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REGIONAL DISTRIBUTION AND CHARACTERISTICS OF BOTTOM SEDIMENTS IN ARCTIC COASTAL WATERS OF ALASKA

Review of Current Literature

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This report includes a discussion of some of the properties and characteristics of offshore marine sediments found in the U.S. Beaufort Sea that could influence aspects of offshore development. A collection of references is also included in an appendix.

Perennially and seasonally frozen sediments are extremely common, with variable distribution and properties. The depth to the top of icebonded permafrost can be as little as 7 m below the seabed many kilometers from the sea coast. The subsea permafrost can contain visible ground ice similar to that

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observed on land, and can be anticipated to cause problems at least as great as those experienced on land.

The distribution and properties of fine-grained sediments are also variable with evidence that they are commonly overconsolidated. The distribution and properties of these sediments can be important in influencing access to material suitable for construction of offshore structures, such as islands. The possible occurrence of gas hydrates and some of industry's experience with this form of natural gas are also discussed.

A recent paper by Barnes and Reimnitz (1979) provides new information on redistribution of seabed sediments during periodic events. Their observations suggest that previous estimates of gouge frequency and maximum depth can be conservative, and that gouging and sediment infilling can be more dynamic than previous data may indicate.

PREFACE

This report was prepared by Paul V. Sellmann, Geologist, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. It was prepared for the U.S. Geological Survey, Office of Marine Geology to provide part of the guidance for evaluating the stability of offshore structures in polar waters.

Technical review of the report was performed by Dr. Malcolm Mellor and Edwin Chamberlain of CRREL.

REGIONAL DISTRIBUTION AND PROPERTIES OF BOTTOM SEDIMENTS

This topic was covered comprehensively in the recent Beaufort/ Chukchi Sea Interim Synthesis Report (OCSEAP, 1978), with emphasis placed on the U.S. Beaufort Sea. Most oceanographic data on bottom sediments deal with observations very near the bed and only limited data exist from deeper drill holes. Both indicate great variability in sediment type and properties. As a result most development activities will have to include detailed site-specific studies. The material that follows is from the OCSEAP synthesis report and is presented verbatim. It is followed by a short discussion that qualifies some of the statements made in the synthesis report. This discussion derives primarily from new information obtained during the recent USGS Conservation Division program (USGS Contract Report, 1979) on the extensive distribution of fine-grained sediment at depth on the Beaufort Sea shelf, which will influence activities such as island construction.

Some sediment property data from the Prudhoe Bay area, for sediments that are not ice-bonded, are also included (from Sellmann and Chamberlain, 1979).

Bottom Sediment Distribution and Character (from OCSEAP, 1978)

> The bottom sediments are reasonably well mapped between Point Barrow and Canada, except on the inner shelf west of Cape Halkett and east of the Canning River (Figure [1])(Barnes and Reimnitz, 1976; Naidu and Mowatt, 1974). The sediment character of the Chukchi Sea floor is fairly well known, primarily from the work of Creager and McManus (1967). Extreme diversity even over short distances is perhaps the most distinctive characterictic of arctic shelf sediments.
>
> The sediments consist chiefly of poorly sorted silty clays and sandy muds containing varying amount of intermixed gravel. The sediments become generally coarser eastward; clayey sediments predominate on the continental shelf west of Cape Halkett and areas of sandy bottom are essentially confined to shelf areas to the east and along the coast (Figure [1]). Lateral variations in mineral assemblages in the sand and clay fraction indicate that the fine sediments are of local derivation, introduced from the major North Slope rivers and by erosion of the coastal bluffs (Naidu and Mowatt, 1974). The finer grain size of bottom sediments

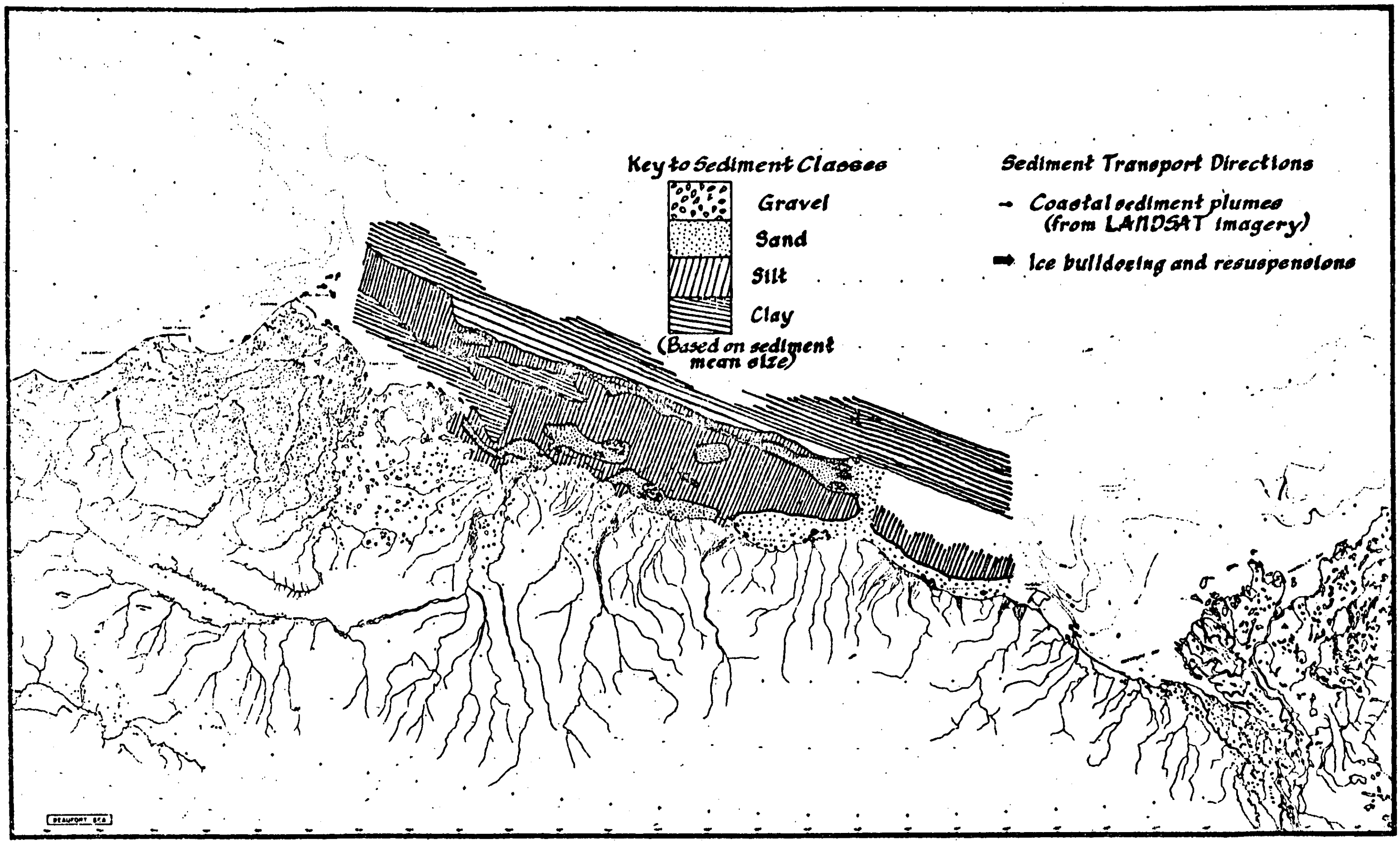


Figure 1. Distribution of bottom sediments and directions of dispersal of sediments by currents and ice. (From OSCEAP 1978.)

west of Cape Halkett reflects the fact that all of the streams west of the Colville River have low gradients and head toward the arctic coastal plain. Rivers east of the Canning flow northward in steep courses from mountains a few tens of kilometers south of the Beaufort Sea coast and bring in coarser material.

Holocene sediment -- that is, marine sediment laid down during the last 10,000 years -- covers only part of the continental shelf. The thicker accumulations consist of silty fine sand and clayey silt less than 10 m thick (Figure [2]). Furthermore, sedimentation rates vary widely. Data from seismic reflection profiling and from the offshore permafrost program suggest rates of less then 10 cm/century for much of the shelf, both inshore and offshore from the barrier islands. However, drillhole data show that sediments in the sheltered basin of Prudhoe Bay have been accumulating at the much more rapid rate of 60 cm/century. High sedimentation rates might be expected off the mouths of the major rivers, but the apparent limited thickness of Holocene sediments and the stability of both the subareal shoreline and the delta front platform off the Colville River seem to indicate accumulation rates of less than 5 cm/century there. By comparison, sedimentation rates are about 10 cm/century on the continental slope north of the Mackenzie River (Pelletier and Shearer, 1972), and rates of less than 5 mm/1,000 years are reported for the deep arctic basin away from sites of turbidite deposition.

Some areas of the shelf lack any substantial thickness of Holocene sediment. In these areas, the Pleistocene Flaxman Formation overconsolidated marine sandy silt containing dropstones of Canadian origin (Leffingwell, 1919) crops out on the sea floor, underlies a few centimeters of soupy, sandy silt, or lies beneath a veneer of gravel.

Patches of gravel and isolated boulders are scattered on the sea bottom. The gravel patches are generally less than 1 m thick and commonly thinner than 15 cm (Figure [2]). They increase in abundance and extend eastward toward the Canadian border and northward toward the outer shelf margin. East of Prudhoe Bay, the gravel consists predominantly of lithologic types that are not native northern Alaska rocks (Rodeick, 1975), but that are found in the Flaxman Formation.

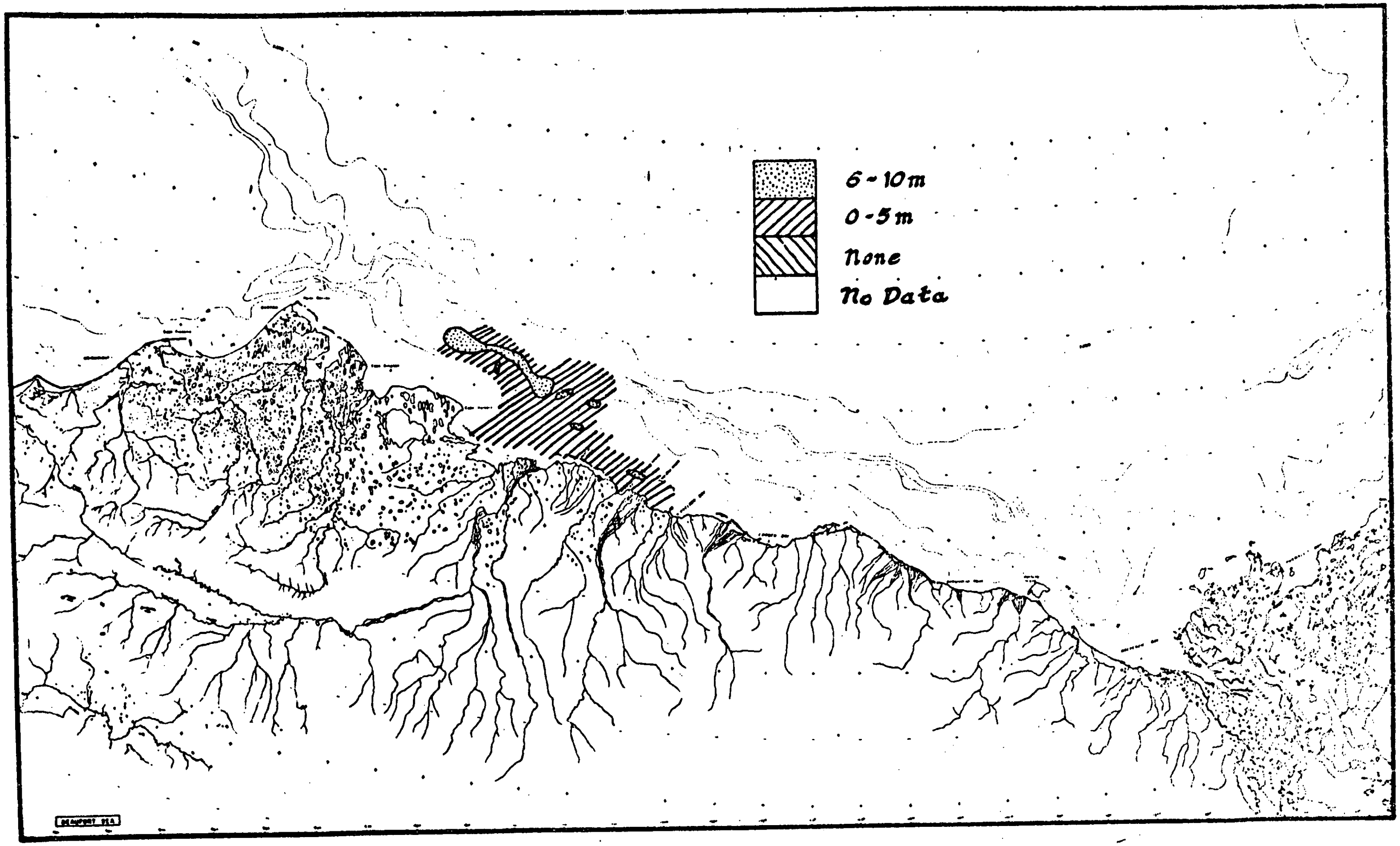


Figure 2. Thickness of recent (Holocene) sediments mapped to date. (From OCSEAP 1978.)

However, chert gravel derived from the Brooks Range is found in shallow water off some mainland beaches, and most barrier islands west of Prudhoe Bay are composed of similar gravel. No gravel is being supplied by modern ice-rafting from distant sources (Barnes and Reimnitz, 1974), and only small amounts are icerafted short distances from local sources. Much of the gravel was supplied by erosion of the coastal bluffs during the transgression, similar to the way in which it is introduced today. The surficial gravel locally and perhaps generally, overlies outcrops of Flaxman Formation on the sea floor. Evidently most of the gravel accumulations are lag deposits that have resulted from the erosion of considerable thicknesses of the Flaxman Formation.

The thickness of gravel deposits merits special consideration, because of the potential requirement for gravel fill for artificial islands and causeways. Aside from the river deposits and the barrier islands, which have been traditional sources of gravel borrow, the only significant gravel sources on the shelf are thought to be widespread Pleistocene gravels lying below finer-grained surface deposits on the shelf. Gravels have been encountered in the permafrost drill holes north and south of Reindeer Island. Access to these gravels may be hindered by the presence of the overlying Holocene marine section and by overconsolidated clays such as those encountered during drilling in the vicinity of Reindeer Island or by the stiff gravelly muds found in vibracores north of Cross and Reindeer Islands.

Studies of soil properties, in detail in the Prudhoe Bay area under the permafrost drilling program (Chamberlain and others, 1978), and reconnaissance information gathered over wide regions using shear vanes, cone penetrometers, and rates of vibracore penetration, show that there are very large variations. The very stiff, overconsolidated silty clay of the Flaxman Formation is dewatered to the plastic limit or lower. The unit apparently underlies large areas of the shelf, locally cropping out at the surface. The Holocene marine sediments, covering the shelf in general with a 5 to 10 m thick layer, have a higher water content and lower strength, but characteristically are much firmer than lower latitude shelf sediments, judging from the lack of coring success with anything but vibratory or rotary tools.

The mechanism causing the overconsolidation of the very dense clays has not been determined with certainty. However, Chamberlain et al. (1978) suggest that the overconsolidation has probably resulted from freezing and thawing. The strength properties and excavation characteristics of the overconsolidated clays are much different from those of more typical, normally consolidated marine silts and clays. For instance, similar overconsolidated clays occur in the North Sea and provide stable foundations for drilling platforms. However, the cyclic action of waves against the drilling platforms causes a significant reduction in the strength of the overconsolidated clays. Access to significant quantities of offshore gravel may require excavation of a surficial layer of the overconsolidated material. For these and other reasons, the distribution and thickness of these sediments is important to the planning for offshore structures.

Discussion

The drilling program sponsored by the Conservation Division of the USGS and conducted by Harding-Lawson Associates provided a considerable amount of new data on the distribution of sediments in the currently proposed lease area on the Beaufort Sea Shelf. The locations of the drill sites for this study are shown in Figure 14.

The logs for these holes indicate that past data from the Prudhoe Bay area obtained by Osterkamp and Harrison (1976) and Chamberlain et al. (1978) create an anomalous impression of the thickness of the fine-grained section that covers the older Pleistocene sediment that is richer in sand and gravel. The recent USGS study suggests that the thick fine-grained section observed off Reindeer Island (Sellmann and Chamberlain, 1979) may be more representative of the region. All of the recent USGS holes removed from possible offshore Paleo-valleys of major rivers revealed extensive thicknesses of fine-grained material. Fine-grained sections thicker than 25 m were frequently observed in the offshore holes east of Prudhoe, with the most easterly hole (No. 18) consisting predominantly of fine-grained material over its 92-m depth. The more nearshore holes contained slightly thinner fine-grained surface surface sections, although more than 10 m of fine-grained material was common. Determining the properties of this fine-grained unit is further complicated by the fact that portions of many of the sections are ice-bonded and commonly consist of dense, overconsolidated materials.

The thickness of this fine-grained material and its properties will have a significant effect on gaining access to the coarser-grained sediment, for island construction, by penetration of the fine-grained

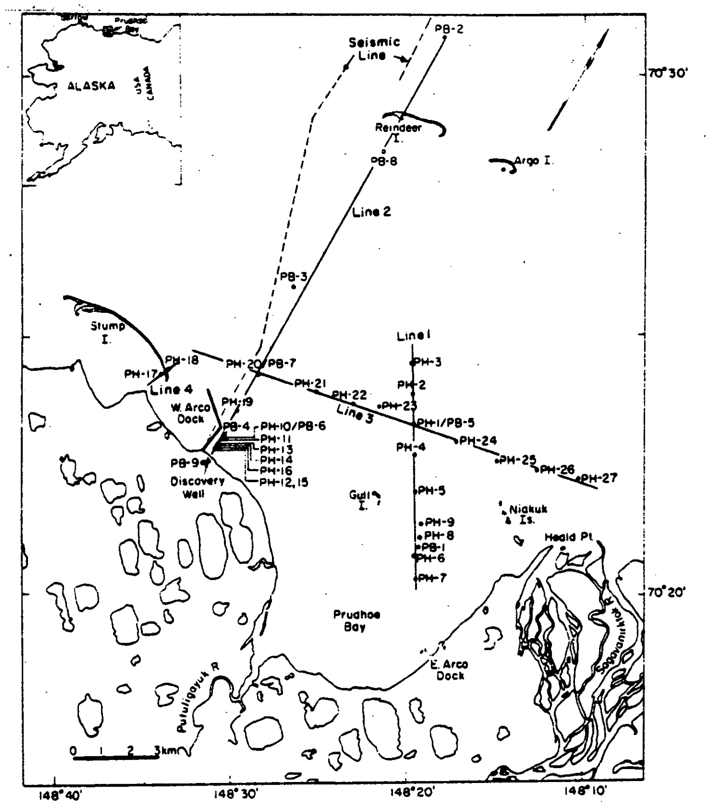


Figure 3. Site locations and major study lines (PB indicates drill hole, PH probe hole, except for PB-4 which is a 1976 probe hole location). The dashed line indicates the location of Rogers' seismic data. (From Sellmann and Chamberlain 1979.)

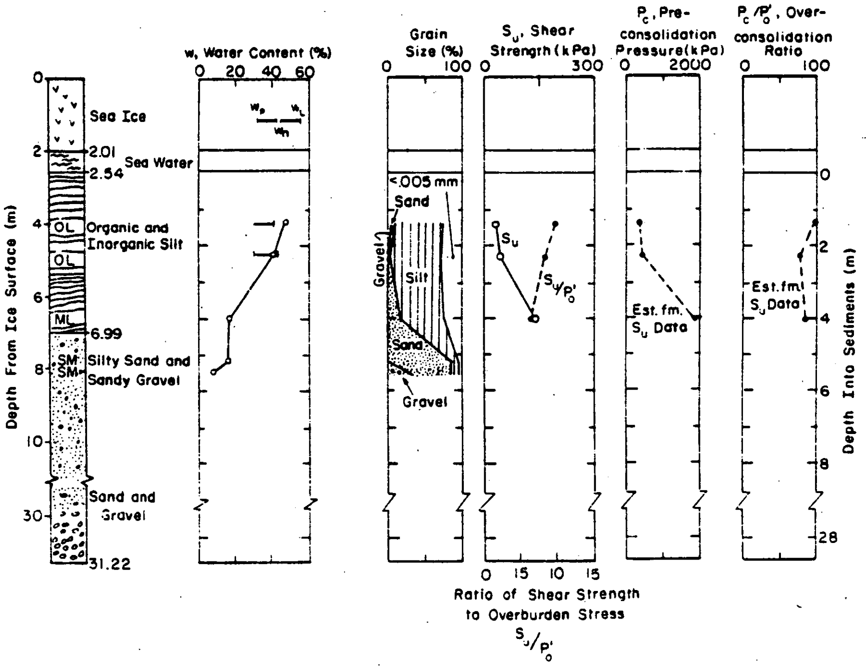


Figure 4. Drill hole log and engineering properties for site PB-1. (From Sellmann and Chamberlain 1979.)

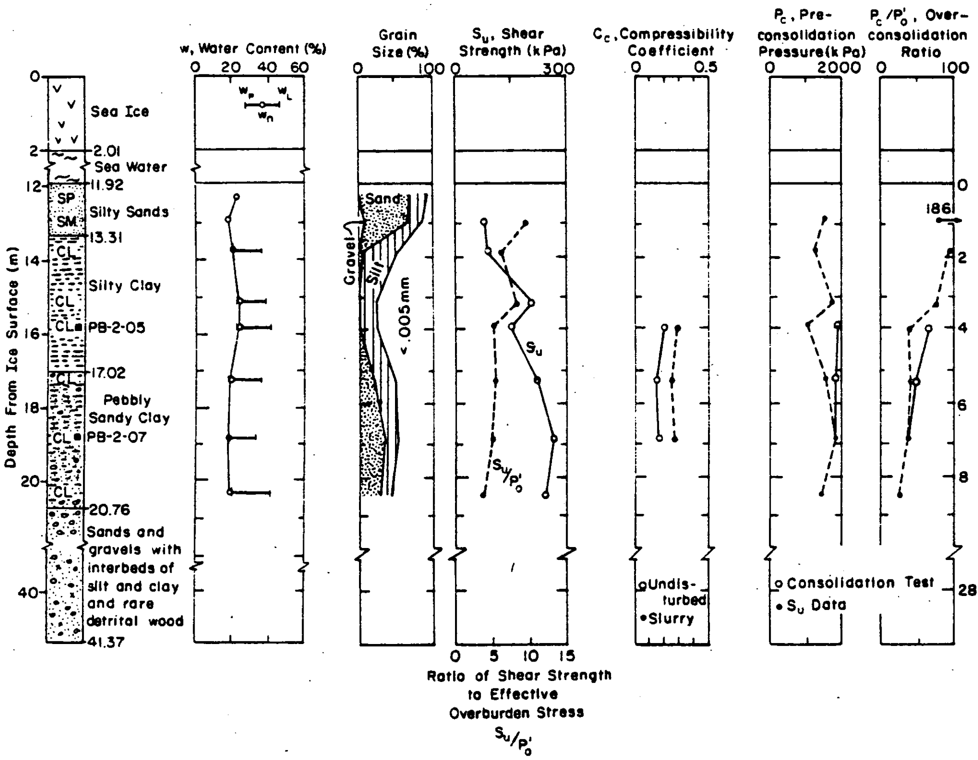


Figure 5. Drill hole log and engineering properties for site PB-2. (From Sellmann and Chamberlain 1979.)

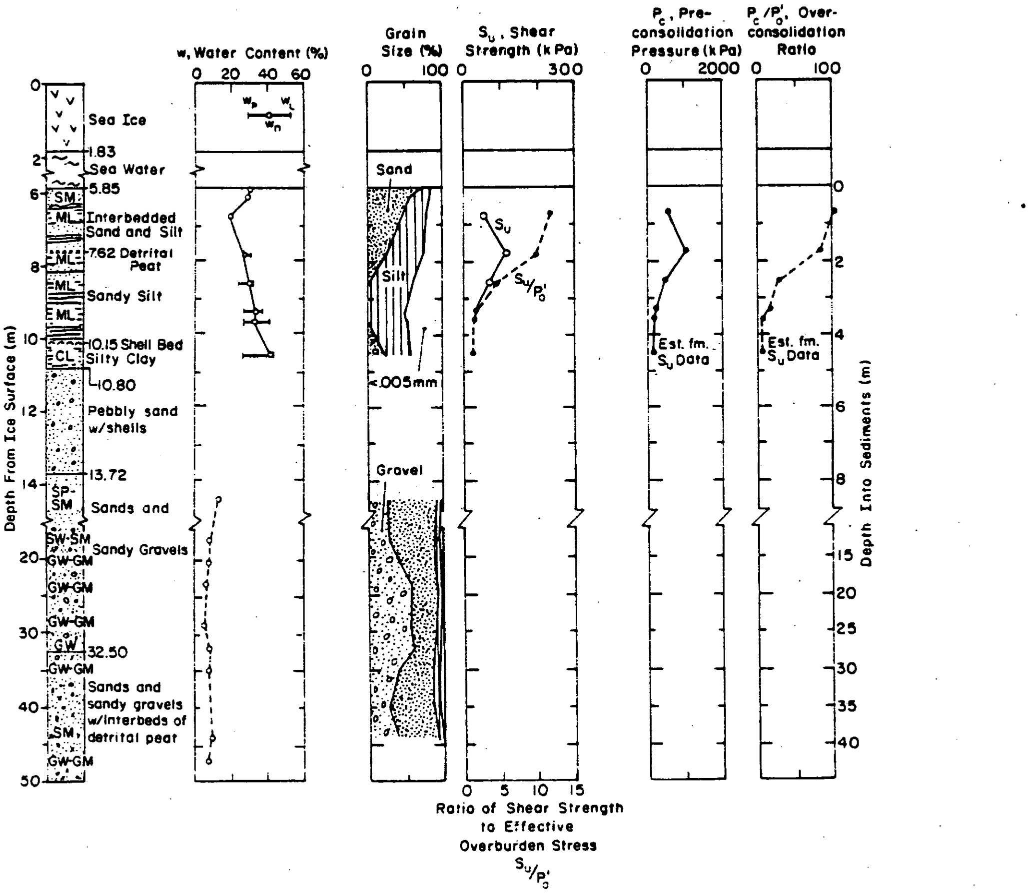


Figure 6. Drill hole log and engineering properties for site PB-3. (From Sellmann and Chamberlain 1979.)

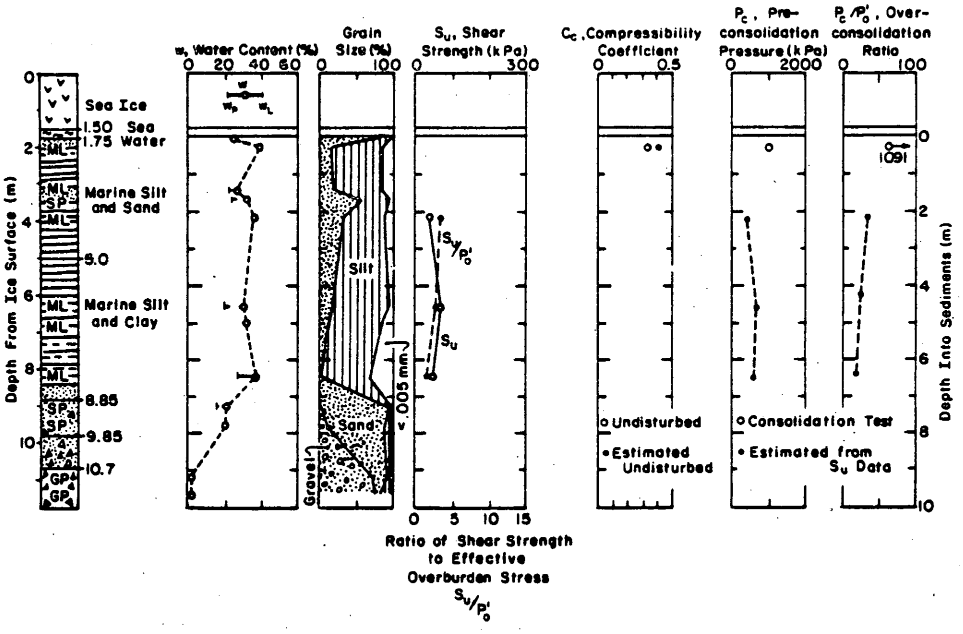


Figure 7. Drill hole log and engineering properties for site PB-5. (From Sellmann and Chamberlain 1979.)

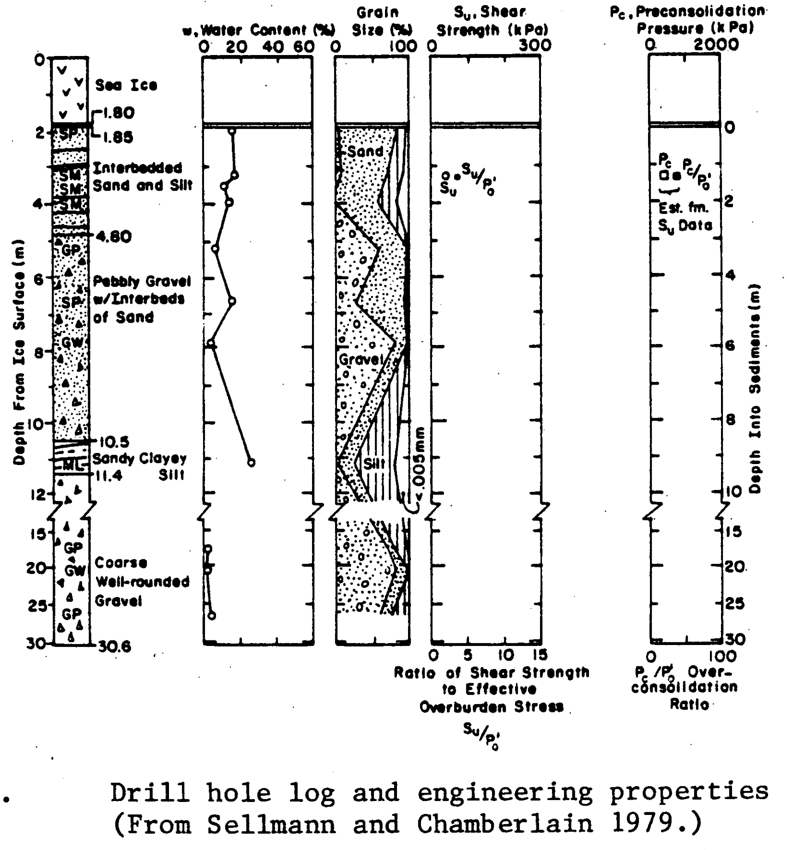


Figure 8. Drill hole log and engineering properties for site PB-6. (From Sellmann and Chamberlain 1979.)

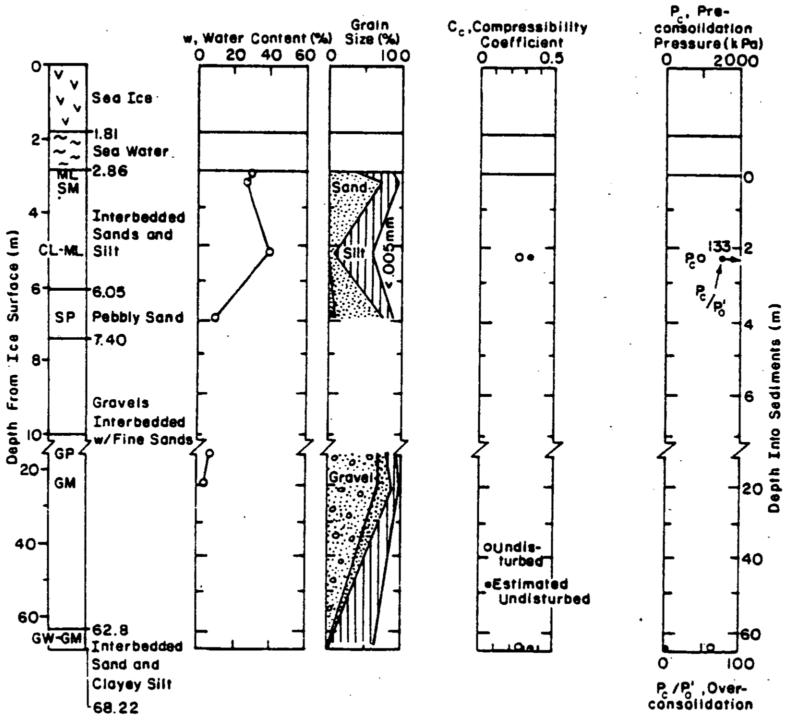


Figure 9. Drill hole and engineering properties for site PB-7. (From Sellmann and Chamberlain 1979.)

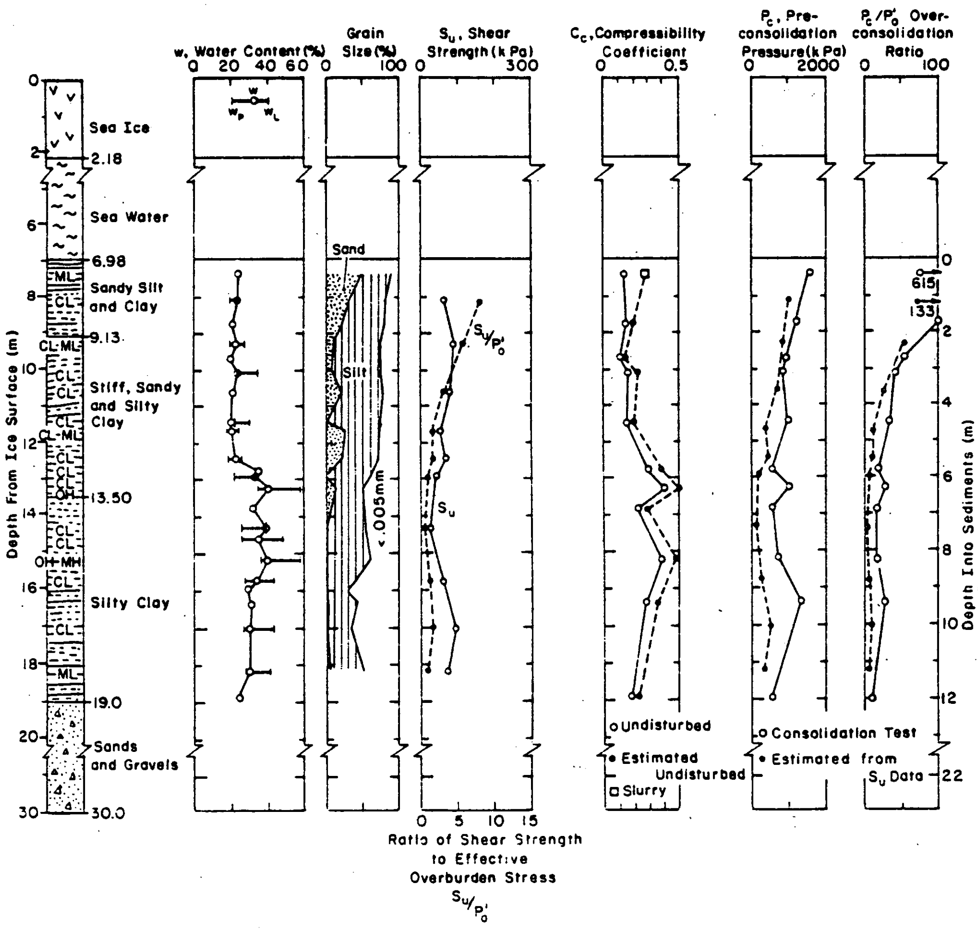


Figure 10. Drill hole log and engineering properties for site PB-8. (From Sellmann and Chamberlain 1979.)

surface section. The variation in thickness and properties of this surface layer will make detailed local site selection for offshore borrow material a necessity.

The extreme variability in properties of the near-bed sediments has also been demonstrated by Blouin et al. (1979). This study was based on penetrometer observations in the Prudhoe Bay area. The 27 sites occupied are included in Figure 3. This study also indicates the need for detailed local investigations prior to any development activity.

A summary of sediment property data from portions of holes in the Prudhoe area that were not ice-bonded is presented in Figures 4-10 (from Sellmann and Chamberlain, 1979). The locations of these holes are also shown in Figure 3. A detailed discussion of these data may be found in Chamberlain et al. (1978) and Sellmann and Chamberlain (1979). Property data from the Harding-Lawson study can be obtained from their contract report (USGS, Contract Report, 1979).

ICE-BONDED SEDIMENTS AND ASSOCIATED GROUND ICE

In the Beaufort Sea, sediments with temperatures below 0°C are extremely widespread. However, these materials are not necessarily frozen since they can contain saline pore water. The ice-bonded sediments in this environment can be grouped into two classes: seasonally frozen and perennially frozen.

Seasonally frozen sediments are most obvious in shallow water areas (<2 m) where the sea ice forms to or near the seabed. This is primarily because the degree of ice-bonding is greatest in this zone, with sediments having strength properties approaching those observed on land (Blouin et al., 1979; Sellmann and Chamberlain, 1979). In deeper water (>2 m) in the Prudhoe Bay area seasonal freezing of the bed was indicated when temperature data and calculated freezing point values of the pore water were compared (Sellmann and Chamberlain, 1979). These data suggest that seasonal freezing could be anticipated, although there was no indication that this freezing and ice formation was complete enough to cause a significant increase in the strength of the bed sediments. In some locations, where the bed sediments are fresher than normal marine sediments, as in bays or at the mouths of major rivers, the degree of bonding could be greater. Therefore, well-bonded seasonally frozen sediments can be expected in shallow water zones and shoal areas along the coastline and around the perimeters of islands.

Perennially frozen ice-bonded sediments can be widespread and in most cases represent permafrost that was formed on land when sea level was much lower, and was subsequently inundated by the sea. Therefore, the distribution of this material can be related to factors such as rate of advance of the sea onto the land, water temperature, sediment properties, and the pre-inundation history of the region. Coastal regions subject to rapid transgression apparently have relict permafrost preserved many kilometers from the present coastline as indicated by the data from the Beaufort Sea shown in Figures 11-14.

The depth to the top of ice-bonded sediments can be expected to be extremely variable in most regions, influenced by the properties of the sediments and the geologic and thermal history of the region. For example, it appears that in the Prudhoe Bay area the top of bonded sediment is close to the seabed in locations where the bed sediments consist primarily of dense, overconsolidated clays. It has been suggested that this could be related to the reduced rates of salt movement expected in this material. Salt movement in the dense clay would rely on diffusion, in contrast to more rapid infiltration in more permeable material.

In some regions modifications to the permafrost that occurred prior to inundation by the sea could account for considerable variability in the surface of bonded sediments due to deep thaw caused by lakes and major streams. No evidence for contemporary formation of bonded sediments exists in the marine environment although it cannot be dismissed.

A provisional estimate of the distribution of perennially frozen sediments in the U.S. and Canadian Beaufort Sea is provided in Figure 11 (OCSEAP, 1978). The Canadian data shown were obtained from Hunter et al. (1976).

A preliminary examination of first returns from seismic records in the U.S. Beaufort Sea obtained from industry offshore ice-shooting and marine reflection surveys also indicated extensive offshore distribution of bonded sediments. A velocity map constructed from these data indicates that velocities commonly associated with bonded sediments occur near the surface in a significant portion of the proposed U.S. Beaufort Sea lease area. Data from the offshore marine lines shown in Figure 12 do not contain velocities great enough to be interpreted as bonded permafrost. Therefore, the seaward limit of the bonded sediments must lie between the nearshore data and the offshore marine records; this limit is currently the subject of further investigation (Sellmann et al., 1979).

No data are available on the thickness of the offshore permafrost in the U.S. Beaufort Sea, although frozen sections of substantial thickness are anticipated along the inner part of the continental shelf. Data from recent seismic investigations indicate that near the shore in the Prudhoe Bay area the thickness can exceed 300 m (Sellmann et al., 1979).

Additional information on offshore permafrost can be obtained from investigations conducted as part of the OCSEAP program (Osterkamp and Harrison, 1976; Rogers and Morack, 1978; Chamberlain et al., 1978). Some of these data have been summarized in Figure 13.

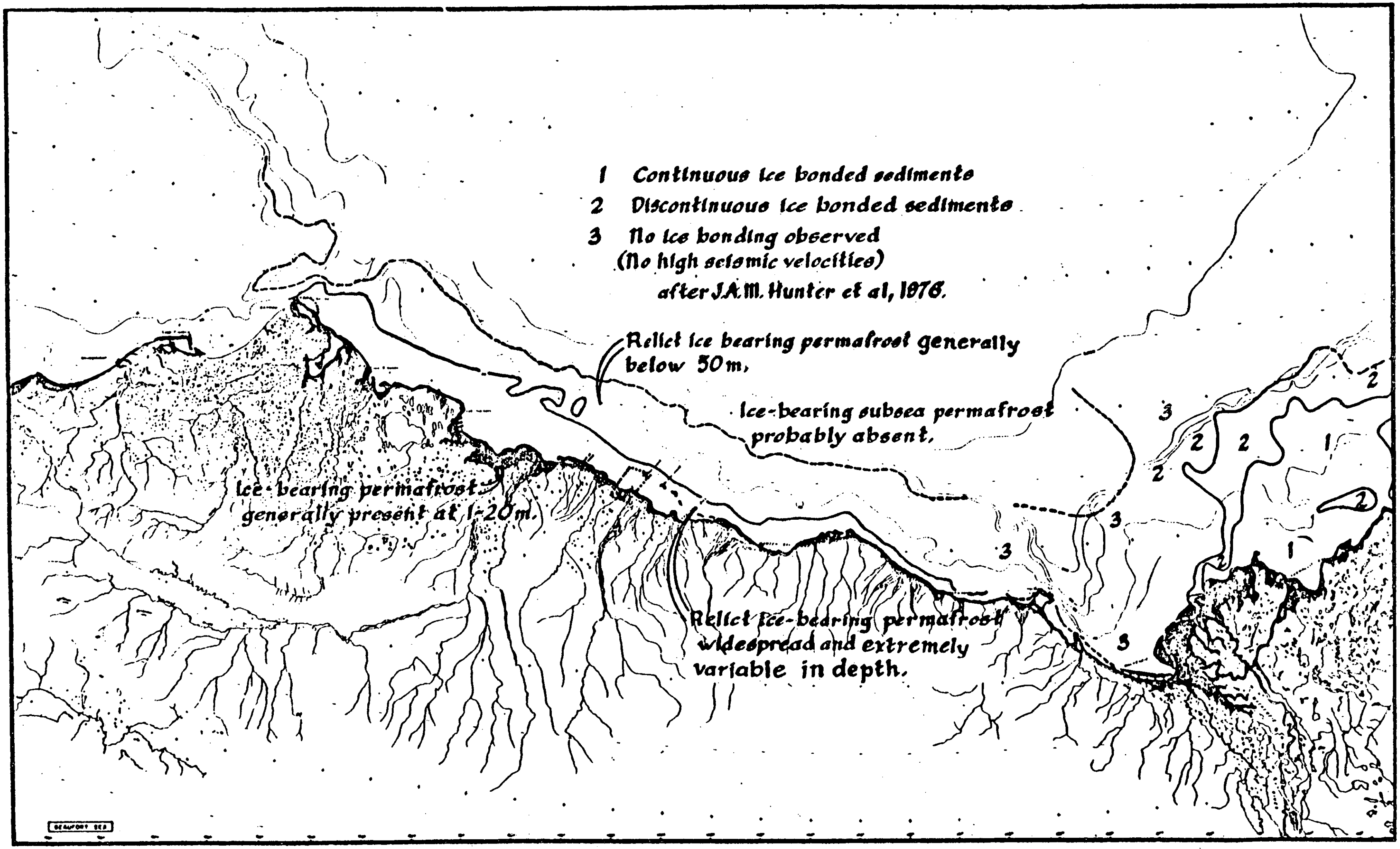


Figure 11. Early estimate of bonded permafrost distribution in U.S. Beaufort Sea. (From OCSEAP 1978). Canadian data are from examination of seismic records, from Hunter et al. (1976). Recent studies support general comments for nearshore categories in the U.S. Beaufort Sea. The seaward limit of bonded sediments may not be as great as indicated by the dashed line, based on examination of seismic records (Sellmann et al. 1979).

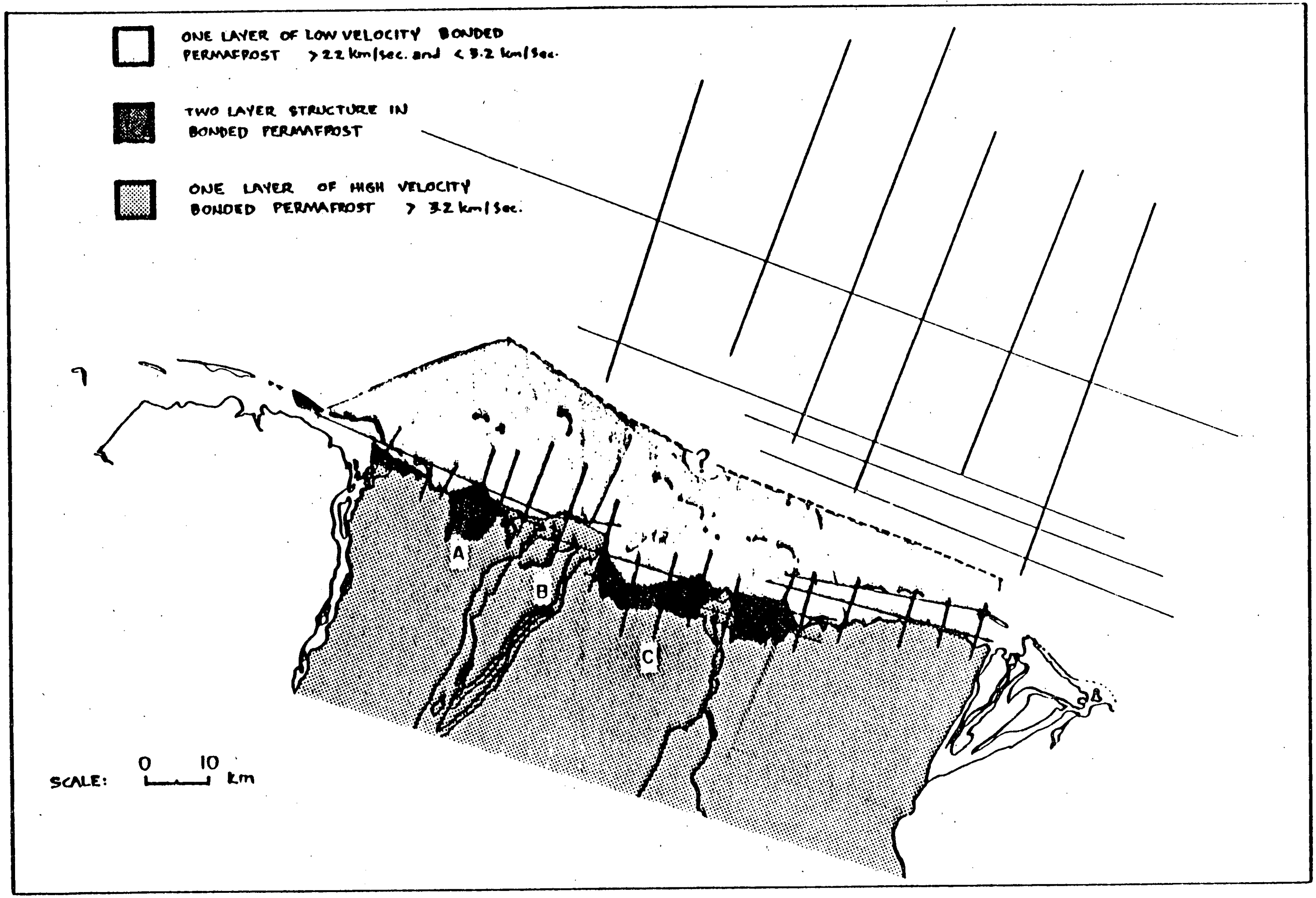


Figure 12. Map of shallow offshore velocities from analysis of first returns from industry type seismic records. Lines shown indicate location of data examined. "A" is Prudhoe Bay Area; "B" is on Sagavanirktok Delta. (From Sellmann et al. 1979.)

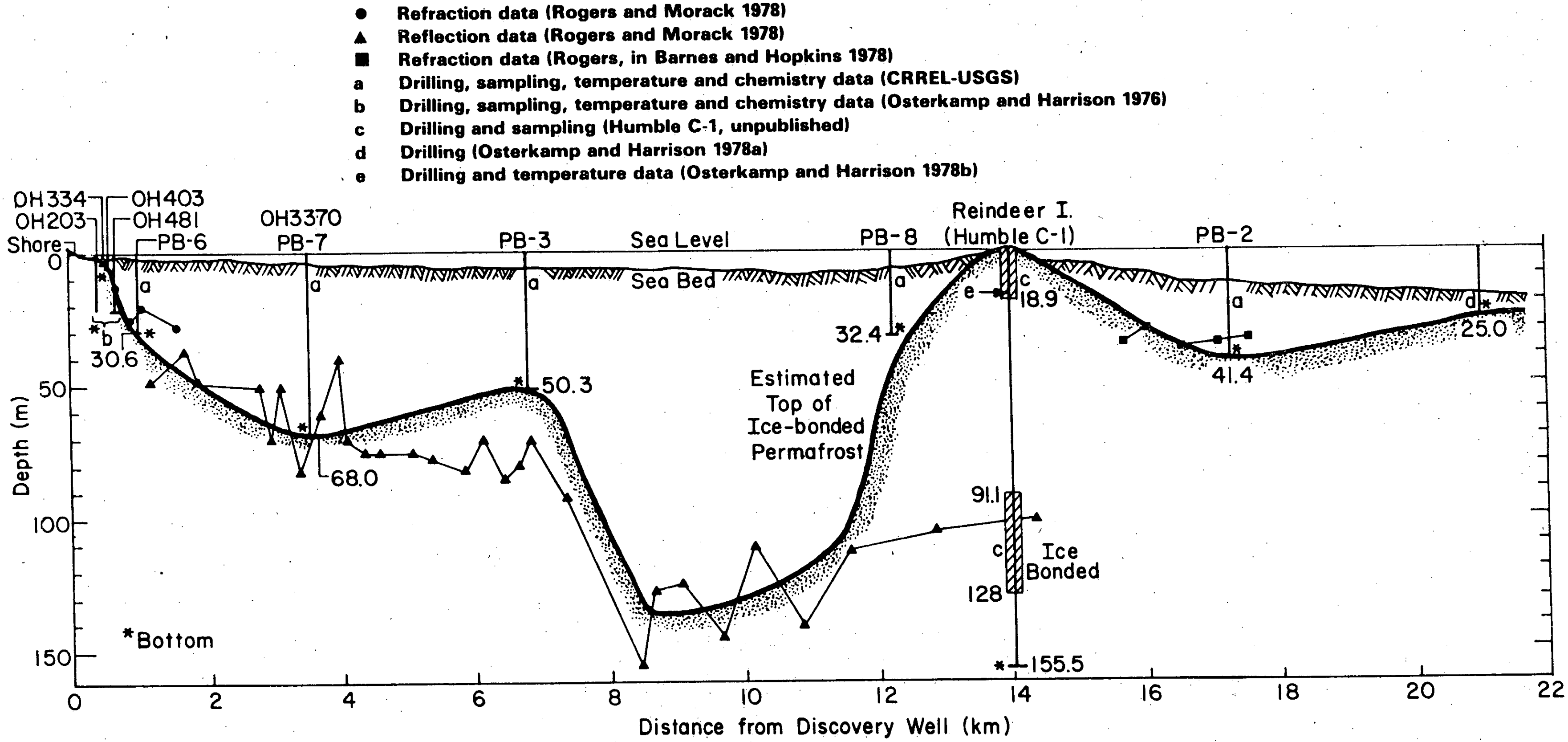


Figure 13. Summary of available data on depth of ice-bonded permafrost along a line from the West Dock at Prudhoe Bay through Reindeer Island. The dark shaded line is the estimated position of the top of ice-bonded permafrost. (From Sellmann and Chamberlain 1979.)

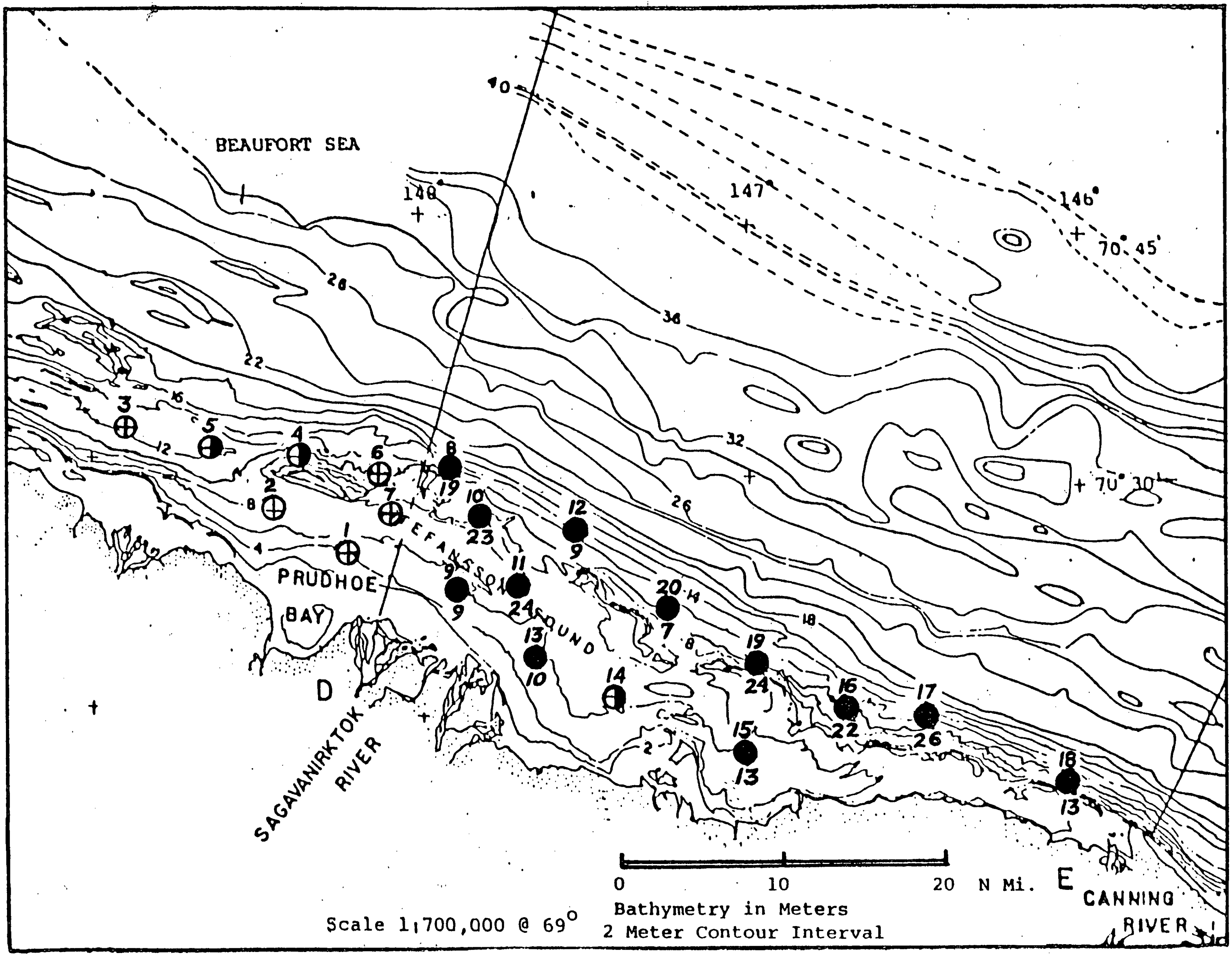


Figure 14. Holes drilled during 1979 USGS (Conservation Division) subsea Permafrost study. Harding & Lawson Associates drill hole numbers are above the dots; values below indicate depth in meters to bonded permafrost that contained visible ice. Half-filled circles indicate locations where bonded sediment was tentatively identified. (After Harding & Lawson Associates 1979; map from Hartz and Hopkins 1979.)

The recent study conducted by the Conservation Division of the USGS also provides a considerable amount of new information on bonded permafrost distribution. This study found that ice-bonded sediments were common, with significant thicknesses of frozen sediments found in 12 of the 20 holes drilled during their 1979 program, and that bonded permafrost was possibly encountered in at least three additional holes (USGS, Contract Report, 1979). The locations of the drill sites studied during this program are shown in Figure 14. The sites at which bonded sediments were observed are indicated by a solid dot, and locations where bonded permfrost may have been encountered are indicated by half shading of the hole locations. The drill site numbers assigned by Harding and Lawson are shown above the site locations. The depths, to the nearest meter, below the seabed of bonded sediments that contained visible ice are noted below the hole locations. Values were not included for locations where bonded permafrost was only tentatively identified and no visible ice was observed.

Previous studies in the Prudhoe Bay area are in good agreement with permafrost observations from the Conservation Division program (Sellmann and Chamberlain, 1979; USGS, Contract Report, 1979). These earlier studies suggest that the USGS Conservation Division drill holes 1 and 7 may not have been deep enough to reach bonded material (Figure 14).

Only a limited amount of data are available on the ice content of the perennially frozen sediments from the Beaufort Sea. However, the shallow depth of the ice-bonded sediments over extensive portions of the near-coastal waters indicates that significant offshore regions exist where ice lenses and massive ice can occur (Figures 12-14). This is particularly true since the properties of the offshore relict permafrost should be much like those of the permafrost on land. The extensive distribution of ice-bonded sediments with their higher velocities (Hunter et al., 1978; Sellmann et al., 1979; Rogers and Morack, 1978) observed both in the U.S. and Canadian Arctic, as well as their increased strength characteristics, indicate that at the minimum they contain significant quantities of pore ice (Blouin et al., 1979; Chamberlain et al., 1978).

Samples containing ice lenses were obtained from several locations offshore in the Canadian Beaufort Sea between 6.1 and 18.3 m below the seabed (Golden, Brauner and Associates, 1970).

Results from the recent U.S. Geological Survey, Conservation Division program provide the greatest amount of information on the position and distribution of ice, other than pore ice (USGS, Contract Report, 1979). The hole locations, indicated by solid dots in Figure 14, all contained visible ice at intervals within the bonded section. In 11 of these holes excess ice in the form of lenses and seams was observed. Lenses in the fine-grained material were as thick as 0.5 in. (12.7 mm) in at least two holes. Lenses on the order of 0.13 to 0.25 in. (3.3 to 6.4 mm) thick were more common. More detailed information on excess ice morphology and distribution can be obtained from the USGS Contract Report (1979). The data from this study provide direct evidence that the morphology and distribution of the excess ice in the marine sediments are not unlike what is seen on land.

In general, permafrost problems in the marine environment can be anticipated to be at least as great as on land, and possibly greater because of higher ground temperatures.

OVERCONSOLIDATED SEDIMENTS

A number of investigations conducted in the U.S. Beaufort Sea suggest widespread distribution of dense overconsolidated sediment near the seabed. Based on extensive shallow bottom sampling, Reimnitz et al. (1977) report that stiff clays occur widely near the bed eastward of the Colville River to the Canning River. Their sampling indicates that they occur in shallow waters and out to more than 100 km offshore in 1062 m of water. Hopkins and Hartz (1977) report that much of the sea floor to the north of the Colville River is underlain by compact stony mud of the Flaxman Formation. These sediments can be observed on the outer margin of the coastal plain in this region.

This widespread occurrence of stiff, fine-grained sediments near the bed was supported by other local investigations. Reimnitz and Barnes (1974) observed stiff, cohesive sediment seaward of Reindeer Island. Their assessment was that a stiff, cohesive silty clay of undetermined thickness underlies Holocene marine sediments in extensive areas of the inner shelf and some parts of the central outer shelf. This was confirmed by extensive diving observations in 1972 which indicated dense, dry, consolidated silt near the seabed (Rodeick, 1979). Reimnitz et al. (1974) also observed very stiff silty clay underlying a scour feature about half a kilometer seaward of Egg Island near Simpson Lagoon. More recently, Reimnitz and Toimil (1979) reported dense clay in the deepest part of Leffingwell Channel, which is near the Canning River.

The recent study conducted by Harding-Lawson for the USGS (1979) provided data on the distribution of overconsolidated sediments. In the 20 sites investigated, shown in Figure 14, all sections containing a significant thickness of clayey sediments were described as being stiff to hard. Stiff, fine-grained material was observed at every site, although in several cases the fine-grained zones were thin.

Engineering property studies in the Prudhoe Bay area (Chamberlain et al., 1978; Sellmann and Chamberlain, 1979; Chamberlain, 1979) established that overconsolidated sediments were present at all eight of the drill sites investigated. The degree of overconsolidation varied greatly from very weak sediments in the center of Prudhoe Bay to very dense, highly overconsolidated material offshore of Reindeer Island with a maximum thickness approaching 10 m.

Overconsolidated bed sediments have also been reported in the Canadian Beaufort Sea. A study was conducted to determine the degree of this overconsolidation in Shallow Bay, located in the MacKenzie Delta. It was observed along the line investigated that sediments consisting of fine sand, silts and minor amounts of clay and organic material were highly overconsolidated in the upper 4 m and more weakly consolidated to depths of 11 m (Hollingshead et al., 1978).

The above observations all suggest that overconsolidated sediments near the seabed can be expected as a common feature of the bed sediments in the Beaufort Sea. This could be considered unique since most of the common mechanisms normally responsible for their formation are not available for sediment modification in this region. The more common mechanisms, such as overburden pressure and subsequent erosion, desiccation, and loading by thick masses of glacial ice, do not appear appropriate for much of this region (Chamberlain et al., 1978). Because temperature conditions appear to have been favorable over much of the late Pleistocene time for deep freezing of the exposed land surface, and since freezing of bed material can occur in shallow water zones in the existing marine environment, freeze-thaw consolidation was given serious consideration. A discussion of the process is given by Chamberlain and Blouin (1978). Hollingshead et al. (1978) also suggest freeze-thaw as a mechanism and provide supporting data from modeling potential depth of seasonal frost penetration in various water depths. Laboratory tests conducted on remolded samples from Prudhoe Bay confirmed that significant consolidation is possible from only one freeze-thaw cycle (Chamberlain et al., 1978). For a significant thickness of these sediments to exist they would most likely have to have been frozen when the coastal plain was exposed during a period of low sea level. Thick sections could also occur when seabed sediments were directly coupled to the atmosphere, for example in locations where offshore bars or islands occur, or have existed.

If freezing and thawing provide the mechanism for their development during a period of low sea level, then these sediments should be very widespread, with distribution controlled by appropriate material types.

It appears that these sediments can influence the infiltration rate of saline sea water into the sediment, which may have an influence on the position or depth to ice-bonded permafrost, which was closer to the bed in areas where thick sections of overconsolidated sediments occur in the Prudhoe Bay area (Smith and Hopkins, 1979; Sellmann and Chamberlain, 1979). This relationship also appears to exist for observations from the recent USGS study (USGS, Contract Report, 1979).

Another aspect of these sediments that could influence offshore operations in the Beaufort Sea might be their thickness. These sediments can be thick enough to limit access to desirable material such as coarser-grained sediment required for construction of offshore exploration and production facilities.

NATURAL GAS HYDRATES

Natural gas hydrates are solid clathrate inclusion compounds that resemble ice or wet snow. Water is the host molecule, forming crystal lattice cages or nearly spherical chambers in which the guest molecules of natural gas fit. The guest molecules can be a variety of hydrocarbon and other gases. These hydrates can occur above and below 0°C when appropriate pressure and temperature conditions are met for the various gases (Kaplan, 1974). Given a constant temperature, gases having the greatest density can occur at lower pressures or depths (Oilweek, 1974). However, methane is apparently the most common gas found associated with natural hydrates, unless the gas is very rich in higher hydrocarbons such as propane. Reduction in temperature decreases the formation depth of hydrates as the methane-water phase diagram prepared by Davidson et al. (1978) (Figure 15) helps to illustrate. This figure assumes that water exists in excess of that in the hydrate. The two dashed lines show examples of simple temperature profiles based on mean annual surface temperatures of 0°C and -10°C. The methane hydrate is stable above the temperature-pressure curve and between the intersection points of the -10°C profile. It also indicates that no hydrate can occur when the mean annual temperature is at 0°C, although they can exist at depths between 200 and 900 m with a -10°C mean annual surface temperature. This depth range, in which natural gas hydrates are stable, is compatible with conditions found in areas of thick, cold permafrost, permitting hydrates to exist within and below the permafrost. It should be noted that the temperature profiles used are idealized and that actual profiles, particularly in the marine environment, can be much different than these. Conditions suitable for hydrates can exist when mean annual bed temperatures are around 0°C when temperatures are not in equilibrium.

Limited information on the occurrence of natural gas hydrates in terrestrial permafrost settings indicates the variability of hydrate distribution. This variability may even be greater offshore due to the complex thermal history in this permafrost environment.

Existence of gas hydrates on land has been documented in both the Soviet and North American Arctic. Considerable information is available on gas hydrates from the Soviets' large Messoyakha field, which is situated in the West Siberian Basin (Davidson et al., 1978). In the Canadian Arctic, indication of hydrates was noted at 12 well sites discussed in a recent Arctic Petroleum Operators Association Report (APOA, 1978). Katz (1971) has indicated that at Prudhoe Bay hydrates might be present at depths between 600 and 1035 m. The Canadian Arctic is the only one of these regions for which documentation is available on hydrate occurrence offshore.

Hunter et al. (1976) suggest that offshore hydrates associated with relict permafrost which formed in the terrestrial environment are generally degrading together with the permafrost. But they indicate that this rate is likely slowed by the latent heat required to cause dissociation of the hydrate into either gas and ice or gas and water. The resulting gas, since it is at higher than in situ pressure, will then attempt to migrate to shallower horizons in permeable permafrost to form gas pockets in the sediment. They believe that this free gas may also combine with ice in the permafrost to form new hydrates at shallower depths. They also comment that the actual kinetics of hydrate formation in nature is not well understood, but that formation must be much slower than decomposition because of their essentially explosive dissociation when they are not in equilibrium.

Natural gas hydrates can be of commercial interest as a potential source of natural gas, as well as a source of problems during petroleum exploration and development. Data available from Soviet experience with hydrates in their Messoyakha gas field discussed by Hitchon (1974) indicate that, based on calculations from some zones that contained hydrates, the reserves were 54% higher than they would be if only free gas occupied the reservoir rock. It was also observed (Hitchon, 1974, from examination of information in Makogan et al., 1971) that hydrate zone production was much lower than was observed in free gas zones, although hydrate zone production in test wells was increased by an order of magnitude by methanol injection. It appears that techniques for recovery of natural gas hydrates are in their infancy, with the only data available on production being from Soviet experience in the Messoyakha field (Makogan et al., 1971; Chersky et al., 1972, summarized by Hitchon, 1974). Various proposed injection fluids for increasing hydrate decomposition and production are mentioned in Hitchon's (1974) review and include: saline formation water, alcohols, diesel fuel, and calcium chloride solutions.

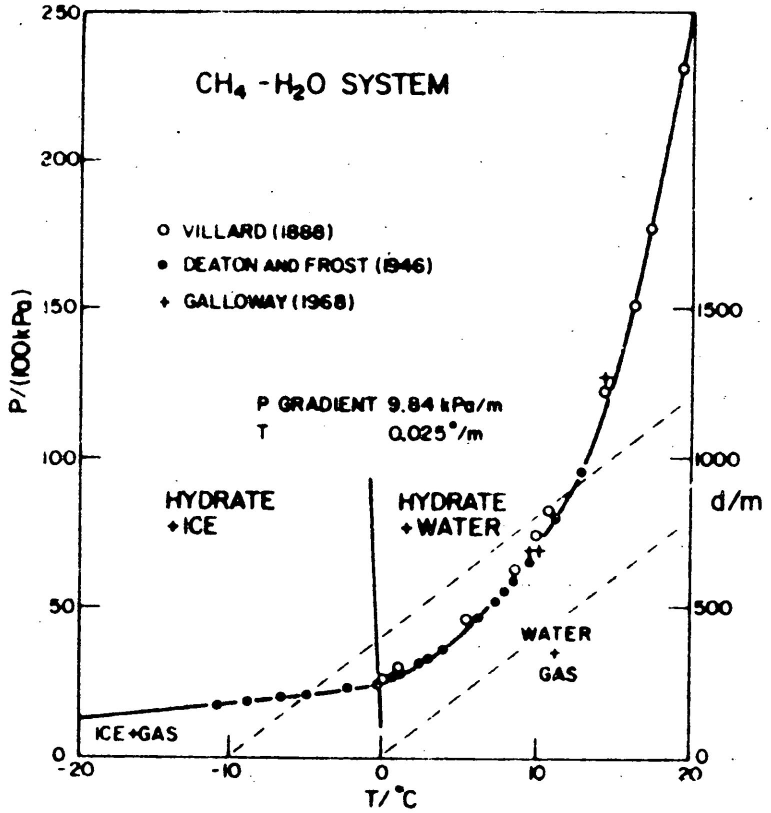


Figure 15. Phase diagram for methane-water system, methane hydrate being stable above the curve. It is assumed that the relative amount of water exceeds that in the hydrate. If methane were in excess the area above the curve would contain both gas and hydrate. (From Davidson et al. 1978.)

As suggested, hydrate occurrence can influence exploration and development activity. Increased velocity in hydrate zones, to velocities higher than are normally encountered in thawed sediments, can influence the interpretation of seismic data. Problems with hydrates can in part be related to their increased pressure and volume upon decomposition: "One cubic foot of hydrate can contain 170 ft^3 of gas" (Oilweek, 1974). High pressures can develop when methane hydrates decompose if no permeable path exists for pressure relief. Goodman (1978) notes that decomposing methane hydrates at constant volume have a decomposition pressure of about 2,000 psi (13,790 kPa) at 60°F (15.5°C) (see Figure 15).

A recent review of oil industry experience with gas hydrates in exploration drilling in the Canadian Arctic was compiled by the Arctic Petroleum Operators Association (APOA) and was presented at the 1978 Canadian Symposium on Permafrost Geophysics. Their observations and conclusions are presented below verbatim:

1. "In most cases, gas hydrate manifestations are inferred from the response of gas influx in a drilled interval to changes in temperature. However, the existence of gas hydrates in many cases cannot be positively established."

2. "Gas hydrate manifestations are the exception rather than the normal case, with twelve reported possible occurrences in 375 wells drilled".

3. "Well control equipment is required to handle free gas accumulations, and the same equipment will handle gas from hydrate decomposition. Well control procedures must be changed to control a gas hydrate since increasing the mud density to control decomposition is not practical."

4. "The combined experience in penetrating gas hydrate intervals would indicate that gas influx from the decomposition of gas hydrates is slow and will create only a small gas kick which can easily be handled. However, it is important that the mud temperature is less than the formation temperature if the well is left in a static condition for any length of time. If this is not done, it is possible that a larger bubble can collect in the well bore. If a larger bubble collects, and if a free gas is associated with the hydrate interval or elsewhere present in the open hole, it is possible that the density reduction resulting from the hydrate gas influx will be sufficient to allow the free gas interval to flow."

5. "The control method for penetrating a zone containing gas hydrates is to cool the mud while penetrating the interval. Any gas liberated is vented at the surface in the normal manner. Once the interval has been penetrated, it is covered with well casing and cemented in the normal manner. If free gas is present, the mud density must be sufficient to prevent free gas influx and the mud temperature must be maintained low to prevent significant gas hydrate decomposition. The well bore should not be left static for long periods of time if the mud is warmer than the formation."

6. "Gas hydrate decomposition behind casing has not created a problem at any of the twelve exploratory wells where hydrates have been suspected."

Even though the above comments suggest that procedures for handling hydrates are routine, it is my understanding that problems with hydrates have been encountered, presumably when the above procedures were not employed. The variable and unpredictable distribution of the hydrates appears to be a problem requiring constant awareness and ability to implement well control procedures in all potential hydrate zones. This will also include consideration of increased external pressure on the production casing as the thaw zone and sediment temperature increase. The greatest problems may occur when a casing is subjected to cumulative stresses related to all aspects of thawing of the permafrost such as thaw settlement and high pressure due to hydrate decomposition in confined situations where no relief of pressure is possible. This may be particularly true in offshore production situations where wells will be closely spaced and permafrost temperatures could be higher, permitting more rapid thaw.

Free gas, rich in methane, observed during the Harding-Lawson subsea permafrost drilling program (USGS, Contract Report, 1979) in the U.S. Beaufort Sea could be an indication of hydrate decomposition at depth.

BED TOPOGRAPHY

The Beaufort Sea shelf is generally a planar feature that ranges in width from 40 to 76 km with the shelf break at approximately 74 m (Carsola, 1954). It has little relief, with a maximum slope of 1.3 m/km and an average slope of 0.5 m/km (Rodeick, 1979).

Submerged ridges form prominent features northeast of Pingok Island (Rodeick, 1979), while the Reindeer-Cross Island ridge, which extends at least to Narwhal Island, forms a dominant feature east of Prudhoe Bay (Reimnitz et al., 1972).

Several bed features that are unique to arctic waters can account for local irregular bed topography in nearshore waters. They include bed scour grooves, strudel erosion depressions, and features that it has been suggested are submarine pingos. The first two are related to the occurrence of sea ice, while the latter, if true pingos, could be related to the occurrence of subsea permafrost.

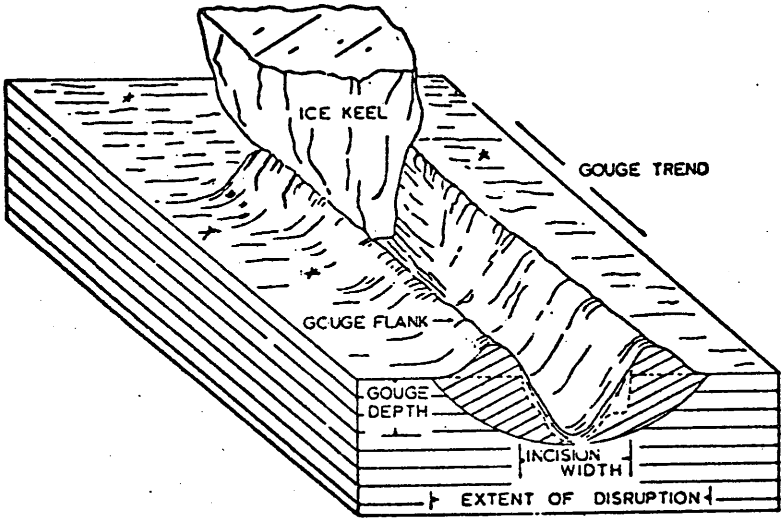
Ice Gouge Patterns

Ice gouges, by far the most common of these features, can form a wide variety of bed patterns on the inner part of the shelf.

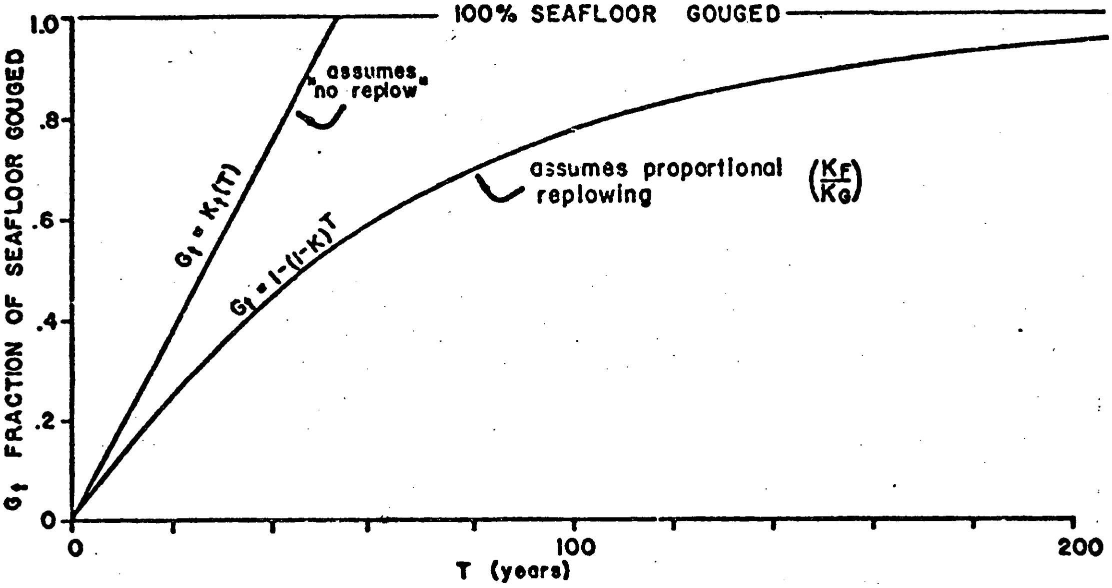
Scouring and gouge formation occur when sea ice and berg ice contact the bed sediments. This can occur in a wide range of water depths, depending on size, frequency of occurrence, and movement patterns of sea and berg ice. These features can range from gouges more than 6.5 m deep to shallow grooves in shallow water areas. Usually these grooves are bordered by ridges and mounds of material displaced from the incision (Figure 16a). The gouge can also be filled in, leaving the parallel ridges as the dominant relief feature. It appears that the ridges themselves can also act as sediment traps, causing preferential ponding of sediment on one margin of the linear features depending on the direction of sediment transport (Barnes and Remnitz, 1979).

These features and their dynamic formation mechanism will be of considerable significance in offshore development activities. Their distribution, frequency of formation, and depth will influence the design of seabed pipelines and well completions and any other seabed installation planned on the inner shelf. Considerable lateral variability in sediment strength properties can be associated with these features, where rapid infilling of soft sediment occurs in regions of dense clay common to much of the shelf (Barnes and Reimnitz, 1979).

The zone of greatest interaction between ice and the bed is the margin of the stationary coastal ice and the moving polar pack, as marked by a zone of grounded ice ridges (Reimnitz et al., 1977). The



a. Drawing of an idealized ice gouge feature with terminology showing the disruptive effect on the sea floor.



b. Graph illustrating fraction of the sea floor disrupted by ice (G_t) as a function of time, assuming no replowing $K_t(T)$ and proportional replowing $1-(1-K)^T$.

Figure 16. Ice gouging. (From OCSEAP 1968.)

inner edge of this grounded ridge zone is generally located between the 10 and 20 m isobaths, and is commonly associated with shoals. Gouging is especially intense in this zone and on the seaward slopes of bathymetric highs (OCSEAP, 1978). Also, in the OCSEAP synthesis report it is stated that "Ice gouge densities, depths of incision, and dominant trends are reasonably well known for the region between Cape Halkett and Flaxman Island inside 15 m (Figure [17]) but poorly known in deeper water in the easternmost and westernmost parts of the Alaskan sector of the Beaufort shelf (Reimnitz and Barnes, 1974)."

Gouges are commonly more than 1 m deep within and seaward of the zone of grounded ice ridges and generally less than 1 m deep shoreward of this zone (Figure 18) although maximum values are much greater (OCSEAP, 1978). The following information on depth and orientation is provided directly from the OCSEAP synthesis report.

> "Extreme observed incision depths are 4.5 m in 38 m of water in the Chukchi Sea, 5.5 m in the same water depth in the Alaskan sector of the Beaufort Sea, and in excess of 6.5 m in water depths between 40 and 50 m in the Canadian sector (Lewis, 1977). Individual furrows may be oriented in any direction, but by far the majority are oriented parallel to the coastline (Figure [17]), reflecting the westward drift of the polar pack. Inside the stamukhi zone there is a subordinate trend southwestward obliquely toward the coast, reflecting onshore ice movement, although the dominant trend is still parallel to the coast. Detailed studies northwest of Oliktok Point indicate that ice gouging in shallow water occurs yearly at all water depths studied (Figure [18]). Gouging occurs frequently enough to rework essentially the entire sea floor to a depth of 0.2 m in less than 100 years (Figure [16b]). The recurrence rate for ice gouging within the stamukhi zone, although presently unknown, is no doubt much greater. Large variations in shear strength occur across individual gouges, with much greater strength in the gouge troughs than on the flanks, ridges, or undisturbed bottom. It may be that repeated physical impacts by ice are responsible for the overconsolidated sediments previously mentioned. Repetitive summer surveys show ice gouging can occur both in summer as well as winter, although it is believed to be most intense in winter. Canadian researchers believe that gouges at water depths greater than 50 m are relict (Lewis et al., 1977; Pelletier and Shearer, 1972). Researchers in the U.S. have cautioned against that hypothesis. Diver observations of the process of erosion and deposition around individual gouges, the presence of strong current pulses on the outer shelf, the association of gouges with hydraulic bedforms, and the consideration of sediment strength suggest that gouging may presently be occurring in water depths from 50 m to the shelf break in both the Chukchi and Beaufort Seas.

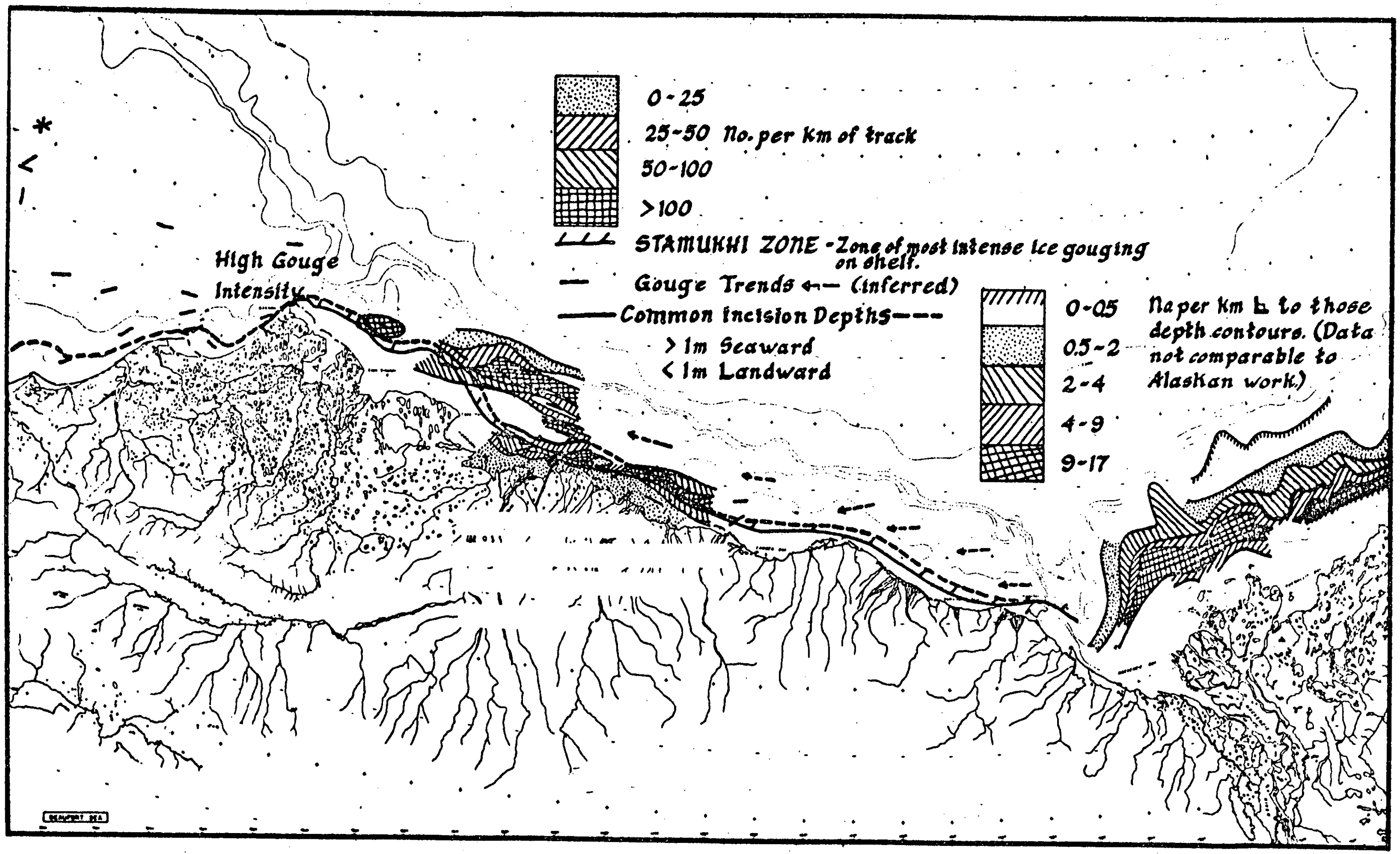


Figure 17. Ice gouging of sediments. (From OCSEAP 1978.)

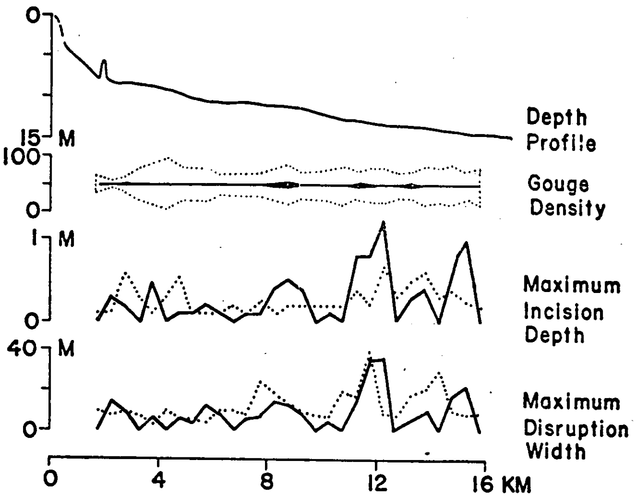


Figure 18. Ice gouge characteristics along a trackline northwest of Thetis Island in Harrison Bay. Data have been summarized for 500-m segments. The dotted lines represent a summary of all gouges observed on 1975 data while the solid lines represent the characteristics of new gouges that were made between 1975 and 1976. (From OCSEAP 1978.)

> "Communities of benthic organisms are severely disrupted by ice gouging, with lower abundances being recorded in the stamukhi (grounded ice) zone. On the other hand, ice gouging must function to bring buried nutrients to the surface. In water depths shallower than 15 m, the bottom is reworked by ice to depths on the order of ten times the sedimentation rate, which should almost completely obliterate bedding and bioturbation structures. The ubiquitous presence of well-defined crossbedded sand layers in 1.5 m cores from this region is presently unexplained. Data from farther seaward on the shelf are limited to the upper 50 cm and generally show complete disruption of sedimentary structures."

Other investigators have discussed the influence of ice interaction with the seabed and the resulting formation of gouge patterns (Kovacs, 1972; Kovacs and Mellor, 1974). The composite list of references included at the end of this section also reflects the literature examined in their studies. The paper by Kovacs and Mellor provides an extensive assessment of the forces involved in ice gouging.

A recent paper by Barnes and Reimnitz (1979) discusses seabed sediment redistribution during periodic events caused by unusually ice-free conditions which increase wave and current action on the shelf. These new observations provide much new and important data on the age, apparent depth, and role of gouges in bed sedimentation. This study indicates that previous estimates of gouge frequency and maximum incision depth have been too conservative, and that ice gouging and obliteration of these features is much more dynamic than is reflected in previous data. It also indicates that past estimates of age were probably too great. the hydrodynamic reworking of the bed during an open water period in 1977 caused extensive obliteration of ice gouges to water depths of at least

13 m in their study area and caused sediment ponding and gouge infilling at even greater water depths. Sedimentation rates during this event were an order of magnitude greater than average accumulation rates on the Beaufort Sea shelf. The preferential infilling of the gouges caused maximum values for incision depth to be less than actual ice keel penetration. This study also indicates the significance of ice gouges in controlling sediment distribution on the inner shelf.

Scour Pits

Scour pits or "strudel" scour depressions are another bed feature unique to the inner shelf in arctic regions. During spring breakup on the Arctic Coastal Plain discharge from the major streams becomes very great. This takes place when much of a stream is frozen to its bed. During the period of initial peak flow, river water flows over the sea ice, reaching depths of 1 to 3 m, and in some areas extends many kilometers offshore. This water drains from the sea ice surface through holes and cracks in the ice. In these zones of localized drainage, bed scour occurs which can form cylindrical depressions as much as 4 m deep and tens of meters across (Reimnitz et al., 1974). Sediment excavated by this hydraulic mechanism is redeposited on the flanks of these depressions, forming debris mounds. An indication of the outer limit of these features observed between Harrison Bay and Prudhoe Bay is shown in Figure 19 (Barnes and Reimnitz, 1977). This process, including the associated regional flooding, could have some effect on coastal development activities (OCSEAP, 1977).

Subsea Mounds (Pingos)

Numerous subsea mounds, referred to as pingos, have been observed on the outer part of the shelf in the southern Beaufort Sea by Shearer et al. (1971). These features were detected by shallow reflection seismic studies. The origin of these features has not been positively established, although their link with permafrost has been suggested. If they are pingos, they could have formed on land prior to inundation or, as suggested, they could have formed in thaw lake basins after being covered by the sea (Hunter et al., 1976). Another possibility is that some non-permafrost mechanism could have been responsible for their formation. If they are permafrost-related and formed in the marine environment as true pingos they would have required mean seabed temperatures below 0°C and sediment pore water with very low salinity. The occurrence of such conditions cannot be discounted. Some of these submarine mounds are as much as 30 m high, and are within 15 m of the surface (Hunter et al., 1976).

To my knowledge no published accounts exist of similar features in the U.S. Beaufort Sea, although the shallow depths observed to ice-bonded sediment suggest that large features of this type could be preserved in the offshore environment. If these features are permafrost-related their distribution can be used as a permafrost mapping tool and an indication of locations that can contain significant quantities of massive ice.

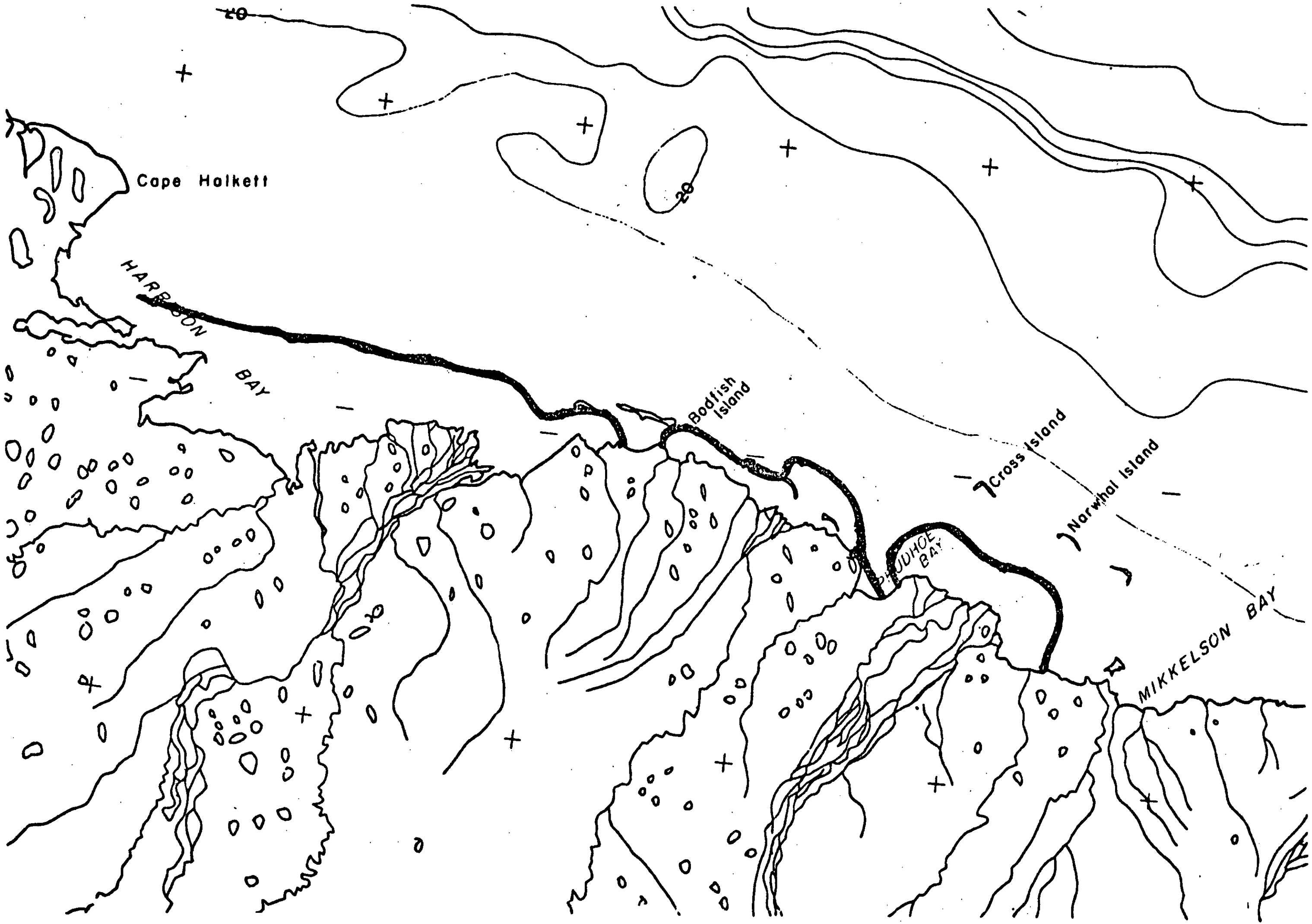


Figure 19. Outer limit of "strudel" scouring, observed between Harrison Bay and Prudhoe Bay. (From Barnes and Reimnitz 1977.)

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