PLANNING AND EXECUTION OF A 500 M COREHOLE THROUGH OFFSHORE PERMAFROST

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Abstract

The saline permafrost that extends offshore under the Canadian Beaufort Sea is in a delicate state of equilibrium. Conventional production of warm oil through these soils would cause thawing. This thawing would result in excessive axial and bending strains within the well casings and system components. Relatively continuous core is required to evaluate the extent, native and engineering properties of the permafrost interval. This information will be used to determine the effects of permafrost thaw on casing system components. This paper describes the operational aspects of the 1988 offshore permafrost coring program conducted by Gulf Canada Resources Ltd. The objectives of this program were to collect site-specific data, determine correlations between geophysical and geotechnical parameters, and develop techniques which could be applied to oil-well drilling. Through the development and application of state-of-the-art drilling and sampling technology, these objectives were met. Future papers will discuss the geological and geotechnical aspects of this project.

Résumé

Le pergélisol salin qui s'étend au large sous la mer de Beaufort au Canada se trouve dans un état d'équilibre fragile. Un mode de production classique de pétrole tiède à travers ces sols provoquerait un dégel. Ce dégel produirait des déformations axiales et de flexion excessives dans les tubages de puits et les composantes du système. Il faut prélever des carottes relativement continues pour évaluer l'étendue et les propriétés naturelles et techniques de la couche de pergélisol. Cette information servira à déterminer les effets du dégel du pergélisol sur les composantes du système de tubage. Ce mémoire décrit les aspects opérationnels du programme de carottage dans le pergélisol sous-marin mené en 1988 par Gulf Canada Ressources Ltée. L'objectif du programme était de recueillir des données caractéristiques de la région, d'établir des corrélations entre les paramètres géophysiques et géotechniques, et de mettre au point des techniques applicables au forage des puits de pétrole. Grâce à l'élaboration et à l'application de la technologie de forage et d'échantillonnage de pointe, les objectifs ont été atteints. D'autres articles à venir porteront sur les aspects géologiques et géotechniques de ce projet.

Introduction

Purpose

This paper will describe some of the operational aspects of the 1988 offshore permafrost coring program at the Amauligak F-24 location in the Canadian Beaufort Sea, (fig. 1). This program was completed from the drilling structure Molikpaq as part of Gulf Canada Resources Ltd. ongoing research into oil production from its Beaufort Sea reserves. Future papers will discuss the geological and geotechnical aspects of this project.

Precedent

This coring program represents development of state-of-the-art sampling technology in the exploration of permafrost. Indeed, prior to this program, a continuously-sampled borehole in excess of 500 m into warm, partially frozen soil was considered to be beyond the state-of-the-art. Equipment and techniques developed, therefore, represent an advance in drilling and sampling techniques for this environment.

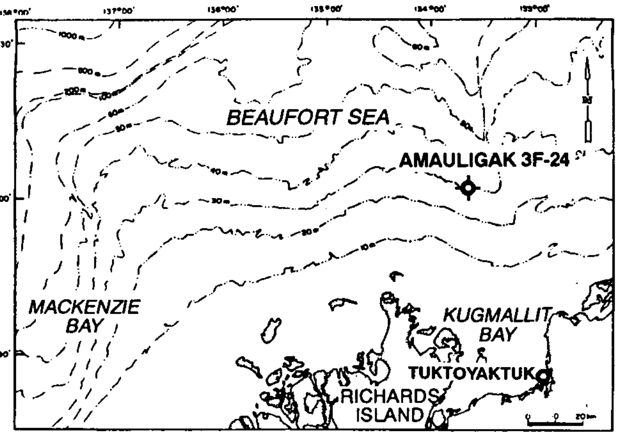

Figure 1. General location map.

Mackay (1972) predicted a widespread occurrence of relic land permafrost below the southern Beaufort Sea. Subsequent studies have confirmed its presence under large areas of the Alaskan and Canadian Beaufort Shelf. The majority of these studies have involved geophysical techniques, both by refraction seismic and downhole testing of oil exploration holes. To date, the presence of permafrost has been confirmed by near-surface sampling (generally limited to 100 m below mudline) and to minor sidewall sampling completed during the development of oil and gas wells.

Very little precedent for continuous sampling of submarine permafrost exists. Previous practice in the Canadian Arctic has been limited to an attempt by Canadian Marine Drilling in 1982 to continuously sample the whole thickness of permafrost at the Gulf Tarsiut N-44 location. In this case, the oil-well rig was used to collect discontinuous samples from the upper 212 m of the section during the drilling of the surface casing. This attempt was only moderately successful and was subsequently abandoned in favour of interpretation of downhole geophysical data.

Since 1982, little work has been done in this regard. Investigation of the permafrost interval has been limited to cuttings sampling programs and downhole geophysical interpretation related to oil-well drilling, and to periodic investigations of the upper section of the permafrost interval in routine geotechnical investigations.

Clearly, the high cost of boreholes in the offshore Arctic environment has deterred specific deep coring exploration of the permafrost interval. This coring program, therefore, provided a unique opportunity to investigate both the geological and the geomechanical properties of the permafrost body.

Geological environment

Permafrost extends offshore under the Canadian Beaufort Sea shelf. It is believed to be strongly controlled by continental ice advances and their associated sea level fluctuations, interglacial marine transgressions, and the position of the delta lobes of the Mackenzie River (Fortin, 1988): The permafrost body appears monolithic below major lobes of the Mackenzie delta, whereas alternating frozen deltaic sands and unfrozen prodelta and marine clays exist at the fringes of these lobes.

Unlike the terrestrial permafrost of the adjacent land mass, submarine permafrost is often saline and is in a delicate state of equilibrium, degrading at the base due to geothermal heat and being insulated from aggradation by the Arctic climate by a relatively warm sea.

The Beaufort Sea shelf was subaerially exposed to the climate similar to that of today's High Arctic during several Pleistocene lowstands of sea level (Mackay, 1972; Hunter *et al.*, 1976; Craig *et al.*, 1985). This exposure resulted in aggradation of permafrost to a thickness up to 600 m (Neave *et al.*, 1978). Subsequent submergence of the shelf led to degradation of the upper layers of permafrost through the advance of warmer seas and advection of saline fluids. Also, the affect of the Mackenzie River distributaries selectively thawed areas of the sea bottom.

There have been numerous advances and retreats of glacial ice, resulting in sea level changes, during the deposition of sediments which are presently frozen. As recently as 20 000 years ago, a thickness of up to 300 m of glacial ice existed in the Tuktoyaktuk area. The climate was cold and dry, conditions which allowed the ice to sublimate. A tongue of the glacier extended along the Mackenzie trough. The continental shelf, which includes the Amauligak site, was exposed to at least the current 105 m isobath. Aeolian processes dominated.

Approximately at this time, a major change occurred. The ice sheet retreated quickly, generating a large amount of sediment and water, creating an outwash plain.

Initially, the rate of accumulation of the sediments of the plain exceeded the rate of rise of sea level. A stream pattern was developed on the plain, and the sediments were subaerially exposed and frozen as they were deposited.

With time, when the ice front was further away and less sediment was being deposited in the Amauligak area, sea level rise exceeded the accumulation of the sediments. A migration of relatively warm saline water, accompanied by warm brackish water from the Mackenzie River began to degrade the upper layer of sediments, reworking them in a high energy environment. Some areas of the shelf were protected by islands and by the deposition of fine-grained soils in sheltered depressions.

It is believed that four similar cycles have occurred prior to this cycle in the last 2 million years, two of which are preserved at this site. These cycles are preserved in the core drilled during this program. The Geological Survey of Canada is currently analyzing pore fluid origin (rain, freshwater, saline), the crystalline structure of the pore ice, and the biostratigraphy in order to evaluate the depositional history (processes, date, freeze-thaw cycling) of the permafrost. The results of these studies will significantly enhance our current understanding of the complex geological setting of this site.

Requirement for quality permafrost information

Conventional production of warm oil through permafrost would cause thawing around the well casings. Volumetric changes associated with thawing, and, possibly, longer term consolidation, would result in deformations within the thawed soil column, in turn resulting in axial and bending strains within the well casings. Analyses demonstrate that axial strains may be compressive or tensile; are most likely to exceed the yield strain of the casing resulting in post yield ductile strains; and, are most pronounced in zones having higher volumetric soil strains, at the top and bottom of the permafrost, or at pronounced stratigraphic gradational changes within the permafrost interval.

Subsidence within the permafrost at depth would result in settlements at the seabed, the magnitude being a function of the depth and extent of permafrost subsidence. Design impacts could be reduction of the freeboard in the event of overall structure settlement, partial loss of bearing support beneath rigid base structures, distortion of pipeline tie-ins, differential movements between wellheads and the structure, and reduced foundation strength.

The production system components must be able to tolerate the impacts of permafrost thaw. Mitigative measures to reduce thaw would be required if these impacts were unacceptable for safe, cost effective system component design and operation. In order to predict and evaluate these impacts the designer must know the depth, thickness, nature and properties of the subsea permafrost.

An additional concern is the drilling, installation and cementing of well casing within the permafrost. Circulation of drilling fluids at inappropriate velocities, temperatures and mud weights could thaw the hole wall and result in washed out intervals. Incomplete cementing within washed-out zones would result in unsupported lengths which may experience buckling or an unacceptable magnitude of axial strain. Consequently, there is significant merit in drilling gauge holes without thawing the surrounding permafrost.

High quality permafrost information and accurate geothermal, soil deformation and soil-casing interaction analytical models are required to analyze the impacts of permafrost thawing on the well casings and seabed structural installations. Because significant strains are most likely to occur at stratigraphic changes and in under-consolidated layers with excess pore ice, a relatively continuous coring program is essential. As the subsea permafrost is relatively warm and ranges from well bonded to marginally frozen with lithology and depth, typical land-based drilling and coring methods are inadequate.

The data required from the permafrost is as follows:

1. Depth, thickness and distribution of permafrost including well-bonded, partially-frozen, marginally-frozen and unfrozen strata.
2. Detailed lithology including index parameters.
3. Pore ice, excess ice and phase change thaw strains.
4. Porewater salinity which affects the temperature versus frozen water content distribution.
5. Ground temperature profile.
6. Thermal properties such as thermal conductivity, latent heat and specific heat, which may be estimated based upon the above items, and/or measured.
7. Mechanical and consolidation properties.
8. An evaluation of creep characteristics.
9. Any additional information such as pore fluid origin, crystalline structure of pore ice and biostratigraphy testing in order to, along with engineering properties, evaluate the depositional and thermal history of the permafrost.

Objectives

The objectives of the program are therefore threefold:

1. To provide site-specific data regarding the index, mechanical and thermal properties of the permafrost layer that underlies the Amauligak field. This data is to be used for the site-specific engineering analysis of the field, and to further the understanding of the geological and thermal history of the region.
2. To develop correlations between down-hole geophysical data and common geotechnical parameters. This will allow extrapolation to other parts of the field where only geophysical data has been/will be collected.
3. To develop techniques which, if scaled to oil-well dimensions could be used to drill gauge holes through the permafrost layer: It is of importance to minimize thermal degradation of the permafrost if several closely-spaced wells are to be drilled from a single location to develop the field.

Drilling operations and equipment

Introduction

Figures 2 and 3 present a schematic of the drilling system layout below the main deck of the Molikpaq on its sand core, and on the main deck, respectively. Drilling operations proceeded as follows:

- drilling mud was mixed in surface mixing tank with a high powered "Normix" mixer and transferred to primary and secondary mud tanks located on the Molikpaq core.
- the mud was then circulated between the insulated mud tanks and chiller until the desired downhole circulating temperature was reached (generally -9 °C). Inlet and outlet temperatures in the mud tanks were monitored using thermistors located approximately at these locations, and using a hand-held temperature probe. A circulation time of 1 to 2 hours was generally required to lower the temperature to -9 °C for a fresh batch transferred from the surface mixing tank.
- the mud was then circulated downhole for coring operations, maintaining a gauge hole when coring was not in progress.
- the return mud was pumped across the shaker. Cuttings were collected in 45 gallon drums. The separated mud was diverted to the primary mud tank, then pumped through the chiller into the secondary mud tank and returned back down the hole.

Drilling system

The drill rig used for this program was a custom built Foundex HP200 electric drill rig. The specifications for the drill rig are presented in Table I.

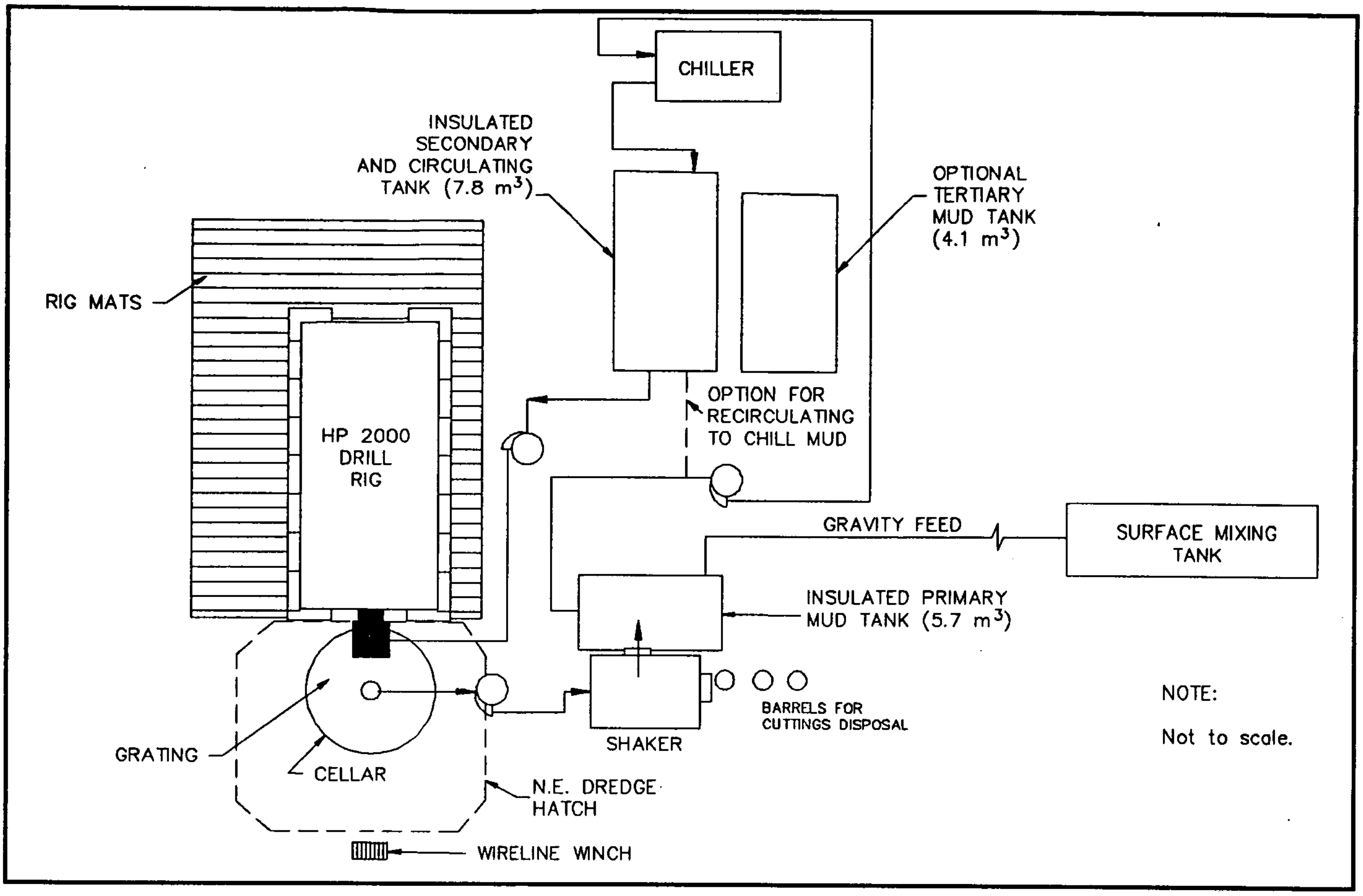

Figure 2. Drilling system setup.

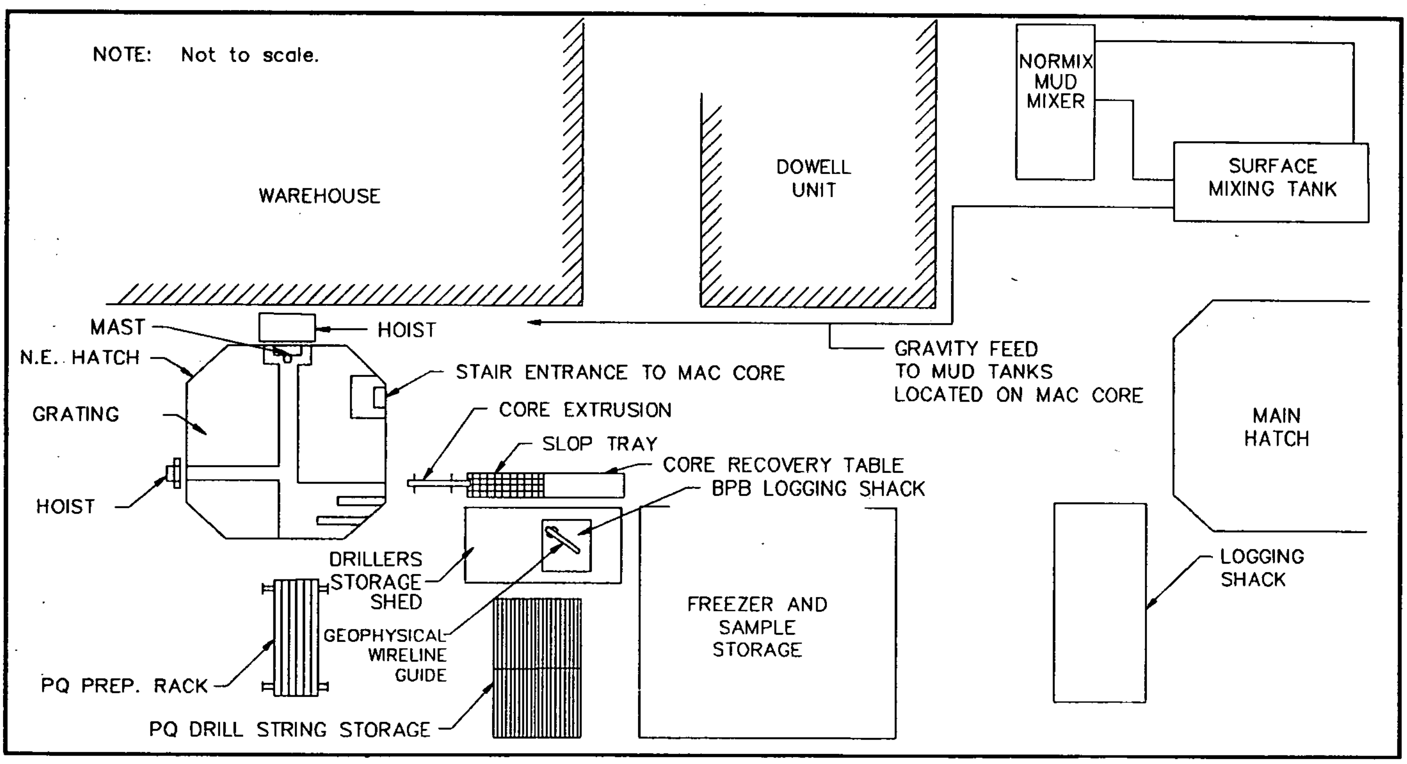

Figure 3. Main deck layout.

TABLE I. Drilling rig specifications

ITEM	RATING
Head Torque Rating[1] (Nm)	20,360
Maximum Rated Lifting Capacity (kN)	195
Maximum Rated Thrust (kN)	178
Hoist Bare Drum Line Pull (kN)	200
Weight of Rig and Ancillary Equipment (kg)	2,000

1. At maximum continuous pressure rating of hydraulic pump.

The rig was designed for at least 30 % over-capacity over anticipated string weight and the wireline. The capacity of the hydraulics gave an ample margin of safety for control of the progress of the bit and for tight hole problems. The wireline pull over-capacity allowed the wireline to be used for pipe removal from the hole, which considerably expedited round-trips. The mast was modified to a full mast section to allow for removal of 10 m sections.

The drill string configuration is presented in Table 2.

Several coring bits were designed and built for this project. The bits were built for the range of the following attributes:

- diamond-faced polycrystalline bit.
- 8 to 9.5 mm ports for optional fluid flow and flow area of approximately 756 mm^2.
- 143 to 149 mm bit size to ensure a nominal 12 mm annulus around the string.

Plate 1 shows three of the bit types constructed for this project.

An integral part of the drilling system was the mud chiller. The chiller was designed to have the following capabilities:

- 640 litres/min. chilling capability.
- 40 HP electric compressor with control panel and pump.
- two-circuit cooling system: freon to glycol to drilling mud.

Returns from the hole were pumped across a shaker table to remove suspended solids to a minimum size of 75 mm.

Drilling mud characteristics

An oil base mud was selected over a brine base to eradicate the erosion of ice from the sampled core and from the borehole walls by free salt in the brine: It was reasoned that it would be impossible to maintain the mud at a temperature equivalent to the freeze-point depression of the brine in the hole and thus that excess salt would be available to react with any free water, i.e.ice. Also, the use of oil base mud was attractive at this site because of the availability of a large quantity of winter grade diesel fuel.

TableII. Drill string configuration

DESCRIPTION	OD (mm)	ID (mm)
PQ Coring String	117.5	113.2
Core Barrel (length - 3.5 m)	122.6	83.0

The mud had a 90:10 oil/water ratio. The initial concentration of chemicals as supplied by Technifluids NMC, consisted of:

Primul	10	L/m^3
Normul	10	L/m^3
Lime	28.5	kg/m^3
Technivis	25-30	kg/m^3
Technitrol	10	kg/m^3
Barite	590	kg/m^3

When the drilling mud was initially made, not enough heat and shear was administered to completely activate the emulsification package and get full yield of the organophilic clay. As the barite was added to increase density the emulsion stability dropped and barite settling occurred. To overcome this problem, higher shear was applied at the mixing unit which provided an increase in pressure, approximately 1.5 times greater than that initially used. The higher shearing pressure increased the mud temperature which subsequently increased the emulsion stability, yield point, gels and mud density. This increase in shear pressure was successful in breaking down the water droplets to provide a stable emulsion. It proved that heat and shear are especially important to building the drilling mud since it experienced no heat or shear once it was transferred to the insulated mud tank and chiller. The addition of Technisurf, a surfactant used to reduce mud wetting of the mix, also helped to stabilize the mud system.

Cutting samples were collected at 25 m intervals to determine quantity of oil absorption. Quality control and formulation of the mud was monitored on a regular basis to determine return and tank temperatures.

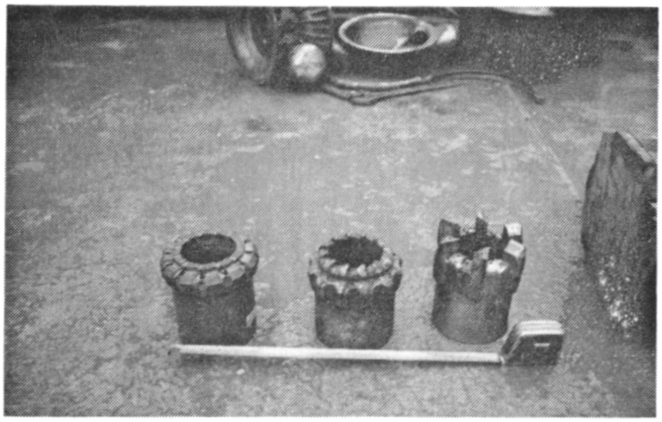

Plate 1. Bit types used in program deep core project - Amauligak 3F-24.

Environmental protection and borehole preparation measures

A 3 m diameter by 3 m long steel culvert was installed in the sand of the Molikpaq core to house the blow-out prevention (BOP) system in the event of encountering *in situ* gas, and contain any mud that might be spilled during drilling operations. A 50 mil PVC liner was placed on the core sand in the area housing the drilling operation. The liner was placed directly on the sand and over berms, and subsequently covered with approximately 0.6 m of sand. This precaution was taken to ensure that any contamination of the core sand, by spilled drilling mud, would be adequately contained and could be subsequently removed.

Cuttings collected from the shaker and contaminated sand from the core was stored in 45 gallon drums and subsequently shipped to shore for disposal. The cuttings and contaminated sand were burned in an incinerator and then re-used as general fill. The remaining mud was stored in tanks and was subsequently incinerated.

The hole was spudded with 305 mm diameter surface casing to 106.5 mRT (referenced to Molikpaq rotary table). The hole was circulated clean and 244.5 mm casing was run to 0.3 m from the bottom. A spacer comprising 2 m^3 of cement was pumped down to the bottom of the borehole and then displaced using a wooden plug attached to the end of the 117.5 mm diameter drill string. This provided a cement plug between 68.2 and 106.5 mRT. The next step to providing well control was to install the hydril and complete the BOP layout. To commence the sampling operations, a hole was drilled through the cement plug with the 117 mm diameter drill string with sampling beginning at 110.45 mRT.

Sample handling

Core samples were generally handled in the following manner:

1. Determine sample priority and insert appropriate core barrel liner into core barrel.
2. On termination of each core run the length of core run was determined.
3. The core barrel was brought to surface and core temperature was measured by inserting a hand-held temperature probe into the bottom end of the core sample.
4. The sample was extruded over the slop tray to catch mud retained inside the core barrel.
5. The sample was placed on the core recovery table and all visible mud cleaned off using absorbent pads. A quick visual inspection was made to determine soil type, length of recovery and core quality.
6. The core was transported to the logging shack for sample storage preparation and testing.
7. Depending on the sample priority, a decision was made immediately as to the portions to be saved and what would be tested.
8. The samples to be saved were; cut to length, given a quick visual description without causing any disturbance, wrapped with clear plastic film, wrapped with aluminum foil and labeled, before inserting into the protective sleeves. Protective sleeves for Priority 1 samples comprised PVC plastic core barrel liners with plastic end caps. Priority 2 and 3 samples were stored in cardboard mailing tubes with plastic end caps. All protective sleeves were labeled with depth, number, and sample top and bottom information. The samples to be stored were recorded on the sample summary sheets and sample inventory sheets kept for each numbered freezer. Core subsamples from the same core run were separated into different freezers to prevent complete loss of the core run in the event that a freezer failed to function or was somehow lost during shipping. This procedure was completed prior to any detailed logging or testing, to minimize thermal disturbance to the core planned for future testing.
9. The remaining core was logged in detail and subjected to the following tests:
   - bulk density(s).
   - time domain reflectometry.
   - moisture content(s).
   - salinity(s).
   - photograph(s).
10. Representative portions of the disturbed core were kept as bag samples and stored in five gallon pails for possible future index testing.
11. Portions of the sample containing wood chips, visible organics etc., were retained for carbon 14 dating and palynological analysis. At select intervals, samples containing ice lenses were retained for cryological analysis, an analysis used to determine origin of formation.
12. The remainder of the core was discarded.

An initial sampling plan was prepared prior to the beginning of the drilling program based on an interpreted stratigraphy from geophysical data collected in the adjacent F-24 well. This assisted in determining the approximate amount of sampling supplies and quantity of freezers required to store and ship core. During the drilling program, it became apparent that this sampling plan could not be strictly adhered to because of discrepancies between the interpreted geophysical records and what was actually encountered, and changes in sampling intervals. Eventually, sample priority was decided prior to each shift based on the sampling during the previous shift and anticipated lithological variation. In effect, sample priority was assigned by the logging engineer in charge after examining each core return.

Because no samples were recovered between 293.0 and 380.0 mRT, extra freezer storage space become available for core. Consequently, more core was stored between 381 mRT and the bottom of the hole, than was originally anticipated.

Geophysical Logging

Six geophysical logging runs were carried out between 110.4 mRT and 445.2 mRT. A tight hole precluded logging past 447.0 mRT. The intervals at which these runs were conducted are presented on Figure 4. The geophysical measurements taken comprised: sonic, multi-wave sonic gamma, caliper, density, micro-resistivity and neutron. These tools were designed to provide a variety of parameters from the formation material including; material density, dynamic moduli, natural radioactivity and water content. As some of these tools supply similar or complimentary information, the logs can be used to determine material type, and to a degree, their *in situ* density and state (i.e.. frozen or unfrozen).

Prior to each run the drill string was removed and the logging tool was lowered to the bottom of the borehole. The record depths were referenced to the Molikpaq rotary table. The geophysical tools were raised at a speed of 10 cm per second. Runs 1 to 5 were carried out after each coring sequence. Run 6, comprising a micro-resistivity probe, was carried out on completion of the borehole, after the drilling mud had been flushed from the hole and replaced with seawater.

Field Laboratory Testing

Field laboratory testing comprised: moisture content, bulk density, unfrozen moisture content, sample temperature and porewater salinity. Moisture contents were measured on representative core samples and bulk density samples. Bulk density was determined for each sample tested for unfrozen moisture content an for each obvious change in density. Unfrozen moisture contents were determined using time domain reflectometry (TDR, method after Patterson and Smith (1981)). Porewater salinity was determined using a hand-held refractometer on porewater extruded from thawed soil samples. Sample temperature was determined by inserting a hand-held temperature probe into the end of the frozen core.

In situ Temperature Measurement

Temperature Probe

The *in situ* temperature probe, designed and built by EBA, was used to monitor *in situ* temperatures at six locations in the borehole. The sequence of events required to deploy the temperature probe were as follows:

1. attach temperature probe to geophysical cable.
2. reference depth to Molikpaq rig table (RT).
3. lower temperature probe to bottom of PQ string and latch into core barrel.
4. lower PQ string sufficient depth to ensure temperature probe penetrated the soil.
5. monitor temperature on all six thermistors for a period in the order of 30 minutes until a stable *in situ* temperature was reached.
6. withdraw temperature probe from soil by lifting the PQ string.
7. withdraw temperature probe from hole.

Figure 5 presents details of the temperature probe.

Thermistor Cable Installation

Prior to abandoning the borehole, a thermistor cable provided by the Geological Survey of Canada was installed to a depth of 445 mRT. This allowed ground temperatures to be monitored at nineteen locations between 35 mRT and 445 mRT. The temperatures were monitored continuously between well abandonment and Molikpaq liftoff using a data acquisition system.

Freezer Storage

Sixteen 1.3 m^3 (12 ft^3) freezers were shipped to the Molikpaq to store the frozen core saved from the borehole. The original thermostatic control and sensor for each freezer was replaced with a highly accurate thermostatic control to minimize the range over which the freezer, and thus the core, temperature fluctuated.

The freezers were set for a storage temperature of -5 °C and were monitored several times per shift. The freezers were numbered and a sample inventory sheet was kept for each. Prior to shipping the freezers south, a max/min thermometer was placed in each freezer to monitor the fluctuation of storage temperature during shipping. All freezers performed well during shipment and air temperatures inside the freezer never exceeded -3 °C. It is likely that, given the thermal mass of the samples, the core temperature varied over a much smaller range.

Results

In broad terms, the permafrost coring program met its objectives.

Site Specific Data

- 309.1 m of PQ core was collected, totalling approximately 74 % of the interval. This length of core represented two complete cycles of deposition and a portion of the third.
- Core was of very high quality, all natural ice intact, and thick sections of freshwater ice were recovered complete.
- Core was transported successfully to Edmonton and now is permanently preserved in temperature-controlled storage.
- A sophisticated laboratory testing program has been completed to derive the mechanical properties of the permafrost.

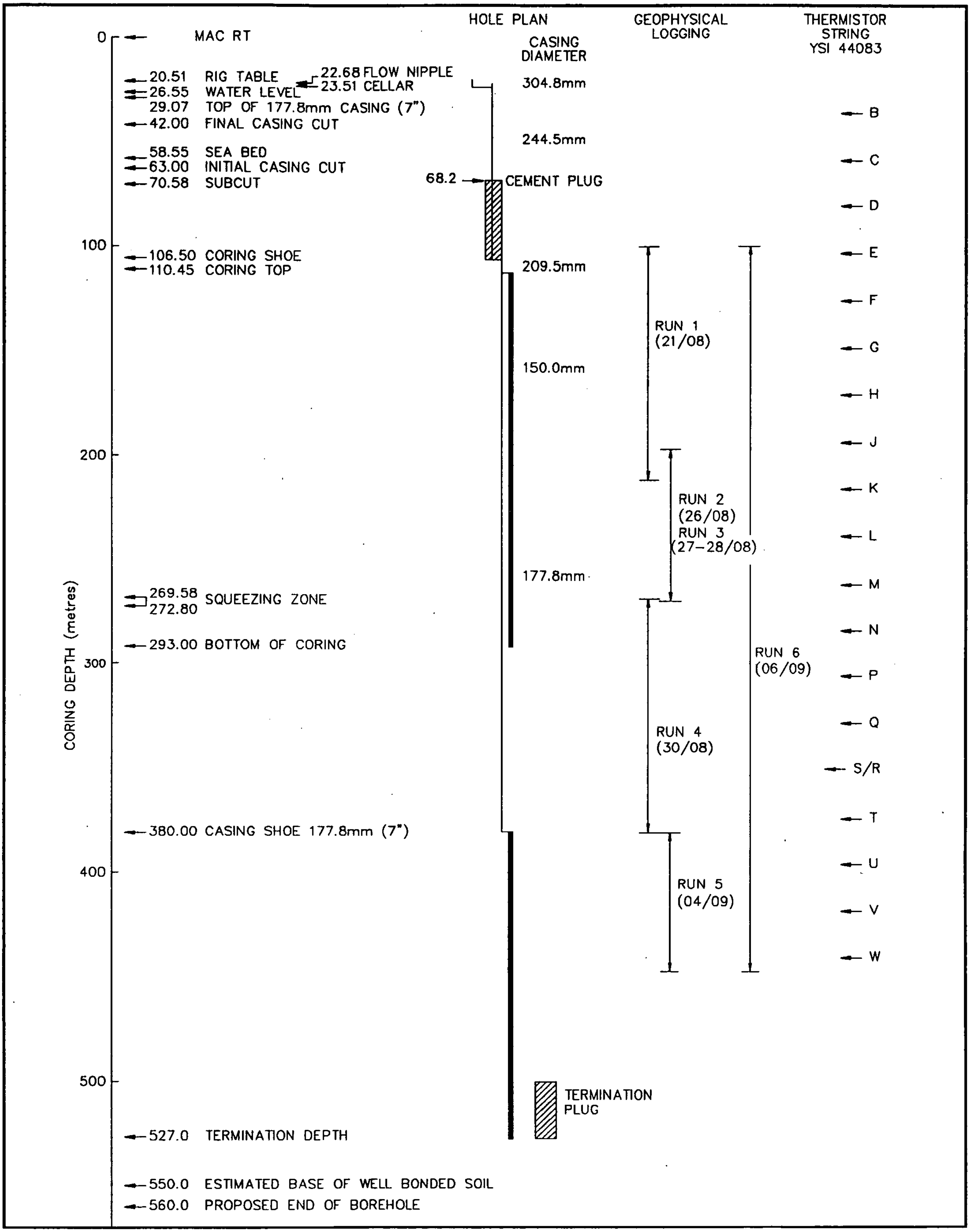

Figure 4. Summary of probehole details.

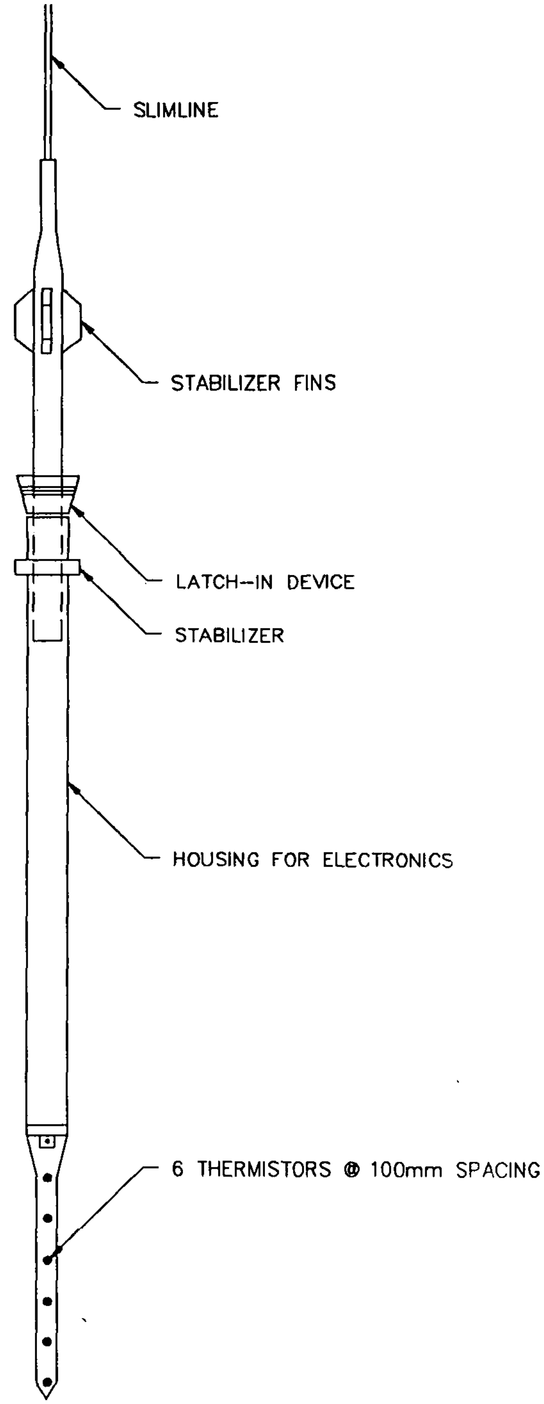

Figure 5. In situ temperature probe.

Correlation between geophysical data and geotechnical parameters

- Multi-parametric analysis of geotechnical data and downhole geophysics has been completed.
- Velocity techniques show most promise, particularly multiwave sonic.
- Established correlations used for the interpretation of geophysical data in soils cannot be used in permafrost, particularly where high ice contents exist.
- The results of geophysical tests in the sampled portion of the hole have been interpolated in the unsampled section.

Development of drilling techniques

One of the major objectives of this program was to develop drilling techniques which could be scaled up for oil-well purposes in order to meet the objective to drill gauge hole in permafrost with no thermal degradation. In order to meet this objective, each of the components of the overall drilling system had to function adequately.

Considerable effort was put into the formulation of a mud mix for the project, the technology of which is beyond the scope of this paper. The proprietary mix used ("Technivis") was designed specifically for high temperature/pressure conditions and its first application as a low temperature drilling fluid presented many challenges.

Overall, the fluid behaved well, maintaining its solids retention properties over the operating temperature range used. The mix required constant monitoring and modification by experienced and resourceful mud engineers. These engineers were often required to react quickly to the changing properties of the overall mud/cuttings mix, brought on by variations in formation temperature and lithology.

Despite the fact that the majority of the material from the hole was removed as core, the single shale shaker did not adequately remove cuttings from the mud flow. Problems experienced in pump failure and the plugging of the chiller were directly related to the lack of cleaning of the mud.

During the planning phase of this project there was much concern about the use and eventual disposal of the drill mud and oil soaked cuttings. Considerable care was therefore exercised in the preparation of the drilling area and in the drilling techniques to minimize contamination of the Molikpaq core fill and to maximize the collection of drill cuttings. The synthetic liner incorporated into the drill pad performed well, as evidenced by no detectable contamination of the underlying fill. Daily reconciliations of the oil "budget" in the form of down-hole requirements, topside storage and cuttings retention, consistently showed losses of less than 1 % by volume throughout the drilling operation. Final disposal of the cuttings and drilling fluids at an on-land combustion site was efficiently completed by Beaudril personnel with insignificant losses.

As noted above, the drilling rig was significantly over-designed for the anticipated borehole dimensions: In particular, this overdesign was incorporated to allow for sticking of the drill string due to hole instability. Frequent bit changes, and the optimization of the core barrel, reamer and bit assembly created a near-perfect gauge hole in which sticking was not a factor. In consequence, the driller was afforded considerable control over the advance of the hole. Incorporation of a weight-on-bit indicator (an instrument common in major oil drilling rigs but not generally incorporated in geotechnical rigs) also allowed the driller to better monitor and control the progress of the hole.

Drilling problems

Three major problems were encountered during the progress of the hole: mud stability problems in the initial portion of the hole, core recovery problems, and hole control in a squeezing zone.

Mud Stability Problems

The application of a mud formulation developed for a high temperature environment presented interesting challenges in the upper section of the hole. Because experimentation with the formulation was carried out while drilling ahead through the permafrost interval, detailed quality control was not carried out adequately with the consequence that the mud very quickly became unstable and lost its solids suspension properties. Barite and cuttings dropping out of suspension over a period of less than one hour plugged shakers, contaminated return tanks and completely blocked the chiller. This problem was avoided for the succeeding sections of the hole by increasing the shear time for the mix and by maintaining very close quality control on the drilling fluid, augmenting the formulation as necessary.

Coring Problems

In the upper sections of the hole, several coring problems were encountered. First, the inner core barrel began to block in the bottom hole assembly at the end of the coring sequence. It was found that modification of the bit to cause the inner reamer to slightly (1.59 mm in diameter) undercut the core essentially solved this problem. As the hole advanced further, the core became progressively more washed out due to thermal disturbance by the mud at the bit. Input mud temperatures were lowered from-2 °C to approximately -9 °C over this zone to counteract the warming of the mud by the drilling process and the relatively warm soil interval. Problems were also encountered in breaking off competent core down-hole at the end of a coring sequence. The core barrel was modified in this instance by modifying and strengthening the lifter springs in the barrel and by increasing the barrel setback to 20 mm. This deviates considerably from conventional practice. Ongoing modification of the drilling techniques such as these ensured that full and complete core continued to be recovered throughout the majority of the hole.

Problems with solids removal from the drilling mud allowed particles to bypass an inadequate shaker system and get into the mud chiller. Once into the chiller heat exchanger, these solids reduced mud flow and allowed the glycol to experience a sudden drop in temperature. The over-cooled glycol then flash froze the mud remaining in the heat exchanger. Disassembly of the chiller was then required for cleaning.

As the chiller problems were clearly the consequence of poor solids removal, our attention was directed to this part of the mud system for the rest of the borehole. However, it is clear that the heat exchanger of the chiller should be designed to allow larger tubing to reduce the probability of blockage and to facilitate cleaning. Efficiency of the unit would be reduced by these design changes.

Hole Stability Problems

A zone of hole instability was encountered at -273.5 mRT when drilling ahead through a gravel zone, which caused a considerable back flow from the hole and generated amounts of free gas. Initial attempts to freeze this zone off by using super-cooled mud were unsuccessful. Large pressures in the hole, up to 770 kPa, prevented significant advance for several hours. Attempts to advance back into the problem section of the hole continued for three days thereafter, using heavier, colder mud. Continued squeezing hole conditions were encountered, which forced redesign of the bottom-hole assembly. This assembly was modified by removal of stabilizers and the replacement of the coring bit by a 216 mm tricone bit.

Finally, the decision was made to trip out, run in with a larger bit to below the problem zone, run geophysical logs and advance casing. Coring began again below this zone one week after the problem started.

Two hypotheses exist for this occurrence: An unfrozen zone within the frozen sequence or gas hydrates. There is evidence in the down-hole geophysical data collected in this sequence that a significant thawed interval existed. Both the seismic velocity and density logs indicated significantly lower densities in this zone. Also, the limited salinity data collected in this zone showed significantly higher porewater salinity, averaging 22 ppt, in comparison with a background level of 8 ppt measured elsewhere in the unit. Unfrozen moisture contents measured in this zone by Time Domain Reflectometry methods also indicated higher unfrozen moisture contents. The *in situ* temperatures of -2 °C measured in this unit when combined with these elevated salinities are not sufficient to conclusively indicate a thawed zone, however.

The fact that gas was generated in this zone, coupled with the evidence that the hole eventually healed itself suggests that a thin zone of hydrate could have existed at this elevation. The temperature/pressure regime would also support the formation of a methane hydrate. The volume of gas was small and short-lived however. Also, no measurable gas was generated during the drilling of the oil-wells in the vicinity. As hydrate occurrences are generally thought to be laterally continuous, and to generate large volumes of gas over a prolonged period of time, the authors feel that this is the least likely of the two hypotheses presented.

Summary and conclusions

The occurrence of relic land permafrost below the southern Canadian Beaufort Sea was predicted in 1972 and has been penetrated by many oil and gas exploration wells since that time. Thawing around warm production wells will result in soil deformation, in turn resulting in strains in the well casings and potential foundation settlement beneath the production platform. Relatively continuous coring is required in order to evaluate the extent, nature and engineering properties of the permafrost interval. This information will be used to determine whether the effects of permafrost thaw on system components are tolerable, or whether mitigative measures are necessary to design a feasible, safe and cost-effective production system.

This first attempt to core the entire permafrost interval represents a development of the state-of-the-art. Its success was highly dependent on the design and construction of specialized equipment and the initiation of novel techniques: Large diameter coring, the use of chilled muds initially designed for high formation temperatures, the use of multiwave sonic geophysical tests etc. The high cost of this venture made it essential to fully exploit this opportunity to maximize the scientific data collected. To the owner's credit, this was accomplished and many groups have had the opportunity to collect data from this environment for the first time . This data will be essential to the further development of resources in this region, although several more projects of this type will be required before this development can be conducted safely.

This paper has concentrated on the operational aspects of the offshore coring program. Future papers considering the findings of the coring program and the geologic and thermal histories of Beaufort Sea permafrost will be published as confidentiality constraints permit.

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