

GAS HYDRATES ASSOCIATED WITH DEEP PERMAFROST IN THE MACKENZIE DELTA, N.W.T., CANADA: REGIONAL OVERVIEW

Scott R. Dallimore¹, Timothy S. Collett²

1. *Geological Survey of Canada, 601 Booth Street
Ottawa, Ontario K1A 0E8, Canada
e-Mail: SDallimo@NRCan.gc.ca*

2. *U.S. Geological Survey, Denver Federal Center
Box 25046, MS-939
Denver, Colorado 80225, U.S.A.
e-Mail: tcollett@usgs.gov*

Abstract

The occurrence of gas hydrates in the Mackenzie Delta-Beaufort Sea region raises a number of concerns for resource and hazard assessments and for global change studies in permafrost regions. In preparation for a major gas hydrate research well planned for February 1998, a detailed evaluation of terrestrial gas hydrate occurrences has been undertaken in the Mackenzie Delta-Beaufort Sea region. This evaluation included the review of the gas hydrate geologic setting, sediment associations, pressure and temperature conditions. After an exhaustive review of all the inferred gas hydrate occurrences in the Mackenzie Delta-Beaufort sea region, it was determined that the Mallik L-38 drill site offered the highest probability of encountering thick gas hydrate occurrences. Open hole well logs reveal that the Mallik L-38 well drilled about 111 m of gas-hydrate-bearing strata within the depth interval from 810.1 to 1,102.3 m, which is within the zone of predicted methane hydrate stability and below the base of ice-bearing permafrost.

Introduction

Gas hydrates are crystalline substances composed of water and usually methane, in which a solid water lattice accommodates methane molecules in a cage-like structure. Gas hydrates are widespread in permafrost regions and beneath the sea within sediments of outer continental margins. The amount of methane sequestered in gas hydrates is probably enormous, but estimates are speculative and range over three orders of magnitude, from about 2,800 to 7,600,000 trillion cubic meters (reviewed by Sloan, 1990). Because methane is a particularly potent greenhouse gas, and gas hydrates are sensitive to changes in temperature, there has been concern in recent years that they may play a role in greenhouse warming. Gas hydrates also represent a significant drilling and production hazard. Russian, Canadian, and American researchers have described numerous problems associated with gas hydrates, including blowouts and casing failures (reviewed by Yakushev and Collett, 1992).

In February of 1998, a research project sponsored by the Japan National Oil Corporation will drill a gas hydrate well in the Mackenzie Delta of northern

Canada. The Geological Survey of Canada, with participation of the Japan Petroleum Exploration Company and the U.S. Geological Survey, will coordinate the science program for the project. After a long review process, a drill site near the Imperial Oil Mallik L-38 industry exploration well was selected for the location of the gas hydrate research well. The primary purpose of the review process, that led to the selection of the Mallik L-38 site, was to identify a site with 'proven' gas hydrates. The site assessment and review process included the evaluation of known and suspected gas hydrate occurrences in the Mackenzie Delta region. It was determined that the Mallik L-38 drill site offers favorable logistics and has the thickest known gas hydrate occurrences in the region. This paper presents the results of the regional assessment of gas hydrates in the Mackenzie Delta including a review of gas hydrates occurring within permafrost. A companion paper by Collett and Dallimore (this volume) deals with quantitative assessment of the gas hydrate concentrations from well log analyses undertaken for the Mallik L-38 drill site.

Gas hydrate occurrences

The geology of the Mackenzie Delta-Beaufort Sea region has been described in numerous publications with extensive regional overviews given in Dixon et al., (1992). Surficial sediments of the Mackenzie Delta are composed in part of modern deltaic sediments and of older fluvial and glacial deposits of Richards Island and the Tuktoyaktuk Peninsula. At depth, the area 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.

Assessments of gas hydrate occurrences in the Mackenzie Delta-Beaufort Sea area 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 hydrates includes well log response (Smith and Judge, 1993), steady build up of shut in pressures during industry production tests, and gas flows during drilling (Bily and Dick, 1974; Weaver and Stewart, 1982). A data base 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 hydrates (Fig. 1). All of these inferred gas hydrates occur 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 hydrates identified in 35 out of 55 wells (63%).

Gas hydrate stability conditions

The stability of gas hydrates is known to be controlled by the physio-chemical properties of the enclosing formation, gas chemistry, pore pressure regime and formation temperatures. In the following section, these geologic controls on the stability of gas hydrates in the Mackenzie Delta-Beaufort Sea region are reviewed.

FORMATION PROPERTIES

A considerable effort has been devoted in recent years to the laboratory study of gas hydrates 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 hydrates observed in coring or inferred from geophysical studies. It has been speculated that porous media effects could impact on the free energy state of the water phase and thus shift the theoretical pressure-temperature relationships determined for pure water and methane mixtures.

Gas hydrates observed in the Mackenzie Delta-Beaufort Sea region occur exclusively within sediments of the Kugmallit, Mackenzie Bay and Iperk sequences. In 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. Re-investigation of well log interpretations of gas hydrate occurrences summarized in Smith and Judge (1993) reveal a clear lithologic control at most onshore sites. Gas hydrates typically have a layered or interbedded character. Gas hydrate layers occur in coarse grained sand dominated facies separated by thin non-hydrate-bearing, fine grained siltstone and claystone facies.

FORMATION PORE PRESSURE

Given the in situ formation temperatures for occurrences of gas hydrates in the Mackenzie Delta, theory would suggest that methane hydrate is stable over a rather narrow pressure field (Fig. 2). 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 also demonstrated that permafrost may cause non-equilibrium compaction within and immediately below ice-bearing permafrost (Serebryakov et al., 1995).

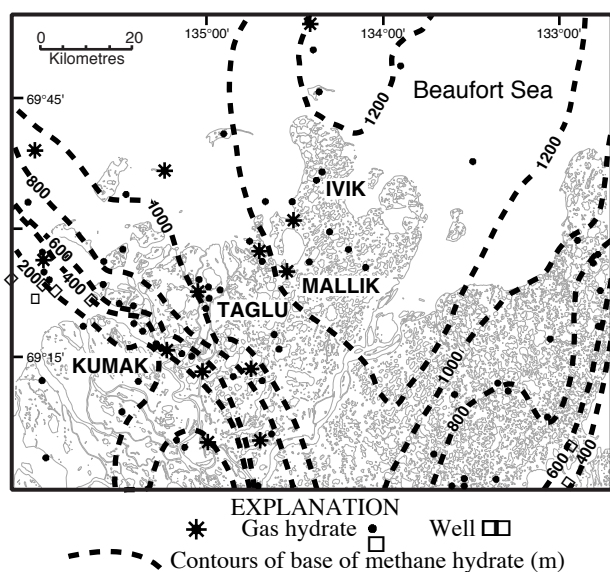


Figure 1. Map of part of the Mackenzie Delta region showing the calculated depth to the base of the methane hydrate stability zone (modified from Judge and Majorowicz, 1992). Exploration wells with well log interpreted gas hydrate occurrences are shown.

In onshore areas of the Mackenzie Delta measurements of in situ stress regime within the permafrost interval are not available. However, it is possible 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 over the Taglu and Kumak hydrocarbon fields, clearly show that permafrost can significantly impede normal consolidation resulting in elevated pore water pressures upon thawing (Dallimore and Matthews, 1997). These observations imply that elevated pore water pressures can be expected where thawing of permafrost has occurred or where warming of the permafrost has caused thawed zones or taliks within the main permafrost body.

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 immediately below the base of permafrost (Hawkings and Hatelid, 1975). However, major over pressured zones have been reported at depths several thousand meters below the zone of predicted methane hydrate stability which are thought to be related to the basin stress history regime (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 hydrate (Sloan, 1990) which can exist under a wider range of pressure and temperature conditions. Analyses of gas samples and mud log gas chromatography data from industry wells reveal that the formation gases within the upper 2,000 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 area.

PORE WATER SALINITY

Experimental data presented by Maekawa et al., (1995), 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 water. Their results suggest that for a fixed temperature of 0°C a pressure shift of approximately 2 MPa can be expected with salinity of 10 weight percent NaCl (wt.%).

Pore water salinities of sediments of Iperk sequence are well documented from core samples (Dallimore and Matthews, 1997). These data suggest that permafrost within the Iperk formation is mainly syngenetic in origin and that the pore water salinities for the most part are similar to those emplaced during primary deposition. Since Iperk sediments are largely terrestrial, low salinities below 0.1-0.5 wt% can be expected. However, in certain instances thin high salinity zones were also observed with values up to 3 wt%. Pore water salinity information from the Kugmallit and Mackenzie Bay sequences is 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 0.5 to 3.5 wt%. Experimental data presented in Maekawa et al., (1995) suggest that these salinity ranges have only a modest effect on the methane hydrate stability conditions.

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 impact greatly on the formation temperatures within the permafrost interval as can be seen on Figure 2 which contains plots of subsurface temperature surveys in four onshore wells that were interpreted to contain gas hydrates on the basis of well log studies (Smith and Judge, 1993). Beneath the permafrost interval the geothermal gradients in the Mackenzie Delta-Beaufort Sea region are more uniform, ranging from about 3.0°C/100m to 4.0°C/100m (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 1, depicts the depth to the base of the methane hydrate stability zone assuming hydrostatic pore pressure gradient, fresh pore water salinities, and a pure methane gas chemistry for the in situ gas hydrates. Based on

these simplifying assumptions the base of the methane hydrate stability zone is more than 1,000 m deep on Richards Island and is extensive beneath most of the continental shelf.

Intrapermafrost gas hydrates

As indicated in Figure 2, in theory methane hydrate can occur at depths greater than about 130 m within the ice-bearing permafrost interval. In some areas of the Mackenzie Delta this intrapermafrost zone of potentially stable gas hydrates may be over 500 m thick. During a recent permafrost coring program in the Taglu area, ice-bearing cores containing visible gas hydrates and possible pore space gas hydrates 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 suggest that other ice-bearing cores from a corehole in the Niglintgak field 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 where a coating of ice encapsulates the gas hydrate, thus preserving the internal clathrate structure. The observations of shallow gas hydrates in permafrost of late Quaternary age suggest that self-preservation may occur over geologic time scales (Dallimore and Collett, 1995).

Mallik L-38 drill site

As mentioned previously, the review of gas hydrate occurrences in the Mackenzie Delta presented in this

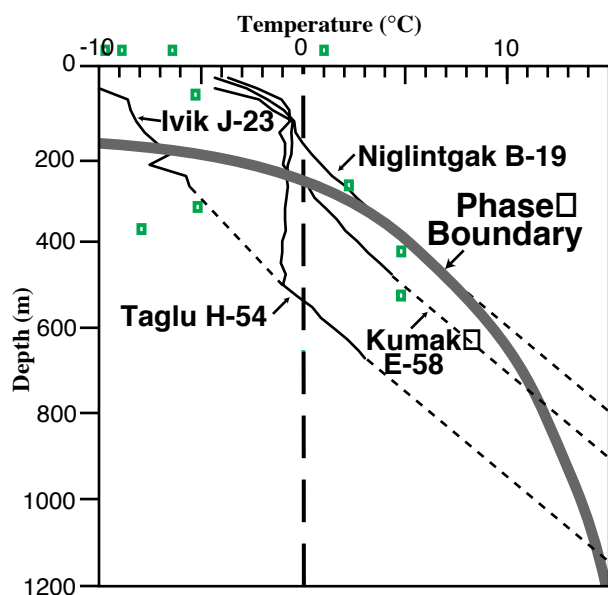


Figure 2. Plot of ground temperatures measured in abandoned industry exploration wells believed to contain gas hydrates (data from Judge et al., 1981 and Taylor et al., 1982). A methane hydrate stability curve is plotted for reference.

paper was conducted in part in an effort to select an ideal drilling site for a collaborative gas hydrate research well. During the course of this investigation all 25 onshore 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 layers 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 hydrates 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 in 1972 by Imperial Oil.

A well log interpretation of the geology, permafrost and gas hydrates occurring in Mallik L-38 is given on Figure 3. Three sequences, each with distinctive natural gamma log response, were encountered in the upper 1400 m. The Iperk sequence (0-350 m) appears to be composed almost entirely of coarse grained sandy sediments. Previous coring experience (Dallimore and Matthews, 1997) would suggest that these sediments are unconsolidated. The Mackenzie Bay sequence (350-935 m) is also sand dominated with a distinct fining upward section near its upper contact with the Iperk Sequence. The Kugmallit sequence (>935 m) consists of interbedded sandstone and siltstone. Chip samples and drilling records suggest that the grain cementation in the Mackenzie Bay and Kugmallit Sequences is quite variable. Interpretation of the resistivity log suggests that the base of ice-bearing permafrost occurs at about 640 m in the Mallik well. Equilibrium ground temperature data are not available from the Mallik L-38 well; however, data available from nearby Mallik A-06 suggests a ground temperature regime very similar to the Taglu Field (Figure 2). It is estimated that Mallik L-38 encountered about 110 m of gas-hydrate-bearing strata in ten distinct layers (Figure 3). A quantitative review of the volume of gas hydrates can be found in a companion paper to this one, presented by Collett and Dallimore (this volume).

Conclusions

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 geologic setting of these deposits and led to selection of

Mallik L-38 as the drill site for a planned gas hydrate research well. On a regional basis, methane hydrates are found exclusively within unconsolidated to weakly cemented sediments of the Kugmallit, Mackenzie Bay and Iperk sequences. Gas hydrates typically occur in coarse grained sandy intervals with fine grained interbeds being non-gas hydrate bearing. 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 indicates primarily a fresh water regime with salinities less than 3.5%.

Formation temperatures are widely variable impacting substantially on the predicted thickness of the methane gas hydrate stability zone.

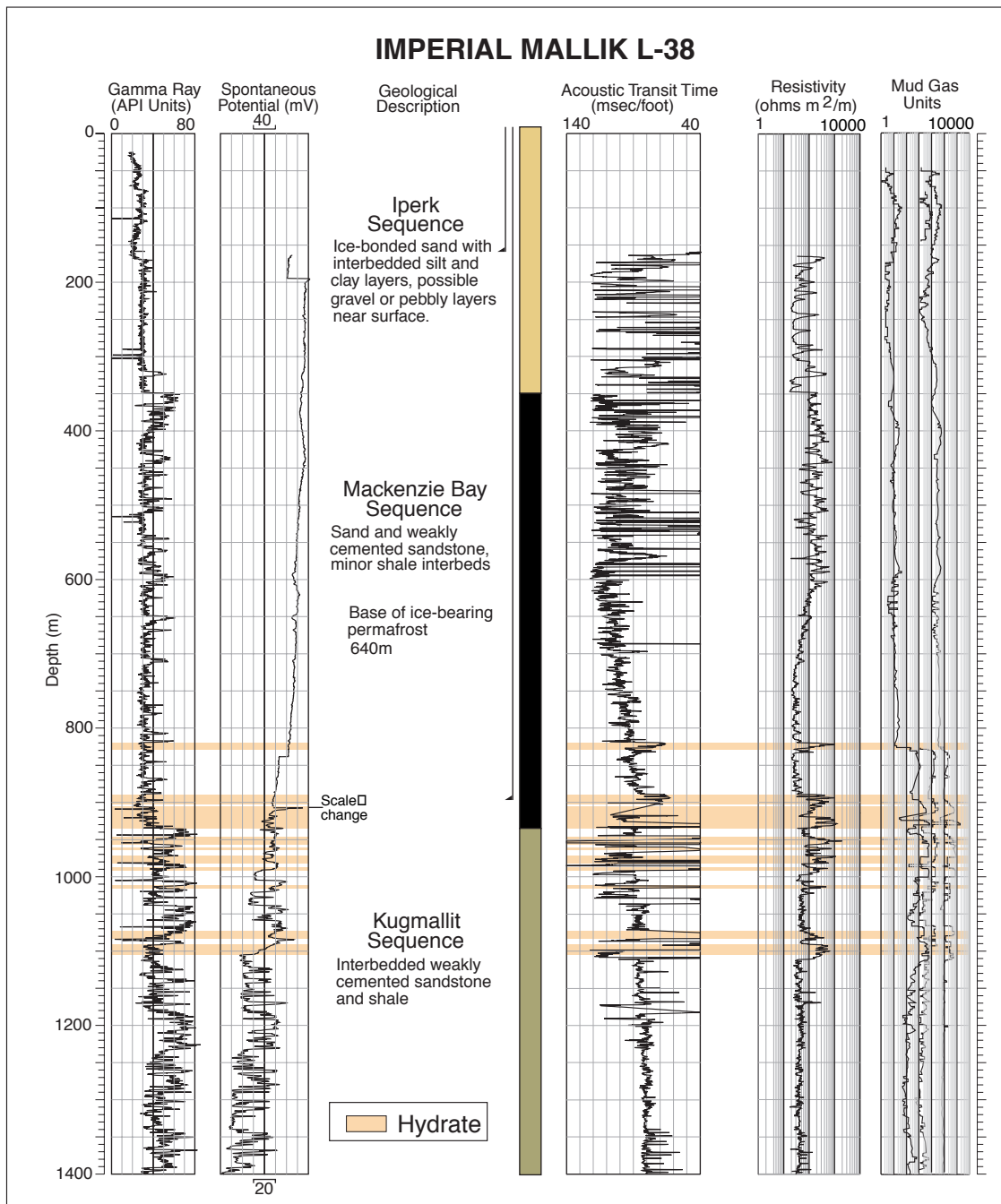


Figure 3. Well log display for Mallik L-38 well showing gas hydrate occurrences and interpreted geology.

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