11. PIPELINE SYSTEMS HAZARDS

In the Arctic Ocean off the northern and western coasts of Alaska (Beaufort and Chukchi Seas), pipelines may be exposed to most of the natural hazards which exist in non-polar regions in addition to many unique to the Arctic. Examples of potential hazards which can exist at almost any location include:

- Wave and Current Action
- Seismic Activity
- Bottom Instability
- Ship Anchors
- Fishing Gear
- Hostile Action and Sabotage
- Sea Creatures

In the Arctic, a number of special problems must be added to complete the list. These include:

- Seabed Scour by Ice
- Ice Crushing
- Frost Heave
- Subsidence from Thawing of Permafrost
- Ice Override
- Pit or Strudel Scouring
- Large Coastal Erosion Rates

Taken collectively,. this list would appear to pose almost insuperable problems for the design of an Arctic submarine pipeline. It should be pointed out, however, that many of these hazards are site-specific and a judicious selection of pipeline routes can eliminate, or at least minimize, many problems. Nevertheless, a knowledge and understanding of these pipeline hazards is a fundamental prerequisite for any Arctic pipeline design.

This section of the report, therefore, endeavors to provide an outline of the conditions and physical processes responsible for hazards to Arctic submarine pipelines. Due to the very limited Arctic environmental data base, most of the material presented is descriptive. Where possible, an attempt has been made to provide supplementary quantitative data which illustrate the range of conditions existing over an area or at a specific location. A definitive numerical description of the Arctic environment is clearly not yet possible since research efforts to provide suitable quantitative data have only begun within the past few years. Presently, our knowledge of various conditions in the nearshore and offshore Alaskan Arctic is very spotty. Certain locations, such as areas north of Barrow and Prudhoe Bay, have been the objects of considerable scientific study. On the other hand, very little detailed information is available for most areas of the Chukchi Sea coast. Likewise, certain subjects have been investigated in more detail than others. The meteorological characteristics of the Arctic, for example, are much better known than the oceanographic conditions. For these reasons, the development of reliable and accurate environmental design criteria for pipelines presently is premature.

A. OCEANOGRAPHIC CONDITIONS

A knowledge of oceanographic conditions, particularly waves and currents, is a prerequisite for determining direct hydrodynamic forces which may be exerted on a pipeline. In areas of soft or unstable sediments, these hydrodynamic forces may produce scour erosion, sediment oscillation, and even mass movements of submarine sediment. Pipeline failures may result from fatigue, sagging, or lateral displacement. Some knowledge of oceanographic conditions also is required during the pipeline installation since most pipe-laying equipment will operate only within defined sea state limits.

The presence of seasonal ice has a profound effect upon the oceanographic climate of the Arctic, particularly surface waves and currents. Because ice cover is present from about October through May or June, waves and surface currents are limited to the summer and early fall, also called the "open-water" season. Another factor which tends to limit the severity of the oceanographic environment is the presence of non-seasonal pack ice which is a more or less solid mass of moving ice found at varying distance offshore even during the open-water period. The existence of pack ice tends to limit wave and surface current generation because it reduces the distance (fetch) which winds can blow over open water.

Present knowledge of the Arctic oceanographic environment is fragmentary at best. This may be ascribed to a general lack of interest in the past and to the difficulty of obtaining good measurements. Suitable Arctic research vessels are scarce, and measurement equipment such as wave buoys or current meters tend to be lost or destroyed by ice. Analytic simulation (modeling or hindcasting) of oceanographic conditions is complicated by ice, shallow water, and the presence of barrier islands along most of the coast. Consequently, conditions are extremely site-specific and would require complex state-of-the-art models to provide an accurate simulation of oceanographic phenomena.

1. Waves

In comparison to mid-latitude areas, the wave climate of the Alaskan Arctic is generally mild. Normal conditions are characterized by low, short-period waves. Measurements made in the vicinity of Point Barrow (Sellman et al, 1972) indicate that 90 percent of the waves were less than lm (3 ft) in height. Similar observations were recorded near Pingok Island and Point Lay on the northern Chukchi coast (Wiseman et al, 1974). Wave measurements had a characteristic energy peak between 2 and 3 seconds with significant heights (average of the highest 1/3 of the waves) of 20 to 30 cm (0.7 to 1.0 ft). Visual observations by numerous sources tend to corroborate these measurements and confirm the benign wave climate which normally prevails during open water.

Under certain circumstances, much more severe waves are apparently possible. During some summers, for example, the offshore pack ice has been observed to retreat as far as 190 to 260 km (118 to 162 mi) north of Point Barrow. Under these conditions, occasional storms are able to move across the shelf and generate waves over a long fetch. An analysis of Beaufort Sea storm systems by Cardone (personal communication, 1979) indicates that the wind fields of such storms are manifested in two basic patterns:

> Strong winds from a westerly quadrant, which are associated with migratory extratropical cyclones moving basically from west to east.
>
> Strong easterly winds, usually of long duration, associated with several different types of weather patterns, which may strengthen the normal sea level pressure gradient over the Alaskan north coast.

Therefore, during periods when the pack ice lies far offshore, winds generated by occasional storms are conducive to wave formation since they tend to blow parallel to the coast. Although it is known that these conditions which allow for greater than normal wave generation exist, there are relatively few observations of extreme waves along the US Beaufort coast. Lewellen is reported (Hufford et al, 1977) to have measured offshore waves in excess of 9m (30 ft). Visual shipboard observations of average wave heights on the order of 4 to 5m (13 to 16 ft) were made during a storm which occurred near Point Barrow in August 1951 (Carsola, 1952). Petroleum industry wave measurement programs performed by various contractors for the Arctic Research Subcommittee of the Alaska Oil and Gas Association have been unable to verify large wave heights due to problems with ice and a lack of severe storms, although the exact results remain proprietary.

Measurement and study programs conducted in the Canadian sector of the Beaufort Sea suggest that much higher than normal waves are indeed possible along the Arctic coast. A storm occurred near Mackenzie Bay in September 1970 (Kovacs and Mellor, 1974). It lasted 36 hours and had sustained winds of 104 km/hr (65 mph), producing offshore waves of 9m (30 ft). During a measurement program conducted in the summer of 1977, maximum wave heights of nearly 6m (20 ft) were recorded north of Mackenzie Bay (Cardone, personal communication, 1979).

Other Canadian work has included an elaborate modeling program which was used to hindcast storm-generated waves during the period 1956-1974 (Berry et al, 1977). The maximum waves produced by these storms were analyzed using extreme value statistics, and the return periods associated with various heights were tabulated as a function of water depth. Partial results of this study are reproduced in Table 2-1.

Table 2-1. Projected Extreme Wave Heights
Mackenzie Bay

Return Period, years'	Water Depth, meters (feet)				
	75(246)	50(164)	35(115)	20(66)	10(33)
2	3.2	3.1	2.5	2.1	2.0
5	4.3	4.2	2.9	2.6	2.6
10	5.2	5.2	3.3	2.9	3.1
20	6.3	6.3	3.6	3.2	3.7
50	8.0	8.2	4.1	**3.8**	4.6

The Canadian data are not directly applicable to the US Beaufort sector as a result of differences in bathymetry, coastal configuration, island sheltering, and a host of other variables which may affect wave generation and propagation. Nevertheless, they are probably indicative of the general magnitude of events which are likely in the region.

Summarizing the available data with respect to the wave climatology of the Alaskan Beaufort Sea, it is known that very mild conditions (wave heights less than lm (3 ft) exist throughout most of the open-water season. Infrequent, but severe storms, may generate extreme waves almost an order of magnitude greater (approximately 8 to 9m (26 to 30 ft) in deep-water areas. In shallow, less than 20m (66 ft) water areas, such as those scheduled for the first Beaufort Lease Sale (OCS 50), the maximum wave heights which might be expected over a long time interval (25 to 50 years) are probably on the order of 4 to 5m (13 to 16 ft).

2. Currents

Currents are an important factor affecting the stability of an offshore pipeline. A rapidly moving current on the seafloor can scour out the support of a buried or unburied pipeline causing spanning or settlement of the pipe or sliding laterally across the seafloor inducing bending stresses in excess of design limitations. In addition, current flow past an unsupported pipe may produce vortex shedding and structural resonance if the shedding frequency is similar to the natural frequency of the pipe. A knowledge of currents is important for pipeline construction. Natural backfilling of trenches, for example, is greatly influenced by current speed and direction.

Currents may be produced by a number of natural forces including winds, tides and density gradients. The speed and direction of currents may be modified strongly by local bathymetry, coastal configuration, river outflow and by ice in Arctic areas. Consequently, generalizations concerning currents along the Arctic coast are difficult to make. This is especially true in light of the sparsity of data presently ,available. Surface currents have been studied in a number of specific locations along the Beaufort coast but there are relatively few observations of near-bottom or under-ice currents which are of much greater concern for pipeline design. Nevertheless, it is possible to infer something about the potential magnitudes of bottom currents from surface data since bottom currents tend to be smaller than surface currents as a rule. Major exceptions to this can occur when bottom currents are constricted by bathymetry or ice, thereby causing an accelerated flow.

For purposes of discussion, the Beaufort region can be divided into three major current regimes. The first two encompass areas of immediate interest for petroleum development:

A nearshore regime composed of semi-enclosed lagoons and open embayments. Simpson Lagoon and Harrison Bay are examples which have received the most study.

An inner shelf regime which lies seaward of the barrier islands in depths between 10 and 50m (33 to 165 ft).

An outer shelf regime which lies between the 50m (165 ft) isobath and the shelf break.

a. Nearshore Regime. The nearshore regime is in the Beaufort Sea and is typified by Harrison Bay and Simpson Lagoon. Harrison Bay is a wide (90 km (56 mi) open embayment extending from Cape Halkett to Oliktok Point. Depths are generally less than 10m (33 ft). A large river, the Colville, empties into the eastern part of the bay. Summer surface circulation in Harrison Bay has been studied (Hufford et al, 1977) and found to be primarily wind-driven. Current speeds varied widely within the range 5 to 50 cm/sec (0.1 to 1.0 kt) and had a dominant westerly component. The estuarine influence of the Colville River is unquantitifed but probably is limited to a short period (two to three weeks) in early summer when the major annual flow occurs (Aagaard et al, 1978). The winter circulation in Harrison Bay is practically unknown but seems likely to be limited to tidal flow and occasional meterological events such as surges which may superimpose temporary but somewhat higher current speeds. Winter measurements (Barnes et al, 1977) near Oliktok Point indicate a westerly flow with speeds of less than 5 cm/sec (0.1 kt).

Simpson Lagoon is typical of the narrow and shallow lagoons formed by the barrier island chains off Alaska's north coast. The lagoon is 50 km (31 mi) long and narrows from 9 km (5.6 mi) in the west to 1 km (0.6 mi) in the east. Depths range between 1 and 2m (3 to 7 ft). Circulation within the lagoon appears largely driven by local winds (Aagaard et al, 1978) with some secondary influences due to river discharge, tides, and density gradients. Several numerical models of the lagoon have been developed but none is fully calibrated with measured data (Aagaard et al, 1978). The models indicated that currents are likely to range from 15 cm/sec (0.3 kt), for mean wind conditions, to 45 cm/sec (0.9 kt) during storms. Flow directions follow the winds quite closely. Modeling also indicated a tidal current of about 5 cm/sec (0.1 kt). Little is known of the winter circulation in Simpson Lagoon although ice thicknesses of about 2m (7 ft) by late winter probably preclude most water movement. However, where tidal flow is not completely blocked by ice, higher than normal currents may occur. Measurements (Barnes and Reimnitz, 1973) showed flows of 25 cm/sec (0.5 kt) beneath ice in shallow water which was attributed to ice restriction. These high rates, although not typical, may be a problem in local areas such as channels where water depths are slightly greater than ice thickness.

River discharge in early summer has little direct impact on currents since this occurs before the melting of sea ice and the discharge flows over the ice surface rather than beneath it. River discharge can result in a localized phenomenon known as "strudel scour" which is discussed in a subsequent section of this report.

b. Inner Shelf. Currents in the inner shelf area, which extends seaward of the barrier islands to depths of about 50m (164 ft), are quite poorly known. Summer surface current observations made between Barter Island and Point Barrow (Hufford et al, 1974) indicate typical speeds of 0 to 50 cm/sec (0 to 1.0 kt) with a predominantly westward component. However, there appears to be a rapid response to changing winds such that under westerly winds, the flow is eastward (Aagaard et al, 1978).

One set of winter measurements is available for under-ice currents on the inner shelf (Aagaard and Haugen, 1977). Two current meters were deployed 10m (33 ft) below the ice in water 30 to 40m (98 to 130 ft) deep offshore from Narwhal Island. Current speeds generally were less than 5 cm/sec (0.1 kt) and never exceeded 10 cm/sec (0.2 kt). Mean flow was toward the west-southwest. The tidal component of the measured current was near 1 cm/sec (0.02 kt).

c. Outer Shelf. Seaward of the 50m (162 ft) isobath, somewhat higher current speeds appear to prevail (Hufford, 1975). Flow rates were monitored at 25m (82 ft) at a water depth of 54m (177 ft) northeast of Barrow in 1972. A mean current speed of 60.8 cm/sec (1.2 kt) was found which was subject to daily fluctuations in the range 21 to 83 cm/sec (0.4 to 1.6 kt). The dominant direction of this strong subsurface current was east-southeast. A set of measurements from 100m (330 ft) at a water depth of 225m (739 ft) has been reported north of Oliktok (Aagaard and Haugen, 1977). From May to September 1976, the current velocity varied from 56 cm/sec (1.1 kt) easterly to 26 cm/sec (0.5 kt) westerly. Tidal currents at this location also were found to be higher than on the inner shelf and had an amplitude of about 5 cm/sec (0.1 kt). Under-ice measurements taken by Aagaard (unpublished data) north of Lonely in 1977 showed great variability in speed and direction but exhibited speeds as high as 60 cm/sec (1.2 kt).

To summarize the available data regarding currents on the Beaufort Shelf, it would appear that the nearshore and inner shelf regimes are characterized by a circulation which is primarily wind-driven and normally quite sluggish. Currents tend to have a westerly trend and seldom exceed speeds of 50 cm/sec (1 kt). The outer shelf, although not of immediate interest for petroleum development, is much more energetic with subsurface currents occasionally as high as 80 cm/sec (1.6 kt).

It must be cautioned, however, that as yet there are no available data on currents during the strong storms which may frequent the area in the open-water season. Indirect evidence of storm surge heights as great as 3m (10 ft) along the coast suggest that strong currents 100 to 150 cm/sec (2 to 3 kt) are probably present during such events (Reimnitz and Maurer, 1978). If this is true, it will be an important design consideration for Arctic pipelines in shallow water and at coastal crossings. As also previously discussed, localized bathymetric features and ice may increase the speed of an otherwise slow current.

B. ICE CONDITIONS

1. Sea Ice Environment

Sea ice is the most characteristic feature of the Arctic offshore environment. With the exception of a narrow band of open water which occurs close to the coast each summer, sea ice dominates the Arctic Ocean at all times. Moreover, sea ice is a dynamic feature. It is in a nearly constant state of motion or potential motion.

To understand the problems which ice may pose for submarine pipelines, it is first necessary to provide some description of the sea ice environment which may vary considerably in time and space. For ease of discussion, this environment can be divided into zones, each having more or less distinct properties from the others. Profiles of this zonation during late winter and spring in the Beaufort Sea are shown in Figures 2-1 and 2-2. This is an arbitrary characterization and the boundaries shown can be subject to considerable variability. Major features of each zone are described below.

a. Landfast Ice Zone. The landfast ice zone can be further subdivided into two units, the bottom-fast zone and the floating-fast ice zone. The bottom-fast zone contains ice which is in continuous contact with the shoreline and the sea floor. The extent of this zone increases seaward during the winter months as more ice forms from the sea surface to the sea floor. The maximum extent of the bottom-fast zone by late winter corresponds to the 2m (6.6 ft) isobath which may vary from a few meters to several kilometers offshore. Because it is in close contact with the sea floor, the bottom-fast zone tends to be more stable than ice which is found further offshore during the winter months. However, before complete freeze-up and after the spring thaw begins,

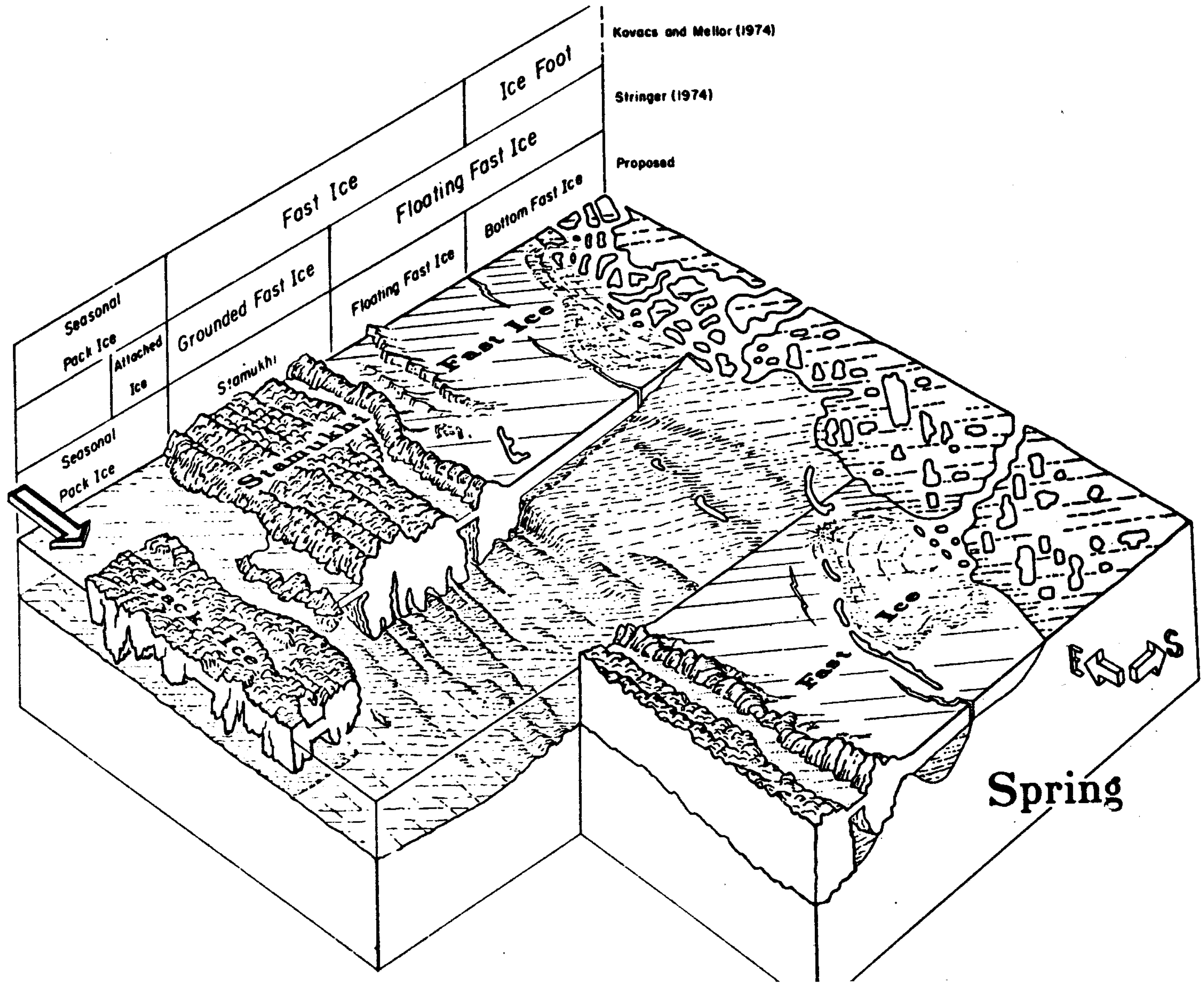


Figure 2-1. Spring Ice Zonation of the Alaska Beaufort Sea (Reimnitz, Toimil & Barnes, reprinted from Proceedings, (c) 1977 Offshore Technology Conference, by permission)

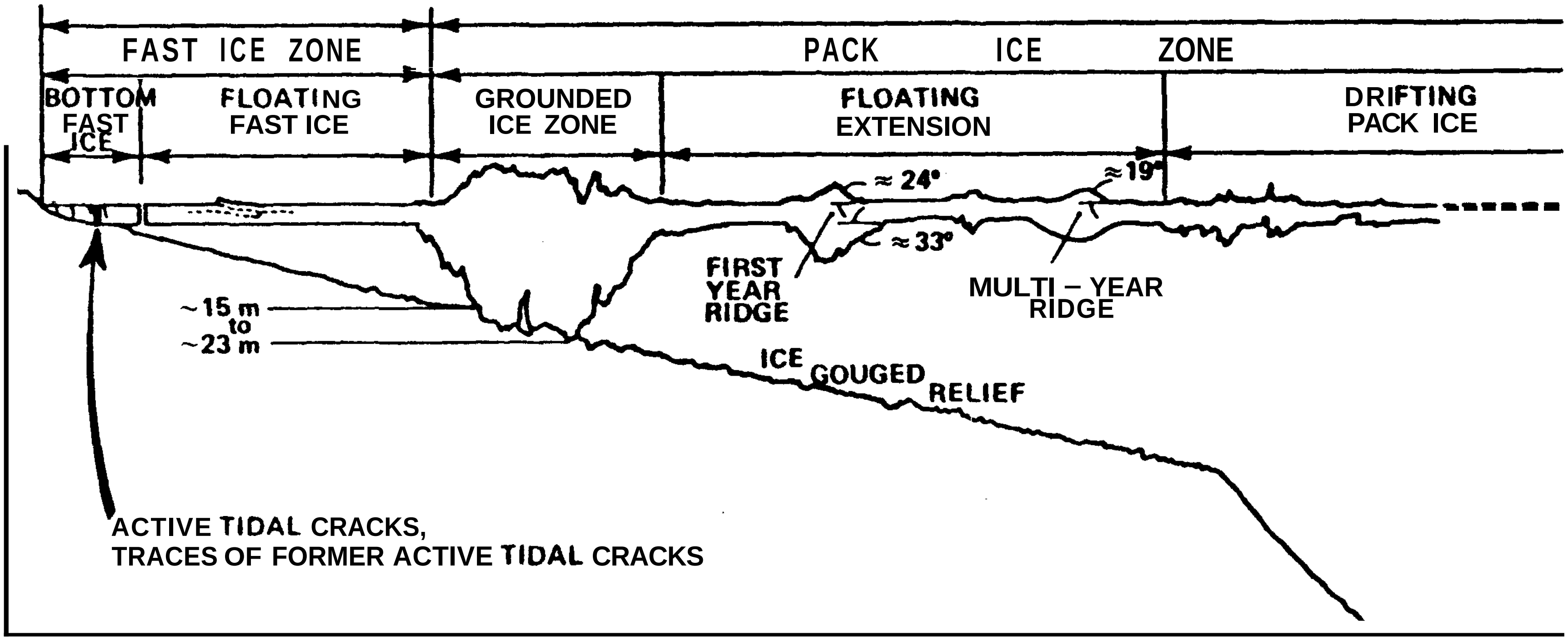


Figure 2-2. Late Winter Ice Zonation of the Alaska Beaufort Sea (Shapiro & Barry, 1978)

appreciable motion is possible. There is, in fact, some evidence of occasional episodes of winter movement whereby large sheets of bottom-fast ice are thrust shoreward across low lying beaches and islands. This phenomenon known as "ice push" or "ice override" is discussed as a special hazard to pipelines in a subsequent section.

b. Floating-Fast Ice Zone. This area extends from the margin of the bottom-fast zone seaward to the zone of grounded ridges (Figures 2-1 and 2-2). The seaward limit of this zone is normally taken as the 15m (50 ft) isobath, although considerable variability occurs from year to year and at different locations along the coast. In the Beaufort Sea, a significant part of the area occupied by the floating-fast ice zone lies shoreward of the barrier islands.

The floating-fast ice zone consists primarily of seasonal or first-year ice, with fragments of drifting multi-year ice embedded in the sheet. Pressure and shear ridges also may be found although they seldom achieve large dimensions. In areas unprotected by islands, sizeable multi-year floes and fragments of ice islands may be incorporated to create formidable ice masses (Kovacs, 1976). If grounded, these features may help to stabilize the first-year ice.

Motion within the floating-fast ice zone depends largely on the degree of protection provided by islands. Within the barrier islands winter movement is believed to be in the range of a few meters (Shapiro and Barry, 1978) and results mainly from thermal expansion and contraction. During freeze-up or thaw, wind may move the ice sheet through distances of several hundred meters. Relatively few measurements of fast-ice motion have been made seaward of the islands although there is one observation of winter motion in excess of 1 km (0.6 mi) (Weeks and Kovacs, 1978).

c. Pack Ice Zone. Seaward of the fast ice zone lies the pack ice zone (Figures 2-1 and 2-2) which has three subdivisions within it: the zone of grounded ridges, the floating extension, and the drifting polar pack ice. Before discussing the characteristics of each subdivision, it is worthwhile to examine a number of major ice features which may occur within the general limits of the pack ice zone. These features pose formidable problems for the deployment of Arctic submarine pipelines.

(1) Pressure Ridges. Pressure ridges are formed from the interactions or collision of ice sheets. They consist of piles of ice blocks forced upward to form sails and downward to produce keels. Large first-year ridges may survive the summer melt season to become multi-year ridges. These ridges may be stronger than first-year ridges because melted water percolates into open spaces between the ice blocks and subsequently refreezes to form a solid, void-free body of ice.

Pressure ridges can achieve impressive dimensions. Sail heights of free-floating ridges as high as 13m (43 ft) have been seen and there is one submarine report of a keel extending to 47m (155 ft) in the open pack (Lyons, unpublished data). However, the vast majority of ridges have sail heights less than 4m (13 ft) and keels less than 12m (40 ft). Sail-height-to-keel-depth ratios have been investigated (Kovacs and Mellor, 1974) and found to have a range of 1:3 to 1:9 in first-year ridges with an average of 1:4.5. Multi-year ridges have an average ratio of 1:3.

Pressure ridges may occur as solitary ice masses surrounded by sheet ice or embedded in multi-year floes of considerable thickness. In the Beaufort Sea, they commonly may occur in a long, continuous row which can extend for tens of kilometers (Kovacs and Mellor, 1974). Such ridge systems normally are grounded and may survive through several seasons.

Eventually they float free and break up into massive fragments. (floebergs) of considerable strength.

(2) Ice Islands. Ice islands in the Beaufort Sea are tabular icebergs calved from the Ellesmere Island ice shelf and transported to the area by the Pacific Gyral (Figure 2-3). Ice islands may remain circulating within the Gyral for tens of years (Kovacs and Mellor, 1974). Ice islands are formidable in both size and strength. Those found in Alaskan coastal waters are typically 30 to 100m (98 to 325 ft) across and 12 to 30m (39 to 98 ft) thick with a draft-to-freeboard ratio of about 5:1.

Little is known about the numbers and distribution of ice islands. A petroleum industry ice reconnaissance study in 1972 indicated the presence of more than 400 islands along the Alaskan coast (Kovacs and Mellor, 1974). Fewer ice islands have been sighted recently.

Pressure ridges, ice islands and their various derivatives are among the most hazardous components of the pack ice zone with respect to man-made structures and equipment. The exact nature of these hazards is deferred to a subsequent section. The following is a continuation of the discussion regarding the characteristics of sea ice zonation.

The first subdivision within the pack ice zone is an area of grounded ridges which marks the location of the first winter interaction between the edge of the land-fast ice and the drifting polar pack (Figures 2-1 and 2-2). This also is called the shear or stamukhi zone. It occurs typically in water depths of 15 to 23m (49 to 75 ft), although in some years, the depth may extend to the 40m (130 ft) contour.

The grounded ridge zone consists primarily of shear and pressure ridges formed by collisions between the moving pack ice and the relatively stable fast ice. The ridges may be

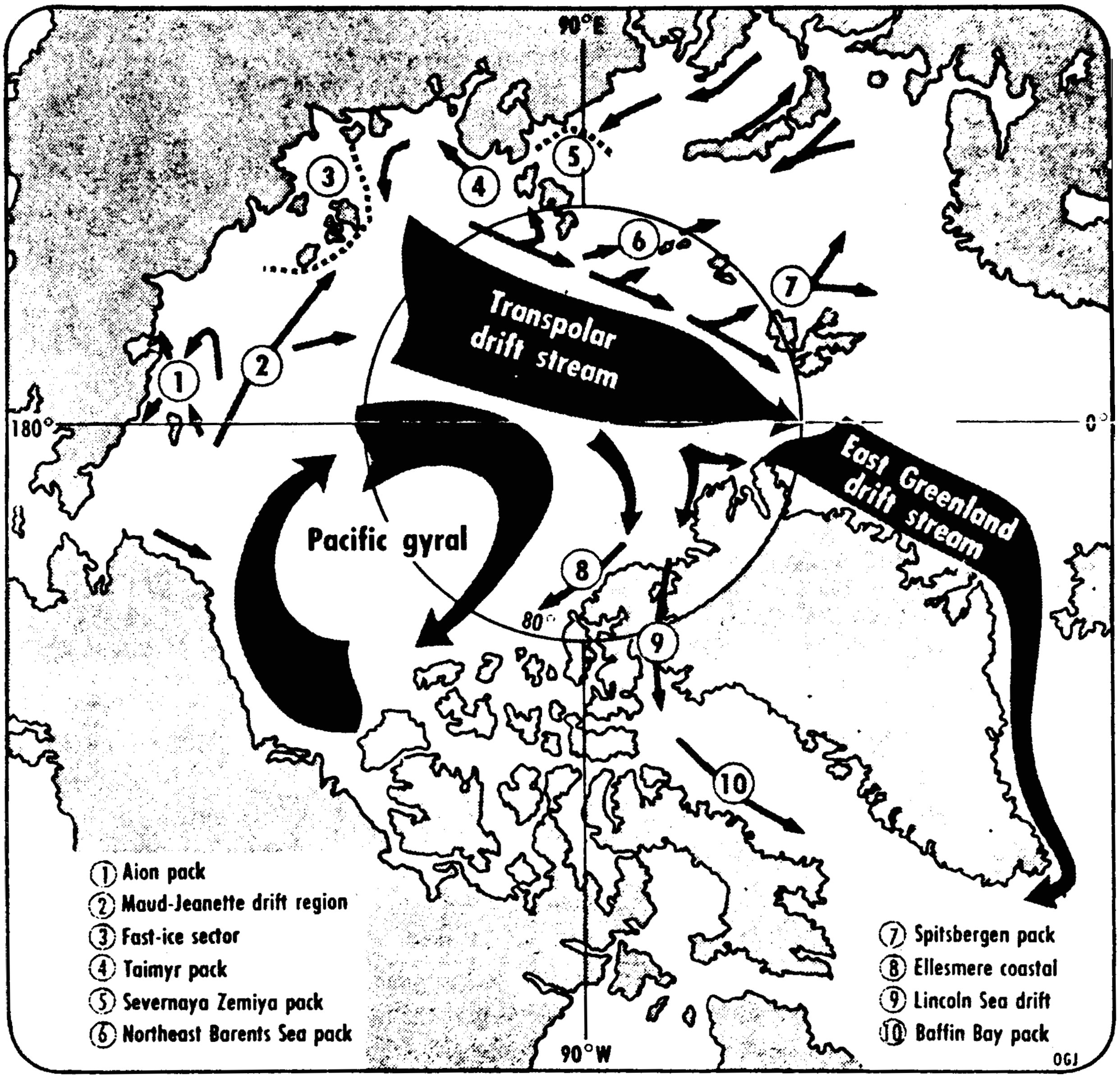


Figure 2-3. Major Polar Drift Streams
(Kovacs, reprinted from Oil and Gas Journal, (c) 1972
Petroleum Publishing Company, by permission)

interspersed with floes of first-year and multi-year ice and occasional ice island fragments. Many of the ridges are embedded in the sea floor, and this grounding helps to stabilize the adjacent fast ice sheet. The grounded ridges also act to prevent the encroachment by pack ice into the fast ice zone.

Between the grounded ridge zone and the drifting pack ice, there is sometimes another zone called the floating extension which develops from ice that has grown seaward after the grounded ridge zone is formed in early winter (Figures 2-1 and 2-2). It is composed of sheet ice and floating ridges which become incorporated as the ice sheet freezes. Because this zone is exposed to constant incursions by pack ice, it is an area of active ridge formation, although the ridges do not ground as they do closer to shore because of increasing depths. This zone also is characterized by frequent flow leads (fractures) which form in response to ice stress.

The last zone is the drifting polar pack ice which begins at the margin of the continental shelf. The polar pack lies within a clockwise moving circulation system known as the Pacific Gyral (Figure 2-3) which extends from the Beaufort Shelf to the North Pole. This circulation is driven by winds of relatively high and constant velocity.

Winter ice conditions are characterized by large multi-year floes surrounded by thinner first-year ice up to 2.3m (7.5 ft) thick (Kovacs and Mellor, 1974). Multi-year ice is estimated at 60 to 70 percent of the area of the polar pack with first-year ice occupying 25 to 30 percent and open-water leads accounting for 1 to 5 percent.

Pressure ridges are ubiquitous features of the polar pack. The number of ridges varies from 17 to 32 km (27 to 51 mi). The majority of these ridges have sail heights less than 4m (13 ft) and keel depths less than 15m (49 ft). Much larger features occasionally occur (Wadhams, 1977). Forty-five pressure ridge keels with drafts exceeding 30m (98 ft) were identified from a submarine sonar profile of 3900 km (2420 mi) taken northwest of Greenland. The deepest observed keel along this track was 42m (138 ft).

Almost constant motion is one feature which distinguishes the polar pack from other ice zones. Ice drift in the southern Beaufort Sea tends to parallel the coast and averages speeds of 20 km (12 mi) per month in winter and 80 to 100 km (50 to 62 mi) per month in summer (Shapiro and Barry, 1978). A brief summary of selected winter ice zone characteristics is found in Table 2-2.

2. Annual Ice Cycle

Descriptions of cyclic ice phenomena in the Arctic are complicated by the exceptional variability of conditions which can occur from year to year. Not only is there a wide temporal variability in the cycle, but there can be significant differences in the physical events which occur. Any description, therefore, will suffer from a degree of imprecision. With this caveat, the following is a summary of the "typical" sequence of events occurring during an annual ice cycle in the Alaskan Arctic. The dates given may vary by two weeks to a month.

New ice formation in the land-fast zone begins in late September to early October. Under the influence of falling temperatures, ice crystals begin to form and mesh, creating a thin, slushy surface layer. If the sea is rough, this layer will be broken up into circular pieces called pancake ice which eventually fuse to form an ice sheet with a rough surface texture. If the sea is smooth, and the temperature low, the ice will form rapidly into a smooth, textured sheet. During October, the ice continues to thicken and, by the middle or end of the month, may form a continuous sheet extending beyond

Table 2-2. Characteristics of Ice Zones in Winter

ZONE	TYPICAL DEPTH RANGE (M)	MAXIMUM OBSERVED MOTION	TYPES OF ICE
BOTTOM FAST ICE	0-2	FEW METERS	FIRST YEAR SHEET SMALL MULTI-YEAR FRAGMENTS
FLOATING FAST ICE	2-15	TENS OF METERS (INSIDE ISLANDS) > 100 METERS (OUTSIDE ISLANDS)	FIRST YEAR SHEET MULTI-YEAR FLOES PRESSURE RIDGES SHEAR RIDGES
GROUNDED RIDGE	15-23	?	PRESSURE RIDGES SHEAR RIDGES
FLOATING EXTENSION	23-SHELF EDGE	> KM/DAY	MULTI-YEAR FLOES SHEET ICE PRESSURE RIDGES SHEAR RIDGES
PACK ICE	BEYOND SHELF	> KM/DAY	MULTI-YEAR FLOES PRESSURE RIDGES ICE ISLANDS SHEAR RIDGES

the barrier islands in the Beaufort Sea and across Kotzebue Sound in the Chukchi.

As the fast ice is forming, a number of changes begin to occur which affect the location and motion of the polar pack. Normally, there is a steepening of the barometric pressure gradient resulting in a wind shift from offshore to onshore. Offshore winds during the summer months tend to prevent the polar pack from encroaching on the coast. With this wind shift, however, the pack ice moves toward the shore and the developing fast ice zone. Concurrently, there is an increase in the size of the polar pack due to the addition of new ice at the pack margin. The rate of shoreward motion depends almost entirely on wind conditions. Fall storms may drive the pack toward the coast with considerable speed and force.

During the early fall, when the land-fast ice sheet is continuous but thin, a zone of interaction is established between the land-fast and moving pack ice. This zone generally forms in depths of 15 to 20m (50 to 66 ft). If the force of the pack ice is of short duration and limited intensity, only the outer edge of the fast ice is affected, resulting in light ridging and low surface relief. If, however, the force is great and of long duration, spectacular ridging may occur.

By November or December, a zone of grounded ridges is formed, preventing further shoreward incursions by the pack ice and stabilizing the land-fast ice inside the 15m (50 ft) isobath. The land-fast ice also is thickened sufficiently to resist deformation from most forces.

Throughout the winter, the zone of ridges may expand seaward. Ridging on the outer edge still can continue, although ridges normally do not become grounded because of increasing water depths. As winter progresses, the polar pack tends to become more massive as loose, multi-year floes are frozen into the main body of the pack. This increases the inertia of the pack so that more force is required to move it toward the shore. Storms decrease during the winter· season resulting in an overall effect of less-frequent and. intense incursions by the pack into the fast-ice zone. By March or April, the fast ice may extend to the 30m (100 ft) isobath and may be relatively stable inside that limit.

In late May, rivers along the North Slope begin to melt and flow northward into the Beaufort Sea. Since the estuaries are filled with ice, the river discharge empties onto the surface, resulting in large areas of flooded ice along the coast. This flooding begins the melting cycle, and by early June, melt ponds are found throughout the fast-ice surface. Through June, there is a gradual melting and weakening of the ice. At about the same time, a lead begins to form in the eastern Beaufort at the mouth of the Mackenzie River. This lead expands rapidly and extends westward to about the Colville River Delta by mid or late July.

With the initiation of the summer fast ice break-up, the pack ice also begins to decay. By the time the fast ice sheet has disintegrated (July-August), the southern edge of the pack consists of broken floes rather than continuous ice and there is usually a large open lead between the pack and the shore. Break-up continues along the shore through July and August. The area of the coast from the Colville River to Point Barrow is normally the last to break up because of prevailing east-northeast winds. There is usually some open water from early August to mid or late September along the length of the Beaufort coast. Summer storms, which can push the pack ice onto the shore, may occur at any time during this so-called navigable season. Normally, these closures last for only a few days, but in bad years the entire navigable season also may last only a few days. Figure 2-4 shows the maximum and average retreat of the polar pack along the Beaufort coast.

3. Ice Hazards Related to Pipelines

The foregoing discussion was intended to provide an overview of the sea ice environment and some of the natural dynamic processes which exist on the Alaskan Beaufort continental shelf. A cursory understanding of this environment is required to appreciate the nature of hazards posed by ice and to understand the problems which must be solved in order to design, deploy, and operate a pipeline in this area. The following discussion is therefore intended to highlight some of the fundamental problems which must be addressed by the pipeline designer, installer, or operator. Certain problems are obvious while others may be more subtle.

a. Ice Scour. Ice scour or ice gouging is the plowing of bottom sediments by the keels of pressure ridges, ice islands or other large displacement ice features. Ice scour is typically manifested as a linear or curvilinear depression with flanking ridges of displaced seabed material (Figure 2-5). Scour marks may occur as solitary features or in groups.

Ice scour marks were first observed about 25 years ago (Carsola, 1954) but it was not until the early 1970's that the complex bottom microrelief was attributed correctly to ice movement. In the last decade, investigations by Canadian and US researchers have shown that the phenomenon of ice scour is widespread on the inner shelf of the Beaufort Sea. Off the Alaska coast, ice gouge densities, depths of incision, and dominant directional trends are reasonably well known for the region between Cape Halkett and Flaxman Island inside the 15m (49 ft) isobath. However, they are poorly known in deeper water and in the eastern and western sectors of the Alaskan Beaufort (Barnes and Hopkins, 1978).

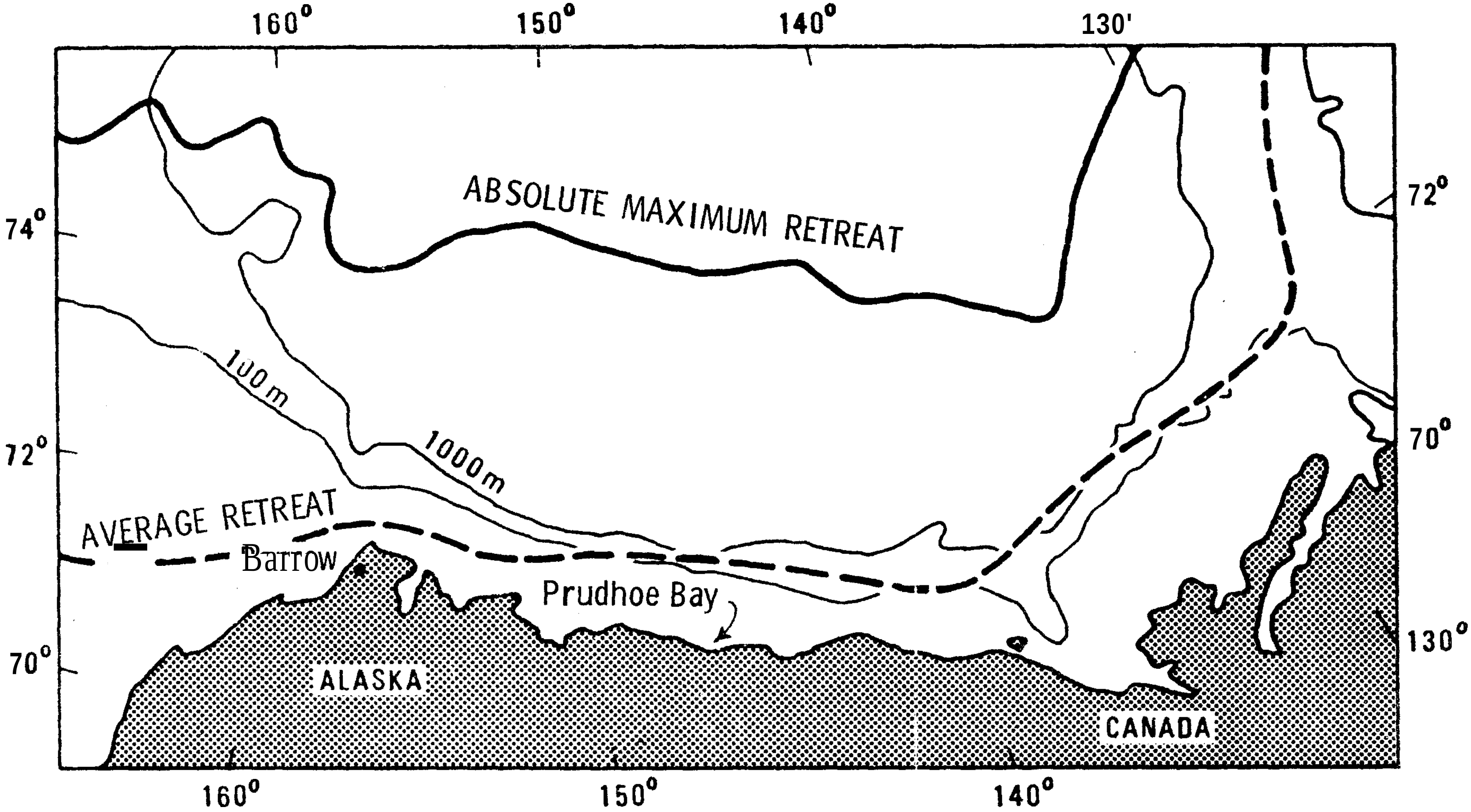


Figure 2-4. Average and Maximum Retreat of Pack ice from Alaskan Arctic Coast (Shapiro & Barry, 1978)

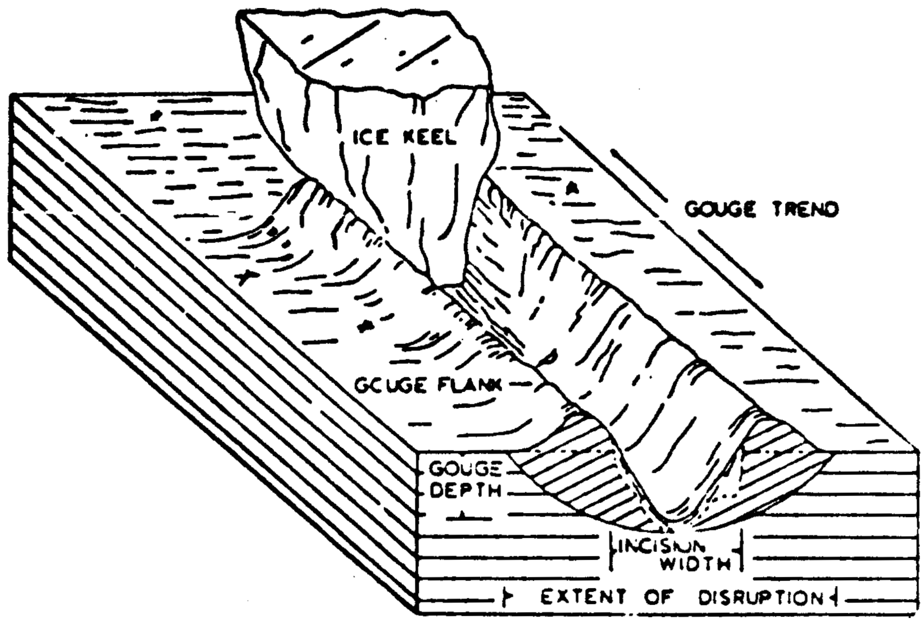


Figure 2-5. Profile of Idealized Ice Scour (Barnes & Hopkins, 1978)

Numerous studies of ice scour on the Beaufort Shelf have been conducted (Reimnitz and Barnes, 1974). Some findings include the following observations. Ice scour distribution on the inner shelf is related closely to ice zonation and bottom topography. Shoreward of the zone of grounded ridges (within the 10 to 22m (33 to 66 ft) isobath) scour incisions are commonly less than 1m (3 ft) deep. Within this zone, the intensity (density) of scour tends to decrease from deeper to shallow water. The dominant directional trend is parallel to the coast (east-west) with a subordinate southwesterly trend toward the coast. Studies conducted in water depths less than 15m (49 ft) northwest of Oliktok Point indicate that ice gouging occurs frequently enough to rework the bottom sediments to a depth of 0.2m (0.6 ft) in less than 100 years.

Within and seaward of the grounded ridge zone, scour incisions are commonly deeper than one meter, and maximum values may be much greater. Observed extremes include 4.5m (15 ft) in 38m (125 ft) of water in the Chukchi Sea; 5.5m (18 ft) at the same depth in the Alaskan sector of the Beaufort; and in excess of 6.5m (21 ft) in water depths between 40 and 50m (131 to 164 ft) in the Canadian sector. The greatest intensity of scouring corresponds to the zone of grounded ridges with localized areas of intense scour on the seaward side of shoals. The intensity of scour tends to decrease with increasing water depth but scour marks have been observed at depths exceeding 100m (330 ft). Seaward and within the zone of grounded ridges individual scour marks may be oriented in any direction but there is a preferred east-west orientation, parallel to the coast. Figures 2-6 and 2-7 summarize various observations on the nature of ice scouring in the Alaskan and Canadian sectors of the Beaufort Shelf.

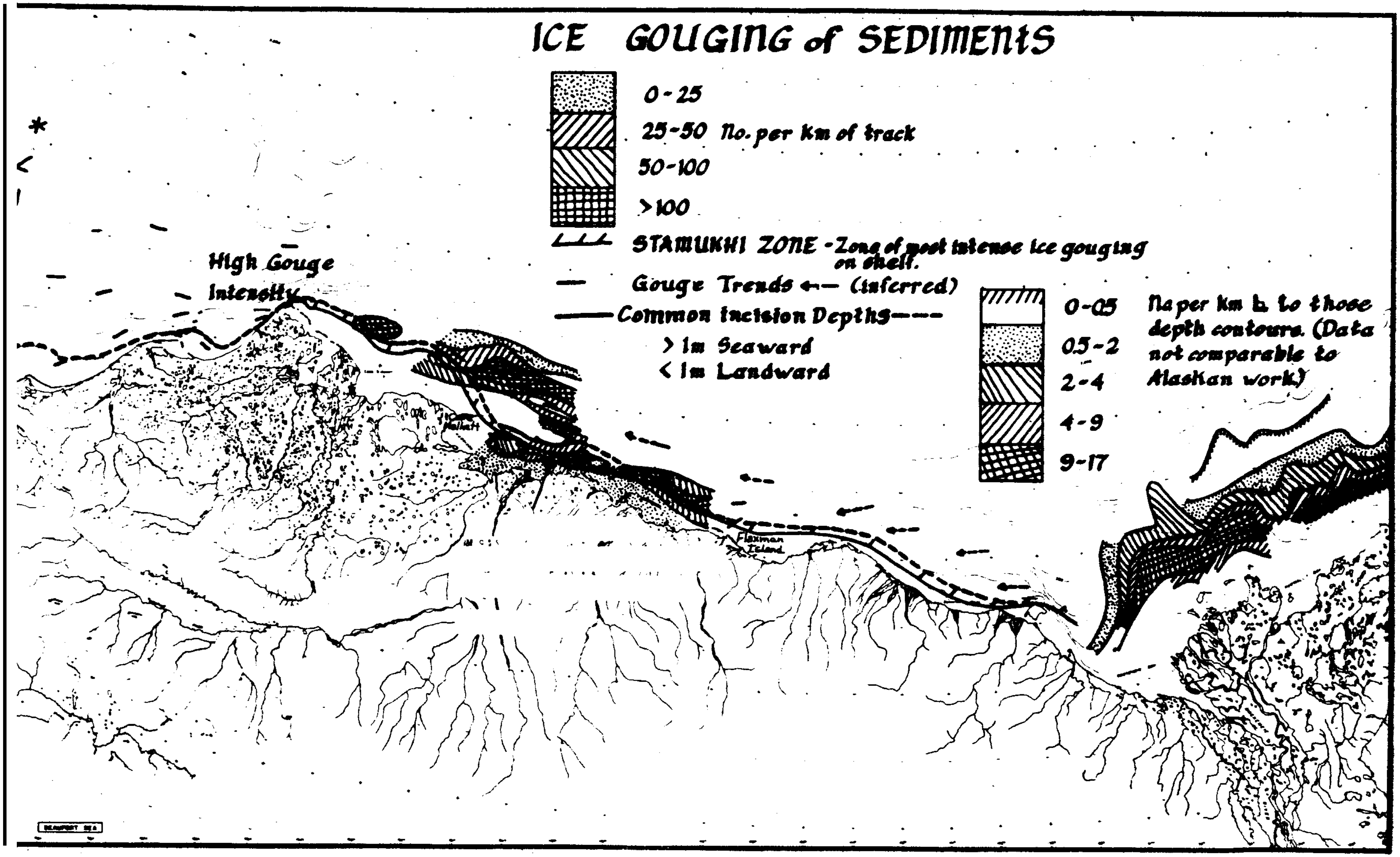
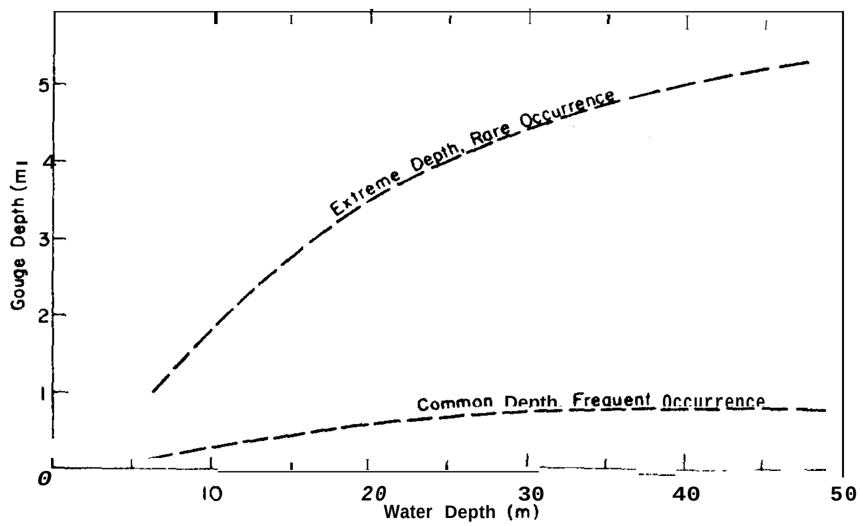


Figure 2-6. Beaufort Sea Ice Scour (Barnes & Hopkins, 1978)



Actual situations are complicated by local bathymetry, currents, ice characteristics, bed conditions, etc.

Figure 2-7. Ice Gouge Depth--Simplified Representation (Mellor, 1978)

The driving mechanism responsible for creating the extensive scour observed on the Beaufort Shelf has been examined by Kovacs and Mellor, 1974. They concluded that the momentum of drifting ice propelled by wind or currents is insufficient to create the long, wide, and deep scores which have been observed. Rather, they hypothesize that the forces required are generated by wind shear acting on an ice sheet which, in turn, drives the ice feature responsible for scouring the sea bottom.

The implication of the ice scour phenomenon for Arctic marine pipelines is fairly obvious. It seems clear that it would be economically infeasible to design a pipeline capable of resisting the forces of moving ice. A small ice island moving at 17 cm/sec (0.3 kt) for example, has a kinetic energy equivalent to a 1.52×10^8 kg (157,000-ton) vessel moving at 375 cm/sec (7 kt). A straightforward solution to the problem is to avoid the ice completely by burying the pipeline to a depth below the level of probable scour. It is difficult to specify safe burial depths on an a priori basis because the depth of scour is very location-sensitive and will require extensive site surveys and data analysis. Part of the difficulty in assessing probable scour depths is that it is difficult to distinguish between contemporary scour activity which occurred during a geologic period when sea levels were much lower than they are today. The low rates of natural Arctic sedimentation (typically 0.04 in/year) have preserved ancient scour marks in a relatively unaltered condition. Nevertheless, a safe burial depth in deeper water and in zones of high scour activity probably would not exceed 4 to 5m (13 to 16 ft). In other areas, burial to depths of 2 to 3m (6 to 10 ft) or less would provide sufficient protection. Burial to these depths is technologically feasible although undoubtedly expensive.

b. <u>Ice Push or Ice Override</u>. Ice push or ice override occurs when sections of land-fast ice separate from the main ice sheet and are thrust shoreward onto islands or coastal beaches. The phenomenon is quite common during freeze-up and break-up when the ice is thin and weak, but fairly large movements also have been observed in mid-winter and have involved 2m (7 ft) thick ice. The driving force for such events is probably wind stress although other geophysical or meteorological forces may be involved.

When an ice push event occurs, the slope of the beach greatly determines the nature of the ice advance or override. Steep beaches normally cause the advancing ice to fracture since it must bend to move onto the beaches. In such cases, a rubble pile is formed which tends to prevent or hinder further encroachment by the ice sheet. Sizeable piles of ice may be formed in this manner. Beaches with low slope angles may be invaded significant distances by ice push. A number of ice push events which occurred during the winter of 1977-1978 were observed along the Beaufort coast (Hanson et al, 1978). Two barrier islands were overriden completely by ice. In one case, ice which had a maximum thickness of 0.9m (3 ft) advanced 140m (460 ft) across an island. The width of the advance was 880m (2890 ft).

The implications of this phenomenon are that pipelines must be protected at coastal crossings, and for some distance onshore, to prevent interactions with ice. There is insufficient knowledge of the mechanisms involved to predict where ice push can occur. Two instances of ice push were observed at the ARCO causeway in Prudhoe Bay which is in a relatively sheltered location (Weeks, 1978). In one case, ice pieces 4m (13 ft) in diameter were thrust on top of the causeway. Any unarmored pipeline, had it been built on top of the causeway, would have been damaged by this event.

Causeways are an attractive alternative to subsea pipeline burial at nearshore locations since they also can be used for year-round logistics. Causeways also would provide protection from ice scour. Nevertheless, any causeway design must provide adequate defense against ice override.

c. Strudel Scour. Strudel scour is seabed erosion which is caused by the discharge of water through cracks and holes in the ice during the spring runoff period. The numerous Arctic. rivers such as the Colville, Sagavanirktok, and Kuparuk tend to have a highly seasonal flow, concentrated during a two to three-week period in May and June. During this period, the river flow is discharged on the surface of the fast ice reaching depths of 1 to 3m (3 to 10 ft) and extending many kilometers (miles) offshore. The inundated ice is buoyant and tends to rise. As it rises, water is transferred through holes or cracks in the ice.

Low pressure water jets thus are created which may scour pits or trenches beneath ice in shallow water. The jets tend to have fairly low nozzle pressures but flow rates may exceed 10,000 gal/min through a 0.6m (2 ft) diameter hole (Mellor, 1978). As a result, large volumes of sediment may be displaced. Cylindrical scour depressions as much as 4m (13 ft) deep and tens of meters across have been reported (Reimnitz et al, 1974).

Although a limited seasonal phenomenon, strudel scour is an obvious hazard to buried pipelines in Arctic coastal areas. Uncovering of pipes, or loss of supporting foundation material which may lead to sagging, are two of the most direct engineering implications. A partial solution may include routing of pipelines around areas of known scour activity such as river deltas. Figure 2-8 shows areas and limits of strudel scour along the Beaufort coast. Another possible solution is the use of coarse backfill material which is less

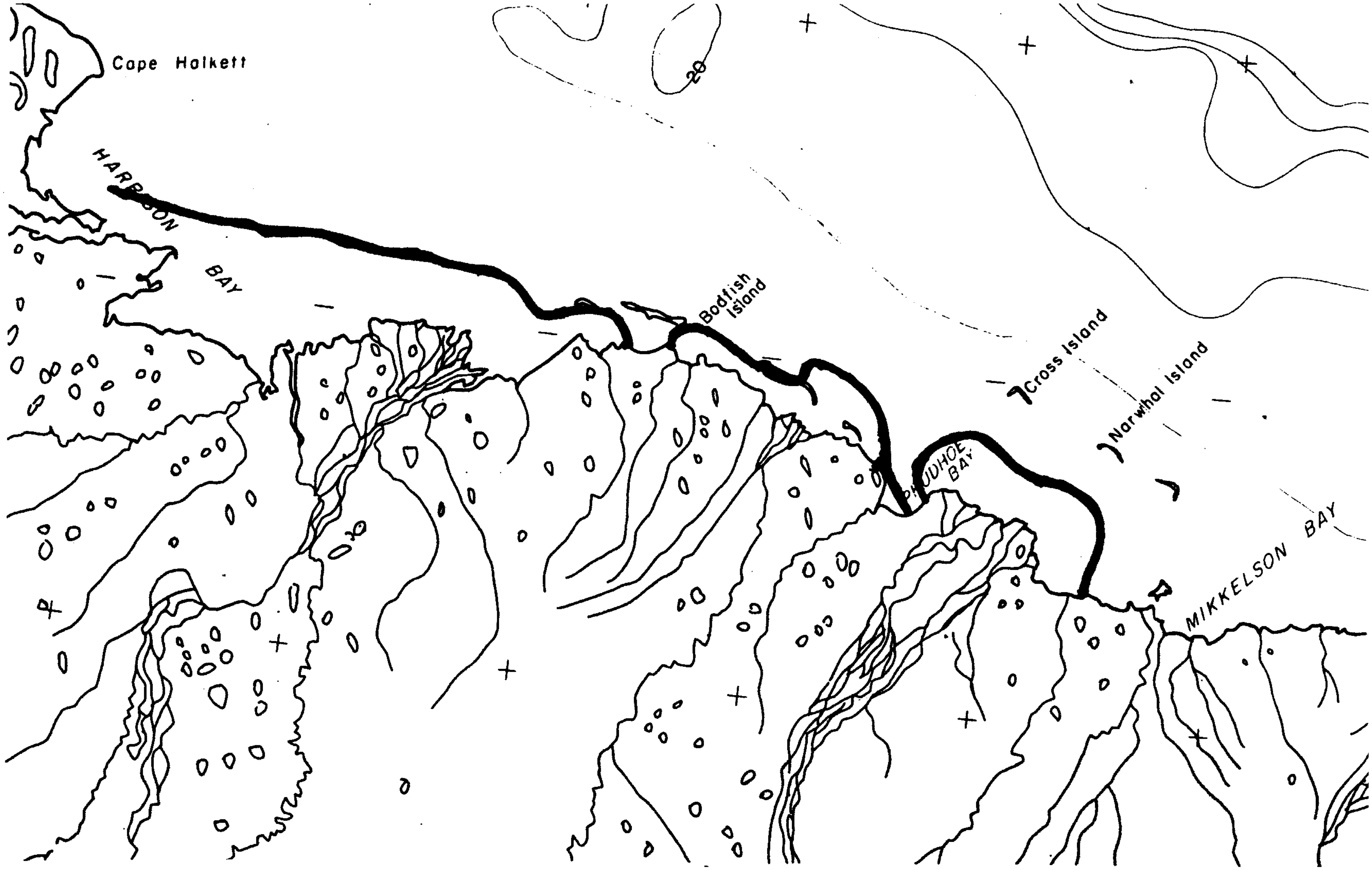


Figure 2-8. Outer Limit of "Strudel" Scouring— Observed Between Harrison Bay and Prudhoe Bay (Barnes & Reimnitz, 1977)

vulnerable to scouring action. As with previous problems, deeper pipeline burial or elevation of the pipeline in a causeway can be used to obviate this difficulty.

C. GEOTECHNIC CONDITIONS

Due to inaccessibility and difficult working conditions, the offshore Arctic, and particularly its geology, is poorly-known in comparison to temperate regions. Only within the last five years have major efforts been initiated to understand the geologic framework of the area and the geotechnical conditions which exist beneath its ice-covered waters. Most of the recent work has been completed under the auspices of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) funded by the Bureau of Land Management and administered by the National Atmospheric and Oceanic Administration. The majority of field studies have been carried out by scientists from the US Geological Survey (USGS), the Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), and the University of Alaska. Consequently, many of the conclusions drawn from this work are tentative and must await additional data for verification. The information provided in this section represents an interim review which may be subject to substantial revision.

1. Sediment Distribution and Properties

Surface sediments on the Alaskan Beaufort shelf are reasonably well mapped except on the inner shelf west of Cape Halkett and east of the Canning River (Barnes and Hopkins, 1978). Figure 2-9 shows the distribution of surficial sediments along the shelf. These are extremely diverse and range from over-consolidated clays to boulders. The predominant forms are poorly sorted silty clays and sandy muds containing various amounts of intermixed gravels (Barnes and Hopkins, 1978). The sediments become coarser eastward; clayey sediments

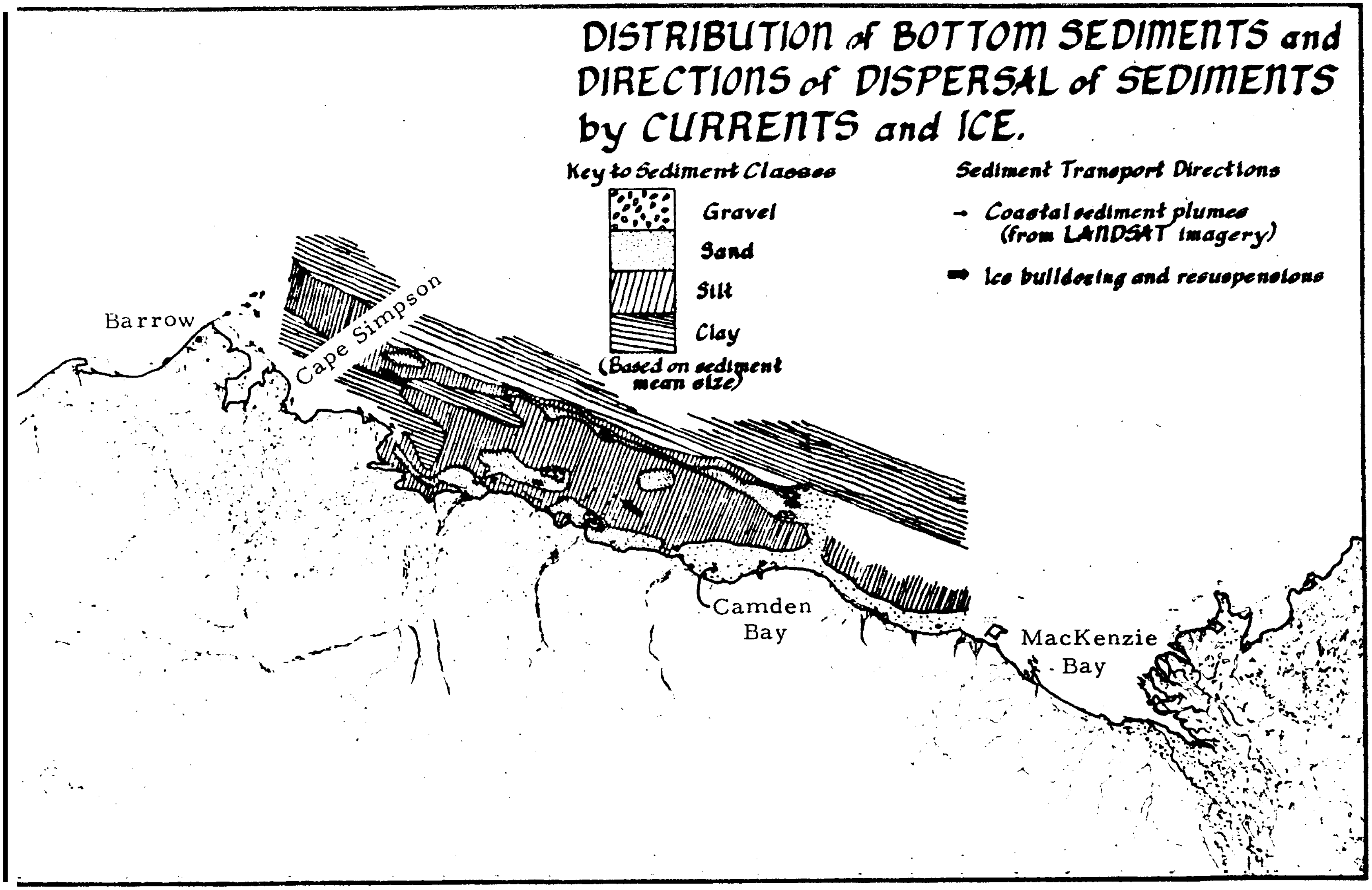


Figure 2-9, Distribution of Bottom Sediments, Alaska Beaufort Coast (Barnes & Reimnitz, 1974) predominate in the area west of Cape Halkett. Sands generally are confined to the immediate coast in the eastern sector.

Most of the fine-grained surficial sediments are of local origin, introduced from North Slope rivers and from erosion of coastal bluffs. In spite of the numerous coastal rivers, marine sedimentation rates are low, averaging less than 10 cm/century (4 in/century) on much of the shelf. Higher sedimentation rates of 60 cm/century (24 in/century) have been noted at Prudhoe Bay. In contrast, some areas of the shelf lack any substantial thickness of Holocene sediment (sediment deposited within the last 10,000 years).

The distribution of sub-surface sediments is best known in the vicinity of Prudhoe Bay as a result of various probe and borehole data taken by USGS and CRREL. The location of these measurements (Figure 2-10) is along three lines normal to the coast and along a fourth line parallel to the coast. Schematic sediment profiles, along lines 1, 2 and 3, respectively, are shown in Figures 2-11 through 2-13. In general, the profiles show that there is a considerable variability in the composition of the upper 8 to 10m (26 to 33 ft) of sediments. They tend to be fine-grained materials which contain high amounts of both organic material and interstitial water (Page and Iskander, 1978). The deeper sediments below 8 to 10m (26 to 33 ft) consist primarily of glacial and fluvial gravels.

Engineering properties of sediments in the vicinity of Prudhoe Bay have been studied (Chamberlain et al, 1978; Sellman and Chamberlain, 1979). Partial results of this work are shown in Figures 2-14 and 2-15. The lithologic sections illustrated for each bore hole confirm the presence of fine-grained marine sediments up to 10m (33 ft) thick which overlie a section of sand and poorly-sorted gravels.

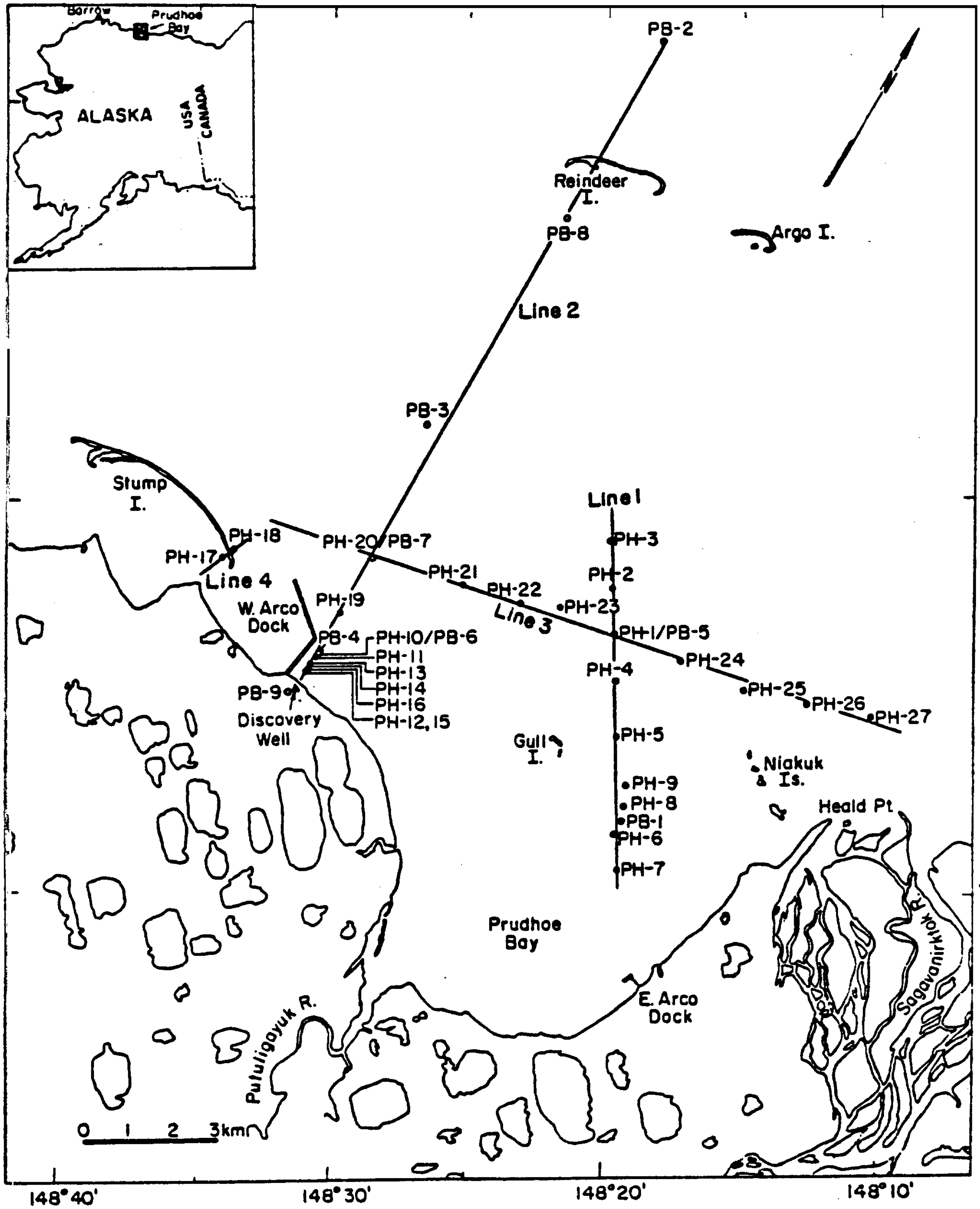


Figure 2-10, Sediment and Permafrost Measurement Locations (Blouin et al., 1979)

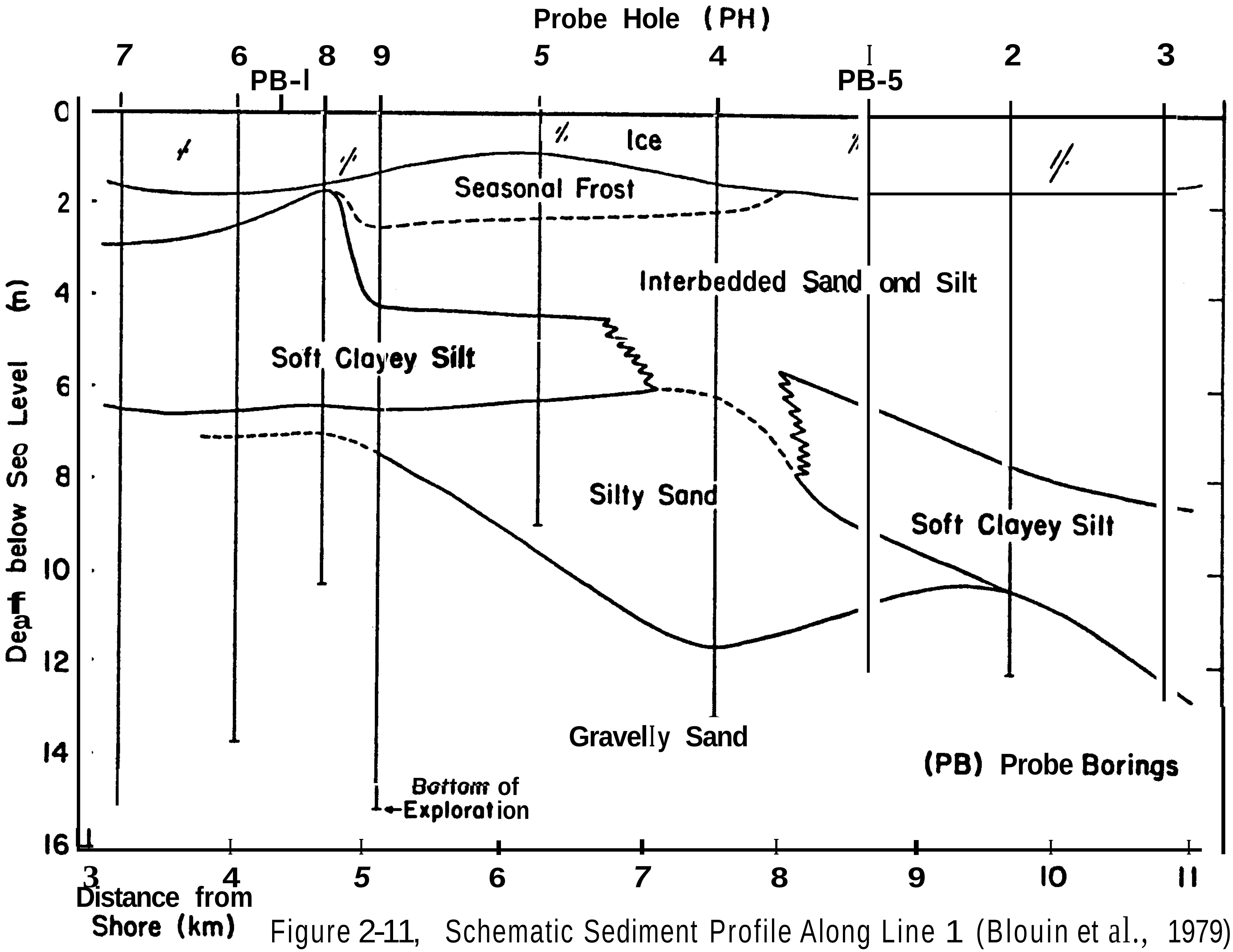


Figure 2-11, Schematic Sediment Profile Along Line 1 (Blouin et al., 1979)

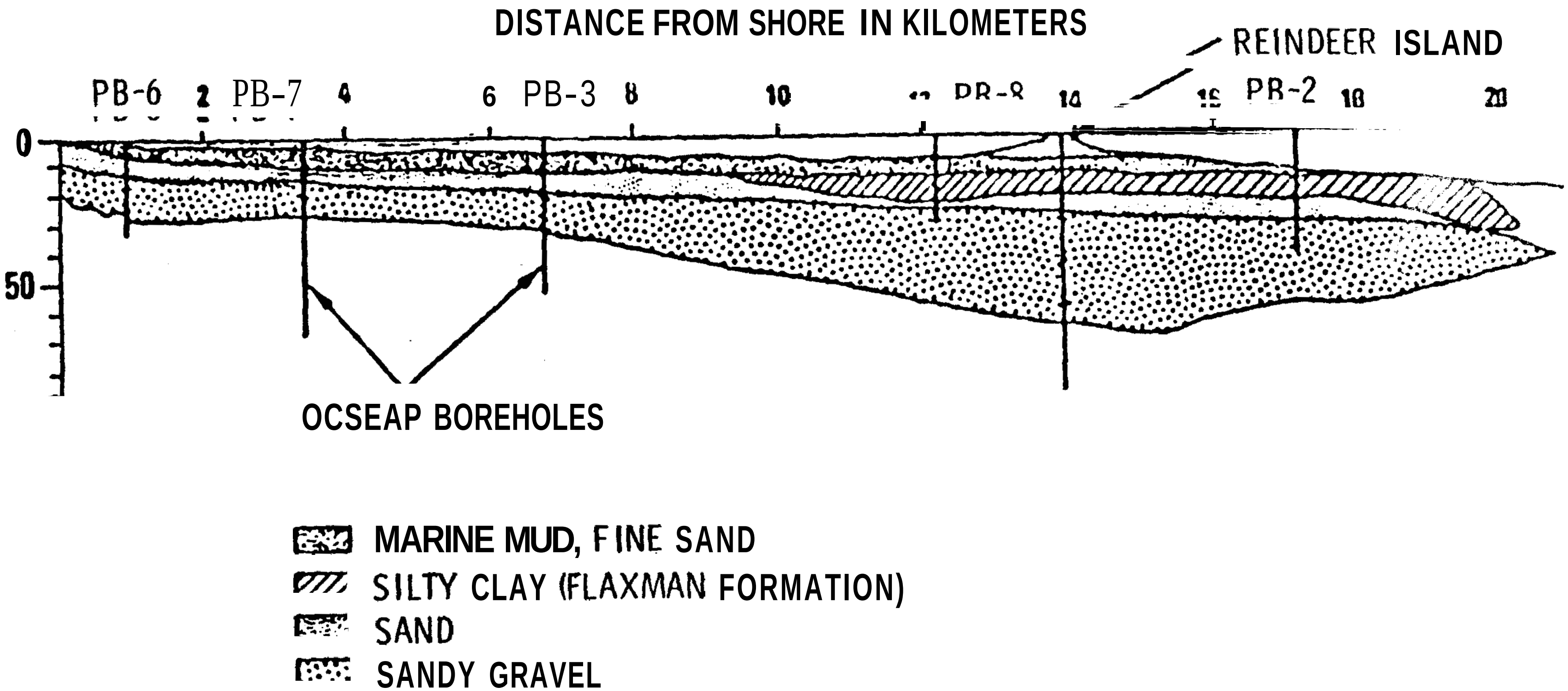


Figure 2-12. Schematic Soil Profile -- Prudhoe West Dock to Reindeer Island (Line 2) (Blouin et al., 1979)

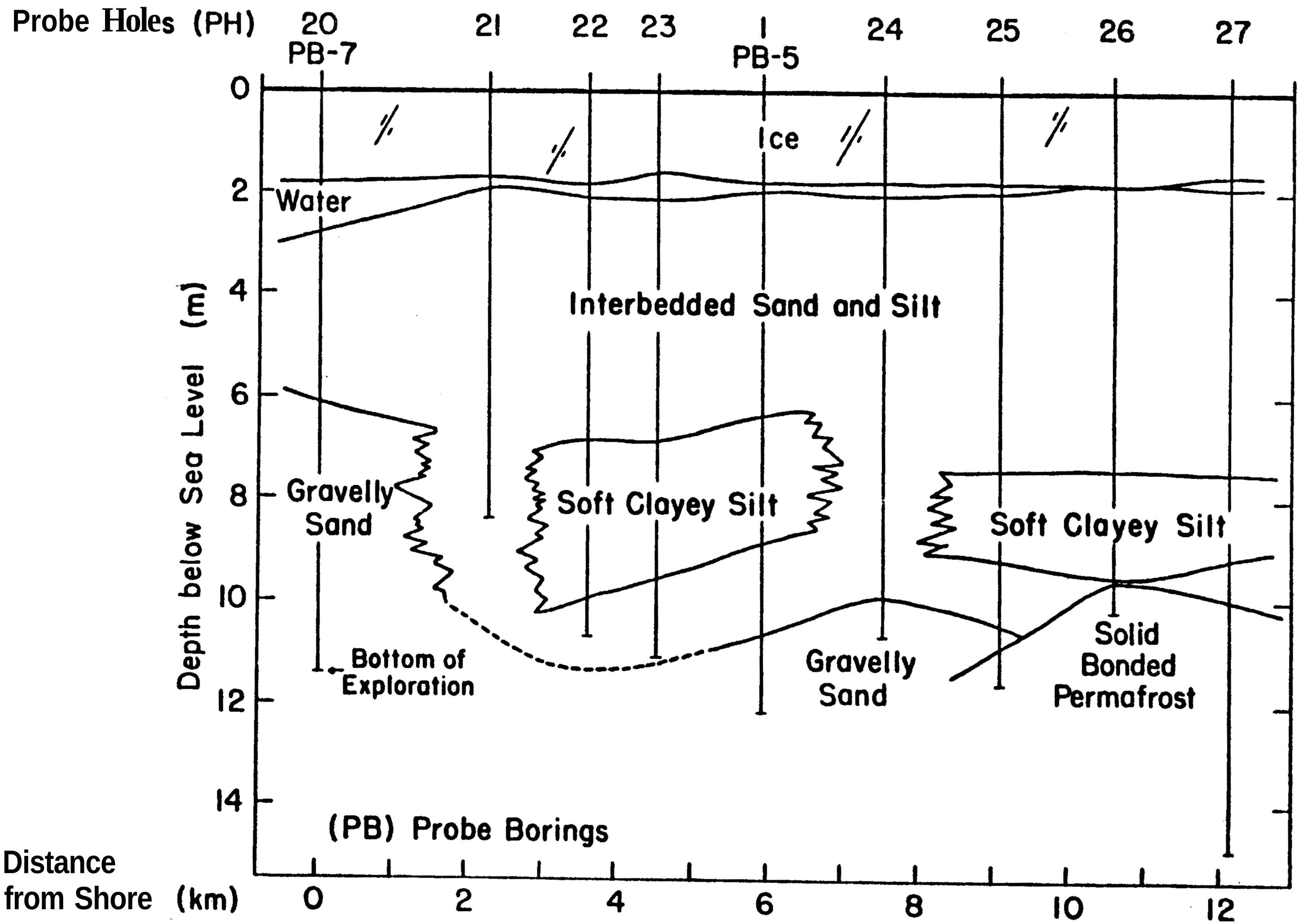


Figure 2-13. Schematic Sediment Profile Along Line 3 (Blouin et al., 1979)

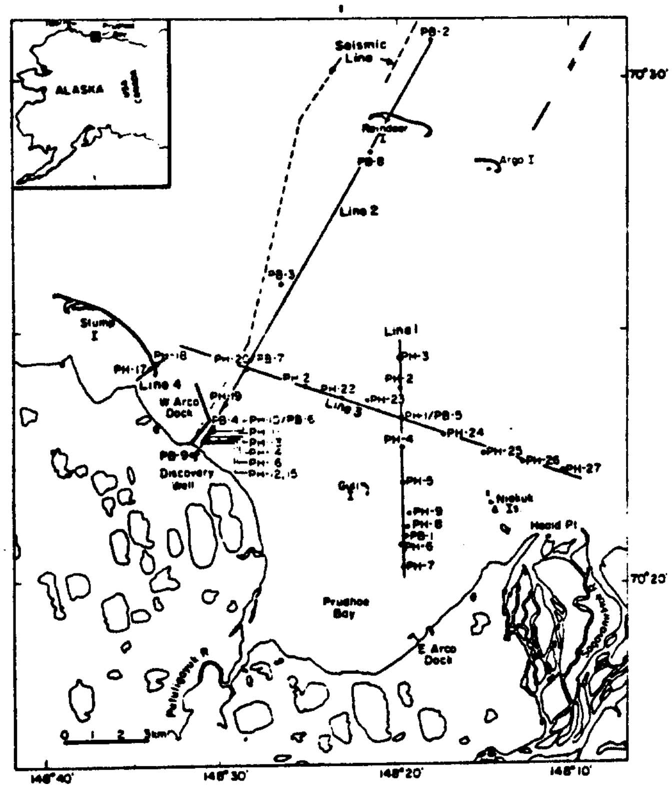


Figure 2-14. Site Locations and Major Study Lines (Sellman & Chamberlain, reprinted from Proceedings, (c) 1979 Offshore Technology Conference, by permission)

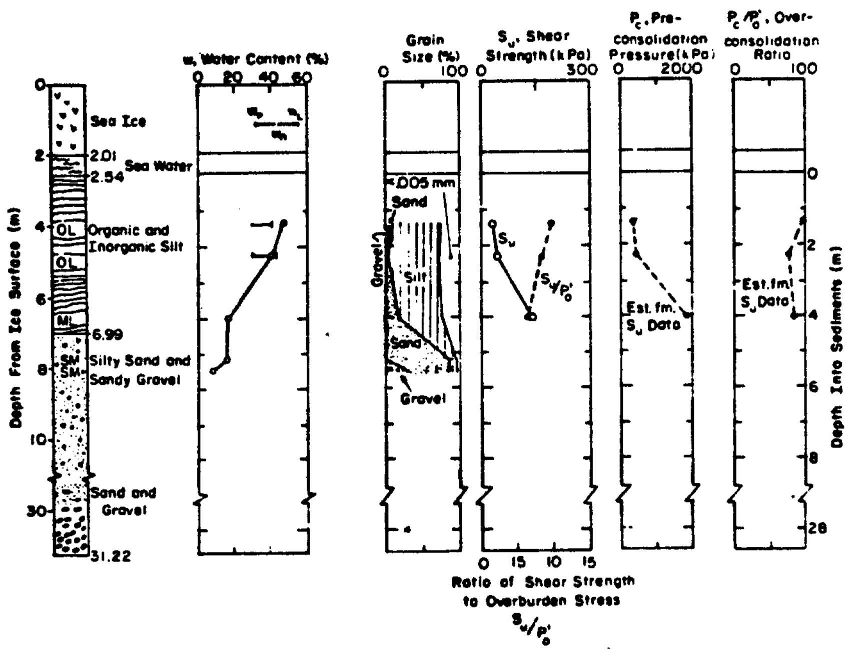


Figure 2-15. Drill Hole Log and Engineering Properties for Site PB-1 (Sellman & Chamberlain, reprinted from Proceedings, (c) 1979 Offshore Technology Conference, by permission)

Within the fine-grained sediments, the index properties are highly variable from site to site and with the depth at any given site. At site PB-1 (Figure 2-15), for example, the water content ranges from about 9 to 43 percent, the latter value exceeding the liquid limit. In contrast, the water content at site PB-2 is quite uniform, ranging from 20 to 22 percent and, in all cases, is at or below the plastic limit.

The fine-grained sediments were found to be overconsolidated at most of the sites although there was considerable variability in the degree of overconsolidation. The estimated values for the preconsolidation pressure (pc) ranged from a low of 540 kPa (78 psi) at site PB-8 to 1900 kPa (276 psi) at PB-2, with overconsolidation ratios (pc/po, the ratio of preconsolidation pressure to effective overburden pressure) varying from 2.2:1 at PB-7 to 1091:1 at PB-5. The sediments thus exhibited lightly to highly overconsolidated values (Sellman and Chamberlain, 1979).

The shear strengths of the samples analyzed were found to be relatively high which is consistent with overconsolidation. The weakest sediments were found near the center of Prudhoe Bay (site PB-1) while the highest values were found north of Reindeer Island (site PB-2).

These same sediment characteristics and properties will not necessarily apply to other areas of the Beaufort shelf. It is agreed generally that most of the shelf is overlain with a thin veneer of fine-grained Holocene sediments ranging in thickness from 5 to 15m (16 to 49 ft). These sediments consist mostly of mud and sand deposited since the post-glacial rise in sea level. Beneath these fine-grained materials lies a layer of coarse sand and gravel associated with the Gubik formation extending seaward from the coastal plain. The thin layer of Holocene sediments is subject to disruption by waves, currents, and particularly ice scour. However, there is no evidence to suggest that the material is subject to large-scale displacements by slumping or slides (Grantz et al, 1976). Such events do occur along the steep continental slope, however.

The engineering properties at Prudhoe Bay suggest that several site-specific measurements will be required if similar variabilities are found elsewhere on the shelf. However, there is no evidence based on the Prudhoe observations to suggest that the sediments are unsuitable for pipeline construction or operation.

2. Permafrost

a. Potential Problems. Permafrost is defined as any earth material that is continuously below a temperature of zero degrees Celcius (32°F) for a period of two or more years (National Academy of Sciences, 1976). Beneath the seabed, permafrost may take several forms ranging from dry, cold rock to sediments containing ice, brine or a mixture of both. From the standpoint of pipeline engineering, permafrost, which contains either ice or water, is a fundamental concern.

Permafrost which contains ice, particularly ice which is mechanically-bonded to the surrounding sediments, is a difficult material to excavate if a buried pipeline is required. Normal methods of pipeline burial such as jetting, plowing, or dredging are made difficult by ice-bonded permafrost, and it is frequently necessary to resort to blasting to loosen frozen material for excavation.

A second problem caused by ice-rich permafrost is differential settlement which may result from thawing of the material. This may be especially serious in the case of subsea permafrost which exists at very close to equilibrium temperatures. Temperatures near the sea floor are often only one or two degrees below freezing in contrast to much lower temperatures found on land. Subsea permafrost is thus subject to thawing with even a slight rise in temperature and might be characterized as "soft" permafrost.

Heated pipelines, such as those carrying oil, must be insulated to protect the permafrost against rapid degradation. Without insulation, ice-rich permafrost rapidly would form a "thaw bulb" around the pipeline, continuing to increase in size until a new thermal equilibrium is reached. As the surrounding soil thaws, it tends to collapse because the ice content is reduced and the soil strength is lowered. Eventually the soil will settle. Typically, the settlement occurs at an uneven rate along the length of the pipeline because of differences in soil conditions. Consequently, the pipeline loses support and may become sufficiently stressed to induce bending or buckling along the length. Clearly, such problems must be avoided.

A related difficulty is frost heave, which may be induced by the use of chilled pipelines typically used to transport gas. Arctic marine sediments have a high moisture content and exist at temperatures at or slightly below freezing. Any loss of heat therefore may result in the formation of ice. Freezing is accompanied by volumetric expansion of the soil which varies with water content, salinity, pore size, pore-size distribution, overburden pressure, and a number of other variables. Expansion causes pressure within the soil which typically is manifested by movement or frost heave. The phenomenon is thus inversely related to the problem of melted ice-rich permafrost discussed above. A pipeline exposed to frost heave may be subjected to stresses by soil movement or by pressures developed within the freezing soil. Frost heave is a complex problem which is not yet understood sufficiently to make accurate predictions concerning the magnitudes of potential pressures or soil movements. It is reasonably certain that Arctic marine sediments are vulnerable to frost heave and engineering solutions will be required to mitigate the effects if chilled buried pipelines are used.

b. Permafrost Distribution. Until quite recently, it was thought that permafrost did not exist more than a few hundred meters offshore. However, separate investigations by Canadian and American researchers have shown that ice-bonded permafrost is widely distributed on the Beaufort shelf. Three areas have been studied quite intensively: the MacKenzie River Delta, Prudhoe Bay, and Elson Lagoon near Barrow. Each location has different geologic and oceanographic characteristics and histories which make intercomparisons difficult. Nevertheless, there are some consistent features between the areas which have led investigators to a few tentative conclusions (Barnes and Hopkins, 1978):

> Shallow, inshore areas, where ice rests directly on the seabed, are underlain at depths of a few meters by ice-bonded permafrost. Ice-rich permafrost and seasonal freezing in an active layer must be anticipated whenever the water is less than 2m (6.5 ft) deep.
>
> Ice-bearing permafrost was once present beneath all parts of the Continental Shelf exposed during the last low sea-level stand. Consequently, relict ice-bearing permafrost may persist beneath any part of the shelf inshore from the 90m (300 ft) isobath. Observed depths to relict ice-bonded permafrost range from a few meters near the present coast to 240m (820 ft) far off the Canadian coast.

Ice-bearing permafrost is probably absent from parts of the Beaufort Sea shelf seaward from the 90m (300 ft) isobath, although subsea temperatures are probably below 0°C (32°F).

Using these generalizations, investigators have developed a provision map (Figure 2-16) showing the potential distribution of permafrost on the Beaufort shelf. It is apparent from this that permafrost probably will be encountered in some areas of potential pipeline construction, particularly in the nearshore zone where water depths are less than 2m (6 ft).

From the perspective of pipeline construction, the vertical distribution of permafrost is probably more important than the areal distribution. For example, permafrost found in the upper 10m (33 ft) of sediment is much more likely to be affected by pipeline construction and operation than permafrost at greater depths. Unfortunately, the vertical distribution is known only in two areas of the shelf — Prudhoe Bay, and to the east off the Sagavanirktok Delta. Using seismic and borehole data, vertical profiles have been constructed (Figure 2-17) which show that the top of the ice-bonded permafrost layer along 18 to 22 km (11 to 14 mi) transects at each location. At Prudhoe Bay, it can be seen that the permafrost layer drops very quickly offshore, but rises again in the vicinity of Reindeer Island and then stays within 50m (164 ft) of the seafloor further offshore. Off the Sagavanirktok Delta, the top of the permafrost layer is less variable and ranges about 10 to 40m (33 to 131 ft) below the seabed at offshore locations. Based on these limited data, it would seem that near-surface permafrost, likely to be impacted by pipelines, could be avoided by judicious selection of pipeline routes in offshore areas. Conversely, in nearshore

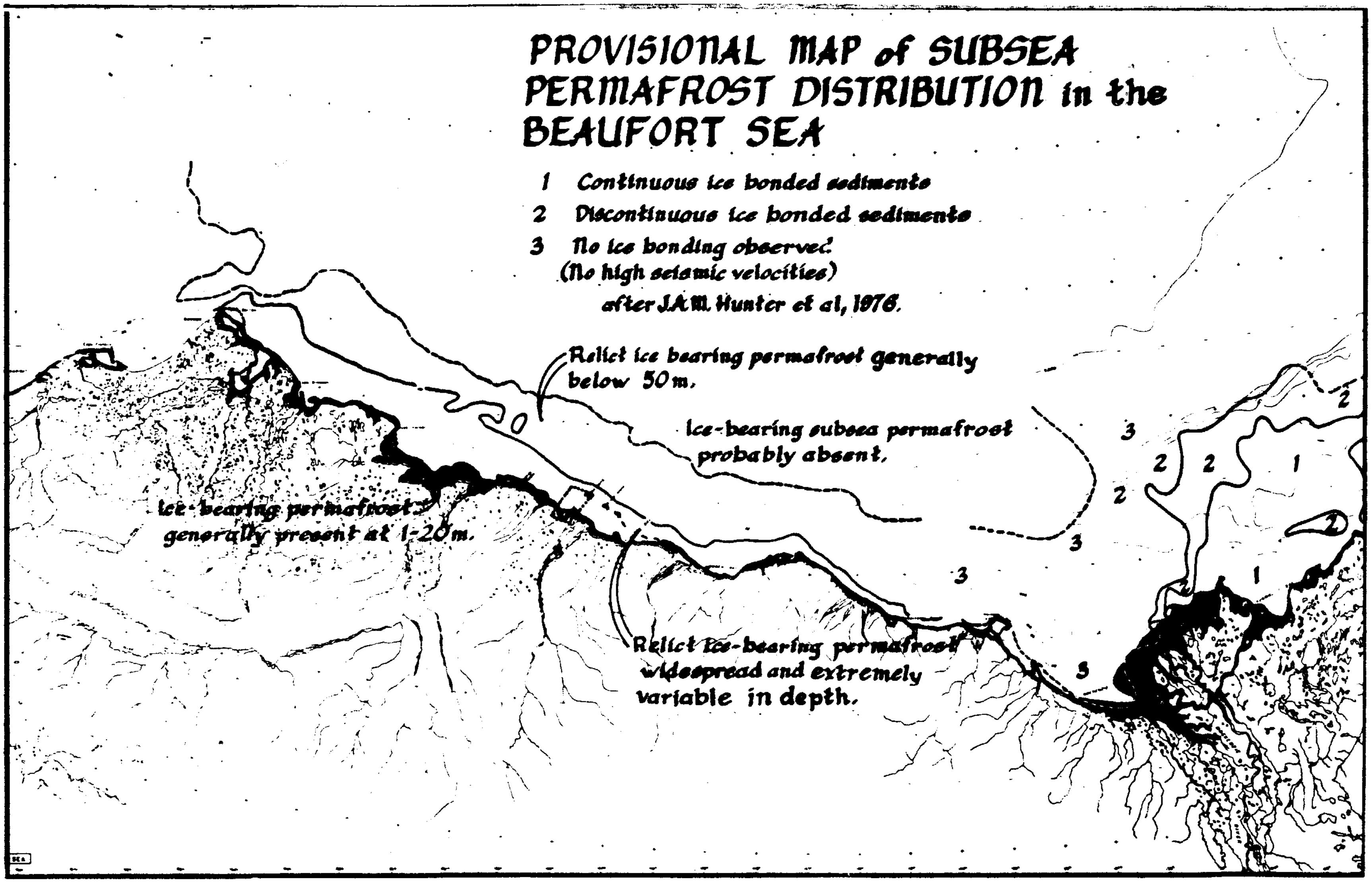


Figure 2-16. Provisional Map of Subsea Permafrost Distribution, Beaufort Sea (Barnes & Hopkins, 1978)

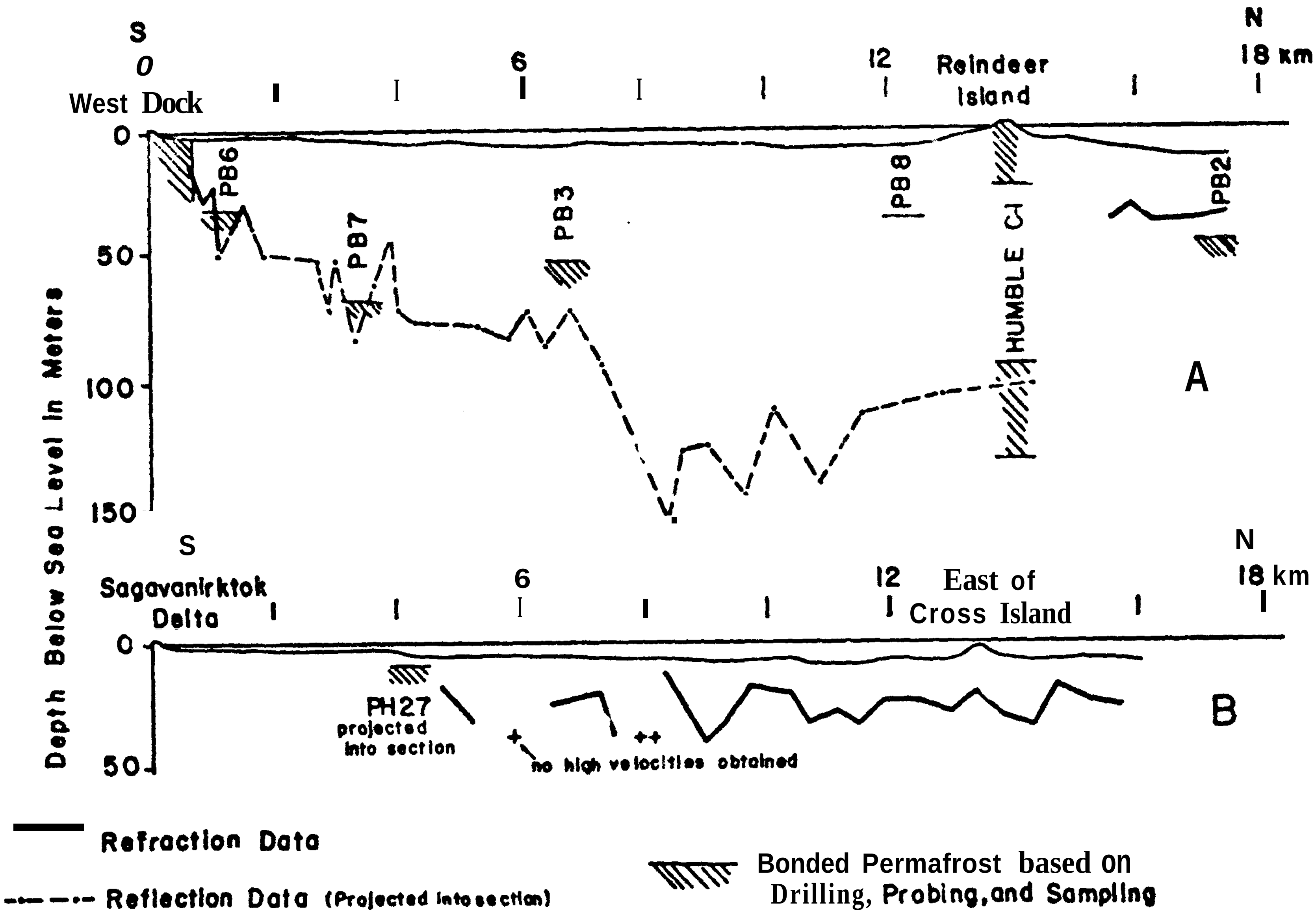


Figure 2-17. Subsea Permafrost Data Offshore from Prudhoe Bay and the Sagavanirktok River (Barnes & Hopkins, 1978)

areas and in the vicinity of barrier islands, near-surface ice-bonded permafrost is highly probable and appropriate engineering measures to deal with permafrost will be required for pipeline construction and operation.

3. Coastal Erosion and Barrier Islands

A potential area of concern for Arctic pipelines is the long-term stability of terrestrial areas where pipeline landfalls are made. In the Beaufort Sea, terrestrial crossings probably will be required at one or more points on the coast and perhaps at barrier islands or offshore bars which lie along pipeline routes. The general concern in these areas is their dynamic nature, namely the shifting or loss of sediments which can occur at high and sometimes spectacular rates.

The mainland shores are characterized by narrow and low-lying beaches composed of coarse sediments which are cemented together by ice during the winter months. The beaches seldom exceed 20m (66 ft) in width and are frequently narrower. The beaches are backed by bluffs generally less than 10m (33 ft) high, and more commonly 2 to 3m (6 to 10 ft) high (Barnes and Hopkins, 1978). The bluffs contain frozen sand and gravels but typically are mantled with 2 or 3m (7 to 10 ft) of frozen peat and mud.

During the summer months of summer and fall, the bluffs are subject to wave attack across the relatively narrow beaches and tend to undergo thermal erosion from thawing. The rates of erosion differ greatly depending upon bluff composition, exposure, and local bathymetry. Figure 2-18 illustrates rates which have been measured along the Beaufort coast. In general, the highest rates of retreat occur on promontories and points while bluffs, protected by deltaic deposits, are the most resistant to erosion. Rates may vary from year to year depending upon the time of ice break-up, the size of open

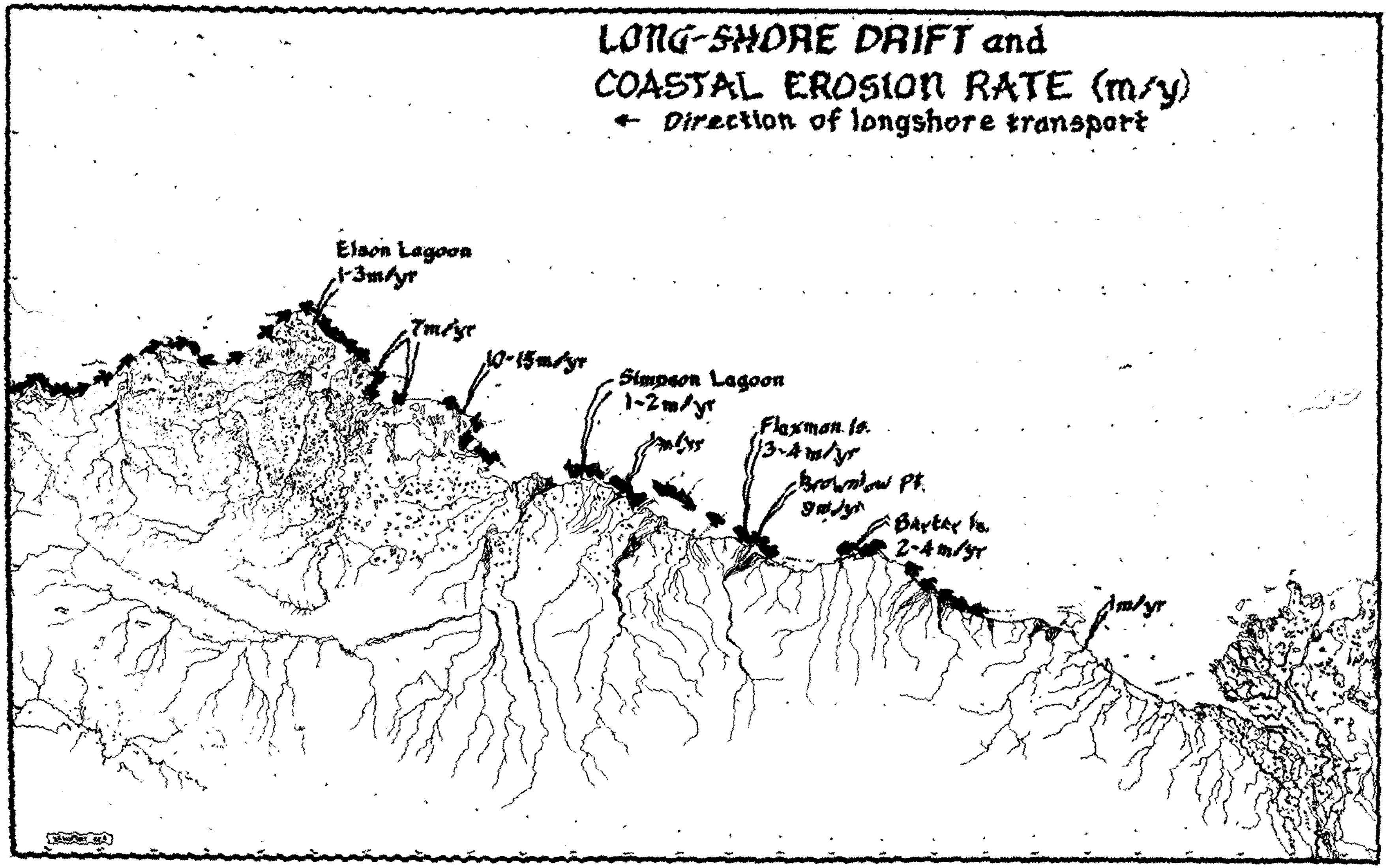


Figure 2-18. Long-shore Drift and Coastal Erosion Rate (Hopkins et al., 1977)

water areas, and the timing and intensity of late summer and autumn storms (Barnes and Hopkins, 1978). With localized exceptions, coastal erosion is lower in the eastern areas from the Colville River to the Canadian Border, where it averages 1.6m/yr (5 ft/yr), than it is in the western sector from Harrison Bay to Barrow. An average retreat rate as high as 4.7m/yr (15 ft/yr) has been suggested for this coastal segment (Barnes and Hopkins, 1978). Within this area short-term erosion rates as high as 30m/yr (98 ft/yr) were measured by Leffingwell (Barnes and Hopkins, 1978).

Three chains of curvilinear islands resembling barrier chains are present off the Beaufort Sea coast. The islands are mostly recent constructional accumulations of sand and gravel. Flaxman Island, however, and several islands in the center part of the central chain contain cores of Pleistocene sediments. The islands may be as long as 9 km (5.6 mi) and are nowhere higher than 3m (10 ft). They are typically 90 to 110m (295 to 360 ft) wide but may be as wide as 450m (1476 ft) (Barnes and Hopkins, 1978).

All of the constructional islands are migrating both westward and landward at a rapid rate. This migration is believed to be due to autumn storm activity and ice push. Migration rates ranging from 13 to 30m/yr (43 to 98 ft/yr) westward and 3 to 7m/yr (10 to 23 ft/yr) landward have been established for various islands in the eastern and central chains. The more-arcuate and isolated islands, such as Narwhal, Cross, Spy, and Thetis Island, appear to be migrating south-westward en masse at rates of 4 to 7m/yr (13 to 23 ft/yr). The islands containing Pleistocene sediments are migrating at the slowest rates, ranging from 1.5m/yr (5 ft/yr) on Pingok Island to about 3.5m/yr (11 ft/yr) on Flaxman Island.

The dynamic nature of the coastal and island sedimentary processes would appear to be a fundamental consideration for pipeline routing and design, particularly if long-term use is anticipated. Pump stations or other land-based facilities, for example, must be sited at a sufficient distance inland to avoid being jeopardized by erosion. Pipelines buried as a protection from ice action likewise should be covered for a sufficient distance inland to avoid exposure at some future time. Pipelines near islands could be subject to variations in burial depths as a result of shifting sediments. If located on the seaward side, they eventually may become uncovered. Conversely, on the shoreward or westward side, overburden levels may become very high, making access difficult.

4. Seismicity

Most parts of the Arctic coastal plain and the continental shelf of the Beaufort Sea are aseismic, except for a limited zone which extends offshore near Barter Island (Barnes and Hopkins, 1978). Seismograph studies begun in 1975 by the University of Alaska show that this zone is a continuation of the earthquake belt which arcs through the Aleutian Islands along the south shore of Alaska and then turns northward through Cook Inlet and central Alaska (Figure 2-19).

Despite a fairly limited data base, several characteristics of the region's seismicity are known. All of the earthquakes recorded thus far have been shallow. Offshore focal depths have been less than 25 km (16 mi) and those on the adjacent coastal plain have been less than 50 km (31 mi). The largest earthquake (M_L = 5.3) recorded within the last 10 years occurred about 30 km (19 mi) offshore from Barter Island. Aftershocks from this quake indicate the presence of an east-northeast/west-southwest seismic trend along axial traces of the offshore folded structures (Barnes and Hopkins, 1978). Figure 2-20 shows the locations of recent earthquake