

Occurrences and X-ray computerized tomography (CT) observations of natural gas hydrate, JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well

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Abstract: The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was drilled through a thick interbedded sequence of gas-hydrate-bearing sediments between 896 and 1106 m. In total, 37.3 m of core were collected between 886 and 952.6 m, using a variety of coring systems. Visual observations at the drill site identified a predominance of pore-space gas hydrate in varying concentrations within framework-supported sands and pebbly sands. Gas hydrate was mainly fine grained (<2 mm), filling the intergranular pores and/or coating mineral grains. Although rare, thin veins (1–2 mm) and clasts or nodules of gas hydrate (up to 0.5 mm) were also observed. The largest gas hydrate occurrence (2 cm in diameter) formed the matrix of a granular sand at 913 m.

X-ray CT imagery, carried out in Japan, has identified eight well constrained signatures of the constituent components of the gas-hydrate-bearing sands and granular sands. These images have been used to establish textural characteristics and the relationship between sediment grains and gas hydrate.

Résumé : Le puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC Mallik 2L-38 a rencontré une épaisse séquence interstratifiée de sédiments renfermant des hydrates de gaz à une profondeur entre 896 et 1106 m. Au total, 37,3 m de carottes ont été extraits entre 886 et 952,6 m à l'aide de divers carottiers. Des observations à l'œil nu sur les lieux du forage ont permis de mettre en évidence la prédominance d'hydrates de gaz d'espace poral en concentrations diverses dans les sables et sables caillouteux à texture jointive. Les hydrates de gaz sont essentiellement à granulométrie fine (<2 mm) et remplissent les pores intergranulaires et/ou enrobent les grains de minéraux. On a également observé de minces (1–2 mm) filons et des clastes ou nodules d'hydrates de gaz (jusqu'à 0,5 mm), mais ils sont rares. La concentration d'hydrates de gaz la plus grosse (diamètre de 2 cm) forme la matrice d'un sable grenu intersecté à 913 m.

Une imagerie tomographique réalisée au Japon a mis en évidence huit signatures bien délimitées des éléments composant les sables et les sables grenus à hydrates de gaz. Les caractéristiques de la texture et les relations entre les grains de sédiments et les hydrates de gaz ont été définies à l'aide de ces images.

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INTRODUCTION

In February and March of 1998, the JAPEx/JNOC/GSC Mallik 2L-38 gas hydrate research well was drilled to a depth of 1150 m at the northeastern edge of the Mackenzie Delta, Northwest Territories, Canada (Fig. 1). A drill site near the Mallik L-38, an industry exploration well drilled in 1972 by Imperial Oil Limited (Bily and Dick, 1974), was selected for the location of the well as it offered favourable logistics and had the thickest known gas hydrate occurrences in the region (Dallimore and Collett, 1999). In addition, substantive geological and engineering data were available from the original well to safely and efficiently plan the operations activities (Ohara et al., 1999). Cores collected from the Mallik 2L-38 well included the first documented gas hydrate samples from beneath permafrost. Gas hydrate in Mallik 2L-38 core samples was observed within a variety of sediment types and provided a unique opportunity to characterize gas hydrate properties in this environment.

The objectives of this paper are to describe the visual characteristics of the gas hydrate found within Mallik 2L-38 sediments and to review the physical behaviour of the core samples after extraction from the core barrels at the drill site. An additional goal is to review the results of X-ray computerized tomography (CT) imagery of several samples, carried out in Japan, as part of the post-field laboratory program. The X-ray CT method has the potential to provide general information on the gas hydrate content and distribution of gas hydrate within sediments in a fast and efficient way. This part of the research was carried out with financial support from the Japan National Oil Corporation (JNOC) and ten oil, gas, and electric companies in Japan.

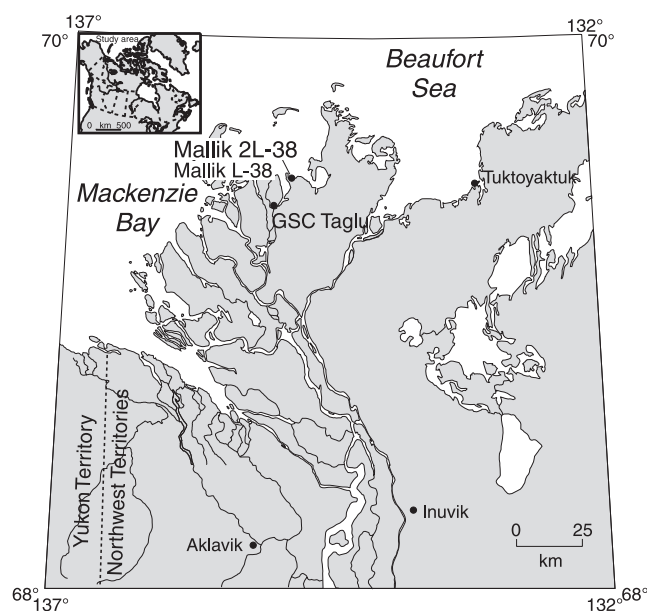


Figure 1. Map of the Mackenzie Delta region showing the location of the Mallik 2L-38 drill site.

GENERAL GEOLOGY

Gas hydrate is a crystalline substance in which a solid water lattice accommodates guest natural-gas molecules in a clathrate cage. While hydrocarbon gases like methane, propane, and other gases can occupy the clathrate structure, methane hydrate occurs most commonly in nature. Gas-hydrate-bearing strata are widespread in arctic sedimentary basins associated with deep permafrost and offshore along the continental margins (Kvenvolden, 1988). While scientific drilling information is available from several marine gas hydrate occurrences, relatively little is known about the geological parameters controlling the occurrence and distribution of gas hydrate in permafrost environments.

In the Mackenzie Delta, methane hydrate is thought to occur within permafrost (intraperafrost gas hydrate) and beneath the permafrost base (subpermafrost gas hydrate) at depths ranging from about 200 to 1300 m (Dallimore and Collett, 1999; Majorowicz and Smith, 1999). Within the Mallik L-38 well, the presence of gas hydrate was interpreted (primarily on the basis of electrical resistivity and mud-gas anomalies) to occur as a layered sequence between 819 and 1007 m (Bily and Dick, 1974). Ten significant gas hydrate layers with a total thickness of approximately 110 m were identified within clastic sediments of the Tertiary Kugmallit and Mackenzie Bay sequences. Volumetric calculations, based on well-log analyses (Collett and Dallimore, 1998), suggested that these strata have porosities in the range of 33 to 40% (average 37%) with pore-space hydrate concentrations ranging from 50% to more than 80% (average 67%). Bily and Dick (1974) originally interpreted the presence of free gas in contact with several gas hydrate layers mainly on the basis of a spontaneous potential (SP) log transition across several intervals. They admitted, however, that this interpretation was questionable since there was a possibility that the free gas might have formed by gas hydrate dissociation due to drilling disturbance.

Prior to the Mallik 2L-38 well, the only actual gas hydrate samples collected from the Mackenzie Delta area were from 92GSC Taglu, a 451 m deep permafrost borehole completed by the GSC in 1992 (Dallimore and Matthews, 1997). Intraperafrost methane hydrate veins and pore-space hydrate were described within a variety of unconsolidated sediments (Dallimore and Collett, 1995).

MALLIK 2L-38 GAS HYDRATE CORING

A total of 37 m of core were recovered from the Mallik 2L-38 well between 896 and 952.6 m, in the interval anticipated to contain gas hydrate (Ohara et al., 1999) (all depths were measured from kelly bushing [8.31 m above sea level]). Three coring systems were utilized. A newly developed pressure-temperature core barrel being field tested collected approximately 1.15 m of core in two core runs between 886 and 890.4 m. A Baker Hughes Intec (BHI) conventional core barrel, yielding 133 mm diameter core, was used for four core runs between 890.4 and 902.6 m. A smaller BHI conventional

core barrel, yielding 90 mm diameter core, was used for seven runs between 902.6 m and 952.6 m. The first physical evidence of gas hydrate in core samples was observed at 897 m within unconsolidated sands and pebbly sands that continued to 926.5 m. Quantitative well-log determinations (Collett et al., 1999; Miyairi et al., 1999) confirmed that this interval contained high, in situ, gas hydrate concentrations with gas hydrate accounting for between 30 and 80% of the pore space. Core samples above and below the sands were composed primarily of unconsolidated silts with no visible evidence of gas hydrate. Well-log interpretations suggest, however, that sediments within these intervals likely contained in situ gas hydrate, albeit with relatively low gas hydrate concentrations (<15%).

In addition to the descriptions of gas hydrate within the core samples in the next section, the presence of gas hydrate in the core samples was confirmed by a number of direct and indirect measurements. Gas hydrate dissociation tests, conducted in the field, confirmed that gas hydrate concentrations in core samples varied from trace amounts to over 40% of the pore space (see Table 1 in Wright et al., 1999). Core samples, when recovered at the surface, were found to be bonded by gas hydrate and ice with temperatures as low as -3°C. Given that in situ formation temperatures are estimated to be between 10 and 14°C, and mud temperatures were approximately 2°C, the negative temperatures were attributed to endothermic cooling resulting from gas hydrate dissociation during core retrieval. Modelling of core-temperature observations by Wright et al. (1999), has confirmed that dissociation caused by this effect likely accounted for substantial reductions in the gas hydrate contents within the core samples compared to in situ concentrations. Qualitative estimates of the volume of gas hydrate within the core sediments were also made immediately after recovering the core by immersing small subsamples in warm water and observing the vigour of gas hydrate dissociation. This testing confirmed a considerable variation in gas hydrate concentrations, with some samples vigorously effervescing for several minutes while others only released small amounts of gas. Because the samples were frozen, the visual observations of gas release were important to identify core zones where gas hydrate concentrations were high relative to pore-ice concentrations.

After initial descriptions and testing in the field, a limited number of core samples containing gas hydrate were stored either in pressure vessels or liquid nitrogen for specialized post-field analyses (Dallimore et al., 1999). The samples were stored in 300 mL and 920 mL pressure vessels charged with nitrogen gas to 7 MPa pressure and transported to Japan. These samples were maintained at -30 to -70°C until analyses were performed at various JNOC and Japan Petroleum Exploration Company (JAPEx) laboratories.

VISUAL OBSERVATIONS

Within core samples retrieved between 896 m and 952 m, gas hydrate was observed to occur primarily within fine- to coarse-grained sands (Jenner et al., 1999), interbedded with non-gas-hydrate-bearing or low-gas-hydrate-content sandy

silts. Sands were well indurated upon retrieval due to the mixture of gas hydrate and pore ice bonding the soil matrix. When thawed, the sands were unconsolidated with no evidence of grain cementation. Sand beds were 10 cm to more than 1.5 m thick with estimated porosities of 25 to 35% (Uchida et al., 1999). Most of the gas hydrate observed within the sands was fine grained (<2 mm), occurring as fillings within sediment pores or as coatings on sand grains. When scraped, the gas hydrate (and ice) within the pore spaces often gave the sands a white sheen (Fig. 2a). In several instances, 1–2 mm thick, randomly oriented veins of gas hydrate were also observed in the sands. The largest visible forms of gas hydrate occurred as small clasts, 2 cm in diameter, forming the matrix of a sandy gravel between 913 m and 914 m (Fig. 2b). These clasts were an opaque white colour and vigorously released gas initially upon recovery. In several instances, random clasts or nodules of gas hydrate, 5 mm in diameter, were also observed within the sands.

The mode of gas hydrate dissociation, in core samples, was observed at the well site within the core trailer which was held at a temperature close to 0°C. Gas hydrate dissociation has been recorded at 20°C, by video, under laboratory conditions for about half an hour. In a few instances, gas hydrate was found to dissociate violently and spontaneously with relatively rapid gas release. In most cores, however, the rate

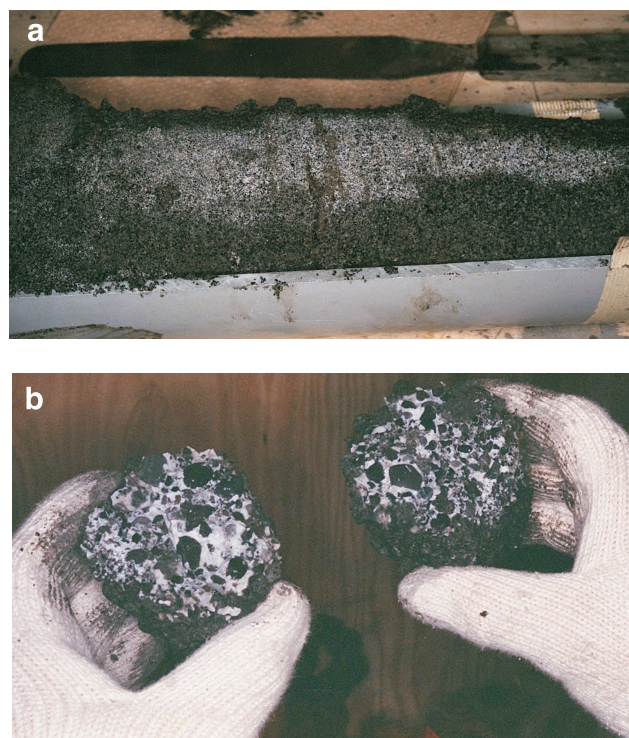


Figure 2. Photographs of natural gas hydrate samples retrieved from the Mallik 2L-38 well (Uchida et al., 1998). **a)** Pore-space gas hydrate fills intergranular pores of unconsolidated sands from a depth of 904 m. Photograph courtesy of T. Uchida. **b)** The largest pore-space and nodule gas hydrate fill intergranular pores of granular sands from a depth of 913.7 m. Photograph courtesy of T. Uchida.

of dissociation was relatively slow, with gradual effervescence of methane gas from the intergranular pores. In many cases, the pore-space hydrate was stable for a period of at least an hour after recovery. Traces of gas hydrate were also observed by sedimentology loggers examining cores several days after recovery (Jenner et al., 1999).

X-RAY CT METHODOLOGY

The X-ray CT scanner is a useful, nondestructive technique for recognizing occurrences of gas hydrate within sediments and their relationship to surrounding host sediments (Uchida et al., 1997). All core samples taken to Japan in pressure vessels were subjected to X-ray CT imagery before undergoing other analyses performed by the Japanese research consortium. The analyses were conducted with a Toshiba X-ray CT scanner (model 'X-force') owned by JNOC Technology Research Center. This equipment, originally designed for medical use on human subjects, has been slightly modified for observation of sediment/rock samples. The resolution of images acquired is 0.35 square millimetre per pixel and 1 mm in thickness due to the low output voltage of 130 kV. The samples were placed on the measuring bed with dry ice to prevent gas hydrate dissociation. A major benefit of this method is that the images can be collected relatively rapidly with almost no gas hydrate dissociation (~16 images per minute).

Measured CT values are unitless, depend mainly on the X-ray absorption coefficient of the substance scanned, and can be related to the bulk density. According to Uchida et al. (1997) and Matsumoto et al. (in press), who conducted a X-ray CT study of gas hydrate samples from Leg 164 of the Ocean Drilling Program, CT values of methane hydrate range from -100 to -250, whereas those of pure water, pure water ice, and dry ice are 0, -65, and 400, respectively (Fig. 3). The CT values of sediment grains (minerals) usually exceed 1000, while common gases diminish to -1000, reflecting their densities.

RESULTS

The X-ray CT imagery of gas-hydrate-bearing sediment samples GH91370 (obtained from 913.70 m) and GH90300 (obtained from 903.00 m) are shown in Figures 4 and 5. The CT value ranges in the images are divided into eight regions: 1) CT values greater than 1600 — region shown as red, 2) CT values between 1600 and 1200 — region shown as pink, 3) CT values between 1200 and 1000 — region shown as orange, 4) CT values between 1000 and 900 — region shown as yellow, 5) CT values between 900 and 200 — region shown as green, 6) CT values between 200 and 0 — region shown as light blue, 7) CT values between 0 and -250 — region shown as blue and 8) CT values less than -250 — region shown as black. Dry ice is represented by the green area at the bottom left corner in Figure 4 and the four corners in Figure 5, which are partly surrounded by light blue, possibly reflecting the boundaries affected by water ice or absent space. Associated frequency histograms of CT values for the images are shown in Figures 6 and 7, respectively.

The two X-ray CT images and their histograms show quite different characteristics which we attribute, in part, to the different sediment characteristics and forms of gas hydrate present in the samples. Visual observations of the sample from 913.7 m (Fig. 2) revealed that it consisted of granules and pebbles (maximum pebble size 1 cm) with lesser amounts of sand and gas hydrate and/or ice. The coarse granules and pebbles are represented by the red (>1600 CT value) and pink (>1200 CT value) areas which are characteristic of CT values for mineral components (Fig. 4). The matrix, which is mainly orange (CT values 1000–1200) and yellow (CT values 900–1000), was interpreted to be a mixture of sand grains, gas hydrate, and ice. The sample from 903 m showed a different X-Ray CT character (Fig. 5) with a more uniform pattern and with a dominance of orange (CT value 1000–1200) and minor yellow (CT value 900–1000). Visual observations indicated that this sample consisted of a uniform, medium-grained sand with high pore-space gas hydrate

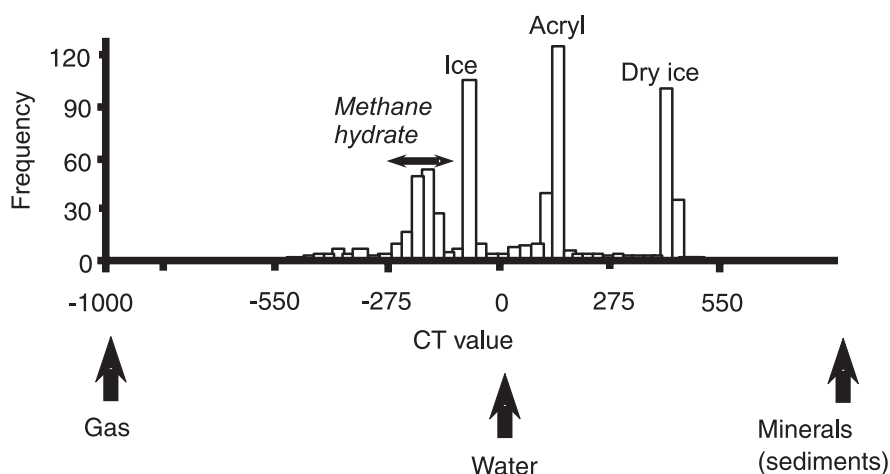


Figure 3. Frequency of CT values in the nodule gas hydrate from ODP Leg 164 (Uchida et al., 1997).

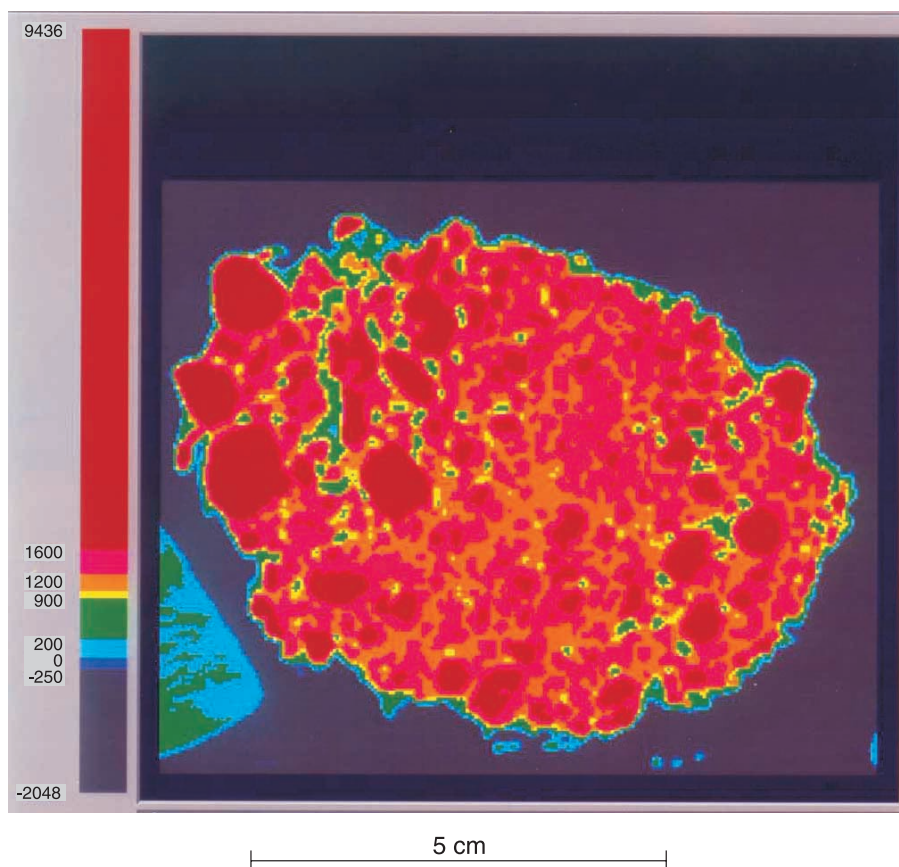
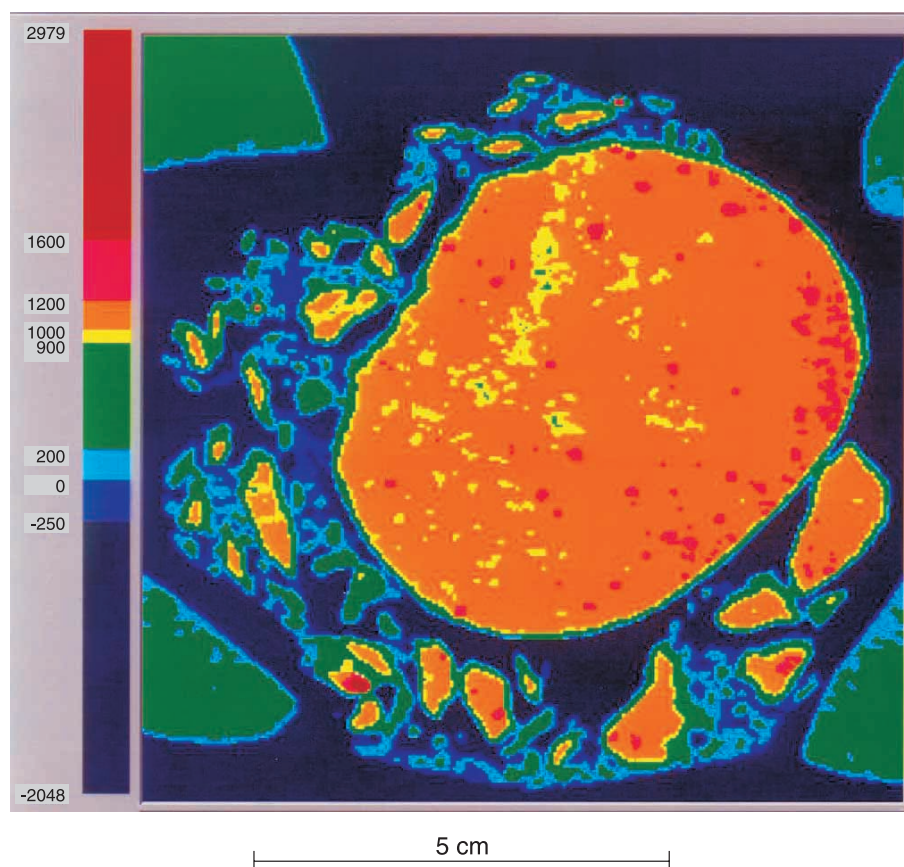


Figure 4.

Computerized tomography (CT) image of sample GH91370. See 'Results' in text for colour value legend.

Figure 5.

Computerized tomography (CT) image of sample GH90300. See 'Results' in text for colour value legend.



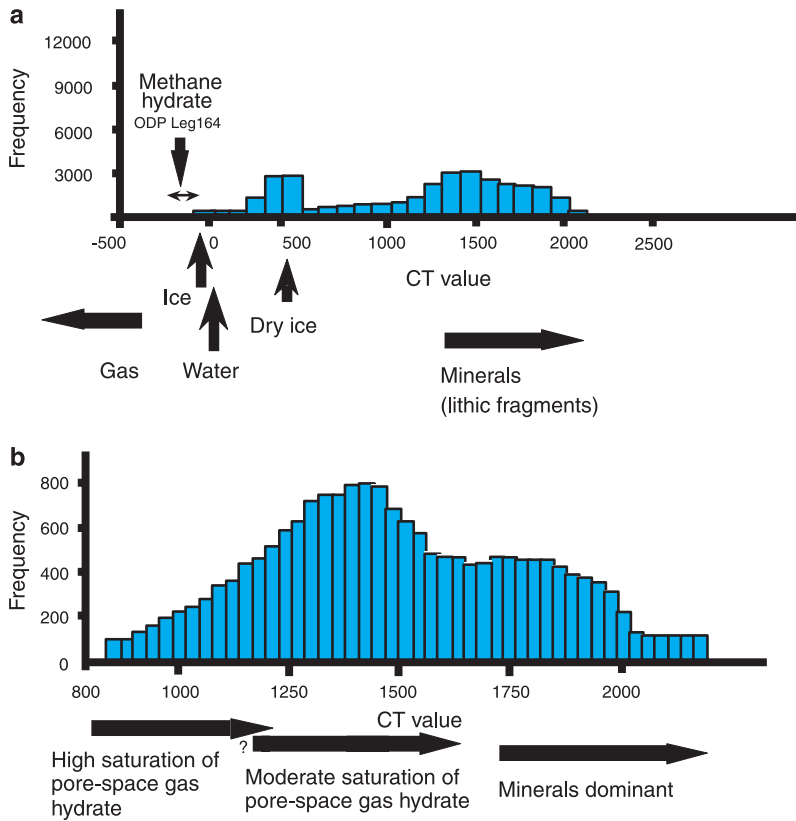


Figure 6.
Frequency of CT values in sample GH91370. a) full range of frequency distribution. b) enlargement of part of the top histogram for a limited range.

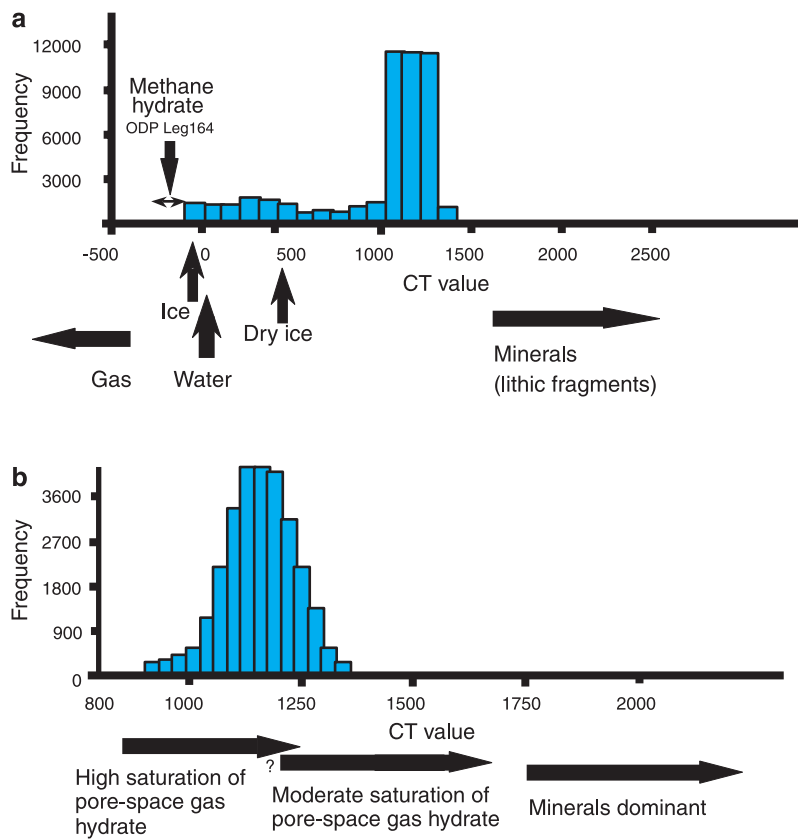


Figure 7.
Frequency of CT values in GH90300. a) full range of frequency distribution. b) enlargement of part of the top histogram for a limited range.

concentrations. The histogram confirmed that the mineral fragments with high CT values (>1250), observed in the sample from 913.7 m, are absent (Fig. 6, 7).

DISCUSSION

Core samples collected from Mallik 2L-38 confirmed that gas hydrate occurs mainly within porous sands, as pore fillings (<2 mm diameter), and as coatings on mineral grains (<2 mm thick). The dominance of pore-space gas hydrate at the Mallik 2L-38 site may be characteristic of gas hydrate occurrences within porous clastic strata. Descriptions of pore-space gas hydrate are rare in marine settings where gas hydrate is generally disseminated as nodules or void fillings (Sloan, 1998). Observations of pore-space gas hydrate recovered in Mallik 2L-38 suggest that in many instances the gas hydrate was stable within the frozen core samples upon initial recovery from the core barrel. This characteristic has been observed in laboratory-prepared gas hydrate samples when the temperature is held below 0°C . In this case, however, the negative temperatures were induced by endothermic cooling caused by gas hydrate dissociation during core recovery. An interesting additional observation in the Mallik 2L-38 core samples was the degree of gas hydrate and ice bonding within the samples. In nearly all cases, core samples were very competent and well indurated, with high estimated shear and compressional strengths. Quantitative and qualitative estimates, however, suggested that the proportions of pore-space gas hydrate and pore ice were quite variable with up to 40% by volume gas hydrate in some cases. We attribute the relative stability of the pore-space gas hydrate within the sands and the bonding to be caused, in part, by the self-preservation phenomena. Ershove and Yakushev (1992) described this as an apparent metastable behaviour of gas hydrate whereby the dissociation is slowed at atmospheric pressures due to an ice coating on the surface of the gas hydrate. The role of the ice phase, either within the sediment pores or as a coating on the surface of the gas hydrate itself, is obviously critical in some situations when gas hydrate dissociates.

The X-Ray CT imagery has proved to be a useful complimentary technique to characterize the gas-hydrate-bearing core samples, the presence of large mineral grains, and some of the matrix characteristics. Of note, however, is the fact that neither X-Ray CT images of the samples from 903 m (Fig. 4, 6), or 913.7 m (Fig. 5, 7) showed peaks in the -100 to -250 range expected for pure gas hydrate, based on observations by Uchida et al. (1997). We attribute this to the fine grain size of the pore-space gas hydrate. While the resolution of the X-Ray CT method apparently was not sufficient to allow unique identification of the gas hydrate, the histograms themselves were shifted because of the presence of gas hydrate. Repeat CT scanning after gas hydrate dissociation, the subject of a complimentary paper (Uchida et al., 1999), confirmed this interpretation.

CONCLUSIONS

Core samples from Mallik 2L-38 provided a unique opportunity to characterize the nature and sediment relationships of gas hydrate in a permafrost environment. Gas hydrate occurred mainly within porous sands, as pore fillings (<2 mm diameter), and as coatings on mineral grains (<2 mm thick). Several thin gas hydrate veins were also observed ($1\text{--}2$ mm) and in one interval large clasts of gas hydrate (up to 2 cm in diameter) formed the matrix of a sandy gravel to granular sand. Because of the abundance of pore space gas hydrate, and the endothermic cooling experienced by the core samples during core recovery, gas-hydrate-bearing sands were often frozen when extracted from the core barrels at the drill site. As a result, core samples were observed to be well indurated, in part due to the bonding of the gas hydrate/ice within the sediment pores. The pore-space gas hydrate samples typically were quite stable when recovered — a characteristic attributed primarily to the role of the ice phase either coating the gas hydrate or being present within the porous media itself.

The X-ray CT observations of the gas-hydrate-bearing core samples revealed that the CT value range can be divided into eight regions. Because of the fine grain size of the pore-space gas hydrate, a unique signature of gas hydrate could not be resolved. The presence of gas hydrate, however, was indicated by shifts in the overall CT histograms. The CT technique proved useful to determine the relationships among granular lithic fragments, associated coarse mineral grains, and gas hydrate occurring within the intergranular pore system of the sediment samples.

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