Contract no. - 01-50-22-2313
Research Unit no. - RU105
Reporting period - 1 April 1976 - 31 March 1977
Number of pages - 10

ANNUAL REPORT

DELINEATION AND ENGINEERING CHARACTERISTICS OF PERMAFROST BENEATH THE BEAUFORT SEA

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1 April 1977

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I. SUMMARY

The overall objectives of the CRREL participation in the subsea permafrost program are to quantify the engineering characteristics of permafrost beneath the Beaufort Sea and to determine their relationship to temperature, sediment type, ice content and chemical composition. These data, in conjunction with those obtained from other Beaufort Sea geological projects, are being used to ascertain the distribution of subsea permafrost. The CRREL spring 1976 drilling and *in situ* probing investigations provided numerous samples, data, and subsequent interpretations and have furthered our understanding of subsea permafrost.

Permafrost was present in the four holes drilled at Prudhoe Bay. Ice-bonded permafrost was absent in the upper 30 meters of sediment up to 17 kilometers from shore. Based on negative temperature gradients and pore water chemistry, ice-bonded permafrost should be encountered at 30- and 43-meter depths at sites PB-2 and PB-3, respectively. It appears that the depth to the ice-bonded permafrost decreases with increasing distance from shore and depth of water. Highly overconsolidated marine clays were encountered seaward of Reindeer Island. The overconsolidation probably resulted from the freeze-thaw history. The presence of these stiff, marine clay deposits is an important consideration for siting structures associated with offshore developments.

Adequate delineation of the engineering properties of subsea permafrost is necessary in order to evaluate the hazards in and constraints of oil and gas developments in the Beaufort Sea.

II. INTRODUCTION

CRREL's involvement in the BLM-OCS subsea permafrost program was designed to provide the near-surface samples and data necessary to characterize engineering properties of subsea permafrost. We are working closely with the USGS and University of Alaska OCS projects and the ongoing ONR project of Lewellen which was previously based at Barrow. Our efforts involve rotary drilling and drive sampling and shallow probing using the spring ice cover as a stable platform. The two-year investigation is limited to the Prudhoe Bay area; however, the combined results of our studies and others can be cautiously extrapolated to other areas along the U. S. Beaufort Sea coast.

Specific objectives can be listed as follows:

(1) Drill the subsea permafrost at Prudhoe Bay, obtain undisturbed samples, conduct engineering tests on the samples, and provide access holes for temperature logging.

(2) Evaluate probe methods for rapid acquisition of subsea engineering and thermal data.

(3) Determine the chemical composition of the interstitial pore water.

Data collected and their interpretation will provide the information necessary to evaluate the subsea permafrost hazards which may exist during petroleum exploration and development. Identification of these potential hazards will lead to the development of appropriate constraints or guidelines and will provide the background data for industry-sponsored, site-specific investigations.

III. CURRENT STATE OF KNOWLEDGE

The data from several drilling programs supported by NOAA and industry at Prudhoe Bay and the Navy (ONR) program at Barrow indicate that permafrost is present to depths in excess of. 80 meters. One additional industry hole on Reindeer Island in Prudhoe Bay suggests bonded permafrost existed in two zones from 0 to 20 m and from 90 to 125 m, although this hole was never thermally logged. The studies conducted by Osterkamp and Harrison (1976)* in Prudhoe Bay established the depth of bonded permafrost along a single line in upwards of 2 meters of water. Lewellen's drilling program at Barrow indicates that bonded permafrost is very near the surface in the zone along the coast where sea ice freezes to the seabed. Thermal data indicate that subsea permafrost is present at least 17 km offshore at Prudhoe and 11 km offshore at Barrow.

Considerable subsea permafrost is indicated by the Canadian government and industry studies from the Mackenzie River region. Drilling and thermal data there have confirmed the widespread presence of subsea permafrost. The top of the bonded permafrost was mapped based on industry seismic investigations.

Other OCS subsea permafrost projects cover the current state of knowledge in more detail.

IV. STUDY AREA

The 1976 drill sites were jointly selected by USGS and CRREL personnel to provide a range of thermal and depositional settings. Two sites were situated within Prudhoe Bay and one site was located north of the barrier islands. These sites were accurately positioned in the field by USGS personnel using a Del Norte ranging system which, based on electronic triangulation, can locate stations with 1 meter (3 ft) accuracy.

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*Osterkamp, T. E. and W. D. Harrison, 1976. Subsea permafrost at Prudhoe Bay, Drilling Report. Geophysical Institute Report UAG-R-245, University of Alaska

Detailed information for each site is:

Site	General location	Lat/Long	Water depth (m)	Hole depth from drill collar (m)
PB-1	Approximately 2 miles north of old ARCO dock in center of Prudhoe Bay	70°20.9'N 148°19.3'W	2.7	33.8
PB-2	Approximately 2 miles north of Reindeer Island	70°30.7'N 148°18.1'W	11.6	42.8
PB-3	Approximately 3 miles northeast of the new ARCO dock	70°25.9'N 148°26.6'W	5.9	51.5

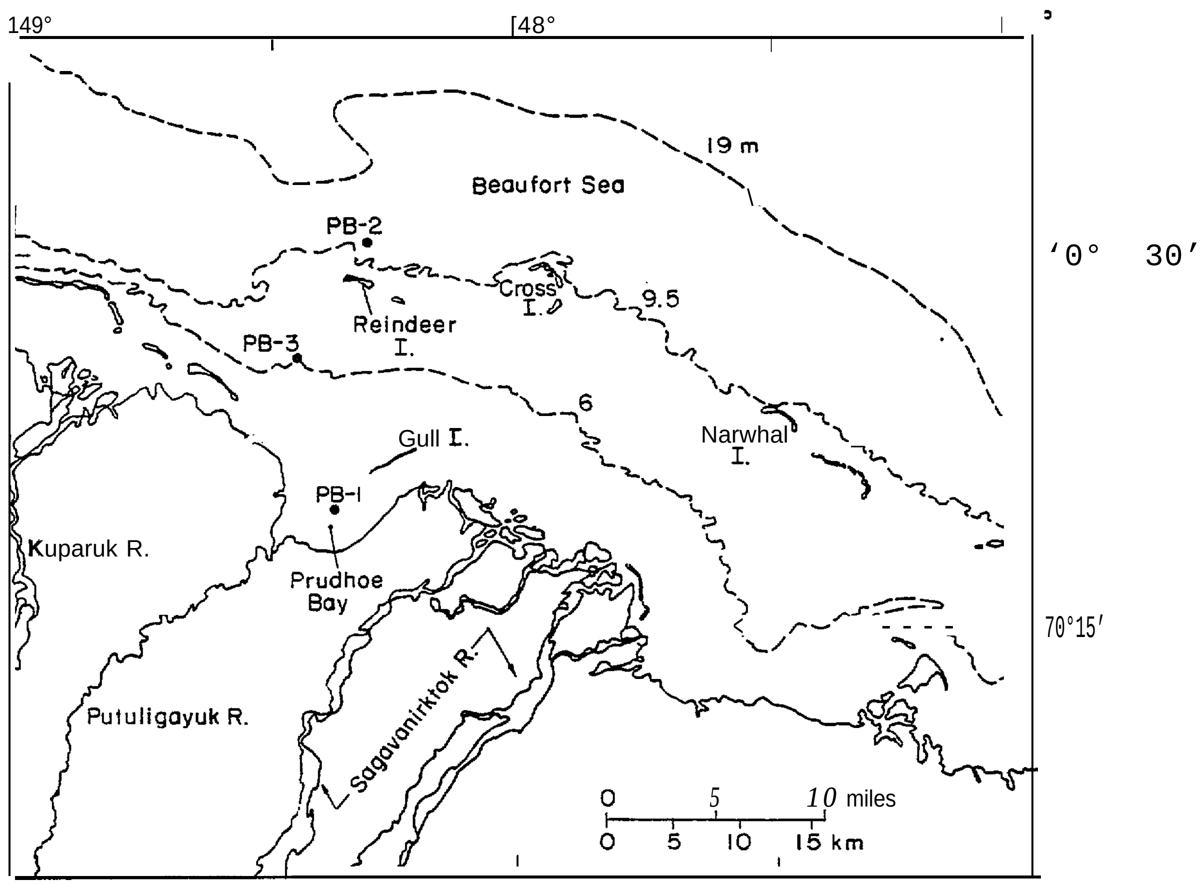

Figure 1. Location map for CRREL 1976 drill sites

SOURCES, METHODS AND RATIONALE OF DATA COLLECTION

CRREL Special Report 76-12, entitled "Operational Report, 1976, USACRREL-S Subsea Permafrost Program, Beaufort Sea, Alaska," by P. V. Sellmann, I. Lewellen, H. T. Ueda, E. Chamberlain, and S. E. Blouin presents details of the 1976 sample acquisition and operations. Briefly, an Acker drill and a Bean horizontal Triplex pump were employed for the drilling. Most samples were obtained by drive sampling thereby reducing the potential for chemical contaminant ion. Rotary sampling techniques were used in coarse-grained materials.

The holes were logged at the time of drilling to provide a complete description of the materials encountered. These logs were based on 1) cores, 2) wash samples, and 3) drillers' observations of penetration characteristics. Preliminary logs of these holes were prepared by the USGS and are reported elsewhere (Sellmann et al. 1976).

Subsampling of the core was also completed in the field. Cores were split for detailed examination of engineering properties, chemical analysis, dating and paleontology. The cores were subsequently boxed and transported to one of two locations, CRREL, Hanover, or the USGS, Menlo Park.

On completion of a hole, a 5cm plastic (PVC) casing was installed for thermal logging purposes. Temperature measurements were made at these sites the USGS personnel using a thermistor probe. Temperature profiles were obtained after the installation of the PVC casing and on several occasions after the initial logging. Sites were revisited as late as early June in an attempt to establish equilibrium profiles for each hole. Results of this study are covered in USGS reports.

Both dynamic and static penetrometer tests in the sediments were conducted using the sea ice as a platform. For the dynamic tests, a standard 64-kg hammer dropped 0.76 m was used to drive the probe string, which was made up of EW drill rod surrounded by EX casing. The probe consisted of a 60° hardened steel cone attached to the drill rod and a 150-mm-long sleeve welded to the base of the casing. The cone and sleeve both had a diameter of 57 mm. The point and sleeve could be driven simultaneously or separately by temporarily adding 0.3-m sections of casing or rod at the top of the probe string as desired. The static penetrometer used the same probe string and was pushed by a hydraulic cylinder mounted atop a quadropod anchored to the sea ice. The temperature profile was determined by filling the bore of the rod with a non-freezing fluid and inserting a thermistor temperature probe. Normally, the temperature in the drill rod fluid was allowed to stabilize 12 hours before readings were taken.

B In the laboratory, undrained, unconsolidated triaxial compression tests were conducted at confining pressures estimated to be equivalent to the <u>in situ</u> overburden pressures on samples prepared from core specimens obtained from the three drill sites. The samples were 50 mm in diameter and 115 mm in length. The samples were tested unfrozen, the test temperatures being maintained at 0°C ± 1°C (chemical analysis of the pore water revealed that the freezing point was -1.8°C or lower). The tests were conducted at a constant rate of strain of approximately 0.045/min.

Interstitial water was extracted from thawed PB-1 and PB-3 samples by centrifugation at 3000 rpm for 30 minutes using special filtering centrifuge tubes commercially available from Millipore Corporation made of plastic and Teflon to assure that the samples were kept free of metal contamination. Interstitial water was extracted from PB-2 samples by shaking the sample with 20 ml of deionized water for one hour, then centrifuging as above, because of low water contents.

Immediately after extraction, interstitial water was analyzed for carbonate, bicarbonate, and PH. The total soluble salts (expressed as specific conductance) were determined by electrical conductivity measurements. A Model A Beckman pH meter was utilized for pH measurements. Carbonate and HC03 were determined by titration in the presence of phenolphthalein and M.O. indicators. A 303 Perkin-Elmer Atomic Absorption spectrophotometer was used for analyses of sodium, potassium, calcium, and magnesium. Calcium and magnesium were determined in the presence of 0.1% lanthanum. Chloride was determined by titration with AgN03 and sulfate was determined according to Hach Chemical methods.

VI, VII. RESULTS AND DISCUSSION

The main results of the 1976 field project have been summarized in two papers intended for presentation at the Third International Conference on Permafrost in Edmonton, Alberta, Canada, July 1978. These papers are:

(1) Engineering properties of subsea permafrost in the Prudhoe Bay region of the Beaufort Sea -- E. J. Chamberlain, P. V. Sellmann, S. E. Blouin, D. M. Hopkins, and R. I. Lewellen.

(2) Chemistry of interstitial water from subsea permafrost, Prudhoe Bay, Alaska -- 1. K. Iskandar, T. E. Osterkamp, and W. D. Harrison.

In addition, a more detailed report on the engineering properties has been prepared for CRREL publication. A bibliography of Soviet subsea permafrost and related investigations was prepared. This bibliographic effort has been transferred to Dr. Vigdorchik at INSTAAR, University of Colorado.

The following highlights the results of our investigations to date, but intentionally leaves out extensive reference to the data. Preprints of the above reports are available upon request.

The field logs all show a fine-grained surface section of marine sediments (fine sand, silt and clay) 4.5 to 8.8 m thick. These appear to overlie beach sediments (well-rounded gravel, coarse sand and some mud). The lower part of the marine mud sequence at site PB-2 contains abundant small pebbles and granules. The fine-grained marine materials are soft and weak at sites PB-1 and PB-3 while at site PB-2 they appear to be very stiff and overconsolidated. The marine sequence is underlain by poorly sorted angular gravel lacking any organic remains and appears to be approximately 18 m thick at sites PB-1 and PB-3 and less than 5 m thick at PB-2. All boreholes terminate in what appears to be an alluvial section of well-sorted sand, pebbly sand and gravel containing lenses of detrital wood and plant fragments. The index properties reveal that, with few exceptions, the fine-grained silts and clays at sites PB-1 and PB-3 have the high moisture contents commonly encountered in marine environments, while the clays at site PB-2 have lower water contents in the range of their plastic limits.

As no ice-bonded samples were recovered, it was initially concluded that ice-bonded permafrost lay at some unknown distance beneath the bottom of the drill holes. However, because of the extremely difficult driving conditions at the termination depths at PB-2 and PB-3, it was suspected that ice-bonded permafrost might have been encountered. From our chemistry data, it is estimated that the freezing point of the interstitial water at *sites* PB-2 and PB-3 was approximately $-1.8^{\circ}C$. Extrapolating the straight line segments of the USGS temperature profiles downward to intercept the $-1.8^{\circ}C$ isotherm resulted in estimated depths to ice-bonded permafrost for sites PB-2 and PB-3 of 29.9 and 43.3 m respectively. These depths correlate extremely well with the 29.5- and 44.2-m depths at which drilling and sampling was terminated because of collapsed casing or very high penetration resistances. Since site PB-2 is farther from shore and in deeper water than site PB-3, it appears that the depth to ice-bonded permafrost decreases with increasing distance from shore and water depth.

Field Tests: At site PB-1, the static penetration resistances were very low (< 2 megapascals) throughout the fine-grained section. Upon entering the coarser-grained sands and gravels, the static penetration resistance rapidly increased to 24 megapascals, where measurements were terminated. Because of equipment difficulties, dynamic penetration data were obtained only in the fine-grained section. The range of penetration resistances was between 12 and 24 blows per meter.

At site PB-2, a few static penetration results were obtained, but they are of questionable quality because of rod buckling problems in the deep water. The dynamic cone capacity rises sharply in the upper 1.4 m of silty sand to nearly 200 blows/m and falls abruptly to 50 to 100 blows/rein the clays beneath.

The cone penetration data at site PB-3 show the best correlation. Both the static and dynamic cone penetration data show an increase of penetration resistance through the upper meter of loose silty sand, a relatively constant penetration resistance through the next meter of more compact silt, and a decrease in the next 0.5 m of softer silts to *a* relatively low penetration resistance in the next 2½ m of very soft silt. At *a* penetration depth of approximately 5 m a very stiff layer of sand was encountered and the penetration resistance increased rapidly with increasing penetration depth.

The greatest penetration depth was achieved at an auxiliary site (PB-4). Using the dynamic cone penetrometer, approximately 11 m of penetration *was* achieved, the penetration resistance being approximately 100 blows/m below a depth of 2 m with an increase to near 250 blows/m near 10 m of penetration. The static cone penetration resistance increased to 8 MPa at the 2-m penetration depth and remained constant to 5 m depth.

Laboratory Strength Tests: For site PB-1, sediments are weak to a depth of [illegible] m or more, the maximum shear strength being 45 kilopascals, while at a depth near the boundary of the fine-grained marine sediments and the coarser-grained glacial outwash material the shear strength increases to 134 kilopascals.

At site PB-2, there is a gradual but significant increase of shear strength with depth. In the overlying sandy material, the shear strength is approximately 84 kilopascals. Near the top of the stiff marine clay section, the strength is only a slightly greater 92 kilopascals but it increases to 225 kilopascals near the bottom.

At site PB-3, the shear strength decreases with depth in the marine section as softer and finer-grained materials are encountered. In the upper half of this section, the strength is as high as 107 kilopascals, while near the bottom it is approximately 28 kilopascals.

Because the clay samples taken from site PB-2 appeared to be overconsolidated, laboratory consolidation tests were conducted on two selected samples, one obtained from core PB-2-05 and the other front PB-2-07. These tests revealed overconsolidation stresses of 3800 and 3600 kilopascals, respectively. The resulting overconsolidation ratios (the ratio of the overconsolidation pressure to the in situ stress) were 99 and 53.

Chemistry: Hole PB-1 is located in the center of a. small closed basin where there was 0.72 m of water under 1.90 m of sea ice. The conductivity of the water under the ice was 93 mmhos/cm, which indicates that the water was not subject to circulation or mixing with sea water. The conductivity of the interstitial water varied from 61 to 72 mmhos/cm. Conductivity values of interstitial water from PB-3 sediments were essentially constant with depth and ranged from 43 to 51 mmhos/cm. The conductivity of overlying sea water was about 53 mmhos/cm. With the exception of the top sample from PB-2, the conductivity of the interstitial water from the PB-2 sediments was similar to that of the sediments from PB-3 . Sea water from PB-2 showed slightly lower conductivity values than sea water from PB-3 (49-50 mmhos/cm).

Analysis of interstitial water for selected ions indicated that chloride ranged from 20 to 30 parts per thousand (ppt) in PB-1 and from 12 to 19 ppt in PB-3 . Sulfate ranged from 2 to 11 ppt in all the samples. Bicarbonates were very low as expected (<0.5 ppt). Calcium and magnesium ranged from 0.2 to 0.8 ppt and from 0.3 to 0.9 ppt, respectively. In general, potassium in interstitial water was higher than that in sea water samples.

The top 4 meters of the sediments near shore (PB-1 and PB-3) contain much higher $CaCO_3$ than the sediment further offshore (PB-2). Values of $CaCO_3$ in the former ranged from 15.5 to 21.3% in PB-1 and from 13.9 to 27.5% in PB-3. This could best be explained by ion exchange reaction in the sediment-brine systems. [illegible] high concentration of NaCl, Na displaces Ca and Mg from the exchange sites, then precipitates $CaCO_3$ and $MgCO_3$ as the concentration in the interstitial water exceeds the volubility product. In contrast, organic carbon was very low (<3%) and was slightly higher in PB-2 than in PB-3.

11. CONCLUSIONS

1. Temperatures below 0°C were present at all sites studied during the spring of 1976.

2. Ice-bonded permafrost did not occur within the upper 30 m of subsea sediments in a region extending from 1 to 17 km distance offshore.

3. Negative gradients in thermal data and analysis of pore water chemistry *suggest* that ice is present at 29.9- and 43.3-m depths at sites PB-2 and PB-3 respectively. Because *site* PB-2 is in the deepest water and is farthest from shore, it appears that the depth to ice-bonded permafrost may be decreasing with increasing distance from shore.

4. Shallow, highly overconsolidated marine clays occur seaward of Reindeer Island, while softer marine muds occur inside the barrier island along our study line. The dense marine *clays* probably have been overconsolidated by freezing and thawing.

5* In situ cone penetration resistance data can be obtained using the sea ice as a platform. This information can be used to delineate the occurrence of soft and stiff marine materials as well as dense sands and gravels and provide rapid access for thermal data.

6. Salinity and ionic composition of interstitial water from Prudhoe Bay subsea permafrost vary from site to site. Conductivity of the interstitial water ranged between 43 and 72 mmhos/cm, but is relatively uniform in each section.

Ix. NEEDS FOR FURTHER STUDY

The 1976 and 1977 subsea permafrost drilling and probing project was confined to the Prudhoe Bay area. The results from Prudhoe and the previous studies at Barrow provide only two points for the entire U. S. Beaufort Sea. A third area to the west of the Colville River delta should also be drilled in order to provide desired ground truth for regional maps and models. Data from additional offshore environments including areas of major fresh water discharges, areas of rapid coastal. erosion and offshore deposition, and deeper shelf waters should also be investigated for subsea permafrost. It is also desirable to have at least one hole that penetrates the bonded permafrost in deep water (20 to 30 meters deep).

Complementary to the drilling approach are the analyses of the existing first-return seismic data obtained by industry. We have begun to explore the availability and costs of these data. Assuming they are available, funds will be required *to* process and interpret them.

SUMMARY OF 4TH QUARTER OPERATIONS

A. Field Activities

1. Field trip schedule: During January and February, activities consisteal of attendance at two workshops: the National Academy of *sciences* Committee

Permafrost Workshop in Hanover, NH, and the OCSEAP's Workshop at Barrow, Alaska. The Committee on Permafrost meeting 6 and 7 January 1977 devoted one-half day to reviewing the status of subsea permafrost. Prior to the meet-g, all CRREL project personnel met for two days with other subsea permafrost vestimators including Osterkamp, Lachenbruch and Hopkins. The discussions summarized plans for 1977 and provided an opportunity to explore means by which industry-obtained geophysical data could be employed for the OCS investigations. Sellmann followed up with a visit to the Geological Survey of Canada in Ottawa to further explore the requirements for processing the near-surface offshore seismic data.

The Barrow Workshop, summarized elsewhere, led to the development of a general but speculative map of subsea permafrost distribution for the U. S. Beaufort Sea. On the return from Barrow, a short visit was made to Prudhoe Bay by Sellmann and Osterkamp to arrange for spring logistics and to further assess the ice thickness. On 3 March, ice thicknesses ranged between 45 and 48 in. Before committing the spring drilling project to the field, Dr. Nevel of CRREL was asked to evaluate the minimum sea ice thickness required for the various drilling and probing operations. It was ascertained that ice thicknesses of 34 in. would provide adequate strength for the rotary drilling and camp operations.

The 1977 field party departed Hanover for Prudhoe Bay on 21 and 22 March 1977. The first week at Prudhoe Bay was spent mobilizing the equipment, some which had been shipped by truck from Hanover, NH to Prudhoe Bay in Febru-. The drilling party was on the ice and ready to drill on 30 March 1977.

2. Scientific Party as of 1 April 1977 at Prudhoe Bay consisted of the following:

Scott Blouin	CRREL	Probe investigations
Edwin Chamberlain	CRREL	Engineering tests and core logging
Allan Delaney	CRREL	Drilling support
Donald Garfield	CRREL	Probe investigations
David Hopkins	USGS	Geology
Robert Lewellen	Arctic Research	Drilling and thermal investigations
Paul Sellmann	CRREL	Drilling and geology
Herbert Ueda	CRREL	Drilling support

3. Methods - Field sampling and laboratory analyses.

The 1977 program will be based on equipment and methods described in the 1976 operational report (Sellmann et al. 1976). Heavier casing and a pneu-ic casing hammer are being employed. A State of Alaska Miscellaneous Land Use mit was arranged for by the OCSEAP Fairbanks Office.

4. Sample locations -- Spring 1977 sites will be reported upon in the next quarterly report.

5* Data collected or analyzed -- No new field data were collected during the quarter.

6. Milestone charts -- All activities are on schedule.

B. Problems encountered/recommended changes

In general, planning and implementation of the field program have progressed reasonably well. Project personnel have had to devote considerable time to logistics as well as in responding to OCS requests and meetings. Although these are necessary to fulfill the overall objectives of the program, they detract from completion of the technical aspects of the scientific project.

C. Estimate of funds obligated.

As of 31 March 1977, a total of $93,500 of the total $225,000 FY77 funding had been obligated.