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PERMAFROST, HYDRATES AND THE OFFSHORE THERMAL REGIME

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1. Introduction

1.1 In spite of the all-encompassing nature of the title, the actual number of offshore sites at which subsurface temperature data are available is very few. Attempting to provide a definitive understanding of the offshore at this stage is a little like a blind man being given the tip of the elephant's trunk and being asked to describe a complete elephant. The limited data that does exist could not have been gathered without the assistance of many other organizations and individuals within government and industry.

1.2 The results described here form part of a continuing study of the subsurface thermal regime across Canada. Hopefully as the opportunity arises further temperature measurements will be made in offshore wells, thus refining our understanding of the physical processes acting now and in the past in the offshore areas. This paper is confined to observations in the Beaufort Sea adjacent to the Mackenzie Delta, the area shown in Fig. 1 .

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2. The Thermal Regime

2.1 The equilibrium thermal conduction regime of the near-surface can be diagrammatically portrayed by Fig. 2 adapted from Brown (1970). Basically the figure shows a variable temperature in the near-surface with an annual period which attenuates rapidly with depth below the surface, an active layer which develops in the summer months when ground temperatures are highest or conversely a frost-prone layer when they are lowest, and a temperature which increases steadily with depth at a rate corresponding to the geothermal gradient below the influence of the annual variation. This latter gradient is dependent on the earth's heat flux and the thermal conductivity of the material present.

2.2 Such a temperature distribution is equally applicable to the subsea situation where a variable temperature may exist corresponding to bottom-water temperature fluctuations over a year and an active or frost-prone layer may develop. Again below the maximum depth of penetration of the annual "wave", the geothermal gradient determines the rate of rise of temperature with depth.

2.3 Under these constraints a similar regime should be observed beneath the waters of the Beaufort Sea. The largest annual variation is observed beneath shallow waters which freeze to bottom in winter and come within the influence of the Mackenzie outflow in the summer months. Mean annual bottom waters may be positive or negative. Beneath waters deep enough not to freeze completely in winter but within influence of Mackenzie outflow mean temperatures are positive to water depths of approximately 15 m below which there is sufficient mixing with ocean water to maintain negative mean temperatures. Beyond the Beaufort shelf in much deeper water, mean temperatures are once again positive. At the greater water depths the annual variation of bottom-water temperature is a few tenths $^{\circ}$C at most. Thus a wide band of sea-bottom with negative temperatures is found in water depths of 15 m to 200 m. The minimum temperatures encountered are approximately -1.8°C and thus the range of permafrost thicknesses will not exceed 100 m.

2.4 Deviations from the ideal equilibrium temperature distribution can be interpreted in terms of surface temperature changes at the surface from year to year, heat transport by moving fluids, a change in heat flux from depth and a variety of other geologic parameters. An analysis of the measured subsurface temperature curves (corrected to eliminate the effect of drilling) by their deviation from the ideal can give considerable, admittedly non-unique, insight into these complex processes.

2.5 The drilling of a well disturbs the equilibrium thermal regime because circulated drilling fluids are normally at different temperatures to the normal ground temperatures. Fig. 3 shows the disturbance from and return to equilibrium of a northern offshore well. Such disturbances are relatively short-term and this particular well shows every indication of a simple logarithmic return to equilibrium.

3. Visual Observations of Ice in Beaufort Sea Sediments

3.1 When engineering drilling was first carried out in the offshore Beaufort Sea by the Arctic Petroleum Operators Association in the early 1970's, ice was encountered in the subsea sediments at 4 out of 11 of the sites. Included in these sites were areas where mean sea-bottom temperatures were believed positive (Mackay, 1972).

3.2 Shallow drilling by the Geological Survey of Canada in Kugmallit Bay in the spring of 1974 recovered cores of frozen sand in two of four holes. The presence of a frozen horizon was inferred in three of the holes from changes in drilling speed and mud circulation temperatures as well as from downhole temperature measurements discussed in the following section (Hunter et al., 1974).

3.3 A hole drilled by Canmar at the Tingmiark deep well site in 1975 encountered a frozen sand at depths of 34 to 43 m below sea-bottom, in a water-depth of 30 m (O'Rourke, 1975).

3.4 Hydraulic drilling conducted 32 km north of Pullen Island in 12 to 16 m of water brought to the surface frozen sand at a depth of 35 m in one of three holes. Although a similar programme in Shallow Bay recovered no frozen core, changes in drilling speed and downhole temperature measurements suggested the presence of frozen material (Judge et al., 1976).

3.5 Considerably more engineering drilling than reported here has been carried out in the Beaufort Sea. The results of such programmes however remain confidential.

4. Subsurface Temperatures in the Offshore

4.1 Subsurface temperature profiles should not only indicate the areas and depths where ice may be found but should additionally provide insight into the complex sequence of events which left ice in the sediments. This section describes the offshore observations derived from a variety of programmes by many different techniques.

4.2 The profiles determined at four sites in Kugmallit Bay are summarized in Fig. 4. Since the results have been presented previously (Judge and Hunter, 1975; Hunter and Judge, 1976) no detailed discussion need be repeated here. Basically the results shows a thawed section at positive temperatures, but with negative gradients, above an ice-bonded sand at marginally negative temperatures and with negative temperature gradients to bottom-hole. Although the results show clearly a positive mean sea-bottom temperature this temperature is not constant from year to year. The 0°C isotherm corresponds closely with the depth of ice-bonding in the sand suggesting fresh-water interstitial ice. The discovery, beneath 3 m to 5 m of warm water, of ice-bonded permafrost at marginally negative temperatures confirms Kugmallit Bay to be underlain by relic permafrost.

4.2 Through the cooperation of Imperial Oil a cable was placed to a depth of 520 m in Adgo P-25, an artificial island site in the western Mackenzie Delta. Onshore studies had suggested that the offshore should contain patches of discontinuous permafrost only where sea-ice is frozen to the sea-bottom in winter (Judge, 1974). The Adgo results confirmed this, exhibiting an apparent mean sea-bed temperature of 2°C and a mean gradient of 18 mkm^{-1} prior to island construction (Taylor and Judge, 1976). Fig. 5 shows the temperature measurements for a period of 8 months prior to destruction of the cable and Fig. 3 shows the simple logarithmic return to equilibrium.

4.3 Several bottom-hole temperature measurements were made during Canmar's test drilling at the Tingmiark site. The hole drilled 80 km north of Tuktoyaktuk to a depth of 60 m below sea-bottom encountered temperatures of -1.6°C in silty clays at bottom-hole, thus confirming the presence of relic permafrost.

4.4 Two thermistor cables were installed to depths of 30 to 50 m and monitored for up to 500 hours in jet-drilled holes in Shallow Bay. Both of the temperature curves shown in Fig. 6 exhibit similar characteristics of high positive temperatures in the near-surface, negative temperature gradients below and negative bottom-hole temperatures. As in the Kugmallit Bay results a close correspondence exists between permafrost depth and the inferred depth of ice-bonding suggesting a pure sand with intestitial fresh-water ice. Judge et al. (1976) have suggested two alternative explanations for the observations; one based on the existence of relic permafrost and a second on the variation of sea-bottom topography in very shallow water.

4.5 Three further cables were installed to depths of 30 to 59 m beneath 12 to 16 m of water along an east-west line 32 km north of Pullen Island. As shown in Fig. 7 the temperature results differ dramatically from each other. Although in all three cases the temperatures at the sea-bottom are similar at -1.5^{o}C, the westernmost site T-4 exhibits a positive temperature gradient of 57 mkm^{-1} with the temperature rising to 0^{o}C at 35 m, whereas site T-3, 7.6 km to the east, exhibits a negative temperature gradient of 15 mkm^{-1} with the temperature decreasing to -1.9^{o}C at 44 m. T-5 the easternmost site is similar to T-3 although the cable failed before conclusive proof was obtained. Judge et al. (1976) have inferred that while T-3 and T-5 are underlain by relic permafrost, T-4 is not.

5. The Regional Thermal Regime

5.1 Of the observed subsurface temperatures to date those in Kugmallit Bay and in some sections of the Beaufort Sea (Tingmiark, T-3, T-5) seem to indicate areas in which the subsurface thermal regime is not in equilibrium and which are underlain by relic permafrost. These same areas are underlain by materials with high seismic velocities interpreted as due to the presence of ice-bonding (Hunter et al., 1976).

5.2 Conversely the results at Adgo P-25 in the western Delta and in parts of the western Beaufort Sea suggest areas underlain by no permafrost or by permafrost which has grown to the current depth. In such areas the subsurface is in or near thermal equilibrium with the earth's flux and present sea-bottom temperatures.

5.3 Although the volume of temperature data is very limited the few results to date do confirm the theoretical speculations of Mackay (1972), Judge (1974) and Hunter et al. (1976) in which the permafrost distribution is related to the sea-level and glacial history of the area.

6. Gas Hydrates

6.1 Ice in nature occurs in two forms, as conventional ice or as a gas hydrate. Natural gas hydrates of water and hydrocarbon gases have been documented on the floors of the deep oceans (Stoll et al., 1971) and in several terrestrial environments (Makogan et al., 1971, in the USSR and Bily and Dick, 1974, in the onshore Mackenzie Delta). In view of their presence in the onshore it is of significance to examine their possible occurrence offshore. Fig. 8 shows the phase equilibrium diagram for an assemblage of gas hydrate, water, ice and either methane (s.g. 0.55) or a natural gas (s.g. 060), adapted from Katz et al. (1959). Pressure has been converted to depth assuming a hydrostatic pressure gradient.

6.2 Superimposed are typical observed onshore temperature curves for the eastern (old) Delta and the western (young) Delta. Temperatures in the eastern Delta are low enough for the formation of a methane hydrate from 250 m to 750 m, or a hydrate of a gas of heavier hydrocarbons to depths in excess of 1000 m, whereas temperatures in the western Delta could support a hydrate of heavier hydrocarbons only and to a depth of only 600 m.

6.3 Also shown are simulated subsurface temperatures for the offshore; both for sand or clay sediments beneath 100 m of water supposing the sediments in thermal equilibrium, and for those beneath 20 m. of water containing relic ice-bonded permafrost. Only those areas underlain by relic permafrost can support a methane hydrate although all areas are able to support hydrates, of a hydrocarbon gas with an s.g. of 0.60.

7. Conclusions

7.1 Thermal profiling of the offshore areas of the Beaufort Sea can provide valuable evidence for the present permafrost and hydrate distribution and character as well as provide some understanding of permafrost genesis and geological history.

7.2 Obviously an explanation for the regional distribution of permafrost in the Beaufort Sea based on a small number of thermal observations is open to question. The combination of thermal and seismic profiles do provide strong supporting evidence for the models proposed in Hunter et al. (1976).

7.3 Further thermal profiling and additional geophysical profiling using electrical and seismic methods are required. Part of future thermal profiling should include instrumentation of both offshore artificial island sites and Dome's drill ship sites.

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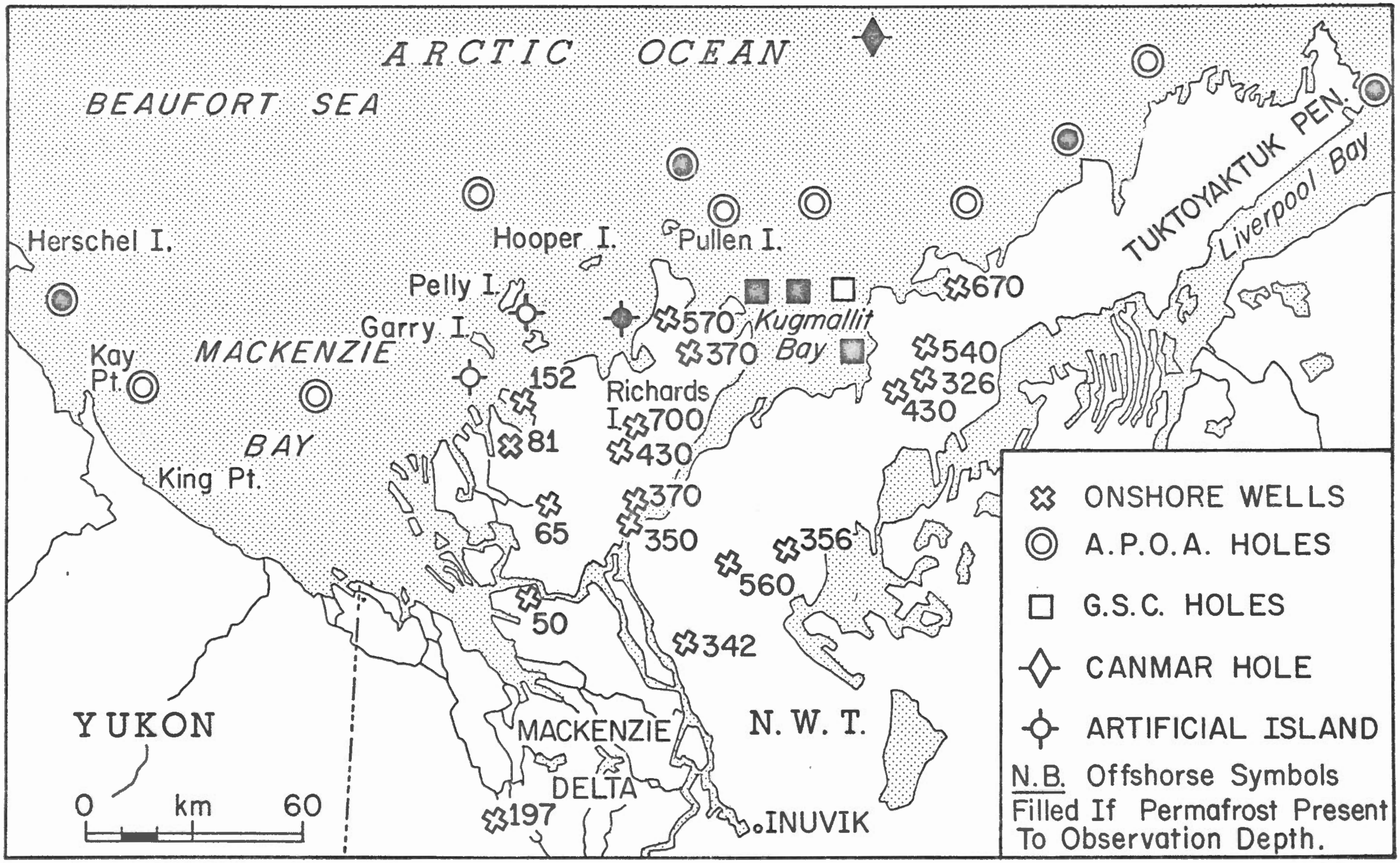


Figure 1 Permafrost Observations in the Beaufort Sea - Mackenzie Delta

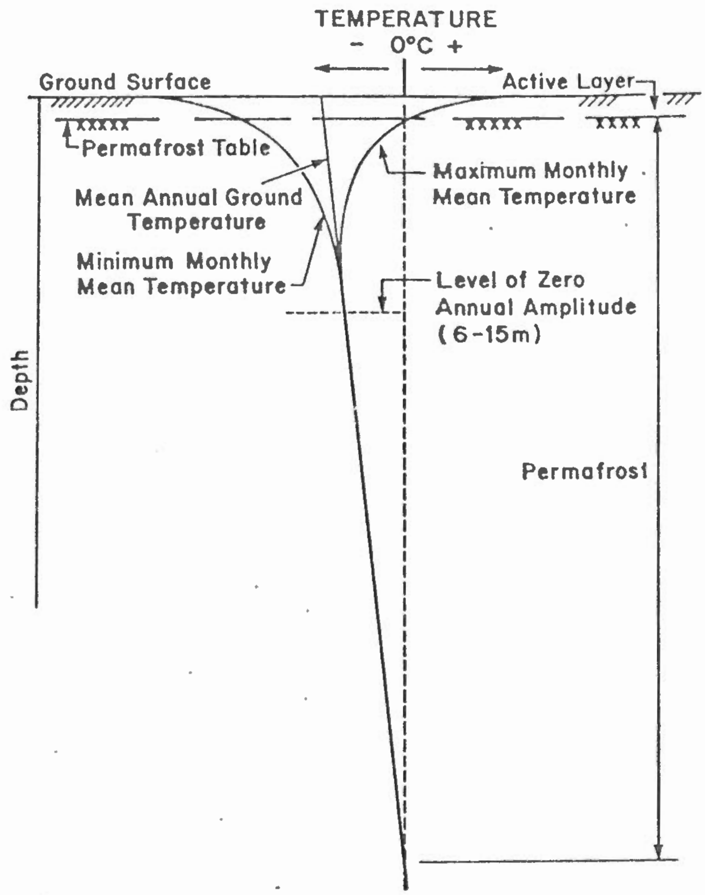


Figure 2 Diagrammatic Sketch of the Thermal Regime in Permafrost

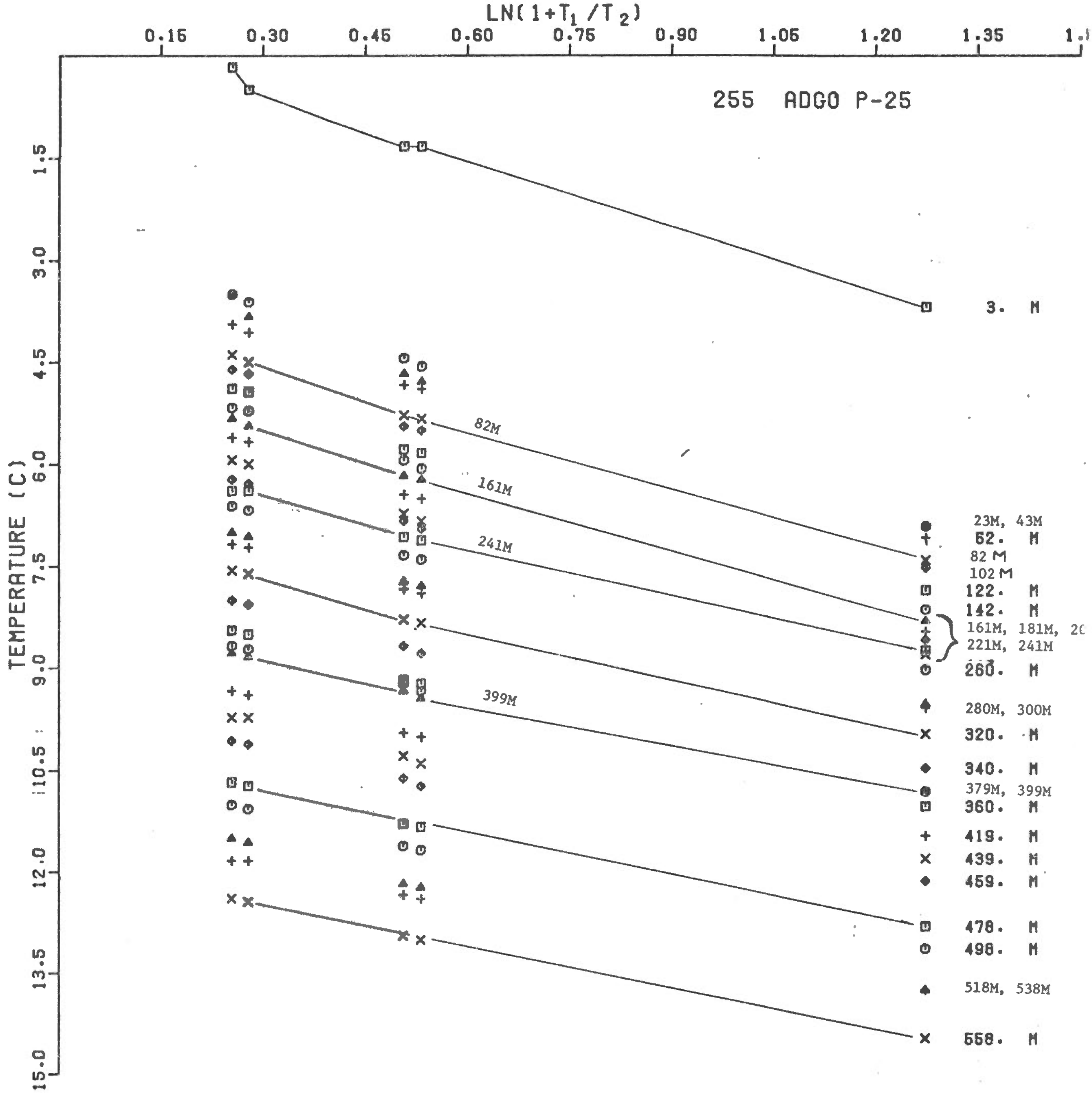


Figure 3. The Return to Thermal Equilibrium Of A Northern Offshore Well

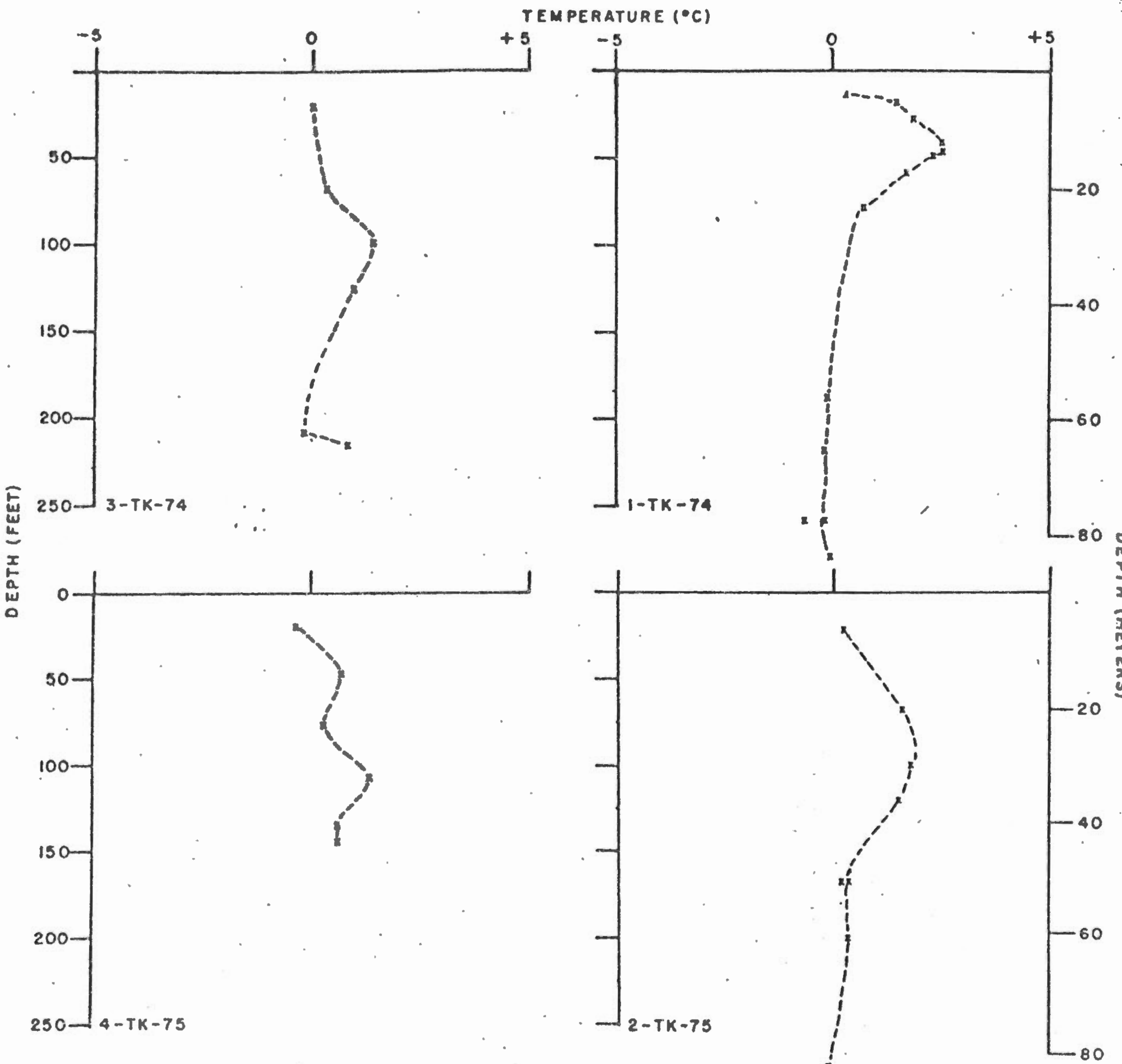


Fig. 4 Sub-surface temperatures measured in the Kugmallit Bay drillholes.

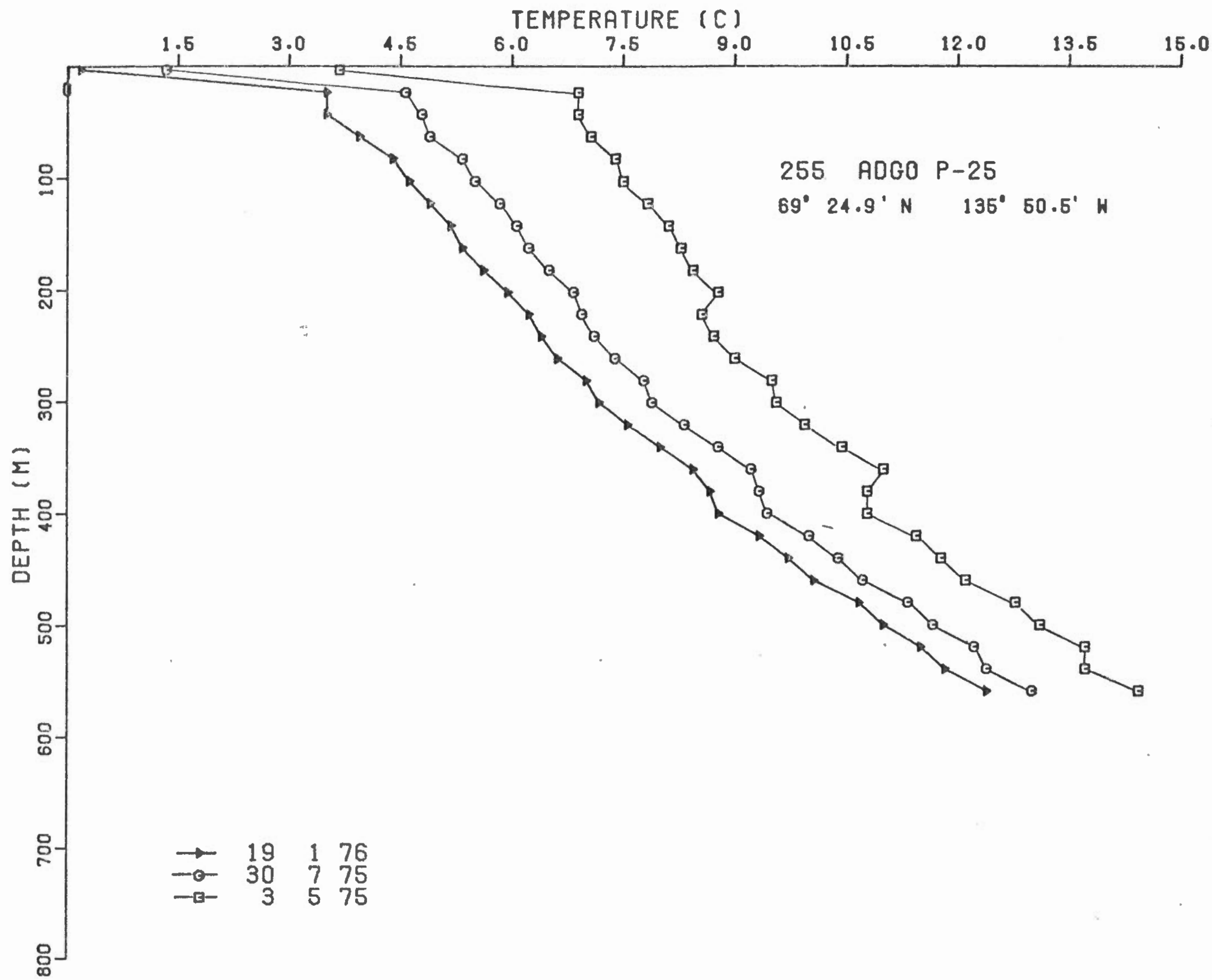


Figure 5. Subsurface Temperatures in Adgo P-25

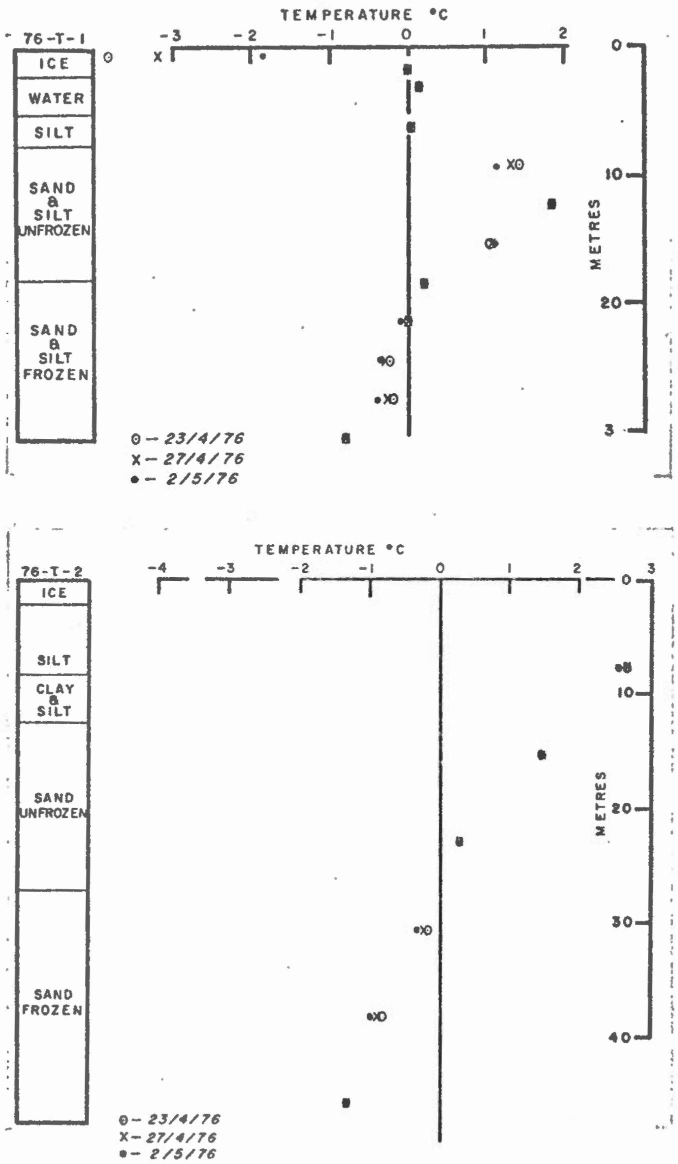
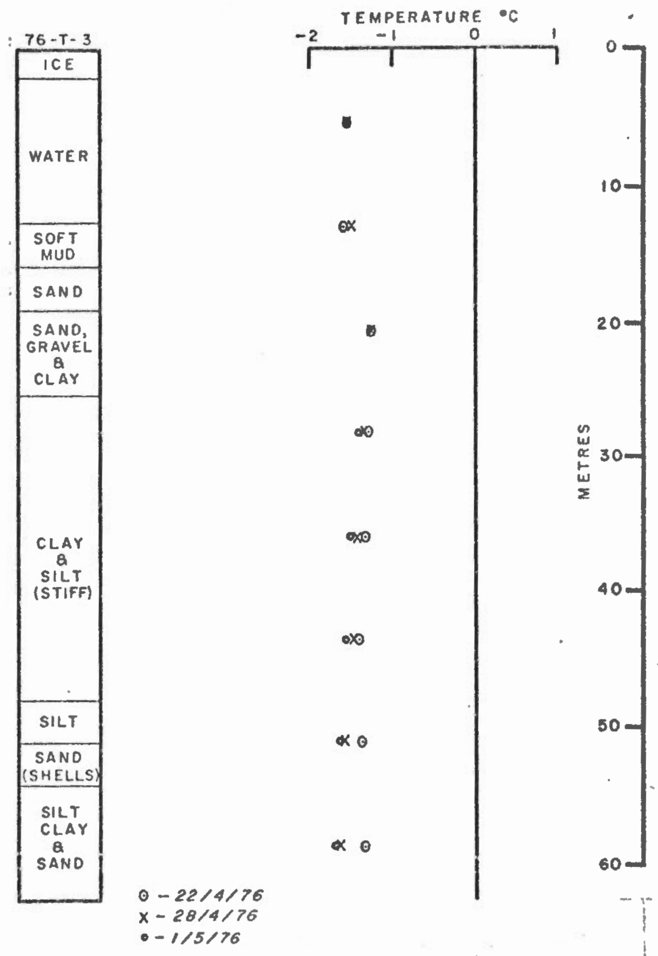
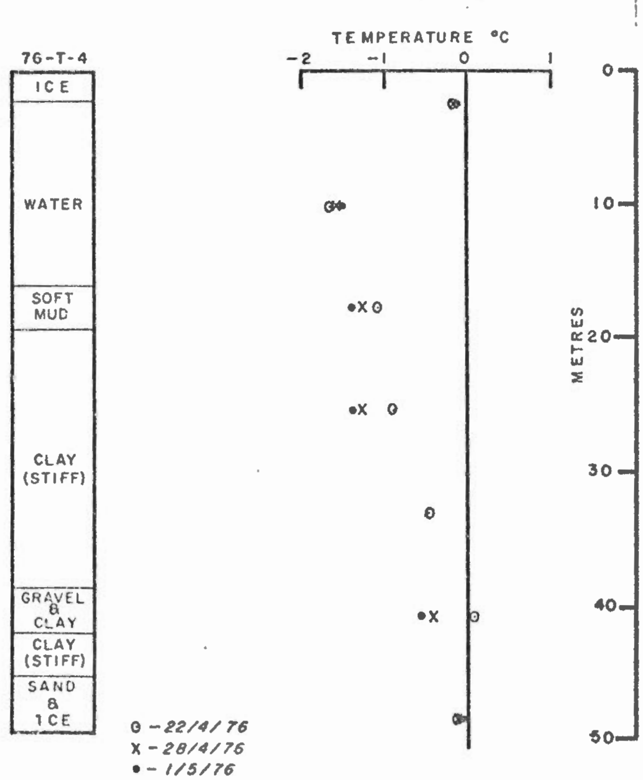


Figure 6. Subsurface Temperatures in Shallow Bay





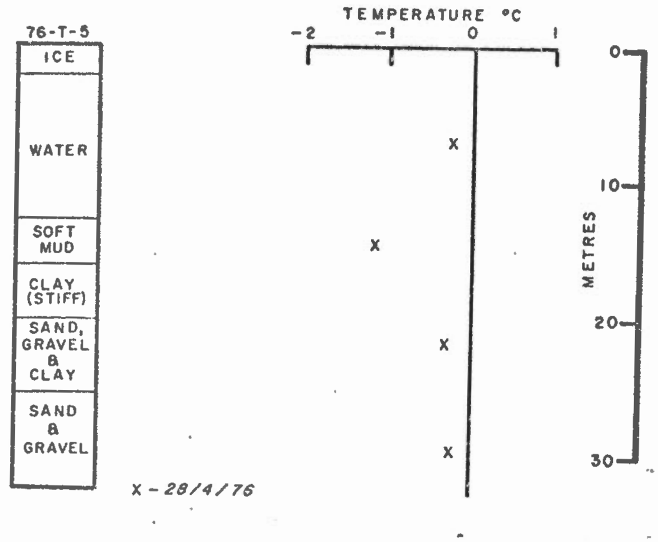


Figure 7. Subsurface Temperatures in the Beaufort Sea

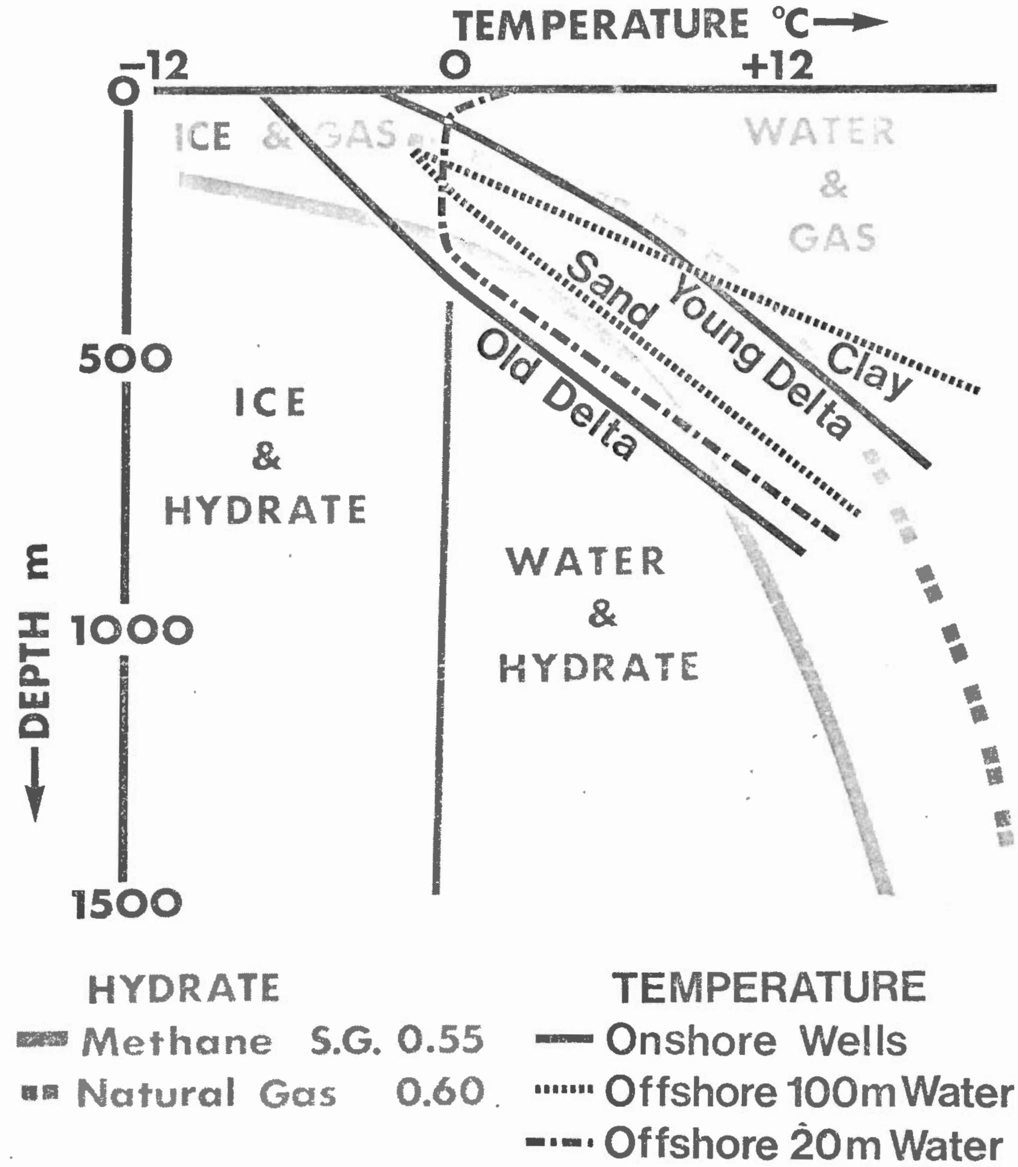


Figure 8. Predicted Hydrate Distribution in the Beaufort Sea