Overview of science program, JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well

S.R. Dallimore[1], T.S. Collett[2], and T. Uchida[3]

Dallimore, S.R., Collett, T.S., and Uchida, T., 1999: 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, p. 11–17.*

Abstract: The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was drilled in February and March, 1998, in the Mackenzie Delta, Northwest Territories, Canada, to a depth of 1150 m. The scientific program was conducted through a collaborative agreement between the Japan National Oil Corporation and the Geological Survey of Canada with key participation by the Japan Petroleum Exploration Company and the United States Geological Survey. A primary objective of the well was to undertake a comprehensive scientific research program to study an arctic gas hydrate accumulation. Field research conducted as part of the Mallik 2L-38 program included collection of permafrost and gas-hydrate-bearing core samples, downhole geophysical logging, and a vertical seismic profile survey. Laboratory and modelling studies undertaken during the field program, and subsequently as part of a post-field research program, documented the sedimentology, biostratigraphy, physical/petrophysical properties, pore-water and gas geochemistry, geophysics, and reservoir characteristics of the Mallik field gas hydrate accumulation.

Résumé : Le puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC Mallik 2L-38 a été foré jusqu'à une profondeur de 1 150 m en février et en mars 1998 dans le delta du Mackenzie, Territoires du Nord-Ouest, Canada. Le programme scientifique a été réalisé dans le cadre d'un accord de collaboration conclu entre la Japan National Oil Corporation et la Commission géologique du Canada, avec la participation exceptionnelle de la Japan Petroleum Exploration Company et de la United States Geological Survey. Un des premiers objectifs du forage était la réalisation d'un programme de recherche scientifique complet axé sur l'étude d'une accumulation d'hydrates de gaz dans l'Arctique. La campagne de terrain faisant partie du programme Mallik 2L-38 comprenait le prélèvement d'échantillons de pergélisol et de carottes renfermant des hydrates de gaz et l'exécution de diagraphies géophysiques en sondage et d'un profil sismique vertical. Des études en laboratoire et de modélisation entreprises au cours de la campagne de terrain et postérieurement dans le cadre d'un programme de recherche ont permis de définir les propriétés sédimentologiques, biostratigraphiques, physiques/pétrophysiques et géophysiques, les caractéristiques de réservoir et la géochimie des eaux interstitielles et des gaz de l'accumulation d'hydrates de gaz du champ de Mallik.

[1] Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
[2] United States Geological Survey, Denver Federal Center, Box 25046, MS-939, Denver, Colorado 80225, U.S.A.
[3] JAPEX Research Center, Japan Petroleum Exploration Company, Ltd., 1-2-1 Hamada, Mihama-ku, Chiba 261-0025, Japan

INTRODUCTION

Interest in natural gas hydrate has grown in recent years with the recognition that gas-hydrate-bearing sediments are widespread in certain marine and permafrost settings on a global basis, and that the volume of natural gas trapped in gas hydrate form is enormous. Unique characteristics of gas hydrate within sediments make it both fascinating and challenging to study in a natural environment. In most geological settings, gas hydrate typically exists close to its equilibrium pressure and temperature threshold conditions, and as a result, can be sensitive to even minor pressure or temperature changes. In addition to releasing a great volume of gas as a consequence of gas hydrate dissociation, the physical properties of the host sediments are also substantially modified during both gas hydrate formation and dissociation. While the challenges in undertaking gas hydrate research are considerable, there is general consensus within the international community on the need for more research on the general topic of gas hydrate in nature. National research programs, underway in several countries, seek to address the potential of gas hydrate as a future energy resource. In addition, research is being conducted to assess marine and permafrost gas hydrate as a geohazard. Finally, because of the potential sensitivity of gas hydrate to a rise in temperature, concerns have been expressed that gas hydrate dissociation may contribute greenhouse gases to the atmosphere in response to climate warming.

In March of 1998, JAPEX/JNOC/GSC Mallik 2L-38, a 1150 m deep gas hydrate research well was completed at the northeastern edge of the Mackenzie Delta, Northwest Territories, Canada (Fig. 1). This project brought together researchers from North America and Japan to complete the first investigation of a gas hydrate occurrence beneath permafrost, which included extensive dedicated coring and associated engineering and scientific studies. From the outset there were two fundamental objectives for the Mallik 2L-38 research well. In preparation for exploration drilling in the Nankai Trough in 1999 (Okuda, 1996), the Japan National Oil Corporation (JNOC), the Japan Petroleum Exploration Company (JAPEX), and other participating organizations from Japan sought to undertake a variety of verification studies to evaluate the effectiveness of gas hydrate drilling, geophysics, casing, and production technologies at an onshore site with a known gas hydrate occurrence. In addition, with a long-standing interest in gas hydrate occurrences in permafrost settings, the Geological Survey of Canada (GSC) and the United States Geological Survey (USGS) proposed conducting a science program to quantify the geological, geophysical, geochemical, and engineering properties of an arctic gas hydrate occurrence. After a long review process (*see* Dallimore and Collett, 1999), a drill site near Imperial Oil Mallik L-38, an industry exploration well drilled in 1972 (Bily and Dick, 1974), was selected for the location of the gas hydrate research well. This site was chosen as it offered favourable logistics and has the thickest known gas hydrate occurrences in the region. In addition, detailed geological, geophysical, and engineering data were available from the original well from the archives of the National Energy Board and Imperial Oil Limited.

This paper provides an overview of the science program carried out for the Mallik 2L-38 well, including the management structure, research goals, and some highlights of the 1998 field investigations. Technical information on the drilling operations and the engineering program are reviewed in a companion paper by Ohara et al. (1999).

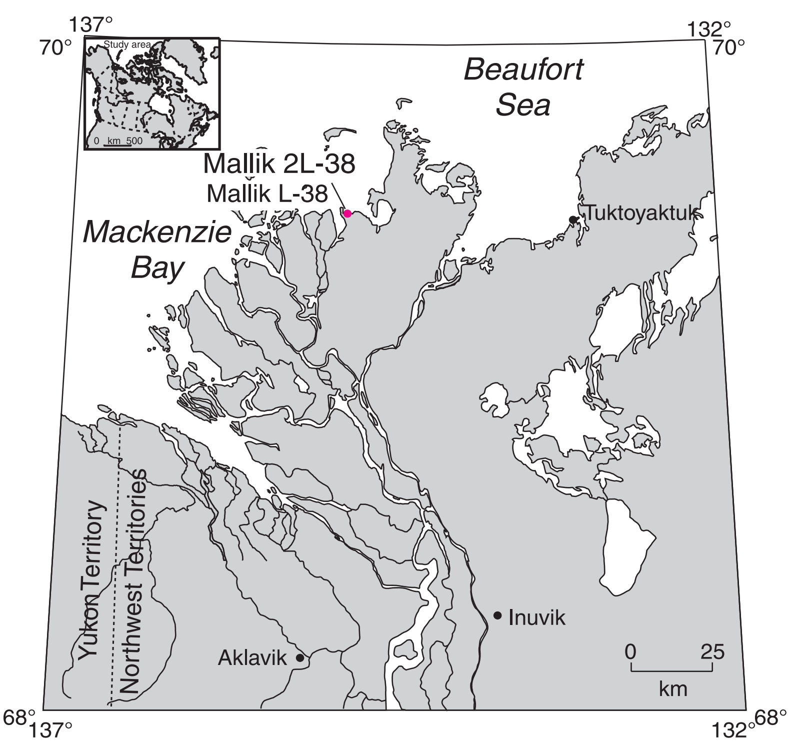

Figure 1.

Location map of the Mackenzie Delta region showing JAPEX/JNOC/GSC Mallik 2L-38 drill site.

PROJECT MANAGEMENT

The JAPEX/JNOC/GSC Mallik 2L-38 research-well project and associated scientific and engineering studies were undertaken through a co-operative agreement between JNOC and GSC. In addition to these lead agencies, key participants in the program included JAPEX and USGS, as well as a number of other Japanese and North American institutes and companies. A steering committee, with membership from JNOC and GSC, was responsible for the overall project management. The science program was conducted as a subprogram of the research-well project with leadership by three chief scientists (S.R. Dallimore, GSC; T. Uchida, JAPEX; and T.S. Collett, USGS) and overall co-ordination by the GSC. A multidisciplinary approach was taken for the science program, integrating fundamental gas hydrate studies with investigations of the regional geology, biostratigraphy, geochemistry, geophysics, and permafrost conditions. More than 25 scientists from North America and Japan participated in the field program, which included drill-site activities, operation of field laboratories, and completion of a surface geophysics program. Subsequent post-field laboratory studies involved a similar number of participants from 10 different organizations. A flow chart showing the management structure, participant organizations, and scientists is given in Figure 2.

FIELD OPERATIONS

Field operations for the science program of the Mallik 2L-38 well were conducted during the months of February and March, 1998, with the participation of more than 25 scientists and six major service companies. At the drill site, a team of 8

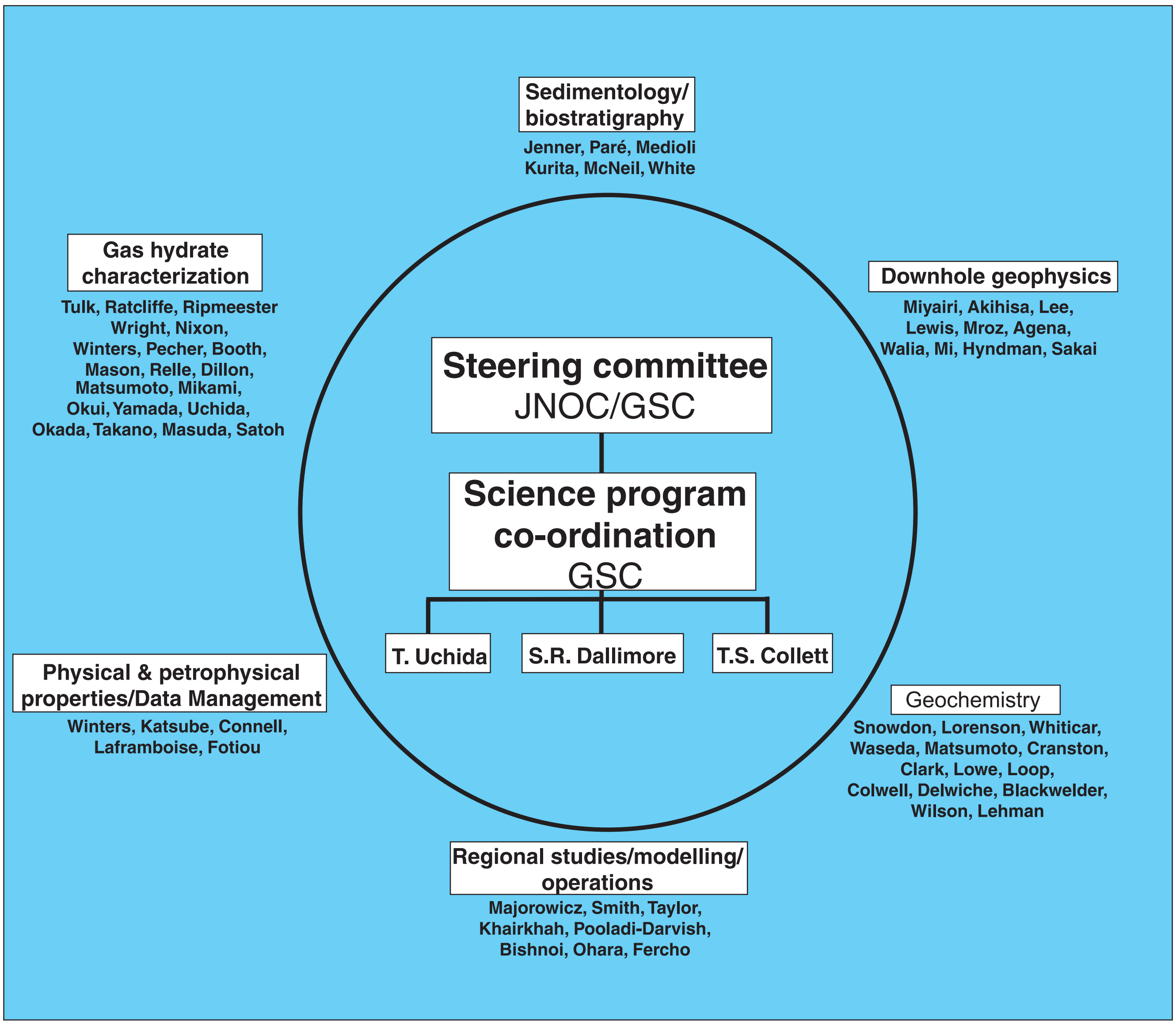

Figure 2. *Organization chart for JAPEX/JNOC/GSC Mallik 2L-38 scientific program showing participants*

to 10 scientific staff supervised core collection and core handling, and conducted a limited suite of field laboratory experiments. The emphasis at that stage was on time-critical observations of minimum core temperatures, gas hydrate characteristics, and gas hydrate concentrations. Gas hydrate samples destined for more specialized laboratory testing were stabilized by storage in liquid nitrogen or placement in pressurized storage vessels. Geotechnical core descriptions recorded at the drill site included strength, ice bonding, cementation, and grain size. The scientific team also supervised the downhole geophysical well-logging program and the zero-offset and single-offset (401 m) vertical seismic profile survey (VSP). In a separate program, a deep-sounding transient-time-domain electromagnetic survey was conducted in the vicinity of the drill site over an 11 km long grid.

During the course of the drilling, a laboratory program was also conducted at the Inuvik Research Centre, 180 km from the field site, in the town of Inuvik. At this location, a team of 8 to 12 scientists completed a suite of physical-property tests on core samples, geochemical testing of gases and pore waters, and a limited number of gas hydrate dissociation tests. In addition, a comprehensive sedimentology program was carried out with core photography, sediment descriptions, subsampling of the core for post-field analyses, and cataloguing of working and archival halves of the cores.

DRILLING, CORING, AND DOWNHOLE GEOPHYSICS

Drilling and coring of the permafrost section (0–670 m) (all depths were measured from kelly bushing [8.31 m above sea level]) at the Mallik 2L-38 well proved to be very challenging, with significant borehole erosion in some zones and limited core recovery. In total, 13.68 m of 50 mm core were collected in the permafrost interval. Difficulties in retrieving core were caused, in part, by the circulation of warm drilling mud (>5°C) and were due to problems with the mud chiller. Permafrost sediments of the Iperk Sequence were particularly prone to degradation because of their loose unconsolidated character when thawed. Problems were enhanced in some zones because of the presence of occasional conglomerate beds and woody detrital material. A 670 m deep, 340 mm diameter permafrost casing was successfully cemented to stabilize the permafrost interval.

Mud temperatures during drilling of the main hole beneath the permafrost casing (670–1150 m) were maintained near 2°C. Hole conditions in this interval were stable, with a near-gauge hole throughout. Coring of the gas hydrate interval was conducted in the zone between 886 and 952 m. Approximately 37.33 m of core were collected (~57% recovery) using core barrels that collected cores 133 mm and 89 mm in diameter. An additional 1.1 m of core were collected using a newly developed core barrel with capabilities to maintain in situ pressure and temperature conditions. Canned drill cuttings and core samples were collected at frequent intervals throughout the depth of the well for headspace-gas analyses and biostratigraphic studies.

Conventional well logging was completed in two surveys: the permafrost interval was logged prior to the setting of the permafrost casing at 670 m and the main gas hydrate interval was logged after reaching the target depth of 1150 m. Permafrost logging was completed in two runs which included the platform express array (HIP) and the dipole shear sonic log (DSI). Four high-quality well-log runs were completed from the bottom of the hole to the base of the permafrost to characterize the gas hydrate interval (*see* Collett et al., 1999; Miyairi et al., 1999). In addition to the logs run in the permafrost interval, the following logging tools were also deployed: the formation micro imager (FMI) and the array induction tool (AIT). A multicomponent vertical seismic profile survey (VSP) was also conducted at a zero-offset position and at a 401 m offset shooting position.

GEOLOGY

A generalized well-log interpretation of the geology, permafrost, and gas hydrate conditions occurring in the Mallik 2L-38 well is given on Figure 3. Following the sequence-stratigraphy model presented by Dixon et al., (1992) and stratigraphic interpretations from Mallik 2L-38 (Dallimore and Collett, 1999; Jenner et al., 1999), three stratigraphic sequences were tentatively identified, each with a distinctive natural gamma-log response. The Iperk Sequence (0–346 m) is composed almost entirely of coarse-grained sandy sediments with several conglomeratic beds and a predominance of woody detritus in some horizons. The Mackenzie Bay Sequence (346–926.5 m) is also sand dominated with a distinct fining-upward section near its upper contact with the Iperk Sequence. The Kugmallit Sequence (>926.5 m) consists of interbedded sands and silts with rare lignite beds. Based on the resistivity response from the Laterolog, the base of ice-bearing permafrost occurs at about 640 m. For the most part, the Mackenzie Bay Sequence sediments above this depth are ice bearing; however, some zones in the Iperk Sequence showed relatively low resistivities (<20 Ω·m) indicating that they may be partially ice bearing or even nonbonded (i.e. taliks). It should be noted that the actual depth assignments for the sequence boundaries are based mainly on well-log response and the sedimentology of core samples in the lower intervals. The depths may be adjusted after completion of further stratigraphic and biostratigraphic studies.

GAS HYDRATE OBSERVATIONS

Well-log interpretations and core samples revealed a strong lithological control on gas hydrate occurrences in Mallik 2L-38. For the most part, gas hydrate occurs within coarse-grained sandy sediments that are typically interbedded with non-gas-hydrate-bearing, or very low gas-hydrate-content, fine-grained silty sediments. Despite the fact that only a relatively small volume of cuttings was produced during coring, significant gas readings were identified in the cuttings in the mud-gas logging program, with values in excess of 10% (Fig. 3). On the basis of the well-log interpretations, more than 110 m of well defined gas-hydrate-bearing sands and silty sands occurred between 897 m and1110 m (see Collett et al., 1999). These are more or less equivalent to gas hydrate layers 2–10 identified in the Mallik L-38 well (Dallimore and Collett, 1999). Interpretations based strictly on the resistivity and natural gamma-ray logs suggested that layer 1, identified in Mallik L-38, was not present in Mallik 2L-38. Quantitative well-log-derived estimates suggested that in situ gas hydrate concentrations are very high, with greater than 60% pore saturation throughout most gas hydrate layers, and in many cases more than 80% pore saturation (Collett and Dallimore, 1998; Collett et al., 1999; Miyairi et al., 1999).

The gas hydrate samples in core collected from JAPEX/JNOC/GSC Mallik 2L-38 were the first confirmed samples collected from beneath permafrost in the world. Between 886

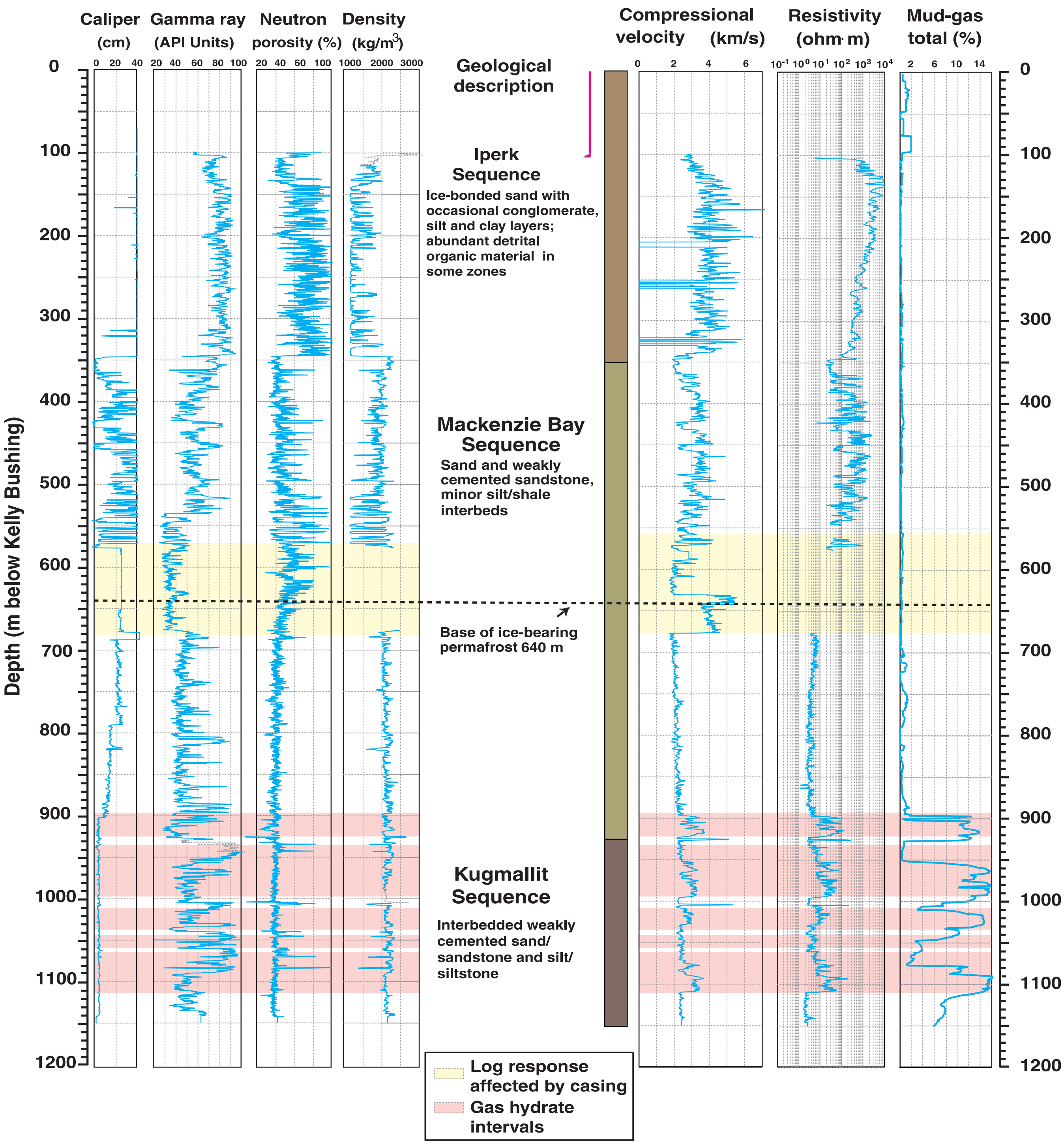

Figure 3. Generalized well-log display for JAPEX/JNOC/GSC Mallik 2L-38.

and 952 m, visible forms of gas hydrate were typically observed in sands and pebbly sands as pore fillings and coatings on grain surfaces. In some sands and pebbly sands there were thin veins of gas hydrate less than 1 mm thick and nodule-like gas hydrate up to 1 cm in diameter. In at least one interval of sandy conglomerate, the gas hydrate actually formed a matrix which supported the pebble clasts.

Indirect indications of the presence of gas hydrate in core samples included evidence of endothermic cooling and high gas yields caused by gas hydrate dissociation. Sandy, gas-hydrate-bearing core samples were ice bonded, with temperatures as low as -3°C when recovered at the surface. Given that formation temperatures are estimated to be 10°C, and mud temperatures were above 2°C, this observation is attributed to the cooling induced by gas hydrate dissociation (Wright et al., 1999). Gas hydrate dissociation experiments undertaken in the field by GSC (direct volume-yield determinations) and JAPEX (pressure-vessel dissociation tests), gave gas yields of 10 cm^3 gas/g pore water to over 60 cm^3 gas/g pore water (maximum value for pure methane hydrate is between 160 and 205 cm^3 gas/g pore water). This indicates that recovered core samples had gas hydrate concentrations within the pore space that approached 30% of the total pore volume.

The reduced gas hydrate concentrations observed in core samples, relative to in situ quantitative estimates based on well-log analyses, are consistent with the methods used to collect core. Unfortunately, attempts at retrieving pressurized core samples were not successful (Ohara et al., 1999). All of the cores were collected with conventional drill-string-deployed coring systems. Trip time to the surface, and core handling time using this method was typically 1 to 1.5 hours, and was certainly ample time for significant gas hydrate dissociation to have occurred simply by the reduction of pressure such that the gas hydrate was outside its pressure stability field.

POST-FIELD LABORATORY STUDIES

An intensive suite of post-field laboratory tests and modelling studies have been carried out on the Mallik 2L-38 well to fully characterize the geology, biostratigraphy, organic and inorganic geochemistry, and geophysical properties of gas-hydrate-bearing sediments. Laboratory studies included fundamental investigations of the petrophysics, molecular chemistry, gas kinetics, specialized gas hydrate geophysical and geotechnical testing, and pressure-temperature stability studies. Separate investigation also quantified in situ reservoir properties from well-log analyses, modelled the geothermal regime, and investigated the production potential of the gas hydrate reservoir.

DATA MANAGEMENT

A fundamental goal of the Mallik 2L-38 gas hydrate research-well science program was to make the scientific results and data widely available. To this end, an interactive CD-ROM is planned for release in 1999 as Geological Survey of Canada Open File D3726 (Dallimore et al., 1999). The CD-ROM includes a comprehensive database for the project in which digital data, including field and post-field data, are archived using Microsoft Access™, a scientific database software program. The database can be accessed through three separate menu options. The core run menu, indexed by coring runs and depths, allows viewing of field data such as core descriptions, core photos, and physical property measurements. A tree view menu allows viewing and interrogation of the main database complete with search options and user help menus. An interactive graphics menu allows plotting and viewing of physical-property and geophysical well-log data keyed by well depth. Separate modules on the CD-ROM have also been developed to view reports and video footage from the well site. A complete well-history report, including daily drilling reports and engineering data, is included in the reports section.

CONCLUSIONS

The JAPEX/JNOC/GSC Mallik 2L-38 well was the first gas hydrate research well completed in a permafrost setting. Initial results from the science program have revealed, in considerable detail, the character of the gas hydrate reservoir. In total, approximately 113 m of gas-hydrate-bearing strata were identified. Enclosing sediments were primarily sand dominated, with gas hydrate occurring as pore-space gas hydrate, coatings on granules, thin gas hydrate veins, and nodule-like gas hydrate. In one instance, gas hydrate formed the matrix for a fine-grained conglomerate. Volumetric estimates and well-log interpretations suggest high gas hydrate saturation values.

The science program for JAPEX/JNOC/GSC Mallik 2L-38 well was co-ordinated by a steering committee with membership from JNOC and GSC. Additional primary participants included JAPEX and the USGS. A multidisciplinary approach has been adopted with an extensive suite of ongoing laboratory and modelling studies. An interactive CD-ROM, which includes all field and post-field data, is available as GSC Open File D3726 (Dallimore et al., 1999).

ACKNOWLEDGMENTS

This paper was authored by the chief scientists for the JAPEX/JNOC/GSC Mallik 2L-38 research program, and, in this capacity, we would like to acknowledge the considerable support given by participating scientists, engineers, and technologists throughout the course of the planning, fieldwork and post-field studies. Leadership from JNOC/JAPEX was provided by four project managers: Y. Arai, T. Tochikawa, A. Suzuki, and T. Yonezawa. From the Geological Survey of Canada, J-S. Vincent served as the project manager with assistance from P. Kurfurst. T. Ohara deserves special praise for his direction of the technical team at JAPEX and for his overall leadership, which successfully steered the project through a variety of critical decisions. M. Imazato and A. Nakamura from JNOC also provided key input throughout the project. In addition to T. Uchida, Y. Sasaki, H. Takeda, and A. Sakai acted as subprogram managers for various JAPEX research programs. H. Nakamura was with the project in spirit despite illness which prevented him from participating in the fieldwork. We appreciate the considerable support provided to the project by P. Tsang, and the Canadian Embassy in Tokyo, who assisted in expediting discussions and exchanges between Canadian and Japanese workers.

The logistics in support of the science program for Mallik 2L-38 were largely mounted independently from the drilling activities. Technical assistance and support provided to the science program by the Polar Continental Shelf Project and the Inuvik Research Centre is gratefully acknowledged. Assistance from T. Baker and his staff at the National Energy Board was helpful during the initial planning stages. Imperial Oil Limited, and in particular D. Hersak and J. Weaver, is acknowledged for arranging access to the Mallik site and providing advice and support to the research program. In addition to support to individual researchers provided within their own research organizations, dedicated financial support for the Mallik science program was provided by JNOC, JAPEX, GSC, USGS, the Panel for Energy Research and Development, and United States Department of Energy.

The efforts of F.M. Nixon, J.F. Wright, R.R. Laframboise, K.A. Jenner, W.J. Winters, R.E. Cranston, and T.D. Lorenson in equipping and operating the laboratories at the Inuvik Research Centre and at the drill site were critical in carrying out the field program. The database for the project was designed and maintained by R.R. Laframboise, M.J. Fotiou, and B.E. Medioli. L.D. Dyke generously provided advice and assistance in the field and L.R. Snowdon assisted with care of the frozen core samples during shipping from the field. A. Casey, B. Sherman, S. Parnham and M-A. Beauchamp are acknowledged for administrative help. Finally the considerable contributions to the logistics by D. Cloutier, L. Kutny, and G. McEchern were much appreciated and helped to maintain a spirit of co-operation and teamwork throughout the fieldwork.

REFERENCES

Bily, C. and Dick, J.W.L.
1974: Natural occurring gas hydrates in the Mackenzie Delta, Northwest Territories; 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.; *in* Proceedings of the 7th International Conference on Permafrost, Yellowknife, Canada, Université Laval, Collection Nordicana, 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 downhole 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. and Collett, T.S.
1999: Regional gas hydrate occurrences, permafrost conditions, and Cenozoic geology, Mackenzie Delta area; *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.J., and Medioli, B.E. (comp.)
1999: 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.

Dixon, J., Dietrich, J.R., and McNeil, D.H.
1992: Upper Cretaceous to Pleistocene sequence stratigraphy of the Beaufort–Mackenzie and Banks Island areas, northwest Canada; Geological Survey of Canada, Bulletin 407, 90 p.

Jenner, K.A., Dallimore, S.R., Clark, I.D., Paré, D., and Medioli, B.E.
1999: Sedimentology of gas hydrate host strata from 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.

Miyairi, M., Akihisa, K., Uchida, T., Collett, T.S., and Dallimore, S.R..
1999: Well-log interpretation of gas-hydrate-bearing formations in the 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.

Ohara, T., Dallimore, S.R., and Fercho, E.
1999: Drilling operations, 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.

Okuda, Y.
1996: Research on gas hydrates for resource assessment in relation to national drilling programme in Japan; *in* Proceedings 2nd International Conference on Natural Gas Hydrates, Toulouse, France, p. 633–641.

Wright, J.F., Taylor, A.E., Dallimore, S.R., and Nixon, F.M.
1999: Estimating in situ gas hydrate saturation from core temperature observations, 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.