

# Physical properties of sediments from the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well

W.J. Winters<sup>1</sup>, S.R. Dallimore<sup>2</sup>, T.S. Collett<sup>3</sup>, T.J. Katsube<sup>2</sup>, K.A. Jenner<sup>4</sup>, R.E. Cranston<sup>4</sup>, J.F. Wright<sup>2</sup>, F.M. Nixon<sup>2</sup>, and T. Uchida<sup>5</sup>

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**Abstract:** A 1150 m deep gas hydrate research well was drilled in the Canadian Arctic in February and March 1998 to investigate the interaction between the presence of gas hydrate and the natural conditions presented by the host sediments. Profiles of the following measured and derived properties are presented from that investigation: water content, sediment wet bulk density, grain size, porosity, gas hydrate quantity, and salinity. These data indicate that the greatest concentration of gas hydrate is located within sand and gravel deposits between 897 m and 922 m.

**Résumé :** Un puits de recherche sur les hydrates de gaz de 1 150 m de profondeur a été foré dans l'Arctique canadien en février et en mars 1998 afin d'étudier l'interaction des hydrates de gaz et des conditions naturelles observées dans les sédiments hôtes. On présente des profils de certaines propriétés mesurées et dérivées, notamment la teneur en eau, la masse volumique apparente des sédiments humides, la granulométrie, la porosité, la quantité d'hydrates de gaz et la salinité. Ces données révèlent que la concentration d'hydrates de gaz la plus importante se rencontre dans des dépôts de sable et de gravier se trouvant entre 897 et 922 m de profondeur.

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<sup>1</sup> United States Geological Survey, Center for Coastal and Marine Geology, 384 Woods Hole Road, Woods Hole, Massachusetts 02543, U.S.A.

<sup>2</sup> Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8

<sup>3</sup> United States Geological Survey, Denver Federal Center, Box 25046, MS-939, Denver, Colorado 80225, U.S.A.

<sup>4</sup> Geological Survey of Canada (Atlantic), Box 1006, Dartmouth, Nova Scotia, Canada B2Y 4A2

<sup>5</sup> JAPEX Research Center, Japan Petroleum Exploration Company, Ltd., 1-2-1 Hamada, Mihama-ku, Chiba 261-0025, Japan

## INTRODUCTION

The determination of physical properties of core sediments is important to verify well-log data and to relate the location of gas hydrate to the physical nature of the host material. These data are also a useful complement to sedimentological studies, petrophysical analyses, and a variety of modelling investigations. The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was drilled in February and March 1998, at latitude 69°27'40.71"N, longitude 134°39'30.37"W, on the northeastern edge of the Mackenzie Delta, Northwest Territories, Canada. A primary goal of the 1150 m deep well was the collection of core samples to document an Arctic gas hydrate occurrence (Dallimore et al., 1999a).

Physical properties, including water content, grain density, and Atterberg limits were measured from core subsamples occurring between 109 m and 175 m and between 886 m and 952 m from widely differing sediments (all depths were measured from kelly bushing [8.31 m above sea level]). Other parameters, such as porosity, wet and dry bulk density, void ratio, and total unit weight were calculated from the index properties. The physical property measurements discussed in this report are supplemented by other data presented in the physical property section of the Mallik 2L-38 CD-ROM (Dallimore et al., 1999b).

## GEOLOGICAL SETTING AND GAS HYDRATE PRESENCE

The well penetrated unconsolidated and lithified sediments from three stratigraphic sequences, which range from Pleistocene to Oligocene (Iperk Sequence 0–346 m, Mackenzie Bay Sequence 346–926.5 m, and Kugmallit Sequence 926.5–1150 m) (Jenner et al., 1999). Approximately 13.7 m of core was collected from the permafrost interval which is present from slightly below ground surface to a depth of 640 m. (All depths were measured from kelly bushing: 8.31m.) In total, 37.3 m of core was obtained between the depths of 886 m and 952 m to document a thick gas hydrate zone which had been identified at a nearby site during exploration drilling by Imperial Oil Ltd. in 1972 (Bily and Dick, 1974).

Gas hydrate typically either filled sediment voids or coated grains within coarse sand and gravel deposits obtained at depths between 897 m and 922 m (Collett et al., 1999; Dallimore et al., 1999a). Nodules less than 1 cm in diameter and thin veins less than 1 mm thick were also observed. In addition, the presence of gas hydrate is indicated by well logs which suggest that gas hydrate exists below the level of sample recovery to a depth of about 1110 m (Collett et al., 1999). The 'standard' Archie relation used for interpretation of the electrical resistivity logs indicate that gas hydrate occupies an average of 47% of the void space. This volume is greater than the amount calculated from dissociation experiments conducted at the drill rig on core subsamples. Well-log interpretation indicates that the gas hydrate in the nearby Mallik L-38 well occupies somewhat more void space (about 67%) than is present at the Mallik 2L-38 well (Collett and Dallimore, 1998).

## METHODS

Different coring systems and techniques were used to obtain the best quality samples. A wireline retrievable system produced 50 mm diameter cores in permafrost, whereas a conventional core barrel was typically used in the gas hydrate interval to obtain larger (133 mm and 89 mm) diameter cores. Overall, the quality of the larger diameter cores was excellent and minimal core deformation or contamination from drilling mud was observed. Pore water near gas hydrate deposits sometimes froze during recovery due to endothermic cooling caused by gas hydrate dissociation. This process probably stabilized the sandy sections. Considerable care was taken at the drill site to characterize the physical properties of core samples with emphasis on time-critical observations such as bonding or strength, gas hydrate or permafrost characteristics, and core temperatures. Subsamples were taken directly at the drill site for water content, pore-water geochemistry, petrophysical studies, and a variety of other investigations. Four 26 cm long, large-diameter samples containing gas hydrate, were also preserved for later specialized physical property studies (Winters et al., 1999). Detailed physical property measurements and geochemical analyses were conducted at a field laboratory in Inuvik, Northwest Territories, located approximately 170 km south of the drill site, where additional subsamples were obtained. Subsequent laboratory work was conducted at the Geological Survey of Canada and the United States Geological Survey. Physical property index measurements included water content, grain density, Atterberg limits, and grain size. Other parameters, such as porosity, wet and dry bulk density, void ratio, and unit weights were calculated from the index properties, which had been corrected for pore-water salinity and adjusted for pores filled with water-ice and gas hydrate (Dallimore et al., 1999b).

Core subsamples, used for physical property measurements, were obtained using two methods. A plunger or syringe, which produced a cylindrical plug, provided a uniform specimen from which volume was calculated using measured sample dimensions. The second type of specimen, which was obtained in greater numbers, was irregular in shape, so that volumes of components had to be back-calculated using density values, assuming 100% saturation of the pore voids by either ice or by a combination of water and gas hydrate. For comparison purposes, the properties of the plunger-obtained samples were also determined using the back-calculation method with the adjusted pore volume and the original measured specimen volume.

The specimens were dried at a temperature of 90°C for at least 24 h in order to determine the amount of fresh water and solids present. The dried specimen was then broken into granule-size pieces, and the volume of dried solids was determined with an automatic gas pycnometer using helium as the purge and expansion gas (American Society for Testing and Materials, 1997). The grain density of the pycnometer specimen was calculated using the mass of solids which was determined immediately prior to insertion of the sample into the

pycnometer. All mass determinations were made quickly using sealed containers, to prevent moisture in the air from being adsorbed by clay minerals that could have been present.

All physical property calculations, except uncorrected water contents, were corrected for the presence of residual salt left on the solid particles after oven drying. In the natural environment, salt and other particles are dissolved in the pore fluid and behave as part of the aqueous phase. The calculations removed the salt precipitate mass and volume from the solids and added it back to the fluid phase. A default 10 ppt (parts per thousand) value was assumed for samples without a nearby salinity measurement.

Sediment pores are filled with in situ water, ice, or gas hydrate and occasionally may contain a combination of those materials. The physical property calculations were adjusted to reflect a 10% pore volume increase due to the presence of ice and a 26% increase from gas hydrate. The amount of pore water that was used to calculate the expansion due to gas hydrate formation was related to the in situ gas hydrate quantities interpreted by Collett et al. (1999) from the resistivity well log using the Archie relation. Pore volumes also were approximately adjusted for the presence of free water caused by ion exclusion during ice or gas hydrate formation.

The following equations were used in calculating the physical property values:

$$\rho_c = M_t/V_{tc} \quad (1)$$

where  $\rho_c$  = bulk density based on a calculated specimen volume,  $M_t$  = mass of the total specimen, and  $V_{tc}$  = calculated total specimen volume;

$$\rho_m = M_t/V_m^* \quad (2)$$

where  $\rho_m$  = bulk density based on the measured volume, and  $V_m$  = measured specimen volume;

$$\rho_s = M_s/V_s \quad (3)$$

where  $\rho_s$  = grain density,  $M_s$  = mass of solid sediment grains, and  $V_s$  = volume of solid sediment grains;

$$n_c = (V_p/(V_s + V_p)) \times 100\% \quad (4)$$

where  $n_c$  = porosity based on the calculated specimen volume,  $V_s$  = volume of solid sediment grains, and  $V_p$  = calculated volume of pores (adjusted for the presence of ice, salt water, and/or gas hydrate);

$$n_{m1} = (V_p/V_m) \times 100\%^* \quad (5)$$

where  $n_{m1}$  = porosity based on the measured specimen volume and calculated pore volume;

$$n_{m2} = ((V_m - V_s)/V_m) \times 100\%^* \quad (6)$$

where  $n_{m2}$  = porosity based on the measured specimen volume; and difference between measured specimen and measured grain volumes;

$$WC_s = M_{pw}/M_s \quad (7)$$

where  $WC_s$  = water content based on the mass of solid sediment grains, and  $M_{pw}$  = mass of pore water; and

$$WC_t = M_{pw}/M_t \quad (8)$$

where  $WC_t$  = water content based on the total specimen mass.

Note that values with the asterisk symbol (\*) are available in the physical properties section of the Mallik 2L-38 CD-ROM (Dallimore et al., 1999b).

Grain sizes were determined using two methods. Dry sieving was used to measure the size of coarse material and a Brinkmann particle-size analyzer, using time of transition theory, was used for the fine fraction.

## RESULTS AND DISCUSSION

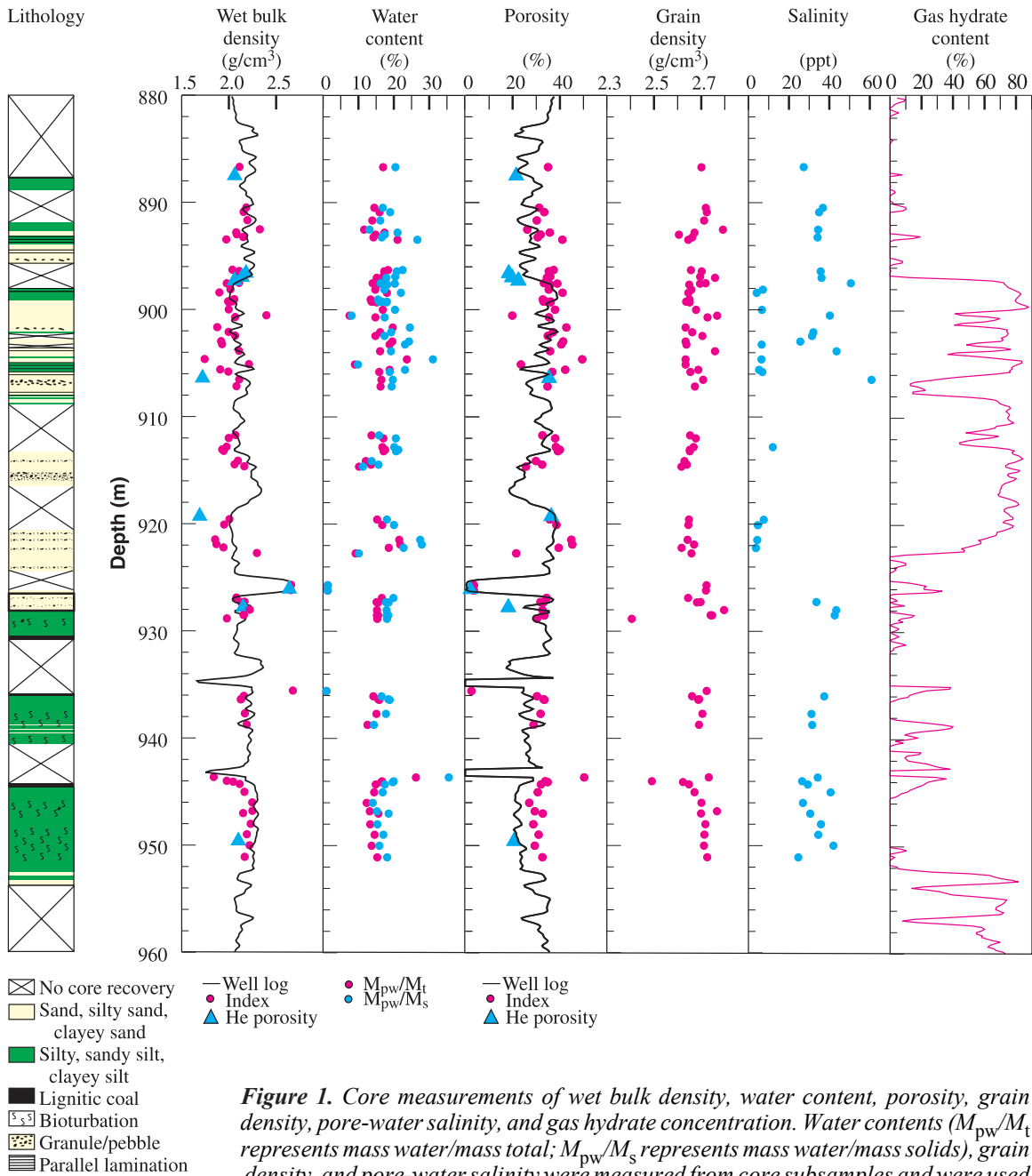
Measurements of water content and porosity are important to the understanding of the host sediment conditions. These characteristics indicate how much water and void space is available to form gas hydrate, provided that gas concentration is not a limiting factor. Both water content and porosity decrease significantly between the zones 109–175 m and 896–952 m. Water contents ( $M_{pw}/M_s$ ) vary from over 100% in organic-rich sediments in the upper zone to about 1% in a thin, cemented sandstone encountered at 926 m. Water contents are often high in organic-rich layers because of trapped moisture within the fibers themselves. Porosities change from 73% to a few per cent over the same interval.

The differences in physical properties between the upper 109–175 m zone and the lower 896–952 m zone reflect the influence of sediment composition, natural compaction, and the presence of permafrost. Sediments in the permafrost zone at the Mallik site characteristically have higher water contents. With few exceptions, porosities in the upper sampled zones are greater than 44%, while most of the samples from the deeper section have porosities less than 44% (Dallimore et al., 1999b). Sediments may exhibit underconsolidated behavior (after thawing) if permafrost formed before primary consolidation was completed. The presence of permafrost may also substantially modify the physical properties of those sediments that would otherwise experience substantial secondary compression (for example in organic-rich sediments).

Physical property index measurements on sediment cores and derived geotechnical parameters are summarized for the gas hydrate interval in Figure 1 and compared with well-log-derived bulk density, porosity, and gas hydrate concentration (Collett et al., 1999). Petrophysical determinations of porosity and bulk density using a helium porosimeter are also presented. In general, within the gas hydrate interval, from 897 m to 922 m, the correlation between the core-measured values and the well-log-derived values is strong. Porosity values range from about 30% to 45%. For some samples, a difference exists between the index-derived values and the measured helium porosimetry values. Good agreement between all techniques is observed in a thin layer at 926 m which has porosity values between 2% and 4% (dolomite-cemented sandstone) (Jenner et al., 1999). A coal layer sampled at 943 m is also well defined by low core-derived and well-log-derived bulk density measurements. Another layer at 935 m is evident from the well-log response.

Salinity determinations on pore water extracted from core samples reveal pronounced changes with values ranging from over 60 ppt to less than 5 ppt. Within the gas hydrate interval sediments containing high gas hydrate concentrations have values less than 10 ppt and usually less than 5 ppt. However, some core samples within this interval had salinity

values from 26 ppt to over 50 ppt. These samples generally correlate with apparent interbeds having lower gas hydrate concentrations and may imply solute migration associated with gas hydrate formation. Salinity in finer grained sediments above and below this interval had more consistent salinity values in the range of 25–35 ppt.



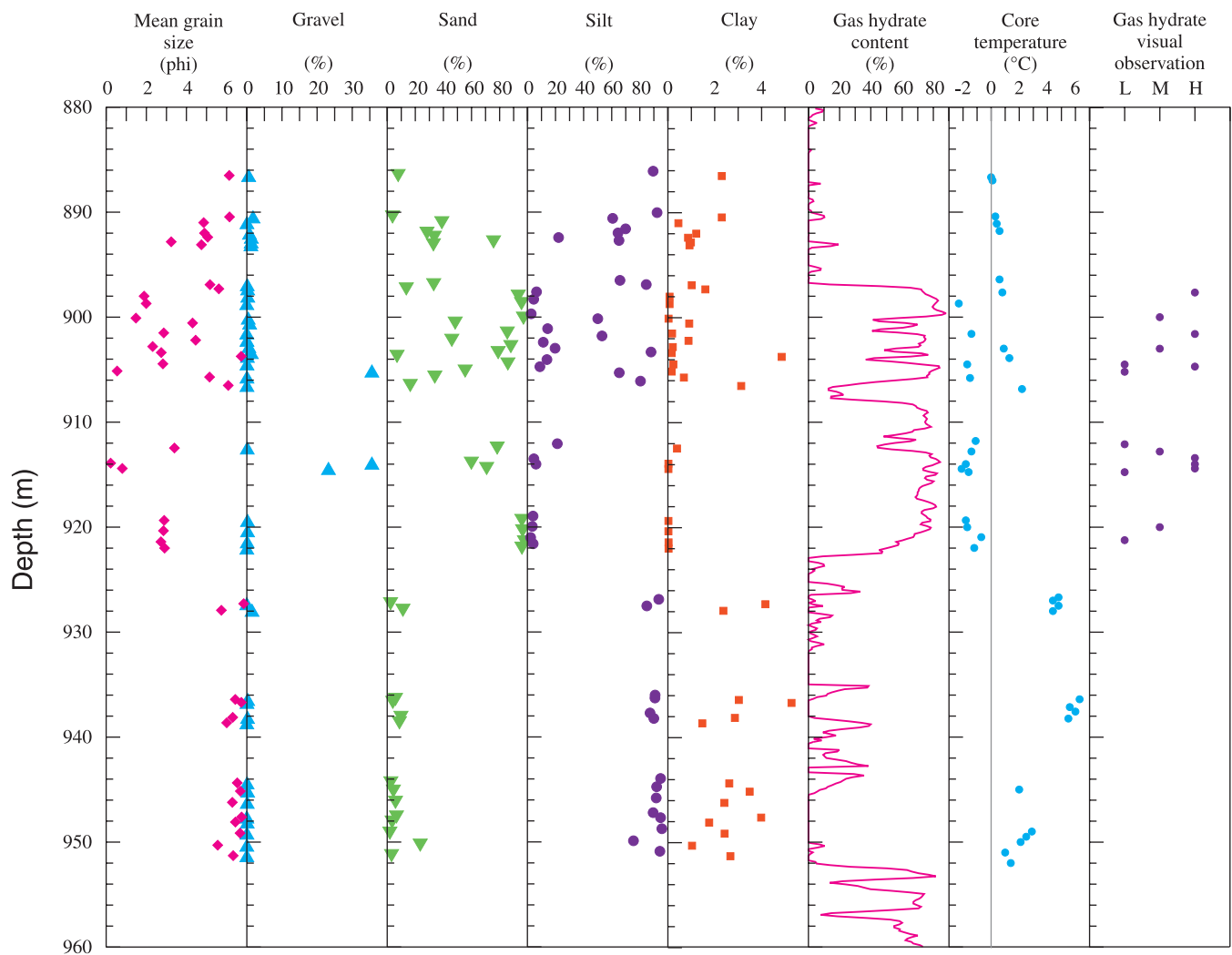
**Figure 1.** Core measurements of wet bulk density, water content, porosity, grain density, pore-water salinity, and gas hydrate concentration. Water contents ( $M_{pw}/M_t$  represents mass water/mass total;  $M_{pw}/M_s$  represents mass water/mass solids), grain density, and pore-water salinity were measured from core subsamples and were used to calculate wet bulk density and porosity (assuming full water saturation and corrected for pore-water salinity and the presence of gas hydrate). Additional porosity and wet bulk density measurements by the helium porosimetry technique are also provided for petrophysical samples. Well-log values are shown for wet bulk density, porosity, and gas hydrate saturation of pore voids from Collett et al. (1999). A complete listing of physical properties is provided in Dallimore et al. (1999b).

Figure 2 shows grain size, core temperatures (measured immediately after sample extrusion from the core barrel), and qualitative estimates of gas hydrate content made by scientists at the drill site. The main gas hydrate interval from 897 m to 922 m is dominated by sand, although some silty sand and low-plasticity silt are present in interbeds with lower gas hydrate concentrations. Sediments above this interval have similar grain-size characteristics, however sediments below consist of low-plasticity silt with trace amounts of sand and clay.

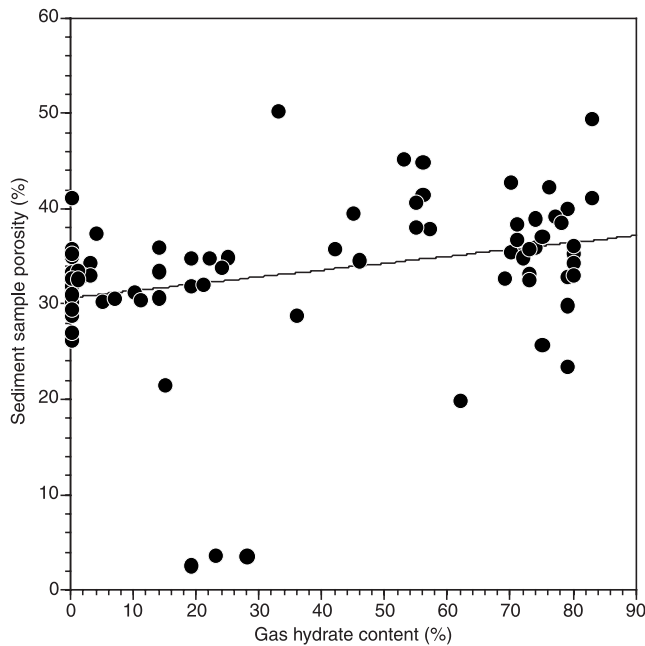
As discussed by Dallimore et al. (1999a), core temperature measurements can provide a proxy indication of the presence of gas hydrate. Given that in situ temperatures were almost certainly above 8°C and mud temperatures were above 2°C, measurements of core temperatures below 2°C are interpreted to result from the endothermic cooling effect occurring as a result of gas hydrate dissociation. Further

evidence of the presence of gas hydrate was documented in sediments with temperatures below 0°C that were observed to be bonded or cemented by either gas hydrate or pore ice interpreted to have formed by this cooling effect. Quantitative visual estimates of gas hydrate concentration were generally made by immersing representative subsamples in water and estimating the intensity and volume of gas hydrate dissociation. Good correlation is observed between visual observations and negative core temperatures.

Gas hydrate was typically recovered in sandy material with a porosity of 32–45% and in gravel with a lower porosity of 23–29% (corrected for the presence of gas hydrate) (Dallimore et al., 1999b). Silt and silty sand that are present above, within, and below the different gas hydrate layers (but do not contain gas hydrate) have similar or slightly lower porosities (26–41%) compared to the sand. This suggests that porosity alone is not a primary control on the distribution of gas



**Figure 2.** Grain-size data, temperature measurements (made immediately after core extrusion), and qualitative estimates of gas hydrate concentration based on observations at the drill site. Well-log gas hydrate saturation values are from Collett et al. (1999).



**Figure 3.** Sediment sample porosity (corrected for the presence of gas hydrate) versus *in situ* gas hydrate saturation of pore voids estimated from the resistivity well log (Collett *et al.*, 1999).

hydrate (Fig. 3) and that gas hydrate may preferentially form in the larger void spaces of sand and gravel, whereas formation is inhibited within the smaller voids of the finer grained sediment. Also the lower permeability of the finer silt and sandstone could influence gas migration and gas hydrate formation. Localized elevated pore-water salinity, which may have resulted from salt exclusion caused by initial gas hydrate formation in surrounding sediments, may also inhibit gas hydrate formation (Wright *et al.*, 1999).

## CONCLUSIONS

Gas hydrate was typically recovered in sandy sediments and in layers with a high gravel content. Silt and silty sand that are present above, within, and below the gas hydrate layers, but contain lesser amounts of gas hydrate, have similar porosities to the sand but higher pore-water salinities. This suggests that porosity may not be a primary control on the distribution of gas hydrate and that gas hydrate may preferentially form in the larger void spaces of sand and gravel whereas formation may be somewhat inhibited within the smaller voids of the finer grained and more saline sediments. Perhaps the lower permeability of the finer silt and sandstone also influences gas migration and gas hydrate formation. Other considerations such as the supply of gas may also be a factor.

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## REFERENCES

- American Society for Testing and Materials**  
1997: Standard test method for specific gravity of soil solids by gas pycnometer D 5550-94; *in* American Society for Testing and Materials, *Annual Book of ASTM Standards*, v. 04.09, Soil and Rock, West Conshohocken, Pennsylvania, p. 380–383.
- Bily, C. and Dick, J.W.L.**  
1974: Naturally occurring gas hydrates in the Mackenzie Delta, N.W.T.; *Bulletin of Canadian Petroleum Geology*, v. 22, no. 3, p. 340–352.
- Collett, T.S. and Dallimore, S.R.**  
1998: Quantitative assessment of gas hydrates in the Mallik L-38 well, Mackenzie Delta, N.W.T., Canada; *in* Proceedings of the 7th International Conference on Permafrost, Yellowknife, Canada, June 10–22, 1998, p. 189–194.
- Collett, T.S., Lewis, R., Dallimore, S.R., Lee, M.W., Mroz, T.H., and Uchida, T.**  
1999: Detailed evaluation of gas hydrate reservoir properties using JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well down-hole well-log displays; *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett; Geological Survey of Canada, Bulletin 544.
- Dallimore, S.R., Collett, T.S., and Uchida, T.**  
1999a: Overview of science program, JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well; *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett; Geological Survey of Canada, Bulletin 544.
- Dallimore, S.R., Laframboise, R.R., Fotiou, M., and Medioli, B.E. (comp.)**  
1999b: JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, Mackenzie Delta, Northwest Territories, Canada: interactive data viewer; Geological Survey of Canada, Open File D3726, 1 CD-ROM.
- Jenner, K.A., Dallimore, S.R., Clark, I.D., Paré, D., and Medioli, B.E.**  
1999: Sedimentology of gas hydrate host strata from the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well; *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett; Geological Survey of Canada, Bulletin 544.
- Winters, W.J., Pecher, I.A., Booth, J.S., Mason, D.H., Relle, M.K., and Dillon, W.P.**  
1999: Properties of samples containing natural gas hydrate from the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, determined using Gas Hydrate And Sediment Test Laboratory Instrument (GHASTLI); *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett; Geological Survey of Canada, Bulletin 544.
- Wright, J.F., Dallimore, S.R., and Nixon, F.M.**  
1999: Influences of grain size and salinity on pressure-temperature thresholds for methane hydrate stability in JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well sediments; *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett; Geological Survey of Canada, Bulletin 544.