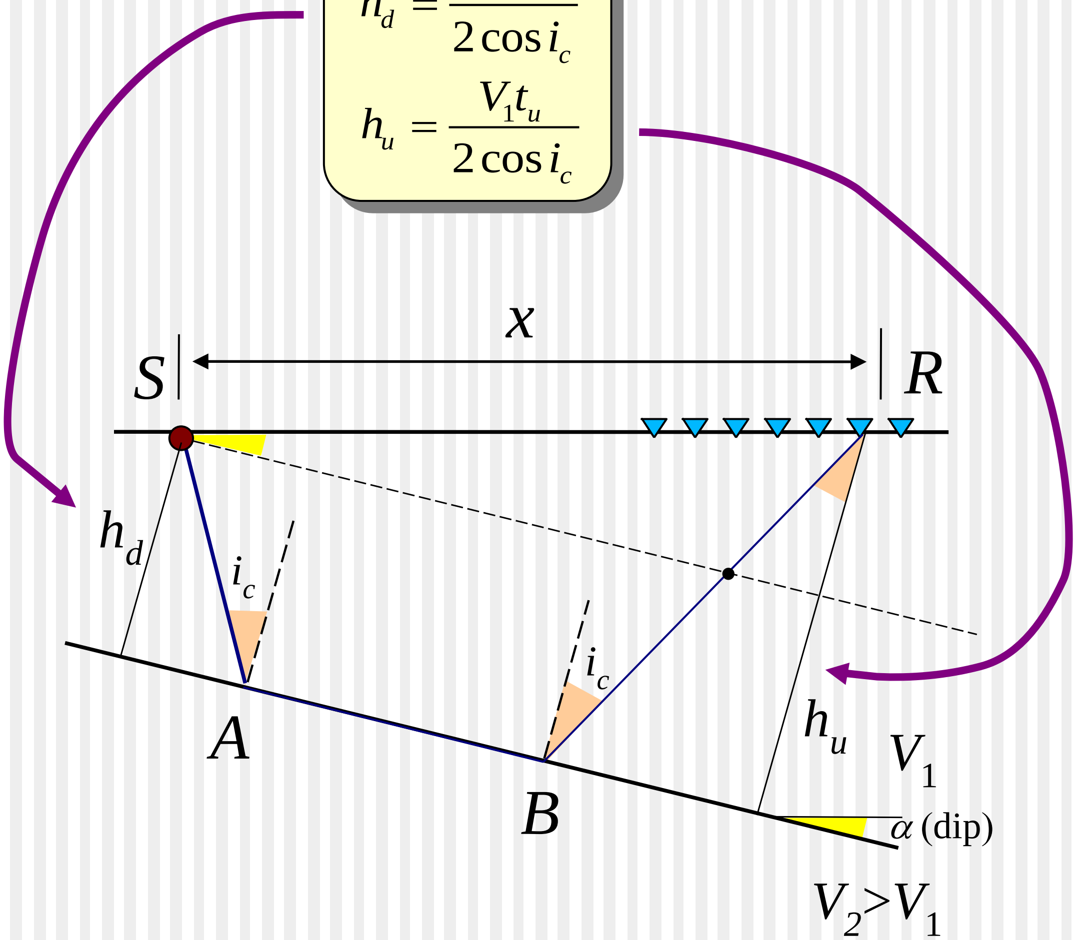
- From i_c, the refractor velocity is: $V_2 = \frac{V_1}{\sin i_c}$

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}:

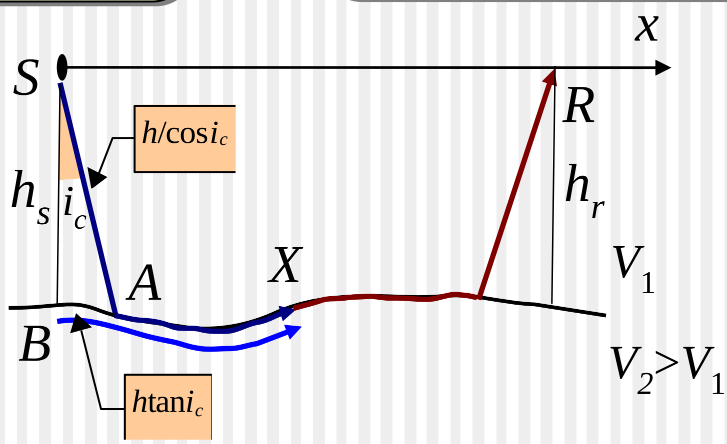
$t_{SX} = t_{SA} - t_{BA} + t_{BX} = t_{S\ Delay} + x/V_2$.

Note that $V_2 = V_1/\sin i_c$

$$t_{SDelay} = \frac{SA}{V_1} - \frac{BA}{V_2} = \frac{h_s}{V_1 \cos i_c} - \frac{h_s \tan i_c}{V_2} = \frac{h_s}{V_1 \cos i_c}\left(1 - \sin^2 i_c\right) = \frac{h_s \cos i_c}{V_{1.}}$$

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

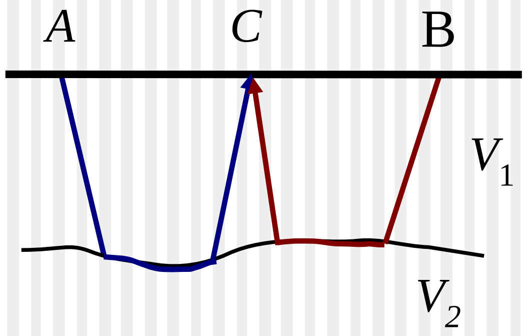
$$t_{S,RDelay} = \frac{h_{s,r} \cos i_c}{V_1}$$ and $$t_{SR} = t_{SDelay} + t_{RDelay} + \frac{SR}{V_2}$$



New!

Basic-formula interpretation
(The ABC method)

- Uses reversed shots recorded at the same receivers
- 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:

$$h_C \approx \frac{V_1}{2\cos i_c}\left(t_{AC} + t_{CB} - t_{AB}\right)$$

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

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

New!

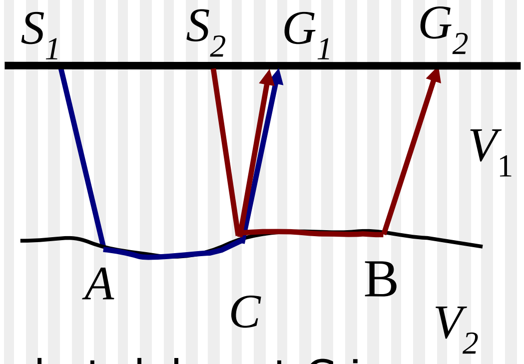
Delay-time methods
Barry's method

- Uses shots recorded in the same direction
- Note that the ABC formula applies to the "reduced" (or "intercept") times, with *any value* of reduction velocity V_R assumed:

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

In this method, V_R is selected so that t^{int} from different shots form a common pattern

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



- Thus, the shot delay at C is:

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

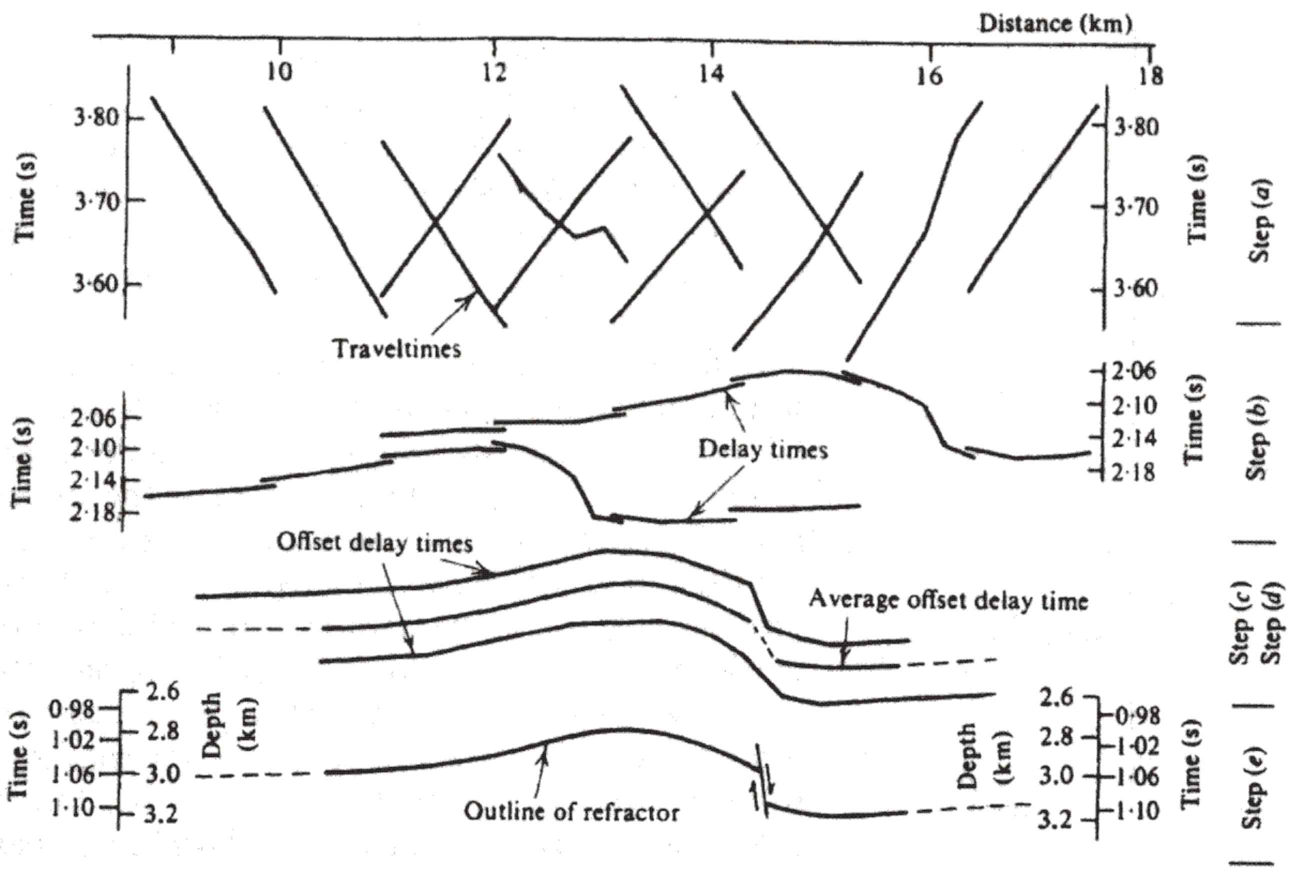
- and geophone delay at B:

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

New!

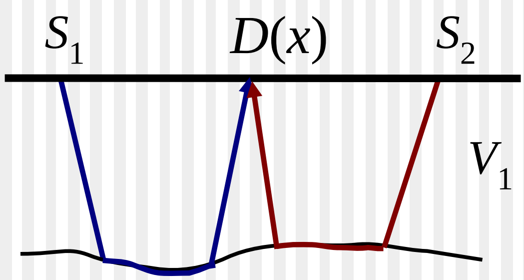
Delay-time methods
Barry's method

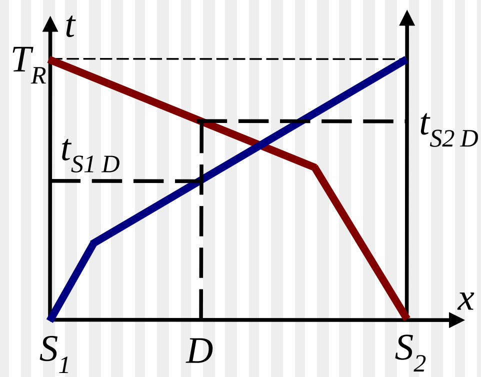
1) Plot the time-reduced travel times.
2) Calculate the geophone delay times.
3) Plot the delay times at the "offset geophone" positions.
4) Adjust V_2 until the lines from reversed profiles are parallel.



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

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

Plus-Minus method
(Continued)

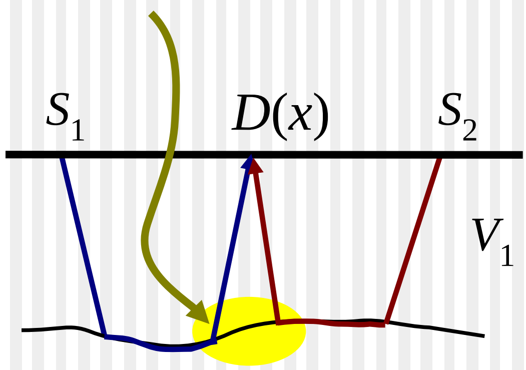
- To determine V_2:
  - Form MINUS travel-time:

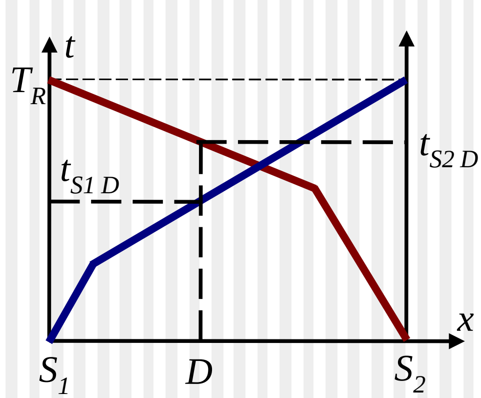
this is a constant!

$$t_{MINUS} = t_{S_1 D} - t_{S_2 D} = \frac{2x}{V_2} - \frac{S_1 S_2}{V_2} + t_{S_1} - t_{S_2}$$

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

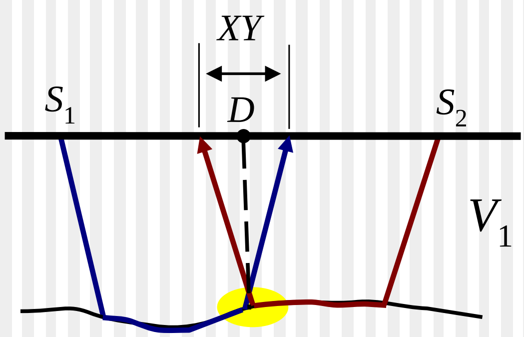
  - The slope is usually estimated by using the *Least Squares method*.
- Drawback of this method – averaging over the pre-critical region.

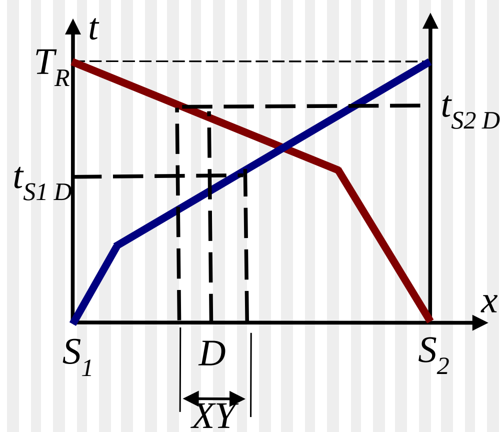




Generalized Reciprocal Method (GRM)

- 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*:

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

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

- The *time-depth function*:

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

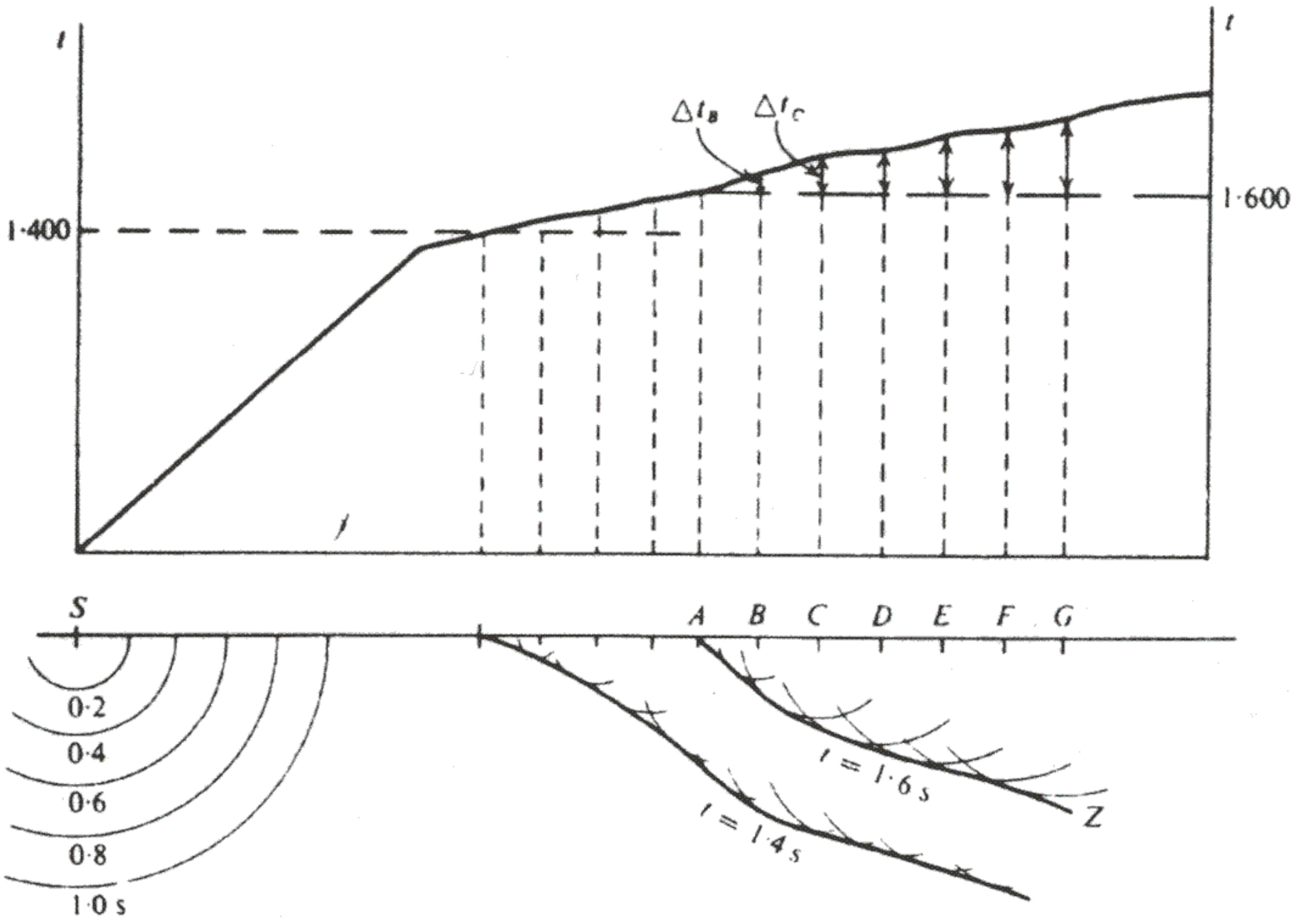
this is related to the desired image:

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

New!

Wavefront reconstruction methods

- For each of the observed travel times, head-wave wavefronts are propagated back into the subsurface...



New!

Wavefront reconstruction methods

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

$$t_{\text{Forward}}\left(x,z\right)+t_{\text{Reversed}}\left(x,z\right)=T_{\text{Reciprocal}}$$

  - Thus, we only need to compute the sum of the two travel-time fields and contour it
  - Note the similarity with the PLUS-MINUS method!