SUBSEA PERMAFROST:
PROBING, THERMAL REGIME, AND DATA ANALYSES, 1975-81

by

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1. SUMMARY, CONCLUSIONS, AND IMPLICATIONS FOR OCS DEVELOPMENT

The purpose of this research was to develop a greater understanding of subsea permafrost in order to evaluate problems it poses for offshore oil and gas lease development and production. Our strategy was to obtain reconnaissance-level information on subsea permafrost over a wide geographic area. Analysis and interpretation of these data and their use in relatively simple models have allowed us to make some general statements on the occurrence and distribution of subsea permafrost in Alaska's continental shelf.

Specific problems for petroleum development include differential thaw subsidence; difficulties with seismic data interpretation; geotechnical problems with structures, pipelines and other facilities in warm subsea permafrost; corrosion associated with concentrated brines in seabed sediments; and the dangers associated with decomposing gas hydrates.

Specialized methods and equipment were developed to investigate the properties of subsea permafrost and heat and salt transport processes that occur within it. These include methods and equipment for lightweight drilling, temperature measurements, in situ sampling of soil pore water, pore water pressure measurements, detection of the presence of ice in the sediments, and measurements of the thermal and hydraulic conductivities of the sediments. A general discussion of the results from our study areas follows.

Norton Sound.—Subsea permafrost does not occur at Nome or on the south side of Norton Sound, except possibly in nearshore areas where rapid coastal retreat occurs. A more detailed analysis taking into account cold, summer seabed temperatures and, possibly, greater-than-normal heat flow, will be required to assess the potential occurrence of subsea permafrost in the main portion of Norton Sound.

Northern Bering Sea and Bering Strait.—This area was not studied in the course of our investigations. Limited oceanographic measurements exist, but the data have not yet been used to estimate the potential for the presence of subsea permafrost in these areas.

Kotzebue Sound.—It appears likely that subsea permafrost occurs under Kotzebue Sound, particularly in shallow nearshore regions. The discharge of the Noatak and Kobuk rivers into the northern port of Kotzebue Sound may affect the subsea permafrost through warmer seabed temperatures and reduced under-ice water salinities. Fresher water found under the ice during winter at Kotzebue could be a source for producing potable water for OCS related development activities.

Chukchi Sea.—In the southeastern Chukchi Sea, subsea permafrost exists in the shallow, nearshore areas. Oceanographic data and thermal models suggest that subsea permafrost may be absent beneath deeper water although it may well occur in areas out to depths of 15-30 m. At Barrow, the seabed temperatures are slightly negative and it appears that ice-bearing subsea permafrost occurs there only very close to shore. Bedrock occurs close to the seabed between Peard Bay and Cape Thompson. This rock cannot be assumed to be a good foundation material since it may contain segregated ice. Trenching of the rock for subsea pipelines would be difficult. Gravel sources for OCS development appear to be relatively sparse and available in localized areas only.

Elson Lagoon, Lonely, and Ham-son Bay.—The sediments in these areas are generally fine-grained. A thawed layer under the seabed of generally increasing thickness can usually be traced out from shore. However, the thawed layer is still relatively thin (10-15 m or less) out to water depths of about 15 m and distance from shore of about 20 km or more. The proximity of ice-bearing sediments to the seabed and the high potential for encountering segregated ice in them suggests that subsea permafrost problems for offshore development are likely to occur. Thaw subsidence problems for bottom-founded structures and pipelines in the seabed could be potentially serious in these areas.

Long Island.—The seabed sediments consist of a layer of fine-grained material, probably clay, which thins seaward and is underlain by thawed gravels. The clay at the seabed may be somewhat difficult to trench.

West Dock-Reindeer Island.—Most of our research was concentrated along this line. There is a thawed layer about 3–4 m thick out to about 400 m offshore. Part or all of this layer freezes seasonally and contains highly concentrated brines. The ice-bonded permafrost table deepens rapidly in a transition zone from about 400-440 m offshore. From about 440 m to about 3.4 km or more offshore, the ice-bonded permafrost table deepens gradually as the square root of distance (or submersion time) offshore. From there to Reindeer Island, seismic data suggest that the ice-bonded permafrost table is deeper than given by this functional relationship, possibly because of the presence of a paleo-river channel.

The sediments within a few kilometers offshore are sands and gravels containing some fines and are capped by a layer of fine-grained material up to about 5 m in thickness. Beyond Reindeer Island, the sediments are fine-grained with overconsolidated clays found at the seabed 15-20 km from the mainland. In this area, ice-bonded permafrost occurs typically from 5 to 15 m below the seabed.

The presence of ice-bearing, and usually ice-bonded, subsea permafrost close to the seabed near shore suggests that special methods will be required to bring offshore pipelines on shore. These pipelines will have to transect the area where the permafrost may be thawing at the rate of 0.3 m/yr and the potential for encountering segregated ice is high.

Beyond Reindeer Island the potential for encountering segregated ice in the sediments is also high. The very stiff clays near the seabed will also be difficult to trench and may hinder access to underlying gravel sources.

Point Brower–Jeanette Island.—The sediments immediately offshore of the Sagavanirktok River are fine-grained, with ice-bonded permafrost found from 5 to 25 m below the seabed. We found what appeared to be segregated ice about 16 m below the seabed about 1.6 km off Point Brewer. A layer of massive ice, 0.6 m in thickness, was also found in this area by the U.S. Geological Survey (USGS) at a depth of 10 m below the seabed at a point about 5.5 km offshore. These observations show that offshore development in areas of fine-grained soils, where the ice-bearing permafrost is close to the seabed, must consider the potential problems associated with ice-rich permafrost, its thawing, and subsequent thaw settlement.

Flaxman Island.—The sediments near the seabed are fine-grained and sometimes hard. South of Flaxman Island the seabed sediments are underlain by gravel. Ice-bonded permafrost was found near the seabed north of the island. Sediment temperatures are relatively cold and suggest that the island may have retreated from these sites recently.

Barrier Islands.—Holes were drilled on Thetis, Cottle, Stump, Reindeer, Cross, and Flaxman islands. Ice-bonded permafrost was found under the islands but the state of ice-bondedness varies in a complex fashion laterally and with depth. Layers of unbended material suggest that gravel islands may have planes of weakness. Gas of biogenic origin was found in one shallow hole on Flaxman Island and could be a drilling hazard.

Substantial progress has been made in our understanding of subsea permafrost during the past decade. However, each new field effort uncovers new and unsuspected facts, suggesting that the database is inadequate. Progress toward an understanding of the heat and salt transport processes responsible for the response of subsea permafrost to natural or man-made disturbances has been inadequate. The present program of offshore development and the results presented here and elsewhere show that subsea permafrost must be considered if offshore petroleum fields are to be brought into production. Sound engineering practice and environmental considerations will require an expanded database and an understanding of the factors controlling the evolution of subsea permafrost.

II. INTRODUCTION

This is the summary report of a program to study the distribution and properties of subsea permafrost in Alaskan waters. Our specific objectives were:

1) To obtain reconnaissance-level information on subsea permafrost conditions over a wide geographic area.
2) To investigate conditions at the seabed relevant to the evolution of the underlying permafrost regime.
3) To study the heat and salt transport processes in subsea permafrost with the eventual goal of predicting its response to natural or man-made conditions.

Field measurements included soil type, temperature, electrical conductivity of the soil pore water, thermal and hydraulic conductivity, in situ ice detection, and pore water pressure.

When this program began in 1975, very little was known about subsea permafrost in Alaska's offshore areas except near Barrow, where navy support had been available (Brewer 1958; Lewellen 1975; Rogers et al. 1975), and for limited proprietary industrial data. This study, related OCSEAP studies beginning the following year, and a USGS (Conservation Division) study in 1979 (USGS 1979; Miller and Bruggers 1980) provided the first offshore data from many regions, including Prudhoe Bay. In the last few years, subsea permafrost data have been obtained by the petroleum industry as part of geotechnical investigations for offshore pipelines and structures. Most of this information is proprietary, and the data obtained by the OCSEAP and USGS studies still compose the bulk of public domain information.

In keeping with the objective of obtaining wide geographic coverage, most of the data from our program were obtained with lightweight equipment, and, except in 1975, few soil samples were obtained. A great deal of information was nevertheless obtained from relatively shallow holes, typically 10-30 m but up to 50 m deep, using the sea ice as a working platform. Our data and detailed descriptions of our methods and results are described in our eight annual OCSEAP reports and in our other published papers and reports listed in Appendix A, covering field observations from 1975 to 1981. They are available from World Data Center A; Glaciology, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309. OCSEAP reports up to 1980 are available from the National Technical Information Service (NTIS), Springfield, VA. Corrections to these reports are contained in Appendix B. This summary is merely an overview; the OCSEAP reports must be referred to for most of the details and data. The overview is restricted to our results; some reference is made to related OCSEAP studies and the USGS program, but a full synthesis was not attempted. A synthesis of conditions in the Alaskan Beaufort Sea has been given by Sellmann and Hopkins (1984). The most relevant of the OCSEAP studies were a CRREL-USGS drilling and probing program in 1976 and 1977 (Hopkins and Hartz 1978a,b; Blouin et al. 1979; Chamberlain 1979; Sellmann and Chamberlain 1979); a seismic program carried out from a small boat (Rogers and Morack 1982; Morack and Rogers 1984); interpretation of industry seismic data (Sellmann and Neave 1982; Neave and Sellmann 1984); mapping of onshore conditions (Hopkins and Hartz 1978a,b; Smith et al. 1980; Smith and Hopkins 1982); and a study of shoreline erosion rates (Lewellen 1977). Additional information on OCSEAP research in the Beaufort Sea is given in Barnes et al. (1984).

This report contains, in addition to the permafrost information, a summary of an ad hoc study of sediments in sea ice (Appendix C).

III. RELEVANCE TO PROBLEMS OF PETROLEUM DEVELOPMENT

A list of some of the information gaps on subsea permafrost and problems posed to offshore development was compiled, with industry input, by the National Academy of Sciences (NAS) (1976). Another version was produced by OCSEAP at the Beaufort Sea Synthesis Meeting in 1977 (Weller et al. 1978). Although there have been some changes with increasing experience, these reports are still relevant. The NAS list is reproduced here with minor changes:

1. Lack of information on the horizontal and vertical distribution and properties of subsea permafrost.
2. Differential thaw subsidence and reduced bearing strength due to thawing of ice-rich permafrost.

a. Thaw subsidence around well bores causing high down-drag loads on the well casing. This problem is aggravated offshore by the need for drilling several holes from a single island and by the warm permafrost temperatures and salty pore water.

b. Differential settlement associated with hot pipelines, silos in the seabed, and pile and gravity structures.

c. Differential strain across the phase boundary between bonded and unbended permafrost.

3. Frost heaving in very shallow water.

a. Well bore casing collapse due to freeze-back.

b. Pipelines-differential movement.

c. Gravity structures including gravel islands-local heaving causing foundation instability.

d. Pile structures-differential stress in pile-founded structures.

4. Seismic data in areas of subsea permafrost, particularly when the latter has a variable thickness and variable properties, can be misinterpreted and can lead to improper design of offshore production and distribution facilities. Special care needs to be taken in the interpretation of seismic exploration data.

5. Excavation-dredging, tunneling, trenching.

a. Increased strength of material associated with bonded sediment.

b. Over-consolidated sediment can influence excavation rates and approach.

c. Thaw can be induced in deeper sediment by removal of material at the seabed.

d. Highly concentrated and mobile brines can be found in the sediment.

e. Insufficient data on engineering properties for design of excavation equipment and facilities.

6. Gas hydrates.

a. Blowouts can result from gas hydrate decomposition during drilling operations.

b. Fire danger.

c. Misinterpretation of seismic data and other geophysical data.

7. Corrosion: Fluids (brines) with concentrations several times higher than is normal in seawater are common, particularly in water less than 2 m in depth.

The original version of this list concludes with a number of precautions and possible consequences if they are not heeded. It notes that detailed site specific information will be required for any development, especially in view of the highly variable nature of subsea permafrost, and that down-hole information at the exploratory drilling stage should be used as much as possible. To date, the latter recommendation has not been followed. From the beginning, a basic concern has been that methods developed for petroleum production and transportation onshore at Prudhoe Bay may not be adequate, because subsea permafrost is warmer, saltier, and more easily disturbed, and because the lithology may be different.

To the original list of special problems associated with subsea permafrost, several more may be added on the basis of our more recent experience. These include the presence of gases in shallow sediments, premature pile failure in salty sediments (Nixon and Lem 1984), and, perhaps most important, the design of insulated pipelines, the optimum design of which requires more information about salt transport mechanisms than is presently available,

IV. METHODS

The measurements made during our studies included soil type, temperature, electrical conductivity of the soil pore water, hydraulic and thermal conductivities, in situ ice detection, and pore water pressure. Although a standard rotary wash boring rig was used in 1975, in other years most of the equipment and many of the techniques were unconventional and had to be developed as part of the program. Most of the details are given in our OCSEAP reports, and by Osterkamp and Harrison (1981b) and Harrison and Osterkamp (1981a,b).

Our strategy was to use the sea ice as a drilling platform, sometimes using snow walls or tents as windbreaks. Transportation to the sites was by fixed wing aircraft, helicopter, snow machine, or hand-drawn sled. Usually the sites were located by distance and orientation with respect to some fixed and prominent onshore feature. Distance was measured by pacing, string measure, tape measure, or by electronic distance measuring equipment. Usually, orientation was obtained by Brunton compass, but in some cases, a l-second theodolite was used. Some holes, usually those farther offshore, *were* located using the Global Navigation System of the NOAA helicopters.

Data on snow depth, ice conditions, ice thickness, freeboard, water depth, and bottom conditions were usually taken but have not been consistently reported in our OCS reports. These supplemental data are available from the authors.

The reconnaissance measurements emphasized by this program required methods for gaining access to subsea sediments with lightweight equipment. Two techniques were used: driving and rotary-jetting. These approaches do not permit the acquisition of the detailed soils data that can be obtained with a drill rig, but they are actually better suited than drilling for certain in situ measurements (such as temperature, pore water pressure, and thermal and hydraulic properties), and for sampling of the pore water in coarse sediments. Shallow soil samples can be obtained, and, with experience, lithologic information can be inferred. The equipment evolved over several years of field experience.

In the driving technique, a portable motorized cathead and tripod and 74-kg drop hammer are used to drive drill rods with attached probes into the seabed. The depth capability depends upon soil type and is optimum for the relatively coarse sediments typical of Prudhoe Bay, where the maximum depth reached was 26 m (determined by our available supply of drill rod). Good results were also obtained with a portable gasoline-powered driver similar to those used for breaking concrete.

In the rotary-jetting method, a 3/4-inch steel water pipe drill string with a bit and a one-way valve at the bottom of the string is rotated and jetted into the seabed using a small gasoline-powered pump and drill. The depth capability depends on soil type and is optimum for fine-grained soil conditions, where depths in excess of 50 m have been reached. When the sidewalls of a hole are stable, the pipe string can be "washed' down without rotation. The types of data that can be obtained with the driving and rotary-jetting techniques are briefly described in the following paragraphs.

Soil Conditions

Information about subsea soil conditions can be obtained from both the rotary-jetting and driving techniques, even when soil samples are not taken. The experience of the driller, as in any type of drilling, is extremely important, and drilling in known material was a factor in building up our experience. In rotary-jetting, the "feel" and sound of the drill are different in clay, silt, sand, and gravel. Compact clays feel like hard rubber when the string is dropped onto the bottom of the hole; bonded materials feel more like concrete and usually drill very slowly. Unbended silt and silty sands usually drill rapidly, as long as the hole walls do not cave, which may happen if too much sand is present. The grains of sand and gravel can be detected when raising and lowering the string off the bottom, and by the roughness of the drilling. Gravels are extremely hard to drill by rotary-jetting, due to loss of circulation, caving, and the difficulties of flushing larger soil particles from the hole. Direct identification of soil type is possible when soil cuttings are washed to the surface, as occurs on land or where the sea ice is frozen to the seabed. Wood, shells, and other items may be recovered in this way, although one must realize that they may not always come from the bottom of the hole but may be washed out of the walls.

The driving techniques work best in the soils that are the most difficult to jet, sands and gravels, which can often be identified by the rapid progress of driving. On some occasions clay can be identified when it comes up stuck on the drill rod. By and large, soil identification is less positive than with the rotary-jetting technique. Both techniques can detect the presence of firmly ice bonded sediments, which can be penetrated by the jetting technique but not to any significant depth by the driving technique.

Temperature

Both techniques are well suited to provide access holes for temperature measurements. In the rotary-jetting technique the pipe is left in the hole. To prevent freezing, the pipe is normally installed with a check valve at the bottom, and upon hole completion a non-freezing fluid is pumped through it. In the driving technique, temperature can be measured inside the drill rod, but this is inconvenient, since the rod has to be left in place until the temperature measurements are completed. In 1978, a new technique was developed, wherein a continuous length of 12.7 mm O.D. tubing is run inside the drill rod, and attached to a suitable driving point at the bottom. When the hole is completed the drill rod is removed and the point and tubing remain behind, providing access for temperature measurements. This frees the drill rod, and the equipment needed to remove it, for immediate use elsewhere while temperatures are equilibrating. The undisturbed or "equilibrium" temperatures can usually be accurately estimated after a few days, depending upon the time spent in drilling and other factors, particularly any loss of drilling fluid. Temperature is logged inside the pipe or tubing with a single thermistor on a cable. Information about the approach to temperature equilibrium, accuracy, and thermistor calibration are given by Osterkamp and Harrison (1976a, 1982b). Other aspects of temperature measurements are discussed in a general way by Osterkamp (1985).

Soil Pore Water Electrical Conductivity

The electrical conductivity of the soil pore water is important in determining the presence or absence of ice, and in giving clues to the past history of the soil. Therefore, considerable effort was devoted to developing techniques for determining the pore water conductivity by using the driving equipment. NSF support was used for this phase of the work. The water is admitted into plastic tubing run inside the drill rod through a porous metal filter at the bottom, and sampled inside the tubing with a special bailer. The tubing can be cleared and a valve closed at its lower end before the rod is driven to the new sampling depth. It is not necessary to pull out the drill pipe between taking samples.

The method has an interesting limitation if the freezing temperature of the pore water is higher than the in situ temperature. Liquid will still be collected, but it will not be representative of the soil bulk H_2O conductivity, because the solid phase fraction of the H_2O in the soil is not collected. Therefore, when the measured freezing temperature of the collected liquid is equal to the in situ temperature, one can only conclude that the soil bulk H_2O fleeting temperature is higher than or equal to the in situ temperature, and that ice may be present in the soil under these conditions.

Hydraulic Conductivity

The saturated hydraulic conductivity (essentially the permeability) of the soil is calculated from the rate at which water from the soil enters the filter, which is determined with a water level sensor. The exact calculation is extremely difficult for some of the geometrically complicated shielded filters that we used, but we were able to derive a simple and reasonably accurate approximate method (Harrison and Osterkamp 1982). However, it was noticed that the incoming water rarely obeyed Darcy's law.

Thermal Properties and the Detection of Ice

Past experience in the interpretation of temperature profiles in fine-grained subsea permafrost and in warm, saturated, fine-grained subaerial permafrost showed that it can be difficult or impossible to detect the position or presence of ice-bearing permafrost soils from temperature profiles alone. The difficulties appear to be associated with the presence of unfrozen pore fluids which lead to a variable ice content or ice bonding at temperatures near, but less than, the equilibrium freezing point of the pore fluids. Our drilling methods in subsea permafrost had the same **difficulties** since they depend on a certain degree of ice bonding to detect the presence of the ice. In addition, since we did not take soil samples at depth, it was desirable to have a technique to determine soil thermal properties in situ. These considerations led us to design a **borehole** heating experiment for the purpose of detecting ice-bearing permafrost and to determine the thermal conductivity, **K,** of subsea **permafrost** soils in situ.

In practice, the borehole heating experiment is similar to the probe method for measuring the thermal conductivity of materials (**Bullard** 1954; **Lachenbruch** 1957; Carslaw and Jaeger 1959). The "probe" in our borehole heating experiment was either l/2° **O.D.** plastic tubing (3/32" wall) or 3/4" schedule 40 black iron water pipe installed in our **boreholes** for temperature logging purposes. The tubing was **filled** with antifreeze and the pipe with a mixture of antifreeze and seawater. A **5-kW** generator was used to heat a length of 2-conductor cable which was placed inside the tubing or pipe in the borehole. Current and voltage were monitored periodically during the time of heating, which varied **from** 15 to 120 minutes. The boreholes were logged just prior to the time of heating and at selected times after heating, usually over a time period of a few days or less. Prior to heating, the boreholes were generally within a few hundredths C of equilibrium. The heat dissipated in the **bore-**holes was relatively small. Where ice-rich permafrost was present, it was probably sufficient to melt the ice in the sidewall of the borehole to a depth of about 0.01 m.

It is usually possible to determine the depth distribution of ice-bearing permafrost in the borehole by comparing temperature profiles measured before and just after heating. **With** ice present in the soil, the latent heat required to melt it tends to **buffer** the temperature against changes. Comparison to an adjacent depth not containing ice often shows a strong temperature difference across the ice-bearing boundary.

The in situ determination of the thermal conductivity of unbended (non–ice-bearing) subsea permafrost follows the same procedure as used in standard probe measurements. For a continuous linear heat source of constant strength in an infinite homogeneous medium the temperature disturbance at a time t is (**Lachenbruch** 1957)

$$AT= (P/4\pi K) \text{ in } (tit-s)$$

wheres is the period of heating and P is the power dissipated per unit length, which can be calculated from the current and voltage measurements and the length of the heating wire. This equation neglects the finite size of the borehole (pipe, water, tubing, fluid, and surrounding disturbed volume of soil), and effects associated with the proximity of the depth of measurement to the seabed or hole bottom, or with layers of varying thermal properties. It is possible to evaluate the associated errors **and/or** to **modify** the equation to take them into account (**Lachenbruch** 1957; **Carslaw** and Jaeger 1959). The usual approach is **to** graph AT vs. In tit-s and to select the straight line portion of the curve, which has a slope of $P/4\pi K$ and thus determines K. In our measurements, an error analysis showed that the total ***error in*** these determinations of K appears to be about 0.3-0.5 W $(C\ m)^{-1}$, and was dominated by the error in power determination.

The addition of heat to ice-bearing permafrost usually results in some melting, basically because the material is often warm and contains salt. The associated latent heat effect may make it difficult or impossible to determine K by this method. Ideally, the temperature rise to determine K by heating the borehole should be held to a very small value to minimize the latent heat effect.

The analysis of these borehole heating data appears to be relatively straightforward in some of the holes and very complex in others. Detection of the presence of ice-bearing permafrost seems possible provided the boreholes are logged immediately after heating. Determination of K appears to be a more complex matter, especially in ice-bearing permafrost. Unfortunately, these two type of measurements are also somewhat at odds since substantial heating seems to be desirable to detect the presence of ice-bearing permafrost, while very small heating is desirable to minimize latent heat effects when trying to determine K.

Pore Water Pressure Measurements

Pore water pressure measurements were made with a pneumatic pressure transducer (Sinco model 51481 with Model 51411A readout). Several of these piezometers were calibrated by us and were found to meet the manufacturers' specifications (typically 0.03 m [water head] sensitivity, 0.1% linearity, and 0.2 m offset) after some factory calibration data reduction errors were corrected. However, we had unsatisfactory results when trying to use the system in very cold weather. The transducer is mounted inside a piece of A-rod, and connected to the probe assembly of the pore water sampling equipment (Harrison and Osterkamp 1981) with a short piece of rubber tubing. The probe assembly contains a filter through which the transducer couples to the soil *pore* water. The tubing and probe assembly are completely filled with antifreeze, and the A-rod driven into the seabed sediments. Pressure is read sequentially at increasing depths down to the ice-bonded phase boundary. Equilibration times may vary from a few hours to a few seconds. Tide is determined concurrently by measuring the water level in a borehole through the sea ice with respect to a mark on a string of A-rod driven into the seabed to provide a stable reference.

V. REGIONAL RESULTS AND DISCUSSION

The primary purpose of our OCSEAP project was to obtain reconnaissance-level field information on subsea permafrost conditions over a wide area on the continental shelves of arctic Alaska. From this point of view, the data described below speak for themselves. However, considering the incredible variability of the subsea permafrost regime, it seems worthwhile first to gain some perspective by a brief discussion of some of the processes responsible for its formation and evolution.

Subsea permafrost is a product of changing sea levels over geologic time and of past cold climates. It forms in exposed continental shelves at times of lower sea level, under low air temperatures, by growth from the exposed surface downward. Subsequent rises in sea level and shoreline erosion at times of static sea level cover the permafrost with seawater, thus replacing the cold surface boundary condition with a relatively warm and salty one. Melting from the surface (seabed) downwards is controlled by salt and heat transfer to the ice-bearing subsea permafrost table. Melting at the base of the subsea permafrost, by geothermal heat, begins once the thermal disturbance (of submergence) has propagated to the base. The time scales for permafrost growth are such that several hundreds of meters of permafrost can be formed in the continental shelves while they are exposed. The time scales for thawing at the permafrost table and base are such that several tens of thousands of years may be required to completely thaw subsea permafrost a few hundred meters thick. Subsea permafrost is essentially a transient phenomenon, and it must have formed and thawed repeatedly over geological time. At present, sea levels are very high.

Melting at the subsea permafrost table, which occurs even in the presence of negative mean annual seabed temperatures, is determined by lithology and local oceanographic conditions. This melting is extremely sensitive to the efficiency of salt transport, which is apparently controlled by soil type. Other soil properties that play a role in the melting process include ice content, thermal properties, and possibly hydraulic conductivity. Oceanographic conditions that play a role in this melting process include seabed temperature and salinity, which are in turn influenced by sea ice cover, bathymetry, presence of nearby rivers, and currents. Sea level and shoreline history are of particular importance since they determine the time of emergence and submergence. The initial conditions, at the time of submergence, are set by the local meteorological and permafrost conditions.

This section summarizes the results of investigations of the permafrost regime in shallow drill holes (usually < 30 m depth) generally in relatively shallow, nearshore waters. Most of the drill holes were within a few kilometers of the coast, although some were up to 20 km offshore. A location map is provided for each area along with a table of information on each hole drilled.

Norton Sound

Five holes were drilled in Norton Sound during March 1980 at the locations shown in Figure 1; the drilling data are given in Table 1.

There is considerable uncertainty in our knowledge of the parameters and conditions needed to assess the presence and distribution of subsea permafrost in Norton Sound, not only over the long time scales involved, but also the spatial variations. In addition, subsea permafrost in the general area of the Bering Sea appears to be a near-borderline case so that an assessment of its potential presence is especially difficult and depends strongly on the assumptions made in that assessment.

The sediments in Norton Sound are primarily silts deposited by the Yukon River (Nelson and Hopkins 1972). Geothermal heat flow in the Norton Sound area may be anomalous. Our four drill holes on the south side of Norton Sound are near the Kaltag fault. An unvegetated lava flow was observed east of St. Michael and several lakes along the coast south of St. Michael were partially free of ice at the end of March 1980. A number of sidehill icings were observed east of Nome and there are several hot springs on the Seward Peninsula. These observations suggest that the geothermal heat flow maybe greater than normal in Norton Sound. Biswas and Aki (personal communication) consider the heat flow in the northern part of the Bering Sea, including Norton Sound, to be about 3 HFU or about

Table I.–Norton Sound drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Nome	N208°E from benchmark on Anvil Mt., 326 m from shore, along this line, 299 m offshore	3.70	0.82	driving	3/25/80	6.8
St. Michael River	About 8.7 km SW of mouth of St. Michael River	2.00	1.10	jetting	3/28/80	25
Charley Green Creek						
Hole 630 (Hole 1)	Near mouth of Charley Green Creek, about 630 m from shore	2.44	1.16	jetting	3/28/80	6
Hole 630 (Hole 2)	Same, but about 610 m from shore	1.69	1.16	jetting	3/30/80	7
Yukon Delta	63°27.2'N; 163°36.7'W, 28 km from shore	10.30	1.05	jetting	3/31/80	18

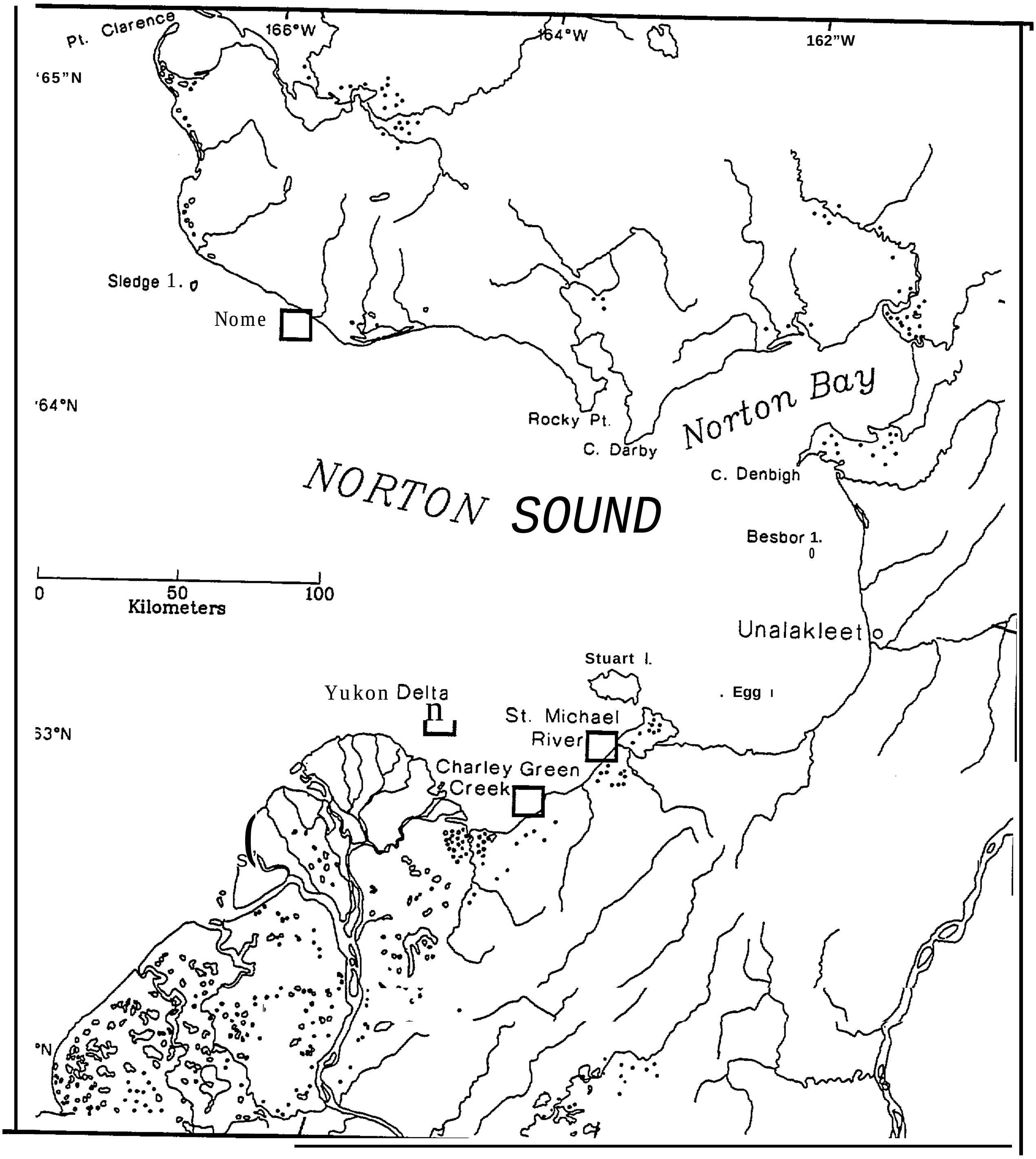


Figure I.—Norton Sound hole location map.

twice the worldwide average. Therefore, basal melting of the permafrost after submergence may be expected to be greater than normal, perhaps several centimeters per year.

Muench and Coachman (1980) found that the eastern portion of Norton Sound contained a two-layered water structure during the summers of 1976, 1977, and 1978 with the bottom layer being colder, more saline, and denser than the upper layer. Bottom

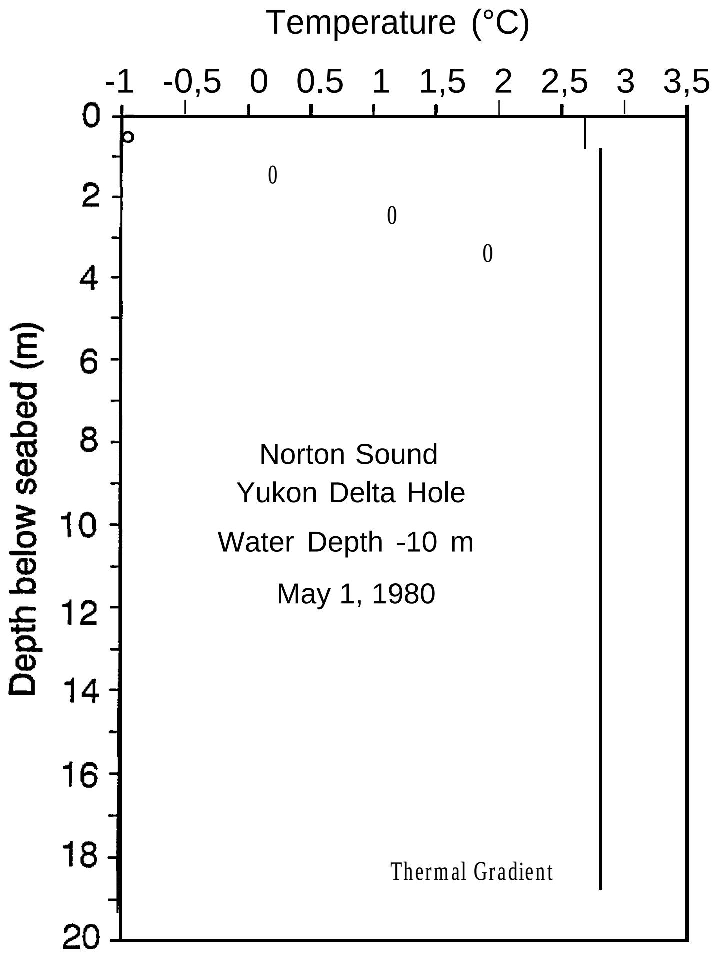


Figure 2.—Temperature profile in the Norton Sound Yukon Delta hole showing the warm seabed sediments and positive temperature gradient near the bottom of the hole.

temperatures on the north side of Norton Sound were colder than on the south side. During July 1977, near Cape Darby, bottom temperatures< O°C were observed, which warmed to 2–3°C by late August. This suggests that the mean annual seabed temperature (MAST) could be< O°C in this area. Bottom temperatures on the south side of Norton Sound were several degrees or more warmer. The persistence of this layering *over* time scales of decades to millennia is unknown.

The temperature data at Nome and on the extreme south side of Norton Sound show that the sediments there are very warm and that the temperature gradients appear to be positive. The temperature profile shown in Figure 2 illustrates the warm seabed temperatures in the sediments on the south side of Norton Sound.

We conclude, on the basis of very sparse data and a preliminary analysis, that subsea permafrost does not occur at Nome nor on the south side of Norton Sound. A more detailed analysis would be desirable. A possible exception for the occurrence of subsea permafrost would be in nearshore areas of rapid coastal retreat as suggested by Hopkins (1980). In the Cape Darby area, we believe that ice-bonded subsea permafrost is also absent except in nearshore areas of rapid coastal retreat. These statements are based on assumptions of the maximum expected permafrost thickness of about 125 m at the time of submergence about 10,000 years ago, a geothermal heat flow capable of melting 2-3 cm per year at the permafrost base, and the assumption that there will be some salt in the sediment pore water.

Northern Bering Sea

We did not take any measurements in the northern Bering Sea from Nome to the Bering Strait. Oceanographic measurements (Coachman et al. 1975) show that a relatively cold bottom water area exists to the southwest of St. Lawrence Island (about –1.5°C during midsummer). The Bering Strait has a mean annual water temperature near the seabed of about 0°C. The sediments along the coast are usually sandy and gravelly and a submerged belt exists, as much as several kilometers wide, where rocks are exposed at the seabed or lie below a few meters of the coarse-grained sediments (Nelson and Hopkins 1972; McManus et al. 1977). Surficial sediments on the northern Bering Sea floor are predominantly poorly sorted, silty, very fine sand, although gravel and coarser sand are common. The mean annual air temperature (MAAT) at Wales is near –6°C, which is several degrees colder than at Nome (about –3.4°C). Therefore, it is expected that, other factors being equal, the *maximum* permafrost thickness at Wales would be correspondingly greater, perhaps 200-250 m. However, the water is deeper (about 50 *m)* and this implies a different history of submergence compared to Norton Sound. The above noted factors have not yet been applied to estimate the potential for the presence of ice-bearing subsea permafrost in the northern Bering Sea.

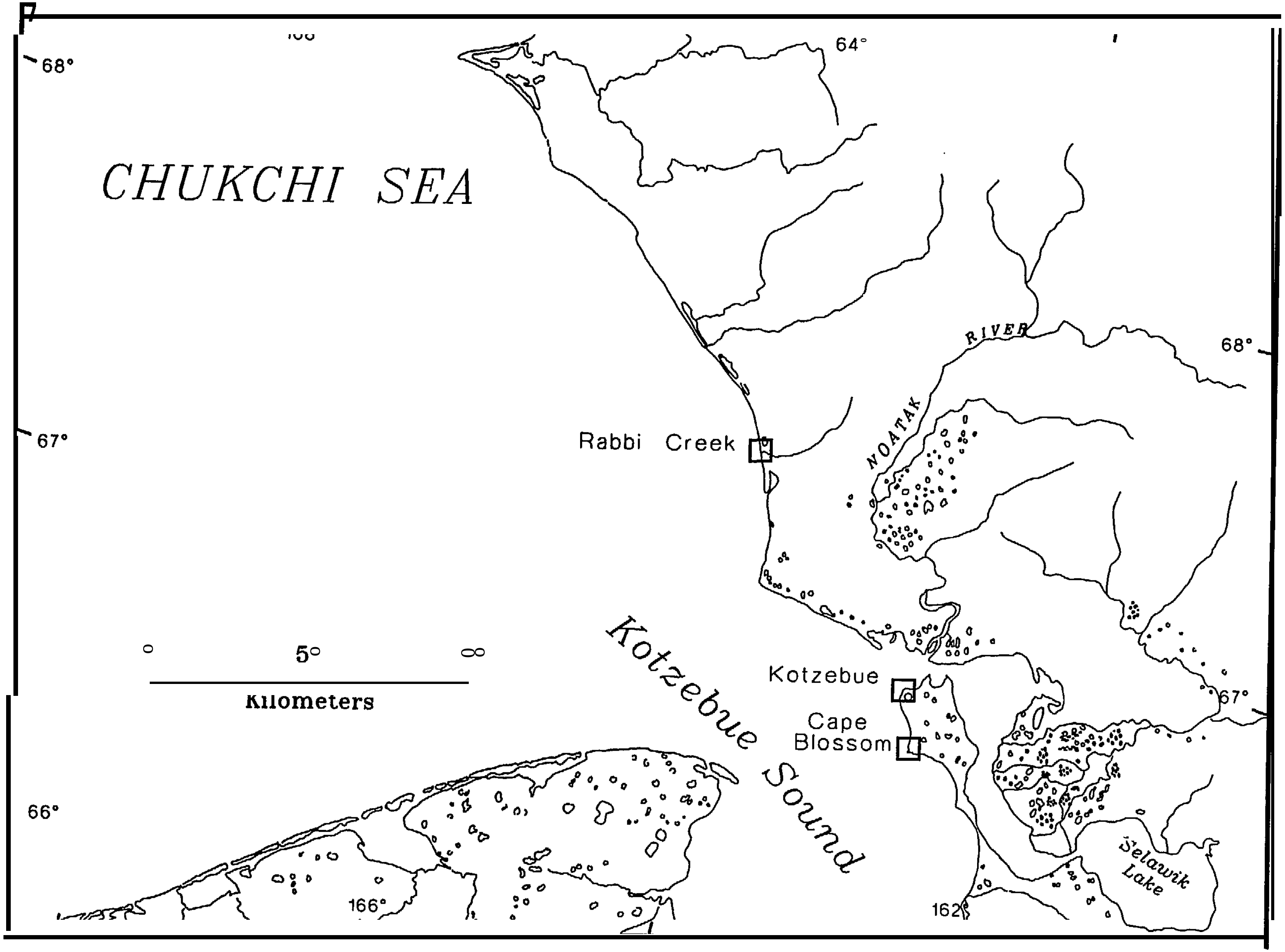
Kotzebue Sound

Our database in Kotzebue Sound is very limited (Figure 3 and Table 2). It consists of five seabed temperature measurements and poorly defined temperature profiles from two shallow holes close to shore; the data from one hole are shown in Figure 4. These holes were drilled during April 1977. The temperature gradients in the holes are both negative, suggesting the presence of ice-bearing permafrost at depth. Seabed temperatures in the main portion of Kotzebue Sound were near normal for winter conditions (about –1.8°C).

Therefore, it seems likely that ice-bearing permafrost exists under Kotzebue Sound, particularly in shallow nearshore regions. The discharge of the Noatak and Kobuk rivers into the north side of Kotzebue Sound produces warmer seabed temperatures and reduced under-ice water salinities. These factors may have a strong impact on subsea permafrost on the north side of Kotzebue Sound. Fresher water under the ice during winter could be a source for producing potable water for OCS development activities.

Table 2.–Kotzebue Sound–Southern Chukchi Sea drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Rabbit Creek	75 m	4.0	1.2	driving	4/26/77	18
Kotzebue	310 m	1.8	≈1.2	jetting	4128/77	25
Cape Blossom	≈300 m	1.37	1.07	jetting	4/27177	10



F gure 3.—Ko Sound hole location map.

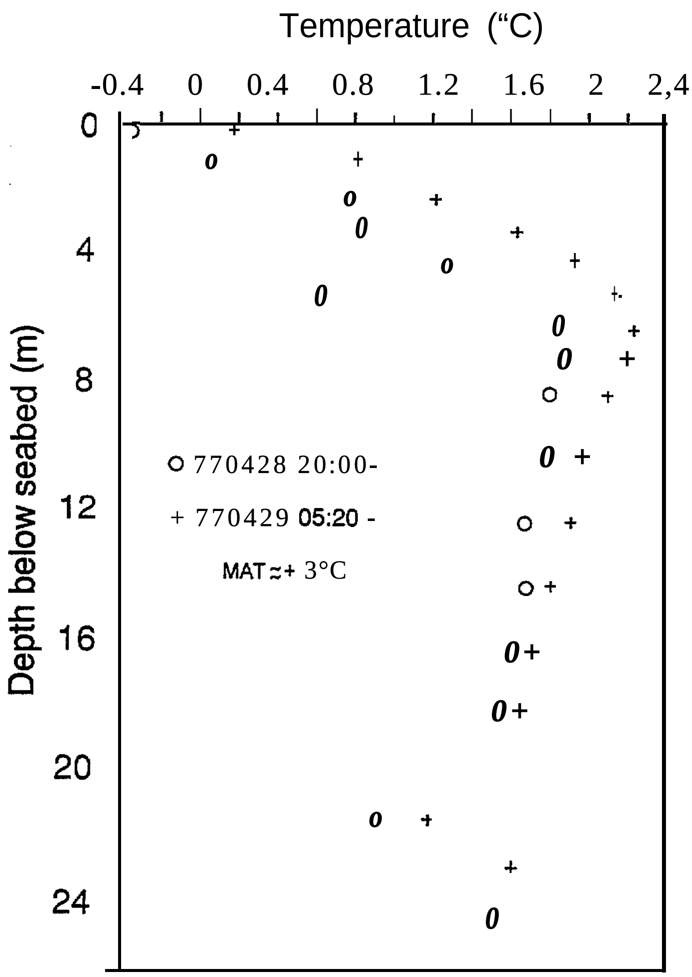


Figure 4.—Temperature profile in an offshore hole off the end of the airport at Kotzebue. The sediments were thermally disturbed but the profile shows a negative temperature gradient suggesting the possible presence of ice-bearing subsea permafrost at depth.

Chukchi Sea

Five holes were drilled in the Chukchi Sea at the locations noted in Figure 5 and Table 3 during the 1977, 1978, and 1979 spring field seasons. Attempts were also made to drill holes at the additional sites shown in Figure 5 but were unsuccessful because rock was encountered at or near the seabed. Rock, at or near the seabed, appears to be common between Peard Bay and Cape Thompson. It was not possible to penetrate the seabed at these sites. The holes at the Naval Arctic Research Laboratory (NARL) (Figure 6) show thermal evidence for along-stable shoreline, and probably any ice-bearing permafrost there exists only very close to shore and is due to the proximity of the cold emergent land. The situation is quite different in the southeastern Chukchi Sea, where the holes show decreasing

Table 3.–Northern Chukchi Sea drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
NARL						
Hole 27 (Hole A)	On a line bearing N330°E from sea ice radar mast at NARL. 27 m from shore	4.12	1.80	rotary-jet	4/18/80	6
Hole 78 (Hole B)	Same, but about 78 m from shore	5.0	1.75	rotary-jet	4/19/80	29
Hole 690 (Hole C)	Same, but 690 ± 100 m from shore	6.5	1.70	rotary-jet	4/21/80	22
Hole 705	705 m offshore	6.57	1.63	jetting	5115/77	16
Peard Bay	In line with runway near Tachinisok Inlet. About 500 m from shore	6.5	rafted?	rotary-jet	4/23/80	2.0
Wainwright						
Hole 265	70°49.7′N; 159°31.2′W	4.75	rafted?	rotary-jet	4/24/80	17
Cape Lisburne						
Hole 1	075° magnetic from Cape Lisburne radome at ≅25 miles	6.10	1.50	driving	3/27/81	No penetration, rock
Hole 2	048° magnetic from Cape Lisburne radome at ≅32 miles	17.16	1.51	jetting	3/28/81	No penetration, rock
Hole 3	0650 magnetic from Cape Lisburne radome at ≅37 miles	17.16	1.51	jetting	3/28/81	No penetration, rock
Hole 4	3570 magnetic from Cape Lisburne-radome at ≅22 miles	30.48	0.40	jetting	3129/81	No penetration, rock

Table 3.–(continued).

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Cape Lisburne						
Hole 5	0050 magnetic from Cape Lisburne radome at ≅10 miles	21.03	0.72	jetting	3/29/81	No penetration, rock
Hole 6	050° magnetic from Cape Lisburne radome at ≅55 miles	14.42	0.76	jetting	3/30/81	No penetration, rock
Ogotoruk Creek	Hole to Crowbill Pt., N303°E; Hole to highest peak of Crowbill Pt., N313°30'E. About 75 m from shore	6.40	0.81	Not attempted, bottom found to be hard by hand probing	3/31/81	No penetration, rock

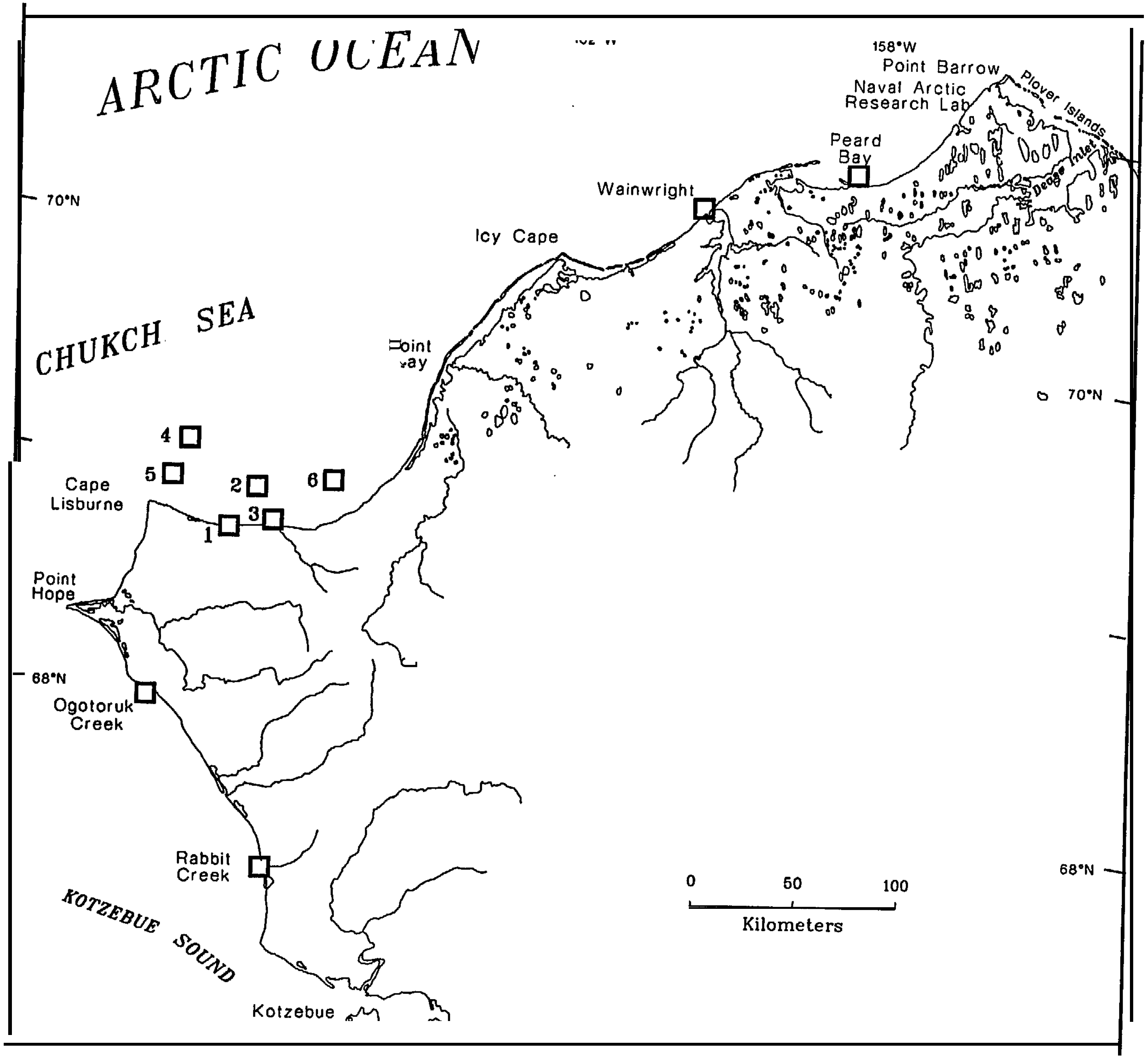


Figure 5.—Chukchi Sea hole location map. The six sites at Cape Lisburne and the site at Ogotoruk Creek encountered rock within 1 m of the seabed. Rock was also encountered in the Wainwright and Peard Bay holes.

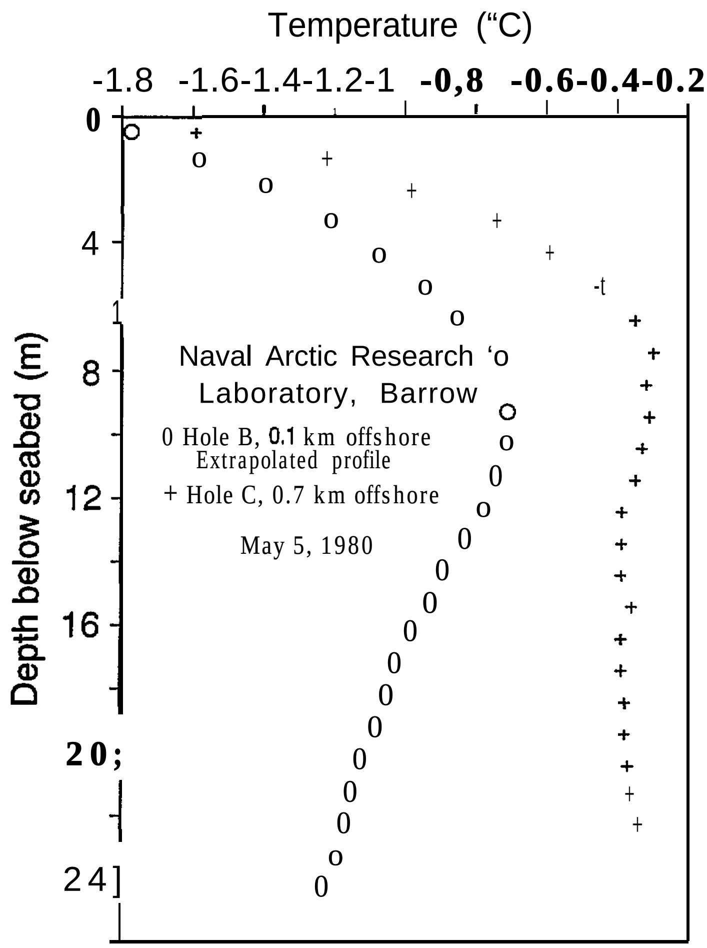


Figure 6.—Temperature profiles at the Naval Arctic Research Laboratory showing colder nearshore sediments with a negative temperature gradient and warmer offshore sediments with a positive temperature gradient.

temperature with depth (Figure 7), the effect of shoreline recession, and indirect evidence for ice at depth. All holes so far are confined to within 1 km of shore.

It seems entirely possible that permafrost might be widespread beneath the Chukchi Sea, because the entire area has been emergent and exposed to cold temperatures several times, and most recently only about 15,000 years ago. We have tried to address the question of the large scale permafrost distribution, using sea level history, seismic data, onshore boreholes, geologic and oceanographic data, and simple theory. This indirect approach suggests that, in the southeastern Chukchi Sea, permafrost may now be absent beneath deeper waters, although it may well survive in areas shallower than 15-30 m. The borehole data indicate that it probably exists in many nearshore areas. Elsewhere in the Chukchi Sea, except at Barrow, the situation is even less clear.

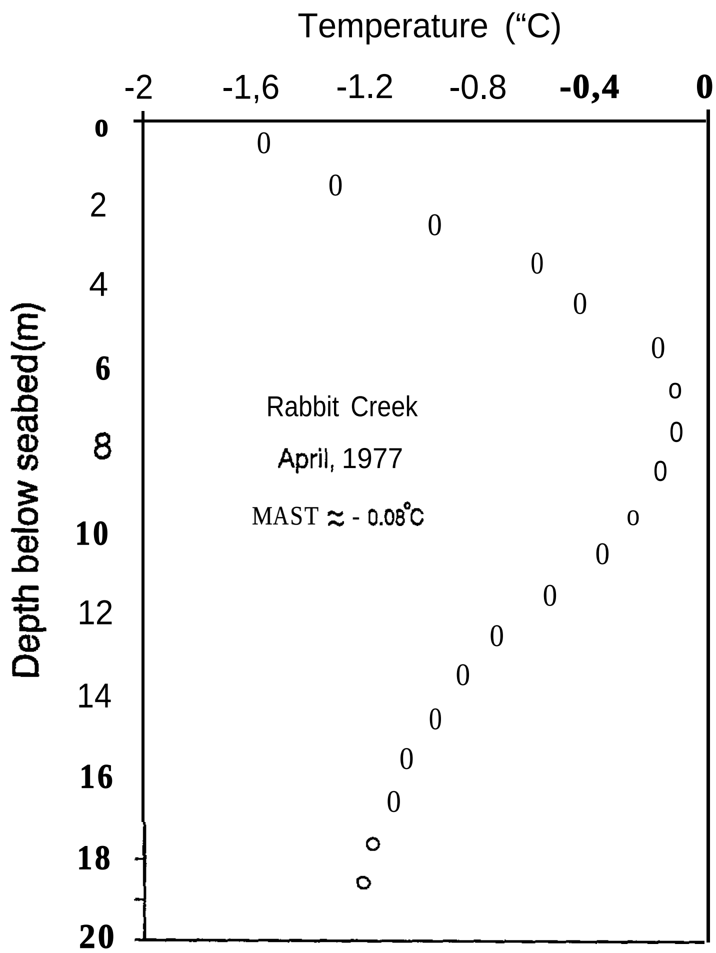


Figure 7.—Temperature profile at Rabbit Creek showing the negative temperature gradient found there.

The presence of rock at or near the seabed poses problems for OCS development. First, it cannot be assumed that the rock does not contain segregated ice. Both temperature profiles and borehole heating data will be required to determine the presence or absence of ice in the rock. The rock cannot be assumed to be a good foundation material for structures unless it can be shown that it does not contain segregated ice. Second, laying pipelines in this rock could be extremely difficult. Third, if the rock is as widespread as our sparse data suggest, then it may be very difficult to obtain gravel for construction of docks, causeways, and artificial islands. A brief discussion of sources of gravel in the Chukchi Sea area is given in Appendix D.

Elson Lagoon

A number of holes were drilled during the spring 1977 and 1978 field seasons along a line from Tekegakrok Point offshore at the location shown in Figure 8 and noted in Table 4. These consisted of eight jetted holes, one of which was started by driving, and three driven

Table 4.–Tekegakrok Point drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Hole 660 (1)	660 m	2.00	1.40	jetting	4/25/78	15.0
Hole 660 (2)	660 m	2.00	1.40	driving	4/21-29178	18.0
Hole 880	880 m	2.32	1.45	jetting	4/26/78	28,0
Hole 1189 (1)	1,189 m	2.52	1.50	jetting	4/27-28/78	34.5
Hole 1189 (2)	1,189 m	2.52	≈ 1.40	driving	4/29–5/3/78	≈ 9.0
Hole 575	575 m	1.25	1.25	jetting	5115/77	19
Hole 611	611 m	1.7	1.68	jetting	5/13/77	21
Hole 798	798 m	2.22	1.65	driving and jetting	5/13-16/77	14.6
Hole 1036	1,036 m	2.5	≈ 1.7	jetting	5/11/77	17
Hole 1466	1,466 m	2.80	1.8	jetting	5112/77	20

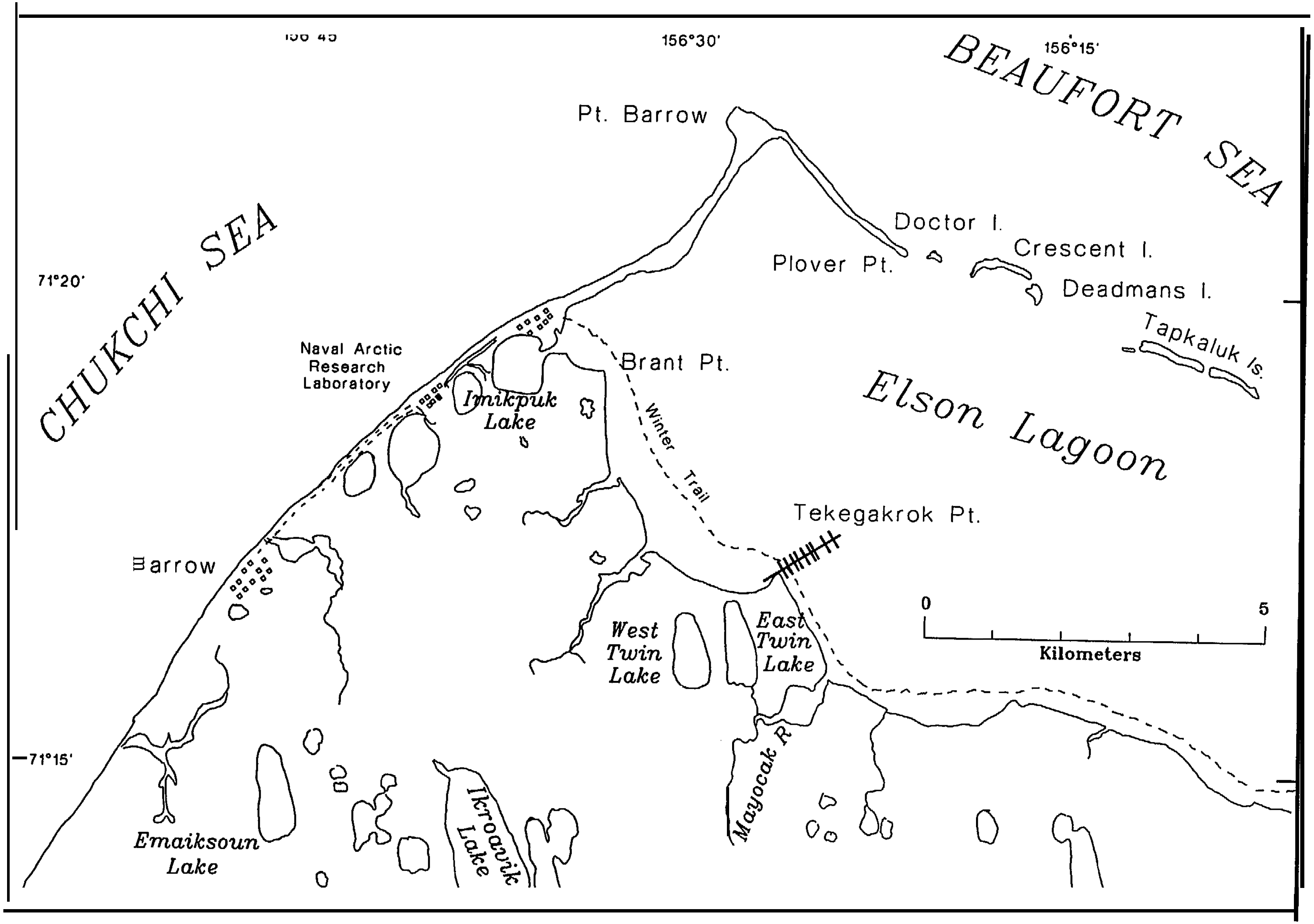


Figure 8.—Tekegakrok Point hole location map.

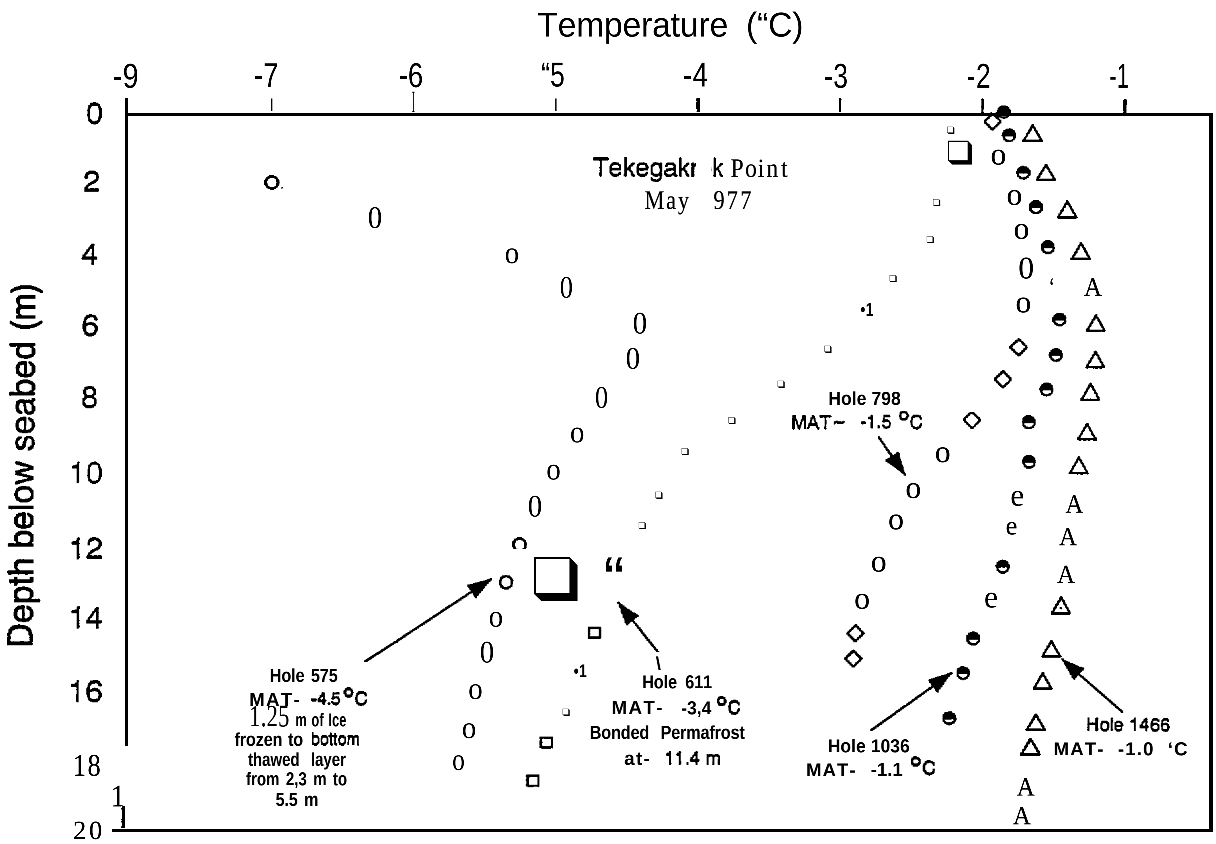


Figure 9.—Five temperature profiles at Tekegakrok Point showing the thermal evolution of the subsea permafrost with distance offshore.

holes. The shoreline retreat rate at these sites was estimated to be about 2.4 m/yr. These holes span the transition from cold nearshore conditions where sea ice freezes to the seabed, to the warmer conditions in deeper water maintained by the presence of seawater of normal salinity under the ice (Figure 9). The sediments were fine-grained.

Temperature, soil pore water conductivity and hydraulic conductivity were measured. A thawed layer of generally increasing thickness can be traced out from shore under the seabed, although the phase boundary may not always be sharp. Simultaneous temperature and pore water conductivity measurements indicate that ice may be present at depths that are not well bonded. Within roughly 600 m of shore, where the sea ice can seasonally freeze to the seabed, pore water salinities in the thawed layer tend to be at least twice that of normal seawater. This high salinity persists to sediment depths of 5–10 m to at least 798 m from shore, but for an unknown reason it is absent at a site 1,198 m from shore, where the salinities to 9 m are only about 40% higher than normal seawater. The measured hydraulic conductivities are extremely low, and are typical of fine-grained silts or clays. This may have an effect on salt transport processes, and therefore on subsea permafrost evolution. A striking exception to this was found 1,189 m from shore, where there appears to be an extremely permeable layer 9 m below the seabed. At the same site a sharp boundary, evidently a lithologic one between the Pleistocene and Cretaceus (Black 1964; Lewellen 1976), was found at the 30-m depth from the temperature and drilling data.

The observations in hole 575 suggest that docks, causeways, or islands constructed from local fill material would likely become ice-bonded to 3 or 4 m during the fist winter, and therefore resistant to ice forces, although some thawing would take place again the following summer. However, the high brine concentrations under the ice-bonded layer, which are probably concentrated during the freezing process, will severely reduce the degree of bonding unless some provision is made for their removal.

Lonely

Five holes were rotary-jet drilled during spring 1980 along a line bearing N328°E offshore from the DEW site at the location noted in Figure 10 and Table 5. Distances from shore were paced and checked by helicopter dead reckoning, but they may contain significant errors. This area was of considerable interest because there were no previous offshore hole data between Elson Lagoon and Harrison Bay. In addition, extremely high shoreline retreat rates, up to 10-15 m/yr, have been measured immediately to the west and to the east (Lewellen 1977). The onshore surficial deposits are mapped as interglacial nearshore and lagoon sand, silty fine sand, and pebbly sand (Hopkins and Hartz 1978b). Drilling data suggest that the offshore sediments are fine-grained to the maximum depth reached (31.3 m). The ice-bearing permafrost onshore at Cape Simpson, about 55 km to the west, is about 300 m thick and this depth contour passes near Lonely (Osterkamp and Payne 1981).

The temperature data (Figure 11) show evidence of rapid shoreline retreat. A preliminary analysis of the data suggests a retreat rate of several meters per year characteristic of the past 100 years or so. It was difficult to assess the presence of ice from drilling data alone at this site, as is often the case when fine-grained soils are present. Therefore, all the boreholes were heated after they had approached equilibrium, and the temperature response was used to determine the presence of ice. Ice-bearing permafrost seems to exist at 6-8 m below the seabed all the way out to the most seaward hole about 7.8 km from shore. Ice bonding exists somewhat deeper, characteristically at about 15 m below the seabed.

Because of the fine-grained soils and presence of ice-bearing sediments, possibly containing segregated ice, near the seabed, subsea permafrost problems for offshore development are likely to be very serious in this area. Thaw subsidence problems for bottom-founded structures and pipelines could potentially occur.

Harrison Bay

Holes drilled in Harrison Bay and seaward and west of Harrison Bay include two holes on the east side of the bay during spring 1977, and three holes near Esook to the west, one hole near Atigaru Point, and two holes north of Thetis Island during spring 1981. The hole locations and drilling information are given in Figure 12 and Table 6.

Table 5.–Lonely drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Hole 88 (Hole A)	Line intersects shore at a point N294 "E from DEW line radar dome. From this point hole line bears N328°E. About 88 m offshore	1.98	1.45	rotary-jet	5/8/80	23
Hole 950 (Hole B)	Same, but about 950 m offshore	3.12	1.58	rotary-jet	5/9/80	31
Hole 2560 (Hole C)	Same, but about 2,560 m offshore	4.80	1.47	rotary-jet	5/10/80	21
Hole 4360 (Hole D)	Same, but about 4,360 m offshore	6.50	2.1 (rafted?)	rotary-jet	5/11/80	17
Hole 7770 (Hole E)	Same, but about 7,770 m offshore	7.70	1.39 (?)	rotary-jet	5/13/80	27

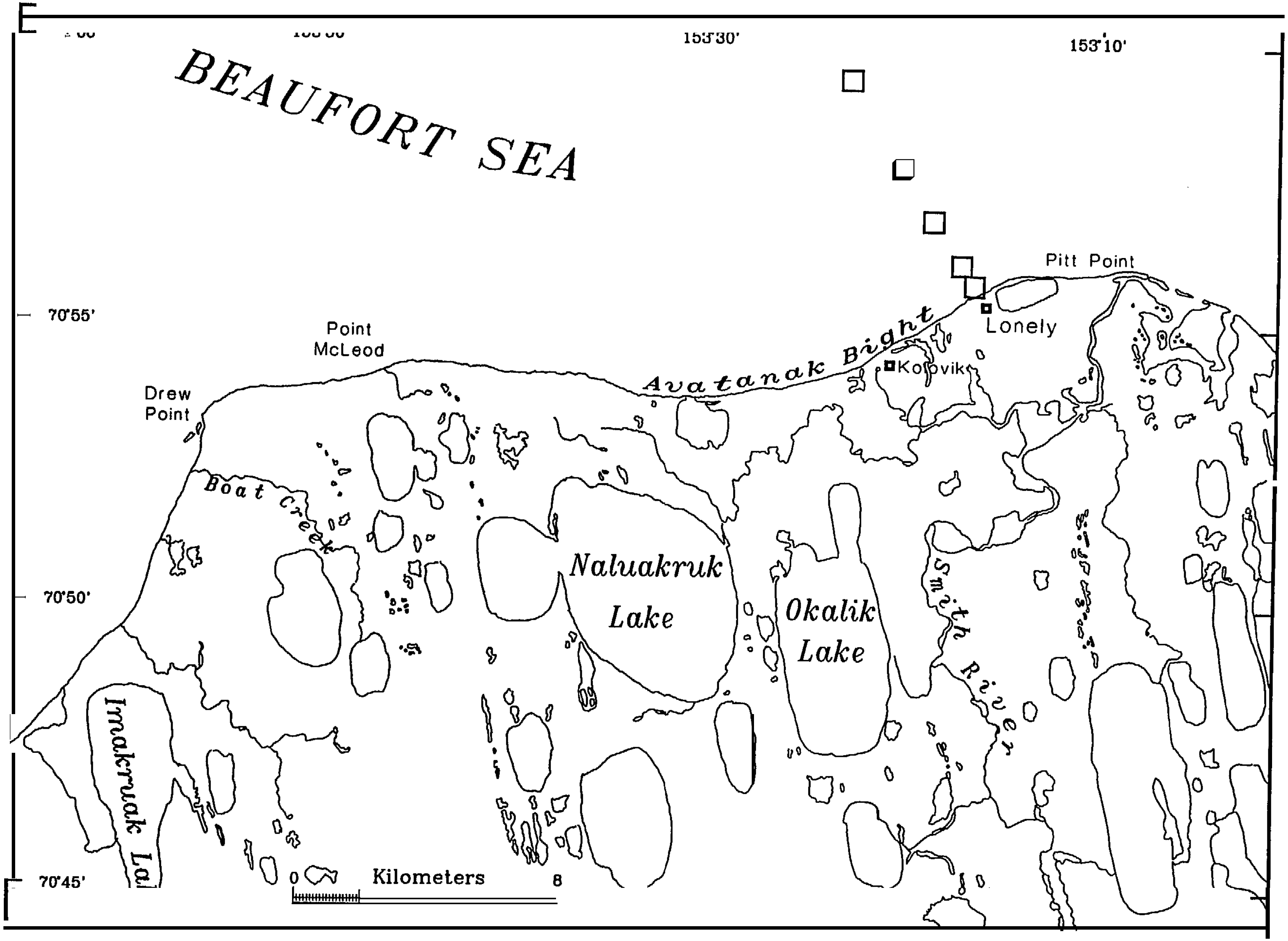


Figure 10.—Lonely hole location map.

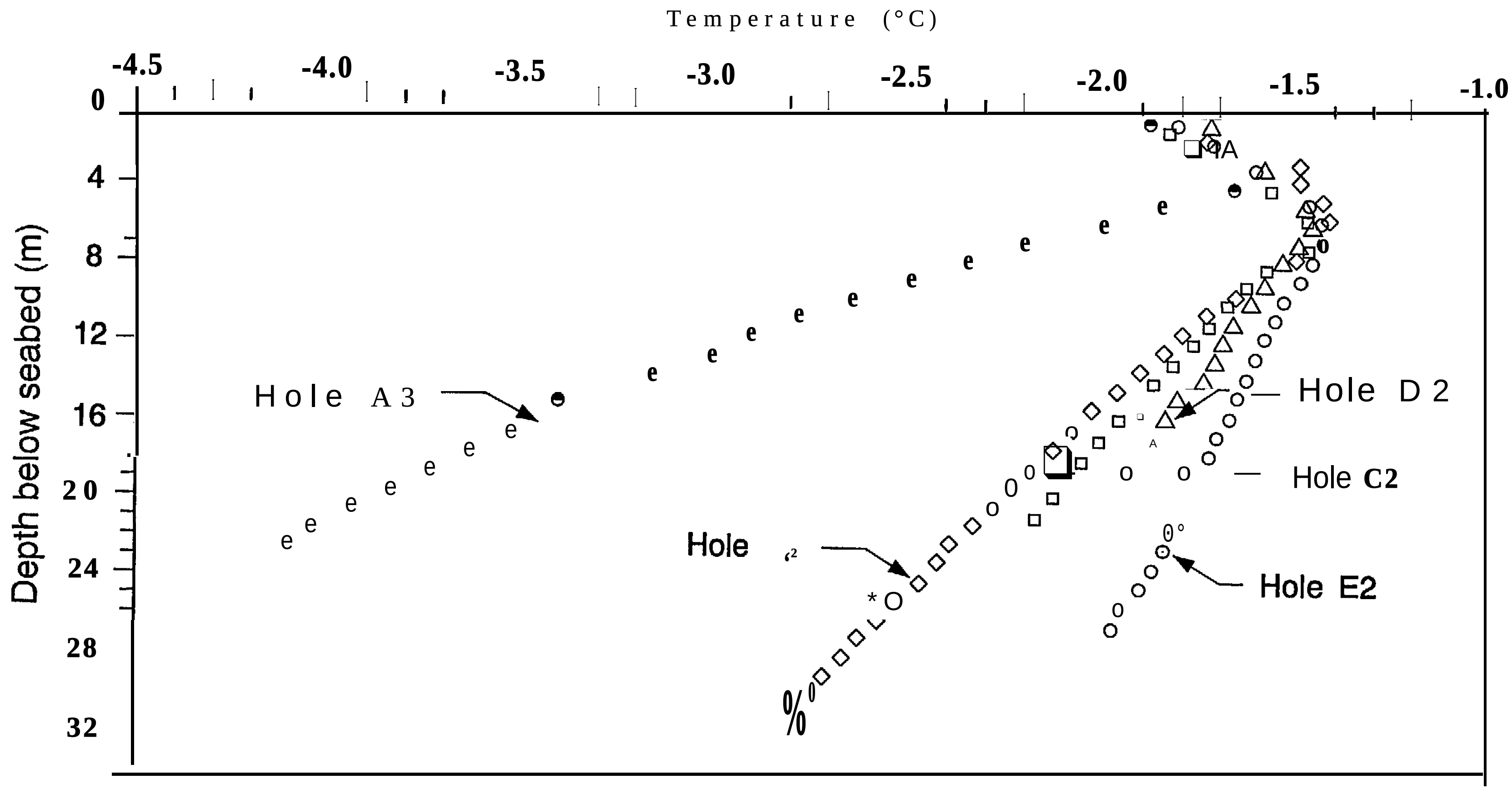


Figure Il.—Five temperature profiles at Lonely showing the thermal evolution of the subsea permafrost with distance offshore.

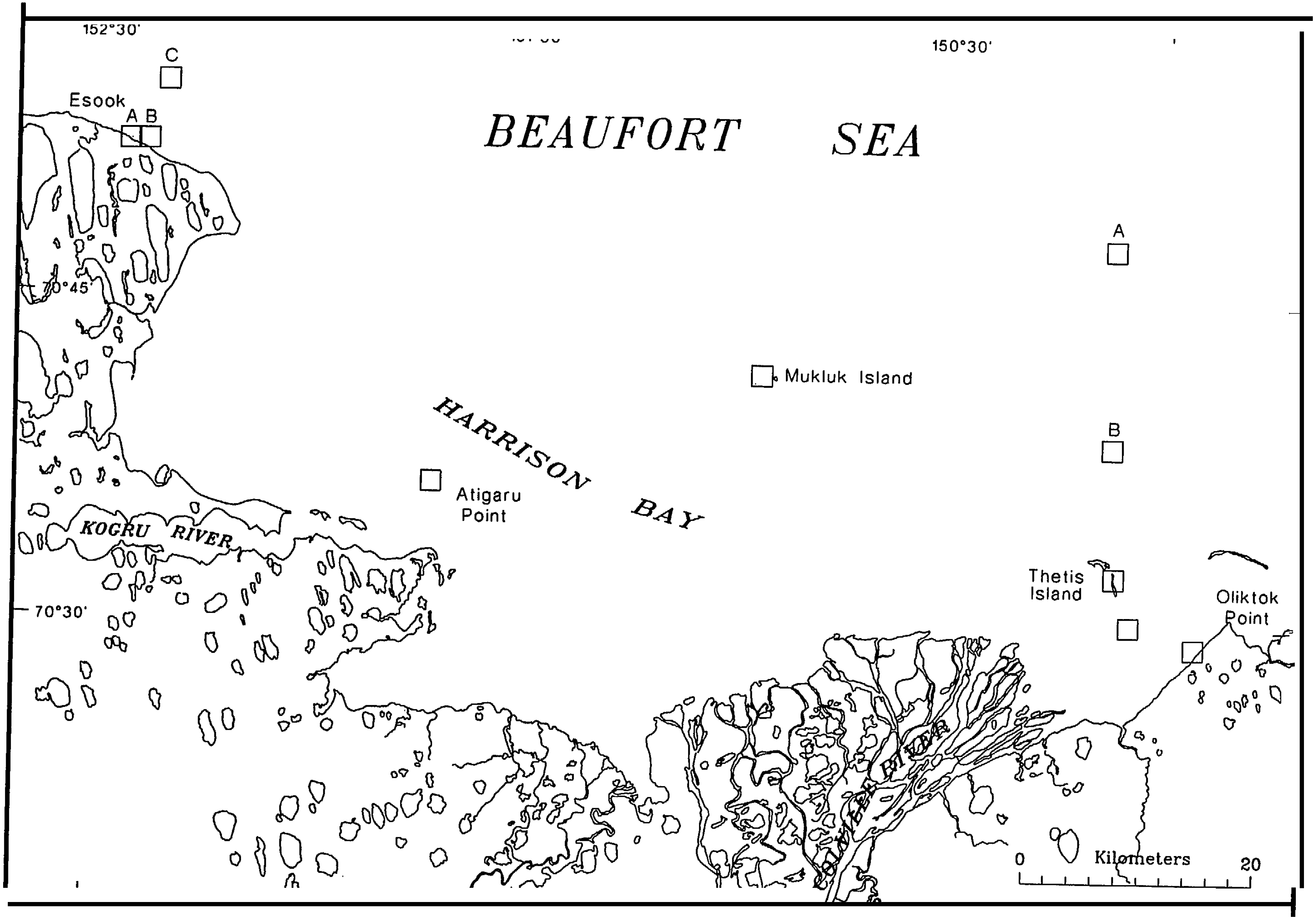


Figure 12.—Harrison Bay hole location map.

Table 6.–Esook-Harrison Bay drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Esook A	70°52.2'N, 152°25.3'W	2.72	1.98	rotary-jet	5/1/81	15
Esook B	70°52.5'N, 152°21.1'W	5.45	1.68	rotary-jet	5/7/81	19
Thetis A	3300 magnetic from Thetis Island hole at 23 nautical miles	25.92	2.82	jetting	4/30/81	4
Thetis B	70°39.2'N, 150°08.9'W N148.5°E hole to Oliktok radome	14.78	1.81	jetting	4/30/81	16
Atigaru Pt.	70°36.4'N, 151°30.5'W	6.83	1.86	rotary-jet	5/1/81	17
Harrison Bay-south of Thetis Island	5.7 km	2.95	2.0	driving	4/30-5/1/77	15
Harrison Bay–Oliktok	≈400 m	2.4	2.1	jetting	5/2/77	8

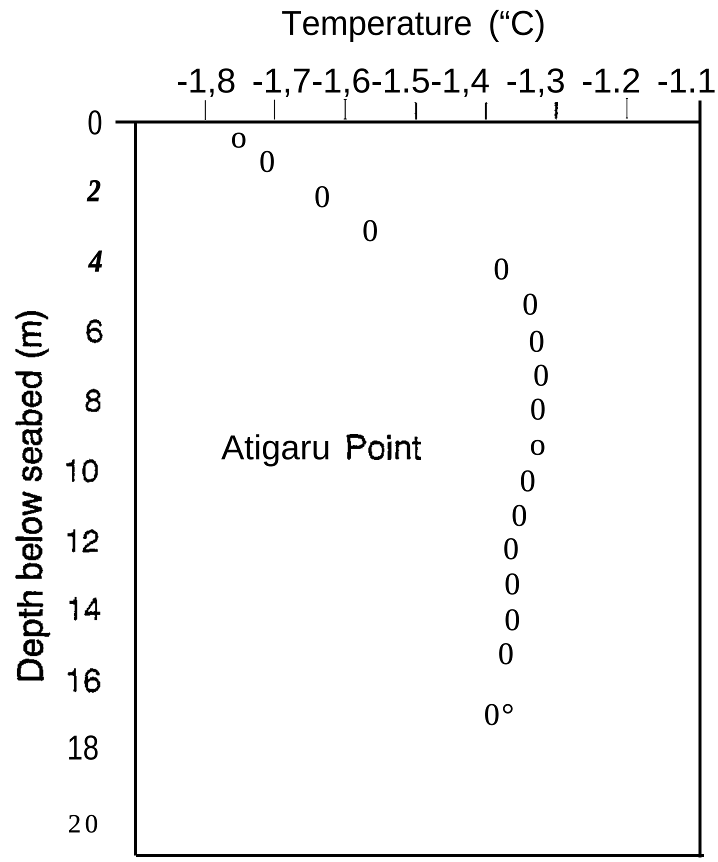


Figure 13.—Temperature profile in the Atigaru Point hole.

The holes drilled on the east side of Harrison Bay appear to straddle the transition zone between the fine-g-rained sediments to the west and the coarser sediments characteristic of Prudhoe Bay. It appears that this transition occurs somewhere between Oliktok Point and Thetis Island. A typical temperature profile for this area is shown in Figure 13.

All holes drilled in the fine-grained sediments encountered ice-bonded subsea permafrost within 15 m of the seabed or less even for a water depth of 15 m. These results are similar to those at Lonely and suggest that subsea permafrost problems for offshore development are likely to be serious in the Harrison Bay area. Gas was encountered in the 1977 hole south of Thetis Island and 8.5 km west of Oliktok DEW station.

A hole was drilled in 14.8 m of water north of Thetis Island and to the east of the Mukluk Island exploration hole. Ice-bearing fine-grained sediments were thought to exist below the 12-m depth in this hole which was about 20 km offshore from Oliktok Point.

Long Island

Four holes were drilled on a line offshore from Long Island during spring 1979 at the locations noted in Figure 14 and Table 7. This line is several kilometers to the west of the

Table 7.–Long Island drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Hole A	70°28.9'N, 148°50.5'W 0.315 km N250 of VABM on Long Island	3.6	2.30	rotary-jet	5/17/79	13.3
Hole B	70°29.0'N, 148°51.0'W 0.600 km N25"E of VABM on Long Island	5.8	2.30	rotary-jet	5/18/79	12.8
Hole C	70°29.5'N, 148°50.4'W ≅ 1.8 km N25°E of VABM on Long Island	9.7	2.00	rotary-jet	5/19/79	11
Hole D	70"30.7'N, 148°45.5'W ≅3.2 km N25 "E of VABM on Long Island	14.0	1.40	rotary-jet	5/20/79	7

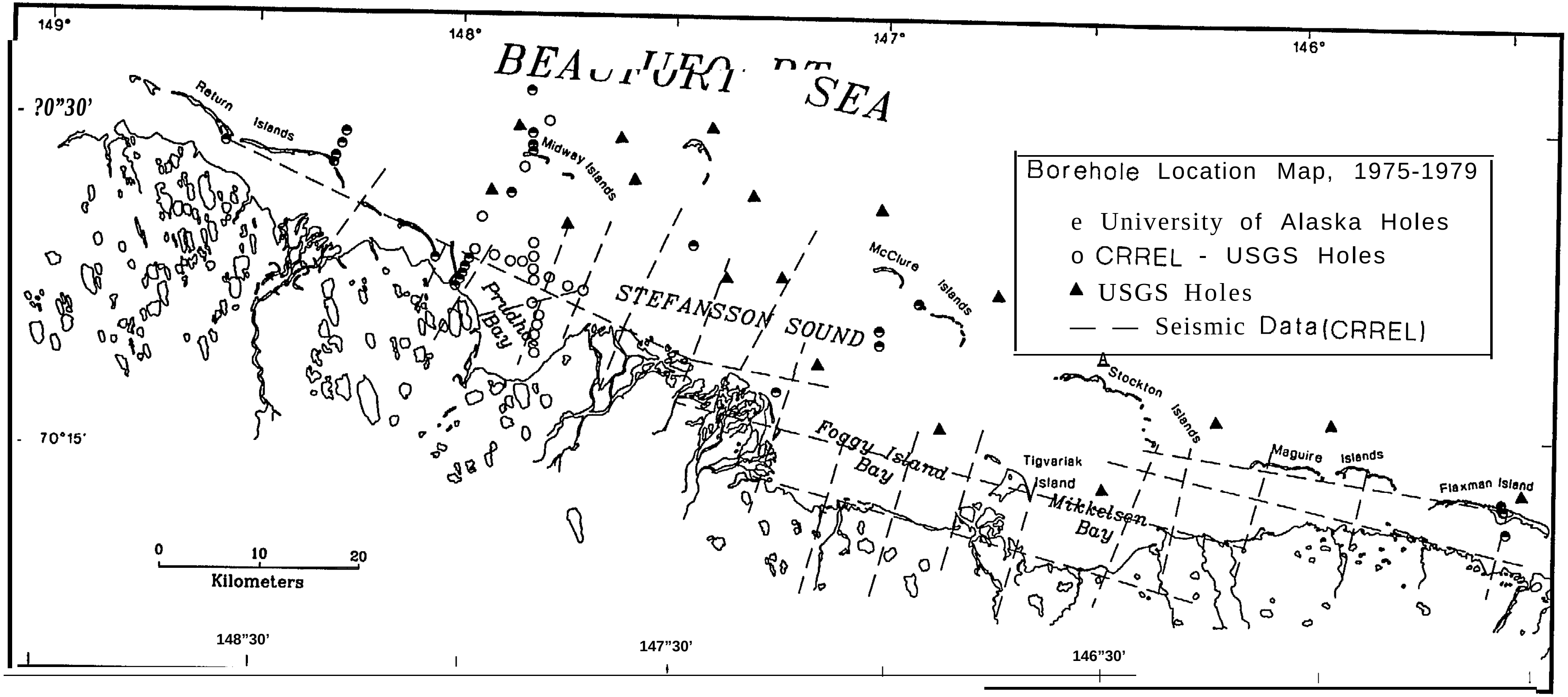


Figure 14.—Prudhoe Bay area hole location map showing USGS, CRREL–USGS, and University of Alaska holes. The dashed lines represent seismic lines investigated by CRREL.

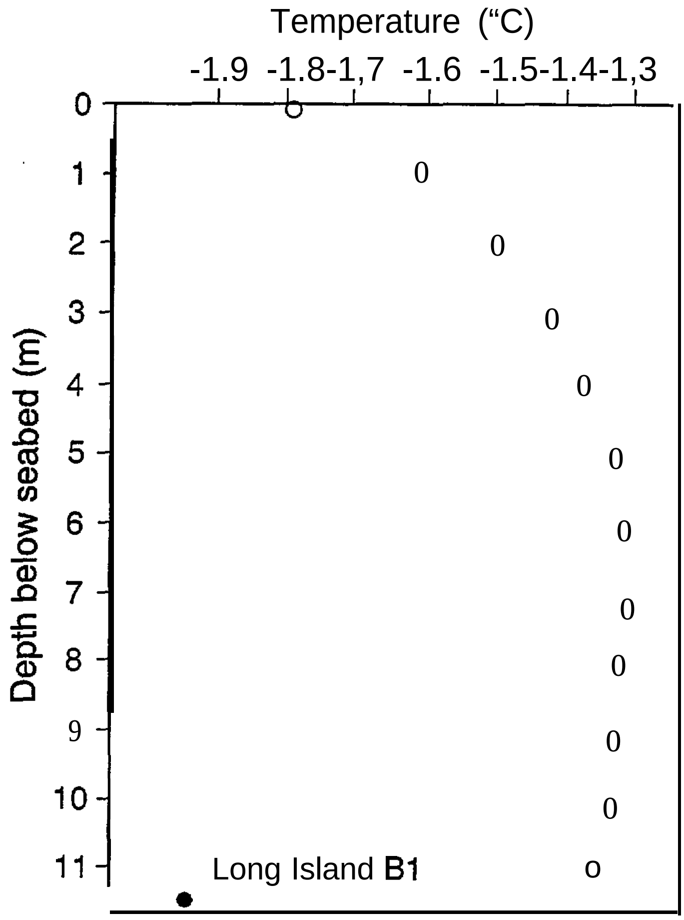


Figure 15.—Temperature profile in Long Island hole B.

Shell artificial Seal Island. The **lithology** determined by rotary jet drilling consists of a layer of **fine-grained** sediments, probably clay, which thin seaward **from** about 7 m thick at water depths of 3-5 m to about 2 m at a water depth of 14 m. These sediments were underlain by gravel-bearing material which could be penetrated about 6 or 7 m. The clay at the seabed may be somewhat difficult to trench. Figure 15 shows a temperature profile **from** a hole where the water depth was about 6 m.

West **Dock**

Prudhoe Bay, particularly its west side, has been the area most intensely studied by the OCSEAP projects (Figures 14 and 16 and **Table** 8). The West Dock line extends **from** North Prudhoe Bay State No. 1 Well **(70°22'36"N, 148°31'28"W)** onshore along a line bearing about **N31.5°E** to Reindeer Island, and then approximately due north. Shoreline retreat is roughly 1 **m/yr.**

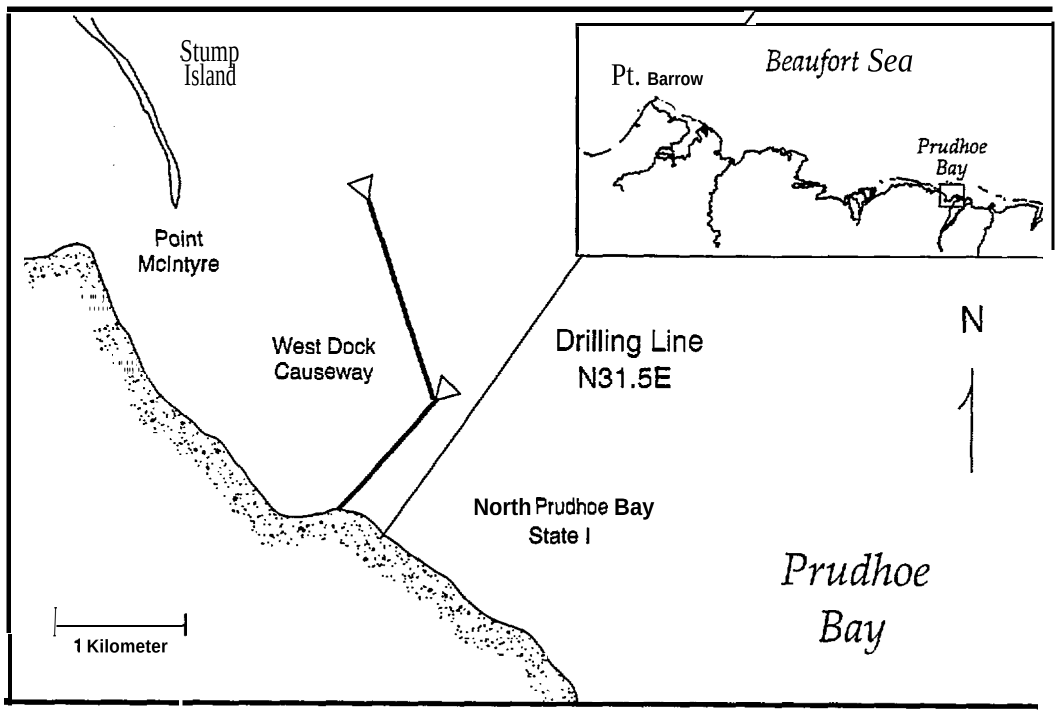


Figure 16.-West Dock line. The line continues to Reindeer Island. .about 14 km fro-m shore, and then turns due north. West Dock is also called the Arco Causeway.

The shallow permafrost regime along the West Dock line can be subdivided into five zones:

1. Nearshore zone, 0-400 m from shore.—In this zone, the permafrost regime is analogous to what is found onshore. There is a seasonably active layer which is ice-unbended to a depth of 3–4 m by fall. Beneath it, judging from conditions onshore at North Prudhoe Bay State No. 1 Well, the permafrost is both ice-bearing and ice-bonded to a depth of about 550 m (Osterkamp and Payne 1981). The lack of deeper thaw in this region is probably due to the low seabed temperatures, which are a result of freezing of the sea ice to the seabed, By late winter, the active layer is mostly ice-bonded, although it seems to contain considerable liquid brine.

2. Ramp zone, 400 to about 440 m from shore.—In this zone, the depth to the ice-bonded permafrost table increases rapidly, and rather linearly, from a few meters below the seabed to about 14 m below it. The ice-bonded and ice-bearing boundaries coincide to within a small fraction of a meter; we usually refer to the ice-bearing boundary as the "phase boundary." To the extent that shoreline retreat is constant (about 1 m/yr), distance offshore is proportional to submergence time. The slope of the phase boundary in this zone therefore implies a thaw rate

Table 8.–West Dock drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date "of drilling	Approximate depth below seabed (m)
Prudhoe Bay, West Dock	All holes on a line bearing about **N31.5** 'E from NPBS #1 well to Reindeer Island					
Hole 398	398 m*	—	1.27	driving	5/27181	2,74 (?)
Hole 418	**418** m	—	1.51	driving	5/27181	8.81
Hole 419	**419** m	—	1.63	driving	**5/31/81**	8.95
Hole 433	433 m	—	1.58	driving	5128/81	10.81 (?)
Hole 438	438 m	—	1.67	driving	5/27/81	13.98
Hole 439	439 m	—	1.54-1.67	driving	5/30/81	14.09
Hole 448	448 m	—	1.61	driving	5/28/81	15.30
Hole 300	300 m	1.37	1.37	auger	5124/80	12.9
Hole 400	400 m	1.58	1.58	driving	5/23/80	3
Hole 438	438 m	1.53	1.53	driving	5/26/80	13.0
Hole 438 S	Same, but slightly displaced	1.53	1.53	driving	5/28/80	13.0
Hole 700	700 m	1.62	1.62	driving	5/23/80	24.8
Hole 701	701 m	1.62	1.62	driving	5/29/80	24.9
Dock Hole 700 (A)	700 m	1.8	1.82	driving	5/14/79	20.87 (?)
Dock Hole 689 (B)	689 m	1.8	1.82	driving	5/26/79	24.6
Dock Hole 701 (C)	701 m	1.8	1.75	driving	5/15179	24.5

Table 8.—(continued).

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Dock Hole 687 (D)	687 m	1.8	1.80	driving	5°23-24/79	24.6
Dock Hole 837 (E)	837 m	1.8	1.76	driving	5126/79	shallow
Dock Hole 700 (F)	700 m	1.8	1.85	driving	5/29/79	10.4
Dock Hole 700 (G)	700 m	1.8	1.85	driving	5/29/79	7.3
Dock Hole 700 (H)	700 m	1.8	1.85	driving	5/29/79	5.8
Dock Hole 700 (I)	700 m	1.8	1.85	driving	5129/79	8.8
Hole 9500	9,500 m	6.9	1.60	driving	5/23-25/78	25.5
Hole 1252	1,252 m	1.97	1.87	driving	5/4-5/77	15
Hole 2114	2,114 m	1.85	1.9	driving	5/8/77	26
Hole -226	226 m onshore	—	—	auger	5/6-7/75	12.2
Hole -225	225 m onshore	—	—	auger	4/30/75	2.9
Hole -69	69 m onshore	—	—	auger	5/8/75	12.2
Hole O	Om	—	—	auger	4/30175	3.5
Hole 190	190 m	(ice frozen to bottom)	1.1	rotary wash boring	5/3-5/75	54.7
Hole 195	195 m	(ice frozen to bottom)	1.1	auger	5/1-2/75	8.8
Hole 196	196 m	(ice frozen to bottom)	1.1	penetration test	5/15/75	2,3
Hole 203	203 m	(ice frozen to bottom)	1.1	auger	5/1-2/75	2.3

Table 8.—(continued).

Hole designation	Loocation or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Hole 334	334 m	(ice frozen to bottom)	1.6	penetration test	5/15175	1.4
Hole 403	403 m	(ice frozen to bottom)	1.6	penetration test	5/15/75	3.1
Hole 481	481 m	<0.1 (water under ice)	1.8	rotary wash boring	5116-18175	26.6
Hole 486	486 m	<0.1 (water under ice)	1.8	penetration test	5/16/75	19.5
Hole 493	493 m	<0.1 (water under ice)	1.8	penetration test	5/15/75	14.9
Hole 964	964 m	0.2 (water under ice)	1.8	penetration test	5115175	14.8
Hole 3370	3,370 m	0.8 (water under ice)	2.0	rotary wash boring	517-14/75	42.9

* The West Dock hole location designation used for the 1981 holes is not entirely consistent with that used the previous year, when “distance from shore” really was from a fixed marker which was about 2 m from the tundra edge in 1981. If 2 m is added to the 1981 distance designations, they are consistent, in a fixed reference system (not one moving with the shoreline), with the 1980 designations.

of about 0.3 m/yr. Although it is virtually certain that this thawing occurs in response to increasing mean seabed temperature seaward of the nearshore zone, it is difficult to understand in terms of any reasonably simple seabed temperature model.

3. Parabolic zone, from about 440 m to 3.4 km or greater from shore.—The phase boundary undergoes a break in slope between this zone and the ramp zone. In the parabolic zone, the phase boundary shape can be considered parabolic and described by

$$Y = a\sqrt{x - x_0}$$

where Y is the depth (m) of the boundary beneath the seabed, x = distance (m) from shore, a = 1.147 $m^{1/2}$ and x_0 = 276 m. This shape seems understandable in terms of a (time)^{M} dependence of thaw layer thickness, which is typical of many simple phase boundary propagation problems. The phase and mechanical ice-bonded boundaries correspond as they do in the ramp zone; this boundary is extremely sharp. The seabed temperature is warmer than its average value in the ramp zone, but the phase boundary temperature is the same, close to -2.40°C, over a distance of at least several kilometers. The shape of the phase boundary in these three zones is indicated in Figure 17.

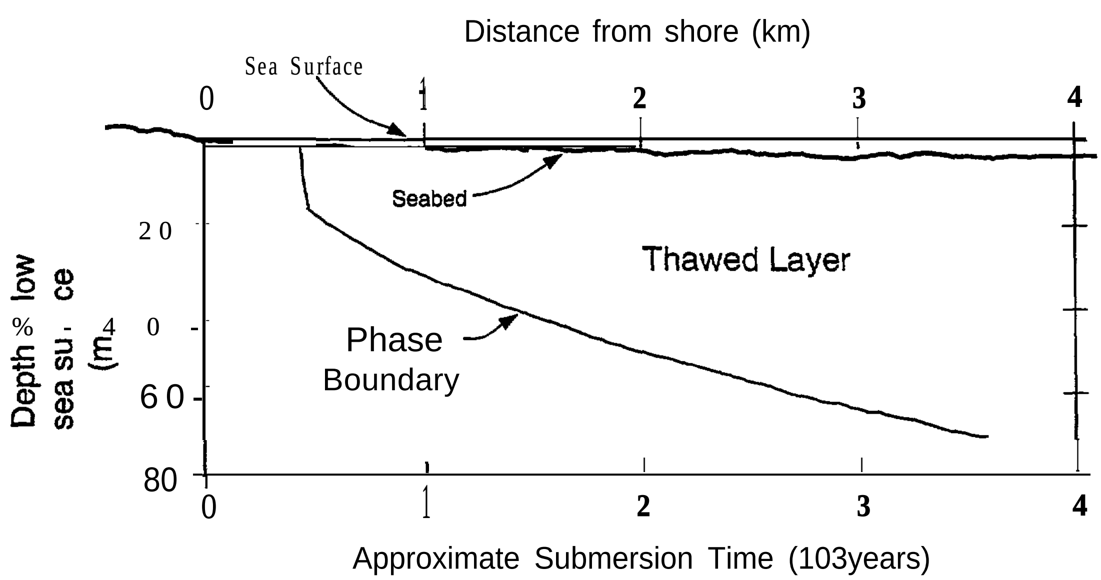


Figure 17.—Profile of the ice-bonded permafrost table along the West Dock line where it coincides with the phase boundary. The nearshore, ramp, and parabolic zones are located from O to 400 m, 400 to about 440 m, and about 440 to >3,400 m from shore, respectively.

4. Intermediate zone, beyond 3.4 km offshore to Reindeer Island.-Fewer data are available from this zone, but seismic evidence suggests that somewhere beyond 3.4 km from shore the ice-bonded boundary becomes deeper than indicated by the above equation. A suggestion that this deep thaw maybe due to the presence of a paleo-river channel was offered by Smith and Hopkins (1982).

5. Seaward zone, outside Reindeer Island.-Ice-bonded permafrost occurs typically 5–15 m beneath the seabed in this zone. Limited drilling data suggest that the phase and ice-bonded boundaries may coincide approximately, and that the phase boundary temperature is roughly –1.8°C, significantly different from the –2.40°C of the ramp and parabolic zones. This zone is also referred to as the Reindeer Island line and is described in more detail in the next subsection.

There are several general observations on the West Dock line that are of interest. The first of these is that seasonal freezing often occurs in the shallow subsea sediments, even beyond the nearshore zone. Beyond the ramp zone, however, there may not be significant ice bonding. Seasonal ice may be found to depths of several meters.

Another observation concerns the nature of permafrost below the phase boundary. A comparison of pore water bulk salinity and in situ temperature of the two existing samples from the nearshore and parabolic zones indicates that 30-50% of the water is in the liquid phase in situ. Evidence for deep briny layers both onshore and offshore also exists (Osterkamp and Payne 1981). Shallow permafrost samples onshore also contain salt, but insufficient to allow complete melting of ice at the phase boundary temperature of –2.40°C. This seems to indicate that a key part of the thaw process is transport of salt from the seabed through the thawed layer to the phase boundary. Other evidence for this important conclusion is discussed by Harrison and Osterkamp (1982b).

Some lithologic information, compiled from both USGS-CRREL and University of Alaska data, is shown in Figure 18. This lithological profile is similar to that reported by Hopkins and Hartz (1978), with minor differences at hole 3370 and hole -226 (onshore).

Temperature data exist from most of the holes on the West Dock line. The most obvious feature in the ramp and parabolic zones, discussed previously, is the uniformity of the phase boundary temperature at close to –2.40°C. Below approximately the 10-m depth of seasonal variations, all temperature profiles show negative gradients and are approximately linear in the thawed layer, although some curvature, suggesting pore water motion or yearly variation, is apparent. Figure 19 shows a typical example. Extrapolation of the linear portion of these profiles to the seabed yields estimates for mean annual seabed temperatures, although there are interpretive problems when the thawed layer is thin, or seasonal freezing at the seabed is significant. The results are summarized in Figure 20. Some data on the amplitude of seasonal temperature variations at the seabed were also obtained.

West Dock, which is really a gravel causeway (Figure 16), and whose leg parallel to the West Dock line is about 1.2 km long, probably has had an important effect on circulation near the West Dock line since its construction in 1974, It is probably influencing the seabed

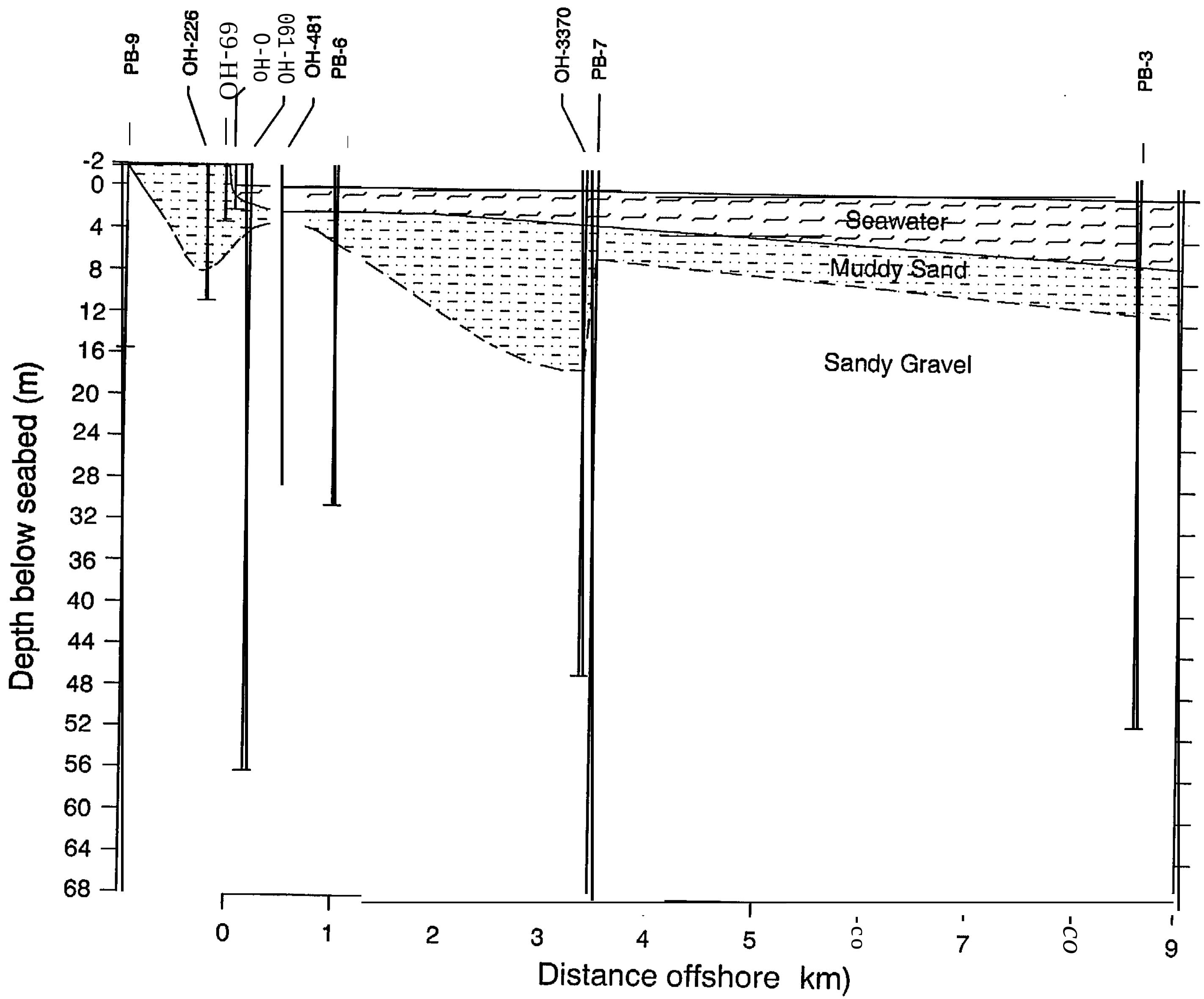


Figure 18.—Lithology along the West Dock–Reindeer Island line showing the contact between the finer-grained near-surface sediments and the underlying coarser sandy, silty gravel.

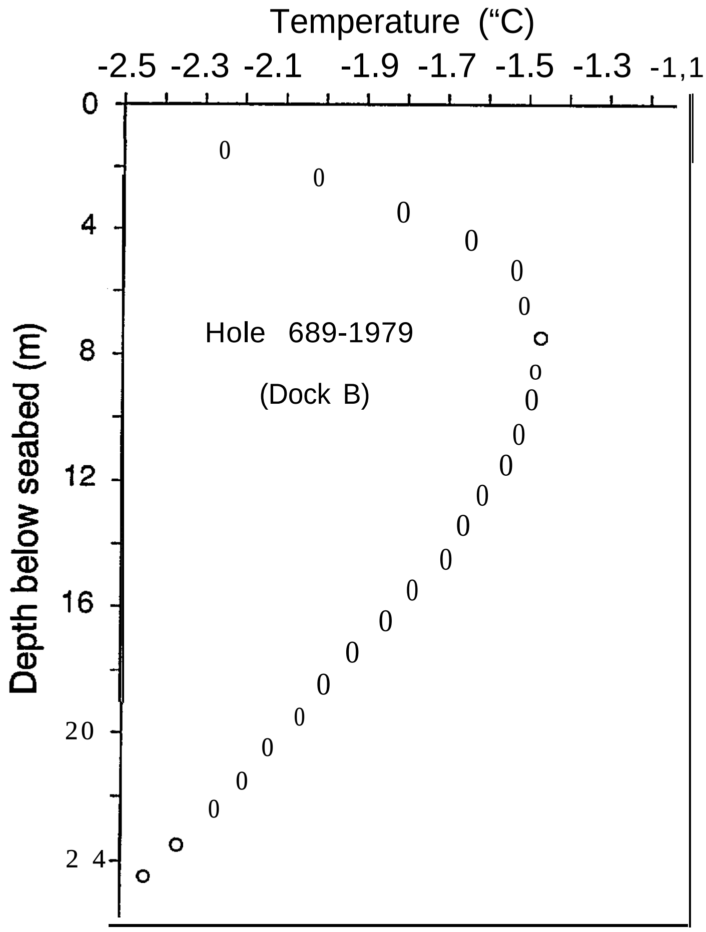


Figure 19.—Typical spring temperature profile through the thawed layer along the West Dock line.

temperature and salinity also, and consequently the evolution of the subsea permafrost regime.

Several special measurements, in addition to soil type and temperature, were made in the thawed layer on the West Dock line. In situ sampling of the pore water, and subsequent laboratory measurements of electrical conductivity, permitted estimates of pore water salinity, under the assumption that its chemical composition is rather similar to that of normal seawater. This assumption is supported by results of the CRREL–USGS program (Page and Iskander 1978). Sample data are in Figure 21. Salinity varies but little with depth and distance from shore. A characteristic value is 43 parts per thousand, which is about 25% higher than normal seawater. Some evidence exists for a thin, weak boundary layer just above the phase boundary, through which the salinity decreases slightly as the phase boundary is approached.

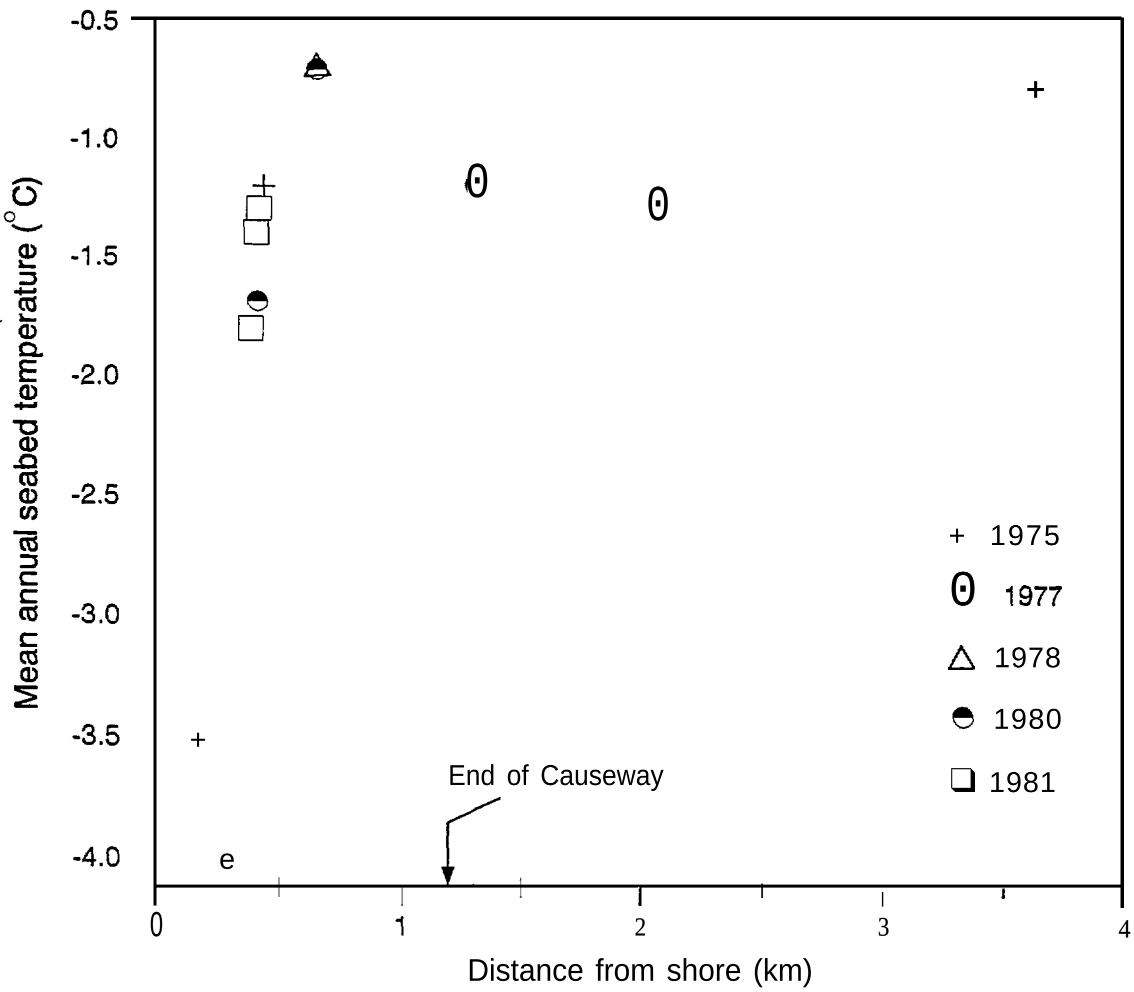


Figure **20.—Estimated** mean annual seabed temperature along the West Dock line. The years in which the estimates were made are indicated.

Both laboratory measurements and the rate of inflow of pore water samples during collection were used **to** estimate hydraulic conductivity. There is a variation of about a factor of 3 (or 10 in a few cases) around the characteristic value of 3 **m/yr. Darcy's** law, upon which the results are based, is not obeyed well. Two laboratory measurements on samples recovered **from** hole 337o gave an average value of 13 **m/yr.**

A pore water pressure profile through the thawed layer was obtained. The pressure was slightly less than hydrostatic, except at shallow depths probably influenced by seasonal freezing (Figure 22).

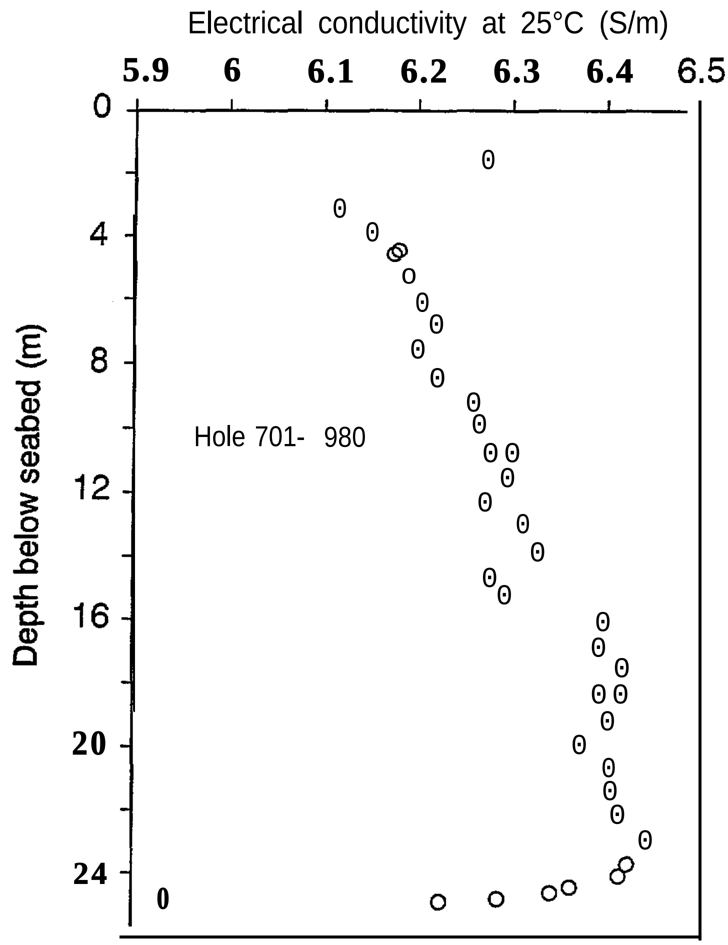


Figure 21.—Typical profile of pore water electrical conductivity measured at 25*C, in hole 701 along the West Dock line.

Reindeer Island

Six holes were drilled on a line due north of Reindeer Island; the farthest offshore hole was 8 km from the island, where the water depth was 21 m. Figure 14 and Table 9 give the locations and drilling information. A temperature profile from the 5-m water depth is shown in Figure 23. The lithology determined during rotary jet (hilling indicates that a layer of fine-grained sediments overlies somewhat coarser sediments. Depth to the ice-bearing/ bonded permafrost first increases and then decreases with distance seaward while the sediments become finer-grained. In the three outermost holes the sediments at the seabed were clay, which appeared to be overconsolidated, and were covered by a thin layer of soft sediments; this suggests that the sedimentation rate is very low. It is difficult to understand this low sedimentation rate in the presence of shoreline erosion rates of 1 m/yr or more.

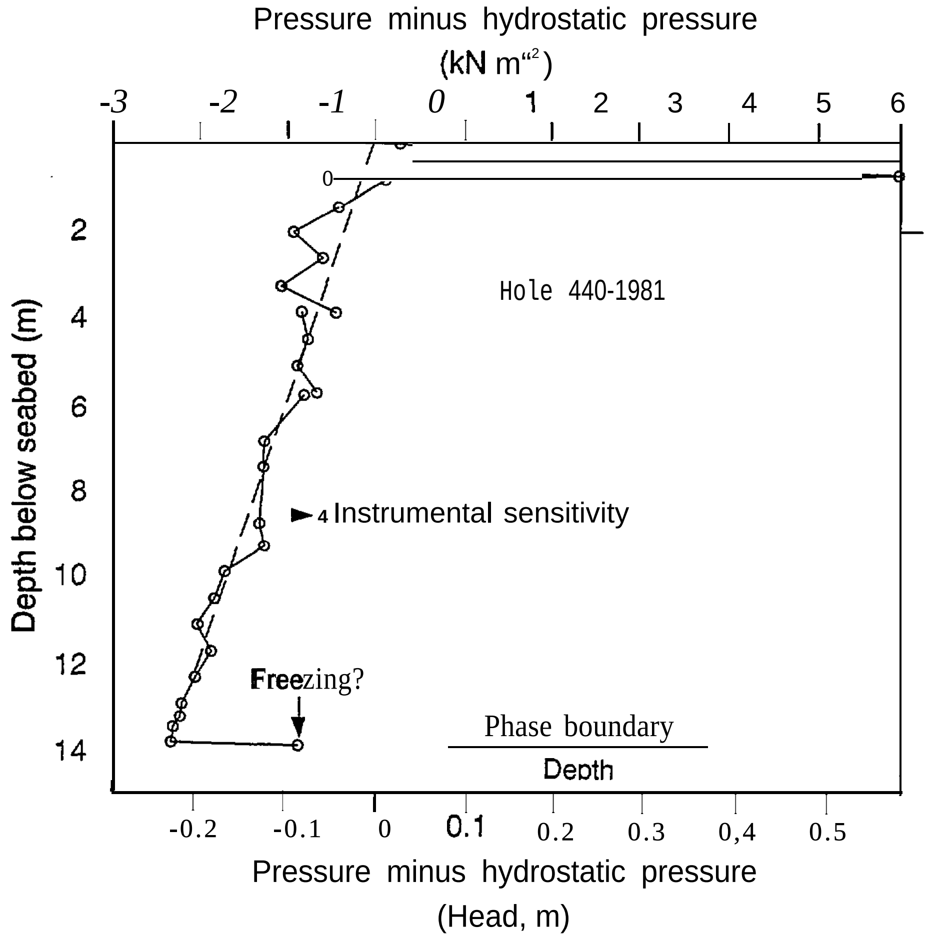


Figure 22.—Pore water pressure profile in hole 440 along the West Dock line.

The depth to ice-bearing permafrost under the clay sediments was less than llm. These clays will be very difficult to trench for laying pipelines in the seabed. Since the ice-bonded permafrost is shallow, the danger of permafrost containing segregated ice and subsequent problems of creep and thaw settlement must also be faced for bottom-founded structures and pipelines.

Sagavanirktok Delta

A hole was driven at a site off the **Sagavanirktok** Delta at the location given in Figure 14 and **Table** 10. The sediments were **fine-grained,** with clay near the bottom of the hole. A hard boundary which was probably ice-bonded **permafrost** was found at 25 m below the seabed.

Table 9.–Reindeer Island drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Hole A	0.352 km N9”E from the USGS Tower on Reindeer Island	3.8	1.93	rotary-jet	5/5/79	23.5
Hole B	**70°29.0'N, 148°21.1** W 0.744 km N1O”E from the USGS Tower on Reindeer Island	5.4	1.90	rotary-jet	5/5/79	23
Hole C	**70°29.7'N, 148°20.8'W** **≅2.6** km N9°E from the USGS Tower on Reindeer Island	11.5	1.91	rotary-jet	5/4/79	17
8 km	8 km true North of Reindeer Island	21	≈ 1.60	jetting	4/21/78	3.5
RDEE (1)	5.9 km true North of Reindeer Island	17	≈ 1.60	jetting	4/20/78	10.0
RDEE (2)	5.9 km true North of Reindeer Island (30 m separation)	17	≃ 1,60	rotary-jet	5/23/78	12

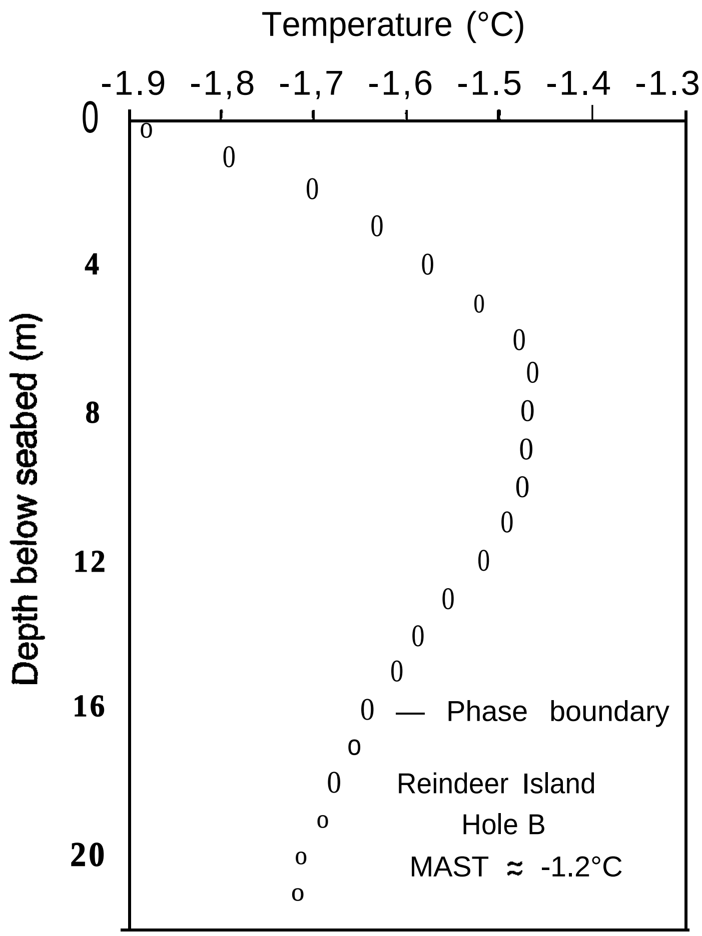


Figure 23.—Temperature profile on Reindeer Island hole B which was located at the 5-m water depth due north of Reindeer Island.

Jeanette Island

Three holes were rotary-jet drilled on a line from Point Brewer through Jeanette Island as shown in Figure 14 and Table 10. The probable existence of ice-bonded permafrost in fine-grained soils at a depth of 5.5 m in the hole approximately 1.6 km offshore from Point Brewer contrasts with what has been found in a different environment at West Dock where the ice-bonded permafrost is typically 5 or 6 times as deep for the same distance offshore. If the very hard layer in this hole at 16.2 m was ice, as we believe, then this is the first observation we have of such a thick ice layer in the sediments. This observation is reinforced by that of the U.S. Geological Survey (1979) in their boring number 13, which is located about 5.5 km offshore and almost on our drill line. They found a layer of massive ice containing clay soils about 0.6 m thick at the 10. O-10.6-m depth. This ice was just under the ice-bonded permafrost boundary at 9.8 m and will produce a thaw settlement of about 0.5 m when it

Table 10.–Sagavanirktok Delta and Jeanette Island drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Jeanette Island						
Hole A	≈ 1 km NE of Jeanette Island	7.5	1.72	rotary-jet	5/1/79	30.3
Hole B	≈ 1 km true North of dive site 11 which has coordinates of 70°19.2′N, 147°35.4′W	6.8	1.83	rotary-jet	5/2/79	15+4
Point Brewer						
Hole C	70°17.3′N, 147°44.3′W ≈ 1.6 km NE of Pt. Brewer	3.4	1.85	rotary-jet	5/3/79	21.9
Sagavanirktok	11.5 km from Sag. Delta #1 well	7.6	1.71	driving	5/25-26/78	18.3

thaws. Unfortunately, no temperature data are available from this hole since ice movement destroyed the pipe before it could be logged. We did not encounter ice-bonded permafrost in the hole about 11.5 km west of USGS boring 20. The ice-bonded permafrost table in the nearshore hole is more than twice as deep as that in boring 20. However, the temperatures there are nearly identical (about –1.6°C).

These observations suggest that offshore development in areas of fine-grained soils must consider the potential problems associated with ice-rich subsea permafrost containing segregated ice, its thawing and subsequent thaw settlement.

Flaxman Island

Four holes were drilled on a north-south line extending across the west end of Flaxman Island at the locations noted in Figure 14 and Table 11. South of the island, there was 9.4 m of clay underlain by gravel. Temperatures were relatively cold in these offshore holes, suggesting that the island may have recently retreated from these sites (Figure 24).

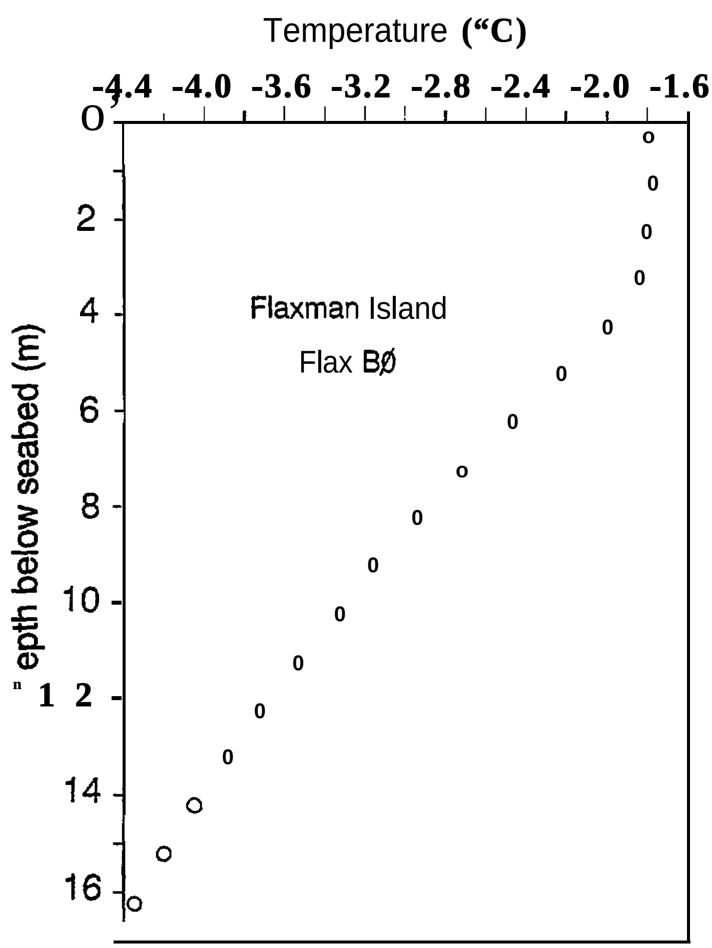


Figure 24.—Temperature profile from hole B which was located at the 3-m water depth on the Flaxman Island line.

Table 11.—Flaxman Island drilling data.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Hole A	0.893 km south of Leffingwell's cabin	2.2	1.75	rotary-jet	5/11/79	13.4
Hole B	0.165 km offshore from spit, bearing N2°E from Leffingwell's cabin	3.2	2.10	rotary-jet	5113/79	17
Hole C	0.684 km offshore from spit, bearing N2”E from Leffingwell's cabin	6.1	2.01	rotary-jet	5/12/79	28.3

A layer of very hard sediments was found near the seabed in the offshore holes. This sediment appeared to be silt or clay with sand, sandy clay, or sandy silt. The USGS (1979) found similar hard sediments at 1–5-m in their bore number 18. They determined that this layer was hard, saturated gray silt, with numerous seams and pockets of gray, black, dense, fine-grained silty sand with small micaceous particles, about 2 m thick lying over a very stiff, saturated, gray silty clay which became less stiff below 5 m. USGS boring number 18 was located c 2 km ENE from our hole C in 11.3 m of water. This suggests that very hard sediments near the seabed may be a general feature of the Flaxman Island area.

Barrier **Islands**

Holes were drilled on the barrier islands along Alaska's northern coast of the Beaufort Sea from 1978 to 1981. The islands included Reindeer Island (five holes), Cottle Island (one hole), Stump Island (two holes), Thetis Island (one hole), Cross Island (two holes), and Flaxman Island (two holes). The drilling data are given in Table 12 and a temperature profile from Reindeer Island is shown in Figure 25.

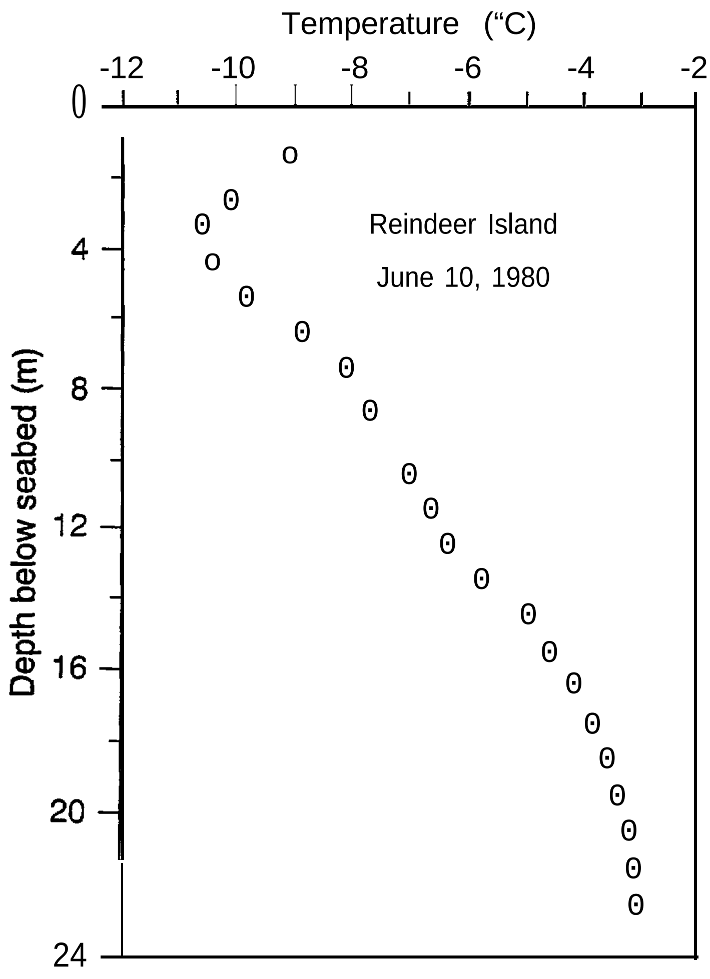


Figure 25.—Temperature profile on Reindeer Island.

Table 12.–Barrier Island drilling data.
The precise location of each hole is given in our previous OCSEAP reports.

Hole designation	Location or distance offshore	Water depth (m)	Sea ice thickness (m)	Drilling method	Date of drilling	Approximate depth below seabed (m)
Cross Island						
Hole 1	N320°E and 276 m from USCG navigation tower	—	—	rotary-jet	7/23/80	4.5
Hole 2	N294°E from USCG tower, and 103 m from south shoreline	—	—	rotary-jet	7/23/80	13.6
Flaxman Island	N118 "E from Flaxman Island exploratory well. N90 "E from Leffingwell's cabin. 213 m due N of shoreline	—	—	rotary-jet	7/28/80	9.9
Reindeer Island						
Hole D	N250°E and ≅300 m from the USGS tower on Reindeer Island, ≅4 m from the shoreline	—	1.91	rotary-jet	8131/79	20
REIS O	West end of Reindeer Island	—	—	jetting	5/24-25/78	12.2
REIS 1	West end of Reindeer Island	—	—	jettinglrotated by hand	8/19/78	6
REIS 2	West end of Reindeer Island	—	—	jetting/rotated by hand	8/19/78	3.5
REIS 3	West end of Reindeer Island	—	—	jetting	8/20/78	27
REIS 4	West end of Reindeer Island	—	—	jetting	8/25178	16
Cottle Island						
COTT	—	—	—	jetting	8/24/78	≈6
Stump Island						
Stump I	—	—	—	jetting	9/21-22178	10.5
Stump 11	—	—	—	jetting	8/21-22/78	7.5

Ice-bonded permafrost was found under all the islands. The state of ice-bondedness in a particular hole varies with depth, sometimes in a complex fashion, and also with lateral position. The temperature profiles from the holes on Thetis and Reindeer Islands suggest that these islands moved over the present hole sites sometime during the past century.

A hole on Flaxman Island had a significant flow of gas which we collected for analysis by the USGS. The isotopic composition suggests that the gas was biologically generated.

VI. HEAT AND SALT TRANSPORT MECHANISMS AND MODELS

Transport Mechanisms

Thaw rates beneath the seabed vary by orders of magnitude. On the West Dock line seaward of the barrier islands, for example, thaw has been on the order of 10 m or even less after 10,000 years, while in the ramp and parabolic zones it is on the order of centimeters to tens of centimeters per year. This incredible variability must be due mainly to the fact that the mean annual seabed temperatures in Alaska's Beaufort Sea are negative, typically -0.7 to –1.5°C. (These are to be compared with mean surface temperatures onshore of about –10"C.) The seabed temperatures are low enough that salt must be present for significant thawing to occur. It was noted earlier that although some salt is present in the permafrost before submersion, it is probably insufficient to account for the thaw that occurs subsequently. Therefore, transport of salt from the ocean through the thawed layer beneath seems to be a key feature of subsea permafrost evolution. This idea can account for the variability of the thaw rates, since the efficiency of salt transport apparently depends sensitively on soil type. Evidence along the West Dock line indicates that this is reasonable because the slow rates occur in over-consolidated clay, while the rapid rates occur in material that is typically silt y, sandy gravel. To understand the thaw rates quantitatively, then, it is evidently necessary to understand the salt transport mechanisms.

Early in this project it was realized that a potentially important salt transport mechanism was gravity-driven convection of the pore water in the thawed layer, the buoyancy of the relatively fresh water generated by thawing providing the driving mechanism (Harrison and Osterkamp 1978; Harrison 1982). This process would indeed be important if the pore water motion were primarily governed by Darcy's law, and if the molecular diffusivity of salt in the pore water were the same order of magnitude as in free solution. However, subsequent interpretation, based on detailed calculation and comparison with data from the West Dock line, indicates that this is not the case (Swift and Harrison 1983; Swift et al. 1984). Another candidate for a significant salt transport mechanism, resulting from the driving of pore water motion by surface wave action, also seems to be unlikely (Harrison et al. 1983).

The mechanism of transport of heat, unlike that of salt, is thought to be primarily conductive. This is indicated by the near linearity of the temperature profiles at all locations below the depth of seasonal variations. In a few cases, a slight curvature is observed, one of the many possible explanations for which could be slow pore water motion.

Until more is known about the salt transport mechanisms, it is doubtful that answers can be given to some of the obvious questions arising from the field observations, such as:

1) Why is the phase boundary temperature so uniform in the ramp and parabolic zones of the West Dock line, in the presence of known large variations in seabed temperature and salinity, and in pre-submergence surface morphology? What determines its particular value, –2.40°C, which indicates a pore water salinity at the phase boundary about 25% higher than that of normal seawater?

2) What is the mechanism of rapid salt transport implied by the rapid decrease of pore water salt concentration near shore at Tekegakrok Point, Elson Lagoon, with increasing distance from shore?

3) Why is the ice-bonded boundary sharp in some cases but not in others, or, perhaps equivalently, why do the ice-bearing and ice-bonded boundaries coincide in some cases but not in others?

One thing does seem to be certain: rapid salt transport occurs in some locations but not in others. There is another key question not clearly answered by either theory or field data: Does salt transport occur through the phase boundary and into the ice-bearing material below? This process, or the presence of salt initially, would influence the thermal properties of the material and greatly complicate heat conduction calculations. As noted, the limited field evidence indicates that this could bean important factor on the West Dock line, and in other locations it maybe behind the failure of the ice-bearing and ice-bonded boundaries to coincide.

Although our interest was focused on salt transport mechanisms in the natural thawing of subsea permafrost, these mechanisms are equally important in the thermal design of insulated hot oil pipelines in subsea permafrost. For example, Heuer et al. (1983) (see also Walker et al. 1983) have shown that the optimum design is sensitive to the temperature at the contact between the developing thaw bulb and the permafrost that is still ice-bearing. This is the phase boundary temperature, and, as stated above, it is controlled by salt transport mechanisms so poorly understood that it cannot be predicted at present, or even any lower limit set on it. The transport of salt beyond the phase boundary may also be important in pipeline design.

Predictive Thermal Models

Even when heat transport is known to be conductive, there is coupling with salt transport processes, because pore water salt concentration controls temperature where brine and ice are in equilibrium. For this reason the lack of understanding of the salt transport mechanisms has restricted the development of thermal models. Thermal models can still be used to investigate the response of subsea permafrost in limiting cases, or at least in well-defined hypothetical examples. This approach has been used to infer shoreline stability in the Chukchi Sea by Lachenbruch (1957), Lachenbruch et al. (1966), and Osterkamp and Harrison (1978). It has also been used to infer the absence of permafrost in much of the southeastern Chukchi Sea as discussed earlier, and to infer the thaw rate at the base of the subsea permafrost along the West Dock line (Lachenbruch et al. 1982).

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Published Articles

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APPENDIX B
ERRATA FOR ANNUAL REPORTS

1. Spring 1976 Report (Report on 1975 Field Work, Osterkamp and Harrison, 1976a)

The spring 1976 report was edited and re-issued as a joint Geophysical Institute (UAG R-249) and Sea Grant (76-5) Report (Osterkamp and Harrison, 1976b). The following errata are based on that report, rather than the original report for OCSEAP.

Page	Line	
iv	22	Change -0.7°C to -0.8°C.
v	11	Insert "in May" after "cover".
21	4 & 5	Replace sentence with "The age was found to be > 22,300 years."
34	Table 34	These values for the major ions are suspect because of lack of balance between cations and anions. See also page 35.[8]
63	5	Change "-0.7°C" to "-0.8°C".

2. Spring 1977 Report (Report on 1976 field work, Harrison and Osterkamp, 1977)

Page	Line	
16	Subsection: Application of Simple Thermal Models	The result, Figure 8, is not in accord with more recent field observations.
Appendix II, page 5	Eq. 1	Subsequent analysis suggests that Equation (1) would better be interpreted as giving a reasonable lower limit to T.
Appendix II, pages 18 and 19		Add the following references to the list:
		Brewer, M. C., 1958. Some results of geothermal investigations of permafrost in Northern Alaska. Transactions American Geophysical Union, 39, 1, p. 19-26.

Wilmovsky, N. J., 1953. Inshore temperature and salinity data during open water periods, Point Barrow, Alaska, 1951-1953, 14 pp. Was in Naval Arctic Research Laboratory, Barrow.

Wilmovsky, N. J., 1954. Inshore temperature and salinity data during open water period, Point Barrow Alaska, 1954, 5 pp. Was in Naval Arctic Research Laboratory, Barrow.

3. Spring 1978 Report (Report on 1977 field work, Osterkamp and Harrison, 1978)

Page	Line	
7	20	Replace "hold" by "hole".
7	22	Replace "Lackenbruch" by "Lachenbruch".
8	3	Insert comma after "temperatures".
18	34	Insert "steady state" after "corresponding".
24	3	Replace "Kruzenstorm" by "Kruzenstern, April, 1977".
24	9 (entry (d))	Place asterisk beside "2".
30	1	Insert "119 m offshore" after "Brewer (1958)".
30	19	Replace "exposed" by "emergent".
31 (Table 5)	2	Insert (1977) after "BEAUFORT SEA HOLES".
31 (Table 5)		Replace in column 1 "Harrison Bay - Thetis Island" by "Harrison Bay - south of Thetis Island".
33	[fro; bottom)	Delete "only".
38	2	Replace "k" by "K".
38	4	Replace "k" by "K".
39	2	Replace "k" by "K".
40	3	Replace "(ohm m^{-1})" by "(ohm $m)^{-1}$".
40	5	" " " "
42	9	Insert "probably" after "The sediments were".

42	11 (from bottom)	Insert "probably" after "this is".
46	1 (from bottom)	Insert "(Figure 25)" after "west dock".
52	Figure Caption 2 (from bottom)	Insert "Rogers and Morack (1978)" after "investigators".
55	Figure 26	Replace "MAT ≈ 1.2°C" by "MAT ≈ -1.2°C".
57	Figure 28	Replace "1.34°C by "-1.34°C".
Appendices I and II	II-1	This page is out of *order.*
11-2	1	Replace "Hole 78" by "Hole 75".
II-6	2	Replace entire line by "Extrapolation of May 18 and 28 data".
11-15	Fourth Reference	Replace "Bering Strait - Sky Cape" by "Bering Strait - Icy Cape".
11-15	Fifth Reference	Replace "Proceedings of the research international conference in permafrost" by "Proceedings of the second International conference on permafrost".
11-15	Sixth Reference	Replace "W. D. Harrison and W. D. Harrison" by "W. D. Harrison and T. E. Osterkamp".
	Twelth Reference	Replace "Reinhoed" by "Reinhold".
11-16		Add the following reference to the list:
		Rogers, J. C. and J. L. Morack, 1978. Beaufort seacoast permafrost studies. In: Environmental Assessment of the Alaskan Continental Shelf, Annual Reports, Vol. 11, p. 651-688.

4. <u>Spring 1979 Report (Report on 1978, Harrison and Osterkamp, 1979)</u>

Page	Line	
29	1 (from bottom)	Entry in first column is "5.2".

5. Spring 1980 Report (Report on 1979 fieldwork, Osterkamp and Harrison, 1980)

Page	Line	
20	6	Replace "B and C" by "C and D".
25	18	Replace "uplife" by "uplift".
20	21	Add at end of paragraph, "The results are in Appendix D".
64	Entries 3 to6 in column 7	Replace "- 27.45, 27.20, 18.81" by "24.6, 24.5, 24.6, shallow" respectively.
68	4 (Table 4)	Replace "Hole 700" by "Hole 701"
Appendix D-9	Entry 13 in column 1	Replace "70°" by "71°".

6. Spring 1981 Report (Report on 1980 field data, Osterkamp and Harrison, 1981)

Page	Line	
3	10 (from bottom)	Replace line by "A hole was driven near Nome, at a site about 326 m from shore along a line".
3	8 (from bottom)	Insert after "(Table 1 and Figure l)", "The shortest distance to shore was 299 m."
4	8	Replace 'driven" by "jetted".
8	8	Replace "increased" by "decreased".
9	6	Replace "29" by "27".
10	15	Replace "80-90" by "70-90".
21		Add to the reference list:
		Lewellen, R. I., 1977. A study of Beaufort Sea coastal erosion, northern Alaska. In: Environmental Assessment of the Alaskan Continental Shelf, Annual Reports, Vol. 15, p. 491-528.
Figure 2		Replace "326" by "299" on figure.
Figure 31		Replace this figure by Figure 21 of the present report.

56 (Table 1)	Entries 3, 4 and 7 in column 7	Replace "{7.28(?), ?, 28.8" by "17.28, 13.1, 24.9 respectively.
57	Entry 20 in column 3	Replace "5.586?" by "6.274?".
57	Entry 21 in column 3	Replace "6.291" by "6.303?".
Appendix B B-4	1	Replace "St. Michael Creek" by St. Michael River".
B-5	1	" " " " " " " "
B-6	1	" " " " " " " "
B-7	1	" " " " " " " "
B-8	1	" " " " " " " "
B-9	1	Line one should read "Charley Green Creek"

7. 1982 Report (Report on 1981 fieldwork, Osterkamp and Harrison, 1982)

In this report the West Dock hole location designation is not entirely consistent with that used in the previous report. In that report "distance from shore" really was distance from a fixed marker which was about 2 m from the tundra edge in 1981. If 2 m is added to the 1981 (1982 report) distance designations, they are consistent, in a fixed reference system (not one moving with the shoreline), with the 1980 designations.

Page	Line	
9	10-14	Delete sentence beginning "There is also...".
11	10-15	Delete paragraph beginning "The nature...".
15	3 (from bottom)	Replace "1.0350" by "1.0350 x 103".
16	3 (from bottom)	Delete sentence beginning "Its high value...".

18	5	Insert "If the interstitial water motion is governed by Darcy's law," at the beginning of the paragraph.
20	1 (from bottom)	Delete sentence beginning "These profiles suggest...".
21	2 (from bottom)	Delete paragraph beginning "The salt concentration...".
25	12	Delete paragraph beginning "Temperature profiles along...".
Table I	Hole 398	Note that the depth in column 7 is significantly greater than the greatest depth reached in temperature measurement (Appendix A}, suggesting that the thermistor did not go down the hole all the way, or that a depth error has been made.
	Hole 433	
	Insert under "HoI e 433"	"Hole 438, same but 438 m offshore, 1.67, driven, May 27-30, 1981, 13.98, pressure".

APPENDIX C
SEDIMENTS IN SEA ICE

summary

Sea ice in nearshore areas of Alaska's coasts has been found to contain concentrations of fine-grained sediment which are up to several orders of magnitude higher than the concentrations normally found in seawater. Measurements of the reduction in light intensity through the sea ice cover show that relatively small but visible sediment concentrations can drastically reduce the light intensity incident on the water column under the sea ice cover. Examinations of thin sections and ice samples from sea ice cores show that the sediments are clay and silt-sized particles with occasional fine sand and organic debris. The sediment incorporated into the sea ice was flocculated with floe sized a few tenths of a millimeter in maximum dimensions. Sediment floes were found at grain boundaries, intersections of three or more grains, and in association with air bubbles, and occasionally they appeared to be interior to an ice crystal. High sediment concentrations were found to be restricted to the frazil ice in the sea ice cover, suggesting that the entrainment processes involve turbulence and frazil ice production during the freeze-up period. An evaluation of potential sediment entrainment processes suggests that those involving turbulence, frazil ice formation, sediment scavenging by individual frazil crystals and filtration by derived forms of frazil ice (e.g., grease ice, shuga, floes, pans, floes) are the most viable.

A tentative sediment scavenging model for sediment entrainment in sea ice including the above components is proposed which is a combination and elaboration of the models of Naidu (1980) and Osterkamp and Gosink (1980). The proposed model assumes sufficiently windy conditions during freeze-up to produce the turbulence required for resuspension of fine-grained sediments and frazil ice formation and their entrainment in the water column.

A tentative filtration model for sediment entrainment in sea ice shows that the filtration process is also capable of concentrating sediment in the sea ice in the observed concentrations. This process will be most effective when the frazil ice has evolved into floes, shuga, or small pans with dimensions up to a few tenths of a meter. The model suggests that as these forms evolve into large forms of frazil ice, the interstitial water and sediment load becomes trapped within the matrix.

When the derived forms of frazil ice congeal into an ice cover, it is proposed, sediment particles are flocculated by surface effects and by rejection of sediment particles from the growing frazil ice crystals which forces them into floes in the interstices between crystals and into association with air bubbles.

While the above tentative models of sediment entrainment in sea ice are crude and somewhat speculative, they provide working hypotheses which can be tested as additional experimental data are obtained.

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APPENDIX D

GRAVEL SOURCES IN THE CHUKCHI SEA COASTAL AREA

Summary

Gravel appears to be scarce in the Chukchi Sea coastal area. Our program has provided some information about sources offshore, but mainly in a negative sense in that rock was encountered close to the seabed at one site off Ogotoruk Creek, at six sites between Cape Lisburne and Point Lay, and at one site in Peard Bay. Farther north, off Wrainwright and Barrow, reasonably good hole depths were achieved by rotary jetting, which suggests that gravel is not present in significant quantities or else is fine. Some soft rock was penetrated near Wainwright. Details are in our 1981 and 1982 reports. Some indications of gravel in the southern Chukchi Sea were found in our holes off Cape Blossom (18 km south of Kotzebue), Kotzebue Sound (where gravel, if present, is at a depth > 25 m), and off Rabbit Creek (36 km north of Cape Krusenstern). Details are in our 1978 report.

We are aware of several other sources of information, which are listed at the end of this appendix. AEIDC (1975) summarizes knowledge of gravel resources prior to 1975; of interest is the work of Creager and McManus (1966), who mapped several areas of gravel at the seabed in the southern Chukchi Sea. More recently, three engineering-geologic maps of northern Alaska (Williams 1983a,b; Williams and Carter 1984) cover the Meade River, Wainwright, and Barrow quadrangles, including the coastal area onshore from Tolageak, just south of Point Hope, to Barrow and beyond to Cape Simpson in the Beaufort Sea. Studies of sediments offshore in the northeast Chukchi Sea are currently being conducted by the OCSEAP project of Phillips and others. Three reports now available cover the nearshore region from Wainwright to Barrow (Phillips et al. 1982; Phillips and Reis 1984, 1985).

Some other information is also available from the coastal or near coastal areas of the southern Chukchi Sea, usually in connection with airport construction or improvements by the State of Alaska, Department of Transportation and Public Facilities (DOTPF), 2301 Peger Road, Fairbanks, AK 99701. The sites investigated by DOTPF include Shishmaref, Noorvik, Kivalina, Point Hope, Wales, Barrow, and possibly others. The offshore sites investigated were in Shishmaref and Kivalina lagoons. Permafrost was found under the latter. Only the reports that we have read are included in the list below. Gravel has been dredged from Kotzebue Lagoon.

Studies for proposed developments on land such as the Wainwright terminal, the Red Dog mine, and the Kotzebue to Chicago Creek highway have yielded, or will yield, other information about gravel sources that may be relevant to offshore development. Of special interest is the Draft Environmental Impact Statement for the Red Dog mine project (Environmental Protection Agency and Dep. Interior 1984).

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