Temperature measurements in subsea permafrost off the coast of Alaska

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Temperature measurements have been made in shallow, small-diameter boreholes in the Beaufort, Chukchi, and Bering seas off the Alaskan coasts since 1975. Methods for making access holes with light-weight equipment are described. These included augering, water jet drilling, rotary water jet drilling, and driving. Pipe or tubing was placed in the access holes and logged at discrete, closely-spaced depth intervals, usually one metre, to obtain the temperature profiles.

Temperature profiles in the Norton Sound area of the Bering Sea show that permafrost is absent except possibly very near shore in areas of rapid shore-line retreat. Subzero temperatures were found in all holes drilled in Kotzebue Sound, and in the Chukchi and Beaufort seas. Holes drilled in the Chukchi Sea near Barrow suggest that the shore-line is stable, or nearly so, and that ice-bearing permafrost is probably thin or absent a kilometre or more off-shore. In the Beaufort Sea (Elson Lagoon) near Barrow, the shore-line is retreating rapidly (i.e., a few metres per year) whereas temperature profiles near Prudhoe Bay suggest a retreat rate of a metre per year or less. The depth to ice-bonded permafrost, as determined by temperature measurements, increases with distance off-shore when the soil conditions are constant. However, ice-bonded permafrost may be found near the sea bed in areas of very fine-grained compact soils even when these occur far off-shore. The thermal data has been used to investigate the nature of heat and salt transport processes in subsea permafrost and to construct thermal models which infer its distribution and thickness in a general way.

Depuis 1975 on relève la température dans des trous de sonde peu profonds et de petit diamètre dans les mers de Beaufort, de Chukchi et de Béring, au large des côtes de l'Alaska. Le présent document décrit les méthodes de perçage des trous d'accès avec un équipement léger: tarière, forage au jet d'eau, forage rotatif au jet d'eau et forage dirigé. Des tuyaux ou des tubes ont été placés dans les trous d'accès et marqués à intervalles uniformes rapprochés, d'habitude 1 m, pour obtenir les profils de température.

Les profils de température dans la région du détroit de Norton de la mer de Béring montrent que le pergélisol est absent sauf peut-être très près de la côte dans les régions de recul rapide de la ligne de rivage. On a trouvé des températures négatives dans tous les trous forés dans le détroit de Kotzebue et dans les mers de Beaufort et de Chukchi. Les trous forés dans la mer de Chukchi, près de Barrow, suggèrent que la ligne de rivage est stable ou presque et que le pergélisol contenant de la glace est probablement mince ou absent à un kilomètre ou plus au large. Dans la mer de Beaufort (lac Elson) près de Barrow, la ligne de rivage recule rapidement (c'est-à-dire, de quelques mètres par an), tandis que les profils de température près de la baie de Prudhoe suggèrent que la vitesse de retrait est d'un mètre par année ou moins. La profondeur jusqu'au pergélisol contenant de la glace, déterminée par les mesures des températures, augmente avec la distance au large lorsque les conditions du sol sont constantes. Toutefois, on peut trouver du pergélisol riche en glace près du fond de la mer dans les zones où les sols sont très compacts et à grains très fins même lorsqu'ils se trouvent loin au large. Les données thermiques ont été utilisées pour étudier la nature des procédés de transfert de la chaleur et des sels dans le pergélisol sous-marin et pour construire des modèles thermiques à partir desquels on peut déduire sa distribution et son épaisseur en général.

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Introduction

Permafrost is formed by freezing from the ground surface downward, under cold surface temperature conditions. Its thickness is determined by the thermal parameters of the soil, ground surface temperatures, geothermal heat flow, and the time of exposure to the cold surface temperature conditions. Ocean water levels have fluctuated by 100 m or more (Müller-Beck 1966) on a geological time scale, alternately flooding and exposing the Beaufort Sea shelf and much of the Bering and Chukchi Sea shelves along Alaska's coasts (Hopkins 1967). These shelves were most recently exposed to the 100-m isobath, about 18,000 years ago, thus allowing permafrost to form in them. Increasing ocean levels since then, and until 3000 to 4000 years ago, have inundated the permafrost, replacing the cold ground surface temperature condition with a relatively warm, salty one. During the past 3000 to 4000 years, the shore-lines have continued to recede by thermal and hydrological erosion of ice-rich permafrost. Along the Beaufort Sea coast, shore-line erosion has been rapid, averaging more than a metre per year, with rates of ten metres or more per year observed (Hopkins and Hartz 1978). Along the Chukchi Sea coast, shore-line erosion is generally slow with many areas considered relatively stable. These differences in shore-line erosion rates affect the timing of new thermal (temperature) and chemical (salt) boundary conditions applied to on-shore permafrost. Further complexities are introduced by variations in soil conditions, geothermal heat flow, sea water temperatures, topography, on-shore permafrost thickness, presence of lakes and rivers prior to inundation, as well as others. As a result, a wide spectrum of subsea permafrost conditions may develop with two distinct near-shore regimes. In one regime, the shore-line has been relatively stable for 3000 to 4000 years, with the subsea permafrost approaching equilibrium with the new thermal and chemical boundary conditions. In the other regime, the subsea permafrost has been inundated recently and is just beginning to respond to the new boundary conditions.

Numerous studies by Soviet scientists (Are 1973; Molochushkin 1973), Canadians (Hunter *et al.* 1976; Mackay 1972), and Americans (Lachenbruch and Marshall, 1977; Lewellen, 1975; Osterkamp and Harrison, 1977; Sellmann *et al.*, 1976) have documented the existence of subsea permafrost in the near-shore areas of the Arctic Ocean. It has been established that the mean annual sea bed temperatures are negative and that the permafrost is very warm. In the Beaufort Sea, along Alaska's coast, there is a thawed layer near the sea bed where the temperatures are negative but where there is no ice in the interstitial pore spaces. Ice-bonded permafrost exists beneath this thawed layer. In some cases a transition zone, ice-bearing but not necessarily ice-bonded, exists between the thawed layer and the ice-bonded permafrost. The thawed layer must be produced by salt transport from the sea bed after the permafrost has been inundated since the sea bed temperatures are negative and the surface sediments usually contain fresh pore water. Methods of investigating the problems of salt transport and measurement of salt concentration profiles are addressed in a companion paper (Harrison and Osterkamp 1982).

This paper is a progress report and review of heat transport studies and the measurement of temperature profiles in subsea permafrost. The experimental methods and equipment for obtaining access holes and temperature data are described. Representative temperature profiles for a variety of subsea conditions are presented. The use of these measured temperature profiles for determining the existence of subsea permafrost, thermal gradients, depth to ice-bonded permafrost, permafrost thickness, nature of the heat and salt transport processes, thermal parameters, ice content, shore-line stability and, ultimately, to develop models of subsea permafrost and its distribution are discussed qualitatively. Quantitative calculations and models will be presented at a later time.

The logistics used for this research included transportation by light aircraft, helicopters, snow machines, and light trucks. All of the equipment developed had to be deployable by these transportation methods. Some of the methods and equipment can also be used for studies of frozen and unfrozen soils and on-shore permafrost. Additional experimental details are given in Osterkamp and Harrison (1976, 1978, 1980, and 1981) and Harrison and Osterkamp (1977, 1979, and 1981).

Access Holes for Temperature Measurements

Access holes for the temperature measurements were made by augering, rotary wash bore drilling using a sea-water-based mud, water jet drilling, rotary water jet drilling, and driving.

Conventional Rotary Drilling and Augering

Conventional augering and rotary drilling methods using drill rigs are described in Osterkamp and Harrison (1976). These methods, as they relate to temperature measurements, involve placing a standpipe or thermistor cable in the borehole for logging at a later time. They have been used by Lewellen (1975) at Barrow, CRREL-USGS at Prudhoe Bay (Sellmann *et al.* 1976) and by the USGS in their pre-lease drilling program in the Beaufort Sea. The advantages of conventional augering and rotary drilling are that standard engineering data can be obtained, soil samples can be recovered, and relatively deep access holes can be drilled in most subsea sediments. The disadvantages are the cost, weight, and extensive logistics required to mobilize the drill rigs.

During the 1980 field season, light-weight augering equipment (Acker Soil Mechanic) was tested at Prudhoe Bay in ice-bonded sands and gravels. A 15-m augered hole was obtained under these difficult conditions. One problem was the severe vibration and chattering caused by the coarse-grained, ice-bonded sediments. When the 15-m depth was reached the auger could no longer be turned and efforts to unbind it bent the mast and stripped the gears of the feed mechanism. Subsequent experience suggests that such light-weight augers may be capable of depths of about 15 m under all but the severe conditions noted. More power and weight would be desirable for augering but these detract from portability requirements.

Water Jet and Rotary Water Jet Drilling

Water jet drilling and rotary water jet drilling are old and well-established methods although their use and application in subsea permafrost is somewhat novel. Alaskan gold miners use several versions of

FIGURE 1. Water jet drilling in Norton Sound using the sea ice cover as a platform for drilling holes in the sea bed. A light-weight, high-pressure, large-volume fire pump forces sea water from under the ice through the drill pipe.

these methods to thaw permafrost so that the overburden can be mined more easily (Boswell 1979). The USGS (Cederstrom and Tibbits 1961) and local Fairbanks well drillers use these methods to drill water wells. A company in Alabama (Deep Rock Manufacturing Co.) advertises light-weight equipment for drilling water wells. Several variations of these methods have been used to make access holes in subsea permafrost. Canadian investigators have used the same principle but with somewhat different equipment and techniques (Judge *et al.* 1976).

The simplest method is water jet drilling (Figure 1). It requires pumping sea water from under the ice through a length of pipe standing on the sea bed. The erosive action of the water jet at the bottom of the pipe and the cutting or chopping action produced by dropping the pipe on the bottom of the hole dislodges soil particles which are flushed up and out of the hole on the outside of the pipe. The pumps used in the authors' water jetting method are light-weight, high-pressure, large volume fire pumps (Pacific Mark 26 and Mark 4 models). A water swivel and a quick-disconnect coupling is sometimes used to connect the pump outlet hose to the pipe (usually 3/4-in. schedule 40 iron pipe). A check valve is placed just above a nipple on the bottom of the pipe to prevent backflow. No bit is required, nor is the bottom of the pipe sharpened. A variation of this method consists of attaching a hose to several lengths of pipe. The pipe provides weight and some cutting action and the hose allows for continuous jetting, so that drilling need not be repeatedly interrupted to add additional pipe sections. Only one operator is required to use this method although two are desirable for safety. Drilling rates are highly variable. It usually requires two to four hours, including set-up and break-down time, to produce a 20- to 30-m hole in fine-grained, unbonded sediments and roughly twice that time in ice-bonded sediments. The advantages of this equipment are that it is simple, cheap, light-weight, and easily portable. An experienced driller can obtain information on the nature of the sediments (e.g., whether they are silt, clay, sand, or gravel) and the depth to the ice-bonded permafrost table by the feel and sound of the pipe. Where the ice is frozen to the sea bed, the sediments are flushed to the surface and recovered. The method does not work in sands and gravels where loss of circulation, caving, and difficulties with flushing large soil particles out of the hole cause the pipe to bind in the hole making it difficult to advance or retrieve.

Rotary water jet drilling involves rotating the pipe of the water jet drill by mechanical means. Our simplest version of this method was identical to that advertised by Deep Rock Manufacturing Company during the late 1970's. Rotation was provided by their light-weight, 3-HP, gasoline engine with gear reduction box, attached to the water swivel of the water jet

FIGURE 2. Rotary water jet drilling on land. This hole was drilled on a slight slope and a plastic-lined pit was used to catch the return water flow and cuttings. The water was then pumped back down the hole. Some cuttings were ingested by the pump causing it to wear rapidly.

drilling apparatus. A large variety of cutting bits was used in an attempt to increase drill rates, especially in ice-bonded permafrost. The heavy duty earth probe bit sold by Deep Rock Manufacturing Company proved to be much cheaper and at least as fast cutting as any of our designs. The addition of a cutting bit and mechanical rotation permits drilling rates in ice-bonded, fine-grained sediments comparable to those for water jet drilling in unbonded, fine-grained sediments. It also allows better penetration in sands and gravels, although the same difficulties still prevent penetration of more than five to ten metres in these coarse-grained sediments. When the bit catches, which occurs frequently in ice-bonded, coarse-grained sediments, the two operators must absorb the reactive force of the engine rotating about the pipe — a situation which can result in injury. The water jet drill with or without rotation can also be used on land by recirculating the water from a mud pit (Figure 2).

A series one-, two-, and three-masted supports for the engine and pipe were designed. The one- and two-masted systems (Osterkamp and Harrison 1981) were distinct improvements, but field tests indicated the three-masted system was a superior design (Figure 3). The three masts are mounted on an aluminum base-plate (1/2 in. thick × 3 ft diameter). Rotary power is supplied by a Diamond Drill 9 HP Mark IX engine and gear reduction drive that attaches to the water swivel. A hand-operated winch can move the engine, gear box, and attached drill pipe up under 3000 lbs force which is useful to free the pipe when it binds in a caving hole. The masts, winch, and base plate minimize vibration, binding, and risks associated with a sticking bit. This system has been used to drill holes in fine, ice-bonded gravel to shallow depths and in soft rock.

FIGURE 3. A three-masted rotary water jet drill. The masts, winch, and aluminum base plate minimize vibration and binding. This system can be operated by one person who can control the drill engine and hand winch simultaneously.

Special care is required to prevent freezing in the pipe or tubing placed in the drilled holes for temperature logging. Normally the pipe or tubing is filled with automotive anti-freeze. Provisions are made for vertical tidal movements of the ice by casing them with a pipe of slightly larger diameter. Additional details are provided by Osterkamp and Harrison (1981).

Driving

Two driving methods have been used to place small-diameter (1/2-in.) plastic tubing in the thawed layer above ice-bonded subsea permafrost. One employs a conventional tripod, cathead, and hammer to drive drill rod and has been described previously (Harrison *et al.* 1981; Osterkamp and Harrison 1981). A second method of driving (Figure 4) uses a portable, gasoline-powered hammer (Atlas-Copco) to drive pipe or drill rod containing flexible plastic tubing into the thawed zone. Special driving tools, driving head, and drive points were fabricated for this purpose (Osterkamp and Harrison 1981). Otherwise the two driving systems are nearly identical in use.

This Atlas-Copco system has been used to drive pipe (1/2- and 3/4-in. iron pipe) and EW drill rod. Schedule 40 pipe can be driven in soft soils, but breaking at the threads is a serious problem. Schedule 80 pipe is better for driving but still breaks at the threads when the driving becomes hard. One set of drive pipe was made by cutting 1/2-in. schedule 80 pipe into one-metre lengths and threading the ends with a 7/8-in. × 8 die. Specially machined stainless steel couplings were tapped with the same thread. Both tap and die were ground to produce a flat-bottomed thread groove in order to reduce stress concentration at the bottom of the grooves. Adjacent pipe sections were also butted against each other to help reduce the stress on the threads. There was no problem with breaking pipe threads made in this way, even under severe driving conditions.

FIGURE 4. An Atlas-Copco hammer used to drive half-inch schedule 80 iron pipe and plastic tubing into the sea bed sediments. Special threads must be used on the pipe to prevent breakage.

FIGURE 5. Two coupled, heavy-duty, automobile jacks used to pull drive rod or pipe. Each jack can lift in excess of 7000 lbs and a full length of rod or pipe (1 m) before reconnecting is necessary.

A conventional, rod-pulling hydraulic jack capable of developing 20,000 lbs pull can be used to remove standard EW drill rod. An alternative jacking system (Figure 5) has been used to pull EW rod and pipe. This system consists of two heavy-duty commercial automobile jacks each capable of developing in excess of 7000 lbs lift. A cross-bar with a hole drilled for the pipe or rod is used to distribute the load between the two jacks. The driving head serves as a collar to pull against, and the length of pull is in excess of one metre which allows one-metre pipe sections to be pulled without reconnecting. A base plate is required to hold the jacks together at the bottom. This jacking system is relatively cheap, light-weight, and more efficient than the commercial jacking system.

The access holes made with either driving system are prepared for temperature logging by filling the plastic tubing with anti-freeze and capping the tube. The tubing must also be cased through the ice, as mentioned earlier, to allow for vertical movement of the ice by tides.

The advantages of the Atlas-Copco driving system over the conventional one are simplicity, light-weight, less set-up time, and less fatigue to the operator. One person can use the system, although two are desirable. The energy delivered per blow is only $\approx$ 24 ft-lbs compared to the 350 ft-lbs per blow for the conventional system. This is offset somewhat by the duty cycle of the Atlas-Copco driver which delivers about 2500 blows per minute compared to about 40 blows per minute for the conventional system. Nevertheless, the conventional system appears to be capable of greater penetration in a wider range of soils.

The driving and jetting methods are complementary; the driving methods work best in coarse-grained soils and the jetting methods work best in fine-grained soils. Temperature equilibrium is achieved more rapidly in the driving methods than in the augering or jetting methods, but it is difficult to obtain information on lithology and it is not feasible to penetrate ice-bonded soils by driving.

Temperature Measurements

Access holes made by the above methods are usually logged at discrete depth intervals over a period of several weeks or months. A multi-thermistor cable was placed in one hole in the Prudhoe Bay area (Osterkamp and Harrison 1976). The rest of the temperature logging was done with a system consisting of a thermistor or thermistor probe sensor on the end of a long cable which was lowered into the pipe or tubing, a cable reel, a resistance-measuring device, and associated hardware. An accurate calibration method is necessary since absolute temperature measurements are required. The measuring system must be operational under extreme environmental conditions ranging from −40°C with wind and blowing snow during winter, to wet conditions with salt water spray during late spring and summer. Similar temperature logging systems have been used by Lachenbruch and Marshall (1977) and by Judge *et al.* (1976) in subsea permafrost although the thermistor probes used in this work are much smaller in outside diameter and length (Osterkamp and Harrison 1981).

Use of this temperature logging system in the field requires a few precautions to minimize errors. A tent is usually used to protect the bridge from snow, rain, sun, etc. A very low temperature coefficient resistor is usually measured with the bridge before and after each hole is logged and at intervals during the logging. The same resistance is also measured in the laboratory at the time of the thermistor calibration. Changes in the resistance measurement between laboratory and field conditions are used to correct the thermistor resistances measured by the bridge in the field. The ice point (IP) resistance of the thermistors is usually checked at intervals during the field season to detect any changes which would affect the accuracy of the measurements. It is also useful to obtain measurements with a second cable, at a few selected depths in each hole, to cross-check the temperatures determined with each cable. Tidal variations require at least one set of simultaneous measurements of the distance from the top of the pipe or tubing (which is usually taken as a reference point during the logging) to the ice, and of the distance from the ice to the sea bed.

Approximately one to five minutes are required for the thermistor probe to come to equilibrium with its surroundings, after it has been lowered to a new depth. The actual time required depends on the temperature gradient in the hole, the thermal properties of the fluid, casing, and surroundings and the time constant of the thermistor probe. In some cases, it has been necessary to take a series of thermistor readings at a given depth over a time period of about 10 to 20 minutes and then to extrapolate them to infinite time to obtain the true *in situ* temperature (Osterkamp and Harrison 1976).

The measured thermistor resistances are corrected for variations in the bridge measurements under field conditions using the measured values of the low temperature coefficient resistor. Corrected thermistor resistance values are then converted to temperature using

$$[1] \quad \frac{1}{T} = A + B \ln R + C(\ln R)^2$$

where T is the temperature in degrees Kelvin, R is the thermistor resistance in ohms at temperature T, and A, B, and C are constants determined by a least squares fit of equation 1 to the calibration data. Graphs of the temperature profiles with depth can then be drawn manually or with a computer.

The best accuracy of these temperature measurements, as demonstrated by repeated measurements of the IP is about 5 mK near the IP and about 1 cK several degrees from the IP. Precision of the measurements approaches several mK. These values may be expected to be somewhat larger for field measurements depending on field conditions.

Results of Temperature Measurements

The temperature data reported here have been obtained in relatively shallow boreholes. The deepest hole was 50 m and most holes were between 20 and 30 m in depth. Since most of the ice-bonded permafrost along Alaska's northern coast varies between 200 and 600 m in thickness (Osterkamp and Payne 1981) then only the top 10 per cent or so of the permafrost has been sampled by these measurements. Interpretation of such shallow temperature profiles is subject to some uncertainty. Temperature profiles to 100-m depths have been obtained by the USGS and there is some information from profiles that penetrate the permafrost on land (Gold and Lachenbruch 1973). These data must be taken into consideration in the interpretation of the shallow temperature data.

A temperature profile obtained in Norton Sound in 10 m of water at a point north of the Yukon River delta is shown in Figure 6. The mean annual sea bed temperature (MAT) is about +2.6°C and the thermal gradient is positive near the bottom of the hole implying that permafrost is not present at depth. Preliminary calculations suggest that the curvature between 8 and 14 m is associated with higher than normal sea bed temperatures during the previous year. Data from other boreholes in Norton Sound are similar and suggest that subsea permafrost is absent, except possibly in shallow water areas near shores with high rates of shore-line erosion.

Three shallow, near-shore temperature profiles obtained in Kotzebue Sound and along the Chukchi Sea coast north of the Sound had negative temperature

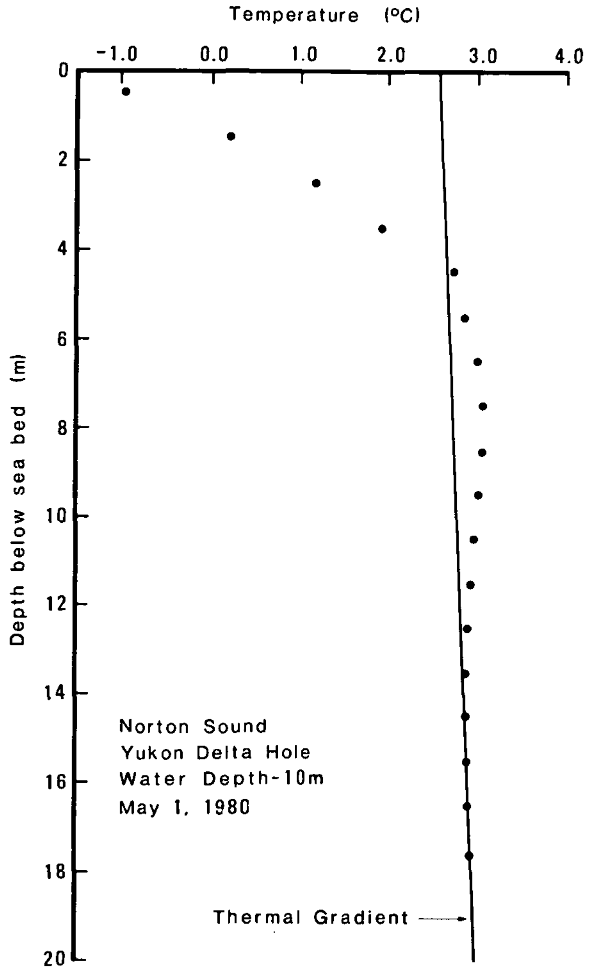

FIGURE 6. Measured temperature profile in Norton Sound at a site north of the Yukon River delta in 10 m of water. The mean annual sea bed temperature (MAT) is near 2.6°C. Curvature in the profile between the 8- and 14-m depths is probably due to greater than normal sea bed temperatures during the previous year. The thermal gradient was constructed by drawing a straight line through the linear portion of the profile near the bottom of the hole.

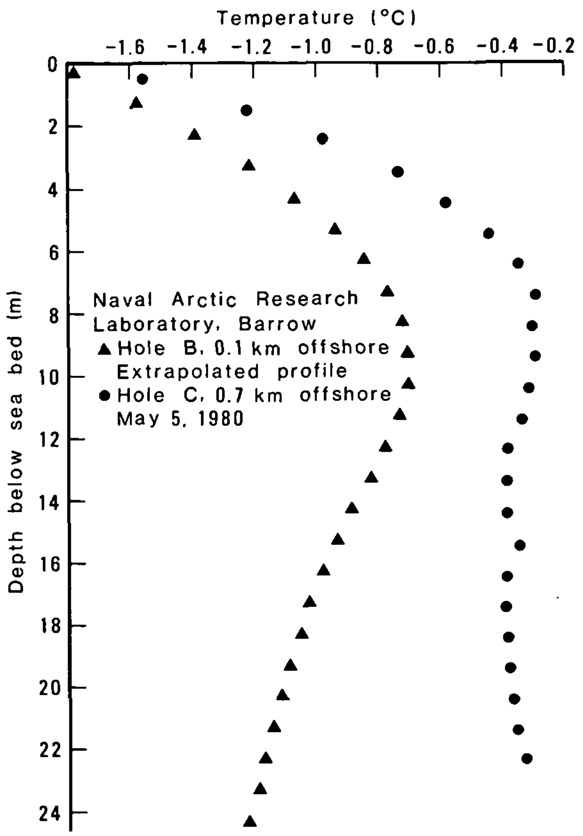

FIGURE 7. Measured temperature profiles in the Chukchi Sea near the Naval Arctic Research Laboratory at Barrow for two sites, 0.1 and 0.7 km off-shore. The mean annual sea bed temperature (MAT) is about -0.5°C for both sites. However, the temperature gradient farther off-shore is positive suggesting that the shore-line is relatively stable and ice-bearing permafrost is thin or absent. Seasonal temperature changes were not taken into consideration in constructing the extrapolated profile in hole B.

gradients suggesting ice-bearing subsea permafrost at depth. Additional temperature data in the southern Chukchi Sea and Kotzebue Sound are required to develop a more complete picture of the subsea permafrost regime in these areas. A near-shore temperature profile in a hole just north of Wainwright, where the water depth was about 4.8 m, has a small negative temperature gradient and a MAT near 0°C. A line of holes has been established in the Chukchi Sea near the Naval Arctic Research Laboratory at Barrow. Temperature profiles obtained in two of these holes at 0.1 and 0.7 km off-shore are given (Figure 7). At 0.1 km off-shore the temperatures and temperature gradient are negative and the MAT is about -0.5°C. At 0.7 km off-shore the MAT is also -0.5°C but the temperature gradient near the bottom of the hole is positive suggesting that the shore-line is stable, or nearly so. The depth of the 0°C isotherm, obtained by extrapolating the temperature gradient in the lower portion of the hole downwards, is 80 to 90 m below the sea bed. The results of Osterkamp and Payne (1981) suggest that the base of the ice-bearing permafrost is usually several 10's of metres above the 0°C isotherm. The *in situ* temperatures at this site and the results of Harrison and Osterkamp (1982) suggest that the presence of ice-bearing permafrost is unlikely. Therefore, these limited data and the results of Lachenbruch (1957) and Lachenbruch *et al.* (1966) imply that the Chukchi Sea shore-line near Barrow and Cape Thompson may be relatively stable and that ice-bearing subsea permafrost may be very thin or absent in most of the Chukchi Sea basin except in near-shore areas. Additional temperature data are required to justify these tentative conclusions.

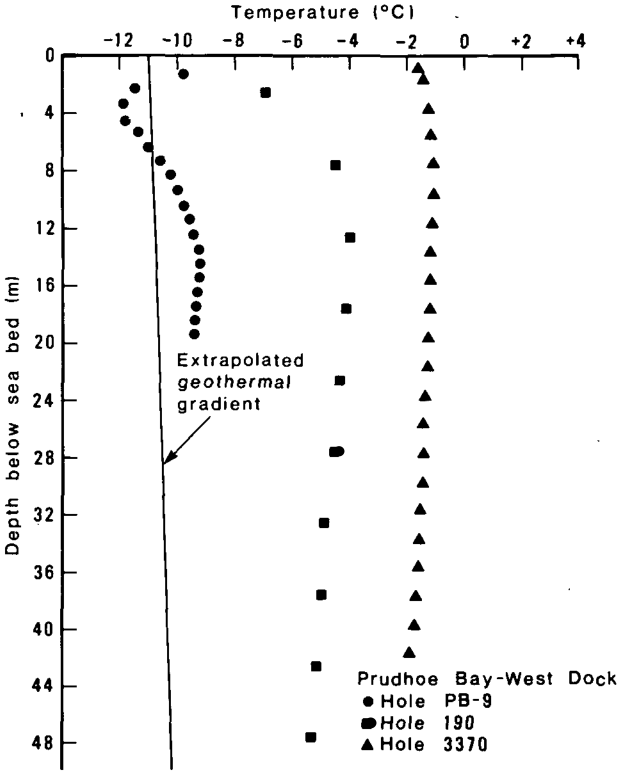

FIGURE 8. Temperature profiles measured in a line of holes at Prudhoe Bay near the west dock where the shore-line erosion rate is on the order of 1 m/a. These profiles illustrate the response of the permafrost to the warm sea bed temperatures. The extrapolated geothermal gradient was obtained from Gold and Lachenbruch (1973). Little thawing has occurred at hole 190 but thawing has exceeded the full depth of the profile in hole 3370.

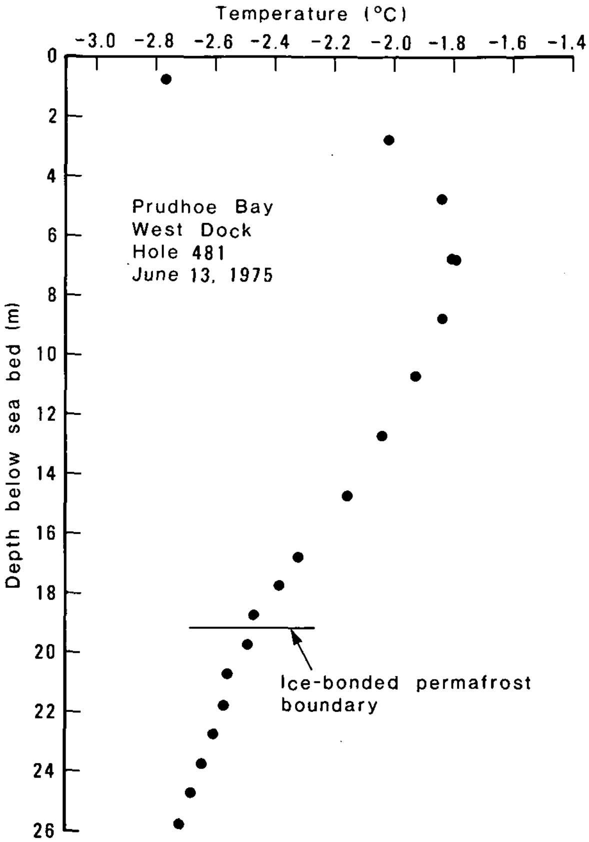

FIGURE 9. Temperature profile in coarse-grained subsea permafrost sediments at Prudhoe Bay near the west dock. The permafrost is thawed above the break in the temperature gradient at 19.3 m and is ice-bonded below it.

Holes for temperature logging along the Beaufort Sea coast have been drilled near Tekegakrok Point (in Elson Lagoon), Lonely, Harrison Bay, Long Island, Thetis Island, Jeanette Island, Prudhoe Bay, Flaxman Island, and in many of the off-shore islands. All of these holes were drilled in areas where the shoreline retreat rate is of the order of a metre or more per year. Typically, the temperature profiles for a line of holes near the west dock at Prudhoe Bay show that, near-shore, where the sea ice freezes to the sea bed at about 1.7 m water depth or less, the subsea permafrost is relatively cold while farther off-shore a warming effect is found (Figure 8). Hole PB-9 is on-shore and holes 190 and 3370 are 190 m and 3370 m offshore respectively.

Temperature profiles in off-shore islands in the Beaufort Sea suggest that present MAT on them are about -10 to -12°C which is somewhat colder than on land (about -9°C). All the islands were underlain by ice-bonded permafrost but drilling information suggests the presence of unbonded layers at depth. Much more information will be required in order to develop an understanding of the complex permafrost regime of these islands.

Use of the measured temperature profiles to determine the presence of subsea permafrost is obvious since it is usual to define permafrost as soil with temperatures less than 0°C for at least two or three years without regard for the phase of the soil pore water. It is more difficult to determine the thickness of subsea permafrost since none of the access holes penetrate it. However, in some cases, it is possible to determine crudely the depth to the 0°C isotherm by extrapolation of the measured temperature profiles (*see* Figure 7). All of the holes in the Beaufort Sea are too shallow to do this although the procedure appears to be useful in the Chukchi Sea. This procedure does not yield the thickness of ice-bearing or ice-bonded permafrost due to the freezing point depression (FPD) of the sub-permafrost water and the existence of a transition zone of ice-bearing permafrost (Osterkamp and Payne 1981).

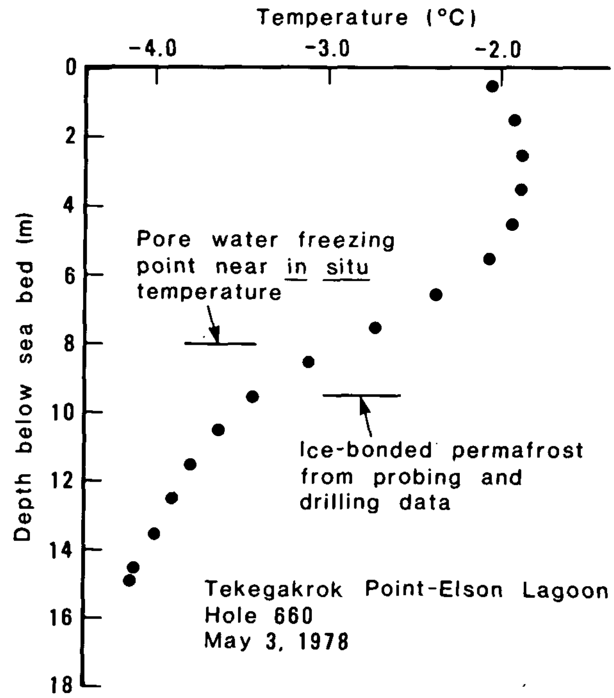

FIGURE 10. Temperature profile in fine-grained sediments near Tekegakrok Point. The profile is curved and smooth through the transition zone so that it is difficult to detect the presence of ice-bearing or ice-bonded permafrost on the basis of the temperature profile alone.

A determination of the thickness of thawed or non-ice-bearing sediments at the sea bed is also made difficult by the FPD of the interstitial soil pore water. The soil pore water remains liquid at temperatures less than 0°C because of the presence of salts, soil particle effects and *in situ* pressures in excess of atmospheric pressure. The effect of the salts seems to be dominant. The measured temperature profiles in subsea permafrost suggest that FPD of the soil pore water by salts may commonly be 2 to 3°C (Figures 9 and 10) and sometimes more.

Salts and soil particle effects produce unfrozen soil pore water which can co-exist with ice at temperatures less than the FPD (Anderson and Morgenstern 1973). The amount of ice increases and the amount of unfrozen soil pore water decreases with decreasing temperature. This consideration leads to the concept of a transition zone between the thawed zone and the ice-bonded permafrost zone. The ice content in the transition zone is thought to increase from zero to a value sufficient to bond the soil particles together so that the transition zone is said to be ice-bearing. A temperature profile in relatively coarse-grained soils (*see* Figure 9) shows a fairly sharp break where the permafrost becomes ice-bonded (as indicated by probing and drilling) suggesting that the transition

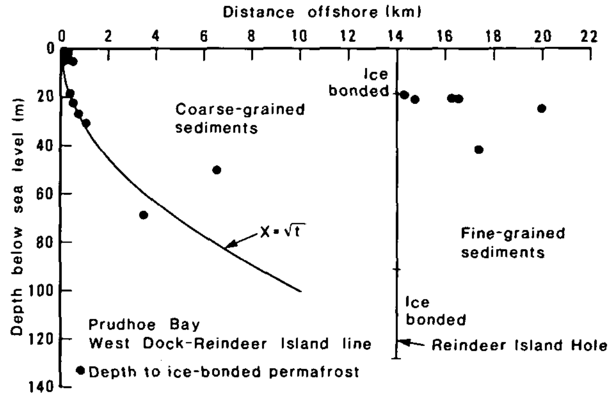

FIGURE 11. Depth to the ice-bonded permafrost table determined from temperature data, probing, and drilling in a line of holes at Prudhoe Bay near the west dock (Harrison and Osterkamp 1977, 1979, and 1981; Osterkamp and Harrison 1976, 1978, and 1980).

zone is thin or absent. This sharp break in the temperature profile is related to the difference between the thermal conductivity of the thawed and frozen soils when there is little or no unfrozen water in the frozen soil, and to the net heat flux into the phase boundary. A temperature profile in fine-grained soil (*see* Figure 10) shows only a curvature of the profile through the transition zone. This curvature is related to the continuous variation of the thermal conductivity with ice content (or equivalently with unfrozen water content) and to the net heat flux into the phase boundary. The FPD of the soil pore water reached the *in situ* temperature at a depth of eight metres while the probing and drilling data suggest that the permafrost is ice-bonded between nine and ten metres (Harrison and Osterkamp 1979). Therefore, the thickness of the ice-bearing permafrost (transition zone) may be about 1 to 1½ m in this case. The temperature profile in Figure 10 also shows some curvature down to 11 or 12 m, where it becomes linear, suggesting that some of the pore water remains unfrozen below the point where the soil is ice-bonded. The presence of unfrozen soil pore water and the resulting temperature profile that varies continuously through the level of ice-bonded permafrost makes it difficult to detect the presence of ice-bearing or ice-bonded permafrost in these fine-grained soils using temperature data alone. Probing, drilling, pore water chemistry, and borehole heating data (Osterkamp and Harrison 1980) are then needed to detect the presence of ice and ice-bonding in the formation.

Depths to the ice-bonded permafrost table were determined by temperature measurements, probing and drilling data and are given in Figure 11 (Lachenbruch and Marshall 1977; Osterkamp and Harrison 1976; Sellman *et al.*, 1976). The MAT and temperature at the ice-bonded permafrost table (phase bound-

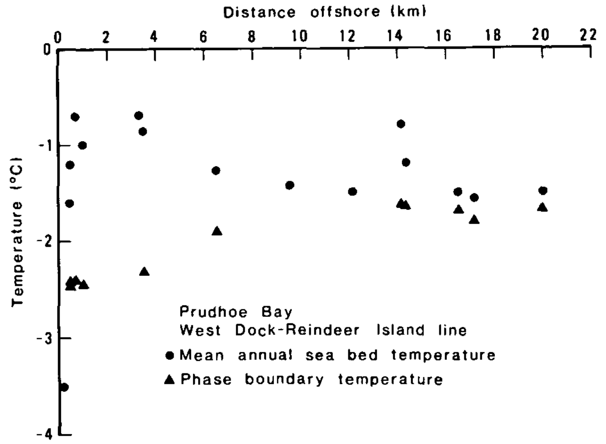

FIGURE 12. Variations of mean annual sea bed temperature (MAT) and phase boundary temperature (PBT) with distance off-shore at Prudhoe Bay near the west dock. The temperature difference is responsible for the heat transfer to the phase boundary from the sea bed.

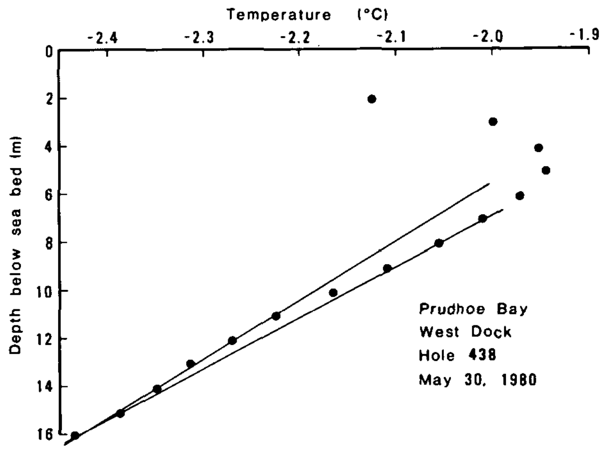

FIGURE 13. Measured temperature profile at Prudhoe Bay near the west dock at a distance of 438 m off-shore. The deviation of the measured profile from a linear one between 8 and 16 m may have been caused by an upward motion of pore water of 0.1-0.2 m/a or by greater than normal sea bed temperatures during the past year.

ary temperature, PBT) along a line of holes extending from near the west dock to Reindeer Island and then northward from the island are given in Figure 12. The depth to the ice-bonded permafrost table increases approximately (*see* Harrison and Osterkamp, 1981*b*, for a more precise relationship) as $(t)^{1/2}$, where t is the time in years, and where an off-shore site has been inundated assuming a shore-line retreat velocity of 1 m/a. This relationship, based on diffusive heat transport (Stefan theory) does not hold near the beach, nor far off-shore where the sediments become fine-grained. Harrison and Osterkamp (1978) have concluded that the rate of thawing in these coarse-grained soils is limited by heat transport rather than salt transport which are thought to be diffusive and convective, respectively. In the fine-grained sediments beyond Reindeer Island, it appears that thawing is controlled by diffusive transport of salt to the phase boundary. Further details are discussed by Harrison and Osterkamp (1982).

The MAT increases with distance off-shore, exponentially with water depth, to the three-metre depth (Harrison and Osterkamp 1977), but then decreases slightly when the water depth exceeds three to four metres to a value of about -1.5°C. The PBT is nearly constant at about -2.4°C between 0.4 and 3.5 km off-shore and then increases to about -1.7 to -1.8°C seaward of Reindeer island. The reasons for the behavior of the MAT and PBT are not well understood at this time. It is the difference between them that drives the heat transfer from the sea bed to the phase boundary and the PBT is also related to the salt concentration at the phase boundary through the requirements for phase equilibrium.

Determination of thermal parameters such as thermal conductivity and ice content may be possible from analysis and interpretation of temperature data in artificially heated access holes. It appears that the thermal conductivity can be obtained under certain conditions, such as in the thawed zone or in the colder ice-bonded permafrost where no unfrozen pore water is present (Osterkamp and Harrison 1980). Much more work is required to develop these methods.

A line of holes extending off-shore can be used to determine, within limits, the stability of a shore-line and to estimate the shore-line erosion rate. An analysis of the temperature profiles (*see* Figures 7 and 8). at Barrow and Prudhoe Bay, suggests that the shoreline is relatively stable at Barrow (on the Chukchi Sea coast) and is retreating at roughly 1 m/a at Prudhoe Bay.

It is theoretically possible to estimate the sign and order of magnitude of the vertical flow velocity of the interstitial pore water from deviations of measured temperature profiles from linearity at depth. A measured temperature profile at the west dock deviates from linearity at depth (Figure 13). Preliminary calculations show that the deviation is consistent with an upward pore water velocity of 0.1 to 0.2 m/a. Unfortunately, other interpretations, such as greater than normal warming of the sea bed during the previous year, are also possible. A few other temperature profiles, measured during previous years, show a similar behavior and it appears that the effects of pore water motion should be observable based on interpretation of salt concentration profiles (Harrison and Osterkamp 1982). Additional temperature measurements and interpretation will be required to resolve the problem.

When the measured temperature profiles are combined with measured salt concentration profiles and other information, models of subsea permafrost and its distribution and evolution with time can be constructed (e.g., Lachenbruch and Marshall 1977; Harrison and Osterkamp 1978). Such information can also be combined with geological data to derive hypotheses with regional application such as Hopkins and Hartz (1978) paleo-river valley hypothesis for the distribution of shallow ice-bonded subsea permafrost.

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