

Comparative Study of the Offset-Geophone and Down-deep Hydrophone Seismic Refraction Survey with Application to the Niger Delta Basin, Nigeria.

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ABSTRACT

This work discusses an uphole survey with the aim of comparing seismic refraction data acquired with the offset-geophone procedure and that acquired using the down-deep hydrophone procedure, and subsequent examination of the validity of each data set for seismic reflection data quality control.

Data was obtained at Grid 5594/1961 on the Trans-Ramos river 3-D prospect in the Niger Delta Basin, Nigeria. Interpretation of the offset-geophone data shows that as shots are taken uphole, vertical time of the shots are initially greater than the time of intercept, and decreases uphole. However, at a particular depth, as shots move up, the intercept time overtakes the vertical time. This would happen only if the shot is taken within the consolidated layer. Therefore, the greatest depth at which vertical time is exceeded by the intercept time qualitatively gives a clue to the base of weathering. This value can then be compared with the value obtained from a quantitative interpretation of the data to ascertain the correctness of the results. Interpretation of the down-deep hydrophone data is only based on theoretical equations and it is nearly impossible to check the computed weathering depth.

(Keywords: seismic refraction, geological data, uphole survey, hydrophone, geophone, weathering layer)

INTRODUCTION

The unconsolidated layer (also known as the weathering layer), which is some distance below the Earth's surface, is a critical zone in seismic operations. It is characterised by low transmission of seismic waves and generation of multiples (at the base of the layer). Shots taken

in this layer tend to be of low frequencies because the layer is capable of absorbing high frequency signals and releasing lower frequency ones. However, since higher frequency signals contain more information on the subsurface, it is appropriate that in order to acquire good quality reflection data, shots have to be taken below the weathering layer.

An uphole survey is a seismic refraction procedure which aims at determining the thickness and velocity of the weathering layer. The survey is therefore a good tool in making decisions on drilled and charge depths in any seismic operation. Uphole data are also utilized in the computation of statics during subsequent processing of seismic reflection data.

When energy is incident at the critical angle to a reflector with a positive reflection coefficient, it is refracted along the interface at the velocity of the second layer. Each point on the interface excited by the refracted wave radiates upwards with hemispherical divergence, causing wavefronts to travel to the surface with raypaths that intersect the interface at the critical angle, Asor (2000). It follows that on a seismic record, a reflection ceases to exist at the critical distance and is succeeded by a refraction.

In an uphole survey, a hole is essentially drilled (up to about 63m depth) where shots are laid (in the case of offset-geophone) or where hydrophone is lowered (in the case of down-deep hydrophone).

TRAVEL TIME EQUATIONS AND THEIR SPECIFICATIONS

We now consider the travel time equation for the cases below:

Shot in the weathering layer ($D_w > D_s$)

Consider a single shallow shot taken at a depth D_s (within the weathering layer i.e., $D_s < D_w$, where D_w is the thickness of the weathering layer (Figure 1).

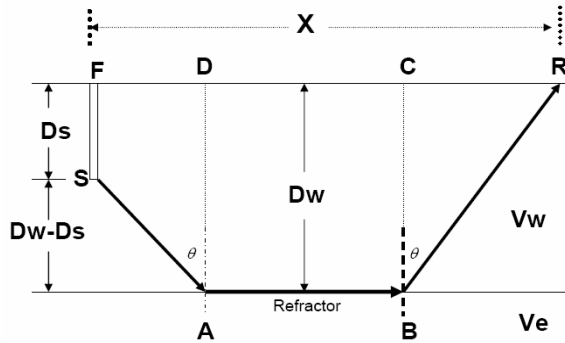


Figure 1: Refraction Path for a 2-Layer Case.

The total travel time, T , between the shot instant at S and receiver at R is given by:

$$T = T_{SA} + T_{AB} + T_{BR} \quad \text{..... (1)}$$

$$T = \frac{SA}{V_w} + \frac{AB}{V_e} + \frac{BR}{V_w} \quad \text{..... (2)}$$

where,

V_w = weathering layer velocity, and

V_e = consolidated layer velocity.

Therefore,

$$T = \frac{D_w - D_s}{V_w \cos \theta} + \frac{AB}{V_e} + \frac{D_w}{V_w \cos \theta} \quad \text{..... (3)}$$

where,

θ is the critical angle of incidence.

Now,

$$AB = X - [FD + CR], \text{ and}$$

$$\frac{FD}{D_w - D_s} = \tan \theta \quad \text{..... (4)}$$

Therefore,

$$FD = (D_w - D_s) \tan \theta \quad \text{..... (5)}$$

Similarly,

$$\frac{CR}{D_w} = \tan \theta, \text{ so that } CR = D_w \tan \theta. \quad \text{..... (6)}$$

Hence,

$$AB = X - [(D_w - D_s) \tan \theta - D_w \tan \theta] \quad \text{..... (7)}$$

$$= X - (2D_w \tan \theta - D_s \tan \theta)$$

Therefore, the travel time equation becomes:

$$T = \frac{D_w - D_s}{V_w \cos \theta} + \frac{2D_w \tan \theta - D_s \tan \theta}{V_e} + \frac{D_w}{V_w \cos \theta}$$

$$= \frac{X}{V_e} + \frac{2D_w}{\cos \theta} \left[\frac{1}{V_e} - \frac{V_w}{V_e^2} \right] - \frac{D_s}{\cos \theta} \left[\frac{1}{V_w} - \frac{V_w}{V_e^2} \right]$$

$$= \frac{X}{V_e} + \frac{2D_w \sqrt{V_e^2 - V_w^2}}{V_e V_w} - \frac{D_s \sqrt{V_e^2 - V_w^2}}{V_e V_w} \quad \text{..... (8)}$$

The weathering depth is obtained from the last equation by setting the offset to zero, i.e., $X=0$. At zero offset, the total travel time $T = T_i$, where T_i is the intercept time. From (8), we therefore have that:

$$T_i = \frac{2D_w \sqrt{V_e^2 - V_w^2}}{V_e V_w} - \frac{D_s \sqrt{V_e^2 - V_w^2}}{V_e V_w} \quad \text{..... (9)}$$

from which the weathering depth can be obtained as:

$$D_w = \frac{T_i V_e V_w}{2\sqrt{V_e^2 - V_w^2}} + \frac{D_s}{2} \dots\dots\dots (10)$$

From Snell's law,

$$\sqrt{1 - \frac{V_w^2}{V_e^2}} = \cos \theta, \text{ so that } \frac{1}{\cos \theta} = \frac{V_e}{\sqrt{V_e^2 - V_w^2}} \dots\dots\dots (11)$$

Hence,

$$D_w = \frac{T_i V_w}{2\cos \theta} + \frac{D_s}{2} \dots\dots\dots (12)$$

The T-X plot for the above case is shown in Figure 2. In some cases, however, there could be more than one layer of weathering.

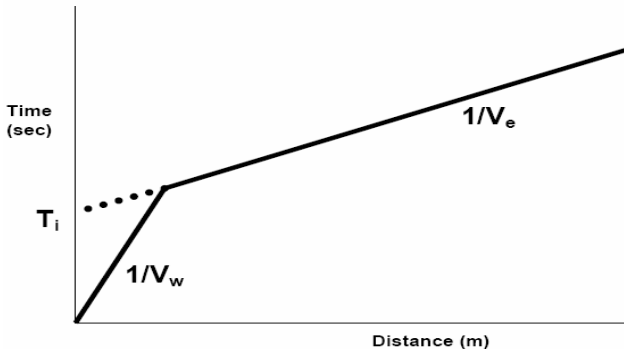


Figure 2: T-X Plot for a 2-Layer Case.

Consider a 3-layer case (i.e., two layers of weathering) as is shown in Figure 3. In this case, the total depth of the weathering is given by:

$$D_w = Z_0 + Z_1 \dots\dots\dots (13)$$

The T-X plot for this case is shown in Figure 4, and the travel time equation is given by:

$$T = \frac{X}{V_e} + \frac{2 Z_0 \sqrt{V_2^2 - V_0^2}}{V_2 V_0} + \frac{2 Z_1 \sqrt{V_2^2 - V_1^2}}{V_2 V_1} \dots\dots\dots (14)$$

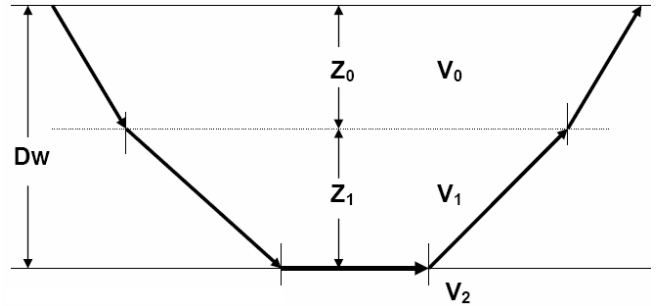


Figure 3: Refraction Path for a 3-Layer Case.

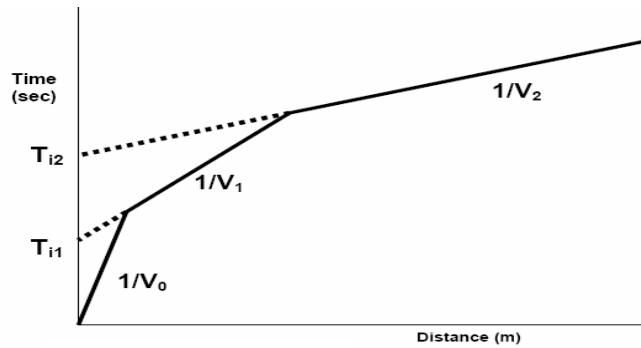


Figure 4: T-X Plot for a 3-Layer Case.

At $X = 0$

$$T = T_{i2} \dots\dots\dots (15)$$

$$\therefore T_{i2} = \frac{2 Z_0 \sqrt{V_2^2 - V_0^2}}{V_2 V_0} + \frac{2 Z_1 \sqrt{V_2^2 - V_1^2}}{V_2 V_1} \dots\dots\dots (16)$$

For a shot $D_s < D_w$, the thickness of the first sub-layer of weathering, Z_0 is obtained as:

$$Z_0 = \frac{T_{i1} V_0}{2 \cos \theta_1} + \frac{D_s}{2}, \text{ where } \cos \theta_1 = \sqrt{1 - \frac{V_0^2}{V_2^2}} \dots\dots\dots (17)$$

Therefore, with T_{i2} read from the T-X plot (Figure 4) calculated as above, the total depth of weathering can be determined as given in Equation 10.

Shot at the base of the weathering layer
 ($D_s = D_w$)

The total travel time T for this case (Figure 4B) is given by:

$$T = T_{SA} + T_{AR} \left. \begin{array}{l} \\ \\ \\ \end{array} \right\} \dots \dots \dots (18)$$

$$= \frac{SA}{v_e} + \frac{AR}{v_w}$$

Therefore,

$$T = \frac{X - D_w \tan \theta}{v_e} + \frac{D_w}{v_w \cos \theta} \left. \begin{array}{l} \\ \\ \\ \end{array} \right\} \dots \dots \dots (19)$$

$$= \frac{X - D_w \sin \theta}{v_e \cos \theta} + \frac{D_w}{v_e \cos \theta}$$

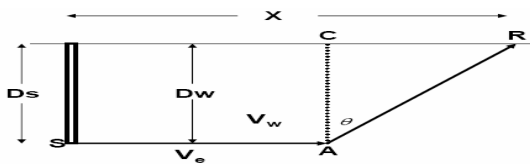


Figure 4 B: Raypath for Shot at Base of Weathering.

And following the same procedure for the 2-layer case, we have that:

$$T = \frac{X}{v_e \cos \theta} + \frac{D_w \sqrt{v_e^2 - v_w^2}}{v_e v_w} \dots \dots \dots (20)$$

At

$$X = 0, T = T_i \text{ so that } T_i = \frac{D_w \sqrt{v_e^2 - v_w^2}}{v_e v_w} \dots \dots \dots (21)$$

Therefore, the weathering thickness is obtained as,

$$D_w = \frac{T_i v_w}{\cos \theta} \dots \dots \dots (22)$$

Shot taken in the consolidated layer
 $D_s > D_w$

In practical field situation, the direct arrival curve from which the first velocity is determined disappears when the shot is below the weathering layer. This makes it practically impossible to determine the weathering thickness for any shot taken below weathering.

DATA ACQUISITION METHODOLOGY

In an uphole survey, a deep hole is drilled at the intersection of source and receiver lines in a seismic reflection data acquisition project. In the case of the offset-geophone procedure, dynamite charges are laid successively in the hole at intervals, starting from the deepest depth level of interest, each charge having a detonator lid extending to the surface with the depth written on it.

The hole is normally tamped after each shot is laid to prevent loss of energy up the hole when a shot is taken. Thereafter, a number of geophones are laid on the surface at respective intervals from the hole. At the end of the shooting, a single geophone jug is planted near the surface, very close to the hole, and a shot is taken with a detonator cap planted near the surface in the hole. The idea is to obtain an uphole pre-trigger time, which is the time that would elapse between the initiation of a shot and its receipt by a geophone on the surface. Figure 5 is a sketch of the field arrangement for the data acquisition.

For the down-deep hydrophone procedure, one single hydrophone is lowered into the hole, and is raised up to a shallower depth after each shot is taken. The hole is not tamped. The shots are normally taken with a detonator cap buried at a depth of about 1m very close to the drilled hole (about 1m from the hole). The arrangement is shown in Figure 6..

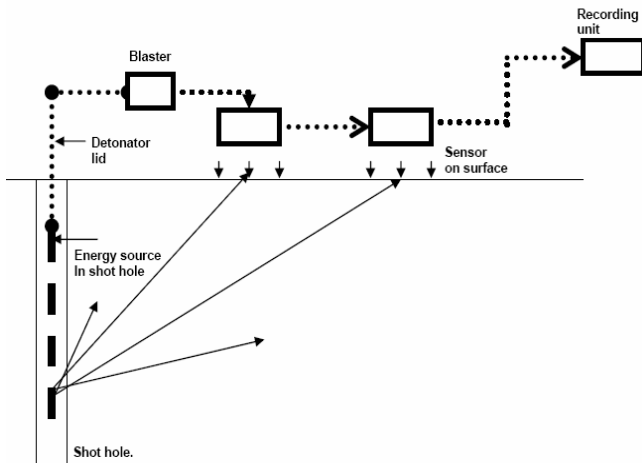


Figure 5: Field Layout for Offset-Geophone Data Acquisition.

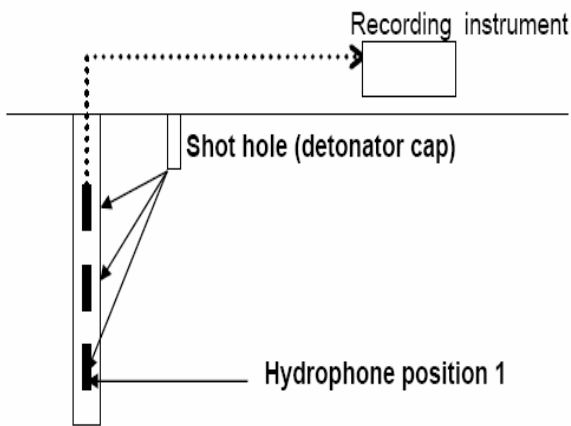


Figure 6: Field Layout for Down-Deep Hydrophone Data Acquisition.

PRESENTATION, REDUCTION, AND INTERPRETATION OF DATA

After a shot is taken, a plot of arrival times versus geophone stations (in the case of offset-geophone) and hydrophone depth (in the case of down-deep hydrophone) is made on a monitor record and this constitutes the data set. In processing of the data, first-break arrival times are picked for various shots. First-break time is the first pick-up time recognised for any trace, and it is the parameter of interest in the interpretation of uphole data (Ojo, 1993).

Details of automatic first-break travel time picked using artificial intelligence techniques have been reported by Veezhinathan and Wagner, 1990; Veezhinathan *et al.*, 1991 and Taner, 1988. Uphole data can also be picked manually with a high level of accuracy. The offset-geophone data are normalised by subtracting the pre-trigger time from the first-break times. By this, it is assumed that the pick-up time of a shot by each geophone is the same, therefore, differences are due to time delays introduced into the data by the weathering layer.

Near-surface depth models are computed from picked first-break times (Taner *et al.*, 1998) and to achieve this, a plot of the corrected time is made against each channel for every shot in the case of the offset geophone. For the down-deep hydrophone data, the time is plotted against each hydrophone position in the hole. We have seen from the theoretical treatment that the weathering depth computation is based on the zero-offset time, which is obtained by extrapolating the refraction curve to the time axis.

Normally in the interpretation of the offset-geophone data, computation of the weathering depth is a function of the plot in question. If the plot is such that the uphole time is less than the intercept time (Figure 7), it implies that the shot is in the weathering layer and Equation 12 may be sufficient to determine the weathering depth. On the other hand, as shown in Figure 8, when the intercept time is less than the uphole time, the curve is no longer that of refraction but reflection, and the inverse slope gives the elevation or consolidated layer velocity. The implication here is that the shot is at the base of weathering or within the consolidated layer. Here, the ray path crosses the weathering layer only once and the weathering depth can be computed from Equation 22.

As we mentioned previously, only one plot is made for the whole data set in the case of the down-deep hydrophone procedure. The depth of weathering in this case is determined using the theoretical relation:

$$D_w = \frac{X_{\text{cross}}}{2} \sqrt{\frac{v_e + v_w}{v_e - v_w}} \quad \text{..... (23)}$$

where X_{cross} is the cross-over distance.

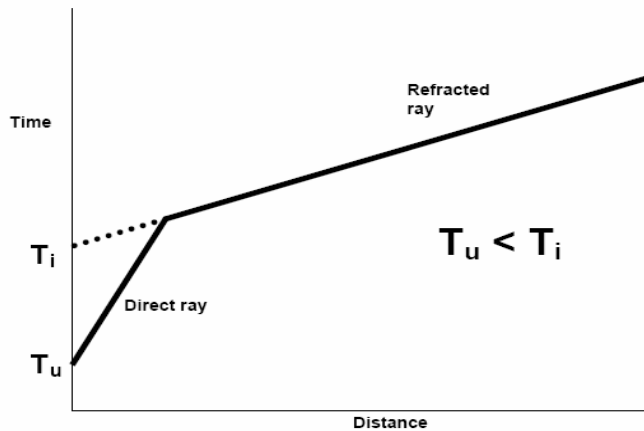


Figure 7: T-X Plot for Shot Taken in the Weathering Layer.

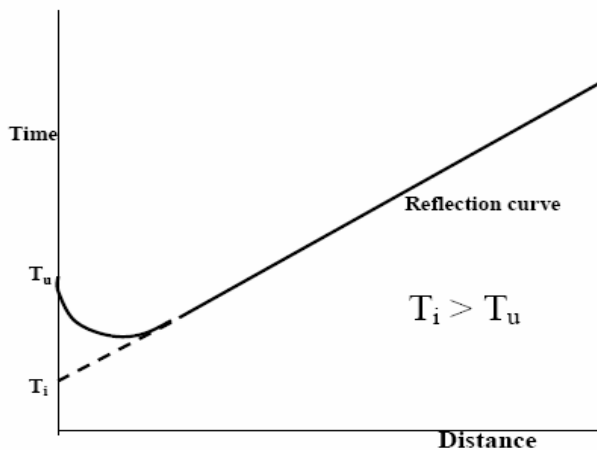


Figure 8: T-X Plot for a Shot within the Consolidated Layer.

COMPARATIVE STUDY

Plotting the offset-geophone data shows a decreasing uphole time as shots are taken uphole. For any shot taken in the weathering layer, the intercept-time is always greater than the uphole time. If the shot is taken in the consolidated layer, the intercept time is exceeded by the uphole time. Thus, at some shot depth, the uphole and intercept time would be approximate. This immediately gives a clue to the depth of weathering because the shot depth at this instance is close to the base of weathering. And for shots taken beyond weathering, no refraction occurs but reflection.

From the above analysis, it is obvious that with the offset-geophone procedure, an estimate of

the weathering depth can be obtained by a qualitative interpretation of the travel time versus distance plots; this estimate can later be compared with the result of the quantitative interpretation for the various shot depth. Normally, the values should agree if a good 'pick' of the first breaks and a good plot had been made.

It is worth pointing out that a good and reliable quantitative interpretation of the uphole data is made only from shots taken well within the weathering layer. This is as a result of the fact that here, the ray crosses the weathering layer twice and this gives a proper representation of the ray path in the weathering layer.

The weathering thickness is confirmed by making a time-depth plot for each trace and then correlating the cross-over distances at all the traces. The correlated value gives, as close as possible, the thickness of the weathering layer. Thus, using the offset-geophone procedure, there could be three different ways of ascertaining the thickness of the weathering layer.

In the down-deep hydrophone procedure, only a quantitative interpretation is made. There are no other ways of checking the calculated value of the weathering depth. The plot is made for first-breaks versus hydrophone depths which range from within the consolidated layer to the weathering layer. Equation 22 is most conveniently used for determining the weathering depth using this method, and in practice, the result obtained would only be an approximation. Erroneous depths, which the interpreter may not be able to correct, could be computed.

Plotting

In our work, we picked first-break at each channel for every shot taken in the case of the offset-geophone procedure (therefore, we had twelve data sets), while first break was picked for each depth in the case of the down-deep hydrophone (and so we had only one data set). Thereafter, the pre-trigger time was subtracted from each first-break to obtain a normalised time. For example, at station 1 for $D_s=5m$, the first break time = 27 ms and so corrected time = $(27-16)ms = 11ms$. The corrected times are shown in Table 1 and Table 2 for the offset-geophone and down-deep hydrophone data,

Table 1: Corrected First Break for Offset Geophone Data.

# TR	Geophone offset (m)	Pick time for 5m charge depth (msec)	Pick time for 10m charge depth (msec)	Pick time for 15m charge depth (msec)	Pick time for 20m charge depth (msec)	Pick time for 25m charge depth (msec)	Pick time for 30m charge depth (msec)	Pick time for 35m charge depth (msec)	Pick time for 40m charge depth (msec)	Pick time for 45m charge depth (msec)	Pick time for 50m charge depth (msec)	Pick time for 55m charge depth (msec)	Pick time for 60m charge depth (msec)
1	1	11	12	32	34	37	37	38	39	41	43	45	47
2	5	18	25	30	33	37	37	38	39	41	43	44	47
3	15	35	29	34	35	38	38	38	39	41	43	44	47
4	15	39	34	35	36	38	38	38	38	41	43	44	46
5	20	49	41	39	40	40	41	41	41	43	45	47	49
6	25	56	49	39	40	39	40	40	40	41	43	44	45
7	35	64	54	44	44	43	44	44	44	45	46	47	48
8	45	69	58	49	49	47	48	48	48	48	49	50	51
9	55	75	63	54	53	52	52	53	53	53	54	55	55
10	65	84	72	62	61	60	60	61	61	61	62	62	63
11	85	99	84	75	75	72	73	73	73	73	73	73	74
12	105	113	99	90	88	88	88	88	88	87	87	87	88

Table 2: Corrected First Break for Down-Deep Hydrophone Data.

Arrival time (msec)	0	17	36	41	44	49	52	56	58	61	66	68	69
Charge depth (m)	0	5	10	15	20	25	30	35	40	45	50	55	60

respectively.. A plot of the corrected time versus geophone station was then made for every shot point (Figure 9) while Figure 10 shows the time-depth plot for the down-deep hydrophone data.

Interpretation

A quantitative interpretation of the offset-geophone data shows that for $D_s \geq 15m$, the uphole time is greater than the intercept time whereas, for $D_s = 5m$ and $D_s = 10m$, the converse is the case (Figure 11). This immediately indicates that the base of weathering is between 10m and 15m.

For $D_s = 5m$,
 $v_w = 500 \text{ m/s}$; $v_e = 1,429 \text{ m/s}$, $T_i = 40 \text{ msec}$. Using Equation 12, $D_w = 13.2 \text{ m}$.

$$\text{Cos } \theta = \sqrt{1 - \frac{500^2}{1429^2}} = 0.936789$$

$$D_w = \frac{T_i v_w}{2 \text{Cos } \theta} + \frac{D_s}{2} = \frac{0.04 \text{ sec} * 500 \text{ m/s}}{2 * 0.936789} + \frac{5}{2} = 13.2 \text{ m}$$

For $D_s = 10m$,
 $v_w = 517 \text{ m/s}$; $v_e = 1,591 \text{ m/s}$, $T_i = 31.6 \text{ msec}$.
 Using the same procedure above, $D_w = 13.6 \text{ m}$.

The two values agree, giving an average weathering depth of 13.4m; this agrees well with the qualitative interpretation of the data. Finally, a time-depth for traces 1, 10, 11 and 12 was made (Figure 12) and the correlated value gives 13.8m thereby confirming the depth of weathering.

For the down-deep hydrophone data,
 $v_w = 341 \text{ m/s}$; $v_e = 1,334 \text{ m/s}$, $T_i = 33 \text{ msec}$.

Using Equation. 21, the computed weathering depth, $D_w = 11.64 \text{ m}$ (Figure 10).

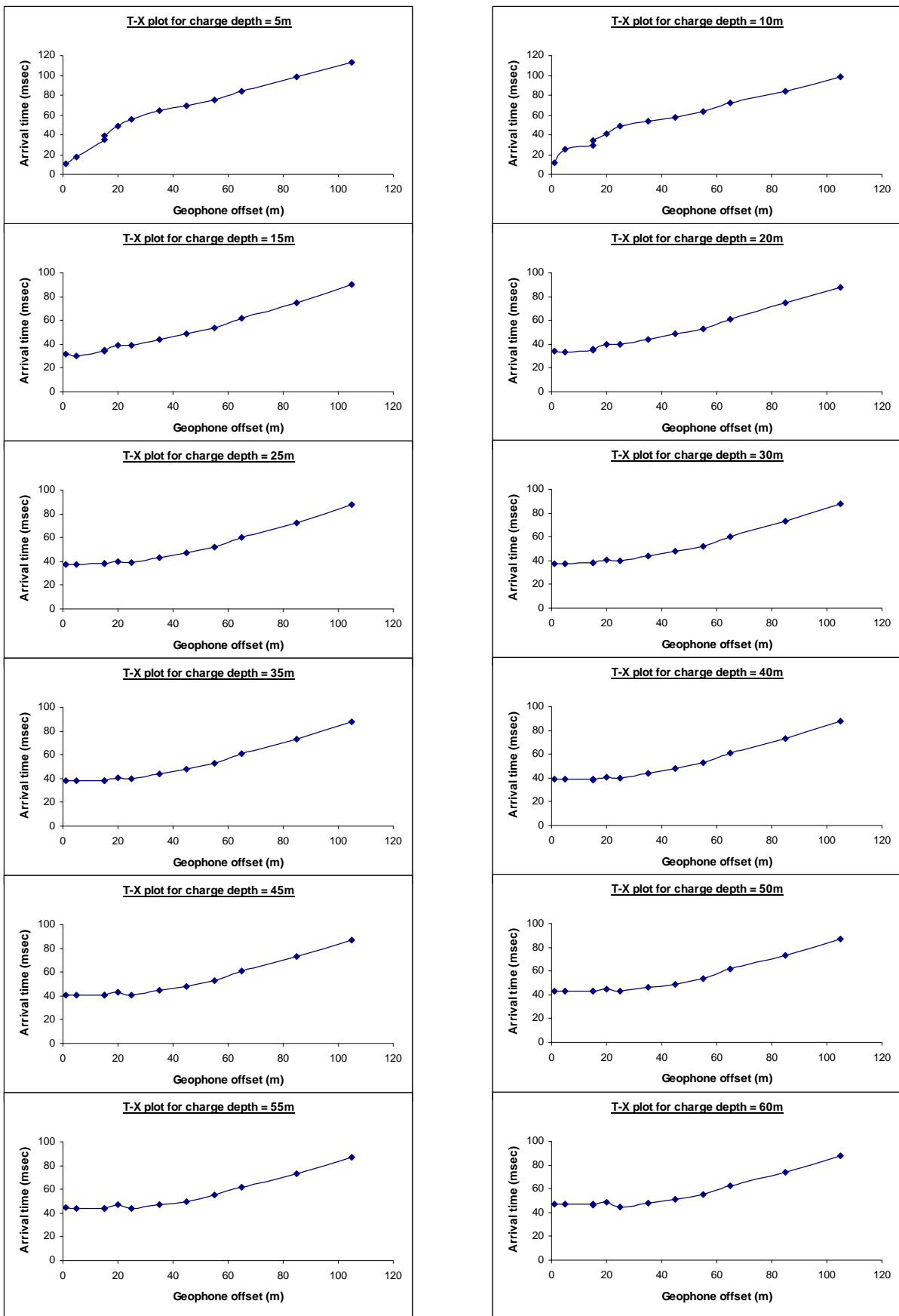


Figure 9: T-X Plots at Different Charge Depth (Offset-Geophone Data Analysis/Interpretation).

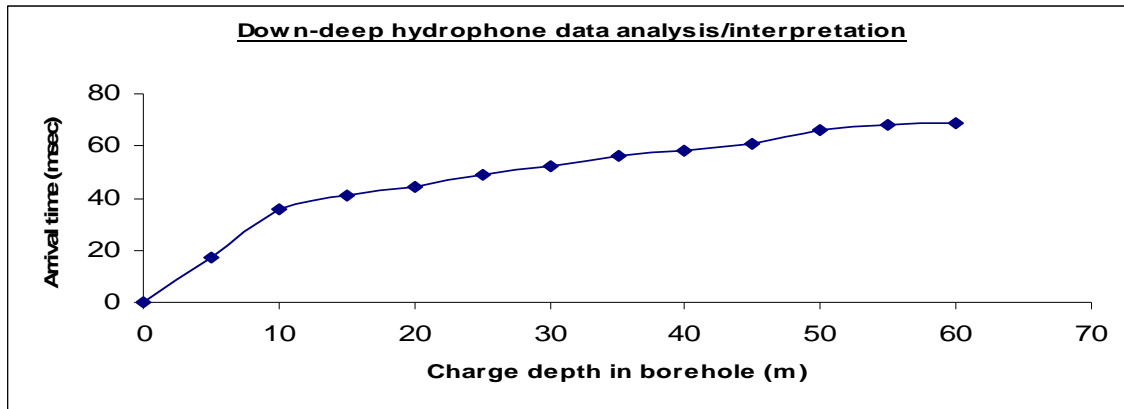


Figure 10: T-X Plot for Down-Deep Hydrophone Data.

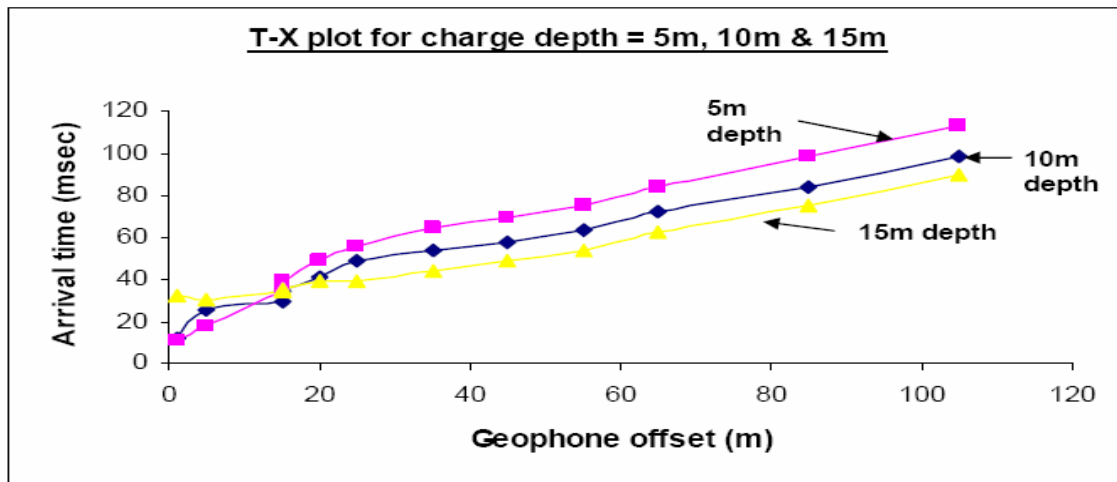


Figure 11: T-X Plots at Different Charge Depth (5m, 10m, and 15m).

The plots show that uphole time is less than intercept time for charge dept 5m and 10 m, but supersedes the intercept time for charge depth 15m.

CONCLUSION

We have compared two methods of uphole survey and have shown that the offset-geophone procedure gives more reliable information concerning the depth of weathering than the down-deep hydrophone method. This information is important for reflection data acquisition as well as the subsequent processing of the reflection data. A method that would determine, as close as possible, the depth of weathering is important in seismic exploration projects. For the purpose of accuracy and reliability of interpreted results, the offset-geophone data are superior to the don-deep hydrophone procedure.

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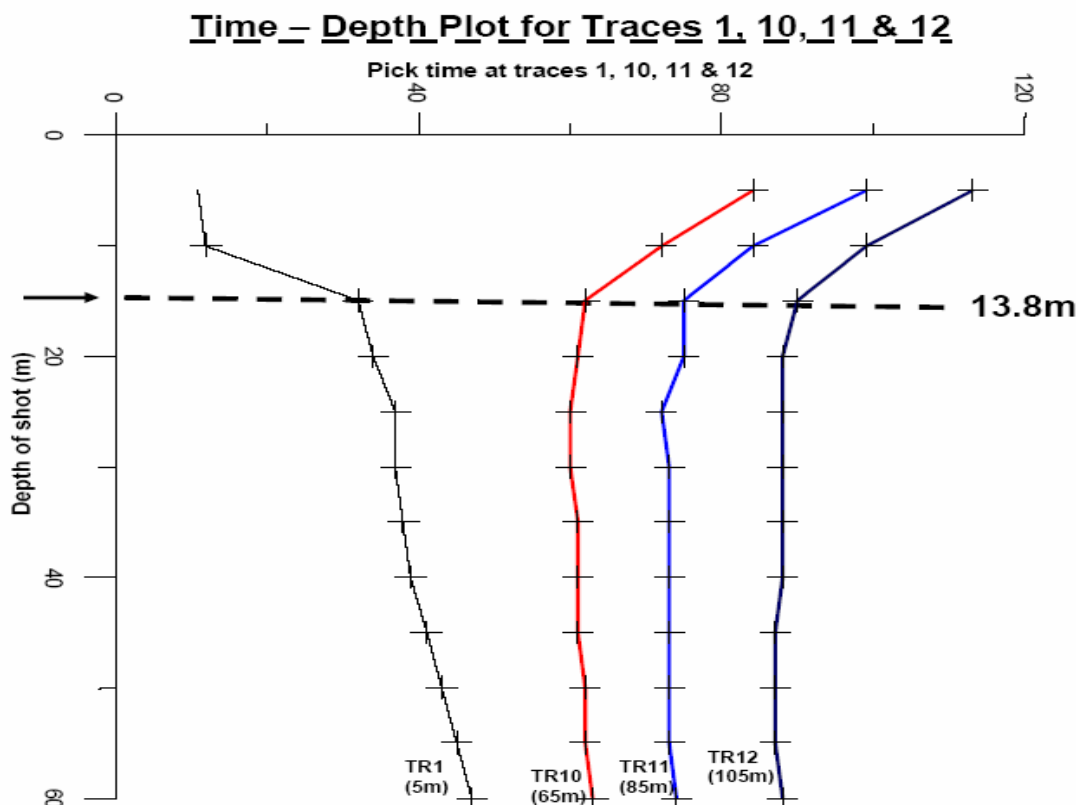


Figure 12: Time-depth plot for traces 1, 10, 11 and 12.

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