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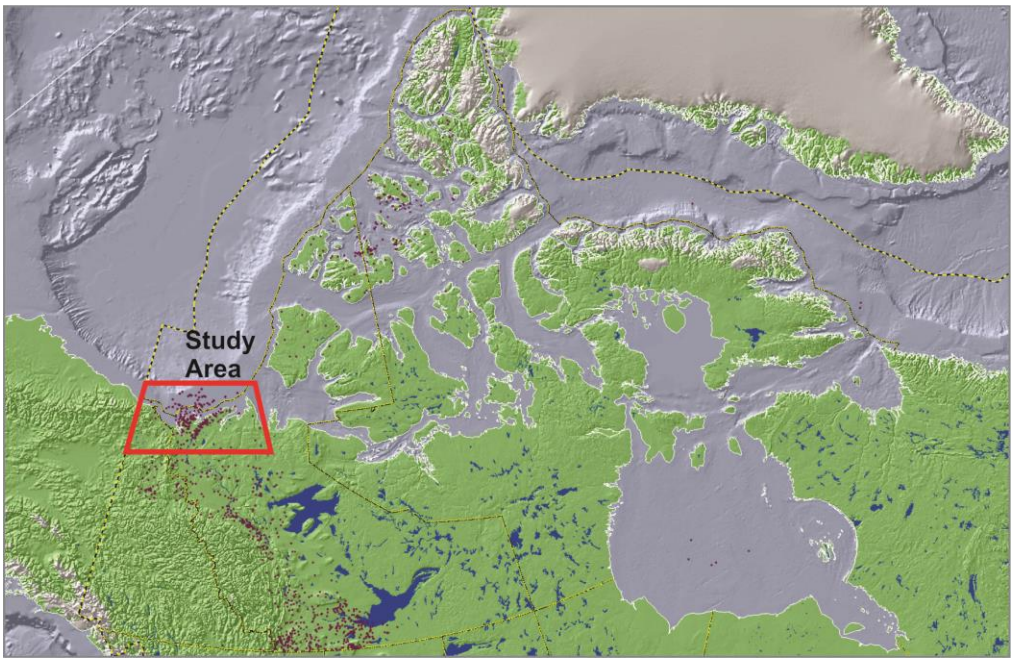
Permafrost investigation by well logs, and seismic velocity and repeated shallow temperature surveys, Beaufort-Mackenzie Basin



K. Hu, D.R. Issler, Z. Chen, and T.A. Brent

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TABLE OF CONTENTS

ABSTRACT 1
INTRODUCTION 2
PERMAFROST DETECTION TECHNIQUES 5
Temperature surveys 5
Quality assessment of base of permafrost from temperature surveys *6*
Well seismic surveys 8
Check shot and VSP *8*
Crystal cable survey *9*
Geophysical well logs 11
Resistivity logs *11*
Borehole compensated sonic *12*
Other well logs and well information *12*
Caliper log 12
Density and neutron logs 13
Gamma Ray (GR) 13
Spontaneous potential (SP) 13
Well history report 13
INTERPRETATION OF PERMAFROST BASE 14
Integrated permafrost interpretation using composite plots 14
IBPF determined from well logs 17
IBPF determined from temperature survey and/or well seismic survey 17
IBPF estimated by temperature-depth profile 18
QUALITY ASSESSMENT FOR IBPF DETERMINATION 18
Quality assessment for geophysical determination of IBPF 19
Comparison of IBPF results from temperature survey and geophysical methods 20
Quality assessment for final IBPF interpretation 20
CONCLUSIONS 23
ACKNOWLEDGEMENTS 24
REFERENCES 25
LIST OF TABLES 30
LIST OF FIGURES 30
APPENDIX A (Figs. 12 to 75) 30
APPENDIX B (Figs. 76 to 126) 30
APPENDIX C (Figs. 127 to 190) 30
APPENDIX D (Figs. 191 to 246) 30

ABSTRACT

This report presents exploration well data and interpretations relevant for mapping the variation in the depth to the base of ice-bearing permafrost (IBPF) for the Beaufort-Mackenzie Basin. This work is part of a larger government-industry funded petroleum systems study of the Beaufort-Mackenzie region that was active from 2001-2013. Geophysical well logs, well seismic surveys, shallow repeated temperature surveys, and deeper borehole temperature-depth profiles are utilized to determine the base of IBPF for 265 wells in the basin. Composite plots of log, seismic velocity and shallow temperature data illustrate typical geophysical responses and provide multi-parameter evidence for integrated interpretations of the IBPF zone. IBPF determinations are quality-assessed in terms of their reliability using a standardised scale based on the type of methods used and the quality of data available.

For many of the wells, a sharp change in electrical and acoustic properties marks the base of the interpreted fully frozen IBPF zone which may represent the base of ice-bonded permafrost. For 135 wells, there is an underlying transition zone between 7 m to 210 m in thickness that is interpreted to represent partially-frozen IBPF. The interpreted co-existence of water and ice may be the result of changes in lithology, grain size, texture and/or pore water salinity which can affect the freezing point. There is a good correlation between the geophysically-determined base of IBPF and the depth to the base of permafrost from temperature surveys. This suggests that the mapped IBPF zone is a useful thermal boundary condition for thermal modelling and heat flow studies.

For most of the wells, IBPF is confined to sandstones and conglomerates within Cenozoic sediments of the post-rift succession. Beneath the Beaufort Shelf, base of IBPF occurs within highly porous sediments of the Plio-Pleistocene Iperk Sequence. For central onshore areas (Richards Island and areas to south), base of IBPF occurs in progressively older, more deeply exhumed Cenozoic strata in a southward direction. Along the southeastern basin margin on Tuktoyaktuk Peninsula, IBPF extends into the Paleocene-Eocene Aklak Sequence. In the southernmost part of the basin and in the fold belt to the west, IBPF is encountered in Lower Cretaceous syn-rift and Upper Cretaceous post-rift strata. Permafrost occurs in exhumed Paleozoic strata in the Anderson Plain southwest of Tuktoyaktuk Peninsula. Depth to the base of IBPF varies from 0 m (no

IBPF) to > 700 m across the study area. It is thinnest along the southern (landward) basin margin and in the deformed and exhumed western part of the basin, and is thickest in the rapidly deposited Cenozoic strata of the eastern shelf beneath the Beaufort Sea. IBPF may be absent over much of the modern delta area around Mackenzie Bay.

INTRODUCTION

Permafrost is defined on the basis of temperature and it occurs where ground (soil or rock) temperatures have remained at or below 0°C for at least two consecutive years (Permafrost Subcommittee, 1988; van Everdingen, ed., 1998). The upper boundary of permafrost coincides with the upper position of the 0ºC isotherm beneath the land surface and it is referred to as the permafrost table. Above the permafrost table, seasonal temperature changes at the ground surface may be associated with freeze-thaw cycles. The permafrost base is defined by the lower position of the 0ºC isotherm and temperatures are perennially greater than 0ºC beneath this boundary. Within permafrost, the ground may be variably frozen or unfrozen, depending on its moisture content and due to various factors that affect the freezing process such as salinity, and matrix mineral composition, grain size and texture (e.g., Anderson and Morgenstern, 1973; Hivon and Sego, 1995). As a result, freezing occurs over a range of temperatures, leading to a transition between ice-bearing permafrost and ice-bonded permafrost in which sediment grains are cemented together by ice.

Knowledge of the distribution of permafrost is important for scientific and economic reasons. Permafrost provides a geological record of paleoclimate change and it affects the thermal stability zone for gas hydrates, a potential fuel source in the future. It also has an important role in future climate change because degrading permafrost can release sequestered carbon as greenhouse gases into the atmosphere from thawed soils and decomposed gas hydrates. In terms of oil exploration and development, permafrost can influence well casing programs, time-depth interpretations from seismic velocity data, and the design of pipelines, gas plants and other related infrastructure (e.g., Hatlelid and MacDonald, 1982). It also represents an upper thermal boundary condition for models of heat flow in arctic sedimentary basins.

Permafrost is widespread in Canada and occurs beneath approximately 50% of the land surface but also exists in the marine environment (Heginbottom *et al*., 1995). In 1970, frozen and icy sediments were first observed in borehole samples recovered from the southern Beaufort Sea shelf, leading Mackay (1972) to predict the occurrence of subsea relict permafrost (formed under different paleotemperature conditions than present) based on a simple thermal model. Judge (1973) showed that permafrost thickness can be estimated for various regions of Canada for planning purposes using information on mean annual ground temperatures, heat flow and rock thermal properties. Research over the last 40 years has led to a better understanding of the characteristics and geographic extent of permafrost in Arctic Canada, especially for the Mackenzie Valley and Delta regions. Research topics include permafrost detection by various geophysical methods (Walker and Stuart, 1976; Hnatiuk and Randall, 1977; MacAulay *et al*., 1979; Hatlelid and MacDonald, 1982; D & S Group, 1983; Hardy Associates (1978) Ltd., 1984; Palacky and Stephens, 1992; Stevens *et al*., 2008), geothermal data collection of deep permafrost temperatures and thicknesses (Taylor and Judge, 1974, 1975, 1976, 1977; Judge *et al*., 1979a and b, 1981; Burgess *et al*., 1982; Taylor *et al*, 1982; Jessop *et al*., 2005), and geothermal modelling of the growth and degradation of permafrost (Allen *et al*., 1988; Taylor, 1991, 1999; Taylor *et al*., 1996a,1996b, 2008, *in press*; Wright *et al*., 2000; Solomon *et al*., 2008). Smith and Burgess (2002) compiled a digital database of permafrost thickness for northern Canada using published and unpublished data that were collected mainly between 1960 and the mid-1980s. Jessop *et al*. (2005) prepared a digital compilation of Canadian geothermal data generated over a 40 year period that includes data gathered for permafrost studies.

Although detailed, multi-year temperature surveys in selected boreholes have provided fundamental scientific data for permafrost studies, the method is not practical for regional-scale mapping of permafrost. Hnatiuk and Randall (1977) used data from a Mackenzie Delta petroleum exploration well to show how conventional wireline logs and velocity surveys can be used to estimate the depth of the base of ice-bearing permafrost based on the electrical and acoustic properties of the frozen sediment. Osterkamp and Payne (1981) used well logs to construct a preliminary map showing the variation in thickness of ice-bearing permafrost (< 200 m to > 600 m) for the North Slope of Alaska.

Judge *et al*. (1987) prepared a similar map showing the variation in depth to the base of ice-bearing permafrost for the Beaufort-Mackenzie region using log-based determinations from 161 wells (D & S Group, 1983), yielding a similar range in permafrost depths (< 100 m to > 700 m) as the Alaska study. In 1990, Fortin and Blasco updated the offshore portion of this map in an unpublished study that included new well data (see Blasco *et al.*, 2013, for a discussion of this work). Subsequently, ice-bearing permafrost was recovered in cores from the Beaufort Shelf (Blasco, 1995) and onshore areas (Dallimore, 1992), providing additional verification of log-based interpretations.

The Judge *et al.* (1987) permafrost map was prepared in the midst of the first cycle of Beaufort-Mackenzie petroleum exploration that lasted from 1962 to 1992. Following a period of quiescence, a second phase of exploration began in 2000 and approximately 280 wells have been drilled to date. A government-industry funded study of petroleum systems of the Beaufort-Mackenzie Basin was initiated by the GSC to coincide with this second phase of exploration. As part of this study, permafrost interpretations were re-evaluated and updated as a consequence of the substantial amount of new data available from wells drilled after the early 1980s.

Figure 1 shows an updated version of the hand-contoured GSC map of the depth to the base of ice-bearing permafrost from Issler *et al*. (2011) based on the integrated analysis of data from repeated temperature surveys, well seismic surveys, geophysical well logs, and temperature-depth profiles derived from wireline and drillstem test temperature data (Hu *et al*., 2010). The map indicates that permafrost is thickest in the east-central onshore/offshore portions of the basin and reaches a maximum (720 m) near the northeast tip of Richards Island. It is thin or absent near the major outflow of the Mackenzie River in the western part of the basin, coincident with much of the offshore Tertiary fold belt (Lane and Dietrich, 1995). This broad pattern is captured in the original map of Judge *et al*. (1987) but the new map differs in some detail because it incorporates significantly more data (265 wells versus 161 wells in the original study).

The main objective of this report is to provide detailed documentation of the data and methods used to construct the Issler *et al*. (2011) map showing the depth to ice-bearing permafrost (Fig. 1, modified version). This report contains data and quality-ranked base of permafrost determinations for 265 Beaufort-Mackenzie wells. An integrated, multi-

parameter approach to permafrost characterisation is presented and quality assessment procedures are discussed.

PERMAFROST DETECTION TECHNIQUES

As discussed above, the base of permafrost is defined by temperature and coincides with the 0°C isotherm. However, except for specialized scientific studies, detailed temperature logging of wells is rare because of the requirement for maintaining open boreholes in order to collect a time series of temperature measurements to correct for drilling-related thermal perturbations within and around the borehole. Conventional log data are common for petroleum exploration wells and offer an attractive means for detecting and mapping frozen or partially frozen sections within the permafrost zone. The base of ice-bearing permafrost (IBPF) is normally a well-defined physical boundary that can be seen on wireline logs because an ice-saturated porous medium has a much higher acoustic velocity and formation resistivity than a water-saturated porous interval. This physical permafrost ice boundary may have a negative temperature and occur at depths shallower than the 0°C isotherm because the freezing point of interstitial water may be depressed by the presence of dissolved salts. The base of ice-bearing permafrost can also be inferred from well seismic surveys which measure acoustic wave velocity at exploration drill holes.

Temperature surveys

Temperature surveys are the most direct indicator of the presence of permafrost and the most reliable method for permafrost thickness determination. However, the circulation of drilling fluid within the wellbore over the weeks to months required to drill a well causes a substantial thermal disturbance around the borehole wall. Mud circulation increases wellbore temperatures in the upper part of the well and suppresses temperatures at greater depth (Oxburgh and Wilson, 1989). The largest disturbance is at shallow depth in the permafrost zone which can lead to extensive thawing around the borehole. Fortunately the initial set of well logs is collected early in the drilling process prior to casing the permafrost zone, commonly before the thermal perturbation can propagate deep into the adjacent formation. By the end of drilling, the permafrost zone may be

highly disturbed and far from thermal equilibrium. As a result, it is necessary to collect a time series of temperature measurements in order to monitor the gradual recovery to thermal equilibrium.

Prior to running temperature surveys, drilling fluids are displaced with diesel fuel to prevent freezing within the borehole. A series of temperatures are recorded at different times at similar fixed depth points within a well using a multisensor thermistor cable or a portable single thermistor probe. After a period of time (months to several years depending on drilling conditions), temperatures in the borehole approach equilibrium with the undisturbed formation temperatures; true temperatures can be estimated by exponential extrapolation of the curves representing time-spaced measurements at the fixed depth points. Most of the temperature logs for the Beaufort-Mackenzie region penetrate the permafrost zone and several hundred meters of unfrozen sediments below. Temperature survey data are available for 42 wells in the Beaufort-Mackenzie Basin and the raw temperature data are included in the Canadian geothermal data compilation (Jessop *et al*., 2005). Equilibrium temperature data from the Canadian Geothermal Data Collection (Taylor and Judge, 1974, 1975, 1976, 1977; Judge *et al*., 1979a and b, 1981; Taylor *et al*., 1982) were digitized for this study.

Quality assessment of base of permafrost from temperature surveys

The quality of the base of permafrost interpretations from temperature survey data depends on the number of temperature surveys and the times that they were run, and the depth of the measured interval. There are four groups of data with corresponding quality rankings of “a” (excellent), “b” (good), “c” (fair) and “d” (poor):

a- Three or more temperature logs are available that extend below the permafrost zone and the depth to the base of permafrost is determined using the equilibrium corrected temperature;

b- Two or more temperature logs are available but the total logged depth may vary between runs, some wells have no equilibrium correction, and existing equilibrium corrections may have larger uncertainty than for “a” quality data because they are based on fewer logging runs. Therefore, in some cases, the permafrost base is interpolated from the most recent log when no equilibrium estimates are available;

c- For shallow logs that did not completely penetrate the permafrost zone, depth to base of permafrost is estimated by extrapolating equilibrium temperature trends to greater depths;

d- For most wells, it is not possible to estimate the base of permafrost reliably due to incomplete and/or poor quality data. Either the depth of penetration is too shallow for reliable depth extrapolation or temperatures from single or multiple logging runs were acquired over too short of a time interval and are far from equilibrium.

Table 1 lists the 42 wells with temperature survey data and the inferred permafrost base with respect to kelly bushing elevation and ground level or seafloor. Column 5 in Table 1 contains estimates of the base of the frozen layer interpreted from step-like changes in temperature profiles (Taylor *et al*., 1982). The thickness of the transition zone between the base of the frozen layer and the base of permafrost is given in column 6. Lakes are numerous in the Beaufort-Mackenzie region and permafrost thickness may vary considerably at a local scale due to the presence of nearby water bodies. Therefore, column 7 lists the distance to the nearest significant water body for each well. Column 8 lists the quality ranking for the interpreted base of permafrost values.

Figure 2 shows examples illustrating the temperature logs, calculated equilibrium temperatures, and inferred permafrost bases for different quality-ranked data. The “a” quality temperature data for the Atigi O-48 well extend below the base of permafrost and the later temperature surveys show a close approach to equilibrium (Fig. 2a). The “b” quality data for the Pikiolik E-54 well penetrate through the permafrost zone but only two logging runs are available for an equilibrium temperature correction (Fig. 2b). The “c” quality data for the Parsons L-37 well lie within the permafrost zone but penetrate close to the inferred base and there are multiple temperature logs available for equilibrium temperature corrections (Fig. 2c). The “d” quality data for the Red Fox P-21 well (Fig. 2d) terminate well above the base of permafrost, making extrapolation uncertain. In other cases, “d” quality data are far from equilibrium, making permafrost estimation unreliable (e.g., Adgo P-25 and Niglintgak M-19; Table 1). Some “d” quality data from single logs appear to give more reasonable estimates for the base of permafrost (e.g., Titalik K-26; Table 1).

Well seismic surveys

Check shot and VSP

The check shot survey is a type of well seismic survey designed to measure the seismic travel time from the ground surface to a downhole geophone at a given depth. Vertical seismic profile (VSP) is a technique of simultaneously recording the up-going and down-going acoustic wavetrains. Both of the survey methods define a relationship between time and depth that can be converted easily to velocity as a function of depth. Velocity information is available publicly in the well history reports curated by the National Energy Board of Canada (NEB).

The borehole seismic survey data for 199 onshore and offshore Beaufort-Mackenzie wells (Table 2) are from check shot reports that consist of measured depth, true vertical depth, travel time, converted vertical, average and interval velocities, and various corrections. Figure 3 shows measured parameters required to convert the observed travel time along the slant path from the shot location to the well geophone (T) to the vertical travel time (T_{gd}) with respect to the seismic reference datum (SRD). Correction to the SRD is necessary if the shot source lies above or below this datum. If the hole is deviated or there is a significant source offset, the observed travel times must be converted to true vertical depth travel times. The average vertical velocity is calculated and corrected to the SRD using the appropriate vertical distance between geophone and SRD (D_{gd}) and the corresponding T_{gd} value (Fig. 3). Interval velocities are calculated between each geophone depth.

In the Mackenzie Delta and surrounding Beaufort Sea, sediment velocity derived from seismic refraction and reflection data can be a proxy for IBPF thickness because elevated seismic velocity characterizes the IBPF layer. If a sufficient amount of near surface seismic velocity data is available, a shift from high to low velocity may be recognised at the IBPF base. In the Mackenzie Delta area, in the top 762 m (2500 ft) velocities have a range of 1524-1981 m/s (5000-6500 ft/s) in unfrozen sediments, but a range of 2438-4267 m/s (8000-14000 ft/s) in frozen sediments (Hatlelid and MacDonald, 1982).

Seismic velocity also responds to changes in lithology, degree of compaction, and fluid in the pore space. As a result, the velocity shift at the IBPF base is sometimes complicated by these factors. This technique is also limited by the vertical resolution and quality of the velocity data. Velocity measurements from borehole seismic surveys are not affected by invasive borehole conditions (unlike wireline tools) because the acoustic wave travel paths are outside the immediate borehole where thawing can occur. The velocity profiles normally lack vertical detail due to relatively large depth spacing of downhole geophone levels. Nevertheless, the seismic method can give an indication of the IBPF base prior to the drilling of a well and can supplement and confirm interpretations of IBPF from well logs. In some cases, well logging was initiated below the permafrost zone and seismic velocity data are all that is available to constrain IBPF interpretations.

Crystal cable survey

The crystal cable velocity survey is a type of higher resolution well seismic survey designed for determination of the shallow (<1000 m) velocity distribution. Prior to VSP technology, it was generally the best seismic method for interpreting IBPF in the near wellbore (Hatlelid and MacDonald, 1982). It provides a consistent method of obtaining relatively detailed near surface velocity information at a reasonable cost (Walker and Stuart, 1976). The crystal cable consists of 12 pressure wave sensitive crystal detectors attached at 50-foot (15.24 m) intervals to a flexible steel-cored cable. The entire cable is fixed at different positions along the borehole and the travel time of a sound wave to each detector is recorded and plotted versus depth. Crystal cable data are much less affected by permafrost thawing than sonic logs and can often provide a useful IBPF indication if a significant volume of the frozen material is present.

For the Beaufort-Mackenzie Basin, borehole sloughing does not appear to be a major problem for the Tuk Peninsula area but it can be for the North Delta/Richards Island area. Commonly it is difficult to obtain a good acoustic bond between the casing and adjacent sedimentary rocks in a badly caved borehole which can lead to the detection of casing kicks on crystal cable records that are shot in cased holes. For some wells in the Richards

Island area, this problem is severe enough to mask all true direct arrival energy on records obtained over the entire IBPF interval (Walker and Stuart, 1976).

Crystal cable survey data are available for 102 Beaufort-Mackenzie wells (Table 2). Most of these wells have original field data for interpretation but a small number of wells also have complete interpreted records. In addition, there are a few wells that lack original data but have time-depth plots included in the NEB well history reports. For some wells, records indicate that crystal cable surveys were run but the data are not available from the NEB. Data quality was not assessed in this study but comments on quality for selected wells in the D & S Group (1983) report are included in Table 2. Vertical depth (D_{gd}) and vertical shot time (T_{gd}) from SRD are calculated using the original crystal cable data and equations (1) and (2) in Figure 3. Data were then converted to interval velocities for plotting as a function of depth (Fig. 4).

Interval velocities within the permafrost zone are highly variable depending on factors such as lithology, porosity, water content, salinity, and temperature. Velocities measured by crystal cable surveys range from 2286 m/s (7500 ft/s) to 4115 m/s (13500 ft/s) in the IBPF section whereas velocities of 1524 m/s (5000 ft/s) to 1982 m/s (6500 ft/s) are typical for the non-frozen section. Commonly the IBPF zone is characterised by interval velocity values in excess of 3000 m/s that decrease sharply to approximately 2000 m/s below its base. Figure 4 shows a typical velocity profile from well seismic survey data (both crystal cable and check-shot survey data) for the Amarok N-44 well that illustrates these features. The average velocity exceeds 3000 m/s in the upper 300 m of the well and then decreases to less than 3000 m/s below the interpreted base of IBPF at 370 m depth. The interval velocity shows an abrupt shift from 2500 m/s to less than 2000 m/s at the base of IBPF. This well encountered pre-rift (Devonian Imperial Fm.), syn-rift (Albian Arctic Red) and post-rift (Paleocene-Eocene Aklak and Pliocene-Pleistocene Iperk sequences) successions illustrated in the stratigraphic column on right side of Figure 4; a detailed correlation chart of Phanerozoic strata is shown in Fig.5 for the Beaufort-Mackenzie Basin (also see Dixon *et al*. (2007), Dixon *et al*. (1992) and Dixon (1996) for stratigraphic nomenclature).

Geophysical well logs

Well logs can be used to identify IBPF because they provide information on specific physical properties of sedimentary rocks (e.g., acoustic, electrical) that can change substantially when ice replaces water in the pore spaces of the rocks. Although paper copies of conventional well logs are available publicly with the NEB well history reports they are difficult to work with for a regional study. IHS Energy Ltd. and Divestco Inc. of Calgary donated digital well log data for the over 250 Beaufort-Mackenzie wells that are used in our study. The basic well logs include gamma ray (GR), spontaneous potential (SP), caliper, resistivity, sonic transit time, bulk density and neutron porosity. The resistivity data are obtained from laterologs or induction logs for most of the wells. In addition, some well history reports contain a drilling log, lithology information and descriptions identifying the base of permafrost and this has been helpful where log signatures are subtle or ambiguous (e.g., Aagnerk E-56, Fig. 12, Appendix A; Umiak N-16, Fig. 226, Appendix D).

Resistivity logs

In general, resistivity is the most useful and reliable log measurement for detecting IBPF because a frozen porous formation normally has a much higher resistivity than when it is unfrozen. Much of the permafrost in the Beaufort-Mackenzie Basin occurs primarily in sand, gravel and other unconsolidated sediments. Ideally resistivity should increase abruptly as the logging tool passes from unfrozen sediment into frozen sediment of the permafrost zone. However, a partially frozen transition zone may exist beneath the base of the fully frozen zone, causing a more gradual decrease in resistivity below the frozen interval. Pressure, grain size and the presence of mineral salts affect the freezing point and can lead to variations in the unfrozen water content.

Dual Induction Laterologs (DIL-SFL or DIL-LL8) can be used effectively to determine the base of IBPF if the thermally invaded zone around the borehole is less than the investigative depth of the logging tool. The Dual Laterolog (DLL) is the best indicator of IBPF in enlarged, deeply invaded boreholes with highly resistive formations and salty drilling muds and this tool was used to log the permafrost zone for many Beaufort-Mackenzie wells. The High-Resolution Laterolog Array tool supersedes the

DLL tool and is used to provide more accurate resistivity values for different horizontal zones of investigation (RLA5, A40H for deep; RLA3, P40H for medium; and RLA1, P16H for shallow) for wells drilled after 2000.

Borehole compensated sonic

The Borehole Compensated Sonic tool measures the compressional wave interval transit time (DT) (inverse of velocity) of a formation and was used widely in the exploration of the Beaufort-Mackenzie Basin. DT values depend on the lithology, porosity and the composition of the pore medium for the formation under investigation. If the velocities of the rock matrix and the pore fluid are known, DT values can be used to compute formation porosity. If the pores contain ice instead of water, the measured transit time decreases significantly, especially in high porosity materials as demonstrated by acoustic velocity experiments for frozen and unfrozen porous strata (King *et al*., 1982). Due to the limited depth of investigation of the sonic tool (a few inches beyond borehole wall), the shorter sonic travel times in the permafrost zone can be obscured when the IBPF has thawed around the borehole during drilling. Therefore, the sonic log is best used to provide supplementary information and confirmation of IBPF determinations based on resistivity logs which are less susceptible to drilling-related borehole effects.

Other well logs and well information

By definition, temperature is a direct indicator of permafrost, and resistivity, sonic transit time and sonic velocity are direct indicators of the physical properties of frozen sediment. Other log-based and drilling methods can be used in conjunction with these techniques to further constrain interpretations of IBPF. Some of these logs are sensitive to degraded borehole conditions related to drilling-induced thawing of the IBPF zone.

Caliper log: For unconsolidated formations, IBPF inhibits the formation of a stable filter cake and thawing-induced caving of the formation can lead to overgauged holes that are identified easily on caliper logs. Overgauged holes can sometimes indicate permafrost but their absence does not mean that there is no permafrost because caving is unlikely to occur in a competent formation with permafrost.

Density and neutron logs: The freezing of formation pore fluids has little effect on density measurements but the overgauged boreholes that can occur in thawed IBPF zones can lead to anomalously low bulk density and high porosity values because the density tool requires close contact with the formation and is very sensitive to borehole conditions. Neutron porosity values tend to be high in permafrost zones because of their high hydrogen content but overgauged boreholes also lead to high neutron porosity values.

Gamma Ray (GR): GR is a good lithology indicator that is mainly used to distinguish between clay (higher GR values) and sand (low GR values). Within the permafrost zone, the degree of freezing can depend on lithology and grain size and therefore GR is used with other logs to detect IBPF in porous sandstone intervals.

Spontaneous potential (SP): The SP log normally responds to changes in temperature or water salinity. In some cases, a negative SP drift has been observed to coincide with the established base of the permafrost when going from unfrozen to frozen sediment. Generally, SP is not a very reliable indicator of permafrost.

Well history report: For some wells, logging was initiated near the base of or below the zone of IBPF, making it difficult to obtain reliable log-based interpretations of depth to the base of IBPF. For these cases, drilling parameters, lithology descriptions and other information from well history reports were used to help estimate this boundary. For example, there are significant step-like shifts in drilling-related parameters at approximately 660 m depth for the onshore Umiak N-05 well (Fig. 224, Appendix D) that was drilled in 2005. The rate of penetration increases, the weight on the bit decreases, and the mud temperature increases below 660 m (coincident with base of casing) where logging was initiated. This is interpreted as a change from frozen to unfrozen strata at this depth and it is consistent with the well velocity survey and regional IBPF thickness trends observed in nearby wells (Fig. 1).

Figure 6 shows a comparison of geophysical log, seismic velocity, and temperature survey data for the upper 1000 m in the Atertak E-41 well. The interpreted IBPF zone is characterized by subzero temperatures, high seismic velocities, low sonic transit times, and high resistivity values for all resistivity logs (deep, medium and shallow). Although the caliper log indicates some borehole caving, thermal invasion and thawing have not been severe enough to seriously degrade log signatures.

INTERPRETATION OF PERMAFROST BASE

Geophysical logs are available for most of the Beaufort-Mackenzie wells and therefore they are the main tool for defining the base of IBPF. In the Beaufort-Mackenzie Basin, the near-surface sediments consist predominantly of unconsolidated sands, gravels, muds and clays. The high porosity of these sediments contributes to the strong contrast in geophysical and petrophysical log character crossing the boundary between ice-saturated and water-saturated sediments. The combined use of different well log curves is an effective method for detecting IBPF accurately because each well log has a unique response to IBPF. In the study area, 206 wells have geophysical logs for the shallow interval of interest (< 1000 m). There are 199 wells with borehole seismic survey data and 102 wells with the higher resolution crystal cable data. The depth to the base of permafrost and IBPF is determined using an integrated approach involving conventional well logs, well seismic survey, and temperature survey data.

Integrated permafrost interpretation using composite plots

A composite plot, consisting of various geophysical logs plus seismic survey and temperature survey data if available, is used to determine zones of IBPF (Fig. 6). Well log and survey data are plotted in six tracks with respect to depth for the upper 1000 m of the well. The first 4 tracks are well logs that include: caliper (CAL) curves (track 1); gamma ray (GR) and spontaneous potential (SP) curves (track 2); resistivity curves for the deep (LLD, ILD, RLA5, A40H, LN), medium (LLS, ILM, RLA3, P40H, SN) and shallow (LL8, SFL, MSFL, MFR, RLA1, P16H) resistivity logs (track 3); borehole compensated sonic transit time (DT), bulk density (RHOB) and neutron log (NPss, NPls, NEUT) curves if a complete well logging set is available for the shallow depth interval (track 4). Track 5 shows well seismic survey data and track 6 has the temperature survey data, including the latest temperature log and calculated equilibrium temperatures if available. A stratigraphic column (Fig.5) is included on the right side of track 6 to provide geological context.

In Figure 6, GR and SP curves indicate that sandstone is the dominant lithology with interbedded shales in the upper part of the Aklak sequence of the Atertak E-41 well.

Sonic transit time shows a sharp change from generally low to high values with increasing depth at 528 m. The seismic velocity profile shows many high interval velocity values (>3000 m/s) above 528 m with a less defined transition to lower velocity values at greater depth. The higher GR intervals tend to have higher transit times and lower seismic velocities and may represent unfrozen shale intervals interbedded with frozen sand layers. Resistivity logs exhibit a smooth transition from very high resistivity values on the order of 2000 ohm·m above 528 m to less than 10 ohm·m at 609 m. The caliper log reveals an unstable, oversized hole throughout the interval above 528 m. The log and seismic velocity data are consistent with a major change in physical properties at 528 m and this is interpreted as the base of the fully frozen ice-bearing permafrost ($IBPF_F$) zone (marked as a solid red line in Fig. 6).

The last temperature survey recorded (track 6; Fig. 6) indicates that the interpreted $IBPF_F$ is at subzero temperatures which, depending on pore-water salinity, could be compatible with complete freezing of the sandstone intervals. The interpreted base of the $IBPF_F$ zone could represent the base of ice-bonded permafrost but we have no direct evidence to confirm this. Osterkamp and Payne (1981) made similar observations in Alaska and mentioned that limited temperature and drilling data for shallow permafrost suggests that the bases of ice-bonded and ice-bearing permafrost are nearly identical in some silts and coarse-grained soils unless salty pore water is present.

A transition zone consisting of predominantly shaly sandstone is observed from 528 m to 609 m (Fig. 6). In comparison to the overlying $IBPF_F$ zone, it has a stable and smaller borehole size, lower resistivity values that decrease with depth, higher sonic transit time values, and lower but variable seismic interval velocity values. Transition zones have also been observed to occur near the base of the IBPF in northern Alaska where they have a typical thickness of 10 m to 60 m but are sometimes absent (Osterkamp and Payne, 1981). For the Beaufort-Mackenzie Basin, 135 wells have transition zones that vary from 7 m to 210 m in thickness with a median thickness of 48 m. Similar to northern Alaska, this transition zone is not present in all wells with an IBPF zone. We refer to this transition zone as a partially frozen ice-bearing permafrost ($IBPF_P$) zone and its base is marked by a dashed red line in Figure 6. The coexistence of unfrozen

water and ice may be related to changes in grain size, lithology and salinity that influence the freezing temperature.

The temperature survey log shows the 0°C base of permafrost (PF) at 542 m which is between the base of the log-determined $IBPF_F$ and $IBPF_P$ zones (red arrow on Fig. 6; a red arrow on plots in appendix show another possible base of permafrost). This temperature log is uncorrected and may overestimate the final equilibrium temperature. Therefore, it is possible that the 0ºC isotherm may occur at or below the base of the $IBPF_P$ zone. Nevertheless, the temperature data indicate that the $IBPF_F$ zone and part of the $IBPF_P$ zone are at subzero temperatures, consistent with freezing conditions. The bases of both IBPF zones occur within the Paleocene-Eocene Aklak Sequence in the Atertak E-41 well (Fig. 6) which is located mid-way along Tuktoyaktuk Peninsula on the southeastern basin margin.

Figure 7 shows another example of permafrost determination using geophysical and temperature survey data for the Taglu D-43 well which is located on the north-central part of Richards Island. Resistivity and caliper log data show a sharp change at 548 m which is interpreted as the base of the $IBPF_F$ zone. The $IBPF_F$ zone is also characterized by high seismic velocity and low sonic transit time values. The upper part of the $IBPF_F$ zone has lower resistivity values related to an enlarged borehole that may indicate that the thermal invasion exceeds the investigative depth of the shallow, medium and deep induction logs (Fig. 7). However, thermal invasion appears to have little effect on sonic transit time values over this interval. Beneath the $IBPF_F$ interval, there is a shift to lower seismic velocity, lower resistivity, and stable borehole conditions within the interpreted $IBPF_P$ zone (Fig. 7). The base of the $IBPF_P$ zone is interpreted to coincide with a change in resistivity gradient at 621 m. There are low sonic transit time values within the $IBPF_P$ zone that may indicate thin ice-bearing sandstone beds but these appear to be too thin to be visible in the lower resolution seismic velocity survey.

The temperature survey did not completely penetrate the $IBPF_F$ zone and has been extrapolated to greater depth to provide an estimate of the base of permafrost at 633 m. The temperature log shows subzero temperatures down to at least 410 m and therefore provides some independent support for the IBPF interpretations. The interpreted bases of

the $IBPF_F$ and $IBPF_P$ zones occur within the upper Oligocene-middle Miocene Mackenzie Bay Sequence in the Taglu D-43 well (Fig. 7).

IBPF determined from well logs

In many cases, complete data are unavailable for defining the base of IBPF. Figure 8 shows an example for the Natagnak O-59 well situated on the northwest coast of Tuktoyaktuk Peninsula. This well lacks seismic and temperature surveys but GR, SP and resistivity log data are available in the upper part of the well. Resistivity and GR data are used to define the bases of $IBPF_F$ and $IBPF_P$ at 535 m and 585 m, respectively. The $IBPF_P$ zone is characterized by a decrease in resistivity from approximately 200 ohm·m to 20 ohm·m that appears to coincide with a lithology change indicating increased shale content toward the base of the zone. This suggests that the freezing temperature may be controlled by lithology. For the Natagnak O-59 well, IBPF is confined to the Plio-Pleistocene Iperk Sequence which is the case for most wells on the Beaufort Shelf (Fig. 8).

IBPF determined from temperature survey and/or well seismic survey

In some situations where well logging was initiated below the base of permafrost, shallow repeated temperature survey data can provide a good estimate of the base of permafrost and IBPF. Figure 9a shows the 0ºC permafrost base at 361 m within the Aklak Sequence of the Parsons N-17 well determined using extrapolated equilibrium temperatures from a series of temperature logging runs (Taylor *et al*., 1982). The corresponding base of IBPF is estimated at 328 m, coincident with a step-like shift in initial temperature-depth profiles that is interpreted to represent the boundary between frozen and unfrozen sediment (Taylor *et al*., 1982). These permafrost estimates are consistent with values determined for other Parsons wells (Figs. 161-169; Appendix C), all of which are located in the southeastern part of Tuktoyaktuk Peninsula.

In other situations, only well seismic velocity surveys are available for defining the extent of permafrost. The base of IBPF cannot be determined accurately because of the lower resolution of seismic velocity data compared with log data. As an example, the estimated base of IBPF is approximately 80 m and 155 m for fully frozen and partially

frozen zones, respectively, within a depth range (green shaded range in Fig. 9b) for the Onigat D-52 well located immediately south of the Parsons wells. This interpretation must take into consideration IBPF estimates from other nearby wells that are based on different data. For some wells, seismic survey data do not show a high velocity interval within the IBPF zone defined using other methods. In such cases, the permafrost zone may be thin and the frozen layers too widely space for detection by the seismic method.

IBPF estimated by temperature-depth profile

Some Beaufort-Mackenzie wells have no temperature survey, seismic velocity or well log data within the shallow permafrost interval. In this case, the base of IBPF is approximated by upward linear extrapolation of quality-assessed bottomhole and drillstem test temperature data (Hu *et al*., 2010) to 0ºC. A geothermal gradient map for the Beaufort-Mackenzie region was constructed using linear fits to well temperature data that intersect the base of $IBPF_F$ at an assumed temperature of 0ºC (Issler *et al*., 2011). Detailed analysis of drillstem test and BHT temperature data shows that a linear gradient is a reasonable approximation for many wells (temperature-depth profiles are described in GSC Open File 6957 that is in preparation). Using this method, the base of $IBPF_F$ is estimated to be at 628 m for the Isserk I-15 well located on the inner central Beaufort Shelf north of Richards Island (Fig. 10). The base of $IBPF_F$ was estimated for 17 Beaufort-Mackenzie wells by extrapolation of deep temperature data. $IBPF_F$ estimates derived from temperature extrapolation have larger uncertainty than those based on other methods but they do allow for some comparison of geothermal gradients and depths to base of $IBPF_F$ in nearby wells.

QUALITY ASSESSMENT FOR IBPF DETERMINATION

Three main methods are used to define the base of permafrost. In general, permafrost determinations based on shallow temperature survey data have the highest reliability. Those based on geophysical methods are less reliable than estimates from temperature surveys but results can be very good. The least reliable method is based on extrapolation of deep temperature-depth profiles. Each method has its own quality assessment standard and limitations.

Quality assessment for geophysical determination of IBPF

Permafrost interpretations from repeated temperature surveys are classified as “a” (excellent), “b” (good), “c” (fair) and “d” (poor) as described above. Quality assessment of IBPF determinations obtained from geophysical methods (well seismic surveys and geophysical well logs) is less straightforward and must take into consideration multiple factors. IBPF interpretations based on geophysical data are classified as “a” (high reliability), “b” (medium reliability) and “c” (low reliability) by considering four main factors. (1) Type of geophysical method used to determine IBPF; generally, resistivity logs are the best indicator followed by sonic logs and then lower resolution seismic velocity surveys whereas drilling parameters and other logs such as the caliper provide supplementary information. (2) Type of geophysical response to the IBPF zone; a sharp change in geophysical response provides the best indication of the base of IBPF. (3) Consistency among different geophysical tools; combination plots show excellent to poor agreement for base of IBPF determinations from different geophysical methods, depending on the well examined. (4) Availability of geophysical data; some wells have limited or no log data within the permafrost zone. Base of IBPF values are assessed according to the following geophysical attributes:

a - high reliability

(1) Resistivity shows a sharp change from high values to low values at the base of IBPF and other well logs show consistent changes;

(2) Resistivity shows a very clear or sharp change from high values to low values. Most of the well logs are consistent and well seismic survey data are compatible with the resistivity results.

b - medium reliability

(1) Resistivity changes from high values to low values for the IBPF zone but there is a transition zone with a diffuse boundary;

(2) Resistivity shows a well-defined base of IBPF but other well logs are not available;

(3) Resistivity can be used to define the base of IBPF but results differ with respect to other well logs or the velocity survey;

(4) Sonic transit time and other logs show a consistent base for IBPF but no resistivity logs are available.

c - low reliability

(1) Only one non-resistivity log is available and it is used in combination with well seismic survey data to determine the base of IBPF;

(2) Only well seismic survey data are used to determine the base of IBPF because no well log data are available.

(3) The base of IBPF is estimated mainly from well history data (such as drilling parameters, and lithology information) because no well seismic survey data or well log data are available.

Comparison of IBPF results from temperature survey and geophysical methods

Figure 11 shows a comparison of the depth to base of permafrost derived from temperature surveys and the base of IBPF determined from geophysical methods (well logs, well seismic surveys including check-shot, VSP and crystal cable surveys). There is a good relationship between the temperature-defined permafrost ("a" and "b" quality data) and the $IBPF_F$ (Fig. 11a) and $IBPF_P$ (Fig. 11b) zones determined from geophysical methods. In general, temperature is between -2°C to 0°C for the base of $IBPF_F$, with most values between -1°C and 0°C (Fig. 11c). There are fewer data points for the $IBPF_P$ zone but most values are in the range, -1°C to 0°C (Fig. 11d). The results in Figure 11 confirm that the base of permafrost can be well approximated using geophysical methods when temperature survey data are not available. A temperature of 0°C was assumed for the geophysically-determined base of IBPF in order to construct a first-order geothermal gradient map for the Beaufort-Mackenzie Basin (Issler *et al*., 2011). This is a reasonable approximation because the temperature variations at this boundary are too small to have a significant effect on calculated geothermal gradients.

Quality assessment for final IBPF interpretation

Interpreted depths to base of permafrost are determined using whatever relevant data are available for a given well. This may include repeat temperature surveys, logs, well seismic surveys, extrapolated deep well temperatures, drilling parameters, and other

information in well history reports. Information from nearby wells can also be useful in constraining interpretations. The final interpretation is based on an integration of different methods and a standardized reliability is assigned to each inferred depth to the base of permafrost according to the following scheme:

a - high reliability

(1) Base of PF is determined from reliable temperature surveys ("a" quality) (Fig. 9a);

(2) Base of IBPF is determined using reliable geophysical methods ("a" quality) (Fig. 6).

b - medium reliability

(1) Base of IBPF is determined from "a" quality temperature surveys but a distinctly different base of IBPF is derived from "a" quality geophysical methods;

(2) Base of IBPF is from "b" quality geophysical data (Fig. 8);

(3) Base of IBPF is from "b" quality repeat temperature survey data.

c - low reliability

(1) Base of IBPF is derived from an extrapolated deep temperature-depth profile (Fig. 10);

(2) Base of IBPF is from "c" or "d" quality repeat temperature survey data;

(3) Base of IBPF is from "c" quality geophysical data (Fig. 9b).

Unsurprisingly, low reliability quality "c" interpretations show the highest range of variability. Many of the wells with "c" quality determinations have enough data to give an approximate depth to the base of IBPF. However, the Blow River E-47 well (Appendix A, Fig. 44), located within the fold belt on the southwestern basin margin, lacks direct borehole evidence for IBPF and a thickness of < 200 m is inferred from regional trends. Only the GR log and low resolution seismic velocity data are available for the upper 200 m of the well. Also, this well encountered exhumed and well compacted Albian mudstones with associated high density and velocity values. It is unclear whether IBPF is even present or easily detected, given the fine-grained lithology and low porosity of this rock formation. Previous authors inferred that permafrost exists at < 238 m, the depth of the casing shoe, presumably based on the assumption that the casing was set to encompass the permafrost zone (D & S Group, 1983; Smith and

Burgess, 2002). From the sample lithology descriptions, shale is dominant for the interval from 31 to 259 m, indicating that the base of permafrost is probably less than 31 m (no samples are available from the surface to 31 m). The nearest wells, Fish River B-60 (Appendix A, Fig. 51) and Spring River YT N-58 (Appendix C; Fig. 190) also suggest that permafrost thickness may be < 100 m.

Permafrost interpretations are available for 265 Beaufort-Mackenzie wells; approximately 71% of the IBPF determinations are of "a" (100 wells) or "b" (88 wells) quality whereas 77 wells have "c" quality values. Base of IBPF determinations for 28 wells are mainly from "a" and "b" quality repeated temperature surveys but four "c" quality and one "d" quality temperature surveys were also used to estimate the base. Other low quality temperature surveys were not used to define permafrost. The bases of IBPF for 212 wells are inferred from geophysical methods; interpretations for 160 wells are based on combined well log and seismic survey data, whereas 32 values are derived mainly from seismic survey data, and 20 values are from well logs. Extrapolated deep borehole temperatures were used to estimate base of IBPF for seventeen wells. For eight wells, the IBPF determinations are based mainly on information in well history reports, including drilling parameters (e.g., Fish River B-60 well, Fig. 51 in Appendix A, and Umiak N-16 well in Appendix D; Fig. 226), and lithology information (e.g., Blow River Yt. E-47 well, Fig. 44 in Appendix A, and Immiugak N-05 well).

Table 3 provides full details of the determination of the depth to the base of permafrost and IBPF for this study. Included in the table are the inferred depths, the method used, the quality of the depth determination, the formation at the base of permafrost, the thickness of the $IBPF_P$ zone, and other relevant information. Detailed composite plots showing integrated PF/IBPF determinations are included in Appendix A (Aagnerk E-56 to Ivik N-17 wells; Figs. 12 to 75), Appendix B (Kadluk O-07 to Minuk I-53 wells; Figs. 76 to 126), Appendix C (N. Ellice J-23 to Spring River YT N-58 wells; Figs. 127 to 190), and Appendix D (Taglu C-42 to Ya Ya P-53 wells; Figs. 191 to 246).

CONCLUSIONS

The depths to the base of ice-bearing permafrost are determined from available detailed shallow repeated temperature surveys, geophysical data, and deeper bottomhole and drillstem test temperature-depth profiles for 265 wells in the Beaufort-Mackenzie Basin. Sharp changes in acoustic and electrical properties are interpreted to indicate the base of the fully frozen zone (and possibly the base of ice-bonded permafrost). An underlying transition zone that is characterised by decreasing resistivity and velocity is observed in 135 wells and is interpreted to represent a partially frozen zone that may be related to changes in lithology, rock texture and/or pore water salinity. The thickness of this zone varies between approximately 10 m and 200 m with a median value of 48 m. Permafrost determinations were quality-assessed in terms of their reliability based on the type and quality of data used to constrain the interpretations. The strong correlation between geophysically-determined base of ice-bearing permafrost and the base of permafrost from shallow temperature surveys suggests that geophysical methods provide reliable information on permafrost distribution with significant applications for basin thermal studies.

A contour map shows that the inferred depth to the base of fully-frozen ice-bearing permafrost varies from 0 m to 720 m across the Beaufort-Mackenzie Basin (Fig. 1 and Issler *et al*., 2011). Ice-bearing permafrost is mainly confined to post-rift Cenozoic strata except onshore along the southernmost basin margin and in the fold belt in the west where it can occur in Cretaceous sediments. Permafrost occurs in exhumed Paleozoic strata of the Anderson Plain southeast of Tuktoyaktuk Peninsula. Although well control is sparse, it appears that ice-bearing permafrost is very thin or absent in the area of the modern Mackenzie Delta, both onshore and in the region around Mackenzie Bay. The deepest ice-bearing permafrost is located around the northeast part of Richards Island and in the adjacent offshore area.

Note: Figure 1 is a layered and georeferenced ADOBE ® (PDF) containing the contents of Table 3 embedded as table data behind the well symbols. A GIS-Formatted (i.e. well point shape file) is also included in this open file download that contains table 3 information in the attribute table and a metadata tag (xml).

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LIST OF TABLES

1. Permafrost base from temperature surveys.
2. Well seismic survey data for the Beaufort-Mackenzie Basin.
3. Depth to base of permafrost from multi-parameter data, Beaufort-Mackenzie Basin.

LIST OF FIGURES

1. Map of depth to fully frozen ice-bearing permafrost for the Beaufort-Mackenzie Basin.
2. Temperature logs and corresponding calculated equilibrium temperatures for representative wells.
3. Definition of terms for borehole seismic survey.
4. Well seismic surveys for the Amarok N-44 well, including check shot and crystal cable data and their relation to the base of ice-bearing permafrost.
5. Stratigraphic column throughout the Beaufort-Mackenzie area.
6. Example showing a combination plot of well logs, temperature survey and well seismic survey data that are used for determining the base of permafrost for the Atertak E-41 well in the Beaufort-Mackenzie Basin.
7. Determination of base of permafrost using temperature survey, well seismic survey and geophysical logs for Taglu D-43 well in the Beaufort-Mackenzie Basin.
8. Example of the determination of base of IBPF using geophysical logs for Natagnak O-59 in the Beaufort-Mackenzie Basin.
9. Determination of base of permafrost from temperature survey or well seismic survey data when no logs are available for the permafrost interval.
10. Base of IBPF estimated from extrapolation of deep well temperature (drillstem test, bottomhole) data (circled points excluded) for the Isserk I-15 well.
11. Comparison of base of permafrost from “a” and “b” quality temperature survey data and base of IBPF from geophysical methods.

APPENDIX A (Figs. 12 to 75)

APPENDIX B (Figs. 76 to 126)

APPENDIX C (Figs. 127 to 190)

APPENDIX D (Figs. 191 to 246)