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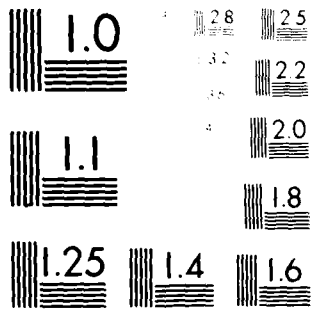
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SITE INVESTIGATIONS AND SUBMARINE SOIL MECHANICS IN POLAR REGIONS

Edwin J. Chamberlain

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Prepared by
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By



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PREFACE

This report was prepared by Edwin J. Chamberlain, Research Civil Engineer, of the Applied Research Branch, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this study was provided by the U.S. Geological Survey, Office of Marine Geology. The author thanks Dr. Jerry Brown and Paul Sellmann of CRREL for their technical reviews of this report.

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SITE INVESTIGATIONS AND SUBMARINE SOIL MECHANICS
IN POLAR REGIONS

Edwin J. Chamberlain

INTRODUCTION

This study was part of a larger project undertaken to provide guidance to the U.S. Geological Survey for evaluating the hazards of placing offshore structures in polar waters for exploring for and producing petroleum. The study concentrates on the region of the Beaufort Sea off the north coast of Alaska and is specifically concerned with site investigation procedures and the evaluation of submarine soil mechanics unique to this region.

Site investigations in the Beaufort Sea are complicated by cold weather and sea ice conditions. Much of the work to date has been done in winter using the sea ice as a platform.¹⁻¹¹ This approach avoids the summertime problem of drifting ice but requires complete protection of workers and equipment from the weather. The sea ice can only be used as a platform for drilling when it is frozen fast. The outer edge of the fast ice extends out to approximately the 15- or 20-m isobath, generally just seaward of the outer barrier islands. Difficulties in accessibility within the fast ice zone, however, have been caused by thin ice, particularly near pressure ridges where fresh cracks have frozen over. These regions, which can be several meters wide, are very dangerous to cross with heavy equipment. Thin ice zones must be circumvented or strengthened by repeatedly flooding the areas with sea water and letting them freeze.

Where site investigations are to be conducted beyond the fast ice zone, the sea ice in most cases cannot be used as a platform because of the difficulty in moving equipment and because of the dangers of thin and flowing ice. In such regions, site investigations must be conducted from ships during the summer months.^{12,13}

In either case the time available for site investigation is limited in winter to about three months (February through April) when the ice is thick and sufficiently stable to be used safely and in summer to a similar period (July through September) when drift and pack ice are not hazards to navigation.

The engineering properties of submarine sediments in polar regions differ from those of warmer waters because of the effects of freezing and thawing and the force of sea ice. Some of the conditions and resulting problems include 1) perennial ice bonding, 2) thaw settlement, 3) seasonal freezing, 4) frost heaving, 5) brine enrichment of pore water, 6) the presence of overconsolidated clays, and 7) ice gouging. An excellent summary of the ways that many of these factors affect wells and structures on land has been prepared by Goodman.¹⁴

Perennially ice-bonded sediments

Perennially ice-bonded sediments occur widely over the Alaskan Beaufort Sea coastal region.^{1,2,11,12} Ice-bonded sediments have high shearing resistances and bearing capacities and excellent settlement characteristics if they remain frozen. However, creep of ice-bonded sediments may be a problem if high stresses are imposed for long periods of time. Because of the high strength of ice-bonded sediments, excavation for fill materials may be difficult where they occur. This will be a critical factor in selecting fill material for artificial islands.

Thaw settlement

If ice-bonded sediments are thermally disturbed during construction or operation activities, unacceptable subsidence or loss of bearing capacity or shear strength may occur. Differential thaw settlement or loss of bearing capacity may affect the stability of structures such as drilling rigs and pipelines. The loss of shear strength may cause slope stability problems in artificial islands or causeways and may reduce the shearing resistance of foundation sediments. Thaw-induced downdrag may cause well casings to rupture.

Seasonal freezing

Seasonal freezing of the bed sediments may occur where the sea ice freezes to the seabed. These seasonally frozen sediments are likely to

contain segregated ice and when thawed may cause the same problems as perennially frozen sediments found on land. Perennially frozen sediments are also likely to occur beneath the seabed in these regions. Seasonal freezing of the seabed also appears to occur in deeper waters. However, ice bonding does not appear to be a significant factor in these regions. Seasonal freezing of artificial islands and causeways will also occur wherever these structures rise above sea level.

Frost heaving

Frost heaving can be a problem wherever seasonal freezing occurs. Artificial islands and causeways will be particularly susceptible to frost heaving unless non-frost-susceptible sands or gravels are used. However, where islands are placed in shallow water, freezing may reach into frost-susceptible bed sediments, where detrimental frost heaving may occur. Moreover, non-frost-susceptible materials may not always be available for fill. For these cases special precautions may be required to prevent or mitigate differential frost heaving. These include insulating to prevent frost penetration into frost-susceptible materials, anchoring foundations in perennially frozen materials, and artificially maintaining frozen ground -- all practices that have proven to be successful on land.

Frost heaving can also cause freezeback problems on well casings.¹⁵ External freezeback pressures on well casings on land can exceed the overburden pressure by 60%.¹⁶ Multiple-well freezeback pressures are of particular concern. When production is shut down for any prolonged period, it may be necessary to artificially heat well casings in the permafrost zone to prevent their collapse. This may be less of a problem offshore because permafrost temperatures appear to be warmer than there than at sites on land.

Brine enrichment

The ice-water phase components may be very complicated in submarine sediments, as the freezing of saline interstitial water often causes salts to be excluded at the freezing front and concentrated ahead of the front. The result is the formation of brine pockets in zones of ice-bonded permafrost. Warm ice-bonded permafrost is, thus, often difficult to identify, and representative sampling to determine engineering properties can be

uncertain. Other problems also occur. For instance, seismic surveying, which has proven to be a valuable tool for identifying zones of ice-bonded permafrost, can be inaccurate because increased brine concentrations in ice-bonded sediments can cause wave velocities to be much lower than normal.¹⁷

Overconsolidated clays

Overconsolidated clay sediments occur over a wide region of the Beaufort Sea. The freezing and thawing of exposed or shallow-water sediments during past sea level changes may have been the principal overconsolidation mechanism.^{2,11} These sediments are frequently extremely dense and strong, with shear strengths exceeding 250 kN/m^2 . The deposits are generally less than 10 m thick; however, the recent U.S. Geological Survey (USGS) Conservation Division study^{1,12} revealed deposits as thick as 30 m. These overconsolidated clays can have a significant influence on offshore operations. On the positive side, they provide high strength and high bearing capacity sites for artificial islands or gravity structures. They may also provide stable foundations for undersea pipelines and may protect them from gouging by sea and berg ice. On the negative side, these clays impede access to underlying sands and gravels for use as fill materials for offshore island construction. In addition, where these clays occur on the inner part of the continental shelf, it appears that the top of the ice-bonded permafrost is much nearer to the seabed than in regions where these clays are absent.²

Ice gouging

The grounding of sea ice pressure ridges and berg ice gouges the bed sediments; the main problem in the Alaskan Beaufort Sea is caused by the pressure ridges.^{19,20} Ice gouges have been observed in very shallow near-shore waters and out to at least the 80-m depth.¹⁸ Shallower scours occur in the denser overconsolidated clays and in coarse-grained materials. Information on the relation of the depth of gouge to the sediment type and properties will be necessary to determine the safe depth of burial for structures such as pipelines.

SITE INVESTIGATIONS

To identify potential problems and to make decisions necessary for safely developing offshore petroleum resources, thorough site investigations are required. Site investigations are necessary, not only for identifying ice-bonded permafrost regions and material properties, but also for identifying the sources and quality of borrow material for constructing artificial islands.

Obtaining information on the lithology and properties of the subsurface materials is basic to a site investigation. The necessary data include 1) sediment type and distribution, 2) relative density or stiffness, 3) caving or upwelling behavior, 4) depth to the top and bottom of the ice-bonded permafrost, 5) visible ice content, and 6) presence of gas including hydrates.

Several methods have been used to investigate the properties of the Beaufort Sea sediments. These methods include 1) drilling and sampling, 2) using the cone penetrometer, 3) using the multipurpose lightweight probe, 4) temperature profiling, 5) using bottom samplers of various kinds, 6) using seismic reflection and refraction, and 7) diving.

Drilling and sampling

Drilling and sampling provides the most complete information on sediment properties. Conventional rotary and drive sampling techniques have been used to depths of 100 m in the Beaufort Sea to recover "undisturbed" samples for laboratory testing.¹ Drive samplers such as those used and by the CRREL-USGS^{3,10} and USGS Conservation Division¹ projects have proven to be successful for obtaining samples of unfrozen sediments. The thin-walled Shelby tube sampler or similar heavier-walled drive samplers with adequate core retainer systems generally recover good undisturbed samples in unfrozen, fine-grained, cohesive sediments. Heavy-walled split-barrel samplers with core catchers are necessary for the coarser-grained, noncohesive sands and gravels. These sampling methods, however, severely restrict productivity because casing must be set to prevent the hole from closing. More productive hollow stem augers have also been used^{20,21} in unfrozen sediments, with sampling being conducted down the hollow stem. Problems with the upflow of sands, however, limit the use of this method.

Pressurized double-walled casing, though, has been successfully used to prevent sand from upwelling during sampling.²¹

Vibratory drills have also been used to rapidly obtain stratigraphically intact samples for delineating the boundaries of different sediment types. Samples obtained with this equipment, however, normally are not suitable for strength or consolidation tests because of severe structural disturbances. Sonic drills have been used with considerable success in the Canadian Beaufort Sea to delineate borrow areas for dredge and fill operations.²⁰⁻²²

Sampling ice-bonded sediments usually requires rotary core drills with carbide or diamond cutters. The coring fluids must be refrigerated and the cutting bit advance and rotation rates controlled to prevent the permafrost from melting. Rotary drilling works well in ice-bonded fine sands, silts and clays. However, rotary drilling for undisturbed samples of ice-bonded coarse sands and gravels may be difficult when temperatures are at -1° or -2°C , as they often are in the Beaufort Sea submarine permafrost. The pulling and breaking of coarse sand or gravel particles during rotary drilling can cause considerable disturbance of the sample.

Harding-Lawson Associates,²³ in their proposal to the USGS, state that they have been successful in drive-sampling frozen sands and gravels when the temperature is near the melting point. This method may provide better core recovery, but probably will not provide the quality of undisturbed sample required for strength and consolidation tests.

However, other information can be obtained from the drive-sampling operation and the properties of the disturbed samples. Drive resistance²⁵ can provide considerable information on strength;^{6,24} the degree of ice segregation (and thus the thaw settlement or weakening potential) may be inferred from laboratory analyses of the ice content and density.

Samples must be protected from both mechanical and thermal stress. Unfrozen samples must be prevented from freezing, and during shipping and storage they should be maintained at temperatures approximating the in situ values. This is particularly important with silts and clays, as freezing and thawing can significantly change the properties of these materials.

Similarly, frozen samples should be maintained at as near to the in situ temperatures as possible. Thermally shocking frozen samples with dry ice should be avoided, as this could cause cracking and changes in engineering properties.

Penetrometers

The cone penetrometer has also been used successfully using the sea ice as a platform.^{4,25} In conjunction with a drilling program, it can provide extensive information on sediment types, engineering properties and sediment temperatures. It has been most useful in determining the properties of the upper 10-15 m of sands, silts and clays. However, gravels and frozen sediments are very difficult to penetrate. Penetration resistances can be obtained at greater depths in the gravels down the bore of cased drill holes. The penetrometer rod can buckle in deeper waters, where sea-floor-based equipment such as the Norwegian Seajack²⁶ is probably more appropriate.

The penetration resistances of subsea sediments have also been determined using the Standard Penetration Test (SPT).²⁴ By correlating the SPT data with the unconfined compression strength, Haley and Sangster could predict the in situ undrained shear strength in silt sediments. Their predictions, however, were limited to the upper 18 m of unfrozen sediments.

Other in situ testing apparatus, such as the shear vane and pressure meter, may provide useful data. The shear vane, however, is limited to cohesive soils, and the pressure meter requires an access hole.

Multipurpose probe

The Osterkamp-Harrison lightweight multipurpose probe can rapidly determine temperature, salinity, hydraulic conductivity, and stratigraphic information.⁷ It is particularly useful in locating the top of ice-bonded sediments. However, it can be used only in shallow, fine-grained unfrozen sediments.

Temperature profiling

Once a drill hole has been completed, it is important that it be logged for temperature. In the relatively shallow holes (less than 100 m deep) drilled recently in the Alaskan Beaufort Sea, temperature profiles were obtained down the bore of small diameter (less than 2 cm) PVC or steel

pipes filled with non-freezing fluids.^{1,6,27-30} PVC is preferable where temperature gradients are large, as it reduces heat conduction along the tube. In the Beaufort Sea this may be a problem in the upper 10-15 m of a hole in shallow water (less than 2 or 3 m deep) or in basins such as Prudhoe Bay where little flushing occurs during the winter and the seawater becomes brine-rich and very cold. Steel pipe, however, is preferable because of its greater strength; it should be used when heat conduction is not a problem, especially when hole depths exceed 50 m.

The fluid used to fill the pipe must be environmentally innocuous and have a viscosity that allows the temperature probe to be inserted while minimizing convection. This is critical in shallow water. Diesel fuel or ethylene glycol solutions are not acceptable environmentally. Harding-Lawson Associates¹ found that mineral oil is satisfactory.

Bore-hole temperatures should be measured with calibrated thermistors using a precision ohmmeter. The system should be capable of resolving temperature changes to a few thousandths of a degree Celsius and have an accuracy of at least a hundredth of a degree Celsius.

Because drilling operations often thermally disturb the sediments surrounding the drill hole, temperature readings should be made at periodic intervals for as long as access is possible. Temperature measurements should also be made in the water column above the drill hole and compared with measurements made at the same depth in the pipe.

Temperature profiles for shallow depths (less than 15 m) can also be measured down the bore of a penetrometer rod^{4,25} or using special probes such as the Osterkamp-Harrison multipurpose probe.⁶ In many cases, though, these measurements and the penetration resistance data may be sufficient to identify the upper surface of the ice-bonded permafrost.

Bottom samplers

Bottom samplers can be used to take samples in the upper few meters of fine-grained sediments. Sampling could be done from the sea ice or from a boat. However, the data would be insufficient for most engineering purposes.

Seismic surveying

Seismic surveying is a valuable technique for mapping the depth to ice-bonded subsea permafrost and for estimating the degree of ice

bonding.³¹⁻³⁵ The best results have been obtained using seismic refraction techniques specifically designed for shallow depths (less than 200 m). The first-arrival refraction data from industry seismic reflection surveys obtained for hydrocarbon exploration have also been used successfully.³²

The success of this method depends on the increase in seismic velocity that occurs across a boundary between unfrozen and ice-bonded sediments. The refraction technique works especially well for sands and gravels (where the change in velocity is abrupt and large), because most of the water is in the form of ice at temperatures slightly below the freezing point of sea water.^{32,36} In fine-grained sediments, however, much of the water remains unfrozen at temperatures just below the freezing point, and the change in compressional wave velocity is smaller and more gradual. Thus, seismic refraction methods can best be used to map areas where coarse-grained, ice-saturated sediments occur or where substantial ice lensing occurs in fine-grained sediments; correlation with drill hole logs³² is essential to provide a reliable control for interpreting the seismic refraction records.

Seismic reflection can also be used to locate the top of ice-bonded permafrost.³² However, this method requires a knowledge of compressional wave velocities and refraction depths. For this reason, high resolution seismic reflection is best used for detailing the topography of the top of ice-bonded permafrost once the position has been established by refraction techniques.³²

The position of the bottom of the ice-bonded permafrost is difficult to identify using seismic techniques because the transition from ice-bonded to unfrozen sediments at the bottom of permafrost is gradual. The attenuation rates of refraction waves have been used successfully to determine the thickness of relatively thin layers of ice-bonded permafrost.³⁷ However, induction logging and down-hole logging using crystal cable surveys appear to be the most reliable methods for determining the position of the base of ice-bonded permafrost.³⁸

Diving

Seabed characteristics have also been determined by hand sampling during dives.³⁹ This method, however, does not appear to be worth the risks involved.

LABORATORY INVESTIGATIONS

Standard laboratory tests of engineering properties including grain size, unit weight, specific gravity, Atterberg limits, moisture content, organic content, permeability, triaxial compression, one-dimensional consolidation and direct shear will be necessary to identify adequately the engineering properties of the Beaufort Sea sediments. The American Society for Testing and Materials provides standards for most of these tests.

Special laboratory tests that may need to be conducted include 1) one-dimensional thaw consolidation, 2) frozen strength and creep, 3) adfreeze and pile support, 4) frost susceptibility, 5) pore-water chemistry and salinity, and 6) hydrocarbon and gas hydrates.

Thaw consolidation

Thaw consolidation tests are necessary to make calculations of thaw settlement and downdrag on well casings. In studies on land it has been difficult to take samples that are representative of in situ conditions, principally because ice-bonded permafrost is heterogeneous, especially when it contains much segregated ice. Because of the extreme variability of ice-bonded permafrost, many more consolidation tests are required to accurately determine its settlement characteristics than are needed for unfrozen sediments. Probabilistic methods may be necessary to analyze the settlement of structures on thawing subsea permafrost from laboratory thaw consolidation test data. More reliable information can be obtained from large-scale field tests, but these are usually very expensive.

There is no easy solution to this problem. Most projects either will be located where there is not much segregated ice or will control the problem by keeping the sediments frozen. The Trans-Alaskan Pipeline, for instance, was designed to keep the ice-rich permafrost from melting by rerouting the pipeline to less sensitive areas, placing it on pile supports above the ground, insulating it, maintaining the permafrost with thermal piles, or a combination of these methods. Nonetheless, laboratory one-dimensional thaw consolidation tests are necessary to locate sensitive areas.

The laboratory apparatus for this test should be capable of consolidating samples at least 6.4 cm in diameter and 2.5 cm thick. The initial temperature should approximate the in situ temperature. Loads should be applied, with each successive load doubling the preceding load until the design stress is exceeded. The sample should be allowed to thaw under this stress; once primary consolidation is complete and the excess pore pressures have gone to zero, the incremental loading should be continued. Room temperature has often been used to thaw samples. However, the rate of thaw and consolidation cannot be determined for in situ conditions if they differ from the test conditions. Furthermore, for fine-grained soils, temperature has an effect on both the rate of consolidation and the position of the consolidation curve in the void-ratio, effective-stress plane. These differences may not seriously affect the safety of a design predicated on these tests, but their impact should be seriously considered before test procedures are specified.

Three strain components should be observed during the thaw consolidation tests: 1) the strain of the frozen material due to the applied load, 2) the thaw strain under constant load, and 3) the strain of the thawed material under increasing loads.

Allowable thaw strains should be determined by the Federal Government. Stipulations such as those imposed by the Department of the Interior on the construction of the Trans-Alaskan Pipeline should be used as a guide for establishing limits on allowable thaw strains.

Strength

Frozen soils normally have strengths an order of magnitude greater than unfrozen soils. Shear strengths over 7000 kN/m^2 are not unusual. However, the strength of frozen sediments will probably be important for only a few cases, such as the design of artificial islands and anchors and the analysis of freezeback stresses on well casings. For artificial islands, the shearing resistance of the frozen crust is an important factor in resisting sea ice forces, and for anchors, the pull-out shearing resistance and creep properties are important.

To analyze freezeback behavior, it is essential to know the cohesion, the angle of internal friction, and the Young's (elastic) modulus for the

frozen material. Goodman³⁸ suggests that these values can be estimated directly from the lithology for sites on land. However, since little is known of the properties of ice-bonded subsea permafrost, these data should be obtained from carefully controlled laboratory tests until there is sufficient background knowledge to make reliable estimates in the field. It may be, though, that this is not feasible when making the freezeback pressure calculations for depths where the overburden pressures exceed the normal stress level capabilities of most testing laboratories.

Triaxial compression tests should be conducted on frozen samples at least 6.4 cm in diameter and 16 cm long to evaluate the frozen shear strength and creep properties. Larger samples (15 cm in diameter and 38 cm long) may be required for ice-bonded gravels. As the strength and creep characteristics of frozen ground depend on temperature, load rate and stress level, the test conditions must be as near to in situ conditions as possible.

Data should be obtained for the cohesion, angle of internal friction, Young's modulus, and Poisson's ratio. As it may not be feasible to run tests for the entire range of stress, temperature, and load rate conditions that may occur, strength testing programs should be designed to provide data for specific conditions.

File support

For pile-supported structures, it is essential to know how piles and ice-bonded permafrost interact. Adfreeze strengths are very important in the performance of piles in permafrost, particularly when sediment temperatures are near the melting point, as they are in the Beaufort Sea. Performance under both vertical and horizontal loads needs to be evaluated. Jacking forces due to frost heave must also be considered. These studies are normally conducted as full-scale field tests, much like pile loading tests in unfrozen soils.

Frost susceptibility

Frost susceptibility tests are necessary to evaluate the potential for frost heave of unfrozen sediments. Most available tests provide index values for selecting materials according to their degree of frost susceptibility. No test can determine the amount of frost heave for a

given material under known conditions. Several frost heave models are now being studied, but none is reliable enough to predict the magnitude of frost heave, particularly over long periods of time. The Casagrande⁴⁰ criterion allows soils to be selected or rejected based on their grain size characteristics. This is the simplest of the frost susceptibility tests and has probably seen the widest use. Freezing tests, such as the CRREL frost susceptibility test,⁴¹ rank soils as to their degree of frost susceptibility and are probably more useful for determining the relative magnitude of frost heave.

Pore-water chemistry and salinity

Analyses of pore-water chemistry and salinity will provide information that is essential to evaluate models for predicting the occurrence of subsea permafrost and to further the understanding of the processes that affect the degradation or formation of subsea permafrost. More important to the evaluation of the hazards of exploring for and developing petroleum resources is freezing point depression (FPD) data calculated from the salinity or total soluble salt concentrations. By comparing the FPD data with in situ temperature measurements, one can determine the boundaries of ice-bonded permafrost. This is a particularly valuable tool, as ice is not always visible in frozen sediments. One limitation, however, is that the FPD data do not account for the effect of pore size.⁴² This effect, however, may be insignificant at the relatively warm temperatures that prevail in the Beaufort Sea submarine permafrost.

Total soluble salt concentrations can be determined by extracting pore water and measuring for Cl, Na, Mg, SO₄, Ca, and K concentrations.^{1,43,44} Salinities can be calculated from electrical conductivity test data for extracted pore water. Procedures for doing these tests and for making the FPD calculations have been reported by Page and Iskandar⁴³ and Harding-Lawson Associates.¹

Hydrocarbons, shallow gas and gas hydrates

Blowouts and fires caused by gas and hydrocarbons in the subsea sediments may be a problem in the Beaufort Sea. Tests to determine the presence of these hazards should be conducted. Detecting hydrates is difficult. Goodman⁴⁴ suggests analyzing the carbon/oxygen ratio. More conventional analyses can be used for hydrocarbons.¹

CONCLUSIONS

Ice-bonded permafrost occurs widely over the Alaskan Beaufort Sea. Sites must be carefully evaluated to avoid ice-rich subsea permafrost. Where this is unavoidable, laboratory tests must be conducted to evaluate the potential hazards of structures thermally disturbing the subsea permafrost.

Highly overconsolidated clays also occur over wide regions of the Alaskan Beaufort Sea. The occurrence of these clays must be carefully considered when selecting sites because they restrict access to gravels for artificial island construction and because they frequently are indicators of ice-bonded permafrost occurring near the sea bed.

Site investigations can be carried out during the summer from ships or during the winter from the sea ice. Only a limited time is available to conduct the investigations — about three months each in summer and winter.

Samples are usually taken by drilling and coring. In situ investigations can also be accomplished with penetrometer and probes; however, these methods are restricted to shallower depths. Drilling and coring is necessary to take quality samples.

In addition to the normal laboratory soil tests, special laboratory tests must be conducted to determine the effects of freezing and thawing on strength and consolidation characteristics of subsea permafrost. These include frozen strength and creep tests, thaw consolidation tests, and frost heave tests. Chemical analyses are also necessary to determine freezing points. Temperature profiles in drill holes must also be determined. In addition it is necessary to test for gas hydrates and hydrocarbons.

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