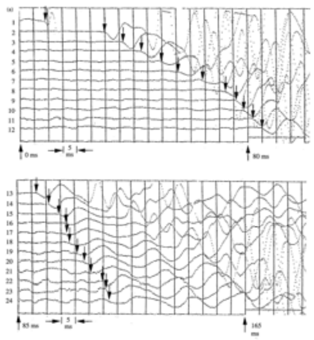
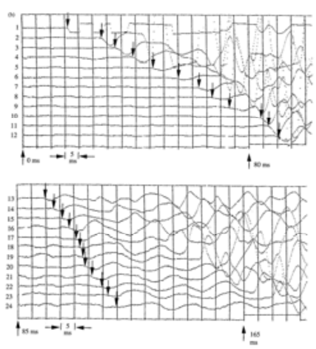
Field Seismographs (Forward)



Field Seismographs (Reverse)



Distance vs. Time

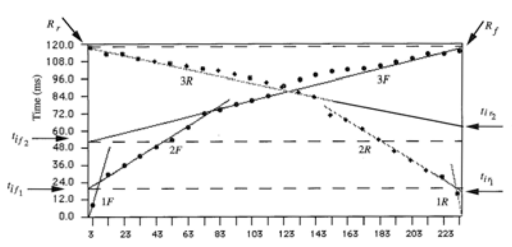


Figure 3-22 Travel-time curve based on data from Figure 3-21.

Interpretation

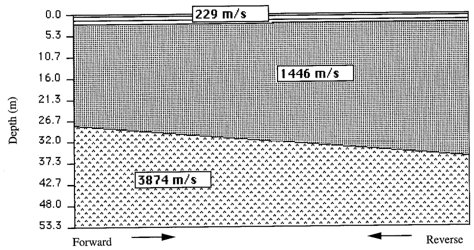
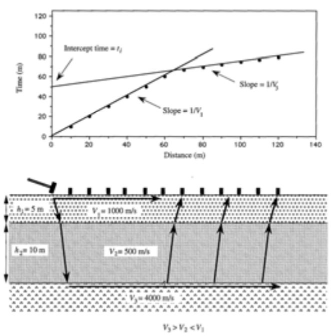
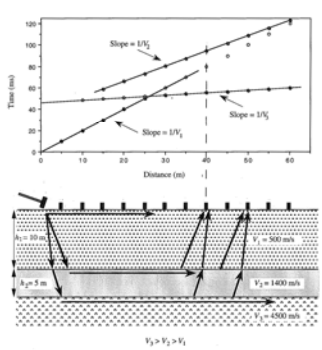


Figure 3-23 Structure computed by RefractSolve from curve segments illustrated in Figure 3-22.

Low Velocity Layer



Thin Layer



Max. Depth to 2nd Interface

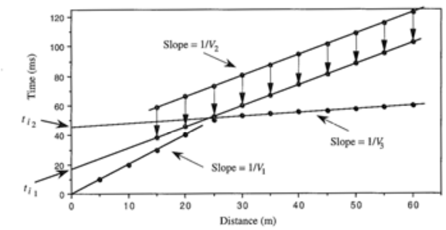
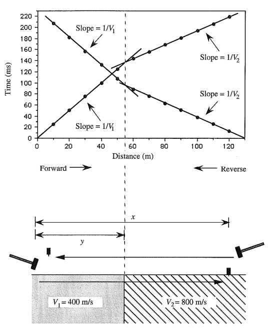


Figure 3-26 How to utilize the travel-time curve in Figure 3-25 to calculate a maximum depth to the second interface. Procedure explained in the text.

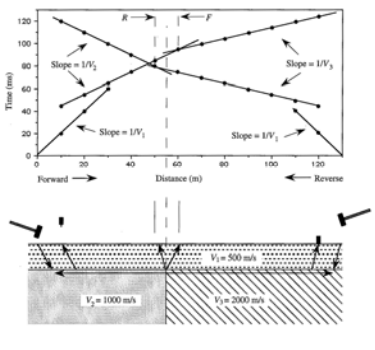
Horizontal Velocity Variation



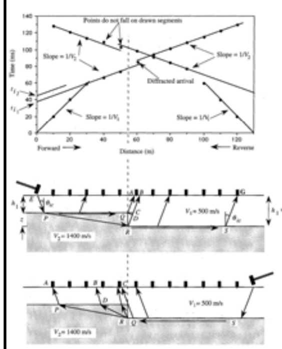
$$\text{time} = \frac{y}{V_1} + \frac{x - y}{V_2} \quad (\text{for } x \geq y) \tag{3-57}$$

$$\frac{dt}{dx} = \frac{1}{V_2} \tag{3-58}$$

Buried Vertical Boundary



Interface Discontinuity



If we compare QA and RB, we see that the difference in intercept times, $t_{i_2} - t_{i_1}$, is due to the extra distance, RD, traveled by RB at V_1. RD is related to the critical angle and the height of the step z:

$$RD = z\cos\theta_{ic} \qquad (3\text{-}59)$$

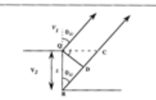
so that the intercept time difference can be computed and z determined by the following:

$$t_{i_2} - t_{i_1} = \frac{z\cos\theta_{ic}}{V_1} \qquad (3\text{-}60)$$

and

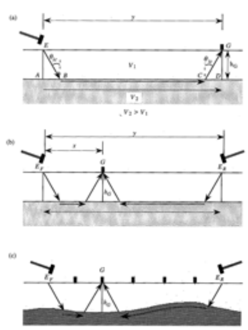
$$z = \frac{\left(t_{i_2} - t_{i_1}\right)V_1}{\cos\theta_{ic}} \qquad (3\text{-}61)$$

$$z = \frac{\left(t_{i_2} - t_{i_1}\right)V_2V_1}{\left(V_2^2 - V_1^2\right)^{1/2}} \qquad (3\text{-}62)$$



Show that the time to travel QC at V_2 is equal to the time to travel DC at V_1.

Delay Time Method



$$T_{EG} = t_R - \frac{y}{V_2} \qquad (3\text{-}63)$$

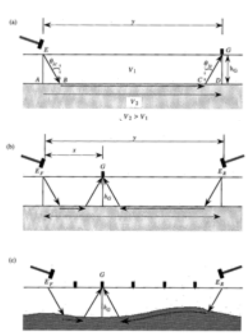
Since, by definition,

$$T_{EG} = T_E + T_G \qquad (3\text{-}64)$$

we can derive an expression for the delay time at a geophone:

$$T_E + T_G = t_R - \frac{y}{V_2}$$

Delay Time Method



$$T_G = t_R - \frac{y}{V_2} - T_E \qquad (3\text{-}65)$$

Also, by definition,

$$T_G = \frac{CG}{V_1} - \frac{CD}{V_2} \qquad (3\text{-}66)$$

Using simple trigonometry and the same relationships we used when deriving Eq. 3-14, we can demonstrate that

$$T_G = \frac{h_G}{V_1\cos\theta_{ic}} - \frac{h_G\tan\theta_{ic}}{V_2}$$

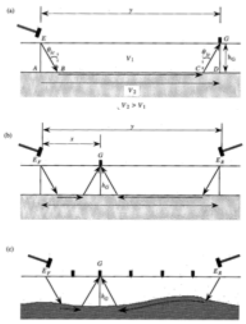
$$T_G = h_G\frac{\left(V_2^2 - V_1^2\right)^{1/2}}{V_1V_2} \qquad (3\text{-}67)$$

and, finally,

$$h_G = T_G\frac{V_1V_2}{\left(V_2^2 - V_1^2\right)^{1/2}} \qquad (3\text{-}68)$$

Thus, we can calculate the depth of the V_1-V_2 interface beneath the geophone if we can determine the delay time at the geophone (and, of course, know V_1 and V_2). How can we determine T_G if we can't measure it directly?

Delay Time Method



Once again, the reverse traverse comes to our rescue. Consider Figure 3-30(b). A geophone is located at G, a forward source is at E_F, and a reverse source is at E_R. We rewrite Eq. 3-65 as an expression for reciprocal time:

$$t_R = T_G + T_E + \frac{y}{V_2} \quad (3\text{-}69)$$

Following our earlier convention, t_{E_FG} represents the travel time from E_F to G which is measured on a field seismogram and plotted on a time-distance plot. Using the basic form of Eq. 3-69, we see that

$$t_{E_FG} = T_{E_F} + T_{G_F} + \frac{x}{V_2} \quad (3\text{-}70)$$

and

$$t_{E_RG} = T_{E_R} + T_{G_R} + \frac{y-x}{V_2} \quad (3\text{-}71)$$

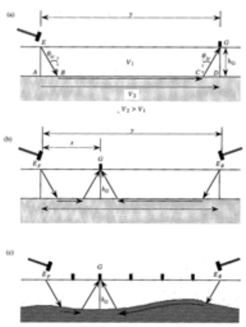
If we assume that the refractor surface is planar beneath G, then

$$T_{G_F} = T_{G_R}$$

and

$$t_{E_FG} + t_{E_RG} = T_{E_F} + T_{E_R} + 2T_G + \frac{x}{V_2} + \frac{y-x}{V_2} \quad (3\text{-}72)$$

Delay Time Method



Because of the requirement of reciprocity,

$$t_R = T_{E_F} + T_{E_R} + \frac{y}{V_2}$$

and, therefore,

$$t_{E_FG} + t_{E_RG} = t_R - \frac{y}{V_2} + 2T_G + \frac{y}{V_2}$$

$$t_{E_FG} + t_{E_RG} = t_R + 2T_G$$

and

$$T_G = \frac{t_{E_FG} + t_{E_RG} - t_R}{2} \quad (3\text{-}73)$$

Delay Time Method

TABLE 3-8 Head Wave Arrival Times for an Irregular Refractor

Position	Distance (m)	Depth (m)	Direct Wave (ms)	Forward Time (ms)	Reverse Time (ms)
Forward source	0	**15**	0.00		55.20
Geophone 1	10	**14**	7.14	21.91	52.14
Geophone 2	20	**13**	14.29	23.62	49.09
Geophone 3	30	**12**	21.43	25.33	46.03
Geophone 4	40	**13**	28.57	28.38	44.33
Geophone 5	50	**13**	35.71	30.76	41.94
Geophone 6	60	**14**	42.86	33.82	40.24
Geophone 7	70	**15**	50.00	36.87	38.53
Geophone 8	80	**16**	57.14	39.92	36.82
Geophone 9	90	**17**	64.29	42.98	35.11
Geophone 10	100	**19**	71.43	46.71	34.08
Geophone 11	110	**20**	78.57	49.76	32.37
Geophone 12	120	**21**	85.71	52.82	30.67
Reverse source	130	**21**	92.86	55.20	

V_1 (m/s)	**1400**
V_2 (m/s)	**4200**
Geophone interval (m)	**10**

Reciprocal time (ms)	55.20

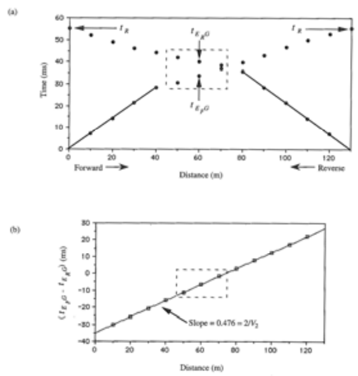
Delay Time Method

TABLE 3.9 Refractor Depths Computed Using Delay Times

Position	Forward Time (ms)	Reverse Time (ms)	Delay Time (ms)	Depth (m)
Geophone 1	**21.9**	**52.1**	9.4	14
Geophone 2	**23.6**	**49.1**	8.8	13
Geophone 3	**25.3**	**46.0**	8.1	12
Geophone 4	**28.4**	**44.3**	8.8	13
Geophone 5	**30.8**	**42.0**	8.8	13
Geophone 6	**33.8**	**40.2**	9.4	14
Geophone 7	**36.9**	**38.5**	10.1	15
Geophone 8	**39.9**	**36.8**	10.8	16
Geophone 9	**43.0**	**35.1**	11.4	17
Geophone 10	**46.7**	**34.1**	12.8	19
Geophone 11	**49.8**	**32.4**	13.5	20
Geophone 12	**52.8**	**30.7**	14.1	21

V_1 (m/s)	**1400**
V_2 (m/s)	**4200**
Reciprocal time (ms)	**55.20**

Determining Slope



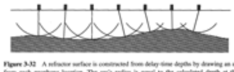


Figure 3-32 A refractor surface is constructed from delay-time depths by drawing an arc from each geophone location. The arc's radius is equal to the calculated depth at that position.

value for V_2, we cannot calculate h_G. How can we circumvent this problem? If we rewrite Eqs. 3-70 and 3-71, we can arrive at the form

$$t_{E_rG} - t_{E_fG} = T_{E_r} + T_{G_r} + \frac{x}{V_2} - T_{E_f} - T_{G_f} - \frac{y-x}{V_2} \quad (3\text{-}74)$$

and

$$t_{E_rG} - t_{E_fG} = T_{E_r} - T_{E_f} + \frac{2x}{V_2} - \frac{y}{V_2} \quad (3\text{-}75)$$

Equation 3-75 demonstrates that travel-time differences plotted against distance yield a line with a slope of $2/V_2$. Figure 3-31(b) is a graph of this type using the times and distances in Table 3-8. Using the calculated slope of 0.476, we arrive at a value for V_2 of 4202 m/s.

planar wavefront arriving at G is located on the refractor at point P. By using the definition of the critical angle and simple geometry, it is straightforward to show that the time for a wave to travel from B to G at V_1 is equal to the time for a wave to travel from B to P at V_2:

$$\sin\theta_c = \frac{V_1}{V_2} = \frac{BG}{BP} \qquad (3\text{-}76)$$

and

$$\text{time}_{BG} = \frac{BG}{V_1} = \frac{BP}{V_2} = \text{time}_{BP} \qquad (3\text{-}77)$$

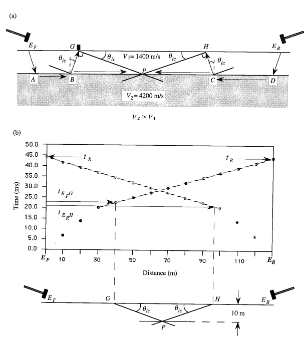
A similar wavefront associated with point P resulting from a reverse shot at E_R defines point H on the surface. As in the previous derivation,

$$\text{time}_{CH} = \text{time}_{CP} \qquad (3\text{-}78)$$

The time to travel $E_F ABP$ plus the time to travel $E_R DCP$ must be equal to the time to travel $E_F ADE_R$ which is reciprocal time t_R. From this relationship and the identities in Eqs. 3-77 and 3-78, it becomes apparent that

$$t_{E_F G} + t_{E_R H} = t_R \qquad (3\text{-}79)$$

Wave Front Method



Geophone Arrangements

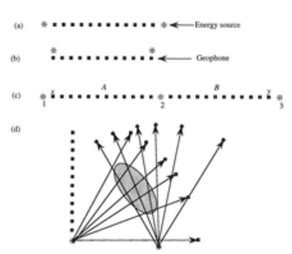


Figure 3-34 Geophone-spread arrangements. (a) In-line spread. (b) Offset spread. (c) In-line with center shot. (d) Fan shooting.

Minimum Bedrock Depth

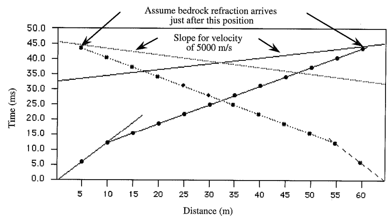


Figure 3-35 Travel-time curve illustrating method to determine minimum depth to bedrock when no bedrock refractions are received at geophones. This approach assumes that a bedrock refraction is present just beyond the last position sampled in the survey.

Corrections for Topography

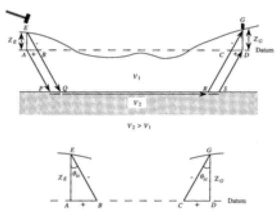


Figure 3-36 Symbols and geometry used in the text to derive the elevation correction.

The correction time at the energy source is

$$t_{c_E} = \frac{Z_E \tan\theta_c}{V_2} - \frac{Z_E}{V_1 \cos\theta_c} \qquad (3\text{-}80)$$

By the critical-angle equation, Eq. 3-80 simplifies to

Corrections for Topography

$$t_{c_E} = Z_E \frac{\sin^2\theta_c - 1}{V_1 \cos\theta_c} \qquad (3\text{-}81)$$

which can be reduced further to

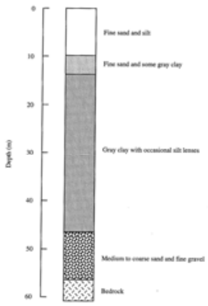
$$t_{c_E} = Z_E \frac{\left(V_2^2 - V_1^2\right)^{1/2}}{V_2 V_1} \qquad (3\text{-}82)$$

The same relationship holds at the geophone position except that Z_G substitutes for Z_E. Thus, the total elevation correction is

$$t_{\text{elevation}} = \left(Z_E + Z_G\right) \frac{\left(V_2^2 - V_1^2\right)^{1/2}}{V_2 V_1} \qquad (3\text{-}83)$$

If a buried shot is used, its depth simply is subtracted from Z_E. If the energy source or geophone is below the datum, the relationship remains the same except that Z_E or Z_G takes on a negative value.

Field Examples



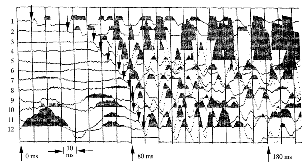


Figure 3-38 Field seismogram from Whately, Massachusetts. Geophone traces are labeled 1–12. The first geophone is located 3 m from the energy source. The geophone interval is 10 m. First breaks for each trace are indicated by a downward directed arrow. Timing lines are at 10-ms intervals. The record encompasses 200 ms.

Field Examples

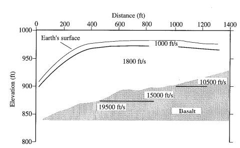


Figure 3-39 An example of a geologic section derived from a detailed refraction study using the Generalized Reciprocal Method (GRM). Note that this method provides much detail on the surface of the basalt refractor and is able to determine lateral velocity changes which are interpreted as layering in the basalt. (Modified from Lankston, Robert W., 1990, High-resolution refraction seismic data acquisition and interpretation *in* Ward, Stanley H., ed., Geotechnical and environmental geophysics; Volume 1: Review and tutorial: Society of Exploration Geophysicists Investigations in Geophysics, no. 5, p. 45–73).