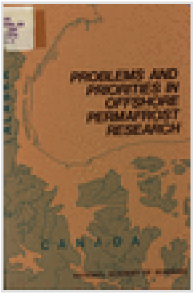


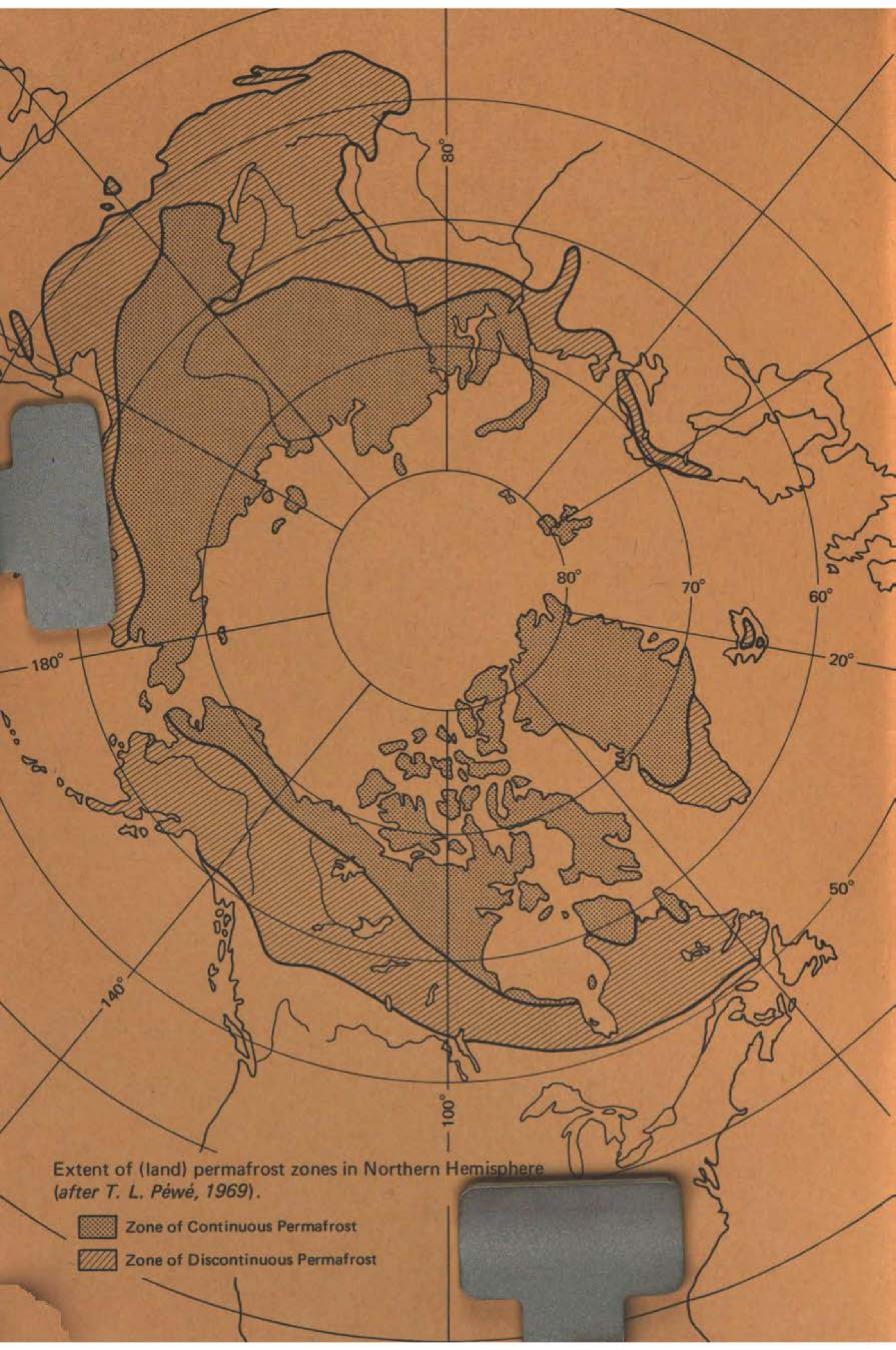
Problems and Priorities in Offshore Permafrost Research (1976)

Pages
57

Size
5 x 8

ISBN
0309346665

Ad Hoc Study Group on Offshore Permafrost; Committee on Permafrost; Polar Research Board; Assembly of Mathematical and Physical Sciences; National Research Council



Extent of (land) permafrost zones in Northern Hemisphere (*after T. L. Péwé, 1969*).

Zone of Continuous Permafrost

Zone of Discontinuous Permafrost

PROBLEMS AND PRIORITIES IN OFFSHORE PERMAFROST RESEARCH

Ad Hoc Study Group on Offshore Permafrost

Committee on Permafrost
Polar Research Board
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C.
1976

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This document reviews the status and problems of permafrost in the Beaufort Sea north of Alaska and makes recommendations for research on offshore permafrost for the years ahead. It was prepared by an *ad hoc* study group of the Committee on Permafrost of the Polar Research Board, in response to a request by the Office of Polar Programs, National Science Foundation.

The study group first met on December 16, 1974, at the U.S. Geological Survey offices at Menlo Park, California. The second (and final) meeting of the study group was held during the Beaufort Sea Conference held in Calgary, Alberta, Canada, on January 20-21, 1975. The Polar Research Board publication *Priorities for Basic Research on Permafrost* (National Academy of Sciences, Washington, D. C., 1974) was a useful reference in the preparation of this document.

The Committee is deeply grateful to William M. Sackinger (Chairman) and members of the study group for their diligent efforts in putting this report together in the brief time allotted for the task.

Troy L. Péwé, *Chairman*
Committee on Permafrost

1. SUMMARY

In response to the request of the National Science Foundation's Office of Polar Programs for a review of "major problems" in offshore-permafrost research, this study group has reviewed evidence for offshore permafrost, has considered possible effects of permafrost on offshore operations, and has examined needs for research so that offshore permafrost might be better understood.

Permafrost is perennially frozen ground, subject to rapid change in its characteristics and structural behavior as a result of changes--especially thermal and hydrologic changes--in its environment. It is found typically in Arctic and Antarctic lands. Understanding of permafrost, its distribution, its physical characteristics, and its behavior is important to basic geology and geomorphology and holds important clues to the solution of related problems--including climatic history and coastline evolution--in the environmental and earth sciences. Because of the peculiar physical characteristics and behavior of permafrost-soil structures, permafrost is of paramount concern in high-latitude engineering.

There is increasing evidence of widespread subsea permafrost off North American Arctic coasts. This evidence, its positive yet fragmentary nature, and early experience in Arctic construction and abandoned and broken projects make very clear, expecially in view of interest in Arctic offshore oil and gas development, that Arctic offshore permafrost must be mapped, better understood, and taken into account in decisions concerning the Arctic environment, its use, and its protection. As is frequent in the environmental and earth sciences, the same studies that are essential to fundamental understanding of earth processes are critical here to safe, well-reasoned exploitation of the earth for human benefit.

Our knowledge of land permafrost is not fully satisfactory. We find that less is known of subsea permafrost today than was known of land permafrost half a century ago. We recommend, generally:

- *Immediate implementation of a program to locate offshore permafrost.*

- *Determination of material index properties for characteristic cores and sample material obtained by drilling and bottom sampling.*

- *Construction of models of offshore permafrost regimes, including the possible variations in the thermal, chemical, hydrological, and electrical properties.*

- *Active participation and cooperation by industry in offshore-permafrost research activities.*

These recommendations are elaborated upon in Chapter 4.

2. REVIEW

INTRODUCTION

Permafrost--perennially frozen ground--occurs commonly in high-latitude and high-altitude land environments, and exists as well in the sea floor along Arctic coasts. Human activity can change physical characteristics of local permafrost-soil structures radically, and permafrost poses substantial problems for construction engineering in regions now subject to resource development, notably hydrocarbon exploration, extraction, and transportation. Land-permafrost problems have been paid special heed in recent oil and gas development in the North American Arctic but still are not understood fully whether from the point of view of basic earth science, engineering geology, or environmental protection (National Research Council, 1974, 1975). Far less is known of offshore permafrost, its distribution, properties, and dynamics of formation and destruction.

The complex Arctic marine environment, replete with moving ice, unknown currents, and complicated chemical, hydrologic, and thermal conditions, offers a major challenge to offshore science and technology. Decisions concerning development of likely petroleum resources off the Arctic coast, in response to energy needs, require thorough understanding of offshore permafrost. Offshore operations might proceed with a higher level of confidence when adequate information on offshore permafrost is acquired in order to permit the safe and economic design of facilities. Northern regions are filled with tragic examples of man's ignorance of permafrost on land--abandoned highways, relocated railroads, destroyed buildings--all of which underscore the importance of basic understanding, followed by informed and prudent design of structures and equipment, before man works offshore in the Arctic.

Permafrost is earth material that is continually below a temperature of $0^{o}C$ for two or more years. Offshore permafrost, found in the sea floor, may consist of soil particles bonded by interstitial ice (bonded permafrost) or it may contain considerable ice volume (ice-rich permafrost). Not all offshore permafrost contains ice; the pore liquids beneath the sea may be rich in brine, resulting in an unbonded salt-rich permafrost with a temperature below $0^{o}C$.

In areas of coastal subsidence, the sea has been transgressing upon permafrost terrain for many thousands of years, replacing the cold terrestrial environment with a warmer seawater regime. In many Arctic coastal areas, seawater has a mean annual temperature colder than $0^{o}C$, thus maintaining a thermal environment in which permafrost can form. Under these conditions thick, cold permafrost originally formed beneath land can take thousands of years to adjust to its new surficial environment. Thus, large offshore areas are underlain by relict permafrost formed in a different and colder environment. The relict permafrost may be degrading, or thinning by thawing, at both top or bottom. Conversely, permafrost may be aggrading, or growing, for example where coastal retreat exposes unfrozen lake sediments to freezing sea-bottom temperatures or under shallow offshore bays and barrier islands in freezing temperatures. Elsewhere, equilibrium conditions can be developed in which permafrost is neither aggrading nor degrading. Consequently the distribution, thickness, physical-chemical regime, and ice content of sea-floor sediments generally are more complex than land conditions. A broad-based research effort is required to understand them. The limits of the area in which permafrost must be considered in planning offshore engineering projects still are unknown. Little is known of the thickness, continuity, and ice content of offshore permafrost in those few areas where its presence has been shown.

BACKGROUND--EVIDENCE FOR OFFSHORE PERMAFROST

Is offshore permafrost a real problem? The reality of offshore permafrost has been demonstrated only recently, and knowledge of its extent, distribution pattern, thickness, and character is sparse and fragmentary. With increasing specificity, the evidence suggests (1) that offshore permafrost is sufficiently widespread to be of concern to science and engineering, and (2) that ignorance of offshore permafrost is commensurately significant.

Ability to predict the probable distribution of offshore permafrost is limited. Little is known of the interdependence of thermal, hydrologic, and sedimentological factors that control its existence. Even if the knowledge of the role of these interactions were more complete, our ability to predict the general distribution of offshore permafrost would be limited by inadequate knowledge of distribution of bottom-water temperatures and bottom currents in the Arctic Ocean.

The presence of offshore permafrost only can be inferred unless direct temperature measurements are made or the sediments are ice-bonded. Hence, much of the evidence reviewed here is for bonded frozen sediments, in particular, rather than for all types of subsea permafrost.

It is possible also that a thin veneer of seasonal ice may form close to the surface of the seabed under certain conditions, and that this might be described incorrectly as permafrost. This is probably the explanation of a frozen sea bottom described by Parry (1821) in Viscount Melville Sound.

The trend of scientific assessment of offshore permafrost has shifted from the highly speculative to the increasingly specific within the past two decades. The scientific literature on offshore permafrost is not long, but overall it points to the existence of substantial permafrost occurrences offshore in the Arctic.

It has long been suggested, at least hesitantly, that permafrost might occur offshore. Black (1954) pointed out that negative temperatures penetrate several kilometers into polar seas and that mean annual ocean temperatures are, in places, below 0°C. However, he concluded that high salinities in the sediments generally would preclude freezing. Lachenbruch (1957) wrote that extensive permafrost in the sea bottom could only occur within a few thousand meters of northern shorelines unless active shoreline regressions were occurring. Werenskiold (1953) confirmed theoretically that frozen ground could exist 100 m offshore as had been observed in a local colliery. Baranov (1959) mentioned the presence of perennially frozen ground beneath the water in recently submerged sections of the continental shelf in the Laptev and East Siberian Seas. Evidence was sparse. Lachenbruch (1968), in discussing sea-bottom permafrost, concluded that "the mean temperature of both sediments on the continental shelves of the Arctic Ocean is less than 0°C and hence these waters are underlain by a thin layer of permafrost on the order of 30 m thick, or less; whether or not ice occurs in these sediments is unknown."

Recently, an increasing number of reports have described frozen sediments recovered from the sea bottom. Lewellen (1973, 1975a, 1975b) reported extensively on frozen sediments in coastal areas along the Alaskan coast of the Beaufort Sea. Seismic data from the Barrow area indicate frozen ground under the Barrow spit but no well-defined high-velocity layer indicative of frozen ground under the adjacent part of Elson Lagoon or in the vicinity of Tapkaluk Islands to the east, site of Lewellen's (1975b) drilling experiment (Rogers *et al.*, 1975). However, temperatures throughout an 84-m-deep borehole located east of the Tapkaluk Islands are below $0^{o}C$; preliminary interpretations indicate that the base of the permafrost is at a depth of approximately 235 m (Lewellen, 1975b).

The presence of permafrost is suggested strongly by features displayed on high-resolution seismic-reflection profile records off Prudhoe Bay, Alaska. Permafrost would not be expected in the Chuckchi Sea south of Cape Lisburne (latitude 69^{o} N) because warm freshwater from the large rivers entering Kotzebue Sound and warm, north-flowing water entering through Bering Strait should result in bottom temperatures too warm for formation or preservation of permafrost. This assumption is supported by the failure of piston cores up to 10 m long to encounter permafrost in numerous sites in the Chukchi Sea southward from latitude 70^{o} N. However, polygonal patterns formed by the thawing of ice wedges beneath the sea bottom extend at least 150 m offshore from some low-lying parts of the Baldwin Peninsula (Kotzebue Sound). Relict permafrost is probably locally present in near shore areas southward along the Alaskan coast at least as far as the Arctic Circle.

Molochuskin (1973) reported on the presence of frozen ground beneath the Laptev Sea. His observations confirm the presence of permafrost in water depths up to 4 m and to distances of 900 m from the coastline. The mean annual water temperature in the area is slightly positive.

Samson and Tordon (1969) encountered frozen sediments beneath Deception Bay in northern Quebec;

the Arctic Petroleum Operators Association recovered frozen sediments from beneath the sea floor of the southern Beaufort Sea in 1970 (Mackay, 1972); Yorath *et al.* (1971) recovered a core containing freshwater ice in the sea floor north of Cape Bathurst, N.W.T.; and Pelletier has described fresh ice in the sea floor of the high Arctic (Mackay, 1972). McDonald *et al.* (1973) investigated shot-hole data from a seismic program along the northwest coast of the Tuktoyaktuk Peninsula and reported the occurrence of frozen ground offshore. They found that bathymetry appears to be a primary control on the depth to the permafrost, at the shoreline. Further indirect evidence of frozen sediments in the southern Beaufort Sea has been given by Shearer *et al.* (1971), who have explained conical mounds in the Beaufort Sea as pingos, large mounds raised by the growth of an ice core. Hunter and Hobson (1975) suggested that high subsurface velocities measured in offshore sediments are due to the frozen state of the sediments. In the spring of 1974, the Geological Survey of Canada supported an offshore drilling program in Kugmallit Bay near Tuktoyaktuk, N.W.T. Recovered frozen and unfrozen cores confirmed the seismic refraction interpretation of the presence of permafrost; temperature profiles beneath the sea bottom were determined also (Judge *et al.* 1975). The continuous permafrost layer mapped at depth beneath the sea bottom of Kugmallit Bay is thought to be relict. Temperatures only fractionally below $0^{o}C$ were measured in the upper portions of the permafrost layer.

Recent sea-level changes, along the Beaufort Sea coast, are believed due mainly to eustatic fluctuations in sea level. Isostatic effects should be minimal, because most of the coast was unglaciated during the Wisconsin (Prest *et al.*, 1968). It is apparent that some areas of the shelf were probably exposed as dry land for tens of thousands of years, during which time the permafrost could have grown to a considerable depth, given ground temperatures comparable with the present. Permafrost should be widespread in the southern Beaufort Sea because water temperatures are negative, except where modified by large rivers. In the shallower coastal zone, where there was a long period of emergence during the middle and late Wisconsin and only a brief period of postglacial submergence, relict permafrost may be present. The depth to the top of permafrost will depend upon factors such as erosion, sedimentation, and water temperatures. In near-shore areas, where coastal erosion has been rapid, relict permafrost as much as 200 to 400 m thick should exist.

PERMAFROST EFFECTS ON OFFSHORE OPERATIONS

Consideration of offshore permafrost will have to influence the design of any facilities to be used in Arctic waters. Frozen soil provides an excellent foundation as long as it remains frozen. If it is ice-rich and thaws, it tends to subside irregularly and its bearing strength is reduced. Experience has taught that these characteristics cannot be ignored in the design of onshore structures for permafrost areas. Offshore, the potential consequences of structural failure are even greater in terms of loss of human life, environmental damage, and costs. Thus, it is imperative that the presence and properties of permafrost be fully accounted for in the design of bottom-founded structures to be installed in Arctic waters.

Because the first facilities to be built off the northern coast of Alaska are likely to be associated with the exploration, production, and transportation of petroleum, permafrost protection for such activities well illustrates the practical need for a better understanding of offshore permafrost. The structures most likely to be influenced by the presence of permafrost are pipelines, wellbores, pile-founded platforms, and large gravity structures resting directly upon the sea floor. In addition, dredging operations and seismic interpretations will be influenced by offshore permafrost.

Pipelines are potentially subject to damage by differential settlement of thawing permafrost. Pumping a hot (e.g., 65°C) fluid through a bare pipeline buried in or immediately above permafrost will produce, over a period of years, a thaw bulb extending up to 30 m below the line. Subsidence of the soil supporting the line will be greater over a zone of ice-rich soil (e.g., an ice lens) than elsewhere. If the vertical and horizontal extent of the ice-rich zone are sufficient, the unsupported portion of the pipeline will be subjected to a bending stress that can result in buckling or even rupture. Overstressing the pipe may be avoided in a number of ways, including the following:

1. Detour the line around areas of ice-rich permafrost. Detailed information on permafrost location and moisture content is thus required along possible routes.

2. Use a small-diameter, heavy-wall pipeline that can conform to any anticipated settlement without being overstressed. Accurate methods of predicting thaw strain are needed for this approach.

3. Insulate the line to extend the time of growth of the thaw bulb and perhaps reduce its extent. Practical application will depend on the depth at which ice-rich frozen soil is found and on the thermal properties of the soil.

4. Insulate the line and trace it with refrigeration lines. Several kilometers of the Trans-Alaska Pipeline will utilize this solution.

5. Elevate the line above the sea floor. This solution may be practical offshore only in very deep water or in very shallow water because of ice scour of the seabed.

6. Chill the fluid to be transported to a temperature less than 0°C before pumping it into the pipeline. This may be an excellent answer for a gas line, but pumping cost is likely to be excessive for the moderately viscous crude oils typical of Prudhoe Bay.

Although none of these possibilities has been tried in Arctic waters, it is reasonable to believe that one or more will be practical. More must be learned about offshore-permafrost extent and properties before safe selection can be made.

Wellbores are subject to permafrost damage by freeze-back and by subsidence. Freeze-back occurs when a well is completed and then shut in. Water both inside the casing and outside in the formation tends to freeze in an irregular manner as heat is lost to the formation. Pockets of water surrounded by ice or impermeable strata tend to be formed. The expansion that occurs as water in these pockets freezes exerts tremendous pressure on the well casing. Workovers of a number of wells at Prudhoe Bay have been necessary because of damage during freeze-back. Offshore, freeze-back should not be as rapid since the permafrost is only a few degrees below freezing. If the well begins production soon after completion, or if the casing is strong enough to resist external freeze-back pressures and the wellbore is cleared of fluids subject to freezing, freeze-back hazards are reduced. Subsidence damage is possible after the well begins production, because of the passage of hot fluids through a wellbore in permafrost, which will thaw a cylindrical zone around the wellbore. If this zone is sufficiently compressible in the thawed state, soil subsidence will impose a vertical load on the well casing. The magnitude of such a load depends on the diameter of the thaw zone and the mechanical properties of the thawed permafrost. High-strength casing and insulation can be used to prevent subsidence damage.

Production platforms supported by piles set in permafrost may be subject to pile failure that is due to thawing caused by production wells completed either through or near the piles. The shear strength of permafrost sediment is often much less in the thawed state than in the frozen state. Even if the permafrost remains frozen, its strength will tend to decrease as the freezing point is approached; creep failure is also a serious problem, particularly near the freezing point, and requires serious study.

Gravity structures, such as the concrete platforms in use in the North Sea, perhaps are less sensitive to permafrost than are the other structures discussed above, but it is possible that thawing due to either production wells or storage of hot oil in the base of the platform will result in differential settlement and structural failure. Even if differential settlement is not a problem, selective insulation and refrigeration techniques may be used to freeze a portion of the foundation to the structure, providing better resistance to ice forces. Information on the thermal and mechanical properties of the sea floor below the structure will be needed in either case.

Dredging operations might be hampered by the presence of permafrost since conventional equipment was not designed to handle material bonded together by ice. The problem has already been encountered in the construction of artificial islands off the northern coast of Canada and is likely to arise in the construction of harbors and artificial islands proposed for the northern coast of Alaska. A good knowledge of offshore permafrost distribution and type will assist in the design of coastal facilities and perhaps avoid dredging in permafrost areas when possible.

Interpretation of exploration seismic reflection records is complicated by the existence of a substantial thickness of permafrost. Misinterpretation of deep structures could result from a patchy lateral distribution of frozen ground exhibiting high seismic velocities. The likelihood that misinterpretations will result in costly dry holes can be reduced by a better understanding of the distribution and seismic properties of offshore permafrost.

The exploration for, production of, and transportation of petroleum off the northern coast of Alaska might be accomplished safely, efficiently, and without serious damage to the environment. This, however, will require further study of offshore permafrost and careful consideration of its extent and properties, along with due consideration to other hazards such as sea ice and pressure ridges.

3.
RESEARCH NEEDS

QUATERNARY HISTORY AND COASTLINE STABILITY

Knowledge of landscape, shoreline, and climate history is critically necessary in order to arrive at a preliminary estimate of the distribution of permafrost offshore. This is true because much of the offshore permafrost is likely to be relict, having originated under an emergent landscape that has been submerged so recently that a new thermal equilibrium has not yet been reached. In addition, knowledge of the Quaternary history can assist in predicting the lithology of subbottom sediments, and lithologic parameters such as grain size and sorting play an important role in determining the distribution and abundance of fluids and solid ice in sediments at subzero temperatures.

The most critical historical requirement is for knowledge of the history of the position of the shoreline, a position that has changed in response to worldwide changes in sea level and in response to local accretion of sediments. Such accretion resulted in progradation of the shoreline and local coastal erosion, resulting in encroachment of the sea quite independent of sea-level changes. It is well established that sea level rose more than 100 m during the last 18,000 years, having risen rapidly until about 4,500 years ago and then very slowly during the last four millenia. Unfortunately, experience has shown that the general worldwide record of sea-level changes cannot be applied in useful detail to individual continental shelf areas. Tectonic crustal deformation, together with isostatic response to crustal loading and unloading due to glaciers, deltas, and the sea itself, introduces perturbations that require local studies in order to establish an adequate local record of chages in the shoreline due to changing sea level. Additional studies devoted to establishing a sea-level curve for the continental shelf of the Beaufort Sea should command a high priority.

Even during the last 4,500 years, there have been changes in the position of the shoreline due to progradation or coastal erosion. Collapse due to thawing of ice-rich permafrost has resulted in shoreline retreat of spectacular dimensions along parts of the coast of the Beaufort Sea. Lewellen (1965) has already collected much data on shoreline changes. Additional observations are needed to relate locally to the sea-level curve and the subsurface geology.

Painful and expensive experience has shown that onshore permafrost is distributed irregularly and that the irregularities are difficult to predict. Permafrost data from a single drill hole in one place may tell us little about permafrost conditions--depth, thickness, and ice content--at another point a few hundred meters away. This is true in part because the geometry of permafrost beneath otherwise homogeneous land areas is affected by surficial drainage features such as lakes, lake basins, and rivers; this geometry is inherited by subsea permafrost when the shoreline encroaches. Moreover, the speed with which the ice-bonding dissipates offshore is affected by the lithology of the sediment. The more we know about the Quaternary geology, onshore and offshore, the more reliably we can estimate offshore permafrost conditions, especially permafrost conditions in the critical first kilometer seaward from the beach. Permafrost studies offshore must proceed hand in hand with studies of the Quaternary geology, both offshore and onshore, and permafrost sampling programs must include attention to the stratigraphic, paleobiological, and paleoclimatic information that can be obtained from the samples.

INVENTORY AND MAPPING

Our knowledge of the extent of offshore permafrost is less now than our knowledge of land permafrost was 50 years ago. A regional inventory is urgently needed.

A logical first step would be to undertake an aerial reconnaissance of coastal areas throughout the zone where permafrost is extensive on land. Areas in which ice-rich relict permafrost persists near the present shore betray themselves by the presence of polygonal patterns on the bottom. The patterns are formed where ice wedges are melting out and contrasting sediment collects in the resulting trenches. The pattern formed by thawing ice wedges is readily seen in quiet, shallow water from low altitudes and appears in some air photographs. Thus, an examination of existing air photos, supplemented by flights along the coast on days when the sea is quiet and free of ice, could quickly delineate many of the coastal areas in which relict permafrost is present.

The inventory ultimately would be in the form of a map portraying (1) the presence or absence of permafrost and particularly the presence of ice-bonded forms. (2) the depth of occurrence and thickness of permafrost, and (3) the sediment type and ice content of permafrost. Several complementary approaches may be used simultaneously to assemble this information: (a) direct observations involving drilling, sampling, and core analyses; (b) seismic surveys; (c) electromagnetic surveys; and (d) thermal modeling.

An offshore borehole program, involving drilling either through shorefast ice or from a floating platform, is required in order to provide ground truth--local data points upon which regional geophysical surveys can be based. Direct observation by drilling is the best available method for obtaining data on temperature, sediment type, the degree of ice bonding, ice content, and salinity. When sediments contain brine, or if clays are a dominant mineral component, the presence of ice-bonded permafrost will not coincide with the 0°C isotherm. Drilling and coring are required to determine in detail the physical properties, phase composition, and temperature of the material. Cuttings, or preferably cores, should be recovered and examined for ice content as well as for other engineering and stratigraphic parameters, and side-hole and bottom-hole temperatures should be measured. Boreholes should extend at least several tens of meters and, if possible, several hundreds of meters below sea bottom in order to provide either direct visual and thermal evidence of the depth to which permafrost extends or, if the base of permafrost cannot be reached, to provide sufficient thermal data for prediction of the position of the base of permafrost. Special attention should be given to the determination of interstitial water chemistry and salinity, sediment temperatures, and thermal conductivity from cores recovered in the offshore drilling. These data are needed as input to predictive permafrost decay and growth models. Perturbations in the distribution of permafrost may be introduced by the presence of grounded shorefast ice and/or perennial grounding of pressure ridges, for example, along the shear zone between shorefast and moving ice. Ice is a better heat conductor than water, and the sea bottom loses heat at an exceptional rate in these places. Some of the offshore boreholes should be sited in positions to examine the permafrost regime beneath areas where ice is frequently grounded and to compare that regime with the regime in areas where water generally remains in contact with the bottom throughout the winter.

Surface mounds found in the Beaufort Sea north of Canada have been interpreted by some as pingos, and similar submerged mounds may be found off the Alaskan shore. If the mounds are indeed pingos, they provide important insights into groundwater movement and indicate the presence now or in the past of an unstable thermal and hydrological condition in parts of the offshore area. Recognition of such a situation would be useful in anticipating unexpected and undesired flows of water during petroleum drilling. These submarine mounds should be drilled to establish whether they contain abundant ice. The distribution of the mounds should be mapped, in any case, because, whatever their origin, they do indicate some sort of unstable situation on the sea floor.

Because offshore drilling is costly and because logistics are a large cost component, the boreholes should be clustered as much as possible in areas of special economic or scientific interest and at intervals optimally spaced to minimize cost while keeping data points relevant to the intervening areas. Offshore boreholes should be located to answer specific questions relating to the permafrost distribution; for example, in the vicinity of shallow bays, near river mouths, or in regions of strong coastal currents. In locations where geophysical surveys indicate lateral changes in permafrost conditions, the exact nature and the cause of such changes should be investigated using drill holes. The interaction of bottom-water temperatures and current flux throughout the year must be established at the drill sites, in order to determine the extent to which subsea permafrost is in equilibrium with modern thermal conditions at the sediment/water interface. The drilling program should be planned in a way that will maximize recovery of historical, paleoclimatic, and paleoceanographic information.

A regional survey should be undertaken of water temperatures and currents. Bathymetric maps need to be updated in the inshore zone to determine the significance of grounded ice in the local distribution of subsea permafrost.

All available seismic records should be searched for evidence of permafrost; new seismic surveys should be conducted where existing coverage is incomplete or ambiguous, and the results combined with other evidence into an offshore permafrost map of the continental shelves of the Beaufort and Chukchi Seas. Under favorable circumstances, the top of permafrost is recognizable on seismic-reflection-profiling records. However, seismic techniques record contrasts in the velocity with which sound waves are transmitted through different bodies of subsurface sediment and rock. Borehole data are required if one is to establish whether this represents a difference between ice-bonded and non-ice-bonded sediment rather than a contrast between, say, unfrozen gravel and unfrozen mud. Conventional seismic techniques are incapable of distinguishing the depth to the <u>bottom</u> of bodies of ice-bonded permafrost. Such techniques cannot provide evidence of a boundary between bodies of brine-saturated sediment at temperatures above and below 0°C. Even if ice is present in brine-rich sediment, the boundary between ice-rich and brine-saturated sediment may be so gradational and so diffuse that no reflecting horizon is present. The same holds true for clays, which commonly contain substantial amounts of unfrozen pore water at temperatures below 0°C. In short, conventional seismic techniques are unlikely to assist in locating permafrost characterized by temperature but rather are capable of finding large frozen bodies containing ice. To remove ambiguities in interpretation, any seismic inventory of the distribution and character of offshore permafrost requires that ground truth be obtained by subsea boreholes. Detailed borehole siting should be based in part on preceding seismic reflection and refraction surveys, in order to choose sites where permafrost is most likely to be encountered and to provide data that can be related to the acoustic characteristics of sediment in which the presence or absence of permafrost has been firmly established.

Given the borehole information and a better regional survey of bottom-water temperatures and hydrology, seismic records may be capable of outlining the general distribution of offshore permafrost. Furthermore, adequate and sufficient seismic records may already be in existence. Experience off northwestern Canada has shown that with some borehole control, the position of the top of permafrost can be established in seismic records of several types. The Geological Survey of Canada (GSC) has pooled government and privately obtained seismic records to assess the extent, distribution pattern, and depth of offshore permafrost. Confidentiality of records bearing on petroleum possibilities at great depth was protected simply by eliminating all returns below 1 second before submittal of records to the GSC. Companies were also encouraged to edit the tapes in order to withhold segments of the records that might contain confidential economic information at depths less than 1 second. Although differing institutional and legal constraints affect the consolidation of seismic records for Alaskan shores, information about permafrost location is so essential to the planning of offshore engineering works, and lack of it can cause such unsafe and costly failures, that an effort must be made to centralize and utilize all available information. We suggest that through an appropriate industrial association, perhaps the Alaskan Oil and Gas Association (AOGA) [and its Canadian counterpart, Arctic Petroleum Operators Association (APOA)] arrangements be made for records to be edited and shared with appropriate government or academic research groups. These records should be pooled with those obtained by universities and government surveys and new seismic records obtained in areas where existing records are inadequate. All records should be searched for evidence of offshore permafrost in the Beaufort and Chukchi Seas and a regional compilation prepared at a scale of 1:250,000, with more detailed compilations prepared in areas where data permit.

Electromagnetic methods for sensing permafrost have been shown to be of great value on land and along the coastline (Daniels and Keller, 1974; Koziar and Strangway, 1974; Hoekstra *et al.*, 1975) but are of limited application offshore because of highly conductive seawater overlying the sediments. However, immediately onshore at the coast line, existing electromagnetic techniques can be exploited to map premafrost thickness and geometry and to obtain information about sediment type. Stanley (1958) and Hoekstra (1974) have shown that the permafrost in the vicinity of Pt. Barrow, Alaska is of low resistivity, indicating brine layers incorporated in the permafrost. The boundary of brine layer regions and their depth below the surface can be mapped by ground and airborne electromagnetic techniques. In river deltas, the boundary between coarse- and fine-grained sediments may be outlined using this approach, and information about brine layers and sediment type may be related to Quaternary history of the shoreline.

In late spring, the offshore water may have a resistivity considerably higher than seawater, allowing some electromagnetic soundings for permafrost directly beneath the sea (Scott, 1975). When such opportunities present themselves, electromagnetic methods furnish information about the salinity, sediment type, and ice content of the permafrost.

PHYSICAL CHARACTERISTICS AND PROCESSES IN THE SUBSEA REGIME

Much of the ice-bonded permafrost under the sea is relict, and the ice-bonded permafrost probably degrades at a rate determined by a complex interaction of thermal conduction, ionic diffusion, and fluid transport mechanisms. The understanding of these processes is of critical importance for estimating and modeling permafrost distribution in the marine environment.

CONDUCTIVE THERMAL REGIME: The distribution of permafrost, its growth and its degradation, cannot be understood without a knowledge of the subsurface temperatures and the factors controlling them. Observations of the temperature distribution suggest that over much of the earth the dominant mechanism of heat transfer is conduction. In the absence of other mechanisms of heat transfer, this distribution in the upper kilometer of the earth is determined uniquely from a knowledge of the temperature distribution at the solid/fluid interface (both at present and in the past), the terrestrial heat flux, and the thermal properties of the medium present. Because of the nature of the phase properties of water, it is necessary to know the moisture content of the medium and the distribution of ice and water in the pore spaces over a range of temperatures. The latter is a function of dissolved solids in the interstitial water and the grain size distribution of the medium. There is some limited evidence that mass transfer processes may play a role in determining the subsurface temperatures in some offshore areas. Evidence of the role of such processes in locally modifying the onshore thermal regime in permafrost areas is cited in the works of Balobaev *et al.* (1973), Obermand and Kanunov (1973), and Van Everdingen (1974). In the offshore areas, extensive degradation of permafrost is probably occurring; permafrost is generally warming and conditions may be considered analogous to onshore areas of discontinuous permafrost. Shearer *et al.* (1971) have described pingolike features in the Beaufort Sea north of Canada as indicative of hydrological processes acting at present or in the past. Judge *et al.* (1975) have described a saline water/sand stream encountered beneath the top of a frozen layer in Kugmallit Bay.

The role of the diffusion of salt is hard to assess at present since there are few field observations bearing upon it (Molochuskin, 1973). Extensive observations of the basic thermal information both onshore and offshore are the key to resolving these problems. At present, onshore subsurface temperature information is limited to Barrow (Lachenbruch and Brewer, 1959), Prudhoe Bay (Gold and Lachenbruch, 1973), and the Mackenzie Delta (Taylor and Judge, 1974). Offshore subsurface temperature information in the Beaufort Sea has been given by Lewellen (1973, 1975a) and by Judge *et al.* (1975).

A thorough understanding of the observed temperature regimes requires a thorough knowledge of the Quaternary history and the oceanographic factors in an area. As an example of the latter, much of the offshore area has gone through four stages (not listed sequentially): (1) emergence with development of surface temperature similar to onshore conditions; (2) submergence in sufficiently shallow water to be covered by ice frozen to the bottom in winter; (3) submergence in the coastal zone with water cover summer and winter but mean annual bottom-water temperatures positive; and (4) submergence offshore with negative mean annual bottom-water temperatures. Once stage 4 is reached, permafrost may be aggrading near the surface, but the base will continue to degrade in response to the overall relative increase in surface temperature between stages 1 and 4.

CHEMICAL REGIME: The presence and movement of soluble substances are likely to play critical roles in the properties and formation of offshore permafrost. After an ocean transgression onto the onshore permafrost, the rate of degradation of the ice-bonded substrate from the top may be controlled by the ionic flux through the thawed layer. In water-unsaturated sediment, the ions from the seawater may be transported in a moving solution; the permeability would then be the controlling factor. In fine-grained material, diffusion might be the primary mechanism for ion movement. These processes are analogous to advection and conduction of heat. Independently of the mechanism of ionic transport, the chemistry of the interestitial fluid also will have a decisive influence on the material properties, phase composition and effective porosity of the sediments, especially in the areas of slightly negative subsea permafrost temperatures that very likely prevail in widespread areas (Anderson and Morganstern, 1973; Baum and Anderson, 1974).

A difference in the ionic concentration of electrolytes (freshwater and salty water) is responsible for natural electric fields of diffusion origin at the bondaries where they mix (Bogoslovsky and Ogilvy, 1974). Negative ions of greater mobility diffuse from seawater into freshwater, which results in a charge layer at the interface. The change in the intensity of the natural electrical fields may also depend on the different absorption activity of the bottom sediments. An understanding of these natural electrical fields is clearly of importance in ionic transport processes. The chemistry of the interstitial water, the grain size, and the ice content must be determined, along with the mechanisms and rates of salt transport. Some of these measurements may be done in the laboratory, but field measurements are badly needed, especially *in situ* borehole measurements and ionic transport measurements. Sea-floor reconnaissance techniques addressing these measurements require development.

HYDROLOGIC REGIME: Movement of freshwater in areas of perennially frozen ground long has been recognized as a factor in the formation of large ice masses and has a major influence on permafrost properties and distribution. The significance of this can largely be related to the grain size of the material. Coarse-grained material provides greater potential for heat and mass flux into the system, while water movement in fine-grained material is more restricted. Offshore, the movement of seawater through thawed regions of high permeability can also obviously affect permafrost distribution, but in the opposite manner, i.e., in causing relict ice masses to melt because of the influx of large quantities of brine transported interstitially through porous and thawed sediments.

COUPLING AND MODELING: The thermal, chemical, and hydrologic processes are all coupled. Hydrologic processes are coupled to the others because fluid motion transports heat and solutes. Thermal and chemical processes are coupled by phase equilibrium requirements at ice/liquid boundaries, for example, and by thermal and ionic diffusion and electric fields at ionic concentration gradients. Heat conduction models have been extremely useful on land and can serve as a point of departure for more complicated situations. Analytical solutions of the heat conduction equation have been applied to problems of explaining and predicting observed temperature distributions in permafrost areas by Gold and Lachenbruch (1973), Mackay (1972), and Sharbatyn (1973) and are adequate for many purposes. However, numerical methods offer greater versatility in approaching complex problems involving phase changes and coupled systems. Although numerical models have been used extensively in recent years to study permafrost, and Goodrich (1973) has summarized much of this literature, they have not been applied extensively to problems of offshore permafrost. Judge (1974a) and Judge *et al.* (1975) have applied a one-dimensional finite-difference model both to estimate current permafrost thickness in the Beaufort Sea and to explain observed subsurface temperature profiles in the Kugmallit Bay area.

Future analytical studies of offshore permafrost degradation should make use of modern numerical methods wherever possible. Provision for all the possible coupled effects should be included, although for specific local sediment conditions, as determined from field measurements, some of the coupling terms may be negligible. As a step in this direction, a combined thermal and chemical model has been devised (Rogers *et al.*, 1975), which illustrates how the rate of thawing from the top of frozen subsea material may be primarily under chemical rather than thermal control. This may be applicable to fine-grained soils, in which molecular diffusion is important. In contrast, control could be predominantly hydrologic in coarser material, in which ions and heat may be carried primarily by liquid convective processes.

Permafrost models that include as many as possible of the coupling effects should be devised, in order to weave the several types of field measurements into a clear understanding of the evolution of offshore permafrost. With such models, the effect of human disturbance of the seabed can be predicted.

MATERIAL PROPERTIES

The crucial input parameters for any predictive model of permafrost degradation are the physical and thermal properties of the material, which must be obtained by a program of field sampling and measurements. An additional requirement for such data is presented by those engineers who must design offshore facilities and by those concerned with environmental regulation who must determine the safety of such designs.

To characterize earth materials and to understand their behavior for engineering purposes, the types of tests or measurements required can be grouped into two general classes: (1) measurements of index properties to characterize the materials; and (2) measurements of behavioral properties needed for engineering design. A better understanding of the correlation between index properties and behavioral properties is required.

High priority should be given to obtaining and understanding the index properties. They are important because they provide a means of quantitatively describing a material as well as providing some preliminary insight into the behavioral characteristics of the material. Common index properties are grain size analysis; particle shape and surface area; densities (total and constituents); and volume (total and constituents), including ice, specific gravity, water and ice content, unfrozen water content, organic content, Atterberg limits, origin and mineralogy, pore water chemistry, and distribution and geometry of ground ice.

Little information of this kind is available in the public domain, although some information of a reconnaissance nature has been acquired by industry. The published data from these areas are restricted to observations reported by Mackay (1972), Judge *et al.* (1975), and Lewellen (1973).

To aid in the initial understanding of the material properties, each sample should be described in a standard way, such as the Unified Soil Classification System (including the frozen soil classification portion of this system). This provides an additional guide to the nature and behavior of material in the frozen state and to the changes that may occur upon thawing.

The second group, behavioral properties, involves the response of material to some physical stress. The importance of some of the tests that define these properties is clearly linked to particular engineering design procedures. (Some of these tests are time-consuming and expensive and need not necessarily be applicable to all samples.) The behavioral-properties tests include:

(a) Consolidation tests (including thaw consolidation);

(b) Strength tests (undisturbed and remolded samples):

(1) Unconfined compression,

(2) Triaxial,

(3) Shear;

(c) Thermal properties (conductivity and apparent heat capacity);

(d) Soil-water regime:

(1) Permeability,

(2) Water movement (pore pressure);

(e) Electrical properties;

(f) Frost susceptibility.

Most of these tests are described in available testing-standards literature. Some procedures will require modification for the special conditions existing in the Arctic offshore environment. Variation of these properties as a function of temperature should be measured. An important part of any testing program involving perennial frozen material or saturated marine sediment is proper sampling and handling practices. Samples must be obtained, transported, and stored under conditions resembling the *in situ* condition, insofar as possible. Sample analysis should be carefully planned to make optimum use of the available sample, staging determinations so that several tests can be done on a particular sample.

Even with extreme care in handling, the samples obtained by drilling and coring inevitably will suffer, on their outer boundary, a disturbance in temperature, pressure, and hydraulic conditions. It would be desirable to obtain index and behavioral properties of the permafrost material surrounding the borehole, *in situ*, by inserting special apparatus or logging equipment into the borehole. Although the disturbed boundary problem still exists for such a measurement, there is the possibility of sampling a far larger annular region of undisturbed material *in situ*. The applicability of standard well-logging instruments should be determined, and the development of selected specialized *in situ* measurement techniques will be needed.

RESEARCH TECHNIQUES

Core barrels and samplers are available that can take relatively undisturbed samples from the sediments beneath the sea. However, for some types of permafrost, equipment and techniques may require minor modifications. In order to obtain the maximum information about the permafrost, the sampling tools, circulating media, and handling environments should be near the same temperature as the sample substrate itself. Chemical contamination should be minimized or avoided in all cases. Any drilling fluids being circulated should be sampled periodically for chemical control. The permafrost samples should be handled and transported to minimize thermal disturbance, jarring, vibration, moisture loss and other disturbances.

Commercially used well-logging techniques have potential usefulness for determining permafrost parameters such as total depth, ice content, total porosity, lithology, and unfrozen water content. Logging instruments for making electrical, acoustical, and nuclear measurements have been well developed, but interpretation of their results in relation to the offshore, near-surface environment will be necessary. Research is needed to define the response of electrical, acoustical, and nuclear measurements to permafrost parameters likely to be encountered offshore in the Arctic.

Mechanical properties of permafrost sediments are needed for feasibility studies of structures designed for use in Arctic waters. Subsidence and freeze-back analyses require information on strength and permeability as functions of temperature, lithology, moisture content, and salinity. The tendency of frozen soil to creep under sustained loading needs further study; little is known about creep behavior in soils with relatively high salinity. Information on the distribution of ice content in offshore permafrost is required to assess the magnitude of structural problems to be expected; perhaps ice-rich permafrost does not exist in significantly large areas offshore. Standard engineering tests to evaluate soil or rock properties may not be directly applicable and may have to be modified to reflect the Arctic offshore environment. A research program should be developed to evaluate the applicability of existing standard tests to the materials found offshore. New testing methods or modification of existing methods may result from such investigations.

Measurement of the stress-strain relationship of ice-bonded permafrost *in situ*, both compressive and shear, would be of considerable value in foundation design and evaluation. Development of special downhole apparatus for this task is necessary and should commence as soon as the range of values to be measured is determined.

Special attention should also be given to the flow of fluids through the earth materials. The temperature and salinity of the fluid may alter any predictions that are based on normal, freshwater conditions. Measurement of the hydraulic parameters *in situ* should also be undertaken. Development of instruments for this purpose will also be necessary.

Some research methods for field measurement of temperature, temperature gradient, and thermal properties of earth materials are already available. Portable equipment capable of precise measurement of temperature has been developed for heat-flow research. Descriptions of such equipment can be found in Beck (1965), Sass *et al.* (1971), and Judge (1974b). The problems of obtaining subsurface temperatures in offshore drillholes are quite challenging. The ideal way to acquire precise detailed temperature profiles would be to preserve an open hole, with occasional monitoring during the period of dissipation of the drilling disturbance.

An alternative is a permanent multisensor cable, installed at the completion of drilling, with the cable head relocated periodically to record or retrieve the temperatures. Whatever techniques are used to install or relocate the cables, they must initially be left in a manner that fulfills environmental safety requirements. Many wells are being drilled from artificial islands in the shallow nearshore water of the Beaufort Sea. However, some of the islands are designed as temporary structures, thus precluding preservation of the wells for long-term temperature observations. Useful temperature information regarding the extent of the frozen section can still be obtained by running careful temperature logs of the upper 600 m of the hole immediately prior to final abandonment of the well (Jessop and Judge, 1974). Sufficient time must have elapsed since circulation of the drilling fluid to allow the fluid to reach bore wall temperatures. Another method is to make temperature measurements in the drillhole during halts in the drilling. Most of the drillhole is thermally disturbed, if a conventional rotary rig is used, but at the bottom this disturbance should be minimal. In non-ice-bonded sediments, an undisturbed temperature can be measured by pushing a temperature sensor several decimeters ahead of the drill bit. In ice-bonded sediments, this is difficult and the temperature is likely to be measured at the bottom of the hole. Many authors have shown that values of the undisturbed temperature can be obtained by extrapolation of bottom-hole temperature data taken for short time intervals. The use of low-temperature circulating fluids is crucial to the use of such methods. In non-ice-bonded materials, caving of the bore walls may occur during halts in drilling, preventing entry of temperature sensors into the drillhole. Therefore either hollow-stem drills or extensive casing of the hole is necessary in order to obtain temperature measurements.

If reasonable models are to be developed to explain the observed thermal regime and to enable prediction of permafrost distribution and evolution at offshore locations, it is essential that the thermal properties of earth materials be measured, either on recovered cores or by *in situ* methods. The high cost of rig time may preclude extensive *in situ* measurements of, for example, thermal conductivity. However, methods for this measurement are highly developed and adequately described in the literature. Judge (1974b) has described laboratory methods of use in permafrost terrain. Beck *et al.* (1973) and Wright and Garland (1968) have discussed the use of *in situ* methods, although not with reference to permafrost.

Generally speaking, the instruments and analytical techniques for thermal measurements exist and await the opportunity to be used. For example, near-surface use of 6-m-long thermal gradiometer probes in unfrozen sea-bottom sediments offers some potential as a detector of whether permafrost exists at deeper depths. Further investigation of this technique should be undertaken.

The variation of seismic velocity in frozen material depends on ice content, grain size, and temperature. Velocity studies based on seismic refraction records, in conjunction with ground-truth evaluation, are potentially useful in measuring these parameters. The measurement of shear and compressional seismic waves in frozen ground may yield dynamic elastic constants. Field techniques to measure shear wave modes in subsea materials should be evolved. The measurement of low-frequency dispersive wave trains (the Rayleigh and Love modes) may lead to the definition of both the upper and lower boundaries of frozen ground. Techniques should be evolved to make such measurements in the marine environment. High-resolution seismic techniques are currently being developed to obtain quantitative measurements of velocity and density contrasts at depths up to 100 m below sea bottom. Such techniques are potentially useful in mapping frozen ground.

The electromagnetic methods that appear most useful for onshore and offshore permafrost detection are those that do not require a low contact resistance to the ground, and both magnetotelluric and inductive coupling methods can satisfy this criterion. Because of the difficulty of driving current into permafrost, resistivity methods are often difficult to use in the Arctic. Fortunately, the theory and interpretative techniques of magnetotelluric and inductive coupling methods are well developed. Equipment for magnetotelluric measurements above 15 kHz is available for routine surveys on the ground and from airborne platforms. Prototype equipment for magnetotelluric measurements below 15 kHz exist, but there is a need to design rugged, portable field equipment in this frequency range. The state of the art in inductive-loop design is not so well advanced, even though many prototypes have been built; further development of equipment and techniques is needed.

Laboratory techniques should be developed that can help to achieve an understanding of the process of salt infiltration into the sea bed, since this process may control the rate of degradation of permafrost from the top. Diffusion of ions in frozen and unfrozen material and rate of infiltration of saline solutions are examples of processes that need to be studied in the laboratory, preferably using representative sea-bed samples obtained from drilling and coring operations.

4. RECOMMENDATIONS

It is critically important that North American Arctic offshore permafrost be recognized as a major problem and that it be far better understood than it is now. Such understanding is necessary if offshore oil exploration is to proceed with confidence.

The following recommendations by this study group summarize points set forth in detail in preceding pages. The problems addressed in this report will be of wide concern, and we have not presumed to direct our recommendations to any one agency.

We recommend *a program to locate regions of offshore permafrost be implemented immediately.*

Seismic refraction and reflection techniques should be used along the entire coastline, with drilling and coring at several selected locations to provide ground truth for seismic interpretation. Existing offshore seismic records should be inventoried and interpreted for permafrost, wherever possible. Quaternary history and geology of the coastal region should be developed from the findings of this field program.

We recommend *material index properties be determined for characteristic cores and sample material obtained by drilling and bottom sampling.*

All applicable index and behavioral properties should be measured, both in the laboratory and *in situ* in the field to the extent possible. Techniques for performing such measurements should be improved. Provision should be made for the judicious storage and distribution of samples.

We recommend *models of offshore permafrost regimes be constructed, including the possible variations in the thermal, chemical, hydrological, and electrical properties.*

These models must be capable of predicting the consequences of a man-made perturbation in the permafrost environment.

We recommend *active participation by industry in offshore-permafrost research be encouraged to obtain the maximum quantity of basic data needed to increase the understanding of offshore permafrost and to minimize costs of obtaining such data.*

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