Geoexploration, 17 (1979) 125—141

VELOCITY INVERSION AND THE SHALLOW SEISMIC REFRACTION METHOD

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(Received May 8, 1978; accepted November 23, 1978)

ABSTRACT

Whiteley, R.J. and Greenhalgh, S.A., 1979. Velocity inversion and the shallow seismic refraction method. Geoexploration, 17: 125—141.

Velocity inversion in the subsurface is one of the most serious limitations of the shallow seismic refraction method. Inversion can occur whenever a geological layer has a lower velocity than that of the overlying layer and is more common than generally believed. Unrecognised inversion layers can create considerable errors in depth interpretation. The magnitude of these errors is examined and theoretical equations for a single velocity inversion in a multilayered earth are presented. In certain situations inversion layers can be identified and incorporated in a modified interpretational procedure using these equations. The methods for recognising velocity inversions are reviewed. A field example from a highway investigation in Australia is also discussed.

It is concluded that a combination of drilling and seismic refraction using both shallow shots and shots within the low velocity layer can, to some extent, reduce errors associated with velocity inversions.

If conventional seismic refraction alone is used to solve the shallow velocity inversion problem then more sophisticated field and processing procedures are required to assist reliable identification of later events on refraction records.

INTRODUCTION

The seismic refraction method is widely used in engineering site investigations, groundwater search and mineral exploration (Hobson, 1970). Velocity inversion in the subsurface is one of the most serious limitations of this method (Nunn and Boztas, 1977).

The velocity inversion problem can arise whenever a geologic layer in the earth's subsurface has a lower seismic velocity than that of the overlying layer. According to Snell's Law (Dobrin, 1976, p. 41) no critical refraction at the top of the low velocity layer is possible so that, in general, it cannot be directly detected in the course of a normal seismic refraction survey.

Situations in which velocity inversions have been reported in shallow refraction surveying are quite common and include shale underlying sandstone, clay beneath a perched aquifer, unweathered basalt overlying water charged sand beds (deep leads), coal measure sequences, solution channels in limestone regions, frozen ground (ice over soil) and sand under compacted till.

In this paper the criteria for recognising a shallow velocity inversion are reviewed, the errors incurred in neglecting a possible low velocity layer are examined. Theoretical computations based on intercept times and incorporating a single velocity inversion in a multilayered earth are presented. A field example from a shallow refraction survey is also included.

RECOGNITION OF LOW VELOCITY LAYERS

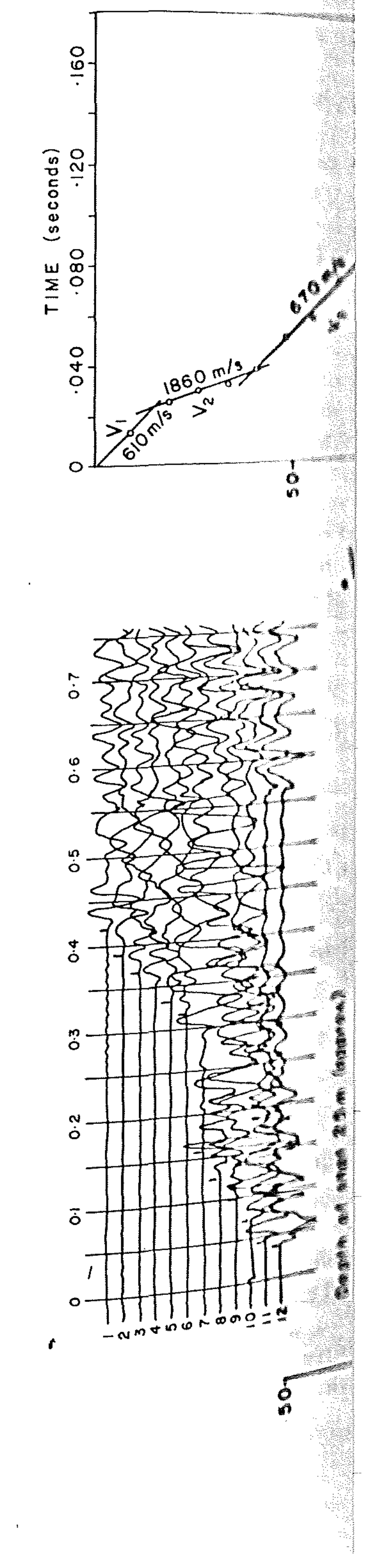
Direct methods

Field indications of a velocity inversion may be given by geological mapping (nearby outcrops, road cut exposure etc.), drilling (Thralls and Mossman, 1952) or supplementary geophysical evidence such as resistivity sounding (Mooney, 1976), seismic reflection (Hunter and Hobson, 1977), or surface wave dispersion (Dorman and Ewing, 1962).

The intersection of zones of low rock quality or high fracture index (Knill, 1970) during drilling may also indicate velocity inversions. Alternatively, in some situations, a solution to the problem may be obtained from a borehole velocity survey (Knox, 1967), uphole seismic survey (Meissner, 1961; Burke, 1973), crosshole seismic survey (Ballard, 1976), or by multiple shooting (Irving, 1965).

Seismic refraction methods — time delays or skips on the time—distance curve

Under certain circumstances velocity inversion may be revealed by time delays or skips in the time—distance curve of first arrivals. Press and Ewing (1948) and Press and Dobrin (1956) have shown that compressional waves propagated horizontally through a thin, high velocity, upper layer overlying a thicker lower velocity section are attenuated by leakage of energy into the underlying lower velocity material. The magnitude of attenuation decreases with increasing frequency. It is possible for a layer of relatively high velocity to act as a high pass filter for energy propagated horizontally and as a low pass filter for energy transmitted downwards. Coupled with the normal frequency selective attenuation in earth materials (Dobrin, 1976, p. 59) the relatively high frequency energy travelling in the high velocity cap layer may die out before the low frequency arrivals from a deeper high velocity layer (beneath the inversion layer) are due to arrive, producing time delays on the travel time curve. A seismogram illustrating this curious behaviour was presented by Knox (1967, p. 209). A section of this record and nearby velocity log showing a velocity inversion in the V_3 layer (data from Knox, 1967) are presented in Fig. 1 together with a time—distance graph plotted from the first



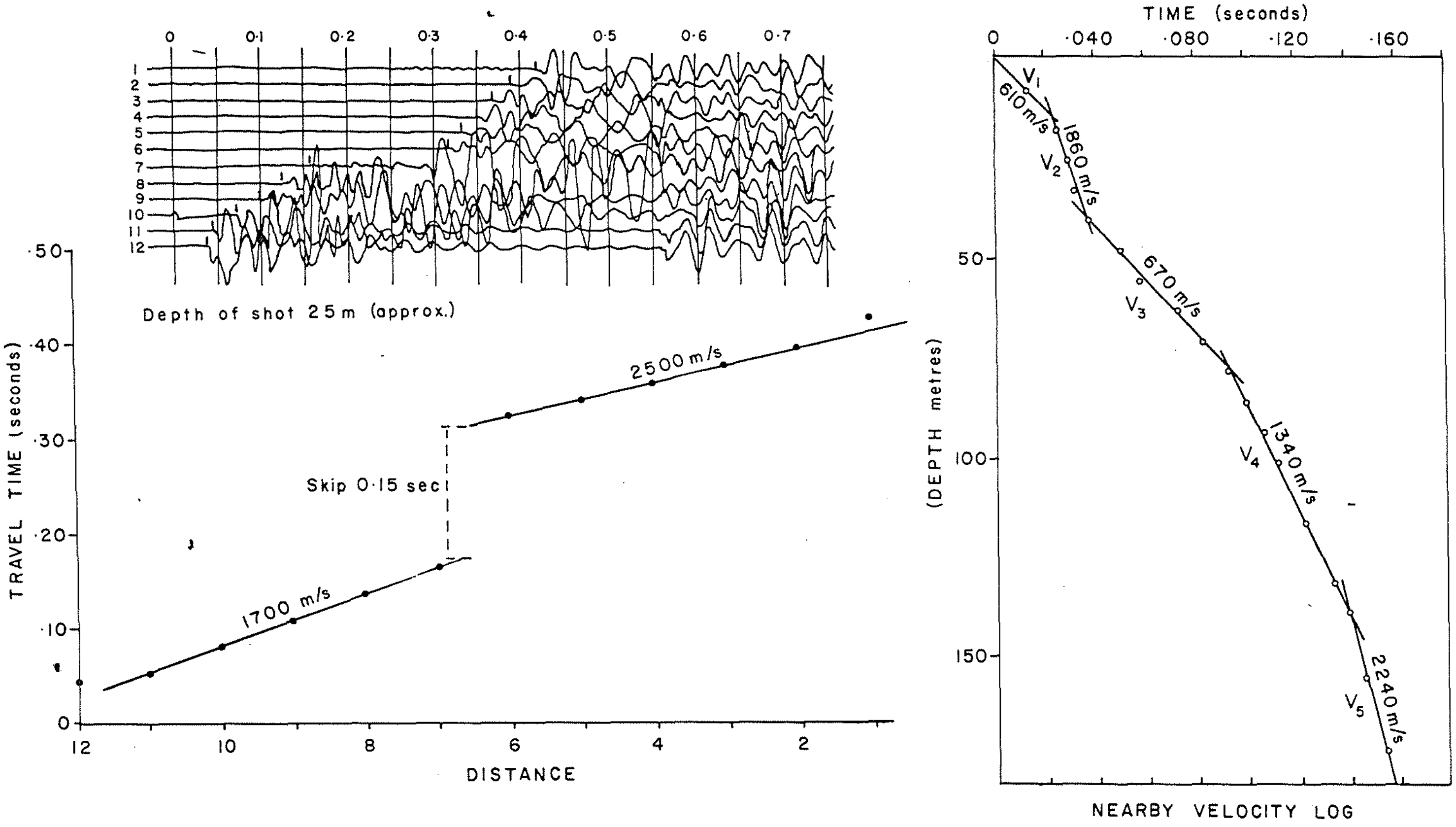


Fig. 1. Pattern of first arrivals associated with a buried low velocity layer with interpretation (data from Knox, 1967).

arrival picks presented by Knox. In this example the shot is within the high velocity (V_2) cap layer.

The arrival times at geophones nearest the shot-point (7 to 12) fall on a travel time curve corresponding to a velocity of about 1700 m/s. This is within 10% of the cap layer velocity (V_2), as shown on the nearby velocity log. The arrivals at more distant geophones (1 to 6) fall on a travel time curve corresponding to a velocity of about 2500 m/s which is close to that for the V_5 layer. Note the large skip on the travel time graph between geophones 7 and 6. Also it is important to note the absence of a travel-time segment corresponding to the V_4 layer even though this layer has a velocity in excess of the low velocity V_3 layer. This behaviour is discussed later in this paper.

Bird (1952) and Irving (1965) also cite examples of similar time delays resulting from shooting over high velocity frozen ground. Examples of delays encountered in glacial materials and unconsolidated deposits have also been given by Brown and Robertshaw (1953), Domzalski (1956), Johnson (1954), and McGinnis and Kempton (1961). Delays due to velocity inversions in consolidated sedimentary rocks have been presented by Press and Dobrin (1956), Trostle (1967) and Mooney et al. (1970). In nearly all cases the cut-off distance (i.e. the distance beyond which the cap layer refraction ceased to be observed) is generally less than 20 to 30 times the cap layer thickness.

Time delays due to a velocity inversion are observed on both forward and reverse shots. This effect should not be confused with delays due to other causes, e.g. faulting (Mooney, 1976, chapt. 15). Also it should be noted that as the cap layer becomes thicker the energy is sustained for longer distances and the "skip" diminishes. This finally disappears resulting in a seismic record with normal appearance.

Later arrivals

The use of reflections and surface waves as a means of detecting a hidden low velocity layer has been mentioned previously. In addition, there are other later events on the refraction record which, if identified, may indicate the presence of a velocity inversion.

Banerjee and Gupta (1975) have suggested the use of mode conversions as evidence for a velocity inversion. Provided the compressional (P) wave velocity in the low velocity layer is higher than the shear (S) wave velocity in the cap layer, then critical refractions of the type SPS are produced. These modes have been utilised in crustal refraction work (Hall and Brisbin, 1965; Smith, 1970) and appear as later arrivals on the seismogram.

In view of the problems of recognition of shear waves in both hard and soft formations (Warrick, 1974; Scarascia et al., 1976) and the low energy of these arrivals due to energy partitioning on mode conversion, it is unlikely that, without sophisticated detection and analysis procedures, such converted waves could be reliably identified in shallow refraction work.

LOW VELOCITY LENS

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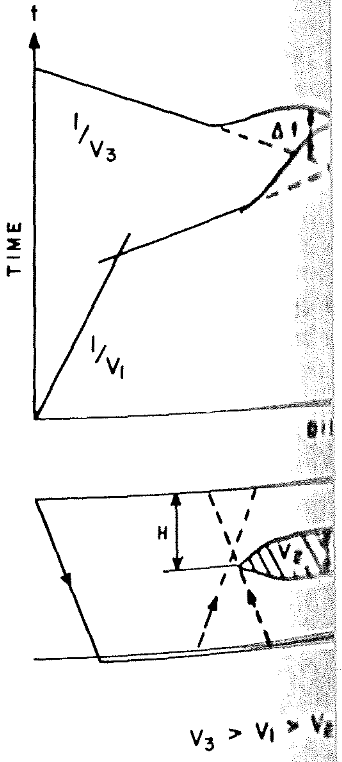


Fig. 2. Time anomaly due to a

undulations in deeper refra
V_2 cannot be obtained from
Z of the lens can be comput

$$Z = \frac{\Delta t}{\frac{1}{V_2\sqrt{1-\left(\frac{V_2}{V_3}\right)^2}} - \frac{}{V_1\sqrt{}}}$$

where Δt is the time anoma

LOW VELOCITY LENS

If the low velocity layer is discontinuous, or more importantly, small in extent compared to a spread length it will cause a positive anomaly (i.e. a hump) on the travel time curve as shown in Fig. 2. Such situations can occur in the search for buried caverns (Watkins et al., 1967) and abandoned mine workings (Burton and Maton, 1975). The lateral extent of the lens is approximately indicated by the length of the anomaly provided other causes such as undulations in deeper refractors do not interfere with this effect. The velocity V_2 cannot be obtained from the travel time data but the maximum thickness Z of the lens can be computed for an assumed value of V_2 using the equation:

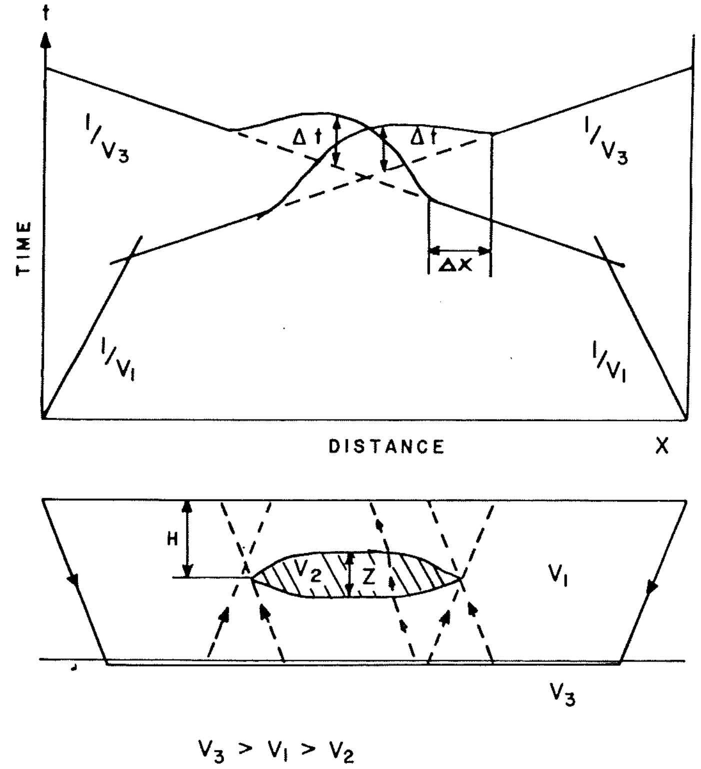


Fig. 2. Time anomaly due to a low velocity lens.

$$Z = \frac{\Delta t}{\dfrac{1}{V_2\sqrt{1-\left(\dfrac{V_2}{V_3}\right)^2}} - \dfrac{1}{V_1\sqrt{1-\left(\dfrac{V_1}{V_3}\right)^2}}} \qquad (1)$$

where Δt is the time anomaly observed and V_1 and V_3 are the velocities as obtained from the travel time data. Depth to the low velocity zone can also be calculated from the equation:

$$H = \Delta X \frac{(V_3^2 - V_1^2)^{1/2}}{2 V_1} \qquad (2)$$

Anomalies similar to those shown in Fig. 2 can also be produced by a local depression in a deeper refractor or a surface hill. A low velocity lens can be particularly troublesome if it occurs to one end of the spread. Generally the ambiguity can be resolved with proper field techniques giving increased subsurface coverage, and using multiple offset shots (Greenhalgh and Whiteley, 1977). Special interpretation procedures (Gardner, 1967, pp. 344—346; Palmer, 1974, pp. 79—80) and sophisticated error analysis techniques (Dampney and Whiteley, 1978) are also of use.

DEPTH CALCULATIONS INCORPORATING A SINGLE VELOCITY INVERSION

Three layer case

Consider a three layer horizontal structure made up of layers of low, medium and high velocity. Six possible combinations of the layers may be encountered (Mooney, 1976, p. 9—15). The case $V_3 > V_2 > V_1$ represents the normal sequence of increasing velocity with depth. All velocities are represented on the travel time graph and interpretation will give the complete depth section (subject to the blind zone limitation; Soske, 1959).

Two sequences:

High	High
Medium ($V_1 > V_2 > V_3$)	Low ($V_2 < V_3 < V_1$)
Low	Medium

produce a travel time graph consisting of a single straight line passing through the origin with an inverse slope V_{high} when the shot is in the surface layer. The underlying layers are not detected even though in the second of these sequences V_2 is less than V_3 and critical refraction at the V_2/V_3 interface would be expected. This, however, does not occur since $V_1 > V_3$. If the shot is at the V_1/V_2 interface or within the V_2 layer, critical refraction at the V_2/V_3 interface is possible.

Two other sequences:

Medium	Low
High ($V_2 > V_1 > V_3$)	High ($V_2 < V_3 < V_1$)
Low	Medium

lead to interpretations which are similar to each other. Only the top two layers can appear on the travel time graph; the deepest layer will be undetected in first arrival information. In these situations relative thicknesses and velocities can influence the nature of the first arrival data as discussed in the previous section.

In this section, attention is confined to the last of the six possibilities, viz.:

Medium
Low ($V_3 > V_1 > V_2$)
High

Without knowledge of the velocity inversion, the interpreter would treat the travel time graph as being due to a two layer structure and compute an erroneous depth to the deepest refractor:

$$D_1^{\star} = \frac{T_2^{\star}}{2} \cdot \frac{V_1^{\star} \cdot V_2^{\star}}{\sqrt{(V_2^{\star})^2 - (V_1^{\star})^2}} \qquad (3)$$

where $T_2^{\star} = T_3$, $V_1^{\star} = V_1$, $V_2^{\star} = V_3$.

In this case true depth D_2 is given by the equation.

$$D_2 = Z_1 + Z_2 = \left(\frac{T_3}{2} + Z_1 \left\{ \frac{\sqrt{V_3^2 - V_2^2}}{V_2 V_3} - \frac{\sqrt{V_3^2 - V_1^2}}{V_1 V_3} \right\} \right) \frac{V_2 V_3}{\sqrt{V_3^2 - V_2^2}} \qquad (4)$$

For a "normal" sequence of layer velocities increasing with depth, Z_1 would be computed from the two layer intercept time equation:

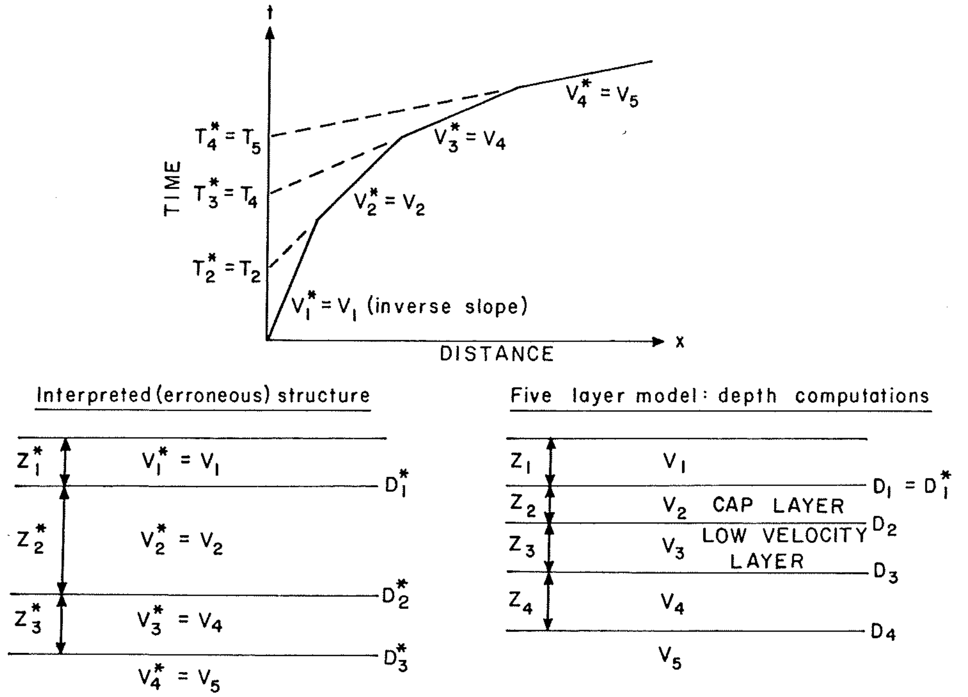
$$Z_1 = D_1 = \frac{T_2}{2} \cdot \frac{V_1 V_2}{\sqrt{V_2^2 - V_1^2}} \qquad (5)$$

But for a velocity inversion ($V_2 < V_1$) T_2 is an unobservable quantity, i.e. T_2 is imaginary as implied from eq. 5. In addition, the inversion layer velocity V_2 is unknown. Without additional information, the only way to arrive at a solution is to assume values for two of the variables and solve for the third. The interpreter may consider a range of values for Z_1 (or Z_2) or the correct thickness may be known from drilling or other control. Alternatively if a "skip" is observed on the T—X curve we may assume that Z_1 is small compared to Z_2. A crude estimate for the thickness of the high velocity cap layer, as mentioned earlier, is $Z_1 \simeq X_{co}/20 \rightarrow X_{co}/30$, where X_{co} is the cut-off distance at which the seismic arrival from the V_1 layer dies out. Information on the inversion layer velocity V_2 may come from geological considerations, borehole or laboratory velocity measurements, or from refraction data on nearby spreads where the cap layer is absent.

Four and five layer cases

An investigation of the velocity inversion problem for cases involving more than three layers may be carried out in a similar manner to the above but is immediately hampered by the increased number of variables. For a four layer case there are 24 possible arrangements of the velocities of the layers; for a five layer case there are 120 possibilities.

Consider the case of a subsurface with a single velocity inversion in an otherwise normal sequence of layers with velocity increasing with depth. Fig. 3 illustrates the depth computation procedure for a five layer earth having a



$$Z_1^* = \frac{T_2^*}{2} \cdot V_{12}^*$$

$$Z_2^* = \left(\frac{T_3^*}{2} - \frac{Z_1^*}{V_{13}^*} \right) V_{23}^*$$

$$Z_3^* = \left(\frac{T_4^*}{2} - \frac{Z_1^*}{V_{14}^*} - \frac{Z_2^*}{V_{24}^*} \right) V_{34}^*$$

where $$V_{jk}^* = \frac{V_j^* \, V_k^*}{\sqrt{(V_k^*)^2 - (V_j^*)^2}}$$

Assumed : reversal layer velocity V_3 and
or
Known cap layer thickness Z_2

Compute :

$$Z_1 = \frac{T_2}{2} \cdot V_{12} = Z_1^*$$

$$Z_3 = \left(\frac{T_4}{2} - \frac{Z_1}{V_{14}} - \frac{Z_2}{V_{24}} \right) V_{34}$$

$$Z_4 = \left(\frac{T_5}{2} - \frac{Z_1}{V_{15}} - \frac{Z_2}{V_{25}} - \frac{Z_3}{V_{35}} \right) V_{45}$$

where $$V_{jk} = \frac{V_j \, V_k}{\sqrt{V_k^2 - V_j^2}}$$

Fig. 3. Time—distance graph and interpreted model for five-layer case with velocity inversion in the third layer.

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in normal refraction work
et al., 1970). The theoretic
additional layers if require
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It is also necessary to assu
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the base of the cap layer. S
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Source within the low velo

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the velocity inversion prob
five layer case is shown in
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can be determined from a

time versus shot depth.

Source within the cap laye

For a source within the
as shown by Knox (1967),
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proceed as shown in Fig. 5
through the V_2 and V_3 laye

If the cap layer Z_2 is thi
will closely approximate V
Z_3.

velocity inversion in the third layer. This structure is commonly encountered in normal refraction work (Press and Dobrin, 1956; Domzalski, 1956; Mooney et al., 1970). The theoretical computations can be quite easily extended to additional layers if required. In all cases it is necessary to assign values to the two unknowns of cap layer thickness and velocity in the underlying material. It is also necessary to assume that the next layer (V_4) represented on the travel time curve does in fact represent the layer immediately below the velocity inversion layer (V_3). Additional layers below the inversion layer having a velocity less than the cap layer velocity (V_2) will not appear on the travel time curve even if they have velocities exceeding V_3. Failure to appreciate this problem can lead to further serious overestimates in calculated depths to deeper refractors. This situation can arise whenever the shot-point is above the base of the cap layer. Subject to this restriction (and possible blind zones) other required quantities (layer velocities, intercept times) can be read off the travel time curve. Furthermore, the relative location of the low velocity layer in the subsurface must be known or assumed.

Errors associated with velocity inversion calculations may be caused by an incorrect choice of the inversion layer velocity or by uncertainty in the cap layer thickness. Such errors are cumulative because of the recurrence of layer thickness in the intercept time equations. Calculations with respect to boundaries above the cap layer are not affected.

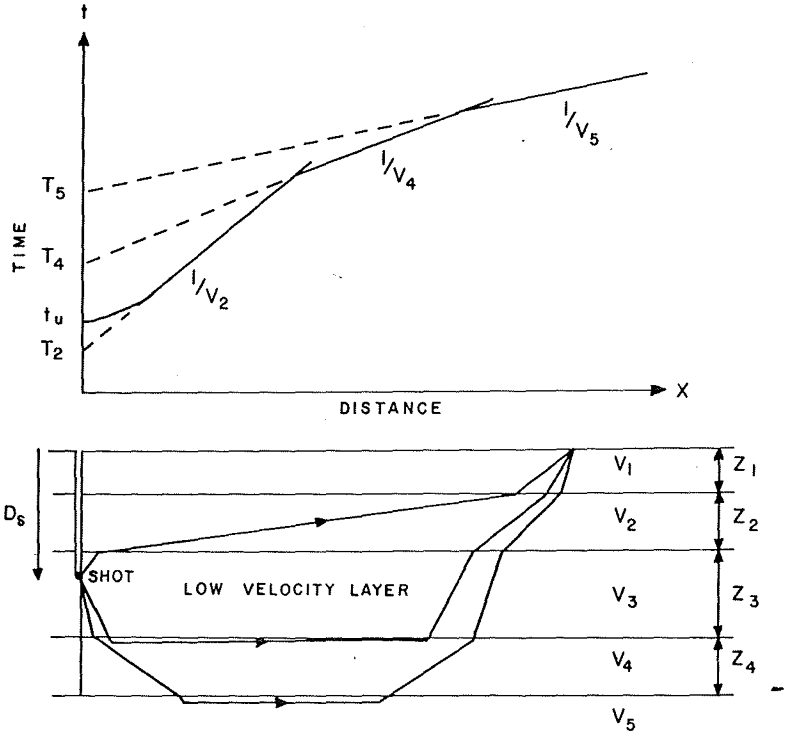
Source within the low velocity layer

If the refraction shothole penetrates the top of the low velocity layer then the velocity inversion problem can be completely solved. The solution for a five layer case is shown in Fig. 4. The quantities T_2, T_4, T_5, V_2, V_4, V_5 can all be read off the travel time graph. The depths Z_1, Z_2, D_s are known from drilling the shothole. The velocities V_1, V_2, V_3 as well as the depths Z_1, Z_2 can be determined from a detailed weathering spread and a graph of uphole time versus shot depth.

Source within the cap layer

For a source within the cap layer V_2 an exact solution is not possible but, as shown by Knox (1967), we may approximate the depth to the V_4 layer by assuming a straight raypath for the critically refracted ray at the V_3/V_4 interface. Computations of the approximate depth to the V_4 layer may then proceed as shown in Fig. 5. In these computations V_a is the average velocity through the V_2 and V_3 layers.

If the cap layer Z_2 is thin relative to the low velocity section Z_3, then V_a will closely approximate V_3 and Z_a will be very nearly the correct thickness Z_3.



$V_1 < V_3 < V_2 < V_4 < V_5$

Read from t-x graph: Intercept times T_2, T_4, T_5; Velocities V_2, V_4, V_5,

Additional data required: V_1 (from weathering spread)

V_3, D_s, Z_1, Z_2 (from drilling and uphole time t_u)

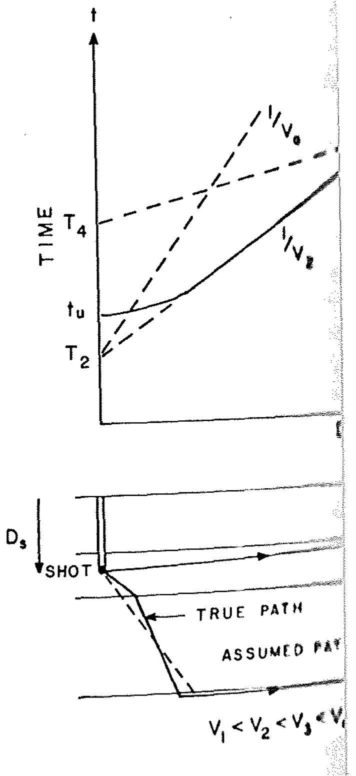
Compute:
$$Z_3 = \left(T_4 - \frac{Z_1}{V_{14}} - \frac{Z_2}{V_{24}}\right)\frac{V_{34}}{2} + \left(\frac{D_s - Z_1 - Z_2}{2}\right)$$

$$Z_4 = \left(T_5 - \frac{Z_1}{V_{15}} - \frac{Z_2}{V_{25}} - \frac{2Y}{V_{35}}\right)\frac{V_{45}}{2}$$

where $Y = Z_3 - \left(\frac{D_s - Z_1 - Z_2}{2}\right)$

$$V_{jk} = \frac{V_j V_k}{\sqrt{V_k^2 - V_j^2}}$$

Fig. 4. Time—distance graph, raypaths and depth computation procedure for shot in velocity inversion layer of a five layer earth.



$V_1 < V_2 < V_3 <$

Read from t-x graph.

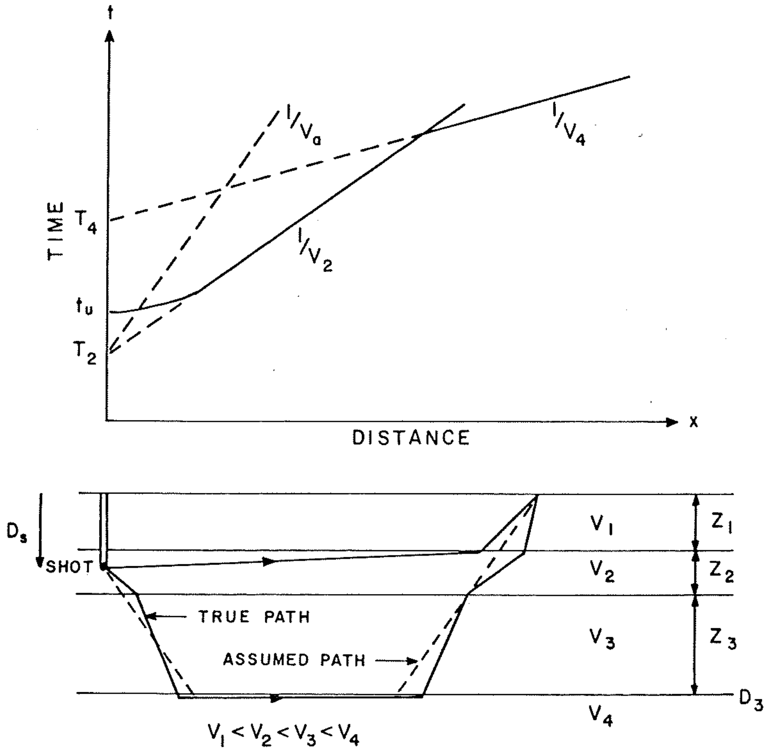
Additional data required

Compute: $V_a = \frac{V_2 + V_3}{2}$

$D_3 \approx Z_1 +$

where $Z_1 =$

Fig. 5. Time distance graph, ra
a buried shot within the cap la



Read from t-x graph: T_2, T_4; V_2, V_4

Additional data required: V_1 (from weathering spread)
V_3 (assumed)
D_s (from drilling)

Compute: $V_a = \frac{V_2 + V_3}{2}$ average velocity of layers 2 and 3

$$D_3 \simeq Z_1 + Z_a$$

where $Z_1 = \frac{T_2}{V_{12}}$

$$Z_a = \left(T_3 - \frac{Z_1}{V_{13}}\right)\frac{V_{a3}}{2} + \frac{D_s - Z_1}{2}$$

$$V_{jk} = \frac{V_j V_k}{\sqrt{V_k^2 - V_j^2}}$$

Fig. 5. Time distance graph, raypaths and approximate depth computation procedure for a buried shot within the cap layer of a four layer earth.

MAGNITUDE OF THE PROBLEM

To appreciate the importance of the velocity inversion problem in shallow seismic refraction work, consider the simplest case of two horizontal layers plus an embedded low velocity layer where the uppermost layer is bounded by the free surface of the earth. By manipulation of eqs. 3 and 4 it can be shown that the fractional depth E error occasioned by ignoring the velocity inversion is:

$$E = \frac{D_1^\star - D_2}{D_2} = \frac{1-P}{P}\left[1 - \frac{D_1}{D_2}\right] \tag{6}$$

where:

$$P = \frac{V_{23}}{V_{13}} = \frac{V_2}{V_1}\sqrt{\frac{1-(V_1/V_3)^2}{1-(V_2/V_1)^2(V_1/V_3)^2}} \tag{7}$$

The quantity P depends only on the velocity ratios V_2/V_1 and V_1/V_3 and is plotted in Fig. 6. Because these ratios are normalised quantities (i.e. $0 < V_2/V_1 < 1$, $0 < V_1/V_3 < 1$), a

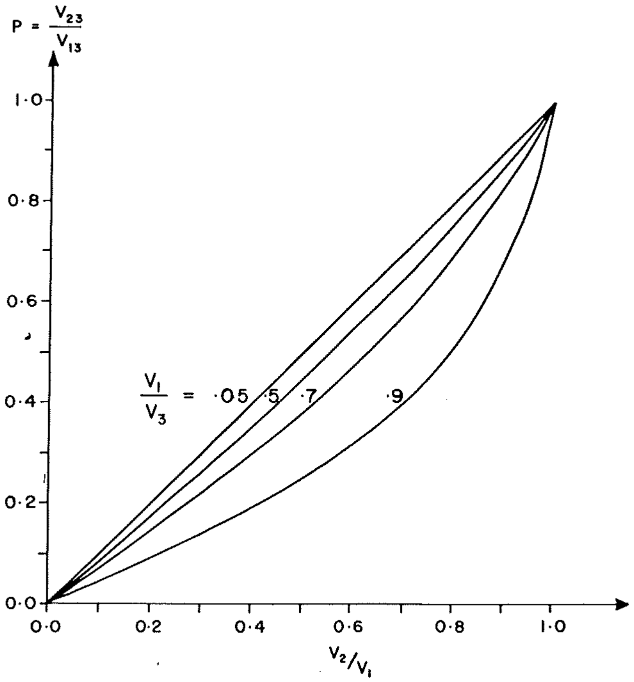


Fig. 6. Nomogram for determining the quantity:

$$P = \frac{V_2}{V_1}\sqrt{\frac{1-(V_1/V_3)^2}{1-\left(\frac{V_2}{V_1}\cdot\frac{V_1}{V_3}\right)^2}}$$

which arises in the calculation of depth errors for a 3 layer case having a velocity inversion in the second layer.

$V_1 < 1$, $0 < V_1/V_3 < 1$), a

scale. From the graph it ca

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The error is always a po

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→ 1) the error is small whe

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Some sample calculation

considerable depth errors c

TABLE I

Depth errors occasioned by ig

D_1/D_2	V_1/V_3	V_2/V_1
.2	.1	.4
		.6
		.8
	.5	.4
		.6
		.8
	.9	.4
		.6
		.8
.5	.1	.4
		.6
		.8
	.5	.4
		.6
		.8
	.9	.4
		.6
		.8
.8	.1	.4
		.6
		.8
	.5	.4
		.6
		.8
	.9	.4
		.6
		.8

$V_1 < 1$, $0 < V_1/V_3 < 1$), a full range of conditions can be covered on a linear scale. From the graph it can be seen that the result depends rather strongly on V_2/V_1. As the ratios between V_2 and V_1 increases the error increases. The error is less dependent on V_1/V_3 and increases only slightly as the contrast decreases over a large range, but rises sharply as V_1 closely approaches V_3.

The error is always a positive quantity i.e. the erroneous depth $D_1^\star$ is always greater than the true depth D_2. Furthermore we observe from eq. 7 that the fractional depth error varies directly with the depth ratio D_1/D_2 (which is also a normalised quantity). For a thin low velocity layer (i.e., $Z_1 >> Z_2$, $D_1/D_2 \rightarrow 1$) the error is small whereas for a thick low velocity layer ($Z_2 >> Z_1$, $D_1/D_2 \rightarrow 0$) the error is large, as is to be expected.

Some sample calculations are presented in Table 1. This table shows that considerable depth errors can result from ignoring a velocity inversion.

TABLE I

Depth errors occasioned by ignoring a velocity inversion in a Three Layer Case

D_1/D_2	V_1/V_3	V_2/V_1	% E
.2	.1	.4	121
		.6	54
		.8	20
	.5	.4	146
		.6	67
		.8	26
	.9	.4	348
		.6	177
		.8	79
.5	.1	.4	76
		.6	34
		.8	12
	.5	.4	91
		.6	42
		.8	16
	.9	.4	217
		.6	111
		.8	50
.8	.1	.4	30
		.6	13
		.8	5
	.5	.4	36
		.6	17
		.8	6
	.9	.4	87
		.6	44
		.8	20

FIELD EXAMPLE

Fig. 7 shows travel time graphs from a shallow seismic refraction survey for a proposed highway in South Australia. The object of the survey was to determine depth and strength of near surface rock material for excavation assessments. A geophone separation of 3 m was used together with multiple reversed shot-points (Greenhalgh and Whiteley, 1977).

As Fig. 7 shows, the travel time curves are normal in appearance. Interpretation of these indicated that, at the northern shotpoint, three layers were present with the thin upper layer having a velocity of about 300 m/s. This layer appears to decrease in thickness rapidly towards the southern shot-point where only two layers are indicated and the upper layer is underlain by a thicker layer with a velocity of about 1280 m/s. The deepest refractor encountered has a velocity of about 2870 m/s.

Using the appropriate equations on the left side of Fig. 3, depths to the deepest refractor were calculated at the northern and southern shot-points. These were 7.9 and 6.0 m, respectively. From the apparent velocities these calculations appear to give an erroneous dip direction. This, however, is due to the rapid thinning of the upper layer towards the southern shot-point. The upper layer has a calculated thickness at the northern shot-point of 0.6 m.

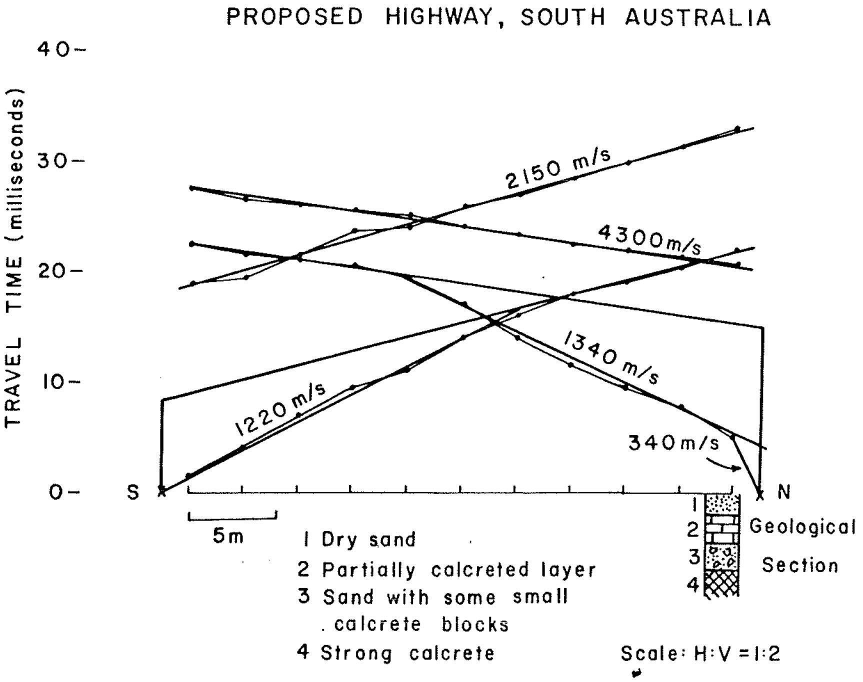

Fig. 7. Field example of velocity inversion, highway investigation South Australia.

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ACKNOWLEDGEMENTS

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Fig. 7 also shows the geological section derived from a nearby road cutting close to the northern shot-point. This revealed a four layer section with dry sand overlying a partly calcreted layer, a sandy layer and strong calcrete at a depth of 2.1 m.

Calcrete is a strongly cemented caliche-type deposit whose in-situ velocity at the base of the cut was measured to be about 2930 m/s. Samples of this material have attained laboratory measured velocities up to 5200 m/s. When calcrete occurs within the depth of a road cut it can pose considerable problems in excavation.

The deepest refractor encountered in the seismic work has a velocity close to that measured at the base of the cut and is attributed to strong calcrete at a depth of 2.1 m.

The initial seismic interpretation has seriously overestimated the depth to the calcrete at the northern shot-point by almost 300%. This is due to velocity inversion in the sandy layer underlying the partially calcreted cap rock. The cap rock has an excavated thickness of about 0.8 m and corresponds to the measured seismic velocity of 1280 m/s. This would not be expected to create problems in excavation. The 300 m/s sand layer has a calculated thickness of about 0.6 m at the northern shot-point which is close to that observed in the cut.

The only unknown at the northern shot-point is the velocity of the sandy, low velocity layer beneath the partially calcreted cap rock. Applying the equations on the right side of Fig. 3 gives a velocity for this layer of 370 m/s which is consistent with dry sand containing minor calcrete blocks.

Using this velocity, and assuming a constant thickness for the cap layer gives a depth to the strong calcrete at the southern shot-point of about 2.8 m.

CONCLUSIONS

The velocity inversion problem can create serious errors in seismic refraction if it is unrecognised. A combination of drilling and seismic refraction using both near surface shots and shots within the low velocity layer can, to some extent, reduce these errors.

If seismic refraction alone is to be used to solve the velocity inversion problem then more sophisticated field and processing procedures are required to allow reliable identification of later events on the seismic record.

Alternatively auxiliary geophysical methods such as resistivity sounding or shallow reflection may be used to identify an inversion layer.

Undoubtedly the velocity inversion problem, as one of the major limitations of the refraction method, has provided considerable impetus to the development of improved shallow reflection techniques.

ACKNOWLEDGEMENTS

The assistance of Professor L.V. Hawkins with the field example is gratefully acknowledged.

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