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QUANTITATIVE ASSESSMENT OF GAS HYDRATES IN THE MALLIK L-38 WELL, MACKENZIE DELTA, N.W.T., CANADA

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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 exploration well planned for February 1998, a detailed evaluation of terrestrial gas hydrate occurrences has been undertaken in the Mackenzie Delta-Beaufort Sea region. Newly developed gas hydrate well log evaluation techniques have been used to calculate sediment porosities and gas hydrate saturations in the gas-hydrate-bearing interval of the Mallik L-38 well. The gas hydrate accumulation delineated by the Mallik L-38 well has been determined to contain about 4,284,000,000 cubic meters of gas in the one square kilometer area surrounding the drill site.

Introduction

In February 1998, a 1150 m deep gas hydrate research well is scheduled to be drilled in the Mackenzie Delta at the site of the existing Mallik L-38 well. The goal of this project is to undertake an integrated scientific and engineering assessment of a permafrost-related gas hydrate occurrence. Participants in the project include the Japan National Oil Corporation, the Japan Petroleum Exploration Company, the Geological Survey of Canada and the U.S. Geological Survey. The Mallik L-38 site was selected after a long review process which included the evaluation of all known and suspected gas hydrate occurrences in the Mackenzie Delta region. A summary of this regional assessment of gas hydrates occurrences and the criteria for selection of the Mallik L-38 site is given in Dallimore and Collett (this volume).

The Mallik gas hydrate well is designed as a research project and will include extensive coring and sampling of gas hydrate intervals, geophysical logging and production testing. Efficient and safe execution of this project requires accurate delineation of the hydrate intervals, their sediment associations and volumetric considerations. Recent advancements in well-log evaluation techniques have contributed to the development of procedures which allow the quantitative assessment of gas hydrate accumulations using "conventional" downhole well-log data. This paper provides a detailed overview of gas hydrates at the Mallik L-38 drill site, providing for the first time a quantitative assessment of the amount of gas associated with the well-log inferred gas hydrate occurrences.

Geology and gas hydrate distribution

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 have been used to assess local geology, permafrost, and gas hydrate conditions. In the upper 1500 m, three stratigraphic sequences have been identified using reflection seismic records and well data (Figure 3 in Dallimore and Collett, this volume). Using the nomenclature of Dixon et al. (1992), these include: the Iperk Sequence (0-350 m), the Mackenzie Bay Sequence (350-935 m), and the Kugmallit Sequence (935 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; Figure 1). The presence of gas hydrates was inferred on the bases 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 hydrates. 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 been trapped within the log-inferred gas hydrate occurrences.

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 (Figure 1). The remaining gas-hydrate-bearing units were drilled and the well was advanced to a depth of 1,843 m, which took a total of about 22 days to complete. The sub-permafrost section was also surveyed with dual-induction-laterolog (DIL), gamma ray (GR), and borehole compensated acoustic transit-time (BHC) well logging devices (Figure 1). In addition, a compensated formation density (FDC) and a sidewall neutron porosity (SNP) tool were also used to log the sub-permafrost section of the Mallik L-38 well (Figure 2). The extended period of drilling subjected the gas-hydrate-bearing units within the sub-permafrost section of the Mallik L-38 well (below 897 m) to significant thermal disturbance, which caused the gas hydrates within the formation near the wellbore to disassociate. The breakdown of the in situ gas hydrates caused significant borehole stability problems which contributed to the development of large borehole "washouts" within the sub-permafrost 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 sub-permafrost gas-hydrate-bearing units (below 897 m) is severely affected by the presence of free gas and exhibits "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

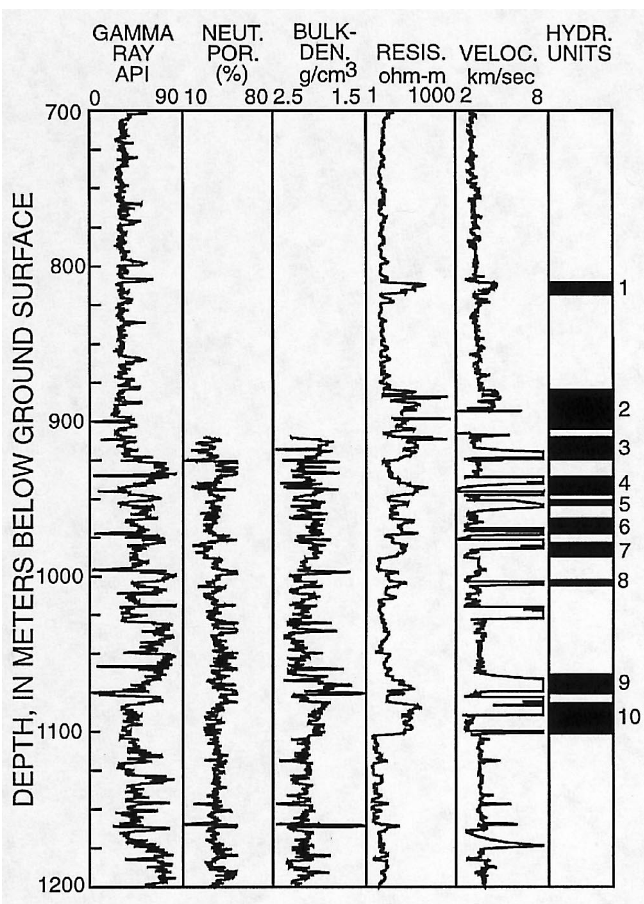

Figure 1. Downhole log data from the Mallik L-38 well. Data shown include the natural gamma ray log from the GR tool, neutron porosity data from the SNP, bulk density from the FDC, deep-reading electrical resistivity data from the DIL, and acoustic velocity data from the BHC. Also shown are the depths of the gas-hydrate-bearing stratigraphic units (Table 1).

Table 1. Depths and thickness of the log inferred gas-hydrate-bearing stratigraphic units in the Mallik L-38 well.

Hydrate unit	Depth from ground surface (m)	Thickness (m)
1	810.1-817.0	6.9
2	880.0-905.4	25.4
3	910.3-925.5	15.2
4	936.5-948.1	11.6
5	951.1-954.5	3.4
6	963.3-973.4	10.1
7	978.6-987.7	9.1
8	1003.2-1006.3	3.1
9	1066.9-1073.7	6.8
10	1082.2-1102.3	20.1
	Total thickness	111.4

Mallik L-38 well logging program was the lack of density or neutron porosity log surveys from the shallow (above 897 m; Figure 1) gas-hydrate-bearing units located above and at the top of the main gas-hydrate section.

The subsurface depths used in this paper were fixed by subtracting 8.99 m (height above ground surface of the Kelley 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 sub-permafrost (below a depth of about 897 m) part of the Mallik L-38 well (Fig. 1) are highly variable with depth. The density log (Fig. 1) is characterized by numerous thin low density zones, ranging in thickness from 2 to 4 meters. It is possible that these low density zones, with measured bulk densities of 1.8 g/cm3 and lower, may contain coal. However, it is possible, but not likely, that these low density log measurements could be caused by "massive" gas hydrate occurrences. The unedited bulk density (rb) log measurements were used to calculate sediment porosities (Ø) in the Mallik L-38 well using both the standard density-porosity relation (Equation 1) and a modified density equation (Equation 2) that has been developed for a three component system (water, hydrate, matrix) (Collett, 1998):

$$\varnothing = \frac{\rho_m - \rho_b}{\rho_m - \rho_w} \quad [1]$$

$$\rho_b = (1-\varnothing)\rho_m + (1-S_h)\varnothing\rho_w + S_h\varnothing\rho_h \quad [2]$$

ρ_b = bulk density, g/cm^3

ρ_m = matrix density, g/cm^3

ρ_w = water density, g/cm^3

ρ_h = hydrate density, g/cm^3

S_h = hydrate saturation, decimal %

Ø = porosity, decimal %

In both equations, the density of the formation waters (ρw) was assumed to be constant and equal to 1.00 g/cm^3 and the grain/matrix densities (ρm) were assumed to equal 2.65 g/cm^3. In Equation 2, the density of gas hydrate (ρh) was assumed to be 0.9 g/cm^3 and gas-hydrate saturations (Sh) 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 standard density-porosity relation (Equation 1) average about 37% (Figure 2). However, 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 2), average about 35% (Figure 2). Under most conditions, the bulk density (ρb) of a water-bearing formation is almost identical to the bulk density (ρb) of a gas-hydrate-bearing formation as measured by borehole density logs. At high porosities and high gas hydrate saturations, however, the standard density-

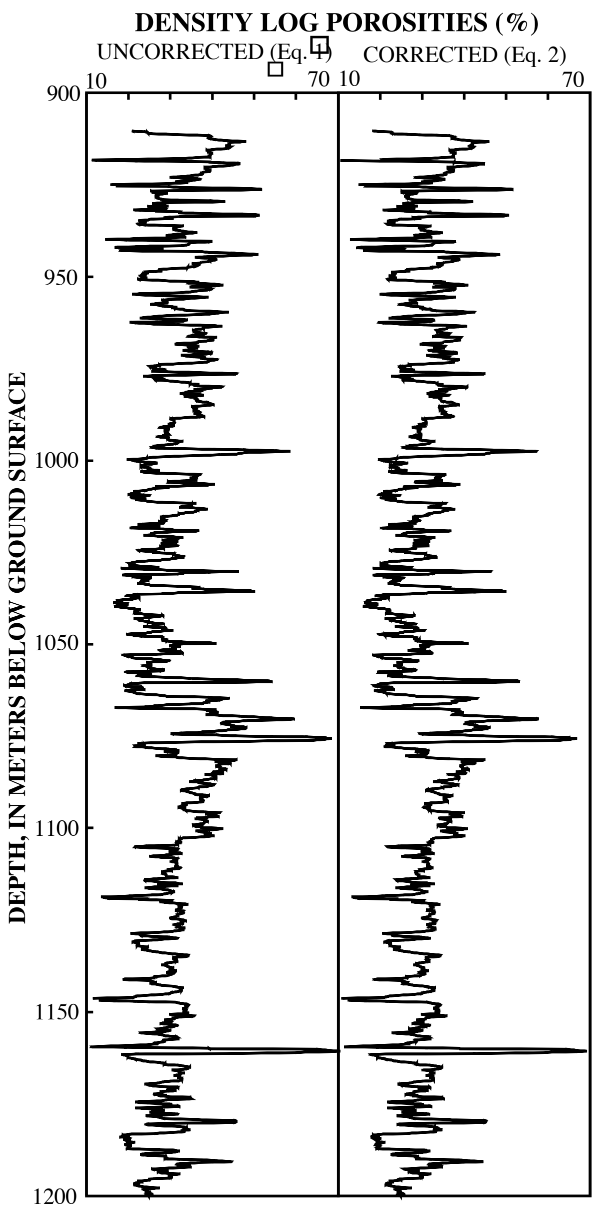

Figure 2. Sediment porosities derived from the downhole density log (FDC) in the Mallik L-38 well. These two density-porosity logs were calculated with the standard density-porosity relation (Equation 1) and a modified three component density-porosity equation (Equation 2) (Collett, 1998).

porosity relation (Equation 1) yields high "apparent" porosities that need to be corrected.

Because of poor borehole conditions, the sidewall neutron porosity log from the Mallik L-38 well (Figure 1) 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 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 Sw)] 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:

$$S_w = \left(\frac{R_o}{R_t}\right)^{\frac{1}{n}} \qquad [3]$$

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

This modified "quick look" Archie relationship is based on the following logic: if the pore space of a 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 ohm-m. Laboratory experiments of different sediment types have yielded a pooled estimate for n of 1.9386 (reviewed by Pearson et al., 1983). Knowing Rt, R_o, and n, it is possible to use the modified "quick look" Archie relationship to estimate water saturations. In Figure 3, the results of the "quick look" Archie calculations are shown as a water saturation (S_w) log trace for the sub-permafrost 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, Figure 1) 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:

$$S_w = \left(\frac{aR_w}{\varnothing^m R_t}\right)^{\frac{1}{n}} \qquad [4]$$

R_t = formation resistivity (from log), ohm-m
a = empirically derived parameter
R_w = resistivity of formation water, ohm-m
f = porosity, decimal %
m = empirically derived parameter
S_w = water saturation, decimal %
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 2). 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 (Rw), and the resistivity of the formation (Rt) which is obtained from the deep resistivity log (Figure 1).

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, 1998). 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 (Rw) are 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 2,000 m, is approximately 10 ppm (Dallimore and Collett, this volume). However, pore water salinity data from the analyses of interstitial water samples collected from formation production

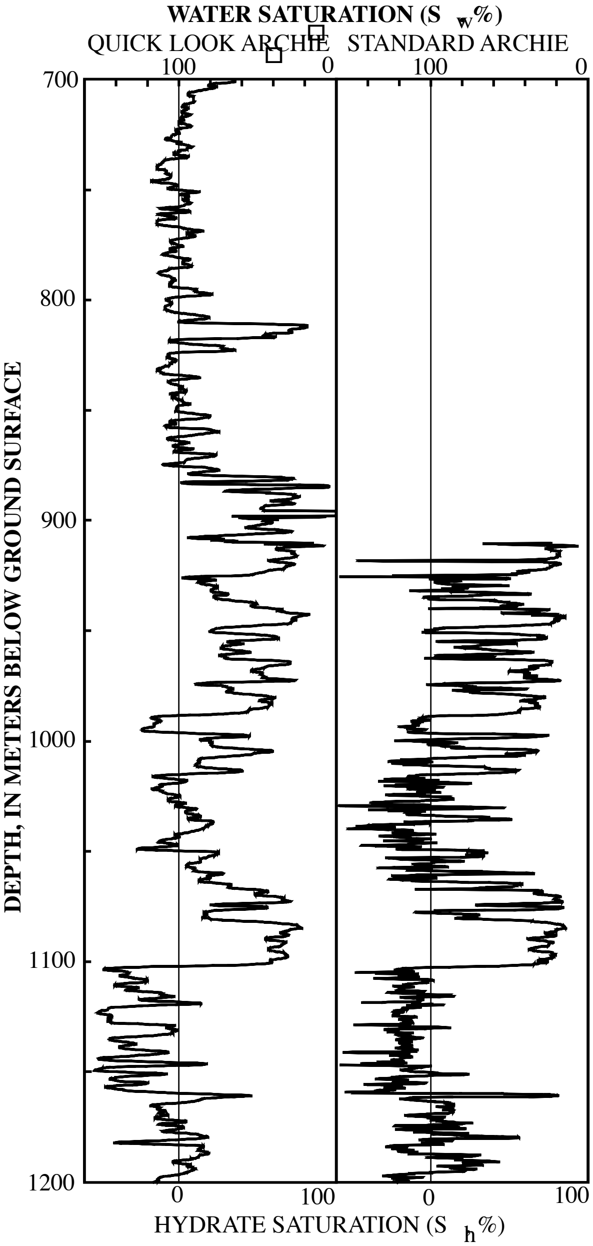

Figure 3. "Standard" and "quick look" Archie derived water saturations (Sw) [gas-hydrate saturation (Sh) is equal to (1.0-Sw)] calculated from the downhole electrical resistivity log in the Mallik L-38 well.

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 enriched 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 sub-permafrost geothermal gradient of 2.7°C/100m and a base of ice-bearing permafrost (640 m) temperature of -1.0°C. Arps formula (reviewed by Collett, 1998) was used to calculate the pore-water resistivities (Rw) 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 (Rw) within the sub-permafrost sedimentary section of the Mallik L-38 well ranges from about 0.30 to 0.38 ohm-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 (Sh) is equal to (1.0-S_w)] from the resistivity log using the "standard" Archie relation. In Figure 3, 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) calculated with the "standard" Archie relation within the gas-hydrate-bearing units of the Mallik L-38 well average 33%. In comparison, the "standard" Archie relation yielded similar, but slightly lower, water saturations than the "quick look" Archie method (Figure 3). The "quick look" method is very dependent on the selection of an accurate R_0 baseline; in general, the "standard" Archie relation yields the most accurate gas hydrate saturations. The zones in each log trace of Figure 3 are characterized by water saturations exceeding 100%, which is theoretically impossible, and are likely caused by poor hole conditions which have degraded the resistivity log measurements. The lower water saturations near the bottom of the log displays in Figure 3 (below a depth of about 1,160 m) are likely due to the presence of free gas.

Volume of natural gas

The volume of gas that may be contained in a gas hydrate accumulation depends on five "reservoir" parameters: (1) areal extent of the gas hydrate occurrence, (2) reservoir thickness, (3) sediment porosity, (4) degree of gas hydrate saturation, and (5) the hydrate gas yield volumetric parameter which defines how much free gas (at STP) is stored within a gas hydrate. In the following "resource" assessment, we have calculated the volume of gas hydrate and associated free gas within a one square kilometer area surrounding the Mallik L-38 well. For this "resource" assessment, we have defined the thickness of the gas-hydrate-bearing sedimentary section as the total thickness of the log inferred gas-hydrate-bearing section in the Mallik L-38 well, which yields a total thickness of 111.4 m (Table 1). The density log derived sedimentary porosities (Figure 2) for the gas-hydrate-bearing units in the Mallik L-38 well average 35%. Gas hydrate saturations (Sh) in the gas-hydrate-bearing units of the Mallik L-38 well, calculated from the "standard" Archie relation (Figure 3), average 67%. In this assessment we have assumed a hydrate number of 6.325 (90% gas filled clathrate) which corresponds to a gas yield of 164 m3 of methane (at STP) for every cubic meter of gas hydrate. Based on these assumptions our calculations indicate that cumulatively, the log inferred gas-hydrate-bearing stratigraphic units drilled in the Mallik L-38 well contain 4,284,000,000 cubic meters (150 billion cubic feet) of gas in the one square kilometer area surrounding the drill site. If correct, this would make the Mallik gas hydrate accumulation one of the most highly concentrated natural gas accumulations in the world and make it one of the ten largest discoveries of natural gas in the Mackenzie Delta/Beaufort Sea area to date (Dixon et al., 1992).

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: 1,095-1,098 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.

Conclusions

Analysis of downhole logs and the results of formation production testing has 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 suggest, 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 has been 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 relation, average 67%. We have determined that if the hydrate deposit at Mallik were laterally continuous, within a one square kilometer area surrounding the Mallik L-38 well, all gas-hydrate-bearing stratigraphic units would cumulatively contain 4,284,000,000 cubic meters of gas.

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