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PERMAFROST DETERMINATION BY SEISMIC VELOCITY ANALYSES[1]

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ABSTRACT

In the Mackenzie Delta and surrounding Beaufort Sea, seismically derived velocities provide the best means for predicting presence and thickness of permafrost. In seismic exploration we define permafrost as a subsurface layer that is permanently at or below the temperature at which the liquid-to-solid phase change begins. This is the point at which the layer is at least partially frozen, and at which a marked velocity change occurs. From seismic refraction velocities we can calculate the depth to the top of permafrost, and from reflection velocities we can determine its thickness.

Permafrost predictions are necessary for: 1) interpreting time-depth relationships on seismic data, 2) designing well casing programs, 3) locating unfrozen sands for dredging, 4) predicting hydrates, 5) planning pipelines, gas plants or other structures.

INTRODUCTION

In the Mackenzie Delta and surrounding Beaufort Sea, we have found velocity analyses of seismic refraction and reflection data the most accurate method for determining presence, depth to top, and thickness of permafrost. From seismic refraction data we can calculate the depth to the top of permafrost, and velocity analyses of reflection data will determine its thickness.

PERMAFROST DEFINITION AND OCCURRENCE

Some scientists, interested in temperature, define permafrost as a subsurface layer whose temperature is permanently at or below 0°C, whether it is frozen or not. Some engineers, interested in rigidity and strength, define permafrost in terms of permanent ice or solidly frozen material. We in seismic exploration, being interested in velocity, find ourselves somewhere in between these two points of view. We define permafrost as a layer at variable depths below surface that is permanently at a temperature at or below the point at which the liquid-to-solid phase change begins. This is usually considered to be 0°C, but is generally somewhat lower depending on permeability, pressure and salinity. In seismic exploration this is the point at which a marked velocity change occurs. This velocity change gives us problems in our time-depth relationship, but at the same time gives us a method for predicting permafrost and correcting the problems it can cause.

In the Mackenzie Delta, velocities in the top 2,500 ft are in the 5,000-6,500 ft/sec range in unfrozen sediments, but from 8,000-14,000 ft/sec in frozen sediments.

Figure 1 shows the Mackenzie Delta area and the wells used in this study. These wells are Sarpik B-35, Netserk B-44 and Immerk B-48 on artificial islands to the west of Richards Island; Taglu F-43 and Ivik K-54 on Richards Island; and Kugmallit H-59 on an artificial island in Kugmallit Bay.

Figure 2 shows a typical velocity profile from a crystal cable survey at Taglu F-43. Time in seconds is across the top and depth down the side. Note the 11,000 ft/sec layer at the surface. Below that, there is a 40-ft melt zone with a velocity of 6,000 ft/sec. Below that again, the velocity increases to more than 12,000 ft/sec, then gradually decreases to 6,300 ft/sec at 1,700 ft, which is considered to be the base of permafrost. The average velocity through the permafrost zone is about 10,000 ft/sec, which seems to be a good average for all wells in the Delta.

The crystal-cable velocity survey is generally the best tool for interpreting permafrost in the wellbore. The three logs on the right are the Self Potential (S.P.), the Dual Induction Lateral Log (Resistivity) and the Caliper Log. They show, as expected, that the melt zone and the high-velocity permafrost are in porous blocky sands whereas the slower-velocity permafrost is in the shales. This is because it takes a much lower temperature to freeze shales solidly than it does to freeze permeable sands.

Figure 3 is a somewhat schematic section showing, by interval velocity curves, permafrost changes across the Delta. For each curve, interval velocity in thousands of feet per second is plotted against depth. Note

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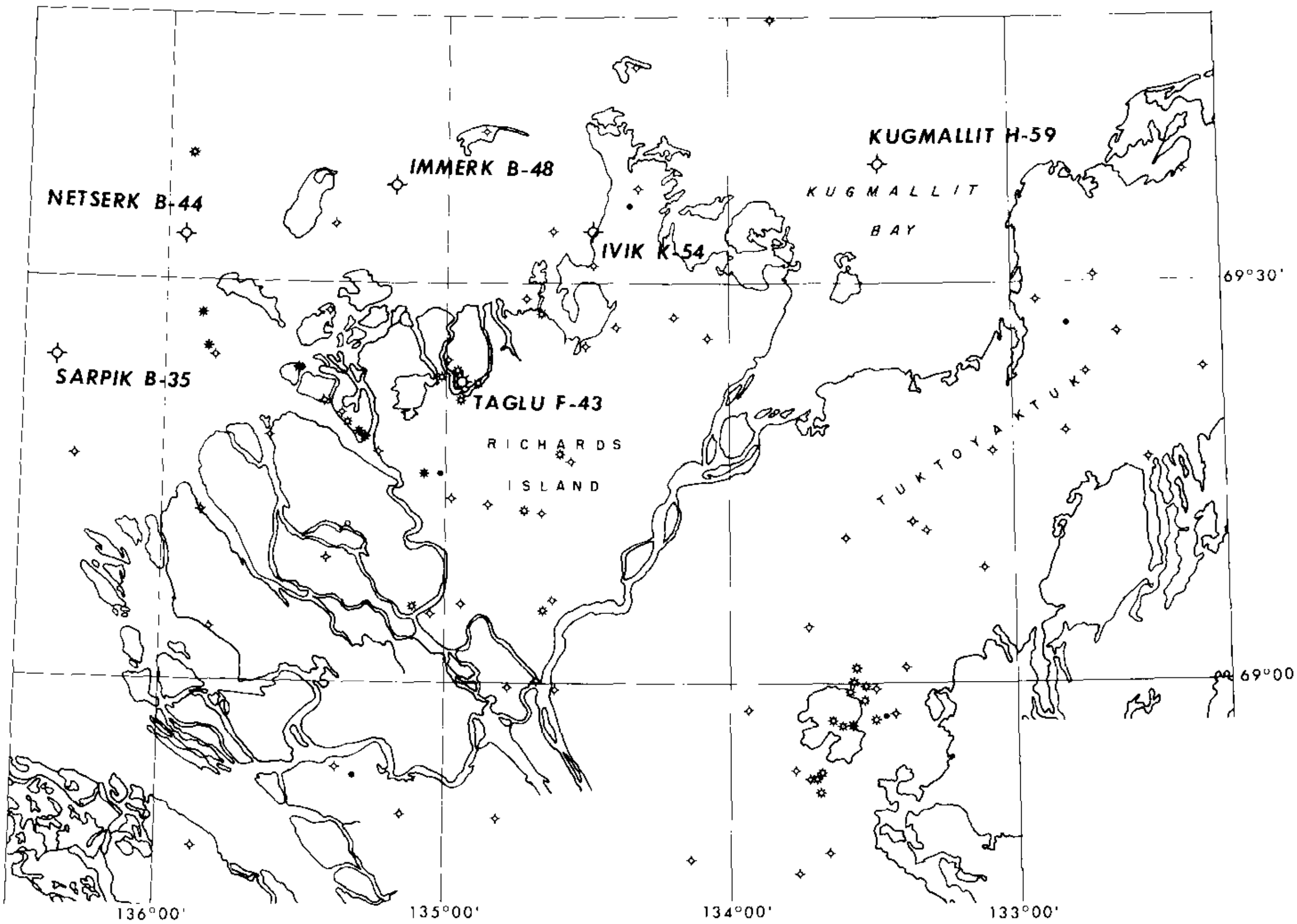


Fig. 1. Mackenzie Delta area and wells used in the study.

the absence of permafrost at Sarpik; the thin sliver, 105 ft, at Netserk; 760 ft at Immerk; 1,670 ft at Taglu; 1,876 ft at Ivik, and 1,600 ft at Kugmallit. Note too that the offshore wells have an unfrozen layer above the permafrost. Where this happens we call it relict permafrost because we think it is left over from the last ice age, when sea level was some 150-300 ft lower than at present. We have, then, a wedge of permafrost with a velocity averaging 10,000 ft/sec, inserted into unfrozen sediments with velocities averaging under 6,000 ft/sec. Across the bottom of the figure is shown the two-way travel time to 3,000 ft at each well. Note that it varies from 0.952 sec at Netserk to 0.667 sec at Ivik, showing the effect that a varying thickness of permafrost has on seismic reflection travel times.

To convert seismic times to depth, we need to be able to predict these velocity changes ahead of the drill. For time-depth conversions, we really don't so much need to know the thickness of permafrost as its time effect on seismic reflections. We do, however, need to know its thickness and depth to its top to:

1) Design casing programs for wells. Government regulations, as well as our own safety and environmental protection rules, require specific casing programs where permafrost is encountered or expected.

2) Predict hydrates. Beneath permafrost we can expect a hydrate zone, which has to be drilled with special care.

3) Locate unfrozen sands for dredging. In our island-building operation, it is important to locate sands in the subsea that are unfrozen and thus dredgeable.

4) Plan pipelines, gas plants, or any other structures.

Permafrost Interpretation

Permafrost can be interpreted in a wellbore by velocity logs and to some extent by other logs, but how can we predict it ahead of the drill? Various other methods have been tried, most of them involving resistivity measurements. All have severe limitations, especially where appreciable thicknesses are involved. As stated at the outset, the seismic velocity method gives by far the most accurate prediction of depth to, and thickness of, permafrost.

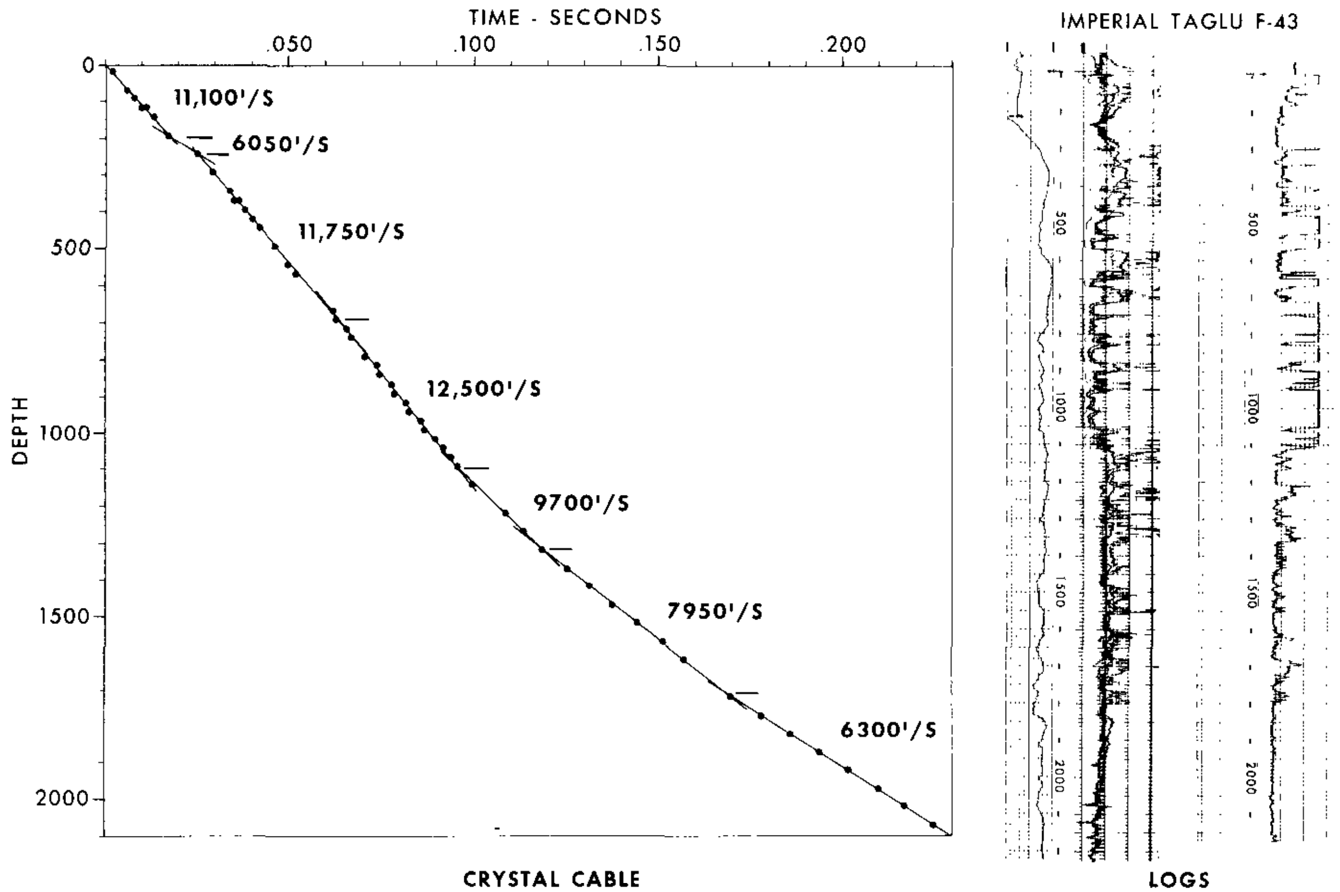


Fig. 2. Typical velocity profile.

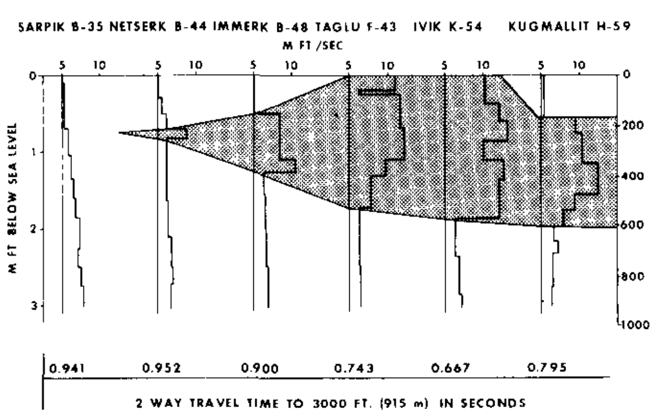


Fig. 3. Schematic section of permafrost changes across the Mackenzie Delta.

Refraction Method

Dealing first with refraction, Figure 4 shows schematic wave fronts and time-distance curves. The shot point is at the top of a layer with velocity V_1 which overlies a layer with a higher velocity V_2. Note the wave front spreading out from the shot point in the V_1 layer. For geophones close to the shot point, this wave

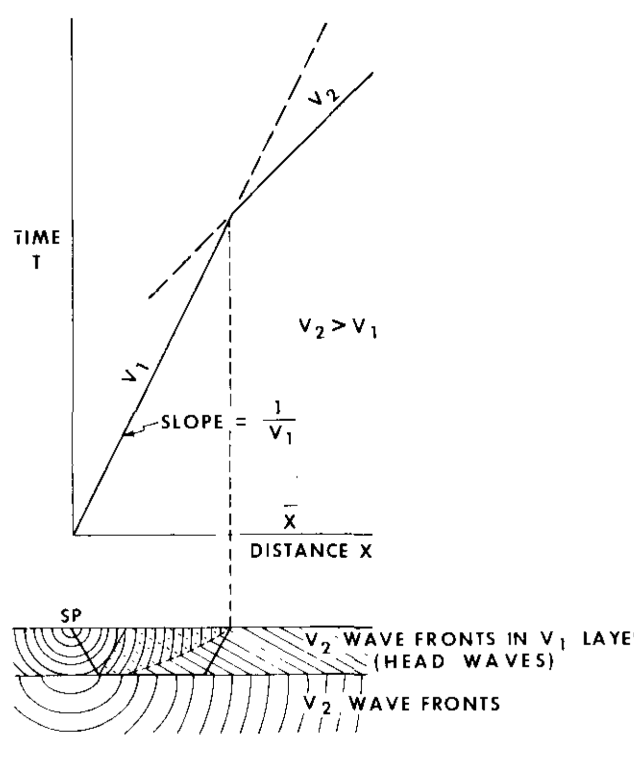


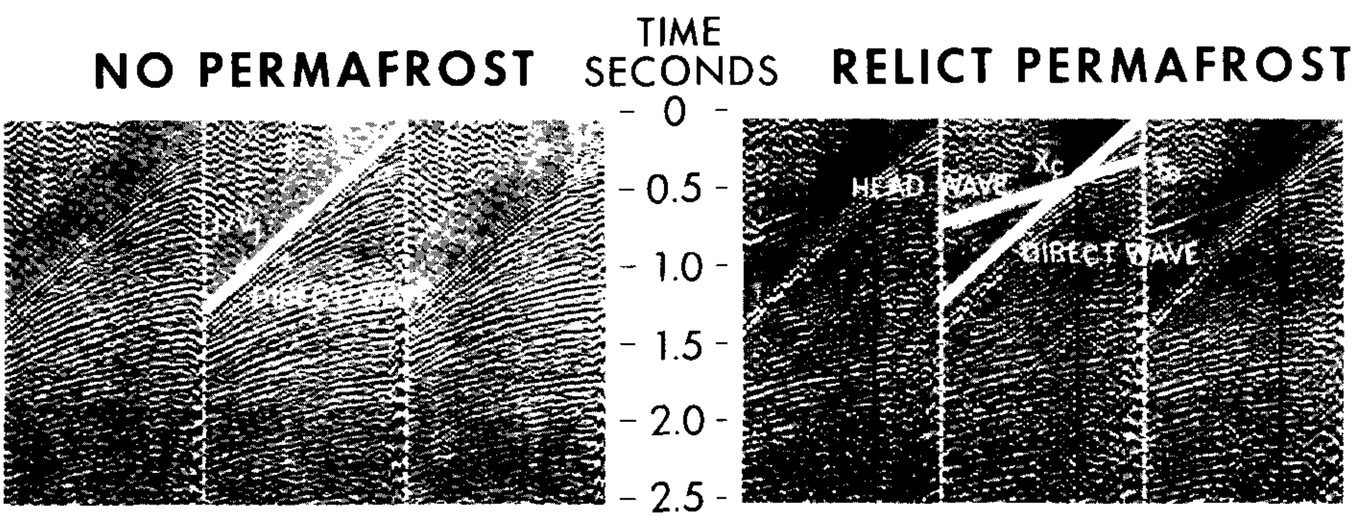
Fig. 4. Schematic wave fronts and time-distance curves.

front will be the first arrival. At a certain distance from the shot point, the first arrival will be the V_2 head wave front refracting back through the V_1 layer. By measuring first arrivals and plotting time versus distance, we can calculate V_1 and V_2 and also the depth to the V_2 layer.

This procedure is illustrated in Figure 5, an example of the use of first-kick refraction breaks for permafrost detection. On the left are three marine seismic records from the Sarpik area. The white line across the top of the centre record joins up the first breaks. Knowing the time and the horizontal distance, we can calculate the slope and thus the velocity. This works out to 4,980 ft/sec, which is the velocity of sound in water and in the shallow sediments at water bottom. As no refraction break to a higher velocity is indicated, no permafrost is expected. The three records on the right, however, show a refraction break at about 0.5 seconds. V_1, the velocity of the direct wave, calculates out to 5,085 ft/sec and V_2, the velocity of the refracted head wave, to 14,458 ft/sec. This value is rather high but indicates definite permafrost. By measuring X_c, the intersect point of the V_1 and V_2 curves, or T_0, the intercept point of the V_2 curve on the time axis, we can calculate the depth to the V_2 or permafrost layer. Note the two formulae below. The first one, using V_1, V_2 and the V_2 intercept, gives a depth of 848 ft. The second, using V_1, V_2 and their intersect point, gives a depth of 809 ft. The difference is due probably to slight inaccuracies in drawing the lines or picking the points.

This method has been described by Hunter *et al.* (1974) of the Geological Survey of Canada in reports on occurrence of permafrost in the southern Beaufort Sea. Unfortunately, there is of course no refraction break from the base of the permafrost, so we cannot use the method to measure thickness of permafrost. On land, where the permafrost is right at the surface, there will be no low-velocity layer. The V_1 will be permafrost velocity and there will be no break to a V_2.

Another example is shown on Figure 6. On the left is a pair of records with first-break arrivals indicating no permafrost. On the right is a pair of records with a normal refraction break indicating a thick relict permafrost. In the centre is a pair of records from near the Netserk B-44 well, which had only 105 ft of permafrost. Note that the refraction head wave attenuates very quickly and can be seen on relatively few traces. Neave *et al.*, also of the Geological Survey of Canada, in 1976 reported an ingenious method of measuring permafrost thickness by equating the attenuation or dispersion of the head wave with thickness. At best, though, this method can work only when the permafrost layer is relatively thin, and then it seems only directionally correct. In one or two test cases, where thick perma-



V= 4980 FT./SEC.

V_1= 5085 FT./SEC.

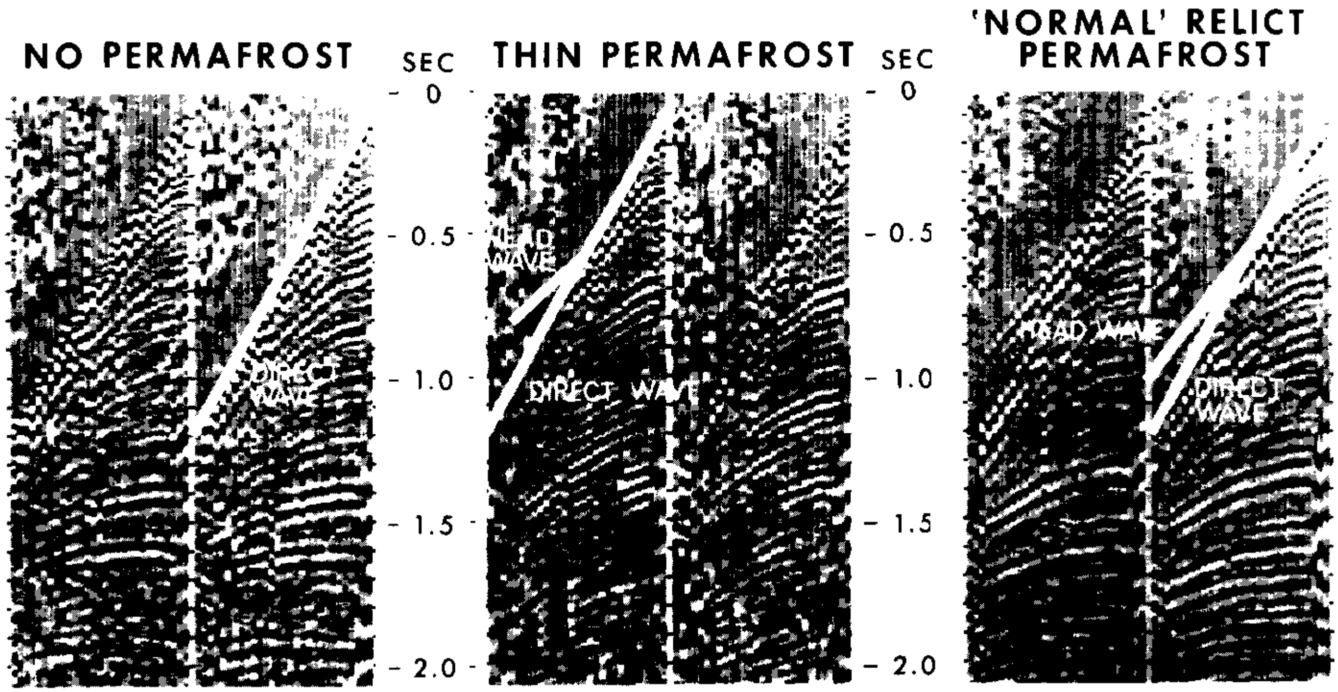
V_2= 14458 FT./SEC.

$$H=\frac{V_1 V_2 T_0}{2\sqrt{V_2^2 - V_1^2}} = 848'$$

$$H=\frac{X_C \sqrt{V_2 - V_1}}{2\sqrt{V_2 + V_1}} = 809'$$

DEPTH TO TOP OF PERMAFROST

Fig. 5. Permafrost detection by refraction.



$V_1 = 5350$ Ft./Sec.

$V_2 = 7895$ Ft./Sec.

$$\text{DEPTH TO TOP OF PERMAFROST} = H = Xc/2\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} = 695 \text{ Ft.}$$

Fig. 6. Permafrost detection by refraction.

frost was subsequently found, the results could hardly be called even directionally correct.

Seismic Reflection Velocity Analysis

For accurate thickness determinations we must go to seismic reflection velocity analysis. Figure 7 shows the derivation of the velocity formula. By measuring T_O, the travel time at zero offset; T_X, the travel time at X offset; and the distance X, we can calculate the velocity from the derived formula:

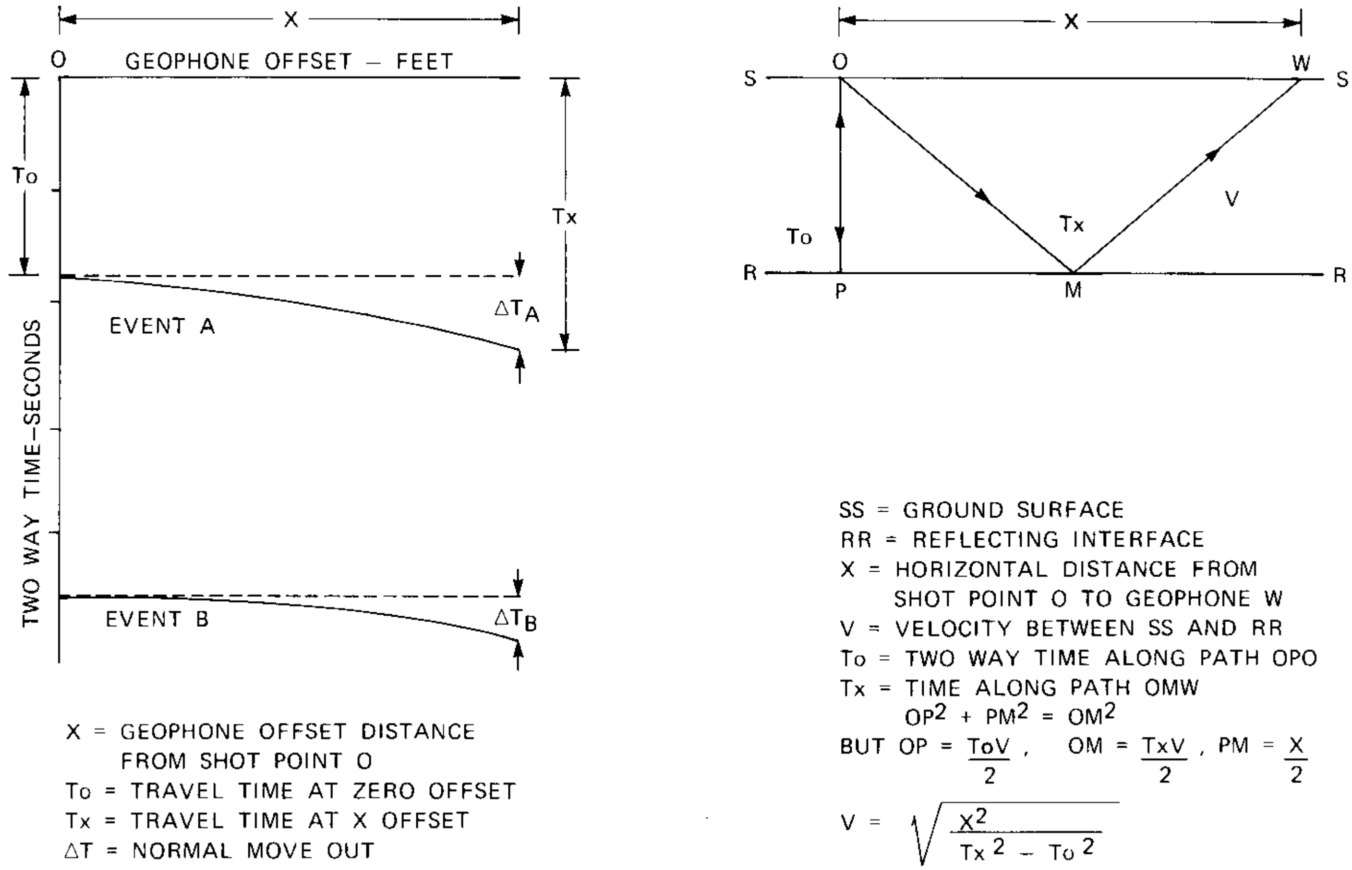
$$V = \sqrt{\frac{X^2}{T_X^2 - T_O^2}}$$

This velocity, calculated from normal moveout time, is called V_{NMO}. It represents the average velocity between surface and the appropriate reflection event, but it is not the true average vertical velocity. For various reasons, V_{NMO} is always somewhat greater than the true average velocity. However, by measuring T_O and V_{NMO} to all significant reflections, we can make approximations that permit us to calculate interval velocities for each layer, and the true average vertical velocity to each reflection.

Figure 8 shows T_O-V_{NMO} curves at the Netserk, Immerk, Taglu and Ivik wells. The V_{NMO} scale is across the top and T_O down the side. As shown previously, Netserk and Immerk have thin relict permafrost with an unfrozen layer above. Taglu and Ivik have thick permafrost sections beginning at surface. Permafrost thickness is increasing from left to right and, as expected, V_{NMO} increases with increasing permafrost. Note the convergence of the curves with depth as more and more unfrozen material is averaged in.

Figure 9 shows a T_O-V_{NMO} curve from a velocity gather in the Umiak area. The positions of the selected T_O-V_{NMO} pairs are shown by the Xs. On the right are listed the values for the T_O-V_{NMO} pairs and the calculated interval velocities between them. Also drawn is the interval velocity (staircase) curve. Note we were unable to make reliable selections above 0.8 sec. By comparing this with a T_O-V_{NMO} curve from a well in the area, however, we can predict what the upper part of the curve should look like.

Figure 10 shows the same curves, on which are overlain in dashed line the T_O-V_{NMO} curve and



$$OP^2 + PM^2 = OM^2$$

$$\text{BUT } OP = \frac{ToV}{2}, \quad OM = \frac{TxV}{2}, \quad PM = \frac{X}{2}$$

$$V = \sqrt{\frac{X^2}{Tx^2 - To^2}}$$

Fig. 7. Derivation of reflection seismic velocities.

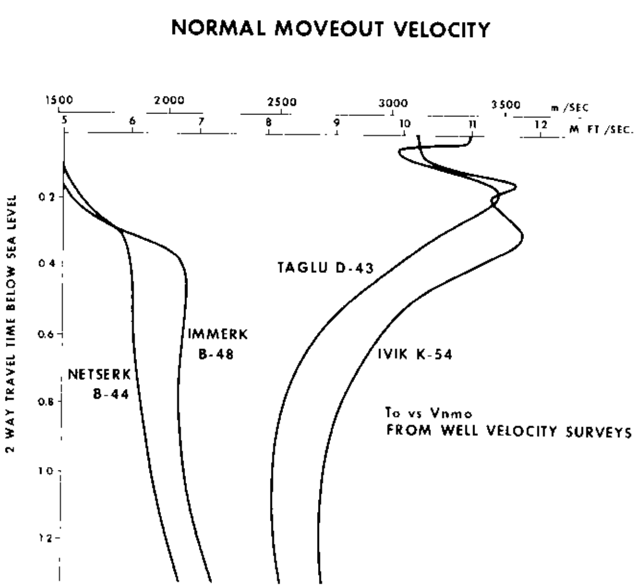
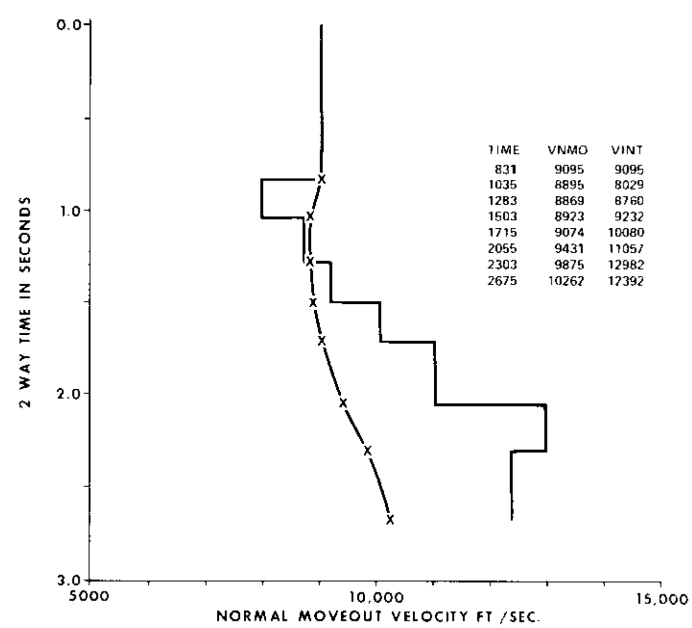


Fig. 8. T_O vs V_{NMO} from well velocity surveys.



TIME	VNMO	VINT
831	9095	9095
1035	8895	8029
1283	8869	8760
1503	8923	9232
1715	9074	10080
2055	9431	11057
2303	9875	12982
2675	10262	17392

Fig. 9. Initial velocity analysis, Umiak area.

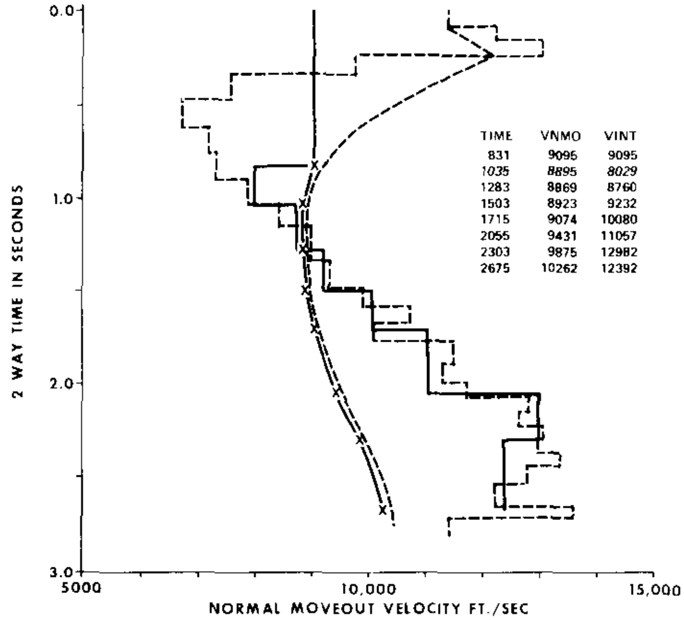


Fig. 10. Comparison of curves in Figure 9 with T_O-V_{NMO} and interval velocity curves from a nearby well (dashed lines).

the interval velocity curve from a nearby well. Note the close fit of the T_O-V_{NMO} curves at the bottom. Knowing, then, what the upper part of the curve must look like, we can pick with more confidence some T_O-V_{NMO} pairs in the upper section, as shown in Figure 11. Because we knew what to expect, we were able to pick T_O-V_{NMO} pairs in the upper section and, as shown in the table on the right, calculate the appropriate interval velocities, draw the interval velocity curve and interpret permafrost thickness.

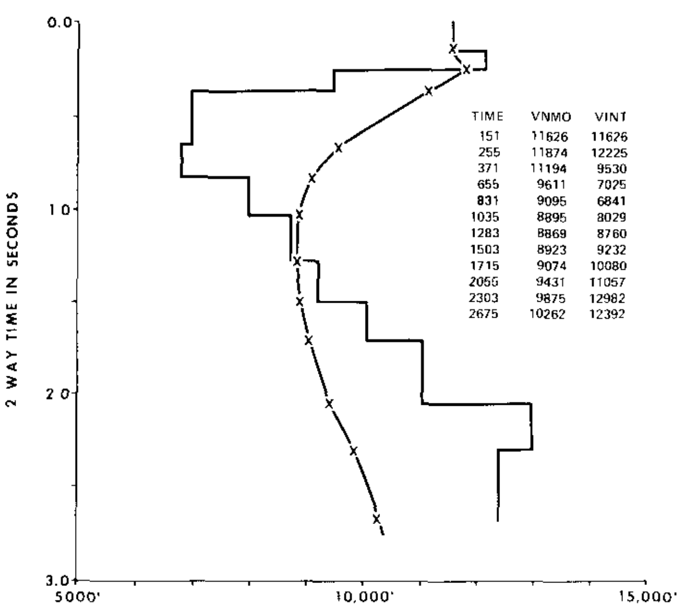


Fig. 11. Final velocity analysis, Umiak area.

Note, though, that even if we hadn't been able to pick upper T_O-V_{NMO} pairs, we could still make a guess at what the upper part of the curve must look like by comparing the curve to the well curve, and deciding whether it represents more or less permafrost, and whether the permafrost begins at surface or at some depth below.

Predrill Calculations at the Kugmallit Well

Figure 12 shows the predrill refraction calculation from first arrivals at the Kugmallit well. The velocity of the direct wave V_1 is 5,360 ft/sec. The velocity of the head wave V_2 is 11,110 ft/sec. Depth to the V_2 layer, or permafrost, was calculated to be 565 ft. Well results showed permafrost top at about 590 ft.

Figure 13 shows the predrill T_O-V_{NMO} curve from a seismic velocity gather in the vicinity of the Kugmallit well. The calculated interval velocity curve clearly outlines the interpreted permafrost, which is about 1,600 ft and almost exactly the amount found.

Figure 14 shows the T_O-V_{NMO} and interval velocity curves calculated from well information overlaid in dashed lines on the predrill curves. You'll note how closely the curves compare. The high-velocity intervals below 1.5 sec are thin calcite-cemented conglomerates.

Shortcut to Calculations

With the knowledge that we can build up in an area, we can take shortcuts and determine permafrost thickness more directly.

Acheson showed, many years ago, that in a normally compacted section velocity increases exponentially with depth. As shown on Figure 15, when time T is plotted on a linear scale against depth Z on an exponential scale, the formula for the straight-line curve is $T = aZ^n + b$ where 'a' is the slope, 'n' the exponential function, and 'b' the intercept on the T axis. The values 'a' and 'n' are functions of the compaction gradient and 'b' is a function of near-surface velocities.

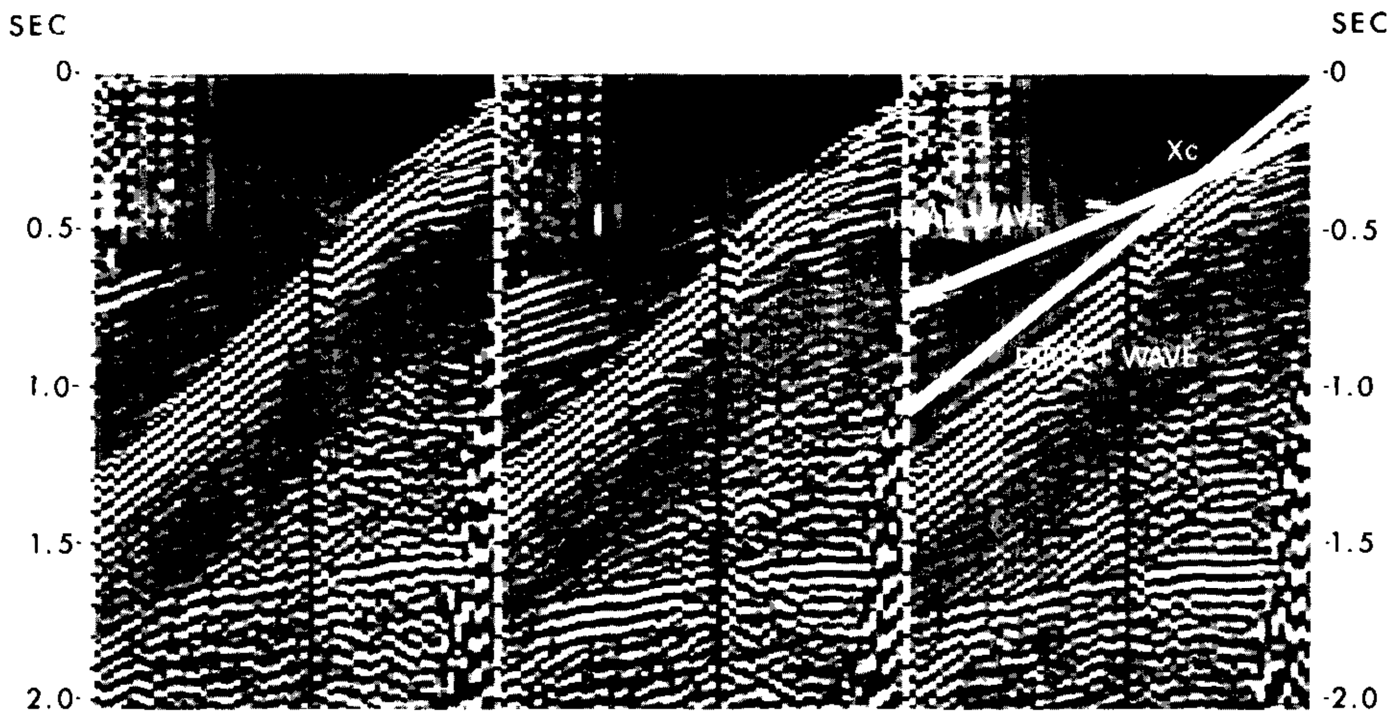
The interval velocity at any point on the curve is given by the formula

$$V_I = \frac{Z^{(1-n)}}{a \cdot n}$$

which is derived by differentiation.

Knowing these time-depth and velocity-depth relationships for normal compaction gradients in an area, we can directly interpret any departure from these relationships in terms of permafrost thickness.

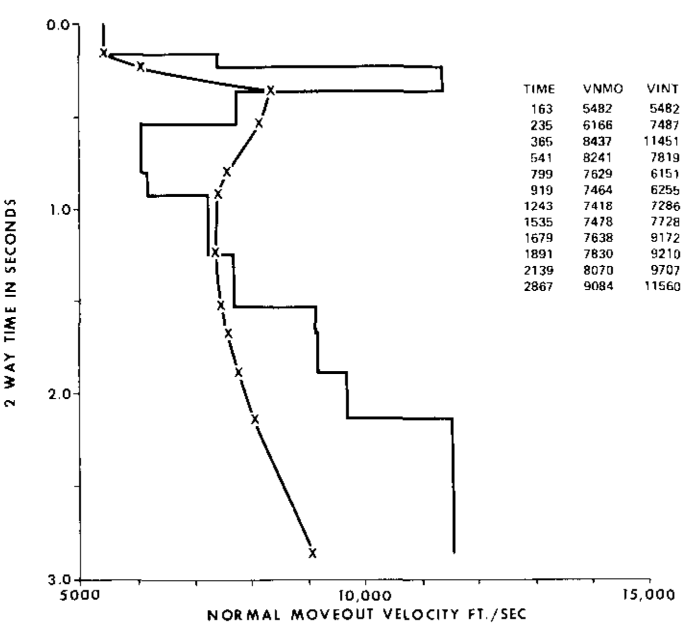
Figure 16 shows the previously illustrated normal-moveout velocity curves at Netserk, Immerk, Taglu and Ivik. The numbers shown are the thickness of permafrost and the V_{NMO} at one second at each well. If normal time-depth and velocity-depth relationships are the same for these wells, then we could directly relate V_{NMO} at one second to permafrost



$V_1 = 5{,}360$ Ft./Sec.
$V_2 = 11{,}110$ Ft./Sec.

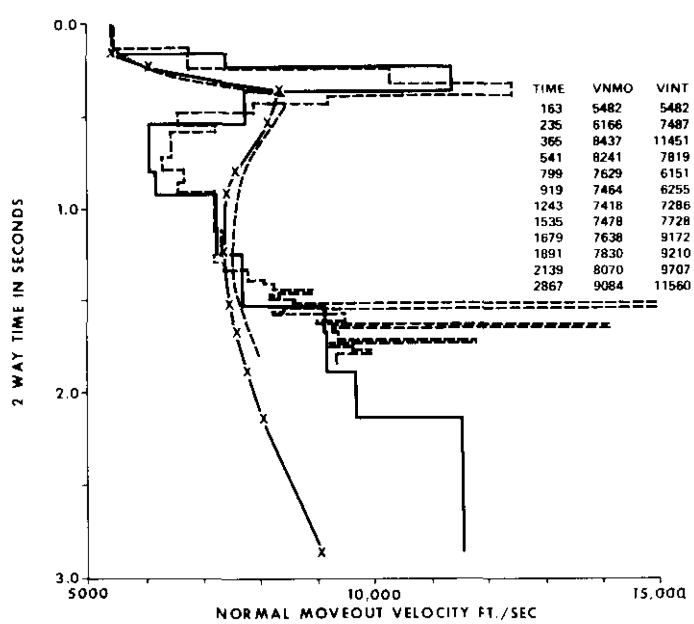
$$\text{DEPTH TO TOP OF PERMAFROST} = H = Xc/2 \sqrt{\frac{V_2 - V_1}{V_2 + V_1}} = 565 \text{ Ft.}$$

Fig. 12. Refraction calculation, Kugmallit well.



TIME	VNMO	VINT
163	5482	5482
235	6166	7487
365	8437	11451
541	8241	7819
799	7629	6151
919	7464	6255
1243	7418	7286
1535	7478	7728
1679	7638	9172
1891	7830	9210
2139	8070	9707
2867	9084	11560

Fig. 13. Initial velocity analysis, Kugmallit well.



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1891	7830	9210
2139	8070	9707
2867	9084	11560

Fig. 14. Comparison of curves in Figure 13 with calculated T_O-V_{NMO} and interval velocity curves.

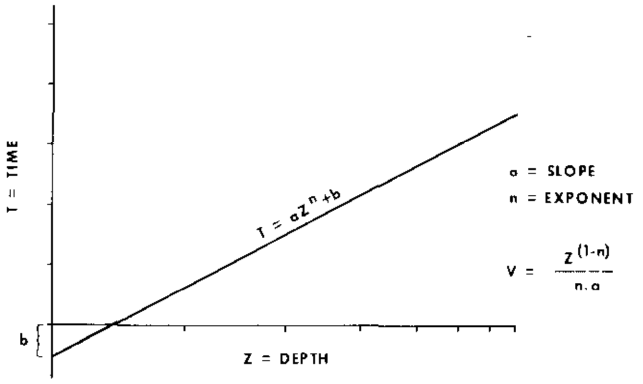

Fig. 15. Time-depth and velocity-depth relationship (Acheson, 1963).

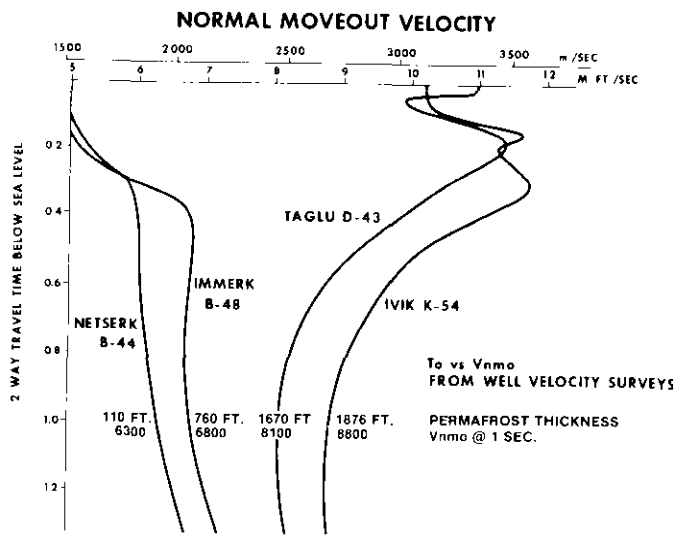

Fig. 16. Same curves as in Figure 8, showing permafrost thickness and V_{NMO} at one second for each well.

thickness. The relationships aren't quite the same, but the differences as represented by the values for 'a' and 'n' can be determined.

Nomograms can be made that have V_{NMO} at one second plotted against 'a' and permafrost thickness, for various values of 'n' and predicted average permafrost velocities. From them it would be possible to predict permafrost thickness directly.

Pitfalls

There is a pitfall to watch out for in this seismic velocity method, and it has to do with the fact that shales will not freeze solidly at the same temperatures as sands. Shales then will usually have a lower permafrost velocity, or they may be entirely unfrozen at the same temperatures at which sands are frozen. Shales will often appear as unfrozen layers between layers of frozen sand.

If we assume, then, that we have a solid permafrost layer at 10,000 ft/sec when the average velocity is really somewhat less, we'll calculate the base of permafrost to be shallower than it really is. For accurate thickness predictions we must incorporate into our calculations a prediction of lithology in the top 2,500 ft or so. Note, though, as mentioned earlier, that as long as we can accurately calculate the effect of the permafrost on seismic travel times, we aren't concerned with its exact thickness for making time-depth conversions. We are, however, concerned with exact thicknesses for designing well-casing programs.

CONCLUSION

As stated at the outset, the analysis of seismic refraction and reflection data is the most accurate method for determining presence, depth to top, and thickness of permafrost.

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