Regional gas hydrate occurrences, permafrost conditions, and Cenozoic geology, Mackenzie Delta area

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Abstract: The occurrence of natural gas hydrate within Cenozoic sediments of the Mackenzie Delta–Beaufort Sea region has been well documented. In preparation for the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, a detailed evaluation of terrestrial gas hydrate occurrences was undertaken to assess the geological setting, sediment associations, pressure and temperature conditions, and the presence of free gas in the Mackenzie Delta–Beaufort Sea region. After an exhaustive review, it was determined that the Mallik L-38 site, drilled by Imperial Oil in 1972, offered the highest probability of encountering a thick gas hydrate occurrence with high gas hydrate concentrations. On the basis of open-hole well-log evaluation, it was estimated that about 111 m of gas-hydrate-bearing strata occur at this location from 810.1 to 1102.3 m, within the zone of predicted methane hydrate stability and below the base of ice-bearing permafrost, estimated to be at 640 m.

Résumé : La présence d'hydrates de gaz naturel dans les sédiments du Cénozoïque de la région du delta du Mackenzie et de la mer de Beaufort est bien documentée. Dans le but de préparer le forage du puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC Mallik 2L-38, on a effectué une évaluation détaillée des indices d'hydrates de gaz terrestres afin de définir le cadre géologique, les associations sédimentaires, les conditions de température et de pression et la présence de gaz libre dans la région du delta du Mackenzie et de la mer de Beaufort. À la fin de cet examen exhaustif, on est arrivé à la conclusion que l'emplacement du puits Mallik L-38, foré par la société Imperial Oil en 1972, était le plus susceptible de rencontrer un indice d'hydrates de gaz de forte épaisseur renfermant d'importantes concentrations d'hydrates de gaz. En se basant sur l'évaluation de diagraphies de trous non tubés, on évalue à quelque 111 m l'épaisseur des strates renfermant des hydrates de gaz qui seraient présentes à cet emplacement, entre 810,1 et 1 102,3 m de profondeur, dans la zone de stabilité prévue des hydrates de méthane et sous la base du pergélisol renfermant de la glace qui serait située, selon les estimations, à 640 m de profondeur.

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INTRODUCTION

In February and March of 1998, JAPEX/JNOC/GSC Mallik 2L-38, a 1150 m deep gas hydrate research well, was drilled in the Mackenzie Delta at the site of the existing Imperial Oil Mallik L-38 well (Dallimore et al., 1999). In preparation for this research drilling project, the occurrences of gas hydrate in the Mackenzie Delta–Beaufort Sea region were reviewed. The primary purpose for this review was to identify a suitable location with 'proven' gas hydrate. The site assessment and review process included the evaluation of all known and suspected gas hydrate occurrences in the Mackenzie Delta–Beaufort Sea region. It was determined that the Mallik L-38 drill site offered favourable logistics and it has the thickest 'known' gas hydrate occurrences in the region.

This paper presents the results of the regional assessment of gas hydrate occurrences in the Mackenzie Delta–Beaufort Sea region and provides a detailed overview of the Mallik L-38 site. The paper begins with a general discussion of gas hydrate occurrences in arctic environments followed by a discussion of geological parameters that affect the stability of gas hydrate in the Mackenzie Delta–Beaufort Sea region. Recent advancements in well-log evaluation techniques have contributed to the development of procedures which allow the quantitative assessment of gas hydrate accumulations with 'conventional' industry downhole well-log data. The latter part of the paper focuses on the re-examination of the well-log data from Mallik L-38 to establish the sediment and gas hydrate characteristics.

PERMAFROST GAS HYDRATE: REVIEW OF RESOURCE , GEOHAZARD, AND CLIMATE-CHANGE ISSUES

Gas hydrate is a crystalline substance composed of water and gas in which a solid-water lattice accommodates gas molecules in a cage-like structure, or clathrate. While methane, propane, and other gases can be included in the clathrate structure, methane hydrate appears to be the most common in nature (Kvenvolden, 1988). Depending on the concentrations of minor heavier gases such as propane, several crystal structures of methane hydrate can result, each with different physical and phase-equilibrium properties (*see* Sloan, 1998). Because of the efficient packing of gas molecules within the clathrate structure, gas hydrate can store substantially more gas per unit volume than free gas. Cubic Structure I methane hydrate, for instance, ideally can store more than 160 times the gas per unit volume of free gas.

Gas-hydrate-bearing strata are thought to be widespread in certain arctic environments associated with deep permafrost. Occurrences of terrestrial gas hydrate associated with deep permafrost are shown on Figure 1. Indirect evidence has been cited from northern Russia, including the West Siberian Basin (Makogon et al., 1972), the Timan–Pechora Province, the eastern Siberian Craton, and Kamchatka areas (Cherskiy et al., 1985). Direct evidence for gas hydrate on the North Slope of Alaska comes from a core test, and indirect evidence comes from drilling and open-hole industry well logs, which suggest the presence of numerous gas hydrate layers in the area of the Prudhoe Bay and Kuparuk River oil fields (Collett, 1993). Well-log responses attributed to the presence of gas hydrate have been obtained in about one fifth of the wells drilled in the Mackenzie Delta, and more than half of the wells in the Arctic Islands are inferred to contain gas hydrate (Judge and Majorowicz, 1992). The combined information from arctic gas hydrate studies shows that in permafrost regions, gas hydrate may exist at subsurface depths ranging from about 130 to 2000 m (Kvenvolden, 1988). Even though gas hydrate is known to occur in numerous arctic sedimentary basins, little is known about the geological parameters controlling its distribution.

The amount of methane sequestered in gas hydrate throughout the world is enormous and is thought to greatly exceed the volume of known conventional gas reserves. However, estimates are speculative and range over three orders of magnitude, from about 2800 to 7 600 000 trillion m^3 (numbers modified from Kvenvolden, 1988). The resource potential of gas hydrate is largely unknown, as the technologies proposed for commercial exploitation have not been tested in field situations and knowledge about gas hydrate distribution in geological environments is limited. Recently, a number of national research programs have been undertaken in various countries, in part to evaluate the economic potential of gas hydrate.

In addition to its considerable potential as an energy resource, gas hydrate also represents a significant drilling and production hazard. Russian, Canadian, and American researchers have described numerous problems associated with gas hydrate, including blowouts and casing failures (reviewed by Yakushev and Collett, 1992). As exploration and development activity moves into deeper water (>300 m) and high-latitude arctic environments, the frequency of gas-hydrate-induced problems is likely to increase. Because

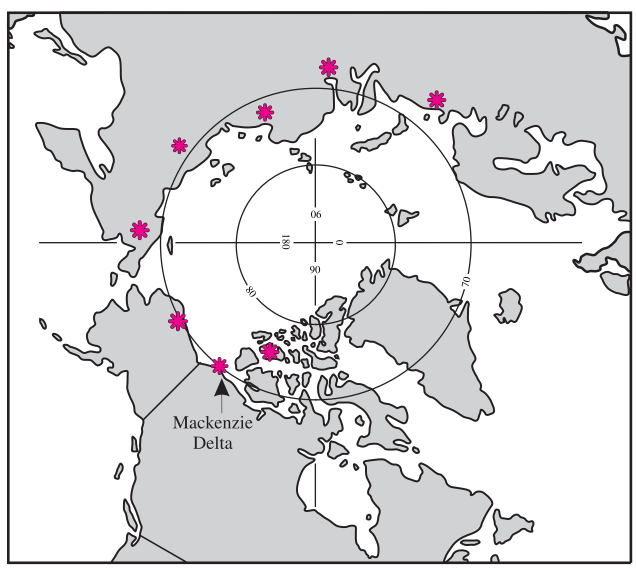

Figure 1. *Map of worldwide occurrences of gas hydrate associated with deep permafrost (map modified from Sloan, 1998).*

gas hydrate in nature typically exists at temperature conditions close to its pressure-temperature stability threshold, it may become unstable even with minor warming. A number of researchers have suggested that dissociating gas hydrate may contribute hydrocarbon greenhouse gases to the atmosphere and play a role in global climate change (reviewed by Kvenvolden, 1988). This is of particular concern since methane is 21 times more effective as a greenhouse gas than carbon dioxide. Arctic gas hydrate occurrences are particularly vulnerable since most general circulation models (GCMs) predict extensive warming in the Arctic over the next 25 years. Terrestrial gas hydrate is also extremely sensitive to geological processes such as marine transgression, which may substantially warm the mean annual ground-surface temperature. However, little is known about the kinetics of gas hydrate dissociation in nature, and about the geochemical processes operating during gas migration to the atmosphere.

REGIONAL GEOLOGY: MACKENZIE DELTA–BEAUFORT SEA REGION

The geology of the Mackenzie Delta–Beaufort Sea region has been described in numerous publications (reviewed by Dixon et al., 1992). Surficial sediments, which dominate surface exposures in the Mackenzie Delta, Richards Island, and the Tuktoyaktuk Peninsula, are composed of modern deltaic sediments and older fluvial and glacial deposits shown in Figure 2. The region is underlain by deltaic sandstones and shales of Mesozoic and Cenozoic age that thicken to more than 12 km over a short distance seaward from the present shoreline. This sedimentary section overlies faulted Paleozoic rocks stepping down steeply beneath the Mesozoic and Cenozoic section.

The post-Paleozoic sedimentary rocks of the Beaufort Sea continental shelf are subdivided into two major sections: pre-Upper Cretaceous and Upper Cretaceous to Holocene

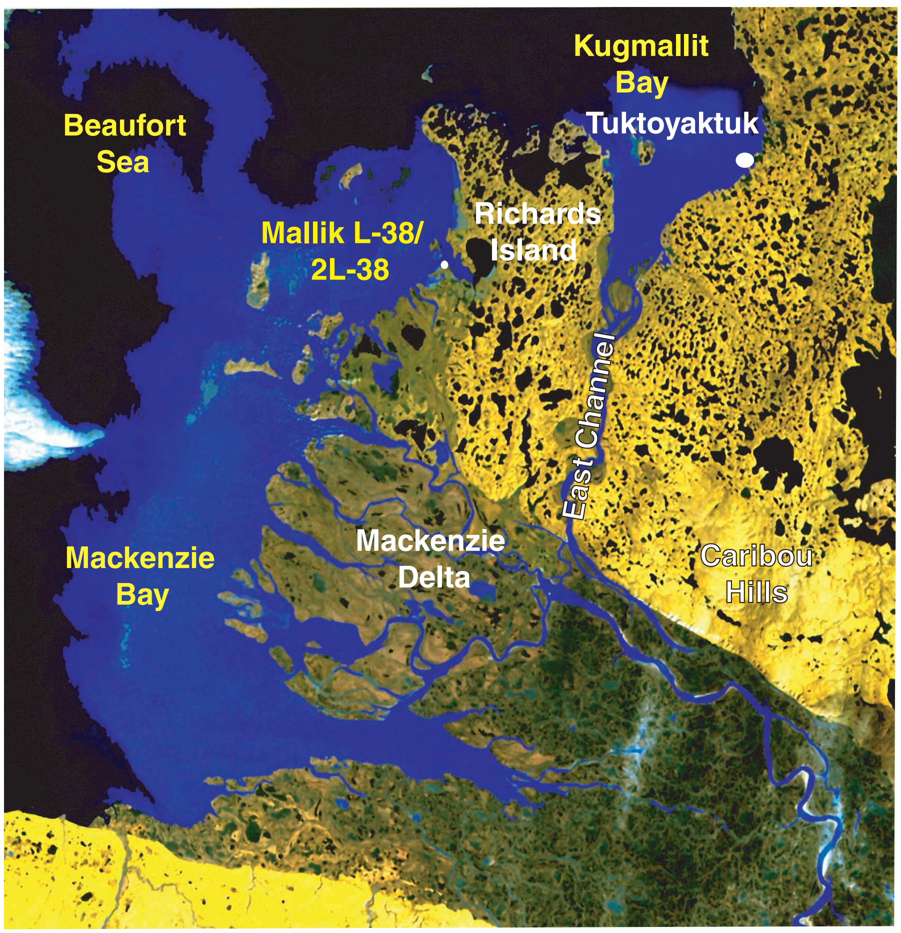

Figure 2. *Landsat I image, September 1973 showing Mackenzie Delta and associated coastal areas as well as the Mallik L-38/2L-38 well site. Image processing allows easy differentiation between the modern Mackenzie Delta floodplain (brown tones) and areas underlain by a complex of Quaternary glacial, fluvial, and eolian sediments (yellow tones). The Caribou Hills include exposure of Tertiary bedrock.*

strata. A major regional unconformity marks the boundary between the Upper Cretaceous and older strata. Above this regional unconformity, sedimentation was dominated by deltaic processes resulting in a series of thick, generally northward-prograding delta complexes, to which sequence-stratigraphic terminology can be applied (reviewed by Dixon et al., 1992). Within the area of the Mallik L-38 well, ten sequences have been identified using seismic-reflection records and well data: Boundary Creek, Smoking Hills, Fish River, Reindeer, Richards, Kugmallit, Mackenzie Bay, Akpak, Iperk, and Shallow Bay sequences (Fig. 3).

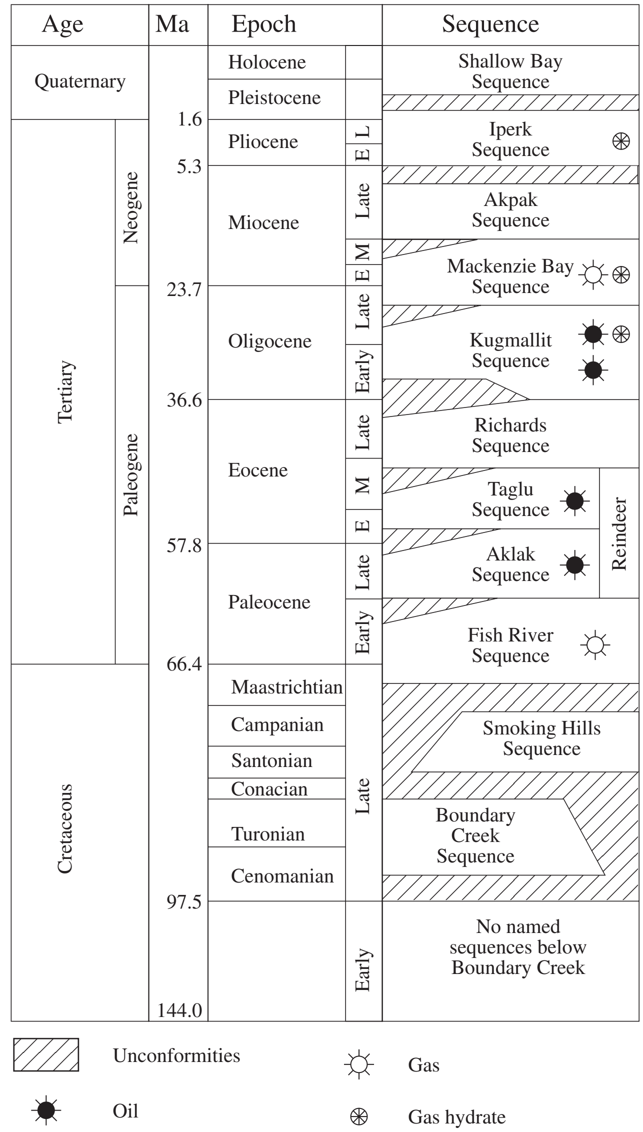

Figure 3. Sequence-stratigraphic nomenclature for the Mackenzie Delta–Beaufort Sea area (modified from Dixon et al., 1992).

GAS HYDRATE STABILITY CONDITIONS

The stability of gas hydrate in nature is controlled by formation temperature, formation pore pressure, gas chemistry, pore-water salinity, and the physico-chemical properties of the enclosing formation sediments. These geological controls on the stability of gas hydrate in the Mackenzie Delta–Beaufort Sea region are reviewed in the following sections.

Formation temperature

In the Mackenzie Delta area, subsurface temperature data come from industry-acquired production drill-stem tests, bottom-hole well-log surveys, and long-term precise temperature studies undertaken in approximately 50 instrumented exploration wells (Judge et al., 1981; Taylor et al., 1982). The thickness of ice-bearing permafrost is known to vary considerably even over relatively short distances. This can be attributed to widely varying surface-temperature histories, significant variations in subsurface lithologies, and latent heat effects related to growth and melting of ground ice (Taylor et al., 1996). These conditions have a great impact on the formation temperatures within the permafrost interval as can be seen on Figure 4, which contains plots of subsurface temperature surveys in four typical onshore wells. Beneath the permafrost interval, the geothermal gradients in the Mackenzie Delta–Beaufort Sea region are more uniform, ranging from about 3.0°C/100 m to 4.0°C/100 m (Majorowicz et al., 1990; Majorowicz et al., 1995).

In a recent review of the thermal conditions controlling gas hydrate stability, Judge and Majorowicz (1992) mapped the base of the methane hydrate stability zone in the Mackenzie Delta–Beaufort Sea region. Figure 5 depicts the depth to the base of the methane hydrate stability zone, assuming hydrostatic pore-pressure gradient, fresh pore-water salinities (no salt), and a pure methane gas chemistry for the in situ gas hydrate. Based on these simplifying assumptions, the base of the methane hydrate stability zone is more than 1000 m deep on Richards Island, and is extensive beneath most of the continental shelf.

Formation pore pressure

Given the in situ formation temperatures for occurrences of gas hydrate in the Mackenzie Delta, theory would suggest that methane hydrate is stable over a relatively narrow pressure range (Fig. 4). In situ formation pressures are known to fluctuate in response to factors such as deposition rate, stress history, and tectonic influences. Experience from other arctic basins has demonstrated that permafrost may cause non-equilibrium compaction within, and immediately below, ice-bearing permafrost (Serebryakov et al., 1995). In onshore areas of the Mackenzie Delta, measurements of the in situ stress regime within the permafrost interval are not available. It is possible, however, to estimate the response of permafrost through controlled thaw-consolidation tests on core samples. Test results from deep core samples, collected from 30 to 386 m depth in the Taglu and Kumak hydrocarbon fields, clearly show that permafrost can significantly impede normal consolidation and result in elevated pore-water pressures upon thawing (Dallimore and Matthews, 1997). These observations imply that elevated pore-water pressures can be

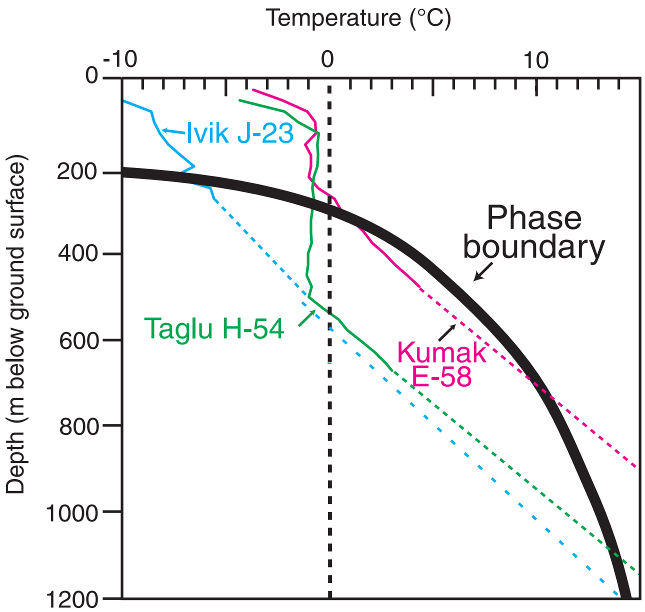

Figure 4. *Plot of ground temperatures measured in abandoned industry exploration wells believed to contain gas hydrate (data from Judge et al., 1981; Taylor et al., 1982). A methane hydrate stability curve (phase boundary) is plotted for reference.*

expected where thawing of permafrost has occurred or where warming of the permafrost has caused thawed zones or taliks within the permafrost section.

Pore-pressure information from beneath the permafrost suggests a variable stress regime. Data from four wells drilled offshore on the continental shelf indicate that pore pressures are abnormally high immediately beneath the base of ice-bearing permafrost, possibly as a result of gas hydrate dissociation (Weaver and Stewart, 1982). Limited pore-pressure data from onshore wells suggest near-hydrostatic pore pressures (9.795 kPa/m; 0.433 psi/ft) immediately below the base of permafrost (Hawkings and Hatelid, 1975). However, major over-pressured zones have been reported at depths below the zone of predicted methane hydrate stability and are thought to be related to the basin stress-regime history (Hitchon et al., 1990; Podrouzek and Bell, 1989).

Gas chemistry

Methane is known to form Structure I hydrate if no other hydrate formers are present. However, even small amounts of propane or ethane (1–2%) can promote the formation of Structure II gas hydrate (Sloan, 1998), which can exist under a wider range of pressure and temperature conditions. Analyses of gas samples and mud-log gas-chromatography data from

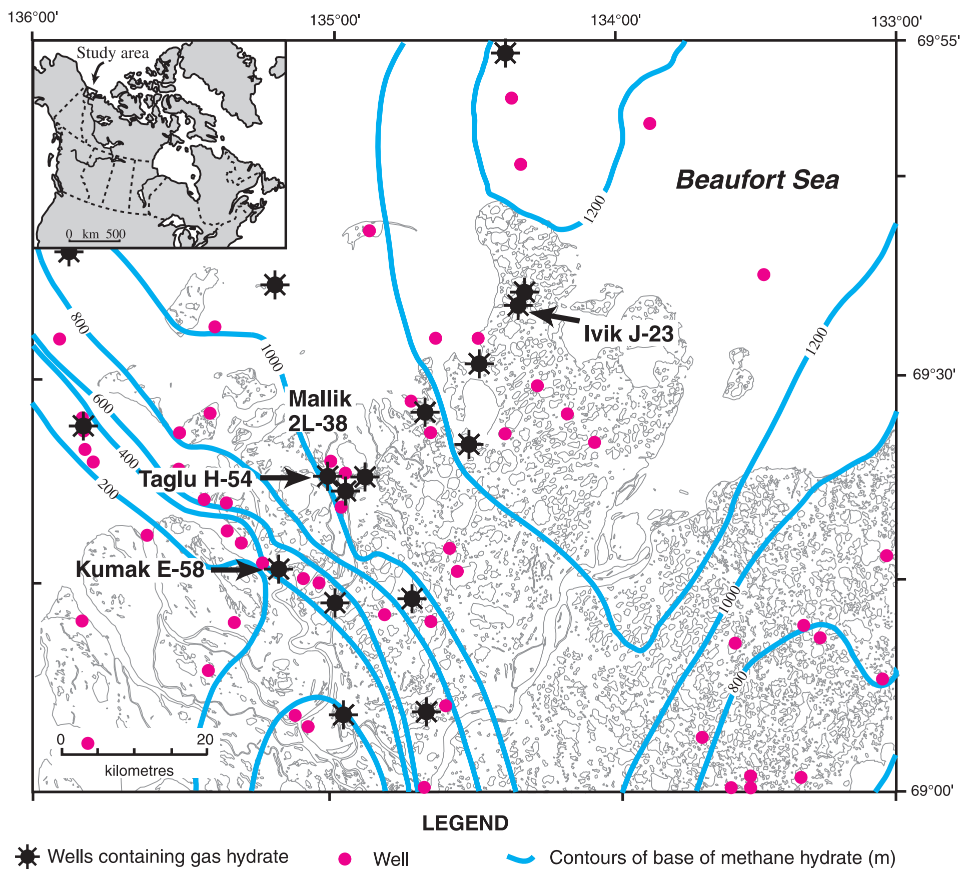

Figure 5. *Map of part of the Mackenzie Delta region showing the calculated depth to the base of the methane hydrate stability zone (modified from Judge and Majorowicz, 1992). Exploration wells with well-log-inferred gas hydrate occurrences are shown, well names refer to sites plotted on Figure 4.*

industry wells revealed that the formation gases within the upper 2000 m of sediment in the Beaufort Sea region consist almost entirely of methane (99.5%) (Weaver and Stewart, 1982). Four drill-stem production tests of suspected gas hydrate occurrences in two wells drilled on Richards Island in the Mackenzie Delta yielded gas composed principally of methane (99.19 to 99.53%) (Bily and Dick, 1974). Similar concentrations were observed from headspace gas samples collected from within permafrost from the Taglu and Niglingtak areas (Collett and Dallimore, 1997). These data confirm that Structure I methane hydrate should be expected as the primary gas hydrate form in the Mackenzie Delta–Beaufort Sea region.

Pore-water salinity

Experimental data presented for pure-water and gas systems have clearly demonstrated that the pressure-temperature stability field for methane hydrate is affected by the salinity of the pore water. For a fixed temperature of 0°C, a pressure shift of approximately 2 MPa can be expected with a salinity of 100 ppt (parts per thousand) NaCl (*see* Maekawa et al., 1995). Pore-water salinities of sediments of the Iperk Sequence in the Mackenzie Delta are well documented from core samples (Dallimore and Matthews, 1997). These data suggest that permafrost within the Iperk Sequence is mainly syngenetic in origin, and that the pore-water salinities for the most part are similar to those of water emplaced during primary deposition. Since Iperk sediments are largely terrestrial, low salinities (below 15%) can be expected. However, in certain instances, thin high-salinity zones were also observed with values of 30 ppt or higher. Pore-water salinity information from the Kugmallit and Mackenzie Bay sequences are primarily from drill-stem tests in industry exploration wells (Hitchon et al., 1990; Weaver and Stewart, 1982) or interpretations of resistivity well logs. Salinities in the upper 1500 m appear to range from 20 to 40 ppt.

Physico-chemical properties of sediments

Considerable effort has been devoted in recent years to the laboratory study of gas hydrate occurring within porous media. In part, this research has been stimulated by field studies where marked differences have been observed between theoretical predictions of the methane hydrate stability field and gas hydrate observed in coring or inferred from geophysical studies. It has been speculated that porous-media effects could affect the free-energy state of the water phase and thus shift the theoretical pressure-temperature relationships determined for pure water and methane mixtures.

Gas hydrate observed in the Mackenzie Delta–Beaufort Sea region occurs exclusively within sediments of the Kugmallit, Mackenzie Bay, and Iperk sequences. In the Mackenzie Delta area, the Kugmallit Sequence is interpreted as a delta-plain deposit composed mainly of unconsolidated to weakly cemented sand, minor clay, and rare lignite. The Mackenzie Bay Sequence is present mainly offshore and is composed of weakly cemented mudstone and siltstone. The Iperk sequence is composed mainly of unconsolidated, coarse-grained (sand-dominated) clastic sediments of varied depositional origin. The re-examination of well-log interpretations of gas hydrate occurrences summarized in Smith and Judge (1993) revealed a clear lithological control on most gas hydrate occurrences. Gas hydrate occurrences typically have a layered or interbedded character. Gas hydrate layers occur in coarse-grained sand-dominated facies separated by thin non-gas-hydrate-bearing, fine-grained silt and clay facies.

GAS HYDRATE OCCURRENCES

Assessments of gas hydrate occurrences in the Mackenzie Delta–Beaufort Sea region have been made mainly on the basis of data obtained during the course of hydrocarbon exploration conducted over the past three decades (reviewed by Judge et al., 1994). Indirect evidence of gas hydrate occurrences includes well-log responses (Smith and Judge, 1993), steady buildup of shut-in pressures during industry production tests, and gas flows during drilling (Bily and Dick, 1974; Weaver and Stewart, 1982). A database presented by Smith and Judge (1993) summarizes a series of unpublished consultant studies that investigated well-log response of 146 onshore exploration wells in the Mackenzie Delta area. In total, 25 wells (17%) were identified as containing 'possible' or 'probable' gas hydrate, some of which are shown in Figure 5. All of these inferred gas hydrate occurrences are in clastic sedimentary rocks of the Kugmallit, Mackenzie Bay, and Iperk sequences. Two of the occurrences were associated with ice-bearing permafrost, while the remainder were beneath the permafrost interval. The frequency of gas hydrate occurrence in offshore wells was greater, with 'possible' or 'probable' gas hydrate identified in 35 of 55 wells assessed (63%).

The most extensively studied inferred gas hydrate occurrences in the Mackenzie Delta–Beaufort Sea region are those drilled in the onshore Mallik L-38 and Ivik J-26 wells (Bily and Dick, 1974) and those in the offshore Nerlerk M-98, Koakoak O-22, Ukalerk C-50, and Kopanoar M-13 wells (Weaver and Stewart, 1982). On the basis of open-hole well-log evaluation, it is estimated that Mallik L-38 encountered about 111 m of gas-hydrate-bearing sandstone units, and Ivik J-26 penetrated about 25 m of gas hydrate. The well-log-inferred gas-hydrate-bearing sandstone units in the Mallik L-38 well occur within the depth interval from 810.1 to 1102.3 m, which is within the predicted methane hydrate stability zone and below the base of ice-bearing permafrost. The gas hydrate occurrences in the Ivik J-26 well are very similar to those in the Mallik L-38. The inferred gas hydrate in Ivik J-26 occupies a series of fine-grained sandstone and conglomeratic rock units within the depth interval from 980 to 1020 m, which is also within the predicted methane hydrate stability zone and below the base of ice-bearing permafrost. Analyses of open-hole well logs and mud-gas logs indicate that the offshore Nerlerk M-98 well penetrated about 170 m of gas-hydrate-bearing sedimentary units, while the Koakoak O-22, Ukalerk C-50, and Kopanoar M-13 wells drilled through approximately 40 m, 100 m, and 250 m of gas-hydrate-bearing strata respectively (Weaver and Stewart, 1982). In all four cases, the well-log-inferred gas hydrate occurred in fine-grained sandstone units, and exhibited significant gas flows during drilling.

As indicated in Figure 4, methane hydrate can occur at depths as shallow as 180 m within the ice-bearing permafrost interval. In some areas of the Mackenzie Delta this intrapermafrost zone of potentially stable gas hydrate may be 600 m thick. During a recent permafrost coring program in the Taglu area, ice-bearing cores containing visible gas hydrate and possible pore-space gas hydrate were recovered (Dallimore and Collett, 1995). The visible gas hydrate occurred at a depth of about 330 to 335 m and appeared as thin ice-like layers that released methane upon recovery. Gas-yield calculations suggested that other ice-bearing cores from a bore hole in the Niglintgak field area also contained non-visible pore-space gas hydrate. In at least one instance, the inferred pore-space gas hydrate occurred at 119 m, a depth shallower than the predicted methane hydrate stability zone. This phenomenon is attributed to self-preservation, a metastable condition whereby a coating of ice encapsulates the gas hydrate, thus preserving the internal clathrate structure. The observations of shallow gas hydrate in permafrost of Late Quaternary age suggest that self-preservation may occur over geological time scales (Dallimore and Collett, 1995).

Davidson et al. (1978) estimated that the gas-hydrate-bearing sediments of the Mackenzie Delta–Beaufort sea region may contain about 88 billion m^3 of gas. However, their estimate was based on a rough analysis of the geological structures containing the inferred gas hydrate and an incomplete subsurface-temperature database. Recently, Smith and Judge (1995) determined that the Mackenzie Delta–Beaufort Sea region may contain 16 trillion m^3 of natural gas in hydrate form.

RE-EXAMINATION OF THE MALLIK L-38 WELL

As mentioned previously, the review of gas hydrate occurrences in the Mackenzie Delta presented in this paper was conducted in part to select an ideal drilling site for a gas hydrate research well. During the course of this investigation, all 25 onshore 'gas hydrate' wells identified by Smith and Judge (1993) were re-examined. For the most part, the original interpretations included in the consultant reports were reaffirmed. In some cases, however, a number of the gas hydrate occurrences originally identified were considered quite suspect. The reasons for concern could be classed into three categories: 1) the quality of the well logs and therefore the interpretations were suspect, 2) the well-log criteria used to confirm gas hydrate occurrence were not consistent, and 3) the interpreted gas hydrate occurrences were anonymously deep and, when combined with formation temperatures, were not consistent with the stability conditions for Structure I methane hydrate. The selection of the Mallik L-38 drill site was based primarily on the confidence in the well-log interpretations and the fact that considerable research had been conducted in the original well when it was drilled.

The Mallik L-38 well (location: 69°27′44″N, 134°39′25″W) was drilled by Imperial Oil in 1972 to a total depth of 2524 m. Data from downhole logging and formation-production testing were used to assess local geology, permafrost, and gas hydrate conditions. In the upper 1500 m, three stratigraphic sequences were identified using seismic-reflection records and well data (Fig. 6). Using the nomenclature of Dixon et al., (1992), these include: the Iperk Sequence (0–350 m), the Mackenzie Bay Sequence (350–918 m), and the Kugmallit Sequence (918 m–bottom of hole). The base of ice-bearing permafrost in the Mallik L-38 well is estimated at 640 m on the basis of available well-log information.

The Mallik L-38 well is believed to have encountered at least 10 significant gas-hydrate-bearing stratigraphic units (Table 1, Fig. 6). The presence of gas hydrate was inferred on the basis of the following observations: 1) While drilling the suspected gas-hydrate-bearing units, large amounts of gas were released into the borehole, which is indicative of gas-hydrate-bearing sediments. 2) The inferred gas-hydrate-bearing units also exhibited very high acoustic velocities and electrical resistivities on the recorded downhole logs, which also indicates the presence of gas hydrate. 3) Low reservoir pressures and slow pressure responses during production test (Production Test 2: 915–918 m) of the inferred gas-hydrate-bearing units were also interpreted to indicate the presence of gas hydrate. Bily and Dick (1974) concluded that each of the gas-hydrate-bearing units contained substantial amounts of gas hydrate. However, no attempt was made to quantify the amount of gas hydrate or associated free gas that may have been trapped within the log-inferred gas hydrate occurrences.

Table 1. Depths and thicknesses of the log-inferred gas-hydrate-bearing stratigraphic units (with thicknesses of 2 m and greater) in the Mallik L-38 well.

Hydrate unit	Well-log depth* (m)	Depth from ground surface (m)	Thickness (m)
1	819.1–826.0	810.1–817.0	6.9
2	889–914.4	880.0–905.4	25.4
3	919.3–934.5	910.3–925.5	15.2
4	945.5–957.1	936.5–948.1	11.6
5	960.1–963.5	951.1–954.5	3.4
6	972.3–982.4	963.3–973.4	10.1
7	987.6–996.7	978.6–987.7	9.1
8	1012.2–1015.3	1003.2–1006.3	3.1
9	1075.9–1082.7	1066.9–1073.7	6.8
10	1091.2–1111.3	1082.2–1102.3	20.1
		Total thickness	111.4

*Depths are directly from Mallik L-38 well logs, to obtain depth below ground surface, subtract 8.99 m from the well-log depths.

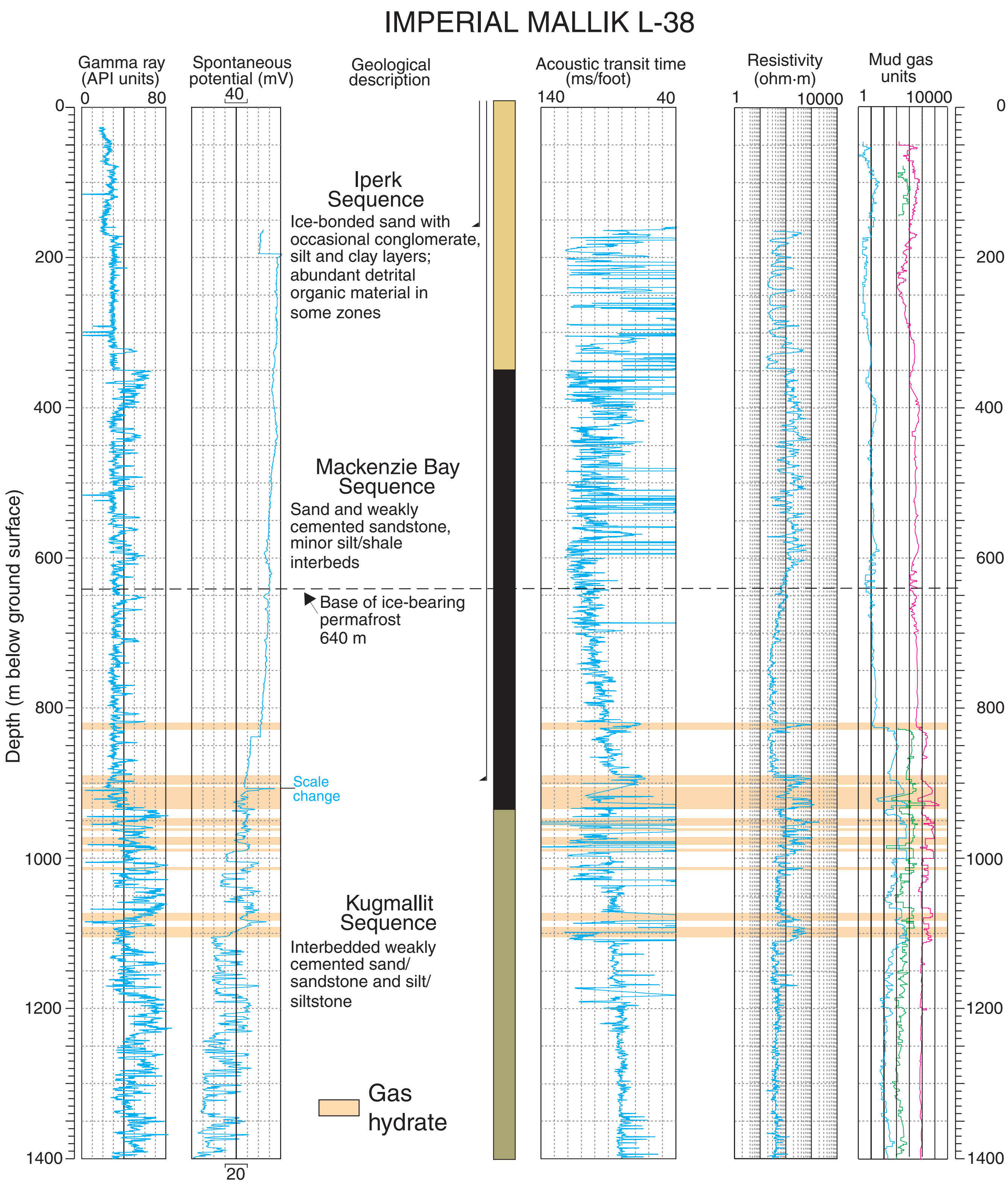

Figure 6. *Well-log display for the Mallik L-38 well showing gas hydrate occurrences and interpreted geology.*

Downhole-logging program

Within petroleum wells drilled in the Arctic, the permafrost and gas-hydrate-bearing intervals are usually drilled and cased before drilling to greater depths. The Mallik L-38 well was drilled in a similar fashion; however, most of the well-log-inferred gas-hydrate-bearing units in the Mallik L-38 well are below the depth of the 'permafrost' casing which was set at a depth of 896.8 m. Before running this 13-3/8 inch casing, the permafrost and several gas-hydrate-bearing units above 897 m were surveyed with dual-induction-laterolog (DIL), gamma-ray (GR), and borehole-compensated acoustic transit-time (BHC) well-logging devices (Fig. 6). The remaining gas-hydrate-bearing units were drilled and the well was advanced to a depth of 1843 m, which took approximately 22 days to complete. The subpermafrost section was also surveyed with dual-induction-laterolog (DIL), gamma-ray (GR), and borehole-compensated acoustic transit-time (BHC) well-logging devices (Fig. 7). In addition, a compensated formation-density (FDC) and a sidewall neutron-porosity (SNP) tool were also used to log the subpermafrost section of the Mallik L-38 well. The extended period of drilling subjected the gas-hydrate-bearing units within the subpermafrost section of the Mallik L-38 well (below 897 m) to significant thermal disturbance, which caused the gas hydrate within the formation near the well bore to disassociate. The breakdown of the in situ gas hydrate caused significant borehole-stability problems which contributed to the development of large borehole 'washouts' within the subpermafrost gas-hydrate-bearing units. The quality of the log measurements in the Mallik L-38 well were moderately to severely degraded by the size and rugosity of the borehole. The borehole-compensated acoustic transit-time (BHC) well log from the subpermafrost gas-hydrate-bearing units (below 897 m) was severely affected by the presence of free gas and exhibited 'cycle-skipping'. Thus data from the acoustic transit-time (BHC) log in the Mallik L-38 well could not be used for quantitative analyses. An additional limitation of the Mallik L-38 well-logging program was the lack of density- or neutron-porosity log surveys from the shallow (above 897 m; Fig. 6) gas-hydrate-bearing units located above, and at the top of, the main gas-hydrate-bearing section.

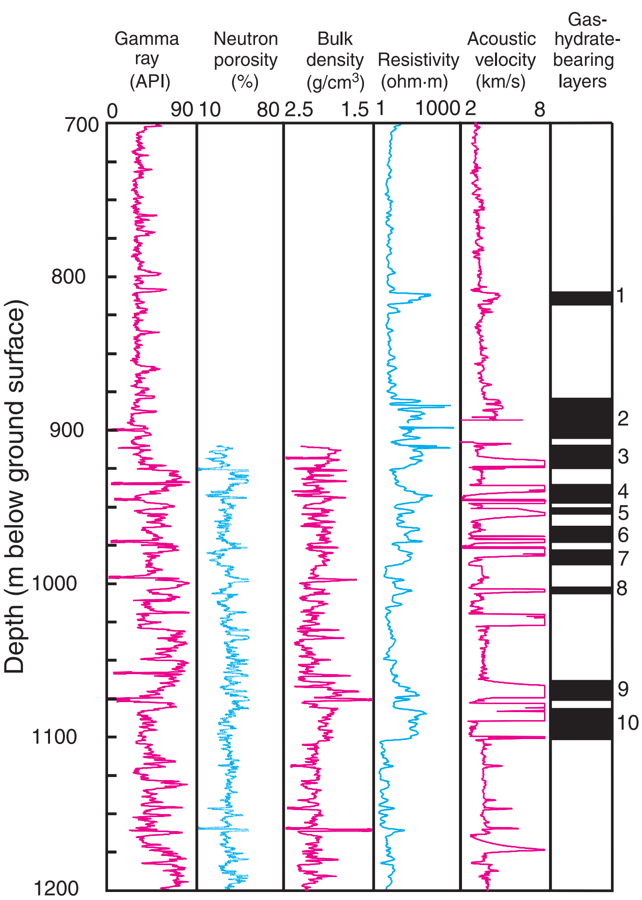

Figure 7. *Enlarged portion of Figure 6 showing downhole log data from the Mallik L-38 well. Data shown include the natural gamma-ray log from the gamma-ray (GR) tool, neutron-porosity data from the SNP, bulk density from the downhole density log (FDC), deep-reading electrical-resistivity data from the dual-induction laterolog (DIL), and acoustic-velocity data from the borehole-compensated sonic log (BHC). Also shown are the depths of the gas-hydrate-bearing stratigraphic units (Table 1).*

The subsurface depths used in this paper were fixed by subtracting 8.99 m (height above ground surface of the kelly bushing on the drilling rig) from the downhole measured log depths.

Sediment porosities

In the Mallik L-38 well, we have attempted to use data from the compensated formation-density and neutron-porosity logs to calculate sediment porosities. The compensated formation-density log measurements of bulk density in the gas-hydrate-bearing part (below a depth of about 897 m) of the Mallik L-38 well (Fig. 8) are highly variable with depth. The density log (Fig. 7) is characterized by numerous, thin, low-density zones, ranging in thickness from 2 to 4 m. It is possible that these low-density zones, with measured bulk densities of 1.8 g/cm^3 and lower, may contain coal. The unedited bulk density (ρ_b) log measurements were used to calculate sediment porosities (ϕ) in the Mallik L-38 well using a modified density equation (equation 1) that has been developed for a three-component system (water, gas hydrate, matrix) (Collett, 1998a):

$$\phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_w} \qquad (1)$$

$$\rho_b = (1-\phi)\rho_m + (1-S_h)\phi\rho_w + S_h\phi\rho_h$$

ρ_b = bulk density, g/cm^3
ρ_m = matrix density, g/cm^3
ρ_w = water density, g/cm^3
ρ_h = gas hydrate density, g/cm^3
S_h = gas hydrate saturation, decimal per cent
ϕ = porosity, decimal per cent

The density of the formation waters (ρ_w) was assumed to be constant and equal to 1.00 g/cm^3, the grain/matrix densities (ρ_m) were assumed to equal 2.65 g/cm^3, the density of gas hydrate (ρ_h) was assumed to be 0.9 g/cm^3, and gas hydrate saturations (S_h) were determined from the Archie 'quick look' method, which will be discussed in the next section of this paper. However, it should be noted that the 'quick look' Archie log-analysis technique is not dependent on knowing porosities. The density-log porosities in the gas-hydrate-bearing units of the Mallik L-38 well, calculated using the modified three-component density relation (equation 1), average about 35% (Fig. 8). Under most conditions, the bulk density (ρ_b) of a water-bearing formation is almost identical to the bulk density (ρ_b) of a gas-hydrate-bearing formation as measured by borehole density logs (Collett, 1998a).

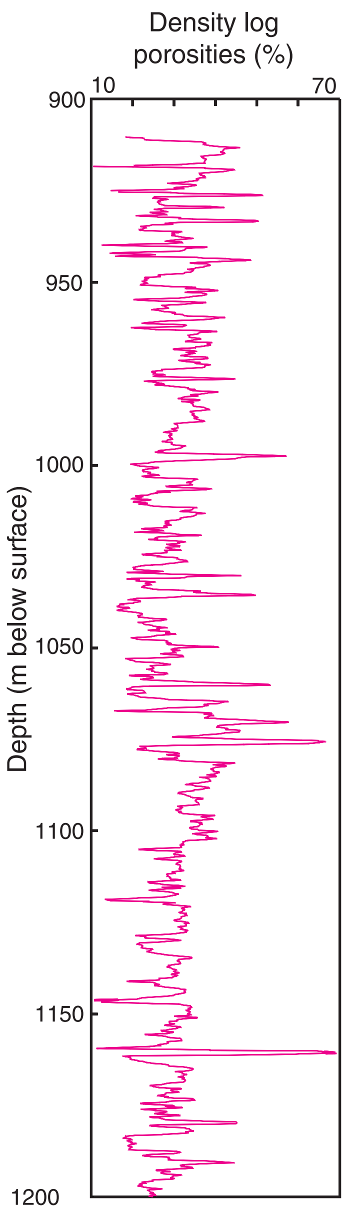

Figure 8. *Sediment porosities derived from the downhole density log (FDC) in the Mallik L-38 well. This density-porosity log was calculated with a modified three component density-porosity equation (Equation 1) (Collett, 1998a).*

Because of poor borehole conditions, the sidewall neutron-porosity log from the Mallik L-38 well (Fig. 7) was severely degraded and was disregarded in this study.

Gas hydrate saturations

In the following section we have used electrical-resistivity data from the dual-induction log in the Mallik L-38 well to quantify the amount of gas hydrate within the logged and tested gas hydrate accumulation in the Mallik area. Two unique forms of the Archie relation (Archie, 1942) have been used to calculate water saturations (S_w) [gas hydrate saturation (S_h) is equal to (1.0-S_w)] from the available electrical-resistivity-log data in the Mallik L-38 well. The first resistivity-log approach used to assess gas hydrate saturations (S_h) in the Mallik L-38 well is based on the modified 'quick look' Archie log-analysis technique that compares the resistivity of water-saturated and hydrocarbon-bearing sediments:

$$S_w = \left(\frac{R_o}{R_t}\right)^{\frac{1}{n}} \tag{2}$$

R_t = formation resistivity (from log), Ω·m
R_o = resistivity of the 100% water-saturated section, Ω·m
S_w = water saturation, decimal per cent
n = empirically derived parameter

This modified 'quick look' Archie relationship is based on the following logic: if the pore-space of sediment is 100% saturated with water, the deep-reading resistivity device will measure the resistivity of the 100% water-saturated sedimentary section (R_o). This measured R_o value is considered to be a relative baseline from which hydrocarbon saturations can be determined within nearby hydrocarbon-bearing intervals. In order to calculate R_o for the gas-hydrate-bearing stratigraphic units in the Mallik L-38 well, we used the log-measured deep resistivities from a series of apparent water-saturated units both above and below the log-inferred gas-hydrate-bearing units, which yielded a R_o of 3.5 Ω·m. Laboratory experiments on different sediment types have yielded a pooled estimate for n of 1.9386 (reviewed by Pearson and et al., 1983). Knowing R_t, R_o, and n, it is possible to use the modified 'quick look' Archie relationship to estimate water saturations. In Figure 9, the results of the 'quick look' Archie calculations are shown as a water saturation (S_w) log trace for the subpermafrost portion of the Mallik L-38 well. The 'quick look' Archie approach yielded an average water saturation (S_w) for the gas-hydrate-bearing stratigraphic units (Table 1, Fig. 7) in the Mallik L-38 well of 41%.

The next resistivity approach used to assess gas hydrate saturations in Mallik L-38 well is based on the 'standard' Archie equation:

$$S_w = \left(\frac{aR_w}{\phi^m R_t}\right)^{\frac{1}{n}} \quad (3)$$

R_t = formation resistivity (from log), Ω·m
a = empirically derived parameter
R_w = resistivity of formation water, Ω·m
ϕ = porosity, decimal per cent
m = empirically derived parameter
S_w = water saturation, decimal per cent
n = empirically derived parameter

In the Mallik L-38 well, the porosity data needed for the 'standard' Archie equation were derived from the available downhole density log and the modified three-component density-porosity equation (equation 1). In addition to porosity, the 'standard' Archie relation also requires as input the value of the empirical Archie constants (*a, m,* and *n*), the resistivity of the in situ pore waters (R_w), and the resistivity of the formation (R_t) which is obtained from the deep resistivity log (Fig. 7).

We were unable to calculate reasonable values for the empirical Archie constants (*a* and *m*) from the available porosity- and resistivity-log data. Therefore, we have used the so-called 'Humble' values for the *a* (0.62) and *m* (2.15) Archie constants which are considered applicable for granular matrix systems (reviewed by Collett, 1998b). The value of the empirical constant *n* was assumed to be 1.9386 as determined by Pearson et al. (1983). The resistivity of pore waters (R_w) is mainly a function of the temperature and the dissolved salt content of the pore waters. It has been determined that the pore-water salinity of the formation water in the Mackenzie Delta–Beaufort Sea region, within the depth range from 200 to 2000 m, is approximately 10 ppt. However, pore-water salinity data from the analyses of interstitial water samples collected from formation-production tests in the gas-hydrate-bearing section of the Mallik L-38 well yielded an average value of 25 ppt. It is possible that solute exclusion during gas hydrate formation has locally increased the pore-water salinities within the gas-hydrate-bearing units of the Mallik L-38 well. Therefore, the higher pore-water salinity of 25 ppt, calculated from the production-test water samples, likely represents in situ salinity of the pore waters in the Mallik L-38 well. Formation-temperature data in the Mallik L-38 well are available from downhole temperature surveys in nearby wells which yield a subpermafrost geothermal gradient of 2.7°C/100 m and a base of ice-bearing permafrost (640 m) temperature of -1.0°C. Arps formula (reviewed by Collett, 1998b) was used to calculate the pore-water resistivities (R_w) in the Mallik L-38 well from the assumed interstitial water salinity of 25 ppt and the measured formation temperatures. The calculated pore-water resistivities (R_w) within the subpermafrost sedimentary section of the Mallik L-38 well range from about 0.30 to 0.38 Ω·m. Given the Archie constants (*a*, *m,* and *n*) and pore water resistivities (R_w), we can now calculate water saturations (S_w) [gas hydrate saturation (S_h) is equal to (1.0-S_w)] from the resistivity log using the 'standard' Archie relation. In Figure 9, the results of the 'standard' Archie calculation are shown as a water saturation (S_w) log trace along with the results of the 'quick look' Archie method. The water saturations (S_w) within the gas-hydrate-bearing units of the Mallik L-38 well, calculated with the 'standard' Archie relation (equation 3), average 33%. In comparison, the 'standard' Archie relation yielded similar, but slightly lower, water saturations than the 'quick look' Archie method (Fig. 9). The 'quick look' method is very dependent on the selection of an accurate R_o baseline; in general, the 'standard' Archie relation yields the most accurate gas hydrate saturations. The zones in each log trace of Figure 9 are characterized by water saturations exceeding

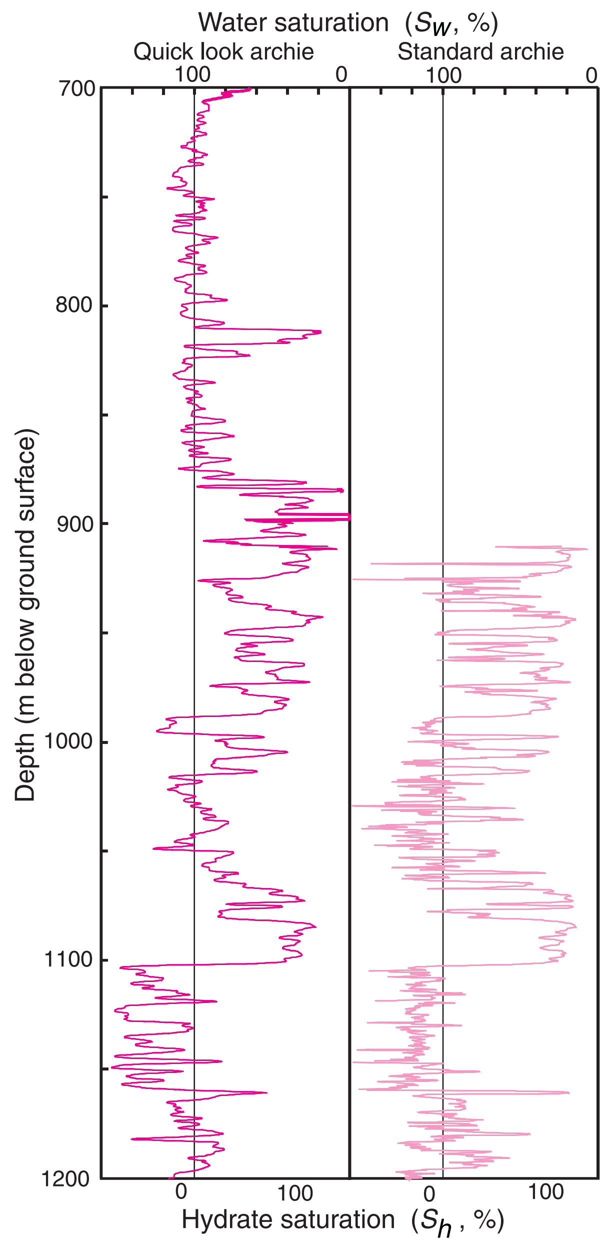

Figure 9. *"Standard" and "quick look" Archie derived water saturations (S_w) [gas-hydrate saturation (S_h) is equal to (1.0-S_w)] (reviewed by Collett, 1998b) calculated from the downhole electrical resistivity log in the Mallik L-38 well.*

100%, which is theoretically impossible. These values are likely caused by poor hole conditions which have degraded the resistivity log measurements.

Presence of free gas at Mallik L-38

The presence of free gas in contact with gas hydrate occurrences is an important consideration in terms of designing possible production scenarios and also in terms of assessing drilling hazards. Bily and Dick (1974) originally interpreted the presence of free gas in contact with gas hydrate on the basis of spontaneous-potential (from the DIL) well-log responses within several intervals. They also speculated that rapid pressure responses during a production test (Production Test 1: 1095–1098 m) within a suspected free-gas unit are evidence of highly permeable free-gas-bearing sediments. Within this study, we were not able to confirm the occurrence of the free-gas-bearing units delineated by Bily and Dick (1974) because of insufficient data. However, the analyses of log data from the Mallik 2L-38 well have confirmed the occurrence of a relatively thin free-gas zone (1108.4–1109.8 m) at the base of the deepest downhole-log-inferred gas-hydrate at the Mallik drill site (Collett et al., 1999).

CONCLUSION

'Possible' or 'probable' gas hydrate occurrences have been observed in 17% of onshore and 63% of offshore wells drilled in the Mackenzie Delta–Beaufort Sea area. A review of these occurrences has established the geological setting of these gas hydrate accumulations and led to the selection of Mallik L-38 as the drill site for the Mallik 2L-38 gas hydrate research well. On a regional basis, methane hydrate is found within unconsolidated to weakly cemented sediments of the Kugmallit, Mackenzie Bay, and Iperk sequences. Gas hydrate typically occurs in coarse-grained sandy intervals with non-gas-hydrate-bearing fine-grained interbeds. Pore-water pressures within and below permafrost in the region appear to be rather variable. Over-pressured zones may occur in some areas, affecting gas hydrate stability. Available pore-water chemistry data indicate a primarily freshwater regime with salinities less than 35 ppt. Formation temperatures are widely variable, having a substantial impact on the predicted thickness of the methane gas hydrate stability zone.

Quantitative analyses of downhole logs and the results of formation production testing have confirmed the occurrence of at least 10 gas-hydrate-bearing stratigraphic units in the Mallik L-38 well. Downhole log data and formation-production tests also infer, but do not prove, the occurrence of a free-gas-bearing unit at the predicted base of the gas hydrate stability zone in the Mallik L-38 well. A three-component density-porosity equation was used to calculate accurate downhole-log-derived porosities from the Mallik L-38 well. The corrected density-log-derived sediment porosities for the gas-hydrate-bearing units in the Mallik L-38 well average 35%. Gas hydrate saturations within the gas-hydrate-bearing units of the Mallik L-38 well, calculated from the 'standard' Archie equation, average 67%.

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