In situ hydrates under the Beaufort Sea shelf

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The evidence for the existence of *in situ* hydrates within the Beaufort Sea shelf is reviewed and the associated implications for hydrocarbon development are briefly discussed.

On examine dans le présent article l'existence *in situ* d'hydrates de gaz naturel sur la plate-forme de la mer de Beaufort et les implications du point de vue de la formation d'hydrocarbures.

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Introduction

Hydrates are ice-like solid mixtures of gas and water. Naturally occurring gas hydrates (*in situ* hydrates) can occupy the pore spaces of soil and porous rocks in regions where natural gas and water co-exist in cool high-pressure environments. These conditions are common in porous sediments both, off-shore in water depths greater than 200 m and, on-shore in continuous permafrost regions.

In northern Canada, *in situ* hydrates have been identified under the permafrost in the Mackenzie delta (Bily and Dick 1974) and in the Arctic islands (Franklin 1981). Thermodynamic conditions are also favourable for the existence of *in situ* hydrates within

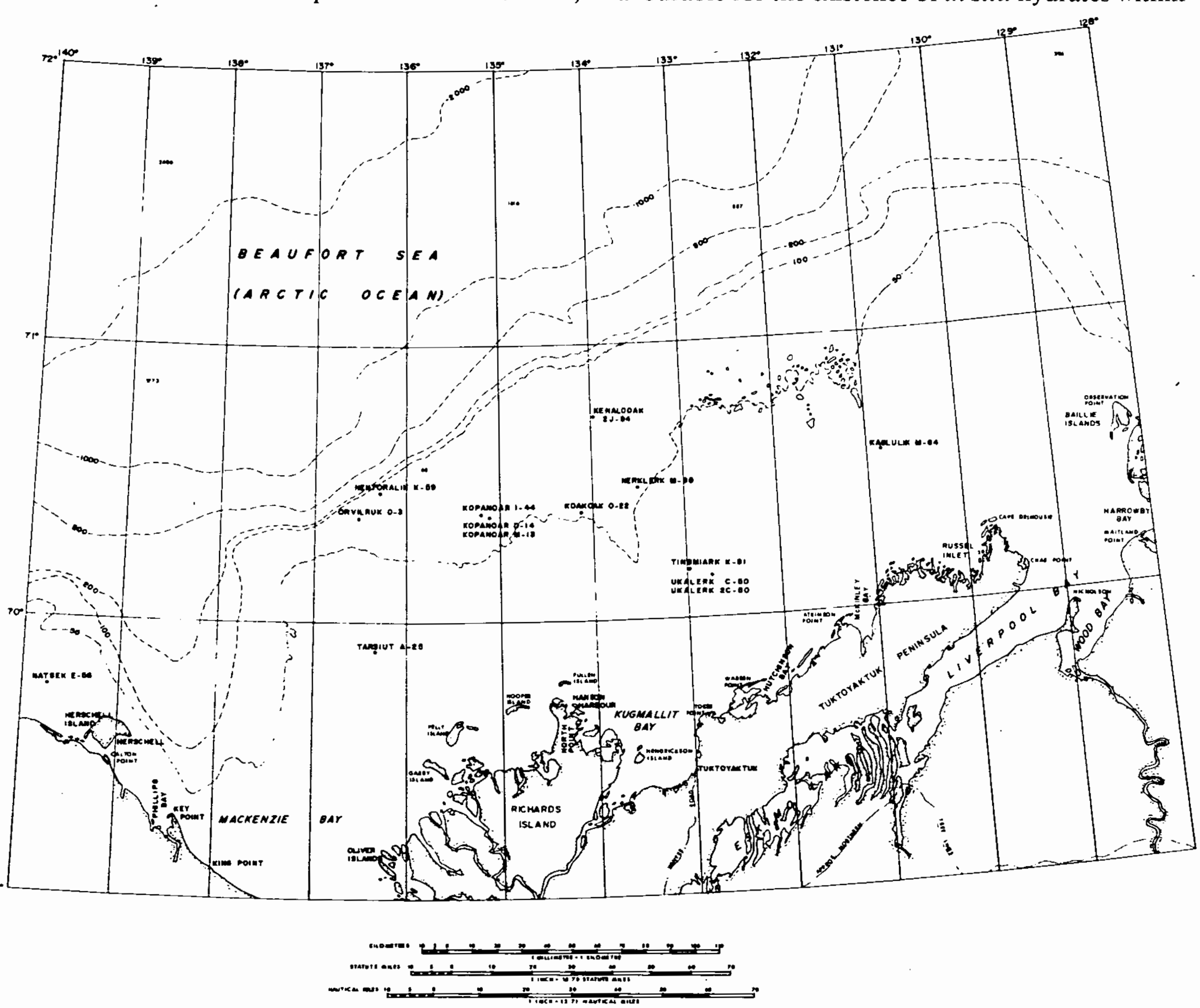

FIGURE 1. Dome exploration wells on the Beaufort Sea shelf.

the porous sediments of the Mackenzie River valley, the Arctic coast-line, and the Arctic Ocean.

The Beaufort Sea shelf is particularly favourable for *in situ* hydrate development since high concentrations of methane gas exist beneath the permafrost in the young, abnormally pressured sediments.

Dome Petroleum has been drilling for oil and gas on the Beaufort Sea shelf since 1976. Exploration wells have been drilled in water depths ranging from 18 to 70 m (Figure 1) and both permafrost and *in situ* hydrates are believed to exist in all of the wells. Both the permafrost and hydrates are relict in nature and, as such, are degrading. The *in situ* hydrates are now being studied with considerable interest since their presence could affect the development of hydrocarbons from the Beaufort Sea shelf. Drilling and production engineers view them as a design issue in completing wells to deeper objectives, and geologists are most interested in them as a potential energy resource or an indicator of deeper hydrocarbons.

This paper documents the evidence for *in situ* hydrates at four typical wells on the Beaufort Sea shelf (Nerlerk, Koakoak, Ukalerk, and Kopanoar) and briefly discusses the associated implications for hydrocarbon development.

In Situ Hydrate Prediction Under the Beaufort Sea

The following information is required in order to predict the occurrence of *in situ* hydrates: a) Composition of formation gases; b) composition of formation water; c) formation pore pressures; and d) formation temperatures.

Formation gases in the upper 2000 m of sediment in the Beaufort Sea usually consist of at least 99.5 per cent methane. Therefore, only methane hydrate is discussed in this paper.

The phase diagram of methane hydrate (methane and pure water), in the temperature range −5 to 20°C is summarized in Figure 2. The effect of increasing water salinity on the phase diagram is to

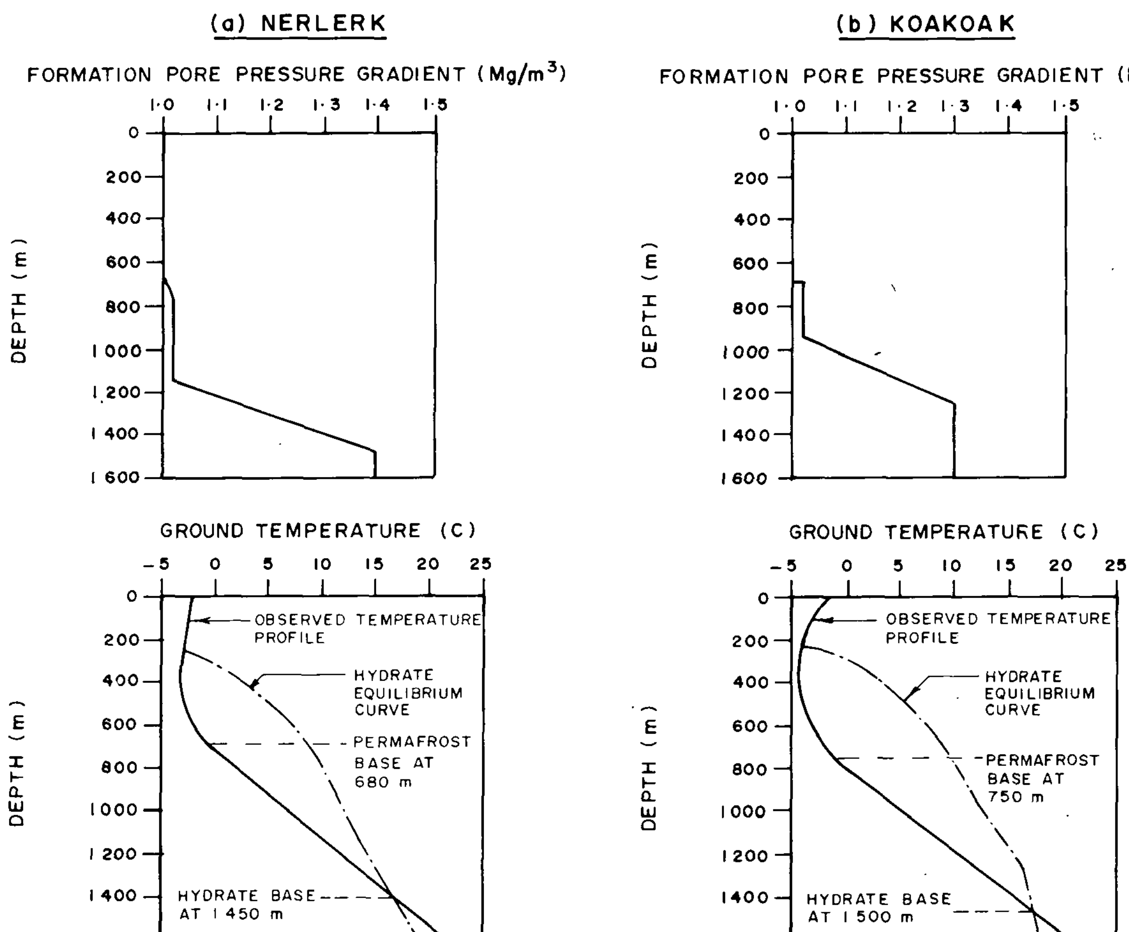

FIGURE 3a and b. Prediction of *in situ* hydrate.

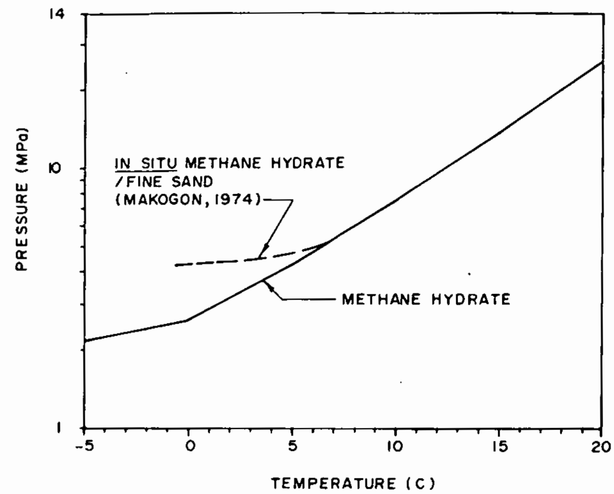

FIGURE 2. Phase diagrams for methane hydrate and *in situ* methane hydrate/fine sand.

inhibit hydrate formation. The salinity of the formation water in the Beaufort Sea, in the depth range 200 to 2000 m, is approximately 10 mg/l (NaCl) and, the influence of salinity on the phase diagram of methane hydrate is insignificant.

The equilibrium conditions for the formation of methane hydrate are relatively well documented. However, the formation of *in situ* hydrates in the pore spaces of porous soils and rocks is poorly understood.

Makogon (1974) described the results of laboratory tests undertaken to determine the equilibrium conditions of *in situ* hydrate in fine sands. These experiments demonstrated that lower temperatures or higher pressures are required in order to form *in situ* hydrate in fine sand. The phase diagram for *in situ* hydrate in fine sand is also summarized in Figure 2. The laboratory results of Baker (1974) and Stoll (1974) suggest that the phase diagram for *in situ* methane hydrate in medium sands is practically iden-

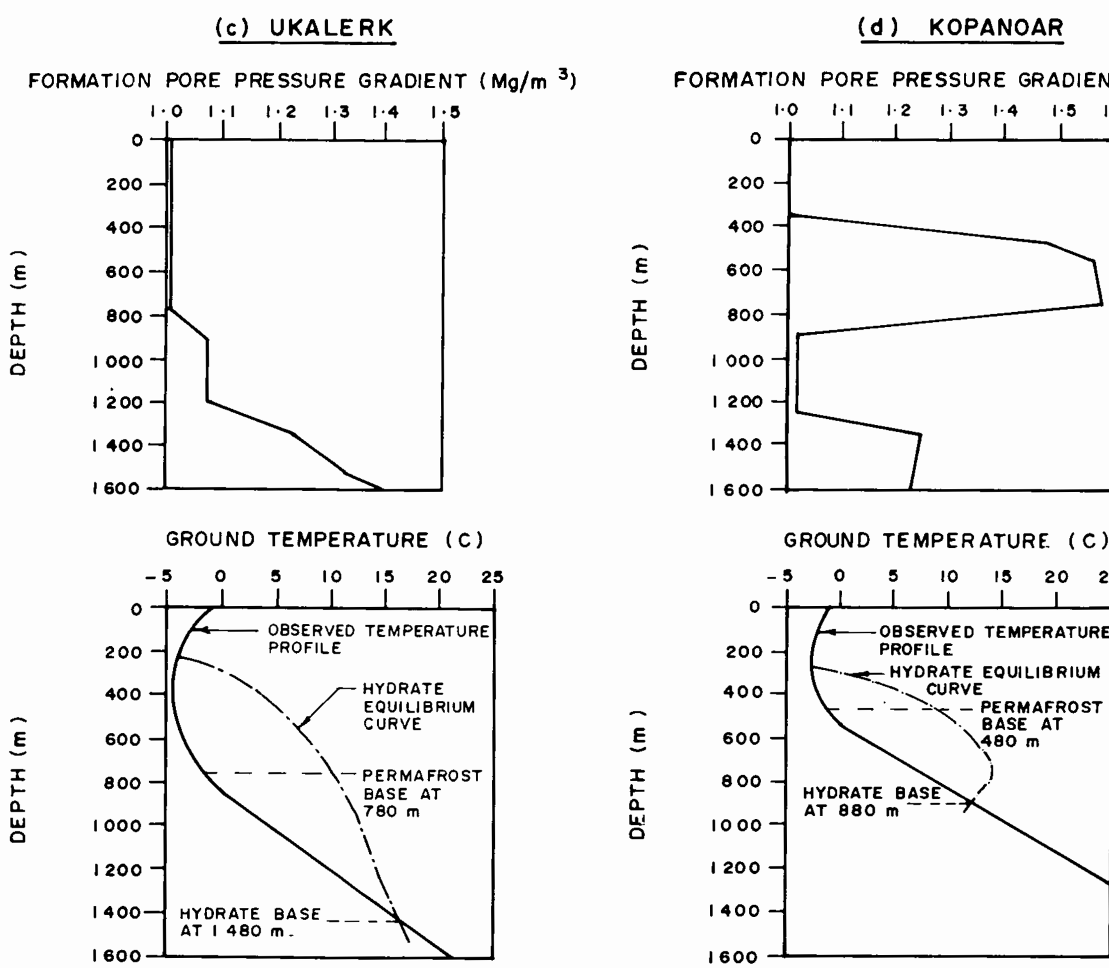

FIGURE 3c and d. Prediction of *in situ* hydrate.

tical to that of methane hydrate. There are no published equilibrium curves for *in situ* hydrates in clays or silts. However, it is speculated that there is a threshold pore-size (or grain-size) within which *in situ* hydrate cannot exist.

In this review, the predicted hydrate zones are based upon the phase diagram for methane hydrate.

Formation temperatures and pore pressures for Nerlerk, Koakoak, Ukalerk, and Kopanoar are summarized in Figure 3. Permafrost thicknesses at these locations vary from 450 to 780 m. Ground temperatures within the permafrost zone are almost constant, varying between −1 and −4°C, and are indicative of relict permafrost.

The geothermal gradient below the permafrost is typically 0.03°C/m. Formation pore pressures are approximately hydrostatic within the permafrost zone, and abnormally pressured below the permafrost. Pore pressure gradients below the permafrost vary between 1.3 and 1.6 mg/m^3.

The phase diagram for methane hydrate (*see* Figure 2) has been transformed into depth–temperature curves for all three locations and superimposed over the temperature profiles in Figure 3. The intersections of the temperature profile and hydrate equilibrium curve define the upper and lower depth boundaries of *in situ* hydrate.

Similar analyses have also been performed at all other locations drilled by Dome in the Beaufort Sea. The results of these analyses are summarized in Table 1. It transpires that the base of the predicted *in situ* hydrate varies from 800 m in the west to at least 1500 m in the east, and the base of observed permafrost varies from 400 m in the west to at least 780 m in the east.

Evidence for *In Situ* Hydrates Within the Beaufort Sea Shelf

In the past, *in situ* hydrates have been detected using the following methods: a) Analysis of cores;

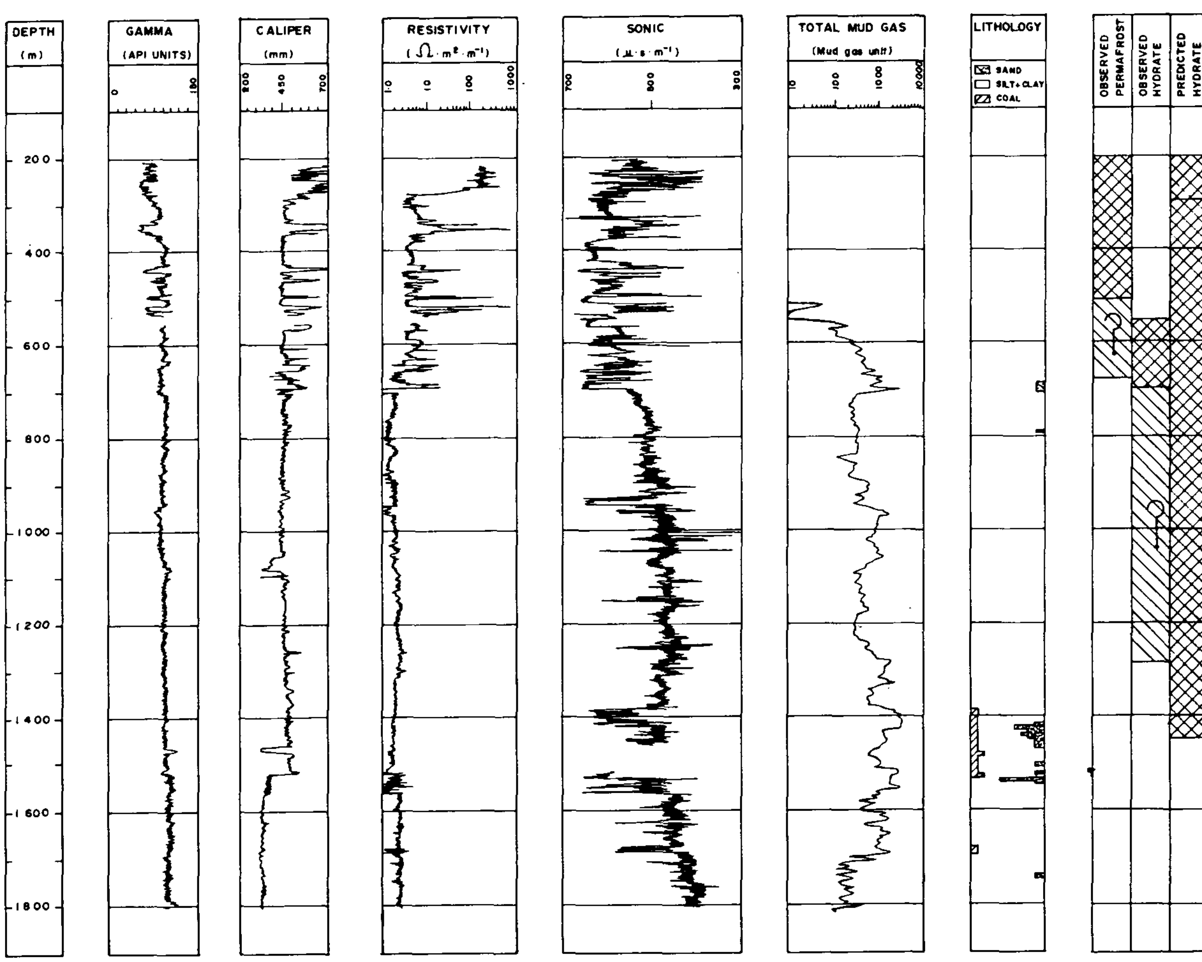

FIGURE 4. Wireline and mud-gas logs for Nerlerk.

TABLE 1. Observed permafrost base and predicted hydrate base

Well	Observed base of permafrost (m below m.s.l.)	Predicted base of *in situ* hydrate (m below m.s.l.)
Tarsiut	400	800
Orvilruk	400	800
Nektoralik	440–670	900–1300
Kopanoar	480	880
Koakoak	750	1500
Kenalooak	600–925	1200–1560
Nerlerk	680	1450
Ukalerk	780	1480
Kaglulik	400+	800+
Kilannak	300	700

b) drillstem tests; c) analysis of seismic records; and d) analysis of wireline and mud-gas logs.

The hydrocarbon reservoir horizons of Dome's off-shore wells are well below the hydrate zone and so no attempt has yet been made to retrieve cores or conduct drillstem tests of suspected *in situ* hydrates.

In permafrost regions, the presence of ice-bonded sediments complicates the interpretation of seismic records since the acoustic properties of ice and hydrate are very similar. Consequently, attempts to identify *in situ* hydrates from seismic records have been largely unsuccessful.

The most convincing evidence of *in situ* hydrates has been obtained from wireline and mud-gas logs. Down-hole records for Nerlerk, Koakoak, Ukalerk, and Kopanoar are presented in Figures 4, 5, 6, and 7, respectively.

High resistivities and acoustic velocities and low mud-gas readings clearly indicate the presence of permafrost in the upper 600 to 800 m. High values of resistivity, acoustic velocities, and formation gas below this depth are interpretated to be *in situ* hydrate (Bily and Dick 1974; Makogon 1974). Therefore, *in situ* hydrates exist at Kopanoar between depths 700 to 740 m (*see* Figure 7), and at Ukalerk between depths of 1150 to 1250 m (*see* Figure 6). In

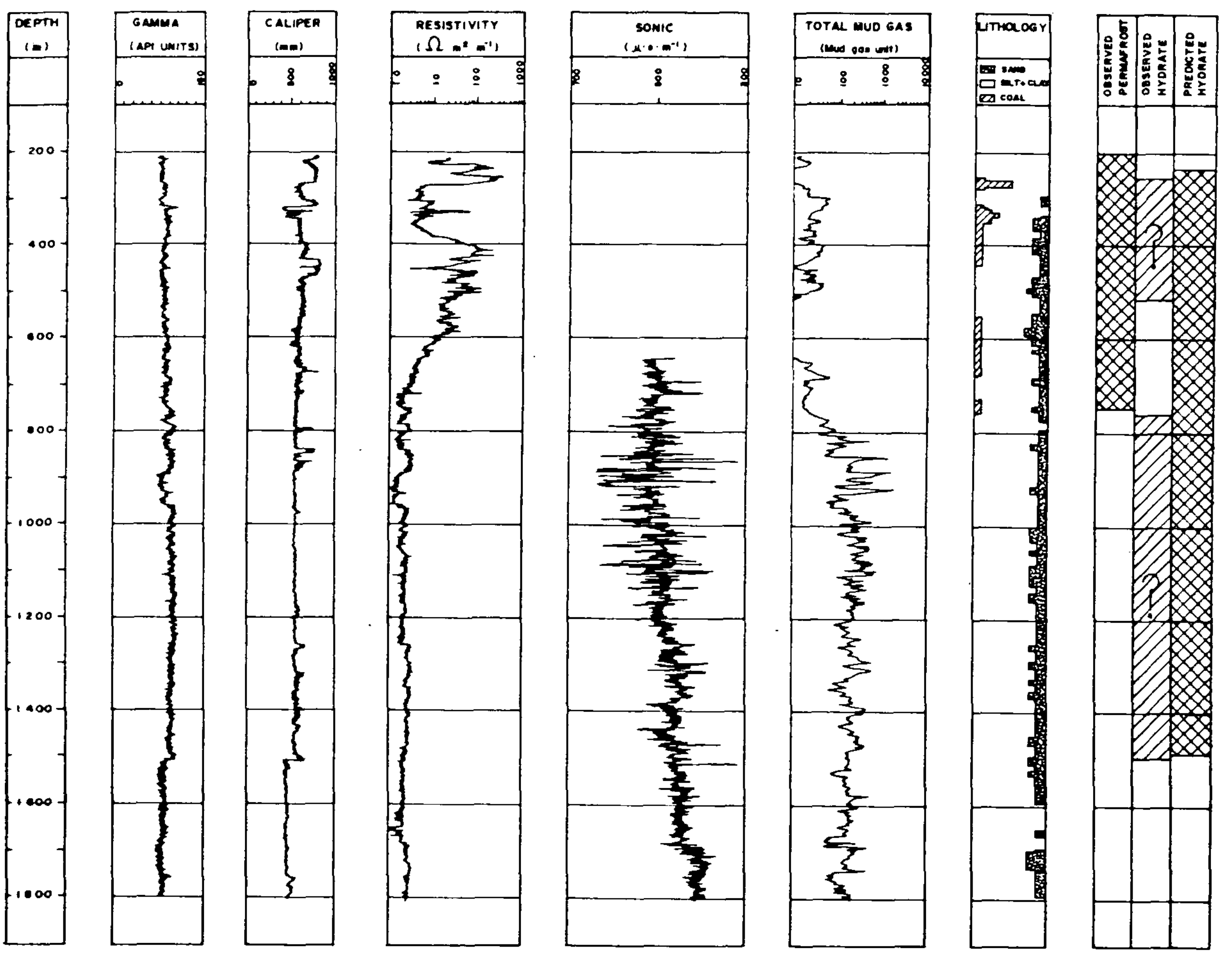

FIGURE 5. Wireline and mud-gas logs for Koakoak.

both cases, the *in situ* hydrate occurs in fine-grained sands.

High concentrations of formation gas have also been detected within the sands at the base of the permafrost at Nerlerk between depths of 510 to 680 m (*see* Figure 4). These sands displayed high sonic velocities and resistivities, but ground temperatures at this depth were not measured and so it is not possible at this time to judge whether the sands are permafrost or *in situ* hydrate.

Significant quantities of formation gas have also been detected within the fine-grained sediments throughout the predicted *in situ* hydrate zone. The higher concentrations of gas were associated with cycle skipping on the sonic log and little or no response on the resistivity log. This phenomenon is well illustrated at Kopanoar between depths of 740 and 990 m (*see* Figure 7). The sonic activity is particularly apparent throughout hole sections which are known to contain numerous thin sand stringers. The holes were drilled overbalanced and all mud-gas was circulated out prior to logging. Therefore, it is speculated that the cycle skipping is due to slow melting (during logging) of thin accumulations of *in situ* hydrate within the sand stringers.

Indirect evidence for the existence of *in situ* hydrates may also be tentatively inferred from formation pore-pressure plots (*see* Figure 3). It is postulated that the formation pore pressures should be higher in the vicinity of thawing hydrates. Thus, at Nerlerk, Koakoak, and Ukalerk where permafrost extends to 600 to 800 metres, thawing would be greatest at the base of the hydrate zone and should correspond with high formation pore pressures. On the other hand, at Kopanoar, where formation temperatures are higher, thawing could be expected throughout the hydrate zone. Therefore, formation pore pressures should be high throughout the hydrate zone.

The above hypothesis is clearly supported by the pore-pressure data (*see* Figure 3), and by drilling data

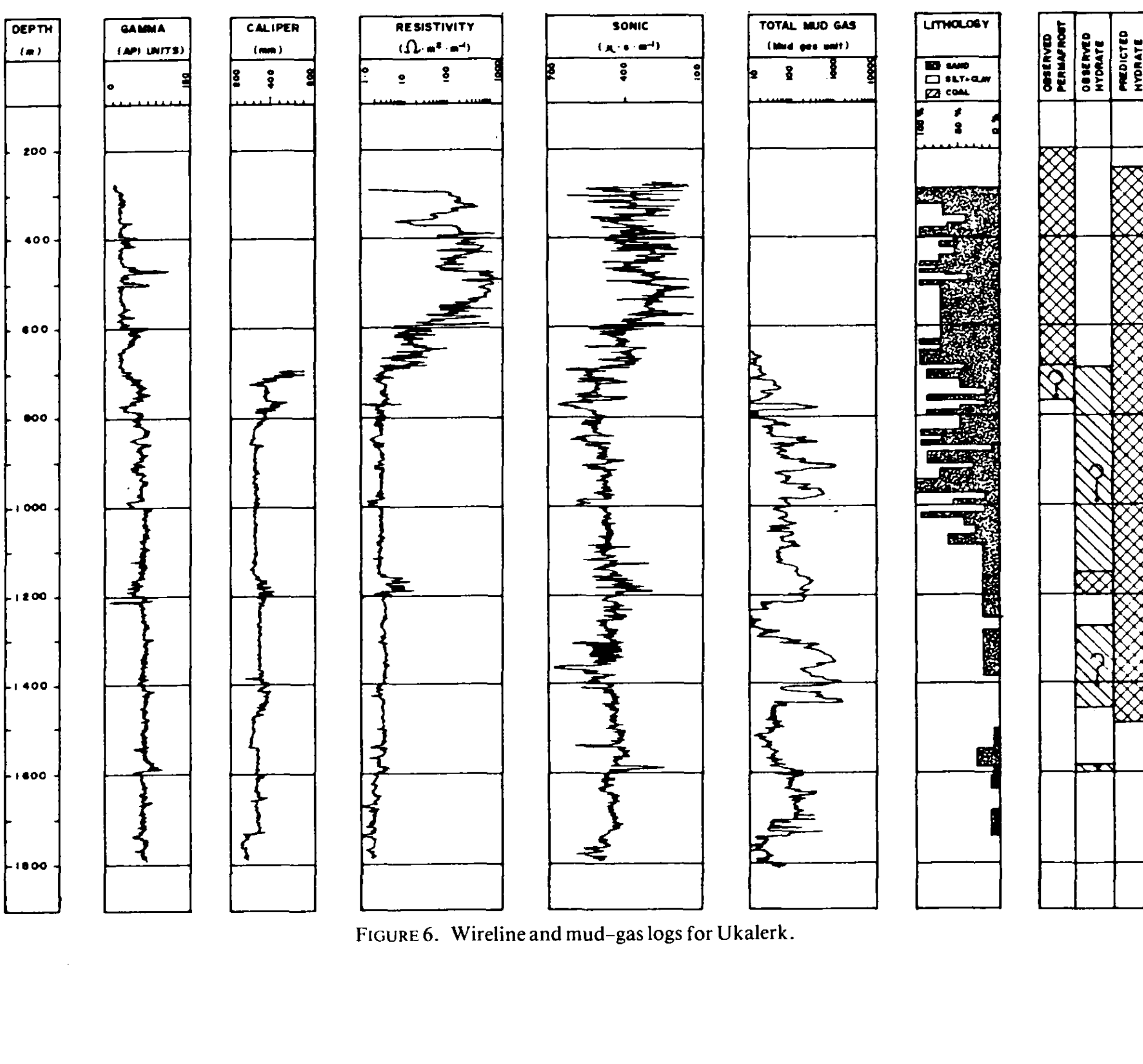

FIGURE 6. Wireline and mud-gas logs for Ukalerk.

collected elsewhere in the Beaufort Sea. Nevertheless, the presented data is not conclusive and the ideas should be viewed as tentative.

Implications of *In Situ* Hydrates

Special precautions have to be taken when drilling through *in situ* hydrates. The following procedures have proven to be the most successful in the Beaufort Sea. During penetration of the *in situ* hydrate, slow drilling rates are maintained in order to control gas influx from the hydrate cuttings. In addition, very careful mud weight control has to be exercised in order to hold back abnormally pressured free gas which usually co-exists with the *in situ* hydrate. After the *in situ* hydrate has been penetrated, cool mud is used in order to inhibit further hydrate decomposition during deeper drilling.

Very high pressures are generated when hydrates decompose under constant volume conditions (Makogon 1974). Therefore, both exploration and production wells must be designed to withstand collapse pressures generated by melting *in situ* hydrates. Fortunately, *in situ* hydrates do not melt under constant volume conditions around a wellbore. Decomposition pressures are limited by the strength of the formation. Pressure relief can occur by one or more of the following mechanisms: a) Gas seepage through porous soils; b) formation fracture; c) elastic expansion of the formation; and d) plastic expansion of the formation (yield).

Thus far, there has been no evidence of decomposition pressures high enough to induce casing collapse. It appears as though the formations in the Beaufort Sea are either soft enough, or else permeable enough, to accommodate hydrate decomposition pressures.

In situ hydrates are also a potential energy resource. The hydrates at Kopanoar probably could be exploited by producing gas from the abnormally pressured free gas zones above and below the hydrates. However, to date, insufficient *in situ* hydrate has been discovered to justify gas production from these zones. Certainly, the *in situ* hydrate finds are much less significant than those discovered in the Mackenzie Delta (Bily and Dick 1974).

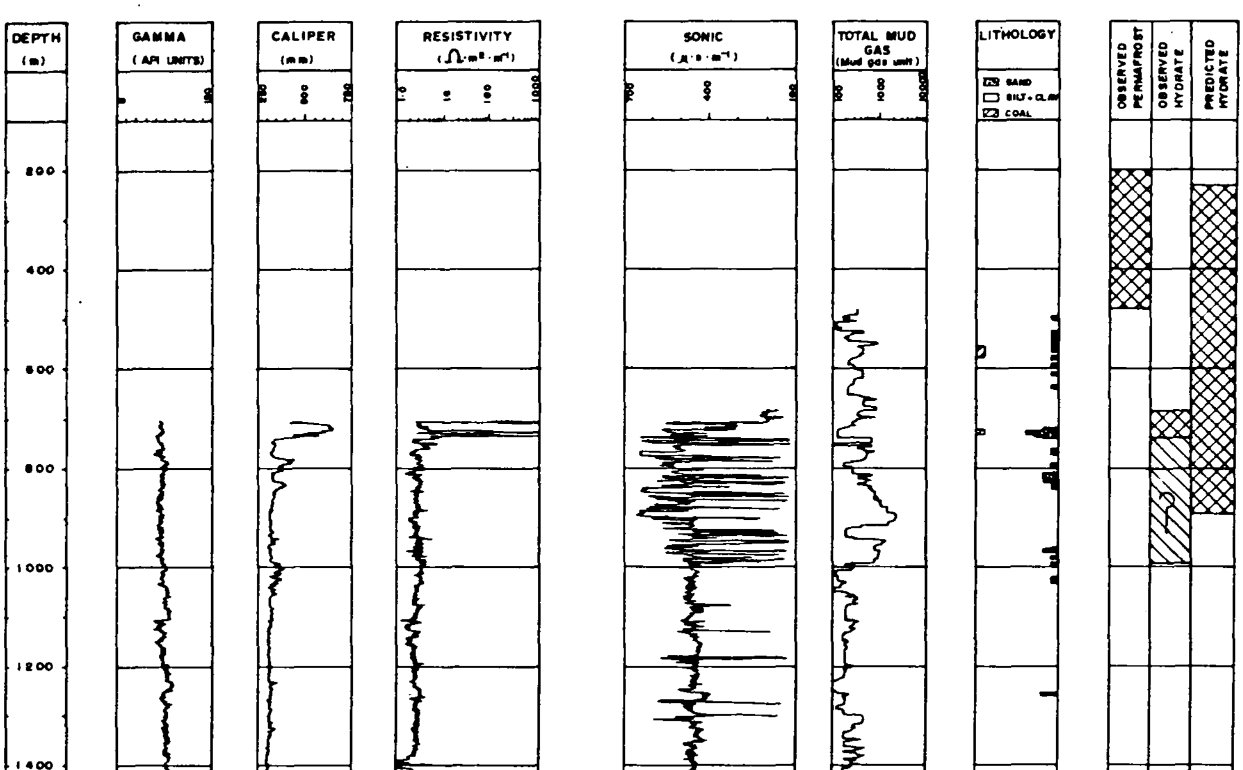

FIGURE 7. Wireline and mud-gas logs for Kopanoar.

Conclusions

1. Thin accumulations of relict *in situ* methane hydrate have been detected in sands beneath the permafrost in the Beaufort Sea.

2. All of the observed *in situ* hydrate deposits lie within the predicted hydrate zone.

3. The relict *in situ* hydrates are associated with abnormally high pore pressure gradients.

4. There is no evidence of *in situ* hydrates existing within clay or silt sediments.

5. Drilling problems have been successfully minimized by using slow penetration rates and cool heavy mud.

6. Insufficient *in situ* hydrate has been discovered to justify gas production from hydrate zones.

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References

BAKER, P.E. 1974. Experiments on Hydrocarbon Gas Hydrates in Unconsolidated Sand. *In:* Natural Gases in Marine Sediments, ed. I.R. Kaplan, Plenum, New York, pp. 227–234.

BILY, C. AND DICK, J.W.L. 1974. Naturally Occurring Gas Hydrates in the Mackenzie delta, N.W.T. Bull. Can. Pet. Geol., vol. 22, no. 3, pp. 340–352.

FRANKLIN, L.J. 1980. In-Situ Hydrates — A Potential Gas Source. Pet. Eng. Int., November, pp. 112–122.

MAKOGON, YU. F. 1974. Hydrates of Natural Gases. Moscow, Nedra (Mineral Resources) Press. (In Russian) 208 p.

STOLL, R.D. 1974. Effects of Gas Hydrates in Sediments. *In:* Natural Gases in Marine Sediments, ed. I.R. Kaplan, Plenum, New York, pp. 235–248.