

ICE-BEARING PERMAFROST

In this study, ice-bearing permafrost refers to strata containing a sufficient volume of ice to be

detected on geophysical well logs without the aid of temperature data. The minimum amount of ice necessary for detection by well-logging devices is unknown. Well-log responses used to determine the base of the ice-bearing permafrost are summarized in table 2. The temperature at the base of ice-bearing permafrost is always at or below 0 °C, therefore, the depth to the base of the ice-bearing permafrost is always at or above the depth of the 0 °C isotherm. Within the thick ice-bearing permafrost sequence, locally found on the North Slope, multiple frozen and thawed horizons are present. In this study, the base of the ice-bearing permafrost is interpreted as the deepest observed frozen-to-thawed phase boundary that may exist in any particular location. Desai and Moore (1968) were the first to report that an ice-bearing horizon exhibits physical characteristics that can be detected with subsurface geophysical devices. They demonstrated that properties such as electrical resistivity and acoustic transit time are affected by the presence of ice within the sediment. Others have shown that the ice-bearing permafrost thickness can be determined from well logs (Stoneley, 1970; Howitt, 1971; Hoyer and others, 1975; Walker and Stuart, 1976; Hnatiuk and Randall, 1977; Osterkamp and Payne, 1981; Osterkamp and others, 1985); however, the term ice-bearing permafrost was used first by Osterkamp and Payne (1981). Their predecessors used the term permafrost to describe both temperature conditions and the presence of ice within pore

Desai and Moore (1968) demonstrated that the spontaneous potential, resistivity, and acoustic logs show significant deflections at the base of the ice-bearing permafrost (called permafrost by these authors) in an unidentified well on the North Slope of Alaska. They observed a significant increase in electrical resistivity, a decrease in acoustic transit time, and a pronounced drift in spontaneous potential from less negative to increased negative values after crossing the boundary from non-ice-bearing to ice-bearing permafrost. Stoneley (1970) also observed similar log responses in the Put River-1 well (well No. 18 in this study) in the Prudhoe Bay oil field, which he also attributed to the presence of ice. In addition, Stoneley (1970) reported that cores recovered from the BP 12-10-14A well, located 4 mi southeast of Put River-1, contained sands and gravels that were bounded by ice downward almost to the same depth as suggested by the well logs, however, the logs could not be found for this study. Stoneley's (1970) observations of ice-bounded cores represent the only direct evidence that verifies the accuracy of well logs as icedetection devices. Also, Howitt (1971) noted that the resistivity-log pick for the depth of the ice-bearing permafrost in the Put River 19-10-15 well (well M in this study) is at the same level as the flexure in the temperature profile representing the base of ice-rich permafrost. Osterkamp and Payne (1981) examined electrical-resistivity and acoustic-transit-time well logs from 61 wells on the North Slope in order to develop a map of the depth to the base of the deepest ice-bearing

Osterkamp and Payne (1981) examined electrical-resistivity and acoustic-transit-time well logs from 61 wells on the North Slope in order to develop a map of the depth to the base of the deepest ice-bearing permafrost. Their map indicates that the depth to the base of ice-bearing permafrost varies from more than 2,000 ft in the Prudhoe Bay area to 400 ft or less in NPRA (Osterkamp and Payne, 1981; column 13, table 3, this report).

INTERPRETATION OF WELL LOGS

During drilling of exploratory and production wells on the North Slope, the well bore is surveyed with a series of well-logging devices that can be used to determine the physical state of the pore waters. Logs used in this study included resistivity, acoustic transit time, spontaneous potential, gamma ray, caliper, neutron porosity, density, drilling rate, and gas chromatograph on the mud log. In many wells, the permafrost interval is logged using only one or two of these devices or not logged at all. The lack of well-log data limits the number of North Slope wells from being used to determine the base of ice-bearing permafrost. Each of the 156 wells selected for this project has had at least a resistivity survey conducted within the shallow substrate. The electrical-resistivity and acoustic-transit-time well logs were found to be the most useful in detecting the base of the ice-bearing permafrost. However, we do not have independent evidence that the well-log pick for the base of the ice-bearing permafrost is the depth of the actual phase boundary between the ice-bearing and water-saturated strata. Short descriptions of the well-log responses within and below the ice-bearing permafrost, in order of importance, are as follows:

Resistivity (RES)—The base of the ice-bearing permafrost often exhibits a substantial resistivity decrease from within to below the ice-bearing permafrost sequence. Ice exhibits relatively high electrical resistivity in comparison to free water.

Acoustic transit time (ATT)—A significant transit-time decrease often marks the base of the ice-bearing permafrost. Ice is characterized by relatively high acoustic velocities in comparison to water.

Caliper (CAL)—The caliper log often indicates an enlarged bore hole within the permafrost horizon, which can be attributed to caving associated with thawing ice-bearing sediments.

Spontaneous potential (SP)—The spontaneous-potential log often shows a pronounced drift from

negative in the ice-bearing permafrost sequence to positive below the base of ice-bearing permafrost. This drift can be attributed to the increased concentration of the remaining salt particles in the unfrozen pore spaces of the ice.

Drilling rate (DR)—In many wells, the base of ice-bearing permafrost coincides with a significant increase in the drilling rate. Ice-bearing sediments apparently exhibit properties similar to a well-cemented rock unit with a relatively slow drilling rate.

Gas chromatography (GC)—Because of the relatively impermeable nature of the ice-bearing permafrost, free gas can be trapped at the base of ice-bearing permafrost. This response was observed in 31 wells. Density (D)—Although generally not available, the density log shows a slight decrease in density coincident with the base of ice-bearing permafrost. Ice has a lower density than water.

Neutron porosity (NP)—In several wells, the neutron-porosity log shows a slight drop in recorded porosity at the base of the ice-bearing permafrost. Because of the density difference between ice and free water there would be a hydrogen density difference between a unit saturated with water and one containing ice.

Gamma ray (GR)—The gamma ray device detects the base of the ice-bearing permafrost because of a high concentration of potassium ions in solution at the freezing front.

Idealized log responses at the base of ice-bearing permafrost are shown assuming a uniform sandstone lithology (fig. 1), and their magnitude of log shifts are summarized (table 2). However, presence of interbedded shales within a ice-bearing permafrost sequence affect the well-log responses, making the interpretation of the depth to the base of the ice-bearing permafrost difficult. The 156 wells and log-determined depths to the base of the ice-bearing permafrost shown on the map are listed in table 3.

RELATIONS BETWEEN PERMAFROST, ICE-BEARING

PERMAFROST, AND ICE-RICH PERMAFROST

Physical factors that control the response of a well log within a stratigraphic section include mineralogy, porosity, temperature, pore fluids, and, of special concern for this study, the physical state of the pore fluids. The ability of a well-log device to indicate presence of ice within a rock mass is dependent on the sensitivity of the device to detect ice and the volume of ice within the rock. Observations made using well logs from the North Slope indicate that a substantially thick wedge of ice-laden strata is present in the Prudhoe Bay area (discussed below). The base of the ice-bearing permafrost in the high-porosity sandstones and conglomerates of the Prudhoe Bay region is easily detected, and the log responses are similar to the idealized ones (fig. 1). Here, the depth of the 0 °C isotherm is at approximately the same depth as the ice-bearing permafrost. However, in many of the wells from NPRA in which the shallow potentially ice-bearing sequences are characterized by siltstone and shale lithologies, the well logs fail to indicate presence of ice, even though the depth of the 0°C isotherm often extends deep into the lithologic section. In these wells, either ice does not exist within the permafrost sequence (above the 0 °C isotherm) or the volume of the pore-filling ice and related physical characteristics were such that the well-logging devices did not respond as expected. Shales that were not deeply buried have high porosity and fluid content; however, waters associated with shales are ionicly bonded to the clays preventing formation of ice. Therefore, ice may not exist within a section where clay-rich rocks are found, even though water and temperatures below 0 °C are present. The thick shale sections present within the shallow substrate of parts of NPRA may affect pore-filling ice conditions; but currently there is no direct evidence to support this possibility. However, many of the NPRA well-bore temperature surveys also fail to reveal a discontinuity in the near-surface geothermal gradients like that observed in the Prudhoe Bay area; this may also be due to the presence of the near-surface shales. The lithologic variability that complicates selecting the base of ice-bearing permafrost from well logs is shown for 11 wells located across the North Slope (fig. 2). Each well is represented by a resistivity and gamma ray log or spontaneous-potential curve. The resistivity log was selected because of

In sections A-A' and B-B' (fig. 2), the base of the ice-bearing permafrost has been identified in 7 of the 11 wells. In the Prudhoe Bay Unit N-1 (fig. 2, A-A'), the apparent base of the ice-bearing permafrost is interpreted to be at 1,919 ft, near the base of a long transition zone from resistive to conductive strata. In the J.W. Dalton-1 well (fig. 2, A-A'), however, the base of the ice-bearing permafrost at 887 ft appears to coincide with a distinct lithologic contact. The interbedded sediments in this well complicate the selection of an accurate well-log pick for the base of the ice-bearing permafrost. Farther to the west, in the South Barrow Test Well-3 (fig. 2, A-A'), the base of the ice-bearing permafrost is obscured; however, it is possible that the slight resistivity deflection at 790 ft represents the base of the ice-bearing permafrost. In many of the NPRA wells, shales may reduce pore-filling ice and effect the extent to which a well-log device

its ability to reveal the presence of ice; the gamma ray and spontaneous-potential curves were used to add

relative lithologic and stratigraphic data. The depth of the base of the ice-bearing permafrost, as picked

from the well-log data (fig. 2), was compared to the depth of the 0 °C isotherm and to the depth to the base

can detect ice.

The plot of the 0 °C isotherm on cross sections A-A' and B-B' (fig. 2) reveals the difference between the well-log pick for the base of the ice-bearing permafrost and the 0 °C equilibrium isotherm. The difference is variable, for instance, in the Prudhoe Bay Unit N-1, it is 115 ft, but in the South Barrow Test Well-3, the difference is approximately 510 ft. A summary list of all North Slope wells, where comparisons of this type can be made, is shown (table 4), and for 7 of the 14 wells, the depths to the base of an ice-rich layer (IRL), as interpreted from temperature profiles (Lachenbruch and others, 1982; 1987), are indicated

ICE-BEARING PERMAFROST THICKNESS

The wells used to map the base of the ice-bearing permafrost were selected on the basis of the quality of the log data and geologic information. Well localities are divided into (1) wells in which depths to the base of ice-bearing permafrost have been obtained (table 3), (2) wells for which temperature profiles but no well-log picks are available (table 1; not used to determine contours), and (3) wells for which both well-log picks for ice-bearing permafrost and temperature surveys are available (tables 1, 3, and 4). Of the 46 wells listed in table 1, only 14 have well-log picks for the base of the ice-bearing permafrost (table 4), while the remaining 32 wells were not logged, or the confidence level was low in the selection of an accurate well-log pick for the base of ice-bearing permafrost.

The depths to the base of the ice-bearing permafrost as selected by Osterkamp and Payne (1981) (table 3) compare closely with the depths we obtained in our study. However, 12 of Osterkamp and Payne's (1981) 61 wells were not incorporated into our work, because of lack of well data in our study or uncertain reliability of the well logs. In addition to the 49 wells used from Osterkamp and Payne (1981), we

have added 107 wells to the data base, which allowed us to reduce the contour interval from 200 m, as

used by Osterkamp and Payne, to 200 ft. Furthermore, this map provides easy reference for evaluation of

In the central and south-central parts of NPRA, no ice-bearing permafrost depths have been denoted

local ice-bearing permafrost conditions at selected sites on the North Slope of Alaska.

because of problems in well-log interpretation. The presence of near surface, thick, shale sequences or highly compacted sandstone probably mask the base of the ice-bearing permafrost in the log data. The pronounced linear trend of the contours, which follows the coastline from the northeastern par of NPRA eastward, shows that maximum ice-bearing permafrost depth is a few miles inland from the coast, and that it thins to the north (offshore) and south (onshore). Offshore thinning of the ice-bearing permafrost has been attributed to presence of the overlying water column of the Arctic Ocean (Lachenbruch, 1957). In the Point Barrow and Cape Simpson area, ice-bearing permafrost thickens toward the coast, similar to the situation in the Prudhoe Bay area. However, the suspected offshore thinning is not shown on the map because of the lack of well sites. The substantial thinning south and west of the Prudhoe Bay area is attributed to a change in the near-surface geology (Osterkamp and Payne, 1981; Lachenbruch and others, 1982). The shallow substrate of the Prudhoe Bay area is characterized by coarse-grained sediments of high porosity, which have relatively low geothermal gradients within the permafrost horizon. This low geothermal gradient corresponds to a thick ice-bearing permafrost sequence. Regions to the south and west into NPRA, however, are characterized by finer grained or lower porosity sediments, which exhibit high geothermal gradients in the permafrost that correspond to a relatively thin ice-bearing permafrost sequence. In this region, permafrost thickness is also influenced by an increase in mean annual surface temperature of approximately 5 °C from Prudhoe Bay to the south into the northern foothills of the Brooks Range (Lachenbruch and others, 1987).

SUMMARY AND CONCLUSION

The primary purpose of this study was to develop a method of quickly and inexpensively evaluating subsurface temperature conditions in order to determine the depth and thickness of the gas-hydrate stability field. We evaluated the response of all available well logs from 440 wells from the North Slope, using information from the U.S. Geological Survey well-log library. Comparison of well-log responses to equilibrium temperature profiles in selected wells showed that the well logs were responding not to rocks with a temperature of less than 0 °C (permafrost) but to rocks with a certain content of ice (ice-bearing permafrost). In addition, the comparison suggests that a certain amount of ice is necessary to produce the characteristic log response. Because the depth to the base of the ice-bearing permafrost is controlled by factors other than temperature, this measurement cannot be used in determining the depth and thickness of the natural gas-hydrate stability field; equilibrium temperature profiles are necessary to determine the depth and thickness of the natural gas-hydrate stability field, this study provides information about a upper limit for the depth of permafrost (0 °C isotherm).

We have summarized and tabulated the depths to the base of ice-bearing permafrost on various logs in 156 wells from the North Slope. Although as many as 9 different logs or borehole measurements may be used to indicate the base of ice-bearing permafrost, we found the resistivity and the acoustic-transit-time well logs to be the best indicators in most wells. This map shows the depths to the base of ice-bearing permafrost based on the well-log determinations and indicates a linear trend of maximum thickness of ice-bearing permafrost that parallels the coastline between the Colville and Canning Rivers. The ice-bearing permafrost depth ranges from less than 200 ft in the west to greater than 2,000 ft in the east and thins to the north and south. Most of the National Petroleum Reserve in Alaska has no ice-bearing permafrost detectable from well logs.

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Sinpson Core Test-24

South Barrow Test Well-3

4 South Barrow Test Well-4

6 South Barrow Test Well-13

South Barrow Test Well-14

South Barrow Test Well-17

10 South Barrow Test Well-20

1 South Barrow Test Well-15

Tulageak-1

Sag River-1

18 Put River-1 19 Socal 31-25

7 Delta State-1

2 Hemi 3-9-11

24 Kad River-1 25 Hurl 5-10-13

27 Lake 79 Federal-1

29 Toolik Federal-2

32 Toolik Federal-3

35 K D Delta 51-1

36 M.lne Point 18-1 37 Prudhoe Bay Unit 4-1 *38 Bl 08-11-13

39 Pradhoe Bay Unit F-1

40 West Sak River State-

28 North Kuparuk 26-12-12

Prudhoe Bay Unit M-1

North Prudhoe Bay State-1

M kkelsen Bay 13-9-19

34 Kı paruk State 7-11-12

Toolik Federal-1

South Barrow Test Well-18

Northwest Eileen State-1

21 West Kuparuk 3-11-11

23 Prudhoe Bay Unit J-1

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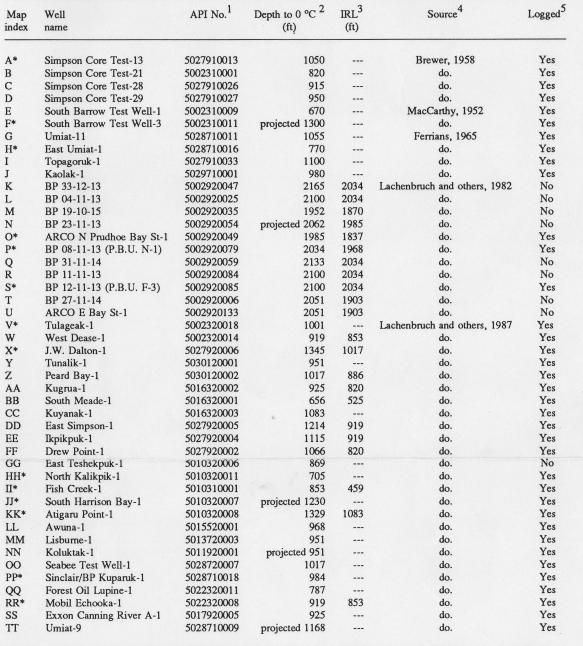
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Table 1. North Slope wells for which temperature profiles were made after the well bore had reached near thermal-equilbrium conditions

[See table 4 for comparison of depths of ice-bearing permafrost (IBPF) from well logs with depths to base of permafrost

(0 °C) and ice-rich layer (IRL) listed here]



American Petroleum Institute well identification number (Alaska Oil and Gas Conservation Commission, 3001 Porcupine Dr., Anchorage, Alaska, 99501).

Depths measured from ground level.

Depth to base of an ice-rich layer from recorded temperature profiles (source identified), measured from ground level. ---, no value reported.

For complete reference see References Cited.

Indicates whether or not well was logged using conventional wireline tools in IBPF.

* See table 3 for the depth to the base of the IBPF as determined from subsurface well-log data.

Table 2. Comparison of well-log responses within ice-bearing permafrost (IBPF) with those below the base of IBPF in sandstone [Resistivity and acoustic-transit-time logs were most reliable for determining the base of IBPF]			
Well-log response	In IBPF	Below IBPF	Remarks
Resistivity(RES)Substantial drop in resistivity; the long- normal curve separates from the short-normal curve within the IBPF.	>1000 Ω•m	5-15 Ω• m	
Acoustic transit time (ATT) Significant increase in transit time.	80 m•s/ft	130 m•s/ft	
Caliper (CAL)Often shows large variations above the IBPF.	Larger	Smaller	Relative change, dependent on engineering parameters
Spontaneous potential (SP) Drift from negative to positive below the IBPF.	more negative	more positive	20 to 30 mV shift
Drilling rate (DR)Increased drilling rate is often observed below the IBPF.	Slower	Faster	Relative rate depending on geologic conditions.
Gas chromatograph (GC) Anomalous pressures or a release of free gas may be detected at base IBPF.	No gas	Gas detection	Geologically dependent

Density (D)--Increase in recorded 2.1 gm/c³ 2.4 gm/c³ --
densities from above to below the IBPF.

Neutron porosity (NP)--Small to 25% 22% --
no reduction in calculated apparent porosities, often masked by geologic conditions.

Gamma ray (GR)--Small deflection to higher API values.

Higher 5- to 10-API unit deflection to higher API values.

41 Prudhoe Bay Unit H-1 42 Prudhoe Bay Unit A-1 43 Prudhoe Bay Unit 4-6 44 Northwest Eileen State-2 45 Prudhoe Bay Unit C-1 46 North Franklin Bluffs 47 West Sak River State-2 48 West Sak River State-49 West Sak River State-5 50 West Sak River State-6 Foggy Island Bay State-1 2 Gwydyr Bay South-1 Niakuk 1-A 5002920158 4 Kuparuk 9-11-12 5002920175 Prudhoe Bay Unit E-2 11 N. 16 E. 5002920176 Sag Delta 33-12-16 5002920177 88 Prudhoe Bay Unit 6-4 59 Kuparuk 30-11-13 60 Gull Island State-2 24 11 N. 11 E. 5002920199 61 Highland State-1 52 Abel State-1 5002920200 63 Prudhoe Bay Unit NGI-7 *64 BP 12-11-13 65 Prudhoe Bay Unit 9-7 66 Prudhoe Bay Unit 3-6 Prudhoe Bay Unit G-4 68 Sag Delta-2 16 12 N. 14 E. 5002920264 70 Point McIntyre-2 Kuparuk River Unit 1D-8 West Sak River State B-10 23 10 N. 9 E. 5002920267 1595 1597 1603 1685 1640 ND 11 N. 9 E. 5002920274 3 West Sak River State-9 12 N. 8 E. 5002920275 4 West Sak River State-11 Duck Island Unit-1 Prudhoe Bay Unit 1-16 78 Prudhoe Bay Unit 7-6 79 Kuparuk River Unit 1A-8 80 Prudhoe Bay Unit Q-3 31 Prudhoe Bay Unit 13-2 2 Prudhoe Bay Unit 14-5 Reindeer Island STRAT TEST-84 West Sak River State-4 R6 Prudhoe Bay Unit TERM-B Prudhoe Bay Unit TERM-C West Mikkelsen Unit-2 39 Gwydyr Bay State-1 1 Prudhoe Bay Unit 12-3 92 Kuparuk River Unit CPF-1(23-9-11-10) Prudhoe Bay Unit X-1 94 Kuparuk River Unit 1D-Prudhoe Bay Unit Y-1 96 Gwydyr Bay State Unit-97 Prudhoe Bay Unit TERM-A 98 Kuparuk River Unit 1D-5 99 West Sak River State-14 1 Kuparuk River Unit 1E-1 2 Kuparuk River Unit 1B-1 O3 Prudhoe Bay Unit 17-1 04 Prudhoe Bay Unit 11-4 05 Gwydyr Bay State-2 Prudhoe Bay Unit 16-11 09 Kuparuk River Unit 1C-1 Prudhoe Bay Unit TR 15-11-12 MP Tract(43-31-11-13) 3 West Sak River Unit-16 114 West Sak River Unit-17 115 MP Tract(22-31-11-13) 116 MP Tract(32-30-11-13) 17 Prudhoe Bay Unit TR T-30 8 Kuparuk River Unit 1C-8 9 West Sak River Unit-23 East Mikkelsen Bay-1 Alaska State A-1 West Staines State-2 4 Point Thomson Unit-25 Point Thomson Unit-2 6 Point Thomson Unit-3 28 Challenge Island-129 Fish Creek-1 130 Colville Delta-1 132 South Harrison Bay-1 134 West Fish Creek-1 136 North Kalikpik-1 10 N. 8 E. 5010320013 137 West Sak River Unit-15 1370 1370 --- ND 1420 1370 --- ---9 N. 8 E. 5010320018 138 West Sak River Unit-20 139 West Sak River Unit-18 16 11 N. 8 E. 5010320019 140 East Kurupa Unit-1 141 Beli Unit-1 142 Canning River Unit B-1 4 N. 34 E. 5017920006 1 N. 16 E. 5022320008 Simpson Core Test-*147 Simpson Core Test-1 24 19 N. 11 W. 5027910013 19 N. 11 W. 5027910018 148 Simpson Core Test-1 149 Simpson Core Test-20 18 19 N. 10 W. 5027910021 *150 J.W. Dalton-1

Table 3. Depth in feet to base of ice-bearing permafrost (IBPF) in wells as inferred from

well-log responses in North Slope

[Names without numbers do not appear on map; see table 2 for abbreviations of well-log responses]

10 10 N. 15 E. 5002920004 1850 1913 --- --- --- --- --- ---

8 N. 12 E. 5002920041 1499 1512 ND ND 1500 ND

6 19 N. 10 W. 5002310003

14 22 N. 18 W. 5002310012

16 21 N. 16 W. 5002320007

14 22 N. 18 W. 5002320008

22 N. 17 W. 5002320009

22 N. 16 W. 5002320011

22 N. 17 W. 5002320015

22 N. 17 W. 5002320016

22 N. 17 W. 5002320017

21 N. 14 W. 5002320018

20 N. 19 W. 5002320019

27 11 N. 14 E. 5002920006 1883 1880

11 N. 14 E. 5002920001

10 N. 14 E. 5002920007

9 11 N. 13 E. 5002920020

4 8 N. 18 E. 5002920021

American Petroleum Institute well identification number.
 2-10 IBPF depths from various well-log devices; See table 2 for abbreviations and explanation of well-log devices and responses.
 ---, no well log available; ND, available well log nondiagnostic.
 IBPF depth interpreted from all logs (this study). ---, no data.

LE IBPF depth corrected to ground surface by subtracting distance between kelly bushing and ground elevation from the interpreted

1 S. 2 E. 5028710016

5 S. 5 E. 5028710017

2 S. 5 E. 5028710018

For complete reference see References Cited. Wells without map number were not used to contour. ---, no data.
* Temperatures measured after well bore reached near-thermal equilbrium conditions (see table 1).

151 East Simpson-2

154 Shale Wall Unit-

156 East Harrison Bay State-1

IBPF well-log depth. ---, no data.

*153 East Umiat-1

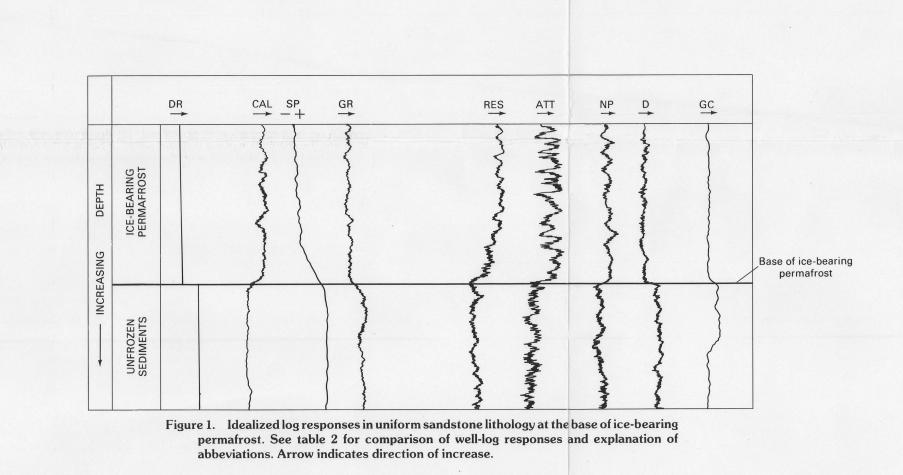


Table 4. North Slope wells in which temperature profiles and diagnostic well logs were used, showing depth to base of an ice-rich layer (IRL) and depth to base of ice-bearing permafrost South Barrow Test Well-3 5002310011 ARCO N Prudhoe Bay St-1 BP 08-11-13 (P.B.U. N-1) Fish Creek-1 South Harrison Bay-1 Atigaru Point-1 North Kalikpik-1 Mobil Echooka-1 5027910013 Simpson Core Test-13 5027920006 150,X J.W. Dalton-1 East Umiat-1 5028710016 5028710018 Sinclair/BP Kuparuk-1 American Petroleum Institute well identification number.

American Petroleum Institute well identification number.

From table 1.

Depth to base of IRL picked from temperature profiles by authours listed in table 1. ---, no

value given.

⁴ Well-log picks from table 3



