1961/79
C

COMMONWEALTH OF AUSTRALIA
DEPARTMENT OF NATIONAL DEVELOPMENT
BUREAU OF MINERAL RESOURCES,
GEOLOGY AND GEOPHYSICS

RECORD 1961 No. 79

THE "DEPTH PROBING" TECHNIQUE USING SEISMIC REFRACTION METHODS

by

K. R. VALE and E. R. SMITH

COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES,

GEOLOGY AND GEOPHYSICS

503875

RECORD 1961 No. 79

THE "DEPTH PROBING" TECHNIQUE USING SEISMIC REFRACTION METHODS

by

K. R. VALE and E. R. SMITH

CONTENTS

ILLUSTRATIONS

1. INTRODUCTION

Experience has shown that Seismic Refraction Traverses can be grossly misinterpreted unless they are very carefully carried out. The "Refraction Depth Probing" technique developed by the Bureau is intended to measure accurately the distribution of refractors beneath any selected station. In the Bureau's method, accurate information is first obtained along a traverse half a mile to one mile in length; the steps are as follows:

(1) A number of refraction depth probes are shot with different shot-point-to-geophone distances.

(2) If necessary some reflection shooting is done.

(3) The results are studied to assess the value of the method in solving geological or geophysical problems.

(4) The most suitable technique can be adopted for the rest of the survey in the area; i.e., the refractors which are easiest to identify, and which yield the most useful structural information, can be surveyed by the most accurate and economical method.

2. LAYOUT OF SHOT-POINTS AND GEOPHONES

To measure the velocities of refractors accurately, it is necessary to shoot in-line profiles of each refractor in opposite directions. A dipping refractor will alter the slope of the time-distance curve from the reciprocal of the true velocity to the reciprocal of an "apparent" velocity, and thus shotting in only one direction would measure only this apparent velocity. If the "apparent" velocities shooting up-dip and down-dip are measured, then the true velocity and also the dip may be calculated.

If:

	Va_n	= average velocity of overburden*
	V_n	= velocity of refractor
	V_{nU}	= "apparent" up-dip velocity of refractor
	V_{nD}	= "apparent" down-dip velocity of refractor
	i_{an}	= critical angle of refraction
	θ	= angle of dip

then (see page 11)

$$i_{an} - \theta = \arcsin (Va_n/V_{nU})$$

$$i_{an} + \theta = \arcsin (Va_n/V_{nD})$$

adding, we get:

$$i_{an} = \tfrac{1}{2} \arcsin (Va_n/V_{nD}) + \tfrac{1}{2} \arcsin (Va_n/V_{nU})$$

---

*Note: For calculations of depth and dip of refractor and for the first estimates of offset distances, two-layer assumptions are made. That is, the overburden is assumed to have a uniform velocity V_1. Practice has shown that the errors from this assumption are not serious. This is discussed further on page 12. For calculating weathering and elevation corrections, however, multi-layer theory must be used.

and subtracting:

$$\theta = \tfrac{1}{2} \text{ arc sin } (Va_n/V_{nD}) - \tfrac{1}{2} \text{ arc sin } (Va_n/V_{nU})$$

and $$V_n = Va_n/\sin i_{an}$$

or $$V_n = 2 \cos \theta/(1/V_{nD} + 1/V_{nU})$$

In the measurement of V_{nU} and V_{nD} it is important that the dip of the refractor (θ) for both measurements should be the same. As the dip of the refractor may not be constant along the line of shooting, a constant value of θ can only be ensured if the refractions recorded in both directions come from the same portion of the refractor. As the rays arrive obliquely at the surface, the portion of the refractor from which they have emerged is not vertically below the detectors, but is offset a distance S_A (or S_B) towards the shot-point (see Fig. 1). This offset distance will depend on the depth and dip of the refractor. Before geophone locations are chosen, this offset distance must be estimated, and the geophones must be placed so that the rays come from the desired portion of the refractor. A simplified arrangement of shot-points and geophones is shown in Fig. 1.

It is impossible to estimate the dip in advance, but usually sufficient two-way coverage is obtained if the geophone spreads A_D and B_D are spaced symmetrically either side of CD, the portion of the refractor to be recorded. To calculate the best offset distance for a refractor, it is necessary to estimate the values of Va_n and V_n, and the depth to the refractor. This may be practicable if seismic work has been carried out previously in the area; if not we can only follow the general rule that by increasing the distance between shot-point and geophones, deeper refractors can be recorded and hence the likely offset distance increases. Thus, as shot-points are moved farther away from the geophones, the geophones should in general be moved in the opposite direction away from CD.

To obtain some approximate figures for estimating the best positions of the geophone spread, we can assume an approximate average value for the ratio of the two velocities V_1 and V_2. Typical average values for the two velocities are:-

Va_n (aver. vel. above refractor)	V_n (vel. of refractor)
6000 ft/sec	9000ft/sec
8000 "	12,000 "
10,000 "	15,000 "
12,000 "	18,000 "

The value of Va_n/V_n in each of the above cases is 2/3 and this value can usually be used until better information is available.

$$\therefore \quad Va_n/V_n = 2/3 = \sin i_{an} \text{ (approx.)}$$

In the case of horizontal layers the "critical distance" for the refractor V_n is the minimum distance from the shot-point at which the refractions from the V_n layer is the first wave to arrive. The depth D_n of the V_n layer can be calculated from this critical distance x_{cn} by means of the equation:

$$D_n = \tfrac{1}{2}x_{cn} \sqrt{(V_n - Va_n)/(V_n + Va_n)}$$

$$= \tfrac{1}{2} x_{cn} \left(1/\cos i_{an}\right) \left(\frac{V_n - Va_n}{V_n}\right)$$ $= \frac{1}{2} x_{cn}$ tan cos i_{an}

The offset distances S_n is given by

$$\begin{aligned} S_n &= D_n \tan i_{an} \\ &= \tfrac{1}{2} x_{cn} (\tan i_{an}/\cos i_{an}) \left(\frac{V_n - Va_n}{V_n}\right) \\ &= \tfrac{1}{2} x_{cn} \frac{Va_n/V_n}{1 - V_{an}^2/V_n^2} \left(\frac{V_n - Va_n}{V_n}\right) \\ &= \tfrac{1}{2} x_{cn} (Va_n/V_n) \frac{V_n^2}{(V_n + Va_n)(V_n - Va_n)} \left(\frac{V_n - Va_n}{V_n}\right) \\ &= \tfrac{1}{2} x_{cn} \left(\frac{Va_n}{V_n + Va_n}\right) \\ &= \tfrac{1}{2} x_{cn} \frac{1}{1 + V_n/Va_n} \end{aligned}$$

For $Va_n/V_n = 2/3$, then

$$S_n = x_{cn}/5 = 0.2\ x_{cn}$$

This relation is true only for horizontal beds, but may still be used as an approximation in gently dipping beds. In a new area where the dip of the strata is not known, it is necessary to assume the relation, so that the likely offset distances can be calculated.

If it is assumed that each geophone-spread under consideration may record a new refractor as the first arrival over most of its length, then the critical distance for this refractor will be approximately the distance from the shot-point to the nearest geophone (x_1 of Fig. 1). Thus the offset distance should be approximately 1/5 of this distance.

i.e. $S_n = 0.2\ x_1$ (approx.)

This means that when we have selected the distance from shot-point to geophone-spread we may, as a first working hypothesis, calculate a reasonable value for the offset distance.

In refraction shooting, when distances between shots and geophones exceed 1000 ft it is advantageous to use large geophone intervals. The interval allowed by ordinary reflection seismic cables is 110 ft; by using four of these cables in series the geophones can be set at 220-ft intervals. Also by having an interval of 440 ft in the middle, a 24-geophone spread covers exactly 1 mile. This is the standard geophone spread used by the Bureau for refraction shooting. Geophone intervals greater than 220 ft are not usually recommended because

(a) there is too great a risk that small changes of velocity, or small faults, will not be detected, and

(b) it is difficult to establish adequate weathering control.

The spread coverage of 1 mile is adequate for depth-probe shooting.

The obvious set-up with which to commence shooting, is a shot-point at each end of a 1-mile spread. The refractor recorded will be the sub-weathering refractor, and the offset distance will be only approximately equal to the depth of weathering; therefore most of the 1-mile spread of geophones will cover the same portion of the refractor

SKETCH OF SHOTPOINT — GEOPHONE SPREAD LAYOUT

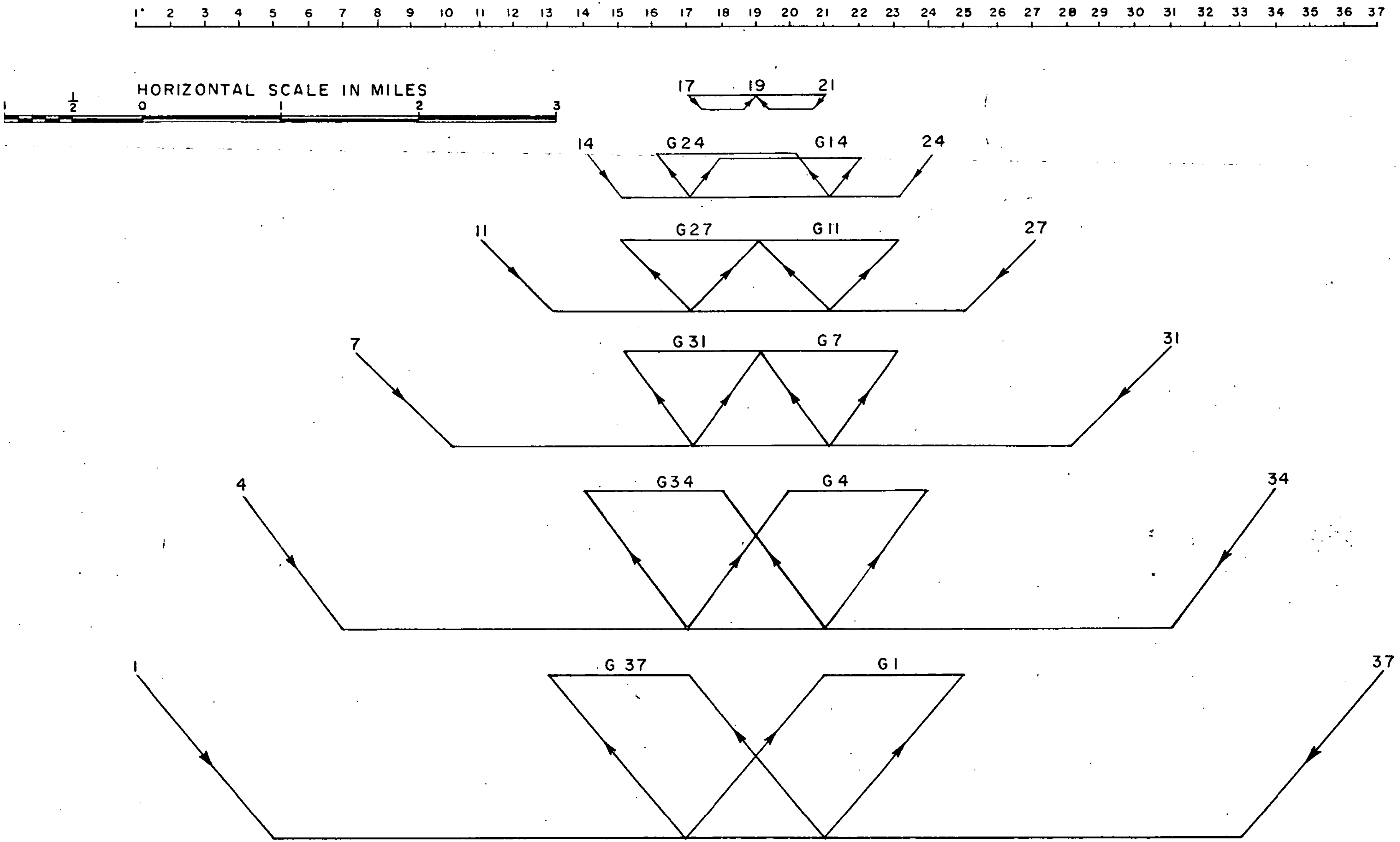


FIG. 2

FACING PAGE 4.

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics

TO ACCOMPANY RECORD 1961 No. 79

G 85-76

when shot from either end. This may not be so, however, if a second refractor is recorded over the part of the spread farthest from the shot-point. A third shot-point in the centre of the spread will usually ensure that the sub-weathering refractor is covered in both directions over the entire length of the geophone spread.

This initial shooting will cover shot-point-to-geophone distances up to 1 mile. The next array of shot-points and geophone spreads should cover from 1 mile to 2 miles between shot-points and geophones. The approximate offset distance will be:-

$$S_n = 1/5 \text{ mile} = 1050 \text{ ft}$$

If we take the portion of the refractor vertically below the first 1-mile spread as the portion to be recorded, the geophone spreads should be offset a distance of 1050 ft from the initial spread in a direction away from their respective shot-points. As one geophone cable covers 1320 ft ($\frac{1}{4}$ mile), it is more convenient in practice to use an offset of 1320 ft. This means that approximately 500 ft of the 1-mile spread length is recorded in only one direction. However, if about 4000 ft is recorded in both directions, that is considered sufficient for the depth-probe technique.

Subsequent distances between shot-points and geophones spreads should be 2 to 3 miles, 3 to 4 miles, etc. The offset of the geophone spread should be the nearest $\frac{1}{4}$-mile to the calculated offset distance. The difference from the calculated distance will then not be greater than 660 ft. The following table shows the offsets corresponding to various distances from shot-point to geophone spread:

Distance from shot-point to geophone spread.	Calculated offset	Geophone spread offset used	
0 - 1 mile	$<$ 300'	0	
1 - 2 miles	1050'	1320'	($1 \times \frac{1}{4}$)
2 - 3 miles	2100'	2640'	($2 \times \frac{1}{4}$)
3 - 4 miles	3150'	2640'	($2 \times \frac{1}{4}$)
4 - 5 miles	4200'	3960'	($3 \times \frac{1}{4}$)
5 - 6 miles	5250'	5280'	($4 \times \frac{1}{4}$)
6 - 7 miles	6300'	6600'	($5 \times \frac{1}{4}$)

The layout of shot-points and geophone spreads is shown in Fig. 2.

It must be emphasised that these recommended geophone-spread offsets depend on assumed conditions; the actual conditions may prove to be very different in particular practical cases. They may differ if:

(1) the ratio of velocities (Va_n/V_n) does not approximate to 2/3; the geophone-spread offsets set out in the above table would then be either too large or too small. Or

(2) the distribution of refractors and their velocities cannot be represented as a two-layer problem. In particular, the relation assumed between depth and critical distance would not strictly apply. If an intermediate refractor has a velocity much greater than Va_n or close to V_n, then the critical distance will be greater than that given by the formulae used. Hence the offset distance will be less than 1/5 of the critical distance, and the geophone-spread offsets will be too great. Or,

(3) as quite often happens in practice, a new refractor is recorded at distances less than its critical distance. Sometimes it is recorded as a later event, and sometimes it appears only because earlier arrivals have been so attenuated that they are not recorded. In these cases, the geophone-spread offsets would be too small.

It is often necessary to revise the geophone-spread offsets and repeat some of the shooting. This is done as soon as enough is known about velocities and depths to allow practical calculation of best offset distances for particular refractors.

3. RECORDING TECHNIQUE FOR REFRACTION SHOOTING.

Refraction shooting requires techniques of shooting and recording that differ in several ways from the usual reflection techniques.

Refraction from the successively-higher-velocity beds of the geological sequence are to be recorded. In order to calculate the depths of these refractors, it is necessary to record the initial onset of the energy. If the desired wave arrives before all others then its onset becomes the "first break". This is most commonly so, but quite often it will be necessary to analyse later events, particularly if they represent deeper (higher-velocity) refractors. However, later events seldom have a clear onset. If the onset is not clear, it is usually possible to estimate where it ought to be; but the depth calculations are then less accurate, and there is always the doubt that the estimated time of onset is in error by one cycle or (particularly for the later events) two cycles. When structure is being investigated by the refraction method, later events, even if their onset is doubtful, are useful in determining variations in the depth of the refractor. If a deeper, higher-velocity refractor is clearly recorded as a later event, then the shot-point-to-geophone distance need not be increased any further; consequently, smaller charges are sufficient to map this refractor. Local checks of the interpretation can be made with special shots to record a first break from the refractor.

The geometrical set-up of shot-point and geophone-spread necessary to record refractions is different from that used in reflection shooting. The deeper the refractor to be recorded, the farther the geophone spread must be from the shot-point. Distances of up to 10 miles between shot-point and geophone spread are common. Because of these great distances, and because it is necessary to record first breaks, very large charges are often used - $\frac{1}{4}$ ton is almost certainly necessary at 10 miles. For economy, and for ease of loading and firing, it is desirable to keep the charge only just large enough to give satisfactory results. Hence it is essential that the receiving system (geophone-amplifier) should operate at maximum sensitivity consistent with microseismic noise.

The refracted waves recorded at large distances (over one mile) from the shot are generally of lower frequency than reflections, and can be as low as 2 to 5 c/s; but in general they are between 15 and 30 c/s.

To accommodate the characteristics of refraction shooting, the following variations and adjustments of shooting and recording techniques should be made:

Shot-point.

(a) Hole. Difficulty is often experienced in loading large charges into a hole. A $4\frac{3}{4}$-in. hole should always be drilled in preference to $3\frac{7}{8}$-in. when it is known that large charges will be fired in it; an even larger hole ($6\frac{3}{4}$-in.) may be desirable. The use of casing should also be considered. The hole should be "bulled" first with a smaller charge to make a cavity big enough to take the whole of the large charge. In some areas it may be found impossible to fire large charges in a single hole; the charge must then be split up between several holes, which should be drilled in line at right angles to the direction of the geophone spread.

(b) Firing. To ensure that the whole of a large charge is detonated, it is essential to fit detonators to more than one stick. For a 100-lb charge, for example, at least three sticks should be fitted with detonators. The detonators should all be connected in series.

(c) Communication. Owing to the large distances between shooter and recorder, telephone communication is impracticable. Instead, special radio transceivers, modified to transmit both time-break and up-hole times, are used.

Geophones.

(a) Frequency. The geophones usually used in reflection work pass frequencies above 19 c/s. This low-frequency cut-off may be too high for satisfactory recording of some refractions; therefore lower-frequency geophones (6-cycle or less) should be used. At least two in series, or better still four in series-parallel, should be used to ensure good average planting characteristics, to give greater sensitivity, and to prevent loss of a channel owing to a faulty geophone. As most 6-cycle geophones are not very robust, they must be tested frequently.

(b) Wind noise. The wind-noise level effectively determines the maximum sensitivity-setting of the receiving system. As it is important in refraction shooting to have the receiving sensitivity as high as possible, time spent in selecting geophone positions away from trees or posts, and in burying and planting the geophones carefully, will be well rewarded. In all places there are seasons when winds prevent recording of long-distance refraction shots between (say) 11 a.m. and 4 p.m. At these seasons long-shot recordings must be made outside normal working hours.

Instrument.

(a) Filters. As indicated above, frequencies of refractions generally range from 5 to 30 c/s, and hence the pass-band of the amplifier should cover this range. The L_0 or L_{00} settings on the low-cut side of the T.I.C. instruments are designed for refraction work. On the high-cut side, the H_5 or H_{55} setting should be used. This may be varied if it is considered likely that sharp first-breaks are obtainable; if so, a higher high-cut may make them sharper. It is unlikely however that sharp first-breaks will be received at distances over one mile. The use of a high high-cut has the disadvantage of allowing more wind noise to pass, thus necessitating a reduction in gain of the amplifier.

(b) Overall gain. In reflection work the gain of the amplifier is initially suppressed and then gradually increased to a maximum towards the end of the record. This technique, in conjunction with the AGC, keeps the record at a readable level. The reasons for this may be seen from curve A (Fig. 3) which shows the way in which the energy received at the geophone varies with time, in reflection shooting.

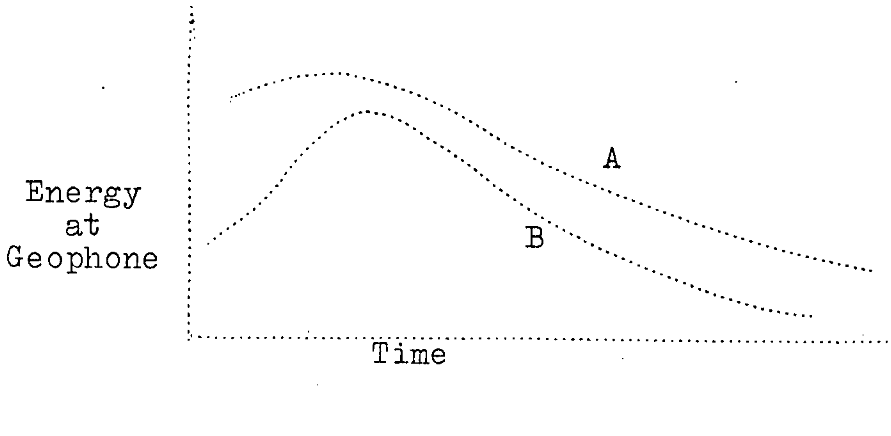


Fig. 3

The initial onset of energy is always well above the recording level and hence the gain at the start need only be small.

In refraction shooting, however, the energy at the geophone varies more in the manner of curve B, and the initial energy may be very small. This initial energy is the most important, and the amplifier should be operating at maximum possible gain for the first arrivals. Initial suppression is therefore unsuitable for refraction work, and should not be used even to suppress wind noise. Wind noise should be removed from the traces by turning back the gain controls of each amplifier until each trace is steady except during occasional bursts of noise; but all gains should be approximately equal, or graded to give greater gain at the farthest geophones. For long shots (say 4 miles or more) at least 30 per cent gain should be used. If there is too much noise to allow 30 per cent gain to be used, shooting should be abandoned until a quieter period. It is apparently general practice to switch off the AGC for refraction shooting. This does not seem necessary, and in fact often would result in much of the later part of the record being lost. However, if the refractions are of very low frequency and the AGC has a fast action, the character of the refractions can be seriously affected by using AGC. In this case shooting with no AGC might be justified. In general it is recommended that the AGC be left on, but a slow rate of AGC attack and decay be used. If it is decided to switch off the AGC, then the shots used to "bull" the hole may be used to record the later events at a readable level.

(c) Paper speed. Several seconds will elapse between the time-break and the arrival of energy from long-distance shots. This results in long records, a large portion of which are of no interest. Reducing the paper speed will reduce the length of the records (and so save paper) and make them easier to handle during both developing and later computation. A slow paper-speed also makes low-frequency and low-amplitude recordings easier to read. The Bureau's T.I.C. camera is fitted with a pair of cogged pulleys which will reduce the paper speed to about 8 in./sec; these should normally be used when shot-geophone distances exceed 2 miles.

4. COMPUTING PROCEDURE

Picking refraction times.

The times to be measured are the times which elapse between the shot and the onset at each geophone of each separate refraction. If good first-breaks are recorded, picking times is straightforward. If they are not, then it is usual to pick the times of a peak or trough of the first readable phase of the refraction; i.e. first trough, first peak, second trough, etc. A constant adjustment is then made to these times to make them equivalent to first-break times. This adjustment is obtained either by measuring it on traces where the first break is readable, or by making an intelligent guess. For later refraction events the first breaks are never readable, and this adjustment can only be estimated. Care should be taken to allow for changes of frequency of the refraction along the spread.

Corrections (Barthelmes, 1946; p. 29).

As in reflection computing, elevation and weathering corrections must be applied to the times before they are plotted. The oblique path of the refracted ray through the weathering and sub-weathering layers makes these corrections slightly more complicated than in reflection computing.

(a) <u>Elevation correction</u>. Consider the correction for geophone elevation which has to be made to times recorded from the "n"th layer (Fig. 4).

The time that has been recorded is for the path ABCD. The corrected time required is for a path PQRS (i.e. the path which would have been followed if the geophone were at P on the datum plane vertically below its actual position). The difference in these path lengths is :

$$ABCD - PQRS = AM - SD \text{ (approx.)}$$

This relation is strictly correct only when all layers are parallel. For the purposes of calculating corrections this assumption will not lead to serious errors. The distance AM is traversed at velocity V_1; and SD is traversed at velocity V_n. Hence, the time difference between the two paths, i.e. the correction to be applied to the observed time, is (assuming parallel layers):

$$Ec_g = (AM)/V_1 - (SD)/V_n$$

Ec_g is known as the elevation correction at the geophone.

As SD = PM and angle PAM = i_{1n} (where $\sin i_{1n} = V_1/V_n$; see page 11)
then

$$Ec_g = AP/(V_1 \cos i_{an}) - (AP \tan i_{an})/V_n$$

$$= \left(\frac{Eg \cos i_{1n}}{V_1}\right)\left(\frac{1}{\cos^2 i_{1n}} - \frac{\sin^2 i_{1n}}{\cos^2 i_{1n}}\right)$$

$$\therefore Ec_g = (Eg \cos i_{1n})/V_1$$

The correction (Ec) at the shot-point is similar except that the elevation of the shot is substituted for the elevation (Eg) of the geophone. That is,

$$Ec = \frac{(Es - ds)\cos i_{1n}}{V_1}$$

where Es is elevation of the shot-point

ds is depth of shot

Thus the elevation corrections at the same geophone or shot-point positions vary according to the cosine factor for each velocity recorded. Before calculating the corrections, therefore, it is necessary to make a preliminary plot of uncorrected times, to determine the approximate velocity recorded. It should be noted that for the first layer, $\cos i_{11} = 0$, and hence there is no elevation correction to be applied for the first layer.

(b) <u>Weathering correction</u> As in reflection corrections, a correction is made for the low-velocity weathered layer, so the corrected time is that which would be recorded if the weathered layer were replaced by the same thickness of sub-weathering material. Consider the correction necessary for the nth layer (see Fig. 5).

In the first place we have to remove the effect of the weathered layer. The recorded path is ABCDE, and the path equivalent to the removal of the weathered layer is PQRS. Assuming all layers are parallel, the difference in path lengths is:

$$ABCDE - PQRS = AB - SE$$

The distance AB of the first ray-path is traversed at the weathering velocity Vo, and the distance SE of the second ray-path is traversed at velocity V_n. Hence the time difference between the two paths is :

$$AB/Vo - SE/V_n = AB/Vo - PB/V_n$$

$$= AP/(Vo \cos i_{on}) - (AP \tan i_{on})/V_n$$

$$= (dw \cos i_{on})/Vo$$

If this time is deducted from the observed time, we have the time which would be recorded if the geophone were at the base of the weathered layer vertically below its actual position. The final ray-path required is AHIJK, where the weathered layer has been replaced by a layer of velocity V_1. The time adjustment from the path PQRS to AHIJK is equivalent to adding an elevation correction for the depth dw, i.e. $(dw \cos i_{1n})/V_1$. The total correction to be made for the effect of the weathered layer on the geophone is therefore

$$Wc_g = (dw \cos i_{on})/Vo - (dw \cos i_{1n})/V_1 \text{ (weathering correction formula)}$$

Usually the <u>shot</u> is placed below the weathered layer and there is no weathering correction to be made at the shot-point. If, however, the charge is fired in the weathered layer, a correction must be made for the slower travel from the shot to the base of the weathered layer. The shot will be a distance (dw - ds) above the base of the weathered layer; the weathering correction at the shot-point is obtained by substituting this expression for dw in the above equation : i.e.

$$Wc = (dw - ds)(\cos i_{on})/Vo - (dw - ds)(\cos i_{1n})/V_1$$

This corrects to the depth of the shot; the elevation correction (Ec) must still be made in the normal manner.

As in the case of the elevation correction, the weathering correction also depends on the velocity being recorded. For the first layer, the second term (elevation term) of the weathering correction formula becomes zero.

The elevations of the shot-points and geophone positions are obtained by normal topographical survey methods. In reflection shooting, the control for weathering corrections is directly obtainable from the shooting alone, but this is not so for refraction shooting; in most surveys, some reflection shooting will have been done along the reflection traverse to provide structural control for the more accurate reduction of the refraction results (see also "Use of Reciprocal Times"). The detailed weathering information available from this reflection shooting should be used to calculate the corrections to be applied to the refraction times. Where this control is not available, special surface weathering shots to determine the thickness of the weathering layer must be fired at intervals not greater than one mile along the traverse.

<u>Calculation of velocity and depth of refractors</u>

Formulae for the calculation of the velocity and depth of refractors are derived in the text-books such as Dix (1952), Heiland (1946), and Jakosky (1949). For convenience of reference they are summarised here:

(a) <u>Two horizontal layers</u>

Let V_1 = velocity of first layer

V_2 = velocity of second layer

D_2 = depth to V_2 or thickness of V_1

i_{12} = critical angle of refraction

making $\sin i_{12} = V_1/V_2$

At a distance x, the travel time t_x is given by

$$t_x = x/V_1 \quad \text{for } x < x_c$$

and
$$t_x = x/V_2 + 2D_2\sqrt{1/V_1^2 - 1/V_2^2}$$
$$= x/V_2 + (2D_2 \cos i_{12})/V_1 \text{ for } x > x_c$$

where x_c is the critical distance.

A plot of t_x against x (a time-distance curve) will consist of one straight line with a slope of $1/V_1$ (for $x < x_c$) and a second straight line with a slope of $1/V_2$ (for $x > x_c$). The velocities V_1 and V_2 can be measured from this time-distance curve. The depth of V_2 can be calculated from the last equation by substituting measured values of x and t_x. It can also be calculated from the intercept time T_2 of the V_2 portion of the time-distance curve, by using the equation.

$$D_2 = \frac{\frac{1}{2}T_2}{\sqrt{1/V_1^2 - 1/V_2^2}} \quad \text{or } \tfrac{1}{2}T_2 \; V_1/\cos i_{12}$$

Again, it may be calculated from the critical distance x_c by means of the equation

$$D_2 = \tfrac{1}{2}x_c \sqrt{(V_2 - V_1)/(V_2 + V_1)}$$
$$\text{or} = \tfrac{1}{2}x_c \; (1 - \sin i_{12})/\cos i_{12}$$

(b) Two-layer case with dipping interface

Let Θ = angle of dip of interface

D_{2U} = depth to V_2 vertically below shot-point, shooting up-dip

D_{2D} = depth to V_2 vertically below shot-point, shooting down-dip

For distances less than the critical distance, the travel-time is again:

$$t_x = x/V_1$$

which is a straight line with a slope of V_1.

For distances greater than the critical distance, the travel-time is:

Shooting up-dip

$$t_{xU} = x\left[(\cos\Theta)/V_2 - \sin\Theta\sqrt{1/V_1^2 - 1/V_2^2}\right] + 2D_{2U}\cos\Theta\sqrt{1/V_1^2 - 1/V_2^2}$$
$$\text{or} = x\left[(\cos\Theta)/V_2 - (\sin\Theta\cos i_{12})/V_1\right] + (2D_{2U}\cos\Theta\cos i_{12})/V_1$$

Shooting down-dip

$$t_{xD} = x\left[(\cos\Theta)/V_2 + \sin\Theta\sqrt{1/V_1^2 - 1/V_2^2}\right] + 2D_{2D}\cos\Theta\sqrt{1/V_1^2 - 1/V_2^2}$$
$$\text{or} = x\left[(\cos\Theta)/V_2 + (\sin\Theta\cos i_{12})/V_1\right] + 2D_{2D}(\cos\Theta\cos i_{12})/V_1$$

Both these equations are linear; their slopes are the reciprocals of the "apparent" velocities with which the wave front passes the geophones. These slopes are:

$$1/V_{2U} = (\cos \theta)/V_2 - (\sin \theta \cos i_{12})/V_1$$
$$= (1/V_1) \sin (i_{12} - \theta)$$

and
$$1/V_{2D} = (\cos \theta)/V_2 + (\sin \theta \cos i_{12})/V_1$$
$$= (1/V_1) \sin (i_{12} + \theta)$$

V_1, V_{2U}, and V_{2D} can be measured from the time-distance curve, and this enables us to calculate i_{12} and θ:

$$(i_{12} - \theta) = \text{arc sin } (V_1/V_{2U})$$
$$(i_{12} + \theta) = \text{arc sin } (V_1/V_{2D})$$

adding $$i_{12} = \tfrac{1}{2} \text{ arc sin } (V_1/V_{2D}) + \tfrac{1}{2} \text{ arc sin } (V_1/V_{2U})$$

subtracting $$\theta = \tfrac{1}{2} \text{ arc sin } (V_1/V_{2D}) - \tfrac{1}{2} \text{ arc sin } (V_1/V_{2U})$$

V_2 is then calculated from

$$V_2 = V_1/\sin i_{12}$$

or $$V_2 = (2\cos \theta)/(1/V_{2D} + 1/V_{2U})$$

The latter equation is useful because for small angles, $\cos \theta$ can be taken as 1, and V_2 can then be calculated directly from V_{2D} and V_{2U} by means of the equation:

$$V_2 = 2/(1/V_{2D} + 1/V_{2U}) \quad \text{(approx.)}$$

The intercept times up- and down-dip are

$$T_{2U} = t_{xU} - x/V_{2U} = 2D_{2U}\cos \theta \sqrt{1/V_1^2 - 1/V_2^2}$$
$$= (2D_{2U} \cos \theta \cos i_{12})/V_1$$

$$T_{2D} = t_{xD} - x/V_{2D} = 2D_{2D}\cos \theta \sqrt{1/V_1^2 - 1/V_2^2}$$
$$= (2D_{2D}\cos \theta \cos i_{12})/V_1$$

Thus the depths can be calculated from these intercept times.

(c) <u>Multi-horizontal layers</u>

Let V_m = velocity of "m"th layer (m less than n)

H_m = thickness of "m"th layer

Consider a ray which has penetrated to the "n"th layer of velocity V_n; if i_{mn} is the angle the ray makes with the normal in the "m"th layer for critical refraction along the "n"th layer, then

$$\sin i_{mn} = V_m/V_n$$

At a distance x, the travel-time t_x for a ray through the "n"th layer is given by

$$t_x = x/V_n + 2\sum_{m=1}^{n-1} H_m \sqrt{1/V_m^2 - 1/V_n^2}$$

$$\text{or} = x/V_n + 2\sum_{m=1}^{n-1} H_m(\cos i_{mn})/V_m$$

The time-distance curve consists of straight line segments of slopes $1/V_1$, $1/V_2$ etc. up to $1/V_n$. Each of these segments has an intercept T_n at $x = 0$, given by

$$T_n = 2\sum_{m=1}^{n-1} H_m \sqrt{1/V_m^2 - 1/V_n^2}$$

$$\text{or} = 2\sum_{m=1}^{n-1} H_m(\cos i_{mn})/V_m$$

Thus the thickness of the "n-1"th layer can be calculated from the thickness of the shallower layers and the intercept time (T_n) for the "n"th layer. The depth D_n to the V_n layer is the sum of the thicknesses H_m

$$H_{n-1} = \left[1/\left(\sqrt{1/V_m^2 - 1/V_n^2}\right)\right]\left[\tfrac{1}{2}T_n - \sum_{m=1}^{n-2} H_m \sqrt{1/V_m^2 - 1/V_n^2}\right]$$

$$\text{or} = \left[(V_{n-1})/(\cos i_{n-1,n})\right]\left[\tfrac{1}{2}T_n - \sum_{m=1}^{n-2} H_m (\cos i_{mn})/V_m\right]$$

$$D_n = \sum_{m=1}^{n-1} H_m$$

(d) Multi-dipping layers

Dooley (1952) has derived general formulae for the case where there are several layers with different dips.

The formulae derived and quoted above are based on the assumption of successive layers each of a uniform velocity higher than that of the layer above; refractors may be relatively thin layers separated by lower-velocity layers. Therefore these formulae will, in general, give depths which are too great because the velocity distribution assumed for the sequence of layers will be too high.

In cases where a vertical velocity distribution is known from a well survey or from a $t, \Delta t$ Analysis of reflections, the depth can be more accurately determined by treating the problem for each refractor as a simple two-layer case. The velocity of the overburden Va_n is taken as the average velocity to the depth of the reflector, given by the vertical velocity distribution. This of course means that the depth must be estimated in order to determine what velocity should be used in calculating the depth.

The final depth estimate is arrived at by successive approximations. First a depth is estimated to decide what velocity to use.

The depth calculated from this velocity is used to decide a better velocity, and so on. Commonly, if the error in the average velocity distribution is less than 5 per cent, about three approximations are necessary before the estimated depth is almost certainly within 10 per cent of the true depth.

A further refinement can be made to the depth calculation by assuming that the velocity of the overburden increases with depth according to some function; usually a linear increase with depth is assumed (Dix, 1952; p. 257).

When the shot-to-geophone distances are large, it is sometimes not reasonable to assume that the dip of the refractor, indicated by the slope of the time-distance curve, continues back to the shot-point. Under these conditions it is not correct to calculate the depth of the refractor from the intercept time. An approximate depth calculation should be made from the travel times at the centre of each pair of geophone spreads (assuming complete overlap) to ensure a common depth point, using the formulae derived for horizontal layers. The formula assuming a simple two-layer case (from page 1) can be written:

$$t_{xu} - x/V_n = (D_{nu} + D_{nc})\ (\cos i_{an})/Va_n$$

$$t_{xD} - x/V_n = (D_{nD} + D_{nc})\ (\cos i_{an})/Va_n$$

where D_{nc} is the depth of the common refraction point below the centre of the layout. If the overlap on the refractor is not complete, then travel times from the centre of the overlap portion should be used. Thus the sums $(D_{nu} + D_{nc})$ and $(D_{nD} + D_{nc})$ can be calculated, and by subtracting we can obtain the difference in depths at the two shot-points $(D_{nu} - D_{nD})$. However, we cannot calculate individual values of D_{nu}, D_{nD}, and D_{nc}. The general profile of the refractor may be known from reflection shooting, and values for the three depths may be selected to satisfy the three values determined above and otherwise give the best conformity with the reflection profile. If the reflection profile does not cover a substantial portion of the reflection layout, a value for D_{nc} is taken as $\frac{1}{4}(D_{nu} + D_{nD} + 2D_{nc})$. Appropriate values of D_{nu} and D_{nD} to satisfy this assumption then follow.

<u>Calculation of profile of refractor</u> (Bartholmes, 1946)

All the formulae derived are based on the assumption that refractors are <u>plane</u> interfaces, and consequently the time-distance plots fall on straight lines. However, if the refractor has an irregular surface, the time intervals from geophone to geophone will also be irregular. If the geophone time intervals, after correction for weathering and elevation, are corrected for the travel-time in the refractor, the residual will be directly related to the change in elevation of the refractor. If Δtc is the residual time difference between two geophones, then the corresponding change in refractor depth (Δ d) is given by,

$$\Delta d = \Delta tc\ v_i/\cos i_{in} \qquad \text{(Bartholmes, 1946; p. 33)}$$

and $\sin i_{in} = v_i/V_n$

where v_i = velocity immediately above refractor (interval velocity).

and V_n = velocity of refractor

If the surface of the refractor is independently plotted as two profiles from the shots in two directions, and if the velocities used and the offset distance used are correct, then the two plotted profiles should be identical. Exact duplication is never achieved in practice but it is often near enough to indicate the correct offset distance (S), and any error in the refractor velocity. For this reason, it is often important to plot both profiles.

If the original offset distances (S) are wrongly estimated, some refraction times used in calculating the velocity of the refractor will be from non-overlapping portions of the reverse time-distance curve. An error in refractor velocity is indicated by different slopes in the overlapping portion of the plotted profile of the refractor.

Once it is clearly established which portions of the plotted profile overlap, the up-dip and down-dip velocities should be calculated from these portions only, by the method of least squares (the Bureau uses a special circular slide-rule to simplify least-square calculations). A final value of refractor velocity can then be calculated.

Before making depth estimates it is usually possible to see whether the records show any distinctive characteristic of the refractor profile which can mark the precise overlap. Alternatively, the records sometimes show that the profile is so straight that errors in offset and overlap will not introduce appreciable error into the calculated refractor velocity.

A useful method of checking offsets, after the preliminary calculation of refractor velocity, is to plot the refractor profile from each of the reverse shots on separate pieces of paper, one being transparent so that it can be overlaid on the other. The two profiles can be moved independently until the best fit for overlap and slope is obtained. The refractor velocity can then be adjusted to the value which gives this best fit. If this can be done, then from Chapter 2 ("Layout of Shot-points and Geophones"):

$$S_n = \tfrac{1}{2}x_{cn}/(1 + V_n/Va_n)$$

$$\therefore Va_n = 2V_nS_n/(x_{cn} - 2S_n)$$

S_n is calculated as has just been described.

x_{cn} can be determined from the time-distance curves; a mean of of the up-dip and down-dip values may be used.

V_n may be derived as explained under "Two-layer case with dipping interface".

Therefore a value for Va_n may be calculated. Because of approximations, and because the observed x_{cn} is actually the critical distance between two refractors and not between a Va_n overburden and V_n refractor, this cannot be accepted as a reliable figure for Va_n, but it is a useful value for commencing the process of successive approximation.

Use of reciprocal times

If a refractor dips fairly steeply, its critical distances up-dip and down-dip will differ greatly. Thus two reverse shots which have the same shot-geophone distances need not record the same refractor. The dip may also cause apparent velocities to differ greatly from true velocities, and the apparent velocities may be mistakenly interpreted as the velocities of other refractors either above or below. For these reasons it is most important to check reciprocal times in refraction shooting, as they can indicate how the reverse time-distance plots should be paired.

The reciprocal time is the surface-to-surface time from shot-point to shot-point. It can only be estimated, and this is done by projecting the time-distance graphs to intersect the ordinate through the reverse shot-point. If all assumptions have been correct, then the two reciprocal times for any one refractor will be approximately equal. If they are not approximately equal, then most commonly the two (reverse) time-distance curves have been wrongly assumed to come from the one refractor; or there is a serious discrepancy between the slope of the refractor where it is being recorded (CD, Fig. 1) and the overall slope between the points on the refractor relative to each shot-point where the seismic waves from the shots are refracted towards the recording place (EF, Fig. 1).

It is wise to shoot depth probes at places where the known structural geology suggests:

(a) that the geophone line is laid out more or less along the strike, and

(b) that there is no serious faulting between shot-points farthest apart, or better still

(c) that the sediments are flat-lying.

It is always worth considering shooting a <u>reflection</u> traverse along the proposed refraction layout. If successful (i.e. if reflections are recorded from the refracting horizons) the reflection traverse will

(a) provide both weathering and structural control that will

(b) allow refraction recordings to be reduced more accurately,

(c) check the dip of the refractors,

(d) establish the structural relief of the refractor between the shot-points and the recording position,

(e) permit a more accurate estimate of depth.

If the reciprocal times shot from both ends are only very roughly equal, they can still usually be used to determine which refractors correlate with the various time-distance graphs. They cannot be so used if the distance between shot-points is near the critical distance for two refractors, but this limitation can usually be overcome by calculating a theoretical reciprocal time for some other distance (i.e., to imagine one of the shot-points is at some other distance). To do this, the reciprocal times are increased or decreased by an amount equal to the gradient of the time-distance graph multiplied by the increase or decrease in theoretical distance between shot-points.

When measuring shot-point intercept times to be used in depth calculations, it should be remembered that the reciprocal times must be equal. A calculated depth that better fits the data will result if we use a shot-point intercept time determined by drawing a straight line from the best estimated reciprocal time (mean of the two obtained by extending the time-distance graphs) through the mean point of the time-distance graph and extending it to intersect the other shot-point ordinate (see Plate 1). This is an alternative method to that described on page 12 for determining D_{nu}, D_{nD}, and D_{nc}. It is not as convenient, and the former method is recommended.

5. PLOTTING AND PRESENTATION OF RESULTS

An example of the time-distance plotting and interpretation of a refraction depth probe is shown on Plate 1. This is the manner in which depth probes are plotted by the Bureau; any departures from this form are explained in the text of the report concerned. All apparent velocities are calculated by the least-square method. Recorded times, corrections made to them, and the corrected times, are shown on the graph; this ensures that all necessary information is available to any reader who wishes to check the interpretation.

The example plotted in Plate 1 demonstrates clearly how corrections are made for elevation and weathering, and also the following points which have already been discussed:

(a) The two profiles of refractor V_4, plotted from the reverse shots through this refractor, have characteristics which leave no doubt as to how they should overlap; therefore the correct offset distance has been used.

(b) The dip of refractor V_3 (7 degrees) causes a large difference in the critical distances for the two directions of shooting. Thus the time-distance plots for shot-points 27 and 11 are not from the same refractor, even though the shot-geophone distances are equal. Further, the up-dip value of V_3 (13,020 ft/sec) is close to V_4 and could be confused with it. Only a study of the reciprocal times would solve which pairs came from the same refractor.

A further point that should be emphasised is the necessity for laying out a refraction traverse along a straight line whenever possible. If shot-points and geophone spreads are not in the same straight line, the calculations are more complicated; moreover, as the geophone intervals are no longer equal, it is not strictly correct to use the least-square method of determining slopes. More important however is the effect a non-linear traverse has in increasing the difficulty of

(a) comparing reciprocal times in order to "match" profiles, particularly when successive refractors have only small differences in velocity, and

(b) covering the same portion of a refractor with spreads in both directions.

6. REFERENCES

BARTHELMES, A. J. 1946 Application of continuous profiling to refraction shooting. Geophysics 2 (1).

DIX, C. H. 1952 SEISMIC PROSPECTING FOR OIL. Harper, New York.

DOOLEY, J. C. 1952 Calculation of depth and dip of several layers by refraction seismic method. Bur. Min. Resour. Aust. Bull. 19 (Appendix).

HEILAND, C. A. 1946 GEOPHYSICAL EXPLORATION. Prentice-Hall, New York.

JAKOSKY, J.J. 1949 EXPLORATION GEOPHYSICS. Trija Pub. Co., California.

FIG. 1

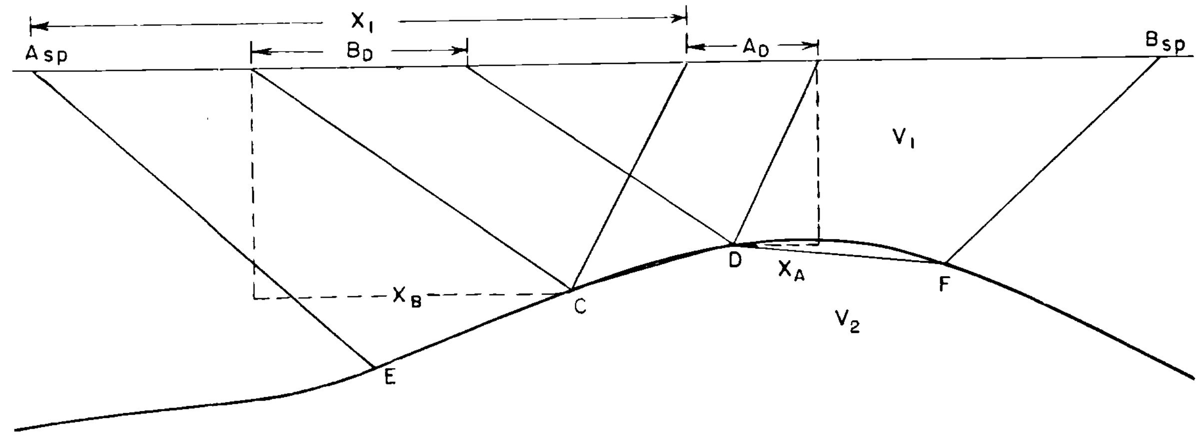
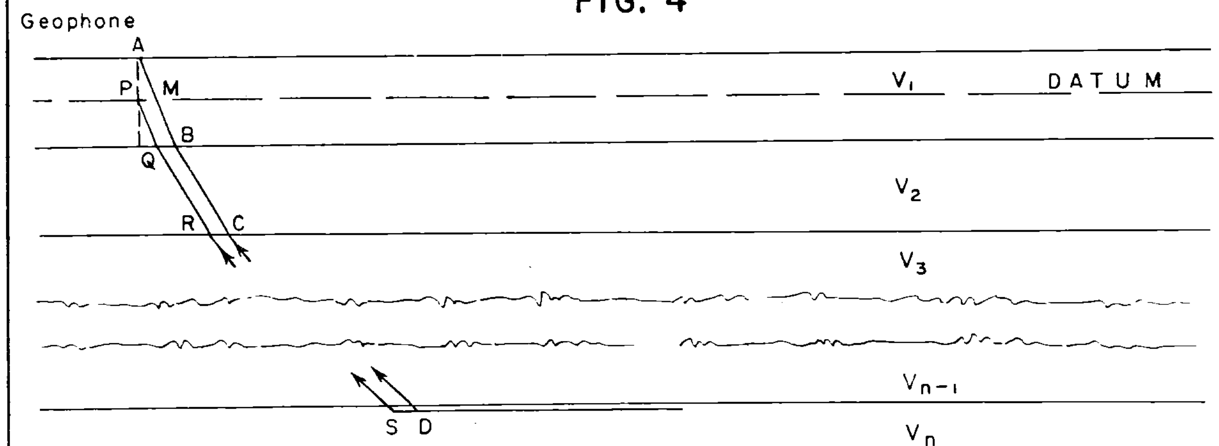


FIG. 4



V_1 = velocity of 1st. layer (elevation velocity)

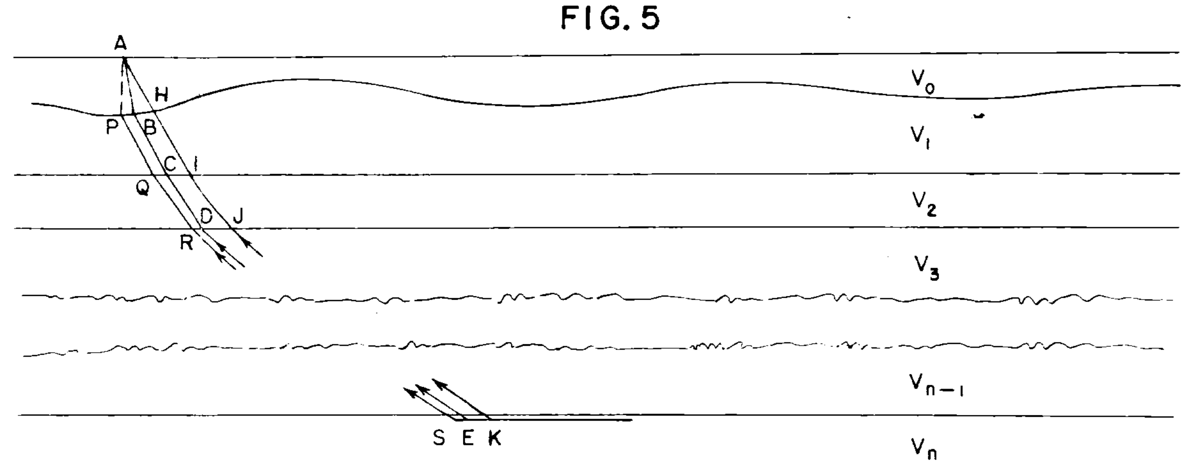
V_2 = velocity of 2nd layer

etc.

V_n = velocity of nth. layer

Eg = elevation of geophone referred to datum level (= AP)

FIG. 5



In addition to symbols already defined, we have:-

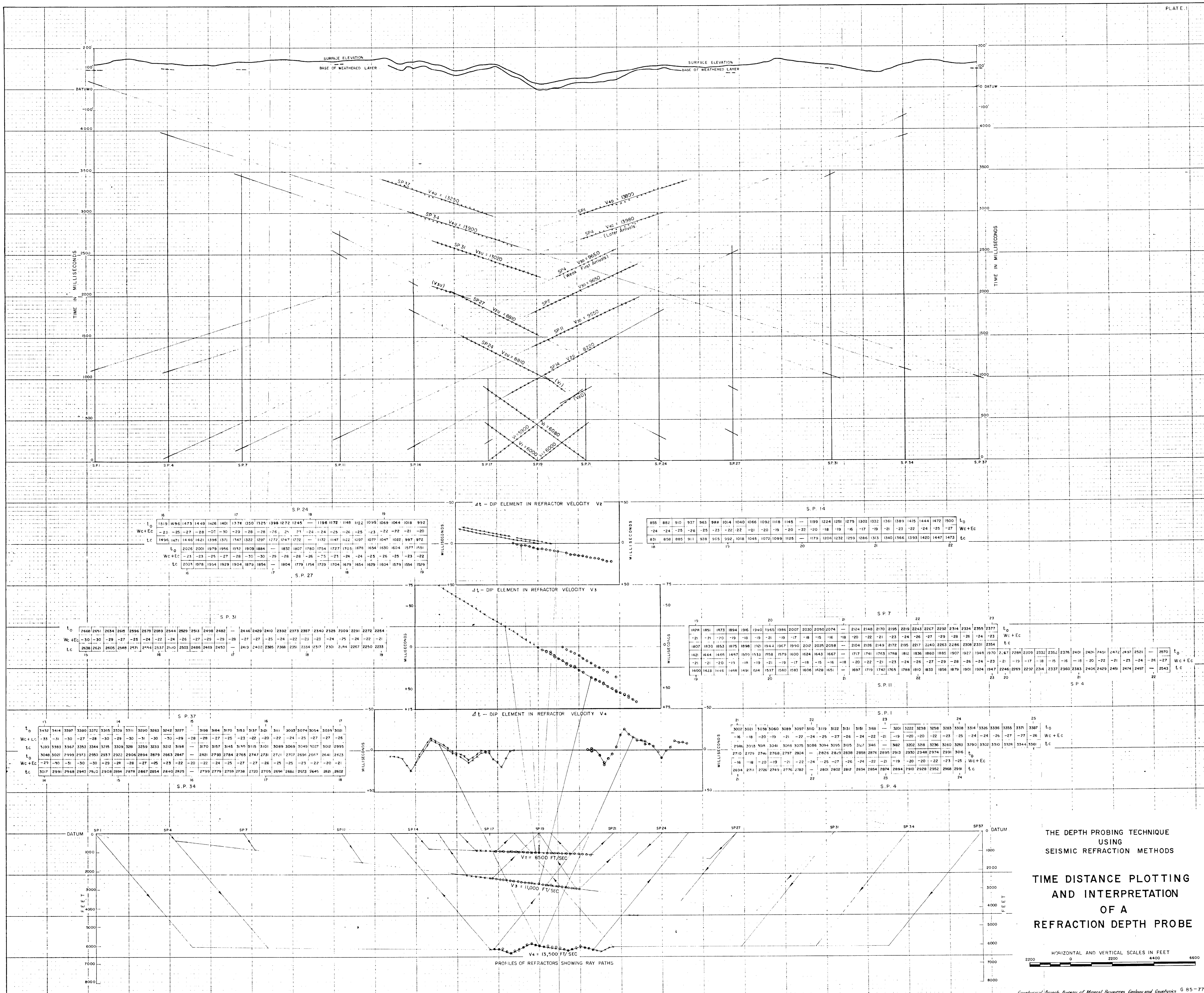
V_0 = Weathering velocity

dw = depth of weathering (= AP)

SEISMIC DEPTH PROBING

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics G 85-100

TO ACCOMPANY RECORD 1961 NO 79



TO ACCOMPANY RECORD 1961 NO. 79