

PERMAFROST INVESTIGATIONS BY CRYSTAL CABLE SURVEYS, MACKENZIE DELTA, N.W.T.†

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ABSTRACT

For the past five years, Imperial Oil has run a crystal cable velocity survey as an integral part of the near-surface borehole logging program in all wells in the Mackenzie Delta. The results have been found to be a useful addition to the data available from conventional logging techniques.

The near-surface lithological conditions in the Mackenzie Delta, consisting predominantly of unconsolidated sands, gravels, muds and clays, are such that distinct velocity differences are exhibited by materials in the frozen and unfrozen states. Under these conditions, the crystal cable velocity survey provides a means of obtaining detailed velocity profiles of the permafrost zone with a minimum of time and effort. These profiles can be used to refine the predrill estimates of depths to deeper seismic markers.

Interval velocities within the permafrost zone are highly variable, a function of such factors as lithology, porosity, water content and salinity, and temperature. Velocities measured by crystal cable surveys range from 7500'/s to 13,500'/s in the permafrost section, in contrast to velocities in the range of 5000'/s to 6500'/s commonly observed in the non-frozen section.

Field examples show that the crystal cable results relate directly to the responses observed on conventional wireline logs, and to properly define a base of permafrost, all available data sources must be used. In general, the base of permafrost defined by log responses does not agree with the 32°F. temperature isotherm, but for the exploration geophysicist, it has a direct bearing on the interpretation of exploration geophysical data.

INTRODUCTION

For the past five years, Imperial Oil has run crystal cable velocity surveys as an integral part of the near-surface borehole logging program on all company-operated wells in the Mackenzie Delta area. The near-surface lithology of this area, consisting predominantly of clays, silts, sands and gravels, is such that distinct velocity differences are exhibited by materials in the frozen and non-frozen states. Under these conditions, the crystal cable results have been found to be a useful addition to the data available from conventional wireline logging techniques.

The crystal cable velocity survey provides a means of obtaining accurate detailed velocity profiles of the permafrost zone with a minimum of time and effort. These profiles may be used to

refine predrill estimates of depths to deep objective horizons, and also to help establish the depth extent of the potential hydrate envelope at the well location.

The permafrost zone is characterized by a wide range of interval velocities which are closely related to such factors as lithology and water content. Velocities as high as 13,500 ft/sec have been observed in a dominantly sand and gravel section, and as low as 7500 ft/sec in a dominantly clay/mud section. These velocities contrast markedly with velocities in the range of 5000 ft/sec to 7500 ft/sec, observed in non-frozen near-surface deposits.

The purpose of this paper is to document typical examples of crystal cable surveys from the Mackenzie Delta area, and to compare the veloc-

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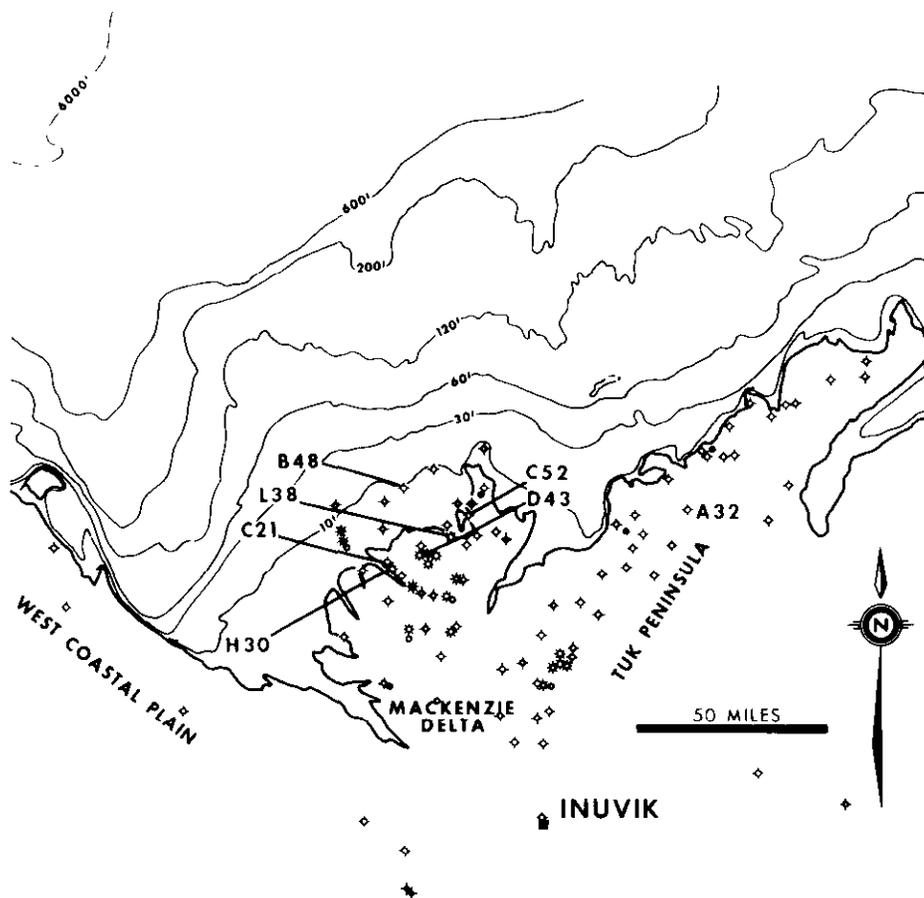


Fig. 1. Location Map. Mackenzie Delta, N.W.T.

ity distributions as determined from the crystal cable data with physical properties determined from conventional wireline logging techniques.

The wells to be discussed are shown on Figure 1, a well location map of the Mackenzie Delta area. From east to west, the wells are: IOE Magak A-32, Imp. Ivik C-52, Imp. IOE Mallik L-38, IOE Taglu D-43, Imp. Immerk B-48, Shell Niglintgak H-30, and Chevron SOBC Upluk C-21.

PERMAFROST

Permafrost has been defined as 'the thermal condition of earth materials such as rock and soil, when their temperature remains below 32°F. continuously for a number of years' (Brown and Johnston, 1964). However, laboratory measurements reported by such authors as Timur (1968) and Desai and Moore (1968) show that frozen material is not synonymous with the 32°F. isotherm.

In general, earth material neither freezes nor thaws in an isothermal process. Saturated sands and gravels usually begin to thaw about 20° to 22°F., and the process is essentially complete at temperatures of 28° to 30°F. Saturated clay has some free water at very low temperatures and rarely reaches a completely frozen state. From the practical viewpoint, clay will commence to thaw at a temperature of -15°F. and complete the process at +18° to 20°F. All these temperature ranges are highly variable, depending on matrix composition, salinity and percentage of water, as well as burial depth. The important point is that freezing and thawing takes place over a range of temperature which is dependent on the material. With the exception of pure ice, and possibly very near surface material, the thaw process is completed before the temperature rises to 32°F. Further, the physical characteristics of the material do not suddenly change from frozen to non-frozen

values but, instead, go through a transition range as the temperature rises.

Viewed in this light, the base of permafrost, as defined by the 32°F. isotherm, has little significance to the exploration geophysicist. Commonly, this point will occur some 100' to 300' below the more seismically significant changes evidenced on a velocity profile. In this paper, the term 'base of permafrost' is used to define that point at which recognizable log responses first occur. This point should not be equated with any specific isotherm.

CRYSTAL CABLE SURVEYS

Crystal cable velocity surveys are run under contract by a velocity logging contractor. The survey is normally carried out prior to running the first intermediate casing string, and a conventional check shot survey is often run at the same time for correlation purposes. Standard survey spacing is generally 50-foot intervals, but closer spacing may be required depending on local conditions.

The crystal cable itself consists of 12 pressure sensitive crystal detectors attached at 50-foot intervals to a flexible steel-cored cable. The detectors have a nominal depth rating of 5000 feet but, with the cable configuration in use at this time, a maximum survey depth of 2500 feet is possible. Field experience shows that high viscosity drilling muds used in drilling the near-surface section often tend to 'hang-up' the cable, thus external factors may limit the maximum survey depth to considerably less than 2500 feet.

As an energy source, both dynamite and airgun have been used with satisfactory results. Standard survey practice on a dynamite-sourced shoot is to use 2½ lb. charges in shot holes located about 125 feet from the well bore. Because of logistics problems, all shot holes are pre-drilled and pre-loaded. Since weather conditions often prevent reloading of shot holes, shot parameters vary from level to level. Use of an airgun source has been confined thus far to the offshore artificial island locations in the Beaufort Sea but this type of energy source is inherently superior to dynamite, due to both the closer location of the source to the well bore and also the consistency of shot parameters from level to level.

As a standard practice, it is advisable to shoot the crystal cable survey in an open uncased hole. Hole sloughing does not appear to be a major problem in the Tuk Peninsula area but, in the North Delta/Richards Island area, this can be a problem. In a badly caved borehole it is often

difficult to obtain a good acoustic bond between casing and formation. As a result, crystal cable records shot in cased holes may be affected by casing kicks. In some wells in the Richards Island area, this problem is so severe as to mask all true direct arrival energy on the records over the entire permafrost interval.

FIELD EXAMPLES

In discussing the data from the various wells, the same basic format will be followed in each case. First, the crystal cable results are described and then compared with the responses observed on the wireline log data.

IMP. IVIK C-52

The thickest and most continuous permafrost sections found in the MacKenzie Delta occur in the area of North Richards Island. A representative well from this area is Ivik C-52, drilled by Imperial in 1973. Available wireline log data from this location includes a borehole compensated sonic log and a dual induction laterolog. A standard 15 inch caliper was run in conjunction with the sonic log.

The crystal cable survey (Figure 2) has good repeatability on overlapping levels. Three high velocity layers have been interpreted in the top 400 feet. These may be reflecting lithological changes in the section or may be indicative of recent changes in the temperature regime. Without further information from other sources, no definite conclusions can be drawn. Between 430 and 1390 feet, a very high velocity layer may well correspond to a predominantly sand sequence. From 1390 to 2065 feet, the velocity is lower — possibly in response to both a mixed sand/shale sequence and a rising temperature. Below 2065 feet, a low velocity layer is present. On the basis of the observed velocity changes, a base of permafrost is suggested at 2065 feet.

No wireline logs were run in open hole above the surface casing point of 533 feet (Figure 3). As a result, the wireline logs provide no assistance in the interpretation of the shallow crystal cable results. Below the surface casing, all the logs are badly affected by the effects of borehole caving.

The caliper log correlates very well with the crystal cable results. Between surface casing and 1350 feet, the caliper is reading wide open at 15 inches. This corresponds to the high velocity layer in the crystal cable data. Between 1350 and 2070 feet, the intermediate velocity layer of the crystal cable, the caliper shows a mix of wide

IMP IVIK C-52 VELOCITY SURVEY

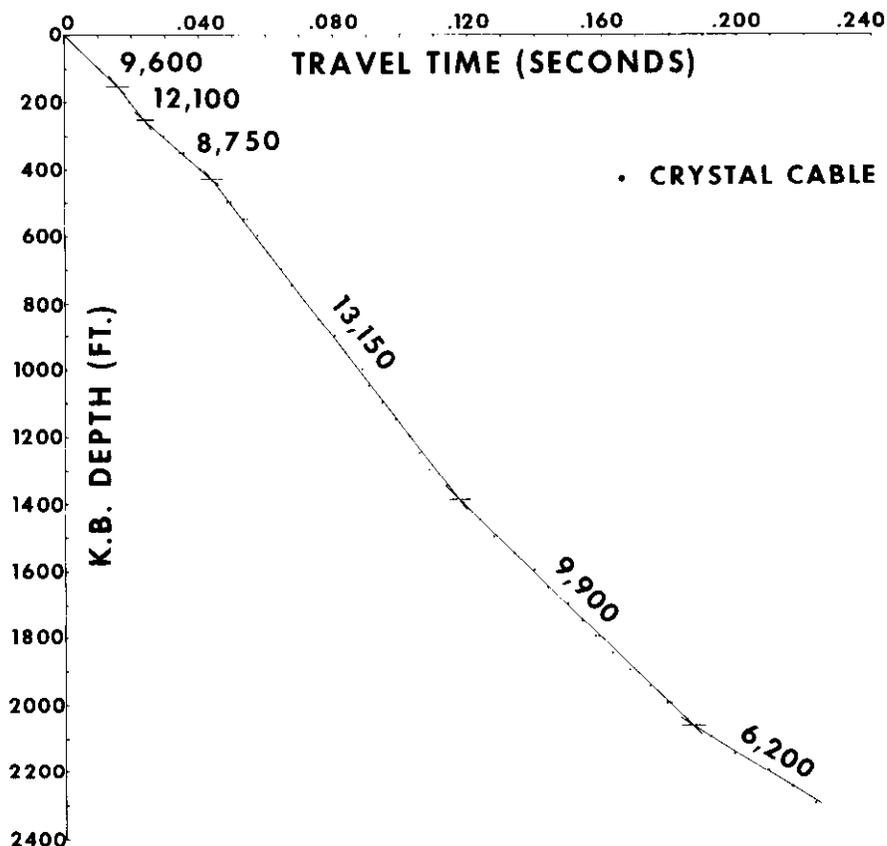


Fig. 2. Imp Ivik C-52. Crystal Cable results.

open and close to gauge readings. Below 2070 feet, the low velocity layer on the crystal cable, the caliper shows essentially gauge hole.

The sonic log is very poor with almost no reliable values present in the section above 2100 feet and a large amount of cycle skipping is present below this depth. However, in a gross sense, there are changes which correspond to the major changes observed on the caliper log, with a marked change occurring just below 2100 feet.

The deep induction derived resistivity curve has the typical, very spiked appearance of a permafrost section curve from the Mackenzie Delta. Very high resistivities are indicated from surface casing to 2130 feet. Below this depth, the resistivity values drift gently lower to a background of 4 to 5 ohm metres at a depth of

2400 feet.

The gamma ray log is badly affected by hole caving and little reliability can be attached to the lithologies suggested by the log response.

There is a reasonable agreement among all the data sources for this well and, on the basis of the observed changes, the base of permafrost at this location probably lies between 2065 and 2130 feet.

IOE MAGAK A-32

As a representative example from the Tuk Peninsula area, Magak A-32 has been selected. This well, drilled by Imperial in 1971, was one of the first wells in which a crystal cable survey was attempted. Two surveys were run in this well, one prior to running surface casing and one after running casing. No differences were observed in

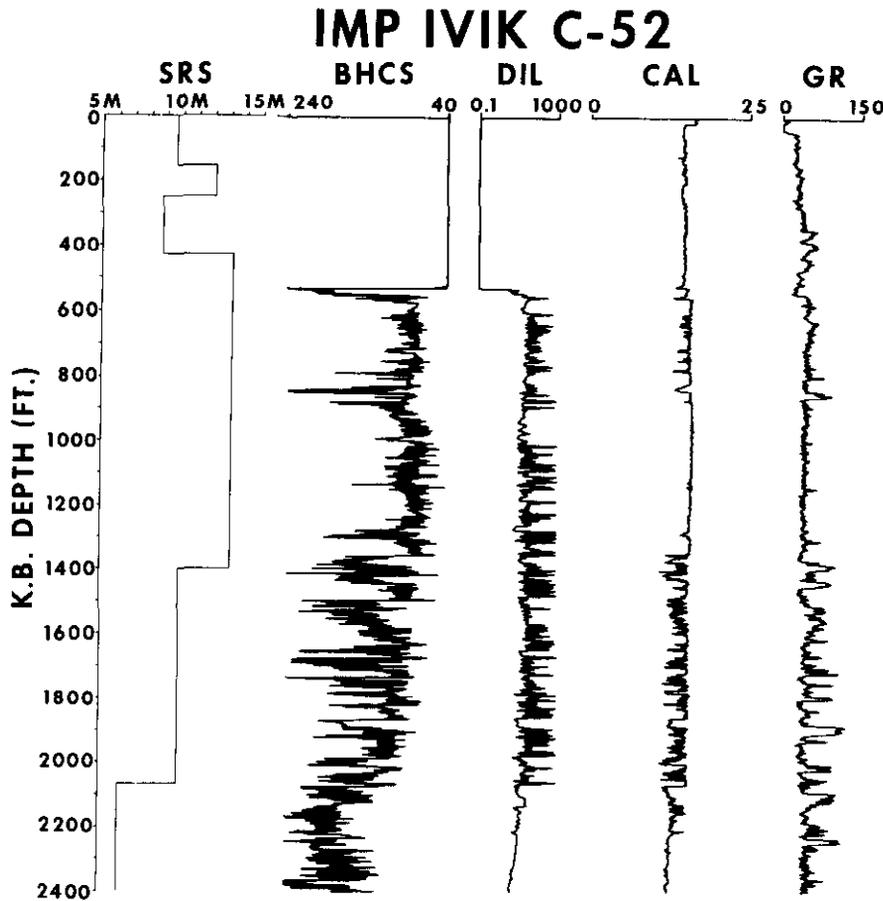


Fig. 3. Imp. Ivik C-52. Wireline log results. SRS — crystal cable. BHCS — sonic. DIL — dual induction. CAL — caliper, GR — gamma ray.

the crystal cable responses between the surveys.

In contrast to the previous example, there is some scatter in the crystal cable data (Figure 4) and one possible interpretation is shown. In this case, the section can be divided into a high velocity sequence from surface to 700 feet, an intermediate velocity transition layer from 700 to 935 feet, with low velocities below 935 feet.

To complement the crystal cable survey, the available wireline logs (Figure 5) include a 16 inch normal electrical log, a gamma ray log and a microlog caliper log. This caliper tool has a nominal maximum span of 40 inches.

The caliper shows that the borehole is badly caved from surface to 590 feet, showing readings of greater than 40 inches over much of this interval, but below this depth the hole is essentially

gauge. The resistivity log, measured by the shallow investigating 16 inch normal tool, has a different appearance from the previous example, but still indicates high resistivities from surface to 775 feet, with a gentle drift down to a background of 10 to 15 ohm metres in the interval from 775 to 1050 feet. The gamma ray log is again very poor in the badly caved section but suggests that the lithology is basically a silty shale below about 800 feet.

In this well, there is not the same agreement among the different sources of information as was present in the previous example. In part, this is due to the lack of a definite sharp velocity break in the crystal cable data and in part to a lack of suitable wireline logs. Using the data available, the base of permafrost at this location probably lies between 775 and 935 feet.

IOE MAGAK A-32 VELOCITY SURVEY

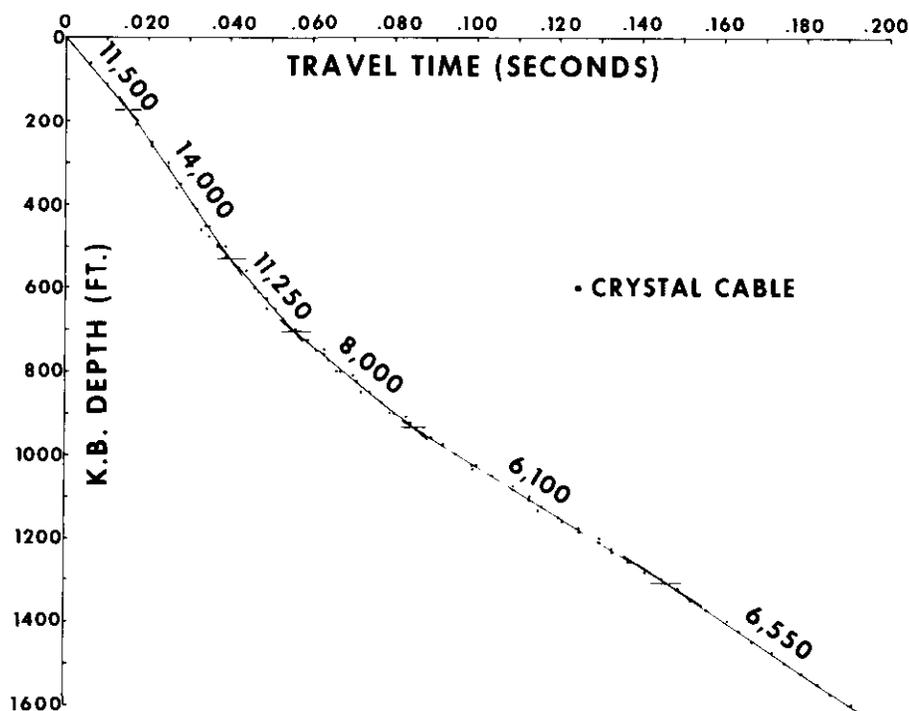


Fig. 4. IOE Magak A-32. Crystal cable results.

IOE TAGLU D-43

The largest gas field discovered in the Mackenzie Delta area is the Taglu field. As is often the case, this area is also one in which rapid variations in permafrost thickness and velocity occur, with the result that high quality seismic data is difficult to obtain. Recognition of these changes and the ability to quantify them to some degree aid significantly in the delineation of the field.

Taglu D-43 has the most complete suite of near-surface logs of the five Taglu wells. The crystal cable survey was of very high quality and to assist in the interpretation the available wireline logs include a borehole compensated sonic log, a dual induction laterolog, a microlog caliper log and an electrical log with data from a 16 inch normal and an 18 feet 8 inches lateral electrode system.

The crystal cable data (Figure 6) can be subdivided into three major sequences: a high velocity sequence from surface to 1130 feet, an intermediate velocity sequence from 1130 to 1730 feet and a low velocity layer below 1730 feet. Based on this data, a base of permafrost is suggested at 1730 feet.

Of particular interest on this survey, especially from the point of view of design of well completion procedures for field production, is the thin low velocity layer occurring between 230 and 275 feet. This layer is present in all the Taglu wells and was recognized from seismic first kick information prior to drilling the G-33 discovery well. Shallow boreholes drilled for site investigation at the G-33 location flowed water from this zone, confirming the presence of a zone of free water, bounded top and bottom by permafrost.

IOE MAGAK A-32

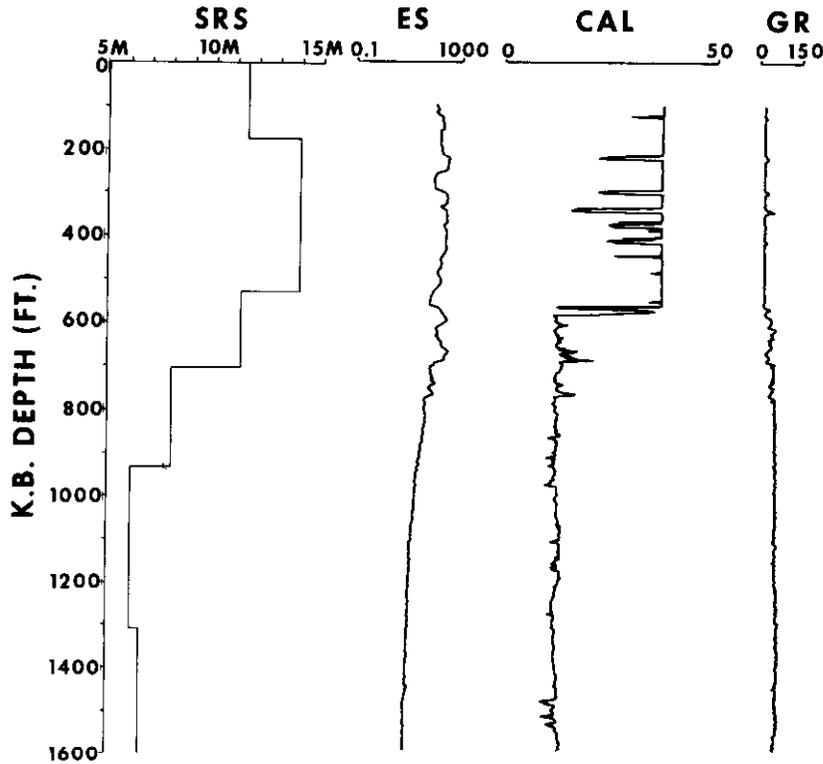


Fig. 5. IOE Magak A-32. Wireline log results. SRS—crystal cable. ES—electric log. CAL—caliper. GR—gamma ray.

The wireline logs (Figure 7) do not give much more information about this shallow zone, other than the fact that it appears to be uncaved. The caliper log breaks down into three major zones, correlating closely with the crystal cable sequences. The upper zone is badly caved with the caliper reading wide open at 40 inches over much of the section down to 1100 feet. Between 1100 feet and 1800 feet, the hole is caved in places, but nowhere does the caliper read much more than about 25 inches. Below 1800 feet, the hole is close to gauge.

The sonic log is typical for a log run in a very large diameter borehole. Cycle skipping is evident in the section above 1900 feet and very little reliability can be attached to the readings. There is a general correspondence with the

caliper log but only in a very few places are there indications of velocities similar to those determined by the crystal cable. Below 1900 feet, the log is still erratic but a closer correspondence with the crystal cable is present.

The deep induction derived resistivity log has almost a one-for-one correspondence with the caliper log, and indicates extremely high resistivities down to 1100 feet. Over the most badly caved zones, as indicated on the caliper log, the resistivity log is simply measuring mud resistivity. From 1100 to 1800 feet, high resistivities are still indicated but across the gauge hole sections, the resistivity as shown may well be a closer approximation to true formation resistivity. Over the interval 1800 to 2100 feet, the resistivities drift lower to a background of 2 to 4 ohm metres by 2100 feet.

IOE TAGLU D-43 VELOCITY SURVEY

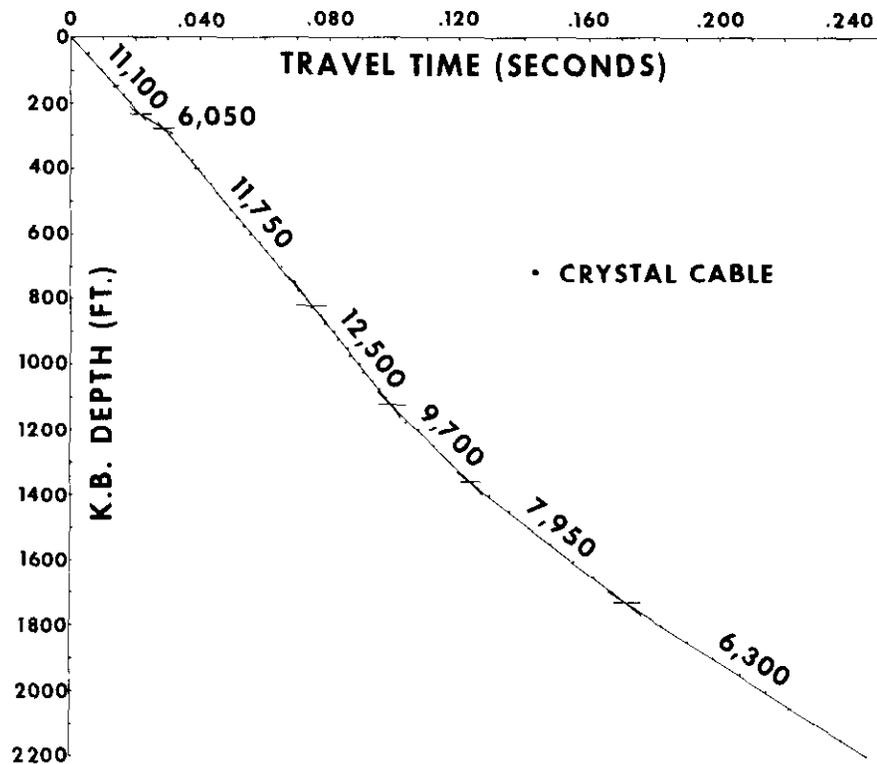


Fig. 6. IOE Taglu D-43. Crystal cable results.

Again, the gamma ray log is not reliable in the first 1100 feet but below this depth there are enough reliable data points to indicate that the lithology is basically alternating sands and clays or muds.

On the basis of the data available, a base of permafrost at this location can be picked in the interval 1730 to 1800 feet.

IMP IMMERSK B-48

As shown by the Ivik example, very thick permafrost occurs in the northeastern portion of Richards Island. Permafrost is also known to exist under the smaller islands offshore from Richards Island, for example, Garry, Hooper and Pullen Islands. It was suspected that permafrost existed in the inter-island areas as well

and this next example documents such a case. Immerk B-48 was the first well drilled from an artificial island in the Beaufort Sea. The island was constructed in an average water depth of 11 feet.

The crystal cable results are shown in Figure 8. A low velocity layer is present from surface to a depth of 535 feet, underlain by high velocity section to a depth of 1320 feet. Below 1320 feet, the section is again low velocity. Note that the crystal cable data do not extend below 1600 feet in this well, problems were encountered running into the borehole. The data points below 1600 feet, shown by open circles, are from normal check shots, taken at the same time as the crystal cable survey. The velocity distribution, as shown, can be explained in

IOE TAGLU D-43

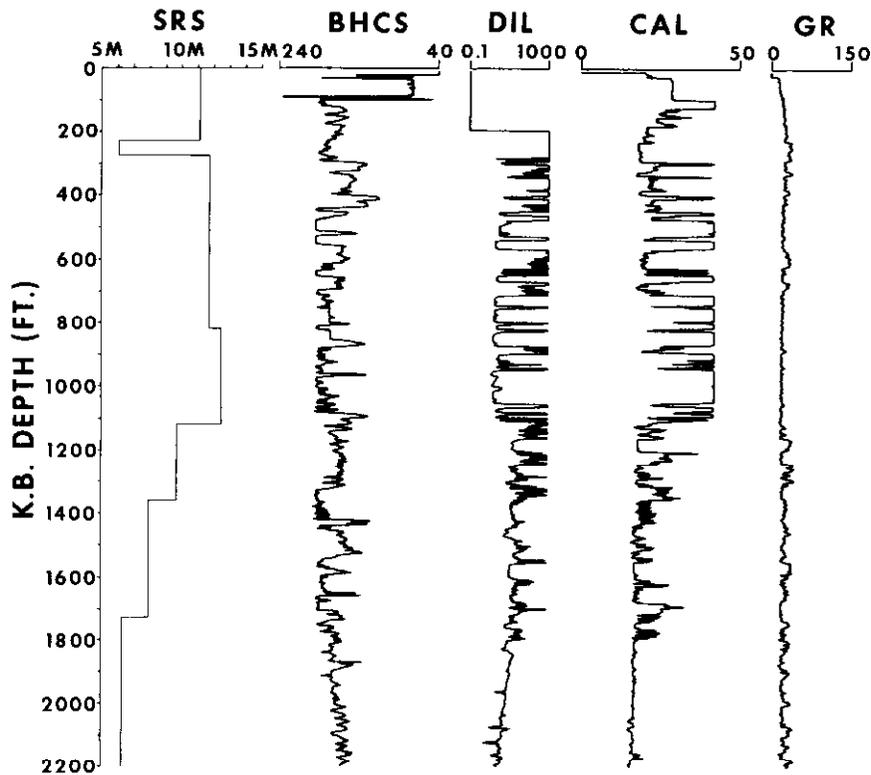


Fig. 7. IOE Taglu D-43. Wireline log results. SRS—crystal cable. BHCS—sonic. DIL—dual induction. CAL—caliper. GR—gamma ray.

terms of a buried zone of permafrost, top at 535 feet, base at 1320 feet, overlain by unfrozen material.

The wireline logs available on this well (Figure 9) include a dual induction laterolog, a formation density log and an extended arm microlog caliper. None of the logs were run above the surface casing depth of 584 feet. On the illustration, the caliper log presented is the standard 20 inch caliper run with the density tool which shows similar results to the extended arm caliper.

The borehole is badly caved from surface to a depth of 1290 feet. Below this depth, the hole is close to gauge or even undergauge, apart from two short intervals just above 1600 feet and between 1700 and 1800 feet. The deep laterolog resistivity curve has the typical permafrost

zone spiked appearance, high resistivities in the badly caved interval with indications of mud resistivities being measured in places. Below 1290 feet, the resistivities are generally low but high resistivities are noted, corresponding to the two slightly caved zones between 1550 and 1800 feet.

The gamma ray log is badly affected by the caving in the shallow section but between 1300 and 1700 feet, the log indicates that the section is dominantly clays and muds. Below 1700 feet, the sand content increases markedly and fairly clean sands are indicated at 1575 feet, between 1760 and 1780 feet, at 1825 feet and again between 1875 and 1960 feet. The high resistivities noted on the deep laterolog curve and the caving indicated on the caliper log correspond to the two shallow sands picked on the gamma

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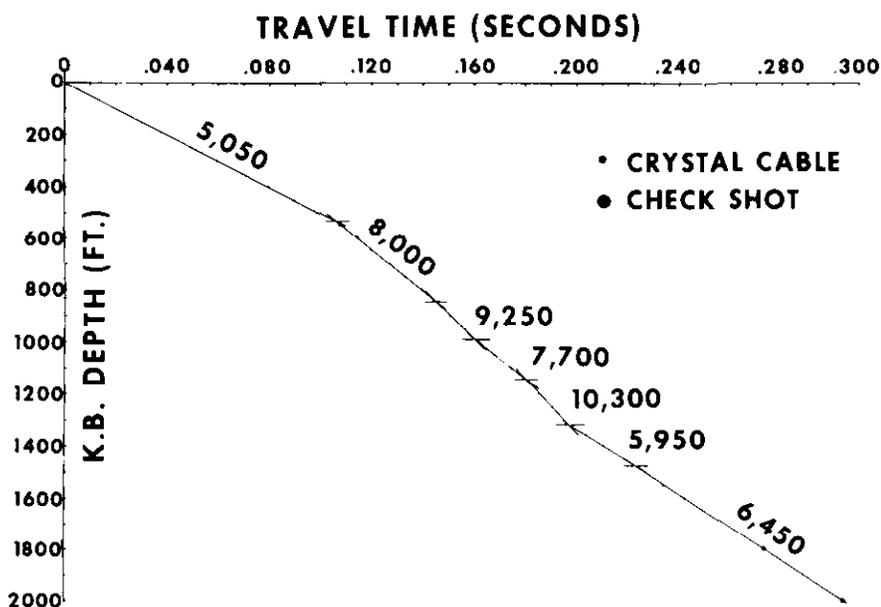


Fig. 8. Imp Immerk B-48. Crystal cable results.

log. The sands below 1800 feet have no caving or high resistivities associated with them.

Since no indications of gas were picked up on the gas detection equipment on the well, it is unlikely that the two sands above 1800 feet contain hydrates. It seems probable that they are permafrost lenses. Because of the lack of detailed velocity control below 1600 feet and probably closely related to the thinness of the sands, there is no indication of higher velocities in this zone on the velocity plot.

On the basis of the wireline log data, the base of permafrost is suggested at a depth of 1800 feet. Due to lack of data from other sources, the velocity data is used to suggest that the top of permafrost occurs at a depth of 535 feet, although it is recognised that thin frozen lenses may be present above this point. In light of the recent rapid transgression of the Beaufort Sea across a previously exposed land surface, as documented by such authors as MacKay (1963)

and Hunter et al. (1976), the permafrost encountered in this well is most probably relic permafrost.

IMP. IOE MALLIK L-38

In view of the mechanical problems occasionally encountered in running crystal cable surveys in open hole, it has often been suggested that adequate results can be obtained from a cased hold survey. In many instances this is true, especially on the Tuk Peninsula, but sometimes problems do arise with cased holes and these problems cannot be overcome. This example is one such case.

The crystal cable plot (Figure 10) is not showing what would be expected from a well in this area. The indicated velocity over the interval 500 to 1700 feet is far too high and the velocity suggested between 1700 and 2000 feet is much too low to be real. When a casing velocity gradient (57 microseconds per foot or 17,540 feet

IMP IMMERSK B-48

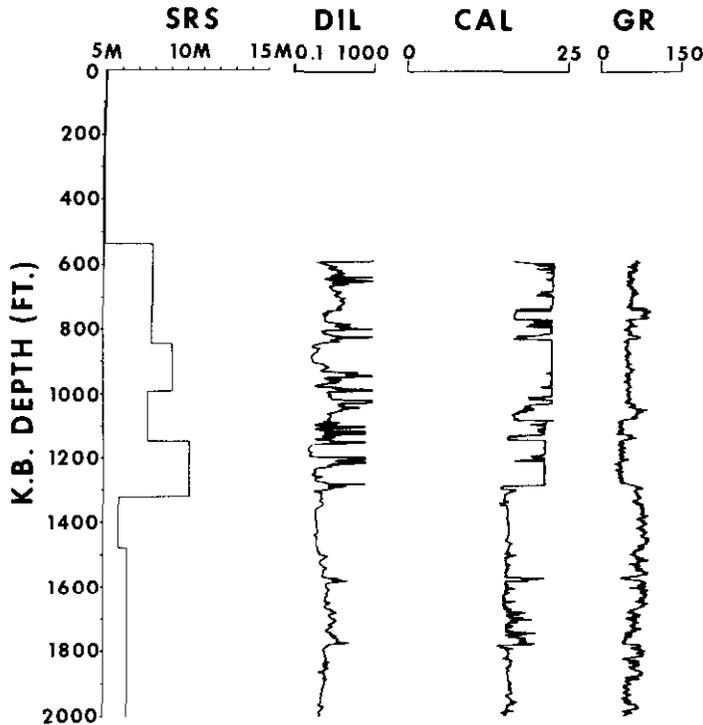


Fig. 9. Imp Immerk B-48. Wireline log results. SRS—crystal cable. DIL—dual induction. CAL—caliper. GR—gamma ray.

per second) is overlain on the data the problem is immediately apparent.

There is obviously a very poor acoustic bond in this well. The first arrival wave path is sub-horizontal from the shot to the well and then vertically down the casing to the geophones. At depth, where the acoustic bond is satisfactory, the casing waves are quickly attenuated until, by 2000 feet, the first arrivals at the geophones are once more the direct waves from shot to geophone.

The wireline logs provided the true picture of the permafrost at this location (Figure 11). The available logs include a borehole compensated sonic log and a dual induction laterolog. An attempt was made to run a microlog caliper but the tool mudded up badly and, as a result, the readings are not considered reliable in any detail. In a gross sense, they suggest bad caving above 1150 feet.

Both the sonic and resistivity plots tend to confirm the poor caliper. The sonic log is skipping very badly above 1930 feet but two major zones can be distinguished with the break between them occurring around 1140 feet. The deep laterolog derived resistivity plot shows the same two gross divisions. Above 1140 feet, the log shows basically mud resistivities with the typical permafrost zone high resistivity spikes. *Between 1140 and 1940 feet, the log is often reading saturation values but some reasonable clay shale resistivities may be present.* From 1940 to 2350 feet, the resistivity drifts lower to a background of 3 to 4 ohm metres.

It is difficult to know how much faith can be placed in the gamma ray log. Above 1150 feet, it is most likely showing borehole effects and almost certainly there are considerable borehole effects below this depth also. Below

IOE IMP MALLIK L-38 VELOCITY SURVEY

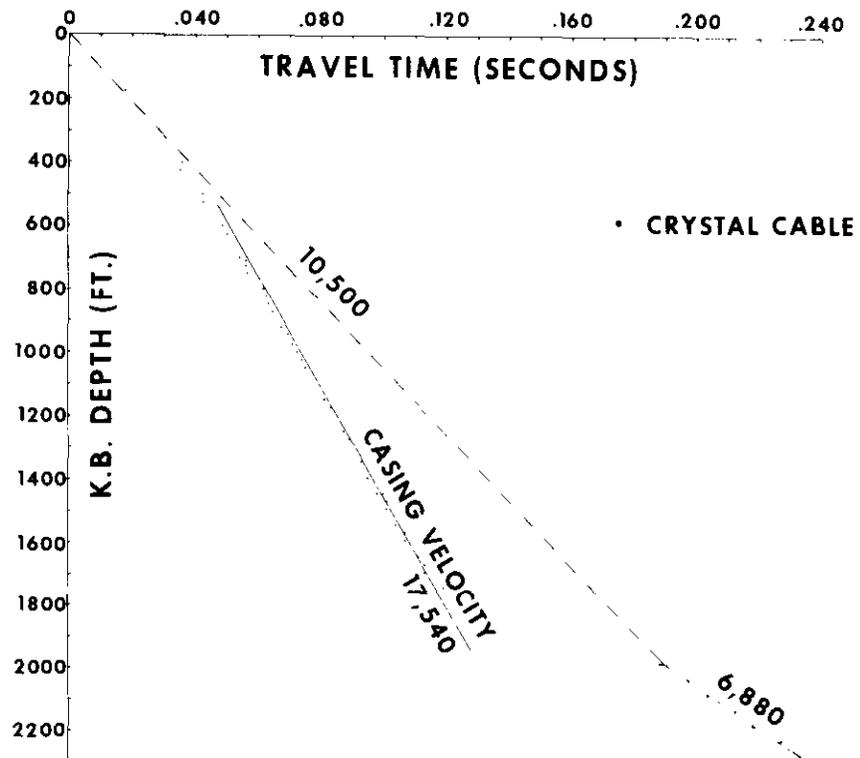


Fig. 10. IOE Imp Mallik L-38. Crystal cable results.

1800 feet, the log may be reliably indicating a mixed sand and clay/mud lithology.

The wireline log representation of the permafrost zone in this well is very similar to that displayed by Ivik C-52. The permafrost here, however, appears to be slightly thinner, with a base of permafrost indicated to be between 1900 and 1950 feet.

CHEVRON SOBC UPLUK C-21: SHELL NIGLINT GAK H-30

Most of the previous examples have exhibited quite well-defined changes in physical characteristics associated with the base of permafrost and there has been reasonable agreement between the different measuring devices. The final examples show that data from all available sources should be examined, to avoid

erroneous conclusions based on misleading or inadequate data. In order to illustrate the point properly, the data is presented in the order in which it was made available to Imperial Oil.

The first data examined was the crystal cable survey from Upluk C-21 which covered the first 1000 feet of hole (Figure 12). The time depth plot shows well-defined high velocity layers from surface to 680 feet, an intermediate velocity transition layer between 680 and 810 feet and low velocity section below 810 feet. On the basis of this data, a base of permafrost pick can be made at 810 feet.

Some time later, a suite of near-surface wireline logs were made available (Figure 13). These included a borehole compensated sonic log, a dual induction laterolog, and a formation

IMP IOE MALLIK L-38

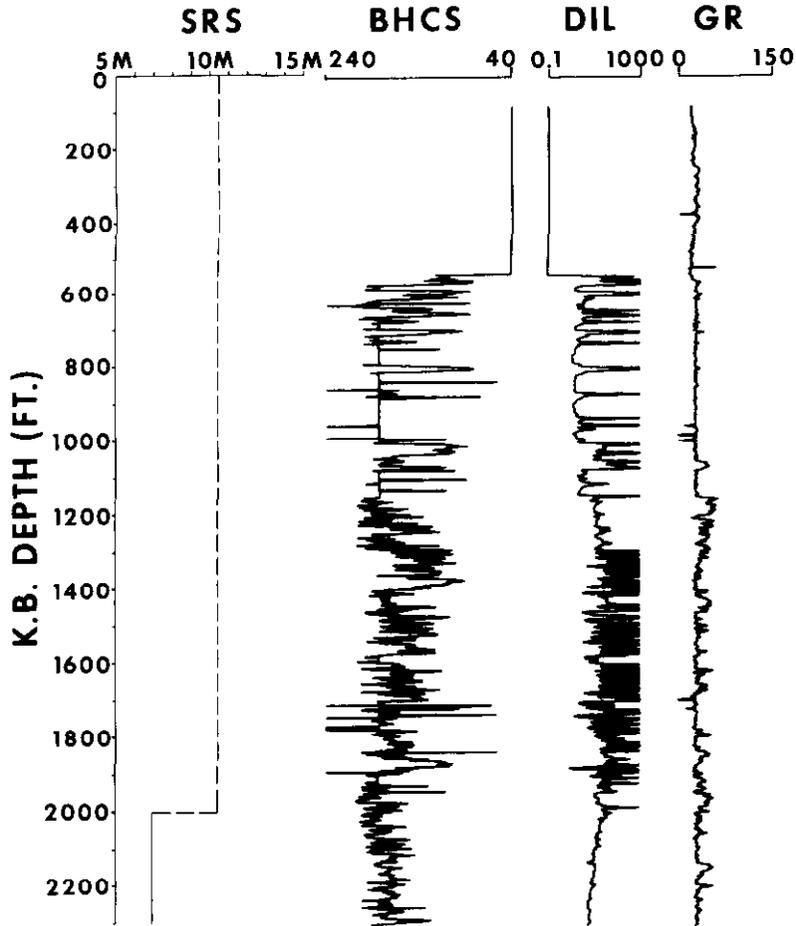


Fig. 11.. Imp IOE Mallik L-38. Wireline log results. SRS—crystal cable. BHCS—sonic. DIL—dual induction. GR—gamma ray.

density log. A standard 20-inch caliper tool was run with the density log. No open hole logs were run above the surface casing depth of 528 feet.

The caliper log is reading wide open from surface casing to 780 feet and shows bad caving to 835 feet. Below this depth, the hole is essentially in gauge. The sonic log is of no value over this entire interval with extreme cycle skipping present. The deep induction resistivity curve shows high resistivities between surface casing and 780 feet, with mud

resistivities evident in a number of places. Below 780 feet resistivities are quite low. The density log shows a one-for-one correspondence with the caliper — reading mud densities down to 835 feet. The gamma ray log is badly affected by hole size but shows that the section below 800 feet consists of clays and muds.

There is good agreement among the different sources of data in this well, with the base of permafrost occurring in the interval 780 to 835 feet.

CHEVRON SOBC UPLUK C-21 VELOCITY SURVEY

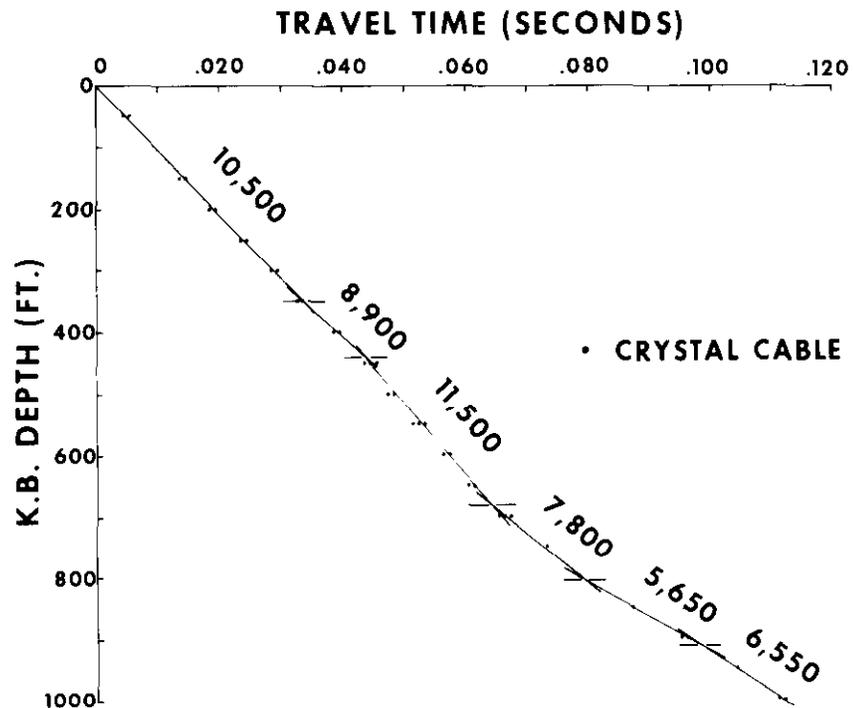


Fig. 12. Chevron SOBC Upluk C-21. Crystal cable results.

After the Upluk data had been examined, the near-surface wireline logs for the nearby Niglintgak H-30 well became available (Figure 14). The log suite for this well included a dual induction laterolog and a formation density log with a 20-inch caliper. A borehole compensated sonic log was run over the interval 90 to 524 feet, but no usable signal was obtained. The caliper run with the sonic tool over this interval indicates a hole size greater than 14 inches.

The density tool caliper shows bad caving below surface casing at 524 feet to a depth of 785 feet, with gauge hole below this depth. The density log reflects this caliper exactly, being badly affected by the overgauge hole. The resistivity log shows high resistivities down to about 300 feet, with isolated high resistivity spikes down to about 600 feet. Unlike previous wells,

there is no obvious change in the resistivity log character associated with the caliper log change at 785 feet.

Based on these log responses, it is difficult to define the base of permafrost without some reservations. The caliper log looks very similar to Upluk C-21, with the major change occurring at almost the same depth, suggesting a base of permafrost at 785 feet. However, on the basis of the resistivity log, a case can be made for a base of permafrost pick at 300 feet.

When the velocity survey results for this well were obtained, the picture was clarified (Figure 15). No crystal cable survey was run in this well but sufficient check shots were taken to provide a reasonable picture of the near-surface velocity distribution. The time depth plot shows

CHEVRON SOBC UPLUK C-21

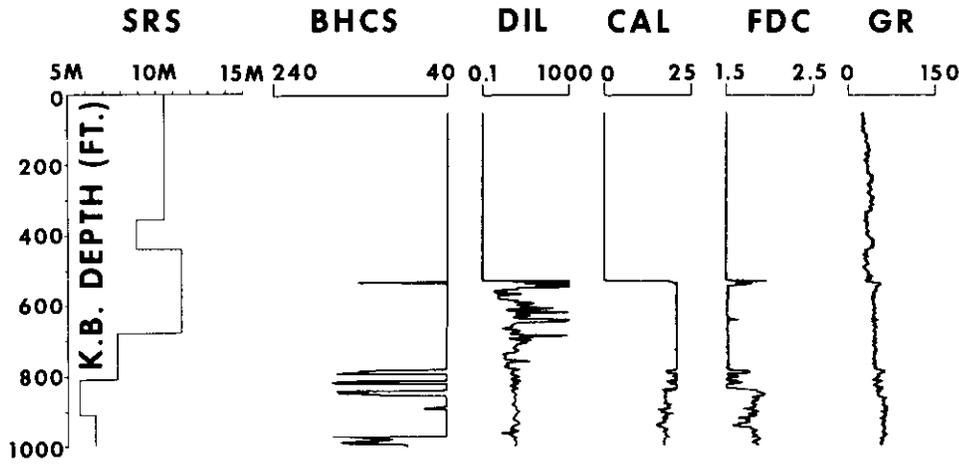


Fig. 13. Chevron SOBC Upluk C-21. Wireline log results. SRS—crystal cable. BHCS—sonic. DIL—dual induction. CAL—caliper. FDC—density. GR—gamma ray.

SHELL NIGLINTGAK H-30

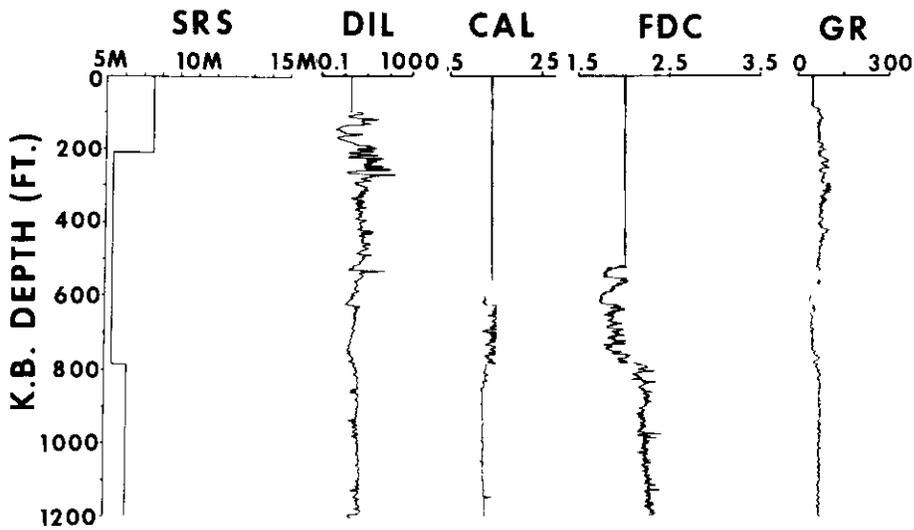


Fig. 14. Shell Niglntgak H-30. Wireline log results. SRS—check shots. DIL—dual induction. CAL—caliper. FDC—density. GR—gamma ray.

SHELL NIGLINTGAK H-30 VELOCITY SURVEY

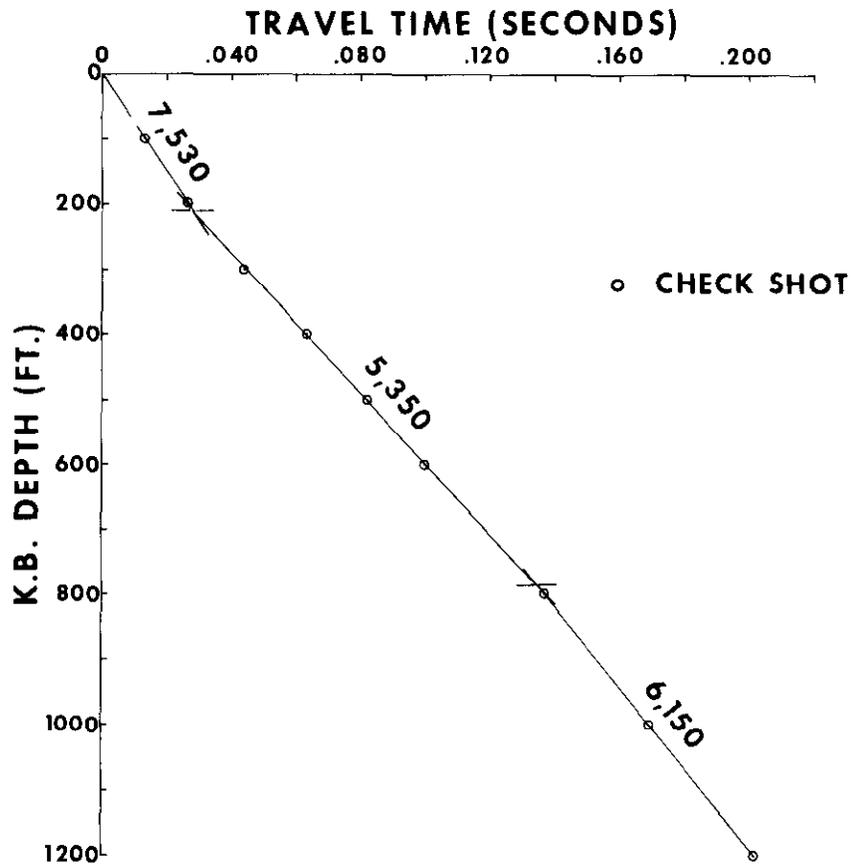


Fig. 15. Shell Niglintgak H-30. Check shot results.

a thin high velocity layer at the surface with low velocity section present below 200 feet. This confirms the response of the resistivity log and suggests that the base of permafrost, as defined by logs, occurs in the interval 200 to 300 feet.

To confirm this picture, a set of temperature surveys is available for this well (Figure 16). A thermistor cable was run to a depth of 950 feet in this well and readings were taken over a period of time. Three temperature curves are shown, illustrating the return of the well to thermal equilibrium.

Two weeks after drilling operations ceased, the minimum well bore temperature measured was 37°F. After eleven weeks the upper 250 feet is below 32°F., and a pronounced breakover in the curve is apparent between 300 and 400 feet. Seven months later, the well has cooled sufficiently that a fairly close approximation to the probable final thermal profile has developed. On the basis of this curve, a base of permafrost, as defined by the 32°F. isotherm, would be in the neighborhood of 400 feet, about 100 to 200 feet lower than the base of permafrost defined by the log responses.

SHELL NIGLINTGAK H-30

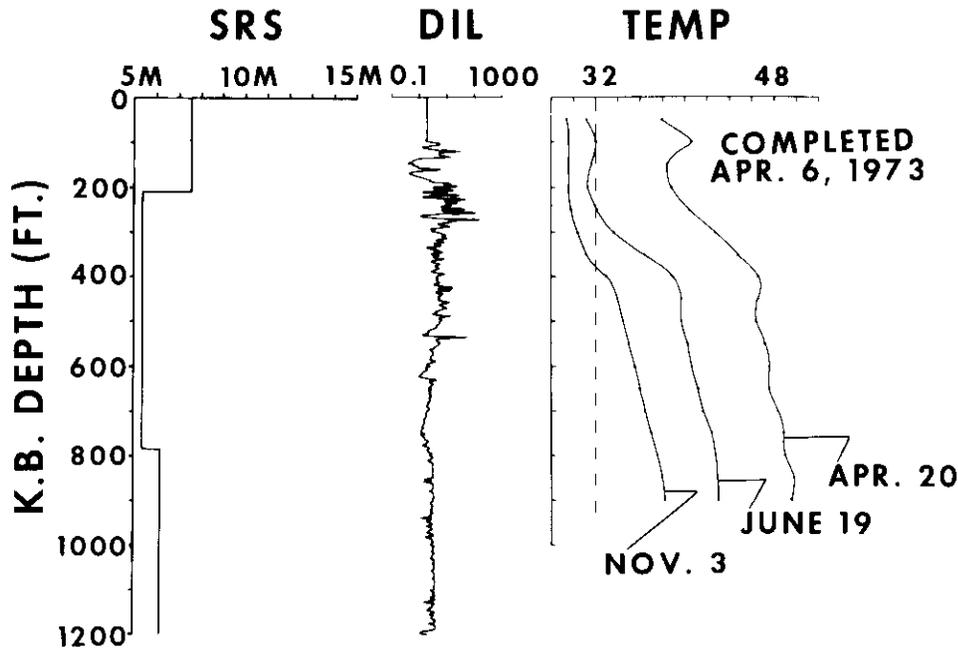


Fig. 16. Shell Niglntgak H-30. Wireline log results. SRS—check shots. DIL—dual induction. TEMP—thermistor cable temperature profiles.

CONCLUSIONS

The examples shown were chosen to illustrate the differences in permafrost encountered in a relatively small area. Not only are there marked changes in permafrost thickness closely associated with lithological changes, there are also marked changes in the physical properties of permafrost as recorded by the different logging tools. It is obvious that no one logging tool will always provide all the answers.

In the North Delta area, borehole caving is a severe handicap to the interpretation of conventional wireline logs but this caving often directly reflects the characteristics of the permafrost zone, thus a caliper log is a very useful tool.

Most resistivity logs are directionally correct in indicating formation resistivities and generally show marked changes associated with the base of permafrost. However, the physical conditions within the borehole often mean that

measurements are being made under hole conditions or resistivity distributions outside the range of tool design. The dual laterolog holds the most promise for accurate resistivity measurements.

Because of hole size problems, the standard borehole compensated sonic log, with a small transmitter-receiver spacing, is often of little use, thus the crystal cable provides the only consistent method of obtaining detailed near-surface velocity information at a reasonable cost. Moreover, in view of the reluctance often encountered to running wireline logs prior to setting surface casing, the crystal cable may be the only method of obtaining reliable data of any kind in the first few hundred feet of hole. Where shallow permafrost is present, this may be the only method available for determining its presence and measuring its thickness.

In the early part of this paper, reference was made to the difficulty in equating changes in

physical properties of different lithological types with the 32°F. isotherm. Only in a few wells in Arctic Canada has temperature measuring equipment, such as thermistor cables, been installed, and of these wells, most have not yet reached thermal equilibrium. As a result, it is difficult to equate the onset of physical changes associated with permafrost development, under other than laboratory conditions, with any single isotherm. In this paper, the term 'base of permafrost' is used in the sense of being the point at which recognizable changes in the physical properties of the rocks first occur, with no isotherm implied. This point has more relevance to the exploration geophysicist in interpretation of exploration geophysical data.

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REFERENCES

- Brown, R. J. E. and Johnston, G. H., 1964, Permafrost and related engineering problems. *Endeavour* 23, 66-72.
- Desai, K. P. and Moore, E. J., 1967, Well log interpretation in permafrost. *Soc. Prof. Well Log Anal. 8th Annual Logging Symp. Trans.*, Paper N, 1-27.
- Hunter, J. A. M., Judge, A. S., MacAulay, H. A., Good, R. L., Gagne, R. M., and Burns, R. A., 1976, The occurrence of permafrost and frozen sub-seabottom materials in the Beaufort Sea. *Dept. of the Environment, Beaufort Sea Project, Technical Report No. 22.*
- MacKay, J. R., 1963, Notes on the shoreline recession along the coast of the Yukon Territory. *Arctic* 16, 195-197.
- Timur, A., 1968, Velocity of compressional waves in porous media at permafrost temperatures. *Geophysics* 33, 584-595.