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PERMAFROST THICKNESSES IN THE OLIKTOK POINT, PRUDHOE BAY AND MIKKELSEN BAY AREAS OF ALASKA

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ABSTRACT

An improved map of the thickness of ice-bearing permafrost in northern Alaska has been constructed by combining the previous data of Osterkamp and Payne (1981) with new data obtained by analyses and interpretation of recently released well logs. The new map provides greater detail and increased coverage, especially in offshore areas. Ice-bearing permafrost reached a maximum thickness of ≈ 629 m in three areas. This suggests that the permafrost thickness (depth to 0°C) may be on the order of 670–680 m. Permafrost thickness may be < 200 m and, therefore, can vary by a factor of about four. Thinning of the permafrost from the Prudhoe Bay area toward the foothills of the Brooks Range appears to be caused by the changing geology (through its effect on the thermal conductivity of the rocks) and the increase in mean annual ground surface temperature with distance from the coast. In the offshore area toward Reindeer Island, relatively simple models explain and give reasonable predictions for thawing of the ice-bearing subsea permafrost at the sea bed and for thawing at its base.

INTRODUCTION

Information on permafrost thickness and its variability is necessary for the solution of a number of engineering and scientific problems. These problems include making corrections to surface seismic data for the "fast" permafrost layer, developing procedures for oil well drilling, completion and production in permafrost, developing regional groundwater models, and evaluating geothermal resources in continuous permafrost areas.

The equilibrium thickness of ice-bearing permafrost

$$X \approx \frac{K}{J} \Delta T \tag{1}$$

where K is the thermal conductivity of the permafrost, J is the geothermal heat flow and ΔT is the temperature difference between the base of the ice-bearing permafrost and the mean annual ground surface temperature. Climate, precipitation, vegetation, nature of the ground surface, geology, topography, presence of water bodies etc., influence the quantities on the righthand side of eqn. (1) and therefore the thickness of the permafrost.

The distribution and thickness of permafrost on Alaska's North Slope is not well known. Osterkamp and Payne (1981) have published a tentative map of permafrost thickness, with a contour interval of 100 m, based on an analysis of geophysical well logs. They have shown that the permafrost thins from the coastal areas to the Brooks Range and from Prudhoe Bay to the west and that it is relatively thin (<200–>300 m) in the National Petroleum Reserve in Alaska (NPRA). The thickest permafrost was found in the Mikkelsen Bay area. Permafrost thickness variations across the North Slope were shown to correlate with

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changes in the major rock-stratigraphic units (i.e., the permafrost thickness appears to be controlled by the geology through variations in the thermal conductivities of the rocks) which was also noted by Lachenbruch et al. (1982a).

Since the initial work of Osterkamp and Payne (1981), a large number of additional well logs have been released. Most of these new wells are in the Kuparuk and Prudhoe Bay areas although a few are in the Mikkelsen Bay area and in offshore areas. These newly released well logs have been analyzed to determine permafrost thickness and, combined with the results of Osterkamp and Payne (1981), to develop new and improved maps of permafrost thicknesses in the Oliktok Point, Prudhoe Bay and Mikkelsen Bay areas. A more detailed profile of permafrost thickness along 148.5° longitude extending from the foothills of the Brooks Range to beyond Reindeer Island offshore has been constructed.

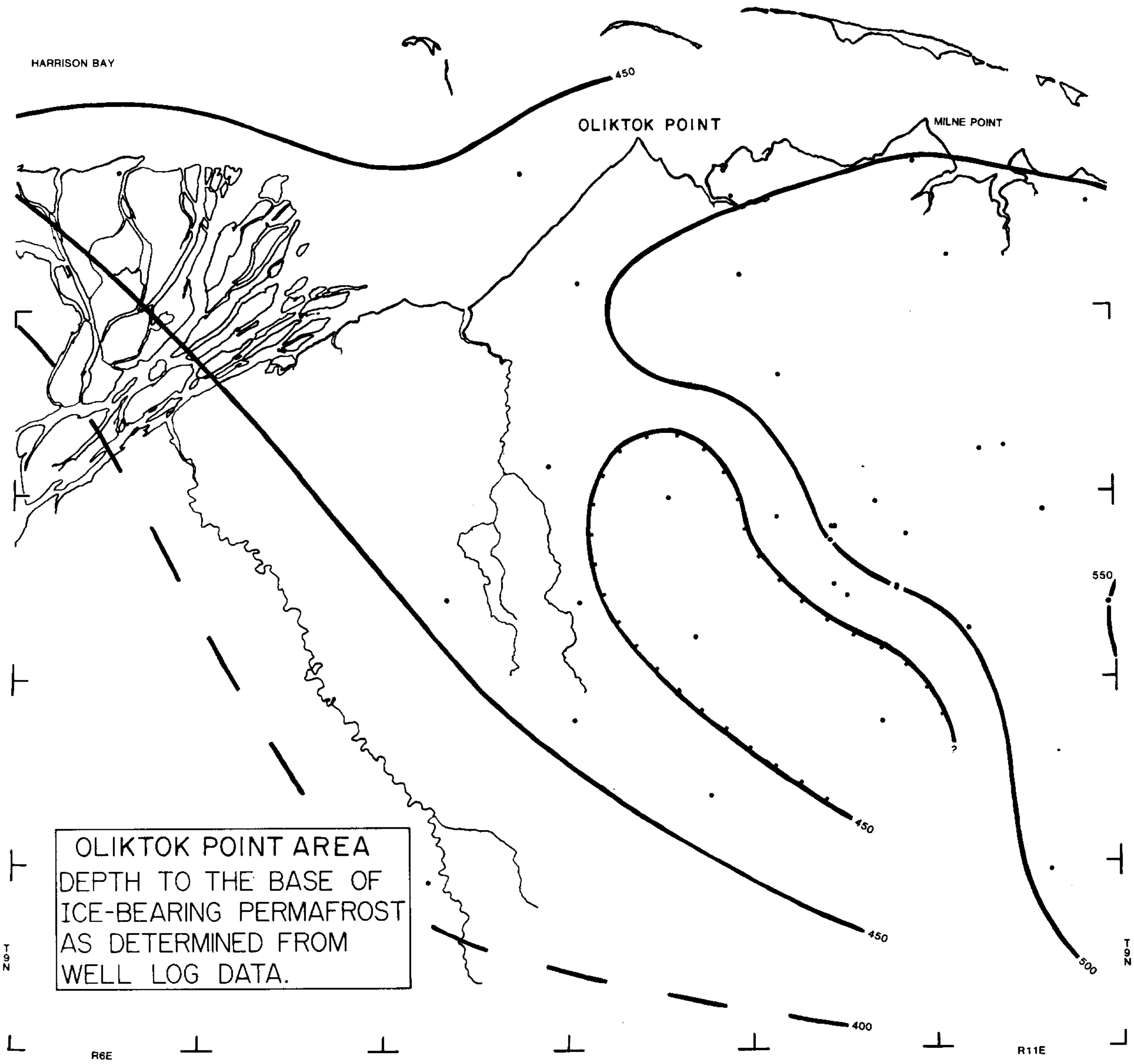

Fig. 1. A tentative map of the thickness of ice-bearing permafrost in the Oliktok Point area. The dots on the map represent well locations.

RESULTS AND DISCUSSION

The details of the techniques for using well logs to determine ice-bearing permafrost thickness have been described previously by Osterkamp and Payne (1981). Maps of the ice-bearing permafrost thickness are shown in Figs. 1, 2 and 3. The dots on these maps represent the locations of the wells. Permafrost thickness contours were drawn at 50 m intervals. In the Oliktok Point and Prudhoe Bay areas, the large number of wells generally support this contour interval, but considerable extrapolation between wells was required in the Mikkelsen Bay area (onshore and offshore), in the area between Gull Island and Reindeer Island and for the 400 m contour in the Oliktok Point area. This means that the maps will be less reliable in these latter areas.

Osterkamp and Payne (1981) reported a maximum ice-bearing permafrost thickness of 629 m in the Mobil Mikkelsen Bay State well at 13, 9N, 19E. Two additional wells, with about the same thickness of ice-bearing permafrost have been identified, the SOHIO MP Tract well at 30, 11N, 13E and the ARCO Toolik Federal No. 1 well at 4, 8N, 15E. Lachen-

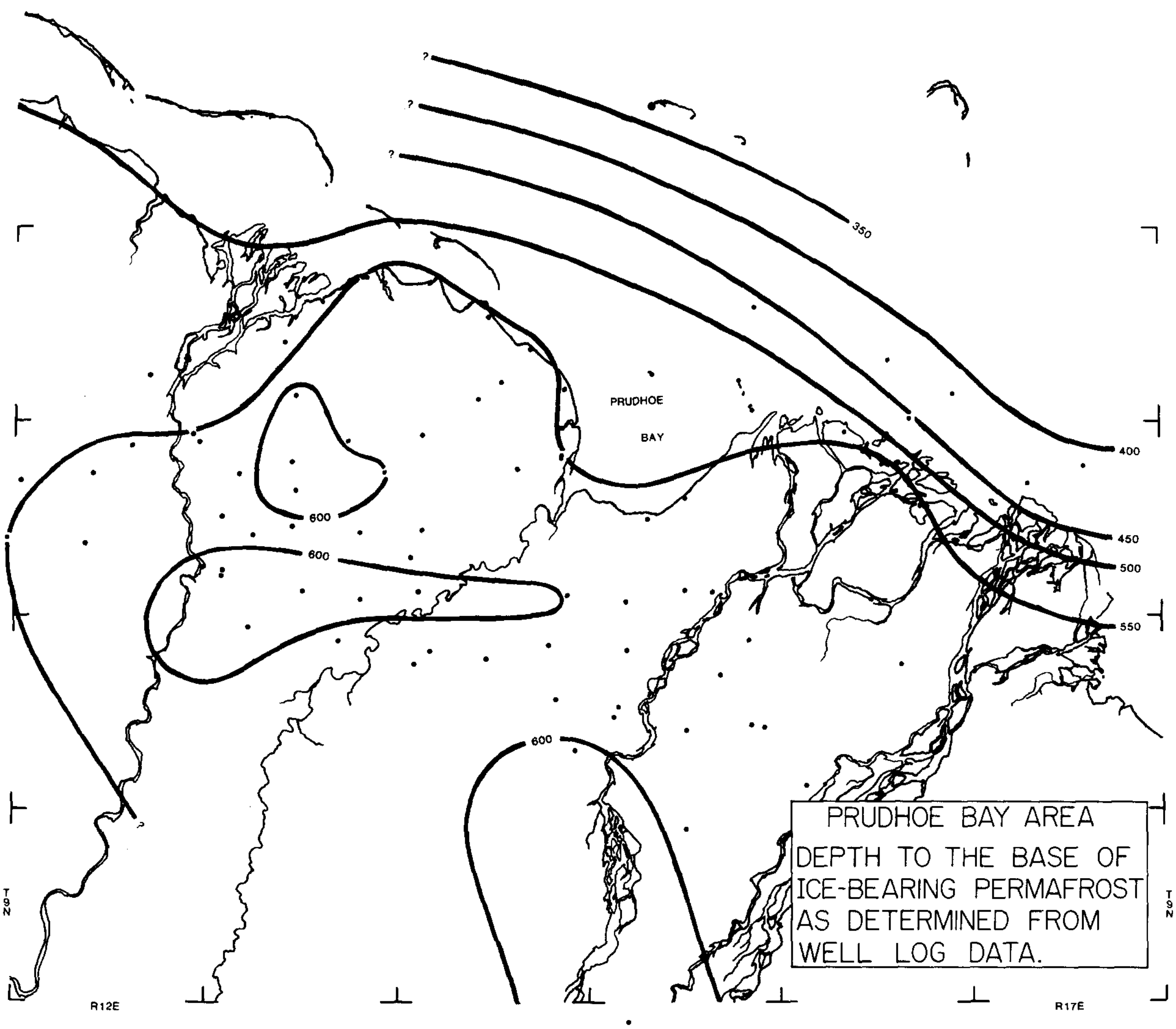

Fig. 2. A tentative map of the thickness of ice-bearing permafrost in the Prudhoe Bay area. The dots on the map represent well locations.

bruch et al. (1982a) showed that the depth of permafrost in the Prudhoe Bay area, as defined by the 0°C isotherm, may be as much as 45 m deeper than the depth of ice-bearing permafrost. Therefore, the maximum depth of permafrost on the North Slope appears to be on the order of 670–680 m (2198–2231 ft.). The minimum permafrost thickness is < 200 m (Osterkamp and Payne, 1981) so that permafrost thickness can vary by a factor of about four, disregarding anomalies associated with water bodies and the presence of hot water springs.

Figure 4 is a profile of the ice-bearing permafrost along ≈ 148.5° longitude which is roughly parallel to the Haul Road extending from offshore of Reindeer Island to the foothills south of the Arctic Coastal Plain. This profile represents the ice-bearing permafrost thickness determined from our data and from the data of Osterkamp and Payne (1981). In the offshore areas, the top of the ice-bearing permafrost (measured from sea level) was obtained from Selmann and Chamberlain (1979) and from Osterkamp and Harrison (1982). This profile illustrates the thinning of the ice-bearing permafrost from Prudhoe Bay toward the foothills of the Brooks Range and offshore toward Reindeer Island.

It was previously suggested by Osterkamp and Payne (1981) that the permafrost thinning towards the Brooks Range was primarily associated with variations in thermal conductivity and/or heat flow. This permafrost thinning towards the Brooks Range can be given a tentative interpretation using eqn. 1. The data of Lachenbruch et al. (1982b) and Osterkamp et al. (unpublished) show that $\Delta T \approx -6$°C near the Mobil Echooka well. Values for K and J are not available, but, judging from the work of Lachenbruch et al. (1982a) and the geology at this site, K should be on the order of 60–70 MJ/m y K. Assuming the heat flow is the same as at Prudhoe Bay (55 mW/m^2, Lachenbruch et al., 1982a), then $X \approx$ 210–240 m which is in reasonable agreement with the measured ice-bearing permafrost thickness of 260 m in the nearby Mobil Echooka well (Lachenbruch et al., 1982b). This suggests that the thinning of the permafrost from the Prudhoe Bay area toward the foothills of the Brooks Range, as shown in Fig. 4, may be the combined result of the change in geology (and therefore thermal conductivity) and the increase in ground surface temperature. The Sagavanirktok Formation and the thin surface deposits in the Prudhoe Bay area are silicious and coarse-

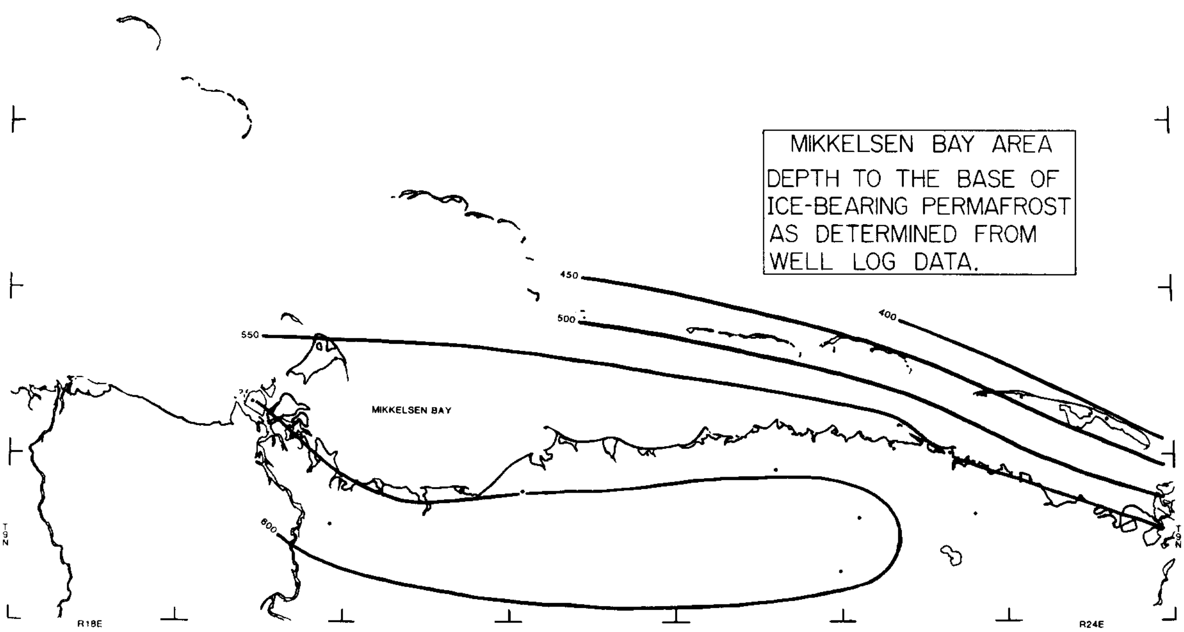

Fig. 3. A tentative map of the thickness of ice-bearing permafrost in the Mikkelsen Bay area. The dots on the map represent well locations.

grained with relatively high thermal conductivity. The rocks of the Colville Group, which underlie the Sagavanirktok Formation and outcrop about 107 km from the coast along the profile in Fig. 4, are primarily argillaceous and fine-grained with lower thermal conductivity. The effect of this change of geology and the resulting change in thermal conductivity and permafrost thickness on Alaska's North Slope has been discussed previously by Osterkamp and Payne (1981) and by Lachenbruch et al. (1982a).

Figure 5 is an expanded profile of ice-bearing subsea permafrost along a line extending from the North Prudhoe Bay State No. 1 well to Reindeer Island and thence north. The basal data point at 4 km offshore was obtained by translating Gull Island into the profile and is, therefore, less reliable.

Interpretation of the thickness of the thawed layer at the sea bed is complex in that it develops in the presence of negative sea bed temperatures after inundation caused by rising sea levels and involves both heat and salt transport (Osterkamp and Harrison, 1977). Thawing is produced by the penetration of salt water into the sediments and by the transport of heat to the ice-bearing subsea permafrost. The relative rates of the heat and salt transport vary strongly with sediment type. In the coarse-grained sediments which are found between the coast and Reindeer Island, salt transport is thought to be convective while the heat transport remains diffusive so that it is the relatively slower heat transport which controls the rate of thawing (Harrison and Osterkamp, 1978). The Stefan theory of diffusive heat transport predicts a thaw depth (in metres)

$$Y \approx t^{1/2} \qquad (2)$$

where t is the time in years that an offshore site has

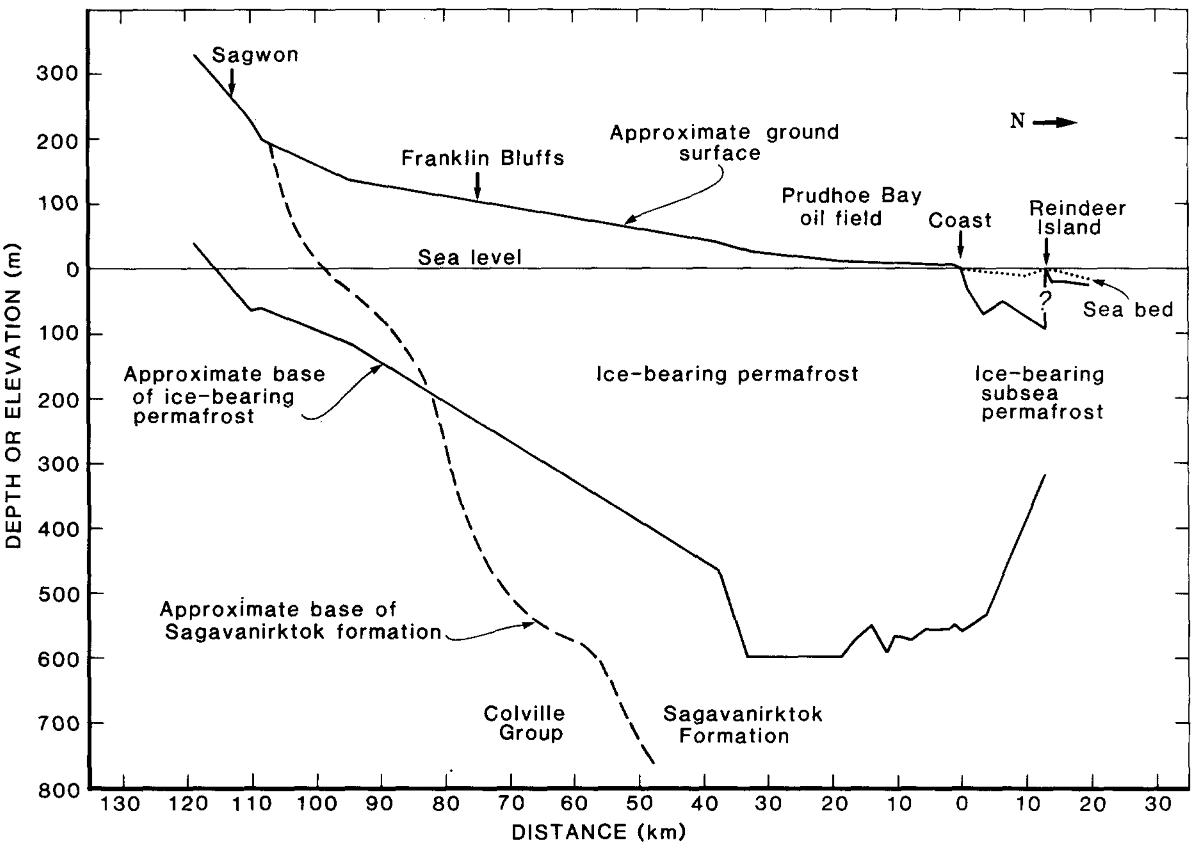

Fig. 4. A profile of ice-bearing permafrost along ≈ 148.5° longitude extending from offshore of Reindeer Island to the foothills south of the Arctic Coastal Plain.

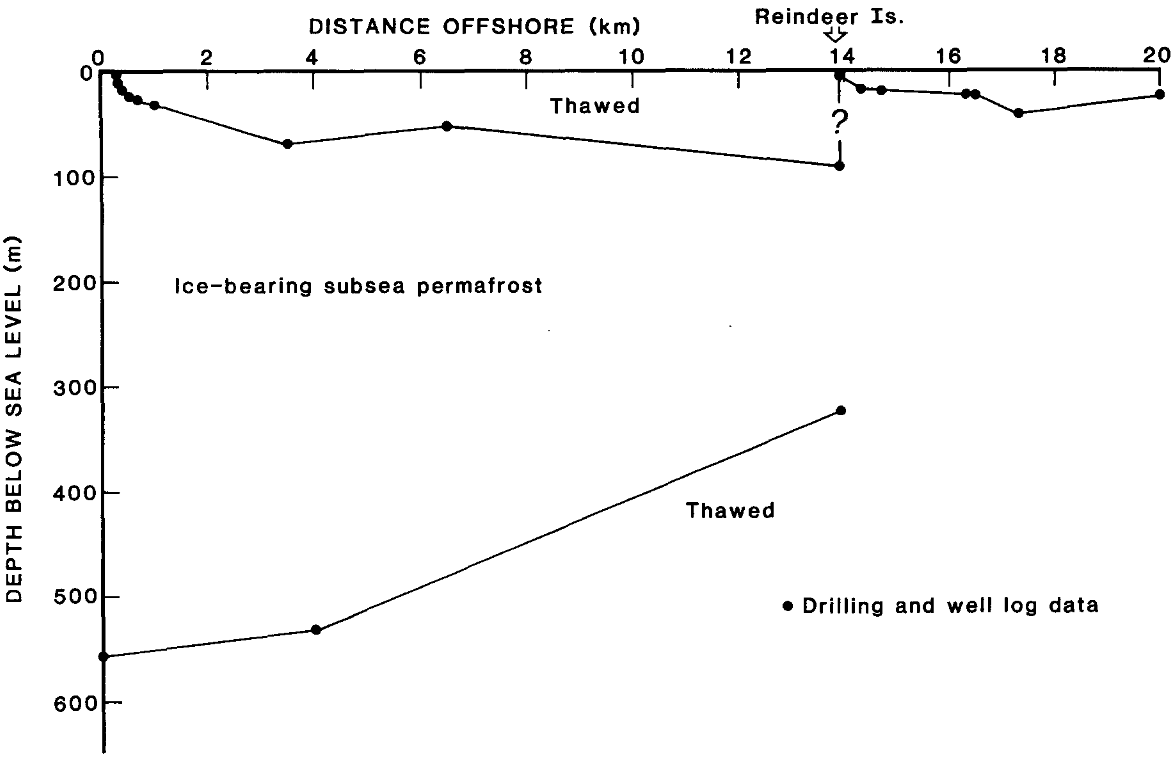

Fig. 5. A profile of ice-bearing subsea permafrost along a line from the North Prudhoe Bay State No. 1 well to Reindeer Island and thence north.

been inundated assuming a shoreline retreat rate of 1 m/y. This interpretation produces a reasonable fit to the drilling data (Osterkamp and Harrison, 1982) but does not hold near the beach nor in the fine-grained sediments north of Reindeer Island. Beyond Reindeer Island, the fine-grained sediments are thought to cause the salt transport to become diffusive and then the relatively slow diffusive salt transport controls the rate of thawing. These semi-quantitative arguments explain the deep thawed layer in the coarse-grained sediments and the relatively shallow thawed layer in the fine-grained sediments even though the fine-grained sediments have been submerged for a longer time.

Thawing at the base of the ice-bearing subsea permafrost after it has been inundated is caused by the geothermal heat flow. An estimate of the basal thawing rate is

$$-\frac{dX}{dt} = \frac{1}{L\phi}\left[J - \frac{k_f(T_b - T_s)}{X} - \frac{2K_f(T_0 - T_s)}{X} \sum_{n=1}^{\infty} (-1)^n \exp(-n^2\pi^2 t/4\tau)\right] \tag{3}$$

where X is the permafrost thickness at time t, $L\phi$ is the latent heat of fusion of the permafrost, J is the geothermal heat flow, K_f is the thermal conductivity of the permafrost, T_b is the temperature at the base of the ice-bearing permafrost, T_0 is the surface temperature prior to inundation, T_s is the new surface temperature and n is an integer (Lachenbruch and Marshall, 1977; Osterkamp, 1983). The time constant

$$\tau = \frac{X^2}{4\kappa} \tag{4}$$

where κ is the thermal diffusivity of the permafrost. Equation (3) predicts an ice-bearing permafrost thickness at Reindeer Island of ≈ 370 m which is in reasonable agreement with the value of ≈ 321 m found from the well log data.

ACKNOWLEDGEMENT

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