UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geology Report for Proposed Beaufort Sea OCS Sand and Gravel Lease Sale

Scott R. Briggs[1]

Open-File Report 83- 606

[1]U S. Geological Survey, Menlo Park, Ca 94025

1983

Page

INTRODUCTION

This document is a reply to a request dated March 30, 1982, by the Manager, Alaska Outer Continental Shelf Office, for a sand and gravel Resource Report for the Beaufort Sea shelf, northern Alaska (Fig. 1). A basic premise of this report is that an understanding of the Quaternary geology of the Arctic Coastal Plain and Beaufort Sea shelf is fundamental to an understanding of the potential sources of sand and gravel. Therefore a major portion of this document summarizes this information. Unfortunately, borehole and high-resolution seismic data on the shelf are sparse, making any attempt to extrapolate our incomplete knowledge of the more accessible coastal plain, to less accessible areas offshore, highly speculative. In addition, the information which has been collected on the continental shelf shows even surficial properties of sediment character to be extremely patchy and variable (Barnes, 1974; Barnes and others, 1980), severely limiting attempts at estimating the sand and gravel resources in such a vast region.

Perhaps the most important observation to be made, after examining the data collected on the Beaufort Shelf, is that an attempt to document sand and gravel resources is premature. Only a major drilling program on the Beaufort Sea shelf will provide the sub-surface samples necessary for a three-dimensional appraisal of these resources. Hopefully, however, the evaluation of public records undertaken for this report has resulted in a document which can be used to help predict these resources even where data are lacking.

SOURCES OF DATA FORMAT OF REPORT

This report on sand and gravel resources in the Beaufort Sea is modelled after summary reports for proposed OCS oil and gas lease sales (see for example Grantz and others, 1982). Much of the text is expanded from a chapter entitled "Gravel sources and gravel management options," edited by D. M. Hopkins, in the Beaufort Sea Synthesis-Sale 71 report (Norton and Sackinger, eds., 1981). The sections on geologic framework and coastal plain geology were taken, often verbatim, from Grantz and others (1982) and Hopkins and Hartz (1978), respectively. Similarly, much of the sections on ice regime, ice scour, and permafrost were taken from Grantz and others (1982). Figure 2 illustrates the public data base used to assess both surficial (Fig. 2A) and subsurface (Fig. 2B) sources of sand and gravel on the Beaufort Shelf, indicating areas with no public data, areas with inadequate public data to properly assess these resources, and areas of adequate data coverage.

The maps accompanying this text are reproductions of the original authors' works at their chosen map projections, or where newly compiled for this document, based on NOAA Chart 16003.

GRAIN-SIZE DEFINITIONS OF SEDIMENT TYPES

The following grain-size scale and size classes have been used throughout this document (after Wentworth, 1922):

Grain size (mm)	PHI(ϕ)	Size class
		GRAVEL (>2 mm)
2.0	-1.0	
		SAND
0.0625	4.0	
		SILT
0.0039	8.0	MUD
		CLAY (<0.0039 mm)

BATHYMETRY

The Beaufort Sea shelf is relatively flat, and ranges in width from approximately 70 to 120 kilometers (Grantz and others, 1981). A complex outer shelf break occurs at depths ranging from 200-800 m, although east of about 147° W longitude an inner shelf break occurs at a depth of approximately 60 m. Landward of the barrier islands average seabed gradients are low (1:1700-1:2000) but local relief is very irregular, reflecting the presence of bars and the complex interaction of ice with the seafloor. From approximately Flaxman Island to the Kuparuk River, the seabed steepens rather abruptly seaward of the barrier islands. Over this 3-kilometer wide zone of increased bottom slope, seabed gradients reach 1:500. To the west, near the Colville delta, this zone of steepening is not apparent and the entire shelf width is characterized by a more uniform slope (1:1250). Deeper than approximately 16 m, the shelf is characterized by an even flatter slope (1:1700). Northeast of Pingok Island, the bathymetry is dominated by submerged ridges, while east of Prudhoe Bay the Reindeer-Cross Island ridge, which may extend beyond Narwhal Island (Reimnitz and others 1972), is most apparent (Fig. 1).

GEOLOGIC FRAMEWORK

The Beaufort Shelf north of Alaska can be conveniently divided into two sectors of contrasting geologic structure and generally distinctive, but overlapping, sedimentary sequences. The western (Barrow) sector extends from Point Barrow to approximately 145° W. long. and the eastern (Barter Island) sector from 145° W. long. to the Canadian border. Data for this section for the offshore are mainly from Grantz and others, 1979, Grantz and others, 1982, and Eittreim and Grantz, 1979. Data for the onshore are from Alaska Geological Society, 1971 and 1972; Brosge and Tailleur, 1971; Jones and Speers, 1976; Grantz and Mull, 1978; and especially Tailleur and others, 1978.

According to Craig and Barnes (Memorandum of February 9, 1982, J. Craig, Minerals Management Service, and P. Barnes, U.S. Geological Survey, to Manager, Alaska Region, Minerals Management Service, and Chief, Pacific-Arctic

Branch of Marine Geology), "the geologic structure of the "Barrow sector" is dominated by the Barrow Arch, a broad feature composed of metamorphic basement rock. Onlap of the Barrow Arch by Mississippian to Jurassic-aged sediments (Ellesmerian) from a northern source area was followed by a major episode of uplift, faulting, and erosional truncation in early Cretaceous time." This episode was associated with the rifting of the northern part of the Arctic platform which created the present continental margin of northern Alaska. Craig and Barnes (Memo, 1982) state that "in Cretaceous to Tertiary time, a thick clastic sequence (Brookian) derived from the Brooks Range was deposited to form a northward-thickening wedge on the nearly flat-lying lower Cretaceous unconformity surface." The Cretaceous beds of this clastic sequence are both marine and non-marine beneath the Arctic coastal plain, but on seismic sections appear to become dominantly or entirely marine on the outer shelf. The Tertiary beds are nonmarine onshore, but appear to also contain marine facies offshore.

To the east, the "Barter Island" sector is structurally dominated by two anticlines and an intervening syncline developed in late Cenozoic sedimentary rocks. Brookian strata resting on pre-Ellesmerian (Franklinian) rocks, and perhaps locally on oceanic crust, underlie this sector. Regional trends indicate that Ellesmerian strata are probably absent (Grantz and Mull, 1978). In the western part of the Barter Island sector the Brookian sequence consists of a thick section of Tertiary strata underlain by a thin section of Cretaceous beds and by Franklinian rocks. In the eastern part of the sector, the Tertiary rocks are inferred, from regional trends and from seismic reflection profiles, to rest on a thick section of Jurassic and Cretaceous clastic sedimentary rocks of southern (Brookian) origin. The Jurassic and Cretaceous beds are predominantly marine onshore, and probably mainly or entirely marine offshore.

Over both the Barrow and Barter Island sectors, Craig and Barnes (Memo, 1982) state that the

> "regressive Brookian sequence is truncated by an unconformity situated 100 m or more below sea level. This inferred Tertiary/Quaternary feature represents a change from rapid prograding deposition to complex transgression/regression cycles in Pleistocene time. Another unconformity (Pleistocene/Holocene) is covered by 0 to 40+ m of recent marine sediment deposited during the latest transgression. The transgressive/regressive cycles in the Pleistocene produced a complex sequence of tundra, marine, glaciomarine, fluvial and lacustrine deposits designated as the Gubik Formation onshore and tentatively correlated to the inferred Pleistocene unit offshore. During Pleistocene regressive intervals, wide portions of the Beaufort shelf were subaerially exposed and subjected to sub-freezing temperatures. As a result, a permafrost layer formed. This layer has been subsequently thawed to varying levels in offshore areas during Holocene and earlier transgressions."

QUATERNARY GEOLOGY OF ARCTIC COASTAL PLAIN

According to Hopkins and Hartz (1978) and studies by L. D. Carter, O. J.

Ferrians, and R. E. Nelson, the coastal plain surrounding the Colville River Delta and east of the Kuparuk River is underlain by Pleistocene alluvial and outwash gravel and sandy gravel of the Gubik Formation, the most important geologic unit on the north slope of Alaska for sand and particularly gravel. These coalescing alluvial and gravel outwash fans, which extend northward from the Brooks Range generally to the coast, contain a gravel of distinct lithology consisting of chert, graywacke, and grit, with the common occurrence of vein quartz. In some areas, however, the coast is occupied by the Flaxman Member of the Gubik Formation (Hopkins and others, in prep.), a marine sandy mud of Pleistocene age containing abundant glaciated pebbles, cobbles, and boulders distinct in lithology from the gravel of the Brooks Range (Leffingwell, 1919; Rodeick, 1979) and foreign to Alaska (Fig. 3). This gravel, rich in dolomite, red quartzite, red granite, pyroxenite, and diabase, has generally been attributed to ice rafting from a source in the Canadian Arctic Archipelago or Greenland. The Flaxman Formation may rest unconformably on older Pleistocene marine deposits (Hopkins, 1979). Where this deposit has been eroded, as in the Boulder Patch of Stefansson Sound (Reimnitz and Ross, 1979), deposits of exotic cobbles, gravel, and boulders remain.

From of the Kuparuk River west to Barrow, the outer coastal plain is underlain mainly by Pleistocene marine sandy silt and clay of the Gubik Formation, except for Pleistocene sandy alluvium along the Meade, Pissuk, Chipp, Ikpikpuk, and Colville Rivers and between southern Admiralty Bay and the western shore of Teshekpuk Lake (Fig. 3). Inland from Teshekpuk Lake and western Harrison Bay the coastal plain is dominated by Pleistocene dune fields of eolian sand (Carter and Robinson, 1978). The sandy alluvial fans of the rivers west of the Colville consist of material redeposited from these dune areas when the rivers re-established themselves in latest Wisconsin and earliest Holocene time (D. M. Hopkins, written comm., 1982). Much of the outer coastal plain and shoreline from the Kogru River to Barrow is underlain by marine sandy silt of the Flaxman Member which contains boulders only in local patches. On this western half of the Beaufort coast, the inner and outer coastal plain is separated by a line of mounds and ridges which extend from Barrow southeastward along the north side of Teshekpuk Lake to Saktuina Point and the Eskimo Islands. This ridge is underlain by Pleistocene beach deposits (sand and fine gravel) of the Gubik Formation, contains a mixture of pebbles of Brooks Range and Flaxman origin, and may be a continuation of a former Pleistocene island chain represented today by Pingok, Bertoncini, Bodfish, and Cottle Islands (Hopkins and Hartz, 1978).

The geology of offshore islands varies from modern, constructional bodies to erosional remnants of the coastal plain. Low-lying islands off the mouths of major rivers are emergent depositional shoals of fine, possibly river sand. Gull Island, off Prudhoe Bay, may be of a similar history and constructed of sand from the Sagavanirktok River. Most other nearshore islands, which tend to be more equidimensional than the outer barrier islands and rise about 4 meters above sea level, are erosional remnants of the mainland. Tigvariak Island, the Niakuk Islands, and Flaxman Island are all composed of the Flaxman Formation or its erosional remnant. The Eskimo Islands of western Harrison Bay are apparently remnants of Pleistocene beach and pebbly sand, while islands off Pogik Bay further to the west appear to be remnant Pleistocene, non-marine sediments (Hopkins and Hartz, 1978).

The three chains of curvilinear barrier islands lying further offshore, running from Brownlow Point to Reindeer Island, from Point McIntyre to Thetis Island, and from Cape Simpson to Point Barrow, are mostly recent constructional accumulations of sand and gravel, although Flaxman Island in the first chain and Cottle, Bodfish, Bertoncini, and Pingok Islands of the central chain have cores of Pleistocene sediments (Hopkins and Hartz, 1978). These offshore erosional remnants stand 3 to 10 meters high and support tundra vegetation. The constructional islands, or constructional portions of erosional-remnant islands, stand 3 meters or less above sea level. Pebble lithologies differ greatly from island group to island group within the island chains, reflecting complex source histories and closed circulation cells of material within these island groups.

Before discussing offshore geology, it is useful to note that the major change in coastal geology near the Kuparuk River may reflect a basic difference in river and coastal plain morphology during times of lowered sea level. Slopes east of the Kuparuk River are steeper than those to the west, where both the coastal plain and the continental shelf are flatter. This basic observation may have strong implications for Pleistocene drainage patterns, and thus indirectly indicate the potential for sand and gravel resources presently available on the continental shelf (J. Craig, oral comm., 1982). Braided, more energetic rivers tend to dominate to the east while meandering, more tranquil rivers dominate to the west. If this scenario were true in the past, then sand and particularly gravel should be far more common to the east of the Kuparuk River and far less common to the west. West of the Kuparuk River gravel might be found only near former or existing river channels.

While agreeing with Craig's observations, D. M. Hopkins (written comm., 1982) suggests that a more fundamental boundary for gravel resources lies at the Colville River, the westernmost river draining to the Beaufort Sea which heads in the Brooks Range. The Colville River and streams to the east head in areas of high relief and flow through valleys carved in hard, firmly lithified pre-Cretaceous rocks. All of these streams have had glaciers in their upper drainages and all carry coarse sands and gravels downstream to the point where the present day fluvial regime is influenced by tides (E. Reimnitz, oral comm., 1982) reports that although this scenario is reasonable for the past, presently no gravel and little sand is being delivered by these rivers to the Beaufort shelf). When sea-level was low, these rivers carried gravel far beyond the present shores, making their paleovalleys prime sources of fairly accessible, shallow gravel on the continental shelf.

West of the Colville River, however, all the streams in the National Petroleum Reserve of Alaska (NPRA) head in the low rolling foothills just south of the coastal plain. Their valleys are carved in soft, mostly fine-grained Cretaceous sediments, and most, if not all of them were defeated by dune activity during Wisconsin time when summer rainfall and winter snowfall were minimal (D. M. Hopkins, written comm., 1982). The small amounts of gravel available in their drainage basins comes from pebbly sandstones in the Cretaceous deposits and pebbly sand in Pleistocene beach deposits. These western streams presently transport sand or finer materials, and their paleovalleys offshore can be expected to contain only small bodies of granular, predominantly sandy alluvium.

QUATERNARY GEOLOGY, BEAUFORT SEA SHELF

The problems of extrapolating coastal geology to the shelf, based on a rather small body of high-resolution geophysical and core/borehole data, are immediately made apparent by the great range in opinion as to the thickness of even the uppermost, Holocene section. The nature of the Holocene material of course varies greatly with location, ranging from the coarser-grained silts, sands, and occasional gravels of offshore beach and modern shoal deposits and the cobbly gravels of the Flaxman lag deposits to finer-grained clays, silts, and sands of Holocene lagoonal, deltaic, and marine deposits. Figure 4 summarizes existing data, and opinion, on the thickness of Holocene sediments over most of the Beaufort Sea shelf. Data sources for this map include work by Dinter (1982), Grantz and others (1982), Reimnitz and others (1972b), Boucher and others (1981), unpublished work off Harrison Bay by Reimnitz and Rodeick, and a cursory look at high resolution geophysics and borehole logs obtained by the U.S. Geological Survey between Simpson Lagoon and the Canning River (Hartz and others, 1979).

Figure 4a illustrates the most complete analysis of Holocene(?) sediment thickness on the mid- to-outer shelf (Grantz and others, 1982; Dinter, 1982). These contours represent the depth to the uppermost prominent sub-seafloor reflector identified on USGS Uniboom records, using a sound velocity of 1.5 km/sec. This basal reflector, which shows morphological evidence of having once been subaerially exposed, dips offshore resulting in an overlying stratum of sediments which, on the eastern third of the Beaufort shelf, reaches 45 m in thickness at the present shelf break (Dinter, 1982). Except for an overlying, 1-10 m thick layer of internally structureless, hummocky-topped sediments over the eastern outer shelf, the sediments lying above the basal reflector appear to represent an episode of uninterrupted marine deposition, presumably deposited since the maximum sea level lowstand of approximately 17,000 years ago. This seaward thickening wedge is interrupted north and northeast of Camden Bay, off Barter Island, where localized Holocene uplift has apparently prevented significant accumulation of Holocene sediment (Dinter, 1982).

An alternative interpretation of the distribution of Holocene sediments on the eastern Beaufort shelf has been presented by Reimnitz and others (1982). Their reconnaissance work, mainly on the inner shelf from the Canning River to the Canadian border, during which Uniboom and side-scan records and surficial sediment samples were collected, suggests a thin Holocene sediment cover (generally <7m) whose thickness exibits no correlation with water depth out to depths of 57 m. All observations of Holocene (?) thickness in water depths greater than approximately 45 m, however, are based on a single transect (line 32) which runs NNW from Barter Island to the shelf break. This geophysical line confirms the existence of a large area of minimal Holocene sediment cover north of Camden Bay (Dinter, 1982), and like other geophysical lines in the area shows thick sections of stratified, tectonically deformed, probably Pleistocene strata dipping at various angles and truncated by the seafloor (Reimnitz and others, 1982). Offshore of this area of minimal Holocene deposition, however, they do not see evidence for the thickening wedge of Holocene sediments reported by Dinter (1982). Further, they cite the character of the ice gouges recorded on their geophysical records for tens of kilometers, plus a sediment sample retrieved at a water depth of 52 m, as evidence for a blanket of relict gravels, not Holocene marine sediments, on the outer shelf (Fig. 5).

In describing the nature of surficial sediments on the eastern Beaufort shelf, Reimnitz and others (1982) state

> "All indications are that modern sediment accumulations, possibly present in lagoons and bays, are essentially lacking on the open shelf. The fine grained, cohesive sediment mapped in a band on the central shelf, may be modern deposits of several meters thickness, and most likely the shoals of the stamukhi zone are constructional features post-dating the last transgression. The coarse granular materials on the inner and on the outer shelf seem to be relict deposits. The relict nature of the shelf edge gravels has been discussed by Barnes and Reimnitz (1974), Mowatt and Naidu (1974), and Rodeick (1975). Their interpretations are based on a) low rates of modern ice rafting of coarse clasts compared to overall sediment accretion rate, b) observed ferromanganese coatings on cobbles, c) about 15,000 year old C^{14} ages for near-surface shelf edge and upper slope sediments, d) source rock considerations, and e) lack of seaward decrease in sediment grain size from coarse grained near the sediment source to fine grained near the outer edge of the shelf."

According to Reimnitz and others (1982), work east of the Canadian border tends to substantiate both the coarse-grained and relict nature of surficial shelf sediments (Vilks and others, 1979).

Only additional geophysical, and particularly borehole drilling information will positively date the Holocene(?) reflector reported by Dinter (1982), answer whether there are significant thicknesses of Holocene sediments on the eastern Beaufort shelf, and show to what depth the coarse grained surficial deposits reported for the inner and outer shelf, and along the shoals of the middle shelf, extend.

While still increasing in thickness in the offshore direction, the Holocene(?) section is reportedly thinner on the western two-thirds of the mid-to-outer shelf, possibly reflecting the greater distance of this area from the Mackenzie River and Brooks Range, or a pre-Holocene difference in elevation between the western and eastern shelf (Dinter, 1982). Offshore from Harrison Bay, Dinter (1982) and Craig and Thrasher (1982) both report Holocene thicknesses reaching 25 m. In contrast, unpublished work by Reimnitz and Rodeick in this same general area suggests that Holocene(?) sediments rarely exceed 10 m in thickness, and seldom 5 m in thickness (Fig. 4b). Reimnitz and Barnes (oral comm., 1982) have consistently identified a reflector on high-resolution geophysical records, generally on the inner shelf, which lies only a few meters below the ice-gouged sediment-water interface. They have tentatively designated this as the base of the Holocene, reflecting their assumption that Holocene marine sediments are presently being, and have always been, reworked to the point of homogenization by ice-gouging processes. This assumption, according to Reimnitz and Barnes (oral comm., 1982) makes the formation of a reflector during the Holocene, as would be required if a considerably deeper basal reflector is chosen, impossible. Dinter and Grantz (written comm., 1982) see little or no evidence for this shallow reflector on the mid-to-outer shelf, but feel that the presence of such a reflector would not in itself rule out a deeper base to the Holocene section. Such reflectors could have formed during well-documented irregularities in the ablation history of the Laurentide Ice Sheet.

Again, it is obvious that there is much need for high-resolution seismic information which overlaps the existing inner and mid-to-outer shelf data sets. Further, the need to translate acoustic stratigraphy into true geology using borehole information, particularly in an area characterized by sediments containing significant concentrations of shallow gas and permafrost, has been well documented on the inner shelf.

On the inner shelf, where boreholes and cores supplement the geophysical data coverage, researchers generally agree that Holocene sediments are thin, rarely reaching 10 meters in thickness (Fig. 4c, d). Early work in Simpson Lagoon suggested areas of significantly greater Holocene sediment accumulation (Reimnitz and others, 1972b), but subsequent work in the area showed that the acoustic stratigraphy upon which this incorrect interpretation was based was significantly influenced by the presence of gas-charged sediments (Boucher and others, 1981). Further possible exceptions to the very thin nature of Holocene cover are areas east of Barter Island, a tongue of deltaic sediments off the Sagavanirktok River, areas north of Oliktok Point, and western Harrison Bay.

Beneath the Holocene sediment cover, offshore facies for any given unit are predominantly silt and clay, representing deeper-water facies of the beach deposits and nearshore fine sands that are commonly recognized onshore (D. M. Hopkins, written comm., 1982).

Reconnaissance work in the Kogru River, western Harrison Bay, produced seismic reflection records which exhibit unusually strong, linear, and continuous reflectors to a sub-bottom depth of about 70 m (Barnes and others, 1977a; Reimnitz and others, 1977c). They tentatively identify at least two units within this 70 m section which underlie 0-5 m of recent (Holocene) fill: 10 m of flat lying eolian, lacustrine, beach, and shallow marine sediments belonging to the Barrow Unit of the Gubik Formation (Black, 1964), and at least 50 m of a uniformly dipping section (1.3° toward NNE) which can be traced northward into Harrison Bay. The difference in seismic character of these records from those collected on the inner shelf to the east, plus the less jumbled, more stratified nature of subaerial outcrops of the Gubik Formation west of Cape Halkett may be evidence for the existence of a boundary which separates Quaternary Gubik deposits underlying the coastal plain from Barrow to Cape Halkett on the west from those to the east (Reimnitz and others, 1977c).

Craig and Thrasher (1982) identify a Pleistocene section in the vicinity of Harrison Bay with a basal reflector at about 100 m below sea level, the nature of this section possibly shifting from non-marine nearer shore to marine at about 32 m water depth (Fig. 6). According to Craig and Thrasher (1982), the non-marine section is characterized by a heterogeneous, high-relief upper surface similar in topography to that of the Arctic coastal plain, with V-shaped stream channels, thermokarst topography, thaw lakes, and beach ridges. In contrast, the marine section's upper surface is sharp, highly reflective, and of low relief (Craig and Thrasher, 1982). Because the transition from marine to non-marine sediment has import implications for the presence of coarse, granular materials in Harrison Bay, it is important to note that this preliminary interpretation is based solely upon acoustic stratigraphy which in the light of the known occurrence of shallow gas and permafrost must be viewed with caution. A possible alternative explanation for the reflector described by Craig and Thrasher (1982) which lies about 100 m below the sea floor, if in fact it represents true stratigraphy, is that it is a weathered surface cut on Pleistocene marine clays and thus represents a compaction boundary within a predominantly fine-grained, presumably Pleistocene section (D. M. Hopkins, written comm., 1982).

In Simpson Lagoon, Reimnitz and others (1972b) identified three subsurface reflectors on high-resolution seismic records which may correlate with the work of Craig and Thrasher (1982) in Harrison Bay. Horizon A of Reimnitz and others (1972b), lying generally less than 5-10 m below the sea floor, was interpreted as the base of the Holocene. Their horizon B, ranging from approximately 100-200 m below the sea floor (based on a sound velocity of 4500 m/sec) may be the base of the Pleistocene Gubik Formation tentatively identified in Harrison Bay by Craig and Thrasher (1982) at 100 m depth. This interpretation fits well with that of Payne and others (1952) and Howitt (1971) who called for the Gubik Formation to lie unconformably on the Tertiary Sagavanirktok Formation in this area. The chosen sound velocity of 4500 m/sec may be 2-3 times too high for Gubik sediments, however, a velocity of 1700-1900 m/sec being more likely (D. Dinter, written comm., 1982). Although this change would reduce the depth to horizon B to approximately 40-80 m, it might still tie in with the major reflector identified by Craig and Thrasher (1982). The deepest horizon described by Reimnitz and others (1972b), Horizon C, tied in reasonably well with Howitt's (1971) marker horizon 10 on land when a sound velocity of 4500 m/sec was used, although the appropriateness of this sound velocity is unknown. This unit, characterized by large scale cross-bedding, dipping gently offshore, probably lies within the Tertiary Sagavanirktok Formation.

East of Simpson Lagoon the nearshore Quaternary stratigraphy can be tied to nine boreholes on the inner shelf north of Prudhoe Bay (Chamberlain and others, 1978; Smith and Hopkins, 1979; Hopkins and others, 1979) and 20 cores collected for the U. S. Geological Survey between the Kuparuk and Canning Rivers (Hartz and others, 1979). Some cores/boreholes are topped by a Holocene marine mud and fine sand (3-10 m thick) sometimes underlain by 1-2 m of basal Holocene beach deposits, which are in turn underlain by 10-20 m of non ice-bonded glacial outwash sand and gravel (Gubik). Below the outwash material in these holes lies a thick alluvial section of sand and gravel (Gubik), again generally non ice-bonded, which reaches depths of over 100 m (Humble C-1 hole on Reindeer Island bottomed out in alluvial gravels at a depth of at least 133 m) (Fig. 7). According to Howitt (1971), these sands and gravels are nearly 170 m thick in some places near the coast.

Other holes show a much older, overconsolidated clay covered by a layer, less than 1.5 m thick, of boulders derived from the Flaxman Member. These boulders are imbedded in soft, ephemeral muds. Beneath the overconsolidated clay, which is generally ice-bonded below depths of a few meters, lies more clay or ice-bonded gravel. Where this overconsolidated clay is underlain by ice-bonded gravel, the gravel at least to depths of about 40 m is probably valley fill deposited during pre-to-early Pleistocene cycles of lowered sea level which were then covered by early Pleistocene interglacial marine clays

(D. M. Hopkins, written comm., 1982).

According to P. A. Smith (written comm., 1982), where the Flaxman member does occur, it is thin (1 1/2- 3 1/2 m) and is overlain by 1/2 to 11 1/2 m of Holocene marine material. It, in turn, generally overlies the overconsolidated clay of the Pelukian transgression (Sangamon). However, in boreholes HLA-16 and HLA-18, the Flaxman is separated from the Sangamon by a 9 to 14 m thick sequence of nearshore (?) marine silts and silty sands that are either barren of microfossils or have very depauperate assemblages.

These borehole and core results have been used by Hartz and Hopkins (1980) to present the following model for the Quaternary stratigraphy of the Beaufort coast and shelf, which is supported by micropaleontological data and is of particular relevance to an understanding of sources of un-bonded gravel:

> "During the height of world-wide continental glaciation that culminated about 18,000 years ago, sea level was lowered. The Bering Sea shelf was exposed seaward to about the present-day 90-meter isobath. The position of the shoreline in the Beaufort Sea 18,000 years ago lay somewhere seaward of the 20-meter isobath and borehole data suggest, in fact, the relative sea level fell at least 90 m below present in the Beaufort Sea. The mantle of marine silt and clay, deposited during Sangamon time (approx. 120,000 years ago), became frozen as did the underlying gravels. The total thickness of bonded permafrost formed at any particular place depended partly upon the duration of exposure to subaerial temperatures, but thicknesses of several hundred meters were formed in most areas of the shelf landward of the present 20-meter isobath.
>
> The major rivers draining the north slope of the Brooks Range aggraded and formed outwash fans extending across much of the present-day coastal plain, although the edges of most of the fans lay within a kilometer inland of or seaward of the present coastline. Seaward from the edges of the fans, the rivers removed the ancient marine silt and clay to form broad, shallow valleys graded to the shoreline of the time. By analogy with the braided gravel flood-plains of present-day north slope rivers we may assume that the top of the ice-bonded layer lay at depths of several tens of meters beneath the river channels but at depths of less than a meter beneath uplands mantled with overconsolidated marine silt and clay.
>
> As continental glaciers waned and sea level began to rise, the shallow river valleys were drowned. In the absence of a cover of ancient, overconsolidated marine silt and clay, the cold but salty sea water gained ready access to the underlying gravel. Ice in the gravel was thawed rapidly and deeply by salt advection. Ultimately these valleys began to collect Holocene sediments carried by current from the river mouths.
>
> Although the sea transgressed over the slightly higher plains away from the sea valleys, salt water was prevented from gaining access to the potentially porous gravel substrate by the mantle of tight overconsolidated marine deposits. Consequently thawing of ice in the shallow bonded permafrost could progress only by heat diffusion and salt diffusion. The water temperatures were below zero and silt diffusion progressed very slowly. As a result, thawing has progressed extremely slowly and only to a very limited depths in most areas mantled by the overconsolidated marine

silt and clay."

Only the Sagavanirktok paleovalley, which seems to run north and west from Prudhoe Bay, has apparently been documented. One would expect similar sand and gravel filled valleys off most of the rivers presently reaching the Beaufort coast, particularly from the Kuparuk River to Camden Bay and from Pokok Bay to Demarcation Point (D. M. Hopkins, written comm., 1982). Also, according to this model the remnants of Flaxman Member exposed along the coast are remnants of interfluves between the river valleys.

It is extremely important that the nature of the Pleistocene section be better defined for the entire Beaufort shelf, particulaly east of the Colville River, since the delineation of marine and non-marine sections is essential to an evaluation of sand and gravel resources. The non-marine section should generally be characterized by outwash and alluvial gravels, while the marine sections, where not eroded, should be characterized by ice-scoured clay, silt, pebbly sand and mud.

ANTICIPATED REQUIREMENTS FOR SAND AND GRAVEL

The importance of structures utilizing sand and gravel fill during offshore exploration and development was discussed by Weller et al. (1978). For example, a requirement for 7 to 14 exploration platforms and 4 to 18 production platforms is anticipated within the Sale 71 area (Memorandum of Oct. 17, 1980, Director, U. S. Geological Survey to Director, U. S. Bureau of Land Management). Some sand and gravel fill used in exploration islands will probably be recycled for use in production islands. Structures in water less than 15 m deep are likely to consist of artificial sand and gravel islands defended by sandbags or other coarse armoring material but otherwise unconstrained. Farther seaward, but within depths less than 30 m, artificial islands confined by concrete caissons are likely, especially during the earlier years of exploration and development. As exploration progresses movable monocones as described by Jahns (1979) may be used in water deeper than 10 or 15 m. Ultimate sand and gravel requirements for offshore structures in the Sale 71 area alone will probably be between 1 and 10×10^6 m^3. In the Canadian Beaufort, Gulf Canada Resources, Inc. is planning to deploy mobile Arctic Caissons in depths ranging up to 20 m, and possibly 40 m. These caissons or large rings of steel will be placed on natural or artificially dredged shallow berms and then filled with sand as ballast. A single caisson suitable for use in 20 m of water would require approximately 9×10^5 m^3 of sand as ballast (Sea Technology, Staff Report, 1982).

The burial of offshore pipelines to protect them from the effects of ice gouging will require, according to plans proposed by EXXON, approximately 6×10^3 m^3 of gravel per kilometer of trench (E. Reimnitz, oral comm., 1982).

Future leases in federal waters of the arctic coast in the Northern Bering, Chukchi and Beaufort seas will call for the utilization of sand and gravel islands as development platforms in shallow water. Work in the Prudhoe Bay area has already lead to the removal of about 7×10^6 m^3 of gravel from the Sagavanirktok River (E. Reimnitz, oral comm., 1982).

The greater distance of the bulk of the Sale 71 area from Prudhoe Bay may call for new logistic bases on shore. A currently proposed causeway-dock that would extend the natural spit at Oliktok Point might serve the Sale 71 area as well as the nearby onland production areas. Other likely sites for new logistic bases are promontories near deep water such as that of Camp Lonely, where a DEW-line site and the logistic base for exploration of the National Petroleum Reserve of Alaska are already situated. A new logistic base would create a continuing and great need for gravel for storage pads as well as for maintenance of the landing dock. Total requirements would probably be about 1×10^6 m^3.

SOURCES OF SAND AND GRAVEL

Onshore Resources

Upland sources of gravel are abundant and widespread east of the Colville River, and sand underlies vast mainland areas west of the Colville River and south of Kogru River, but most of the region north of the Kogru Peninsula and Teshekpuk Lake is devoid of useful concentrations of sand and gravel. The onshore region east of the Colville River is similar to the region around Prudhoe Bay in that frozen gravel is present nearly everywhere at depths no greater than 5 m. The overburden consists mostly of peat, silt, and fine sand. West of the Colville River, quantities of frozen dune sand stabilized by turf or a thin cover of peat underlie the mainland south of the Kogru River and Teshekpuk Lake (Fig. 8).

Immediately north of the belt of stabilized dune sand is a belt 25-35 km wide of marine silty fine sand which extends westward from Kogru River through Teshekpuk Lake.

Small amounts of coarse fill might be obtained from small bodies of sandy gravel and pebbly sand (about 1.0×10^5 m^3 each) that occur as low hillocks and mounds scattered in a linear belt extending from the Eskimo Islands westward through the southern part of Kogru Peninsula and along the north shore of Teshekpuk Lake. The sandy gravel is frozen and is overlain by peat, silt, and fine sand generally less than 1 m thick.

Northward from this strip of gravelly hillocks, the Arctic Coastal Plain is underlain by ice-rich peat and silty, peaty, thaw-lake deposits several meters thick. Beneath these deposits lie frozen overconsolidated clay and silt locally containing concentrations of boulders. Local concentrations of boulders might be sufficiently abundant to furnish riprap to armor artificial islands against surf erosion. There are no other known sources of material useful in construction of piers and offshore islands in this 30-km-wide belt of the arctic coastal plain north of Teshekpuk Lake and west of Harrison Bay.

The beaches along the coast of Beaufort Sea are narrow and thin and contain only small quantities of sand and gravel. Those from Point McIntyre to Pokok Bay tend to be gravel beaches (Hopkins and Hartz, 1978). Otherwise, the onshore resources east of Prudhoe are unassessed. The DEW-line logistic base at Camp Lonely has already fully utilized the fairly large but still limited amount of sand and gravel from the beaches there, and lack of a nearby source of additional coarse fill has stopped further expansion of the site.

Surficial sources on the shelf

There are several potential sites for sand and gravel mining on the surface of the seabed. Most of these bodies are present because hydraulic forces are focused at these locations, sorting and concentrating coarser grained sediments. Barnes (1974) contoured the surface texture of sediments expressed in terms of the mean diameter (Fig. 9). An updated map of Beaufort Sea surficial sediment textures as far east as the Canning River provides a truer picture of the patchy nature of surface sediment types, a character which cores show to extend vertically as well as laterally (Barnes and others, 1980) (Fig. 10). In Figure 10 classification of sediment textures similar to that of Trefethen (1950) was used in which the three end numbers of gravel, sand, and mud have gravel-sand and sand-mud boundaries of 2 mm and 0.0625 mm, respectively. This patchiness results from the complex interaction of ice and hydrodynamic forces on a thin layer of Holocene sediments and underlying sediments whose surface textures reflect earlier depositional environments. Maps of percent mud (<0.0625 mm), sand (0.0625-2 mm), and gravel (> 2 mm) in the surface sediments (Figs. 11, 12, 13) show, as do Figures 9 and 10, that sediments tend to be coarser on the eastern Beaufort shelf, particularly on the central and outer shelf. Northeast of Cross Island, a band of coarser sediments including gravels seems to extend across the shelf (Barnes, 1974). Figure 14 summarizes results of recent work east of the Canning River (Reimnitz and others, 1982) and emphasizes the coarse nature of these surficial sediments.

The availability of gravel suggested by the surficial sediment distribution must be tempered by the uncertain thickness and vertical and lateral variability of gravel, which is known to exist in many areas only as a surface veneer. East of the Canning River gravel appears to be plentiful even in deep water. Here, despite active ice gouging which creates up to 8 m of vertical relief, the seafloor reflectivity and overall appearance is homogenous for many kilometers, suggesting that on the outer shelf fairly clean, coarse granular materials have a thickness of at least several meters (Reimnitz and others, 1982). If this surficial layer should in fact belong to a seaward thickening wedge of unconsolidated sediments (Dinter, 1982), then this source of sand and gravel would be even more volumous than suggested by Reimnitz and other's (1982) inner-to-mid shelf work.

Some local sand shoals stand no more than 1.5 m above the surrounding bottom. Finger Shoals is a field of linear, parallel sand waves oriented north-south that are 1.5 m high and 200 m wide, sitting on a surface of stiff, silty clay. Pacific Shoal lies to the northwest of Finger Shoal (Reimnitz and Minkler, 1981). These areas each contain about 100,000 m^3 of sand. A well-defined shoal between Thetis and Spy Islands contains about 10,000 m^3 of clean gravel (Fig. 8).

Sand ridges, 1 or 2 m thick and 100 m or more wide, lie within the 10 m isobath in a belt extending from Pingok Island westward past Spy and Thetis Islands. Studies by Barnes and Reimnitz (1979) and Reimnitz and others (1980) indicate that these are active hydraulic bedforms. Off Pingok Island, these sand bodies are longshore and transverse bars that affect erosion rates on Pingok Island; mining would accelerate erosion of the island. However, mining of the western part of the zone would probably have few or no adverse environmental effects and could yield about 100,000 m^3 of sandy fill. Numerous other shoals with similar characteristics exist along the arctic coast from Demarcation Point to Barrow.

Other potential sites for fill borrow are the outer fringes of the 2-m benches off the numerous river deltas which consist of fine sand interbedded with mud layers rich in organic matter (Barnes and others, 1979). If suitable for construction material muddy sand might be removed here.

Most of the islands on the Beaufort Shelf, whether nearshore erosional remnants of the coastal plain (Flaxman Formation) or constructional topographic features of the three barrier island chains, are potential sources of sand and gravel. Removal of these sediments may markedly change physical character and processes on the shelf, however, as will be discussed in the "Consequences of Sand/Gravel Mining" Section of this document.

Shoals in the Stamukhi Zone

In water depths of 10-22 m shoals of unknown origin exist (Reimnitz and Maurer, 1978; Barnes and others, 1980; Barnes and Reiss, 1981) which project 5-10 m above the surrounding sea floor. Stamukhi Shoal is adjoined on the west by a sand apron that curves southeastward and consists of hydraulic bedforms up to 2 m thick (Reimnitz and Kempema, 1981). Weller Bank is probably the largest and most equidimensional body of sand and gravel on the western Beaufort Shelf (Fig. 8). Borrow from these sources will also impact the shelf environment as discussed below.

Subsurface Sources

Shelf Paleovalleys

Although several paleovalleys are believed to be present in the Prudhoe Bay area (Hopkins 1979), only the Sagavanirktok Paleovalley has been well delineated by offshore drilling (Hartz and Hopkins, 1980). The Sagavanirktok Paleovalley begins in Prudhoe Bay and turns northwestward to pass between the West Dock and Reindeer Island; it has been traced farther northwestward to a point about 10 km north of the mouth of the Kuparuk River. Gravel in the Sagavanirktok Paleovalley is unfrozen and lies beneath soft, unconsolidated marine clay, silt, and fine sand up to 10 m thick. This paleovalley is a dependable source of coarse, gravelly fill (Fig. 8).

Geological reasoning suggests that a paleovalley should also be present off the mouth of the Colville River in eastern Harrison Bay, and other north slope rivers, but the geophysical techniques employed thus far are not capable of delineating a buried valley filled with gravel, and drilling has been inadequate to verify its presence. Proprietary drilling information and OCSEAP permafrost drilling by T. Osterkamp and W. Harrison (Norton and Sackinger, 1981), however, suggest that off the Colville River a line from Oliktok Point to Thetis Island crosses a submerged and buried geologic boundary between silt and clay to the west and unfrozen gravel to the east. This boundary may mark the western margin of the Colville Paleovalley, or it may simply be related to the hypothesized east-west change in the Pleistocene section discussed earlier. Borehole HLA-15, just northeast of Tigvariak Island, encountered extensive, unbonded gravels at a subbottom depth of approximately 10 m and may be evidence for a paleovalley of the Shaviovik River (P. Smith, written comm., 1982).

Beaufort Shelf

As can be inferred from the Quaternary geology of the Beaufort Shelf, outwash and alluvial gravels and local basal transgressive beach deposits probably exist beneath 0-10 m of Holocene sediments nearly everywhere on the inner shelf east of the area around Oliktok Point and west of the Prudhoe area, and possibly extend to the midshelf within buried paleovalleys. East of Prudhoe, there is some evidence to suggest that the alluvial sediments are overlain by an eastward-thickening section of Pleistocene marine sediments. The nature of a boundary between Pleistocene marine and non-marine sections of apparently equivalent age, as tentatively identified off Harrison Bay (Craig and Thrasher, 1982) must be defined by offshore drilling before a more accurate appraisal of sub-surface sand and gravel resources can be made. West of Oliktok Point the evidence suggests that subsurface sources of sand and particularly gravel may be sparse, localized to former channels of the Pleistocene drainage system, and even these are not very promising. Industry shot holes in the Colville Delta-Oliktok Point area of southeastern Harrison Bay support this picture, showing considerable quantities of gravel in the upper few 10's of meters landward of the Colville Delta coastline and in western Simpson Lagoon, but mainly sand seaward of the delta front and westward from Simpson Lagoon (Fig. 15).

ENVIRONMENTAL CONSIDERATIONS WITH IMPLICATIONS FOR SAND GRAVEL MINING

Ice Regime

The seasonal freeze-thaw cycle along the coast starts with the formation of river and sea ice during late September. By the end of December the sea ice is commonly 1 m thick, and it thickens to a maximum of about 2 m in May. In late May and early June, 24-hour insolation aids rapid thawing in drainage basins and river flow is initiated which floods the as yet unmelted sea ice off river mouths. Much of the lagoonal and open-shelf fast ice inside the 10 m contour melts with little movement by the middle of July. The ice-melt zone off river mouths can reach a width of 10 to 15 km in response to the influx of warm fresh river water. The remaining sea ice continues to melt and retreats offshore through the summer melt cycle in late July, August, and early September.

Following the initiation of freezing conditions in late September, the winter ice canopy overlying the shelf can be divided into three broad categories (Reimnitz and others, 1977b): (1) Seasonal floating and bottom-fast ice of the inner shelf, (2) a brecciated and ridged shear (stamukhi) zone containing grounded ice ridges that mark the zone of interaction between the stationary fast ice and the moving polar pack, and (3) the polar pack of new and multi-year floes (on the average 2 to 4 m thick), pressure ridges, and ice-island fragments in almost constant motion (Fig. 16). The deepest ice keel in the polar pack that has been measured had a draft of 47 m. The general drift of the pack on the Beaufort shelf is westerly under the influence of the clockwise-rotating Beaufort Gyre (Campbell, 1965).

Inshore, the fast-ice zone is composed mostly of seasonal first-year ice, which, depending on the coastal configuration and shelf morphology, extends out to the 10 to 20 m isobath. By the end of winter, ice inside the 2 m isobath rests on the bottom over extensive areas. In early winter the location of the boundary between undeformed fast-ice and the westward-drifting polar pack is controlled predominantly by the location of major coastal promontories and submerged shoals. Pronounced linear pressure and shear ridges form along this boundary and are stabilized by gounding. Slippage along this boundary occurs intermittently during the winter, forming new gounded ridges in a widening zone (the stamukhi zone). A causal relationship appears to exist between major ridge systems of the stamukhi zone and the location of offshore shoals downdrift of major coastal promontories. These sand and gravel shoals, which absorb a considerable amount of kinetic energy during the arctic winter, appear to have migrated shoreward up to 400 m over the last 25 years (Reimnitz and others, 1976).

Grounded pressure-ridge keels in the stamukhi zone exert tremendous stresses on the sea bottom and on any structures present in a band of varying width between the 10 and 40 m isobaths. Thus in places where artificial structures affect the ice zonation, the extent of shorefast ice may be deflected seaward.

Ice Scour

Ice moving in response to wind, current, and pack ice pressures often plows through and disrupts the shelf sediments forming seabed scours which are found from near shore out to water about 60 m deep. The physical disruption of seafloor sediments by moving ice keels is a serious threat to seafloor installations. Most studies of the phenomenon have been conducted in the Beaufort Sea (Barnes and Reimnitz, 1974; Reimnitz and Barnes, 1974; Reimnitz and others, 1978; Rearic and others, 1981). Scours are generally oriented parallel to shore and commonly range from 0.5 to 1 m deep. However, scours cut to a depth of 5.5 m have been measured on the outer shelf. When first formed, the gouges may incise the sea bed to greater than observed depths only to be infilled by subsequent slope failure and shelf sedimentation. Regions of high scour intensity are common within the stamukhi zone and along the steep seaward flanks of topographic highs. Inshore of the stamukhi zone, seasonal scours may be abundant, but can be smoothed over during a single summer by wave and current activity (Barnes and Reimnitz, 1979). Rates of scour inshore of the stamukhi zone have been measured at 1 to 2 percent of the sea floor per year (Reimnitz and others, 1977; Barnes and others, 1978). The product of maximum ice scour incision depth (D_{max}), maximum width of ice scours (W_{max}), and scour density per kilometer interval (Z), here called ice scour intensity (I), is considered the best single measure of the severity of the process, and has been contoured in figure 17.

The plowing and overturning of the upper few meters of the Beaufort shelf by grounded ice is a natural and continuing process. This natural seafloor disturbance is probably very similar to that which would occur from surficial dredging operations. Therefore, surficial dredging should have a comparatively minor impact upon areas already subject to ice scour. It is important to note, however, that ice-scouring processes on the Beaufort shelf are a complicated function of water depth, seabed morphology, ice zonation, and the position and geometry of islands and shoals. Man-induced changes to these features, or the addition of artificial islands, could severely alter the natural ice zonation.

Permafrost (after Grantz and others, 1982)

Bonded subsea permafrost will hamper mining operations by being difficult to work. Further considerations are the effects of disturbing the permafrost during mining operations and the fact that permafrost may contain or cap gas. Prior to about 10,000 years ago, during the last glacial sea-level lowstand, the present Beaufort shelf was exposed subaerially to frigid temperatures and ice-bonded permafrost probably aggraded downward in the sediments to depths exceeding 300 m. Reflooding of the shelf exposed these sediments to saline water and much of the permafrost terrane has probably warmed and some of it has remelted. In areas where overconsolidated silt and clay cover the bottom, salt has entered the sediment by diffusion, a very slow process, and the sediment is probably still ice-bonded at depths of 5-15 m. In areas where there is gravel, possibly covered by a thin veneer of Holocene marine sediments, salt water has been able to advect fairly freely into the sediments and thawing has progressed much more rapidly (D. M. Hopkins, written comm., 1982).

Studies are underway to seismically assess the depth to, and thickness of, relict permafrost over the entire Beaufort shelf. However, only certain terranes on the inner shelf have been characterized thus far. Sellman and Chamberlain (1979) report that there are three obvious groups of seismic velocities which are apparently related to the degree of ice-bonding in the sediments. Fully ice-bonded permafrost with ice-saturated pores and velocities greater than 4.0 km/sec crops out onshore and on some barrier islands, and in adjacent wide zones landward of the 2 m isobath that are overlain by bottom-fast ice in winter. Between the shore and the barrier islands, fully ice-bonded permafrost lies at highly variable depths as great as several hundred meters beneath the sea floor. The ice-bonded permafrost is overlain in this area mostly by materials with velocities centered around 2.7 km/sec which are taken to represent partially ice-bonded sediments containing varying proportions of unfrozen pore water. Materials with velocities less than 2.2 km/sec are sparse and assumed to be unbonded.

Although the distribution of relict permafrost on the coastal and outer shelf is unknown, the base of Holocene marine sediments on the Beaufort shelf, contoured in figure 4, provides a probable minimum depth to its upper surface. This is so because it is unlikely that ice-bonded permafrost aggraded upward into the Holocene saline marine muds deposited on the shelf after the rise in sea level. By analogy with the conditions described nearshore, any permafrost in the uppermost sediments beneath the Holocene sediment "wedge" was probably melted or partially melted down to unknown depths. Depending on such parameters as pore water, salinity, original thickness, temperature of the subaerial permafrost, and the sealing effect of the Holocene muds, fully ice-bonded permafrost may or may not be encountered at depth offshore. Where ice-bonded permafrost exists, care must be taken to consider the potential for melting beneath pipelines and drilling platforms and within frozen intervals encountered in drilling. Artificial islands, being emergent, will be subject to very cold temperatures, and thus some freezeback of the bottom beneath them can probably be anticipated.

In the Harrison Bay area, probing (Harrison and Osterkamp, 1981), high-resolution seismic studies (Rogers and Morack, 1981) and velocity data derived from the study of industry seismic records (Sellmann and others, 1981) indicate that penetration-resistant, high-velocity material interpreted to be bonded permafrost is common, particularly out to the 13 m isobath (Fig. 18). Its distribution is probably as variable as it is to the east near Prudhoe Bay. Bonded permafrost should extend a few kilometers offshore of the islands in the eastern part of the Sale 71 area if conditions are similar to the Prudhoe area. Boreholes seaward of Reindeer Island, for example, suggest that the wedge of secondary ice-bonded permafrost formed beneath and abandoned behind the transient islands dissipates within a few kilometers seaward of a migrating island (D. M. Hopkins, written comm., 1982). The deeper velocity data for Harrison Bay suggest that bonded permafrost can be subdivided into two categories. In the eastern portion of the bay there is an orderly transition away from the shore, with the depth of bonded permafrost increasing and velocity contrast decreasing with distance from shore until the velocity contrast (permafrost?) is no longer apparent. In the western part of the bay, it is less orderly, possibly reflecting the history of the original land surface. This western region may have been an extension of the low coastal plain characterized by the region north of Teshekpuk Lake, which could have contained deep thaw lakes. Shallow bonded permafrost should be common to the west of Harrison Bay based on observations made in the western part of the bay and offshore of Lonely.

The characteristics of onshore permafrost are useful in predicting permafrost conditions offshore. Unfortunately, there is no published onshore temperature data for this lease area as there was from the Prudhoe Bay and Joint Sale areas. However, thickness data acquired from well logs (Osterkamp and Payne, 1981) shows that permafrost thins to the west. Onshore coastal permafrost is about 500 m thick east of Oliktok Point, 400-500 m thick in the Colville River Delta, and 300-400 m thick from the delta to the western boundary of the lease area. If the geology is similar offshore, the onshore values suggest the maximum thickness that might be expected near shore.

Along some offshore seismic lines the high-velocity material in Harrison Bay extends approximately 25 km offshore, as shown in Fig. 18. This map for Harrison Bay indicates two layers near shore, the deep high-velocity layer in this zone increasing in depth and decreasing in velocity with distance from shore, as indicated by a high-velocity refractor. A zone farther offshore is characterized by a deep reflector, suggesting continuation of the high-velocity structure. High resolution seismic data taken in the eastern end of Harrison Bay (Rogers and Morack, 1981) indicate that shallow (< 50 m) bonded permafrost is present in the area adjacent to shore and offshore of the Jones Islands.

Probing has shown that the subbottom material changes from gravel to silt, as one moves westward in the area between Thetis and Spy Islands. However, no shallow bonded permafrost is suggested from the high-resolution seismic data taken near Thetis Island (Sellmann and others, 1981). A seismic line running from Oliktok Point to the west end of Spy Island indicates bonded permafrost near shore at Oliktok Point and again north of Spy Island. The observed velocities were greater than 2,500 m/s, probably indicating gravels. An additional high-resolution seismic line run from shore to the east end of Pingok Island does not indicate shallow bonded permafrost in Simpson Lagoon, and the conclusion is that the bonded permafrost dips quickly in an offshore direction. However, outside of Pingok Island, high velocities suggest that bonded permafrost is again present at shallow depths (< 10 m), and the measured velocities (4,000 m/s) indicate that it has not yet significantly degraded (Rogers and Morack, 1981).

Higher seismic velocities suggest that firmly ice-bonded permafrost is present beneath the somewhat older, sparsely vegetated recurved spits and spurs of Beaufort Sea islands (Rogers and Morack, 1977). These areas can be recognized by the presence of frost cracks extending across ancient wave-constructed ridges and swales. Lower seismic velocities recorded beneath most areas in the vegetation-free parts of the islands, however, suggest that firmly-bonded permafrost is lacking (Rogers and Morack, 1977), although interstitial ice was found in the sediment in a borehole on Reindeer Island; the interstices in the sediment beneath the younger parts of the islands must be filled with a two-phase mixture of brine and ice.

Between approximately the Kuparuk River and Flaxman Island, Hartz and Hopkins (1980) used all available borehole and penetrometer data, combined with the hypothesis that thick, unbonded permafrost occupies paleovalleys filled with gravelly alluvium and outwash capped by Holocene marine deposits, to contour the thickness of unbonded sediments (Fig. 19). This map may assist in both delineating gravel-filled Pleistocene valleys on this portion of the Beaufort shelf and identifying near surface unfrozen sources of sand and gravel. Figure 7 shows the depth to bonded permafrost in a transect from Prudhoe Bay to Reindeer Island (Hopkins and Hartz, 1978).

Overconsolidated surficial deposits

Outcrops of stiff silty clay have been reported in widespread areas of the Beaufort Sea shelf (Reimnitz and others, 1980). Laboratory measurements of a borehole sample of these sediments show that they can be highly overconsolidated (Chamberlain and others, 1978). The cause of these very stiff clays is not known, although at least two mechanisms have been proposed. Data from one borehole site suggests that freezing and thawing cycles of these marine sediments during transgression of barrier islands may have led to their overconsolidation (Chamberlain and others, 1978). Alternatively, since overconsolidated clays are almost universal on the shelf, and don't seem to show a systematic distribution relative to the islands, they may reflect subaerial exposure to freezing temperatures during low sea level episodes (D. M. Hopkins, written comm., 1982). Most importantly the presence or absence of this material could have substantial impact upon any attempts to successfully dredge sand and gravels lying beneath it (Reimnitz and others, 1980).

There are at least 77 known occurences of these outcrops between Cape Halkett and the Canadian border ranging from the nearshore to 80 km offshore (Fig. 20). Hopkins and others (In Smith and Hopkins, 1979) noted that areas of shallow ice-bonded permafrost tend to coincide with areas where overconsolidated clay older than the last rise in sea level (Sangamon age or older) lies at or near the sea bottom, and that areas where the upper surface of ice-bonded permafrost lies much deeper tend to coincide with areas where this clay is lacking and where alluvial or outwash gravel is covered by Holocene marine silt and clay. Noting that areas of deeply thawed permafrost may coincide with drowned and partly buried valleys where this overconsolidated clay was removed in the course of valley erosion during low stands of sea level, Smith and Hopkins (1979) suggest that knowledge of the paleodrainage pattern on the shelf could help in predicting the distribution of shallow and deeply thawed ice-bonded permafrost. Alternatively, knowledge of the paleodrainage pattern may help in predicting the distribution of the surficial overconsolidated clays. Only significantly more borehole, geophysical, and sediment sampling data will delineate the paleodrainage pattern on the Beaufort shelf.

Shallow Gas

Information on shallow gas for the outer Beaufort Sea Shelf has been compiled by Grantz and others (1982), (Fig. 21). Figure 22 shows probable locations of shallow free gas in the Harrison Bay area (Craig and Thrasher, 1982). Sellmann and others (1981) also infer from the presence of free gas above ice-bonded permafrost that gas in hydrate form, within and below the ice-bonded layer, is likely in the Harrison Bay area.

Work in Stefansson Sound off the Sagavanirktok delta has documented the presence of shallow gas, apparently capped by a layer of overconsolidated clays, lying below a prominent reflector at depths of 20-35 m below mud line (Boucher and others, 1981), (Fig. 23). Strong, discontinuous reflectors of similar character are widespread on the Beaufort Sea shelf suggesting that paths of shallow gas are a widespread phenomenon (Boucher and others, 1981). Gravel mining operations may release these gases by disrupting the thermal or physical regime.

CONSEQUENCES OF GRAVEL MINING

Onshore and Beach Areas

The consequences of, and constraints upon, gravel mining from onshore and beach areas are similar to those outlined for the Joint State Federal Lease Sale (JLSA), (Weller and others, 1978). This study noted that stream beds should be avoided as borrowed sites because of potential damage to overwintering fish populations, and that wetlands and especially tidal marshes should be avoided because of their relatively high organic productivity and their value as nesting habitat. Quarrying of sand and gravel from beaches will accelerate the already exceptionally rapid rates of coastal erosion.

Quarrying of sand and development of roads to sand quarries in the large area of stabilized dunes on eastern NPRA will result in local reactivation of blowing sand. Disturbances can be minimized by developing quarries as closed depressions and allowing them to fill with water after abandonment, by limiting quarrying to the winter months, and by using ice roads for haulage.

Offshore Dredging

Discussion of the consequences of dredging in the JLSA (Weller and others, 1978) focused upon the disturbance of the bottom, potential burial of benthic organisms by siltation, and increases in turbidity with possible attendant clogging of gills of filter feeders. All of these disturbances are comparable to the effects of such natural disturbances as ice gouging, resuspension of sediments during storms, and excavation by strudel scour during spring breakup flooding of the shorefast ice. Not considered in earlier discussions is a possible darkening of the ice canopy due to incorporation of suspended material during freezing; the effects here seem comparable to those induced during some years by incorporation of sediment in the ice canopy as a result of resuspension of bottom sediments during late autumn storms (Barnes and others, 1982). However the effects of dredging operations, especially the fate of any sediment plume and the possible remobilization of chemicals from sediment pore waters, is unknown for Arctic operations under the influence of ice. At the least nutrients will be introduced into the system (Bischoff and Rosenbauer, 1978).

Removal of fill from the bottom in certain areas can significantly affect the stability and permanence of offshore islands. Removal of sand waves off Pingok Island could result in accelerated erosion and rapid destruction of the island. Most of the other offshore islands are migrating landward at about 5 to 10 m per year (Barnes and others, 1977a). Development of a submerged borrow pit in the lee of one of these islands could result in the disappearance of the island.

Several lines of evidence demonstrate that the island chains are not unified sediment-transport system, but rather that many of the island groups have or once had their own sediment sources. The presence of gravel on Jeanette, Narwhal, and Cross Islands much coarser than the gravel comprising islands that lie eastward and updrift establishes beyond doubt that a source of sediment lies or once lay somewhere seaward on the continental shelf (Hopkins and Hartz, 1978). The eastern islands within the Plover chain are or once were fed from the bluffs east of Cape Simpson DEW-line Station, while the peninsula leading from Eluitkak Pass to Point Barrow may be fed by sediment moving northward up the Chukchi Sea coast and eastward around Point Barrow. The islands between Eluikrak and Eluitkak Pass, however, differ enough to indicate that they originated from a sediment source that has now disappeared. Thetis and Spy Islands, like Cross Island, seem to "represent the dying phase of the barrier island system off northern Alaska" (Reimnitz and others, 1977a) and to be drifting southwestward from sources that have long-since disappeared. The coarse grained nature of the barrier islands is apparently a result of eolian sand deflation, wind-winnowing of island surfaces being effective during most of the year (Reimnitz and Maurer, 1979).

Karluk, Jeanette, and Narwhal Islands are evidently lag deposits resulting from the erosion and eventual destruction of hillocks of Flaxman Formation that are now preserved only as outcrops of Pleistocene sediment on the sea floor. Ice-push may continue to add new coarse material to the seaward beaches of these islands. Cross Island originated from another hillock of Flaxman Formation, as did Reindeer and Argo Islands, but Reindeer and Argo Islands have now migrated a kilometer or more landward from the site of the former hillock of Flaxman Formation.

Long term comparisons seem to indicate that the islands are migrating with little loss of area and mass. Wave overwash during storm surges helps to move sand and gravel from the nearshore zone onto the body of the island, and ice-push rakes the lagging coarser particles from deep water and returns them to the island surface. However, the islands will eventually disappear. The

Dinkum Sands seem to be an example of a member of the chain that lost mass and eventually became completely submerged.

Because the islands in the Beaufort Sea island chains are mostly lag deposits derived from sand and gravel sources that have now disappeared, they must be regarded as irreplaceable. If they were removed, they may not be replaced by natural processes, and the local oceanographic and biological regime would be perturbed for long periods of time.

Thetis Island seems especially vulnerable, and because of the increasing intensity of use of the island and surrounding waters, conflicts are likely to arise. Because it is the only barrier island in Harrison Bay, Thetis Island is regularly used as shelter for ship and barge traffic. However, during the summer, the island is used by a large bird population (Norton and Sackinger, 1981).

The shoals on the outer shelf control the position of the intense ice ridging of the stamukhi zone (Rearic and Barnes, 1980; Reimnitz and others, 1977c, 1978; and Reimnitz and Kempema, 1981). Because of this, these shoals should not be mined or reduced in any dimension without considering the effects upon ice zonation; on the other hand, we are unaware of any objection to adding fill to build these shoals above sea level. The sand apron to the southwest of Stamukhi Shoal possibly could be reshaped without affecting ice dynamics, but the understanding of the interaction of grounded ice and shoal sediments is presently inadequate.

Weller Bank, the largest and most equidimensional body of sand and gravel on the western Beaufort shelf, is located at the boundary between fast ice and moving ice, controlling the position of the stamukhi zone. A cross section of a reshaped Weller Bank (Fig. 24) with a hypothetical dredged production island on top was prepared to show relative sizes (Barnes and Reiss, 1981). Minor reshaping of Weller Bank may not severely alter ice zonation, but export of the sand and gravel to some other part of the Sale 71 area would severely disrupt the ice zonation and probably would decrease the extent and stability of shorefast ice.

Environmental problems related to the dredging of large gravel pits on the Beaufort shelf must be viewed in light of several factors. Rivers presently contribute little or no sand and gravel to the Beaufort shelf and modern sedimentation rates seem to be low, despite perhaps the fastest retreating coastlines in North America. In spite of this, the ice-related reworking of the sea floor is a very dynamic process and rates of ice-scour infilling suggest that sediment transport on the shelf is far greater than the present rates of accretion would lead one to believe. Therefore, large gravel pits in shallow water would probably soon refill, removing much sediment from circulation and possibly further aggravating coastal erosion (E. Reimnitz, written comm., 1982).

Probably the most significant consequence of construction of artificial islands on the Beaufort shelf will be greatly increased water traffic. Fill probably cannot be trucked in over the ice to the outer part of the area, and will almost certainly have to be carried to artificial island sites by barge, either from stockpiles on the beach or from submerged dredge pits. The problem is intensified by the scarcity of obvious borrow sites in all except the central and eastern parts of the Beaufort Sea Shelf. An increase in vessel traffic in the area will be attended by a higher probability of collisions and accidents and consequent pollution. Industry will probably press for lengthening the barging season through the use of icebreakers during early summer and late autumn; if so, ice hazards to water traffic will increase, and water traffic will be active during seasons that currently are relatively quiet.

The one or more large suction dredges that will probably be used to provide fill for artificial islands will need a deep and sheltered anchorage protected from moving ice. The sheltering of dredges in the lee of barrier islands create sea-bottom depressions that could damage the islands.

SUMMARY

Beaches may serve as sources of sand and gravel, but the fact that coarse sediments are not presently being delivered to the coast by rivers, coupled with very high rates of coastal retreat, may make these areas unsuitable for mining. The creation of large dredge pits near shore, and the subsequent infilling of these features could remove much mobile sediment from the shelf and accelerate rates of coastal retreat. Islands and shoals are rich sources of fill, but their fragile nature and effects upon ice zonation may also make them unsuitable for sand and gravel removal.

Other surficial sources of sand, and particularly gravel, are scattered west of the Canning River. To the east of this river preliminary studies suggest that the inner shelf, out to depths of approximately 15 m, and the outer shelf may have a surficial cover of coarse granular materials.

The subsurface geology of the Beaufort Sea shelf is insufficiently known to quantify estimates of sand and gravel resources in all but a few localized areas. The qualitative assessment of these subsurface resources made in this document must be viewed with caution until verified by drilling and additional geophysical work. In general, the coarse alluvial and outwash materials deposited during the Pleistocene (Wisconsin) extend seaward of the coast only within paleovalleys of the Pleistocene drainage system, as shown by boreholes and the shot-hole survey off the Colville delta. West of the Colville River, coarse sediments should be rare, while to the east these subsurface sources should be plentiful. Sources of gravel between paleovalleys (mid-Pleistocene and older) are generally bonded and overlain by overconsolidated silts and clays. Coarse sediments within paleovalleys are generally unbonded and overlain by less than 10 m of soft Holocene muds. East of the Canning River, the surficial, possibly relict gravels of the inner and outer shelf, may extend to subbottom depths of several meters.

Areas selected for dredging should first undergo extensive studies for the presence of shallow gas. Permafrost is probably not a hazard to sand and gravel mining, although the presence of ice-bonded permafrost will make dredging impractical. Dredging operations , where not injurious to the coastline or barrier islands, will probably have qualitatively similar effects upon the marine environment as the natural process of ice scour, but will be of a quantatively smaller areal impact.

ACKNOWLEDGMENTS

I would like to thank P. Barnes, D. Dinter, A. Grantz, D. Hopkins, E. Reimnitz, and P. Smith for their comments on an earlier draft of this Open-File Report. I wish to especially thank P. Barnes and E. Reimnitz for helping me to sort through the Beaufort Sea literature in the short time provided for the preparation of this report, and D. Hopkins for both his extremely thorough and helpful review of the earlier draft and his willingness to share his keen insight into the Quaternary history of the Beaufort shelf. Finally, I thank La Vernne Hutchison for typing the various versions of this manuscript.

REFERENCES

Alaska Geological Society, 1971, West to east stratigraphic correlation section, Point Barrow to Ignek Valley, Arctic North Slope, Alaska: Alaska Geological Society, Anchorage.

_____1972, Northwest to southeast stratigraphic correlation section, Prudhoe Bay to Ignek Valley, Arctic North Slope, Alaska: Alaska Geological Society, Anchorage.

Barnes, P. W., 1974, Preliminary results of marine geologic studies off the northern coast of Alaska: An ecological survey in the Beaufort Sea, WEBSEC 71-72, Department of Transportation, U. S. Coast Guard Oceanographic Report No. CG 373-64, p. 183-227.

Barnes, P. W., McDowell, D. M., and Reimnitz, E. 1978, Ice gouging characteristics: Their changing patterns from 1975-1977, Beaufort Sea, Alaska: U. S. Geological Survey Open-File Report 78-730, 42, p.

Barnes, P. W., and Reimnitz, E. 1974, Sedimentary processes on Arctic Shelves off northern coast of Alaska: in Reed, J. C., and Sater, J. E., (eds.) The Coast and Shelf of the Beaufort Sea. Proceedings of the Arctic Institute of North America Symposium on Beaufort Sea Coast and Shelf Research, Arlington, Virginia, Arctic Institute of North America, p. 439-476.

Barnes, P. W., and E. Reimnitz, 1979, Ice gouge obliteration and sediment redistribution event; 1977-1978, Beaufort Sea, Alaska. U. S. Geological Survey Open-File Report 79-848, 22 pp.

Barnes, P. W., Reimnitz, E., and Drake, D. E., 1977a, Marine environmental problems in the ice-covered Beaufort Sea shelf and coastal regions: Annual Report to National Oceanic and Atmospheric Administration, Environmental assessment of the Alaskan continental shelf, Principal Investigators' Report for year ending March 1977; v. 12, p. 1-229.

Barnes, P. W., Reimnitz, E., Drake, D. E. and, Toimil, L. J., 1977b, Miscellaneous hydrologic and geologic observations on the inner Beaufort Sea shelf, Alaska: U. S. Geological Survey Open-File Report 77-477, 95 p.

Barnes, P. W., Reimnitz, E. and D. Fox, 1982, Ice rafting of fine-grained sediment, a sorting and transport mechanism, Beaufort Sea, Alaska: Journal of Sedimentary Petrology, v. 52, no. 2, p. 493-502.

Barnes, P. W., E. Reimnitz, and C. R. Ross, 1980, Nearshore surficial sediment textures - Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA OCEAP Quart. Rep. 2:132-170.

Barnes, P. W., and T. Reiss, 1981, Geological comparison of two arctic shoals. Environmental assessment of the Alaskan continental shelf. NOAA OCSEAP Ann. Rep. (in press).

Barnes, P. W., Reimnitz, E., Toimil, L. J., McDowell, D. M., and Maurer,D. K., 1979, Vibracores, Beaufort Sea, Alaska Descriptions and preliminary interpretation: U. S. Geological Survey Open-File Report 79-351, 103 p.

Bischoff, J. L., and Rosenbauer, R. J., 1978, Chemical Changes in Seawater Caused by Resuspension of Deep Sea Sediments from DOMES sites A, B, and C, Marine Mining, v. 1, No. 4, p. 283-304.

Black, R. F., 1964, Gubic formation of Quaternary age in northern Alaska: U. S. Geological Survey Professional Paper 302-C, p. 59-91.

Boucher, G. Reimnitz, E. and Kempema, E. W., 1981, Seismic evidence for an extensive gas-bearing layer at shallow depth offshore from Prudhoe Bay, Alaska: Cold Regions Science and Technology, no. 4, p. 63-71.

Brosge, W. P., and Tailleur, I. L., 1971, Northern Alaska petroleum province, In Cram, I. H., ed., Future petroleum provinces of the United States--their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 68-99.

Campbell, W. J., 1965, The wind-driven circulation of ice and water in a polar ocean, Jour. Geophys. Res., 70:3279-3301.

Carter, L. D., and Robinson, S. W., 1978, Aeolian sand and interbedded organic horizons at Kaoluk Creek; regional implications: U. S. Geol. Survey Open-File Report.

Chamberlain, E. J., P. V. Sellmann, S. E. Blouin, D. M. Hopkins, and R. I. Lewellen, 1978, Engineering Properties of Subsea Permafrost in the Prudhoe Bay Region of the Beaufort Sea, Proceedings of the Third International Conference on Permafrost, Vol. 1, 1978, p. 629-635.

Craig, J. D., and Thrasher, G. P., (1982), Environmental Geology of Harrison Bay, Northern Alaska, U. S. Geological Open File Report 82-35.

Dinter, D. A., 1982, Holocene Marine Sediments on the Middle and Outer Continental Shelf of the Beaufort Sea North of Alaska, U. S. Geological Survey Miscellaneous Field Studies Map, MF-1182 B.

Eittreim, S. and Grantz, A., 1979, CDP Seismic sections of the western Beaufort continental margin: Tectonophysics, v. 59, p. 251-262.

Grantz, A. Barnes, P. W., Dinter, D. A., Lynch, M. B., Reimnitz, E. Scott, E. W., 1980, Geologic framework, hydrocarbon potential, environmental conditions, and anticipated technology for exploration and development of the Beaufort Shelf north of Alaska: U. S. Geological Survey Open-File Report, 80-94, 40 p.

Grantz, A., Dinter, D. A., Hill, E. R., May, S. D., McMullin, R. H., Phillips, R. L., and Reimnitz, E., 1982, Geological Framework, Hydrocarbon Potential and Environmental Conditions for Exploration and Development of Proposed Oil and Gas Lease Sale 87 in the Beaufort and Northeast Chukchi Seas, U. S. Geological Survey Administrative Report, Menlo Park, CA., 73 p.

Grantz, A. Eittreim, S. and Dinter, D. A., 1979, Geology and tectonic development of the continental margin north of Alaska: Tectonophysics, v. 59, p. 263-291.

Grantz, A., Eittreim, S., and Whitney, O.T., 1981, Geology and physiography of the continental margin north of Alaska and implications for the origin of the Canada Basin, In: The Ocean Basins and Margins, A. E. M. Nairn, M. Churkin, Jr., and F. G. Stehli (eds.), v. 5, pp. 439-492.

Grantz, A. and Mull, C. G., 1978, Preliminary analysis of the petroleum potential of the Arctic National Wildlife Rante, Alaska: U. S. Geological Survey Open-File Report 78-489, 20 p., 4 figs.

Greenberg, J., Hart, P. E., and Grantz, A., 1981, Bathymetric map of the continental shelf, slope and rise of the Beaufort Sea north of Alaska: U. S. Geological Survey Misc. Investigations Series Map I-1182-A, 1 sheet, scale 1:500,000 and 5 pages of text.

Harrison, W. D., and T. E. Osterkamp, 1981, Subsea permafrost: probing, thermal regime and data analysis. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Hartz, R. W., and Hopkins, D. M., 1980, A review of offshore permafrost studies, Beaufort Sea, Alaska, 1976 to 1980: In" Smith, P. A., Hartz, R. W., and Hopkins, D. M., Ofshore permafrost studies and shoreline history as an aid to predicting offshore permafrost conditions: Annual report to NOAA, Environmental assessment of the Alaskan continental shelf, Principal Investigators' report for the year ending March, 1980; v. 4, p. 167-177.

Hartz, R. W., Holden, K., Hopkins, D. M., and Shearer, G., 1979, Location map and summary logs for the Geological Survey's 1979 Beaufort Sea Over-the-ice drilling program: U. S. Geological Survey Open File Report 79-1303.

Hopkins, D. M., 1979, Offshore permafrost studies, Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. 16, 396-518.

Hopkins, D. M., Carter, L. D., Brigham, J. K., Brouwers, E., McDougall, K. A., Marincovich, L. N., Nelson, R. E., Repenning, C. A., and Williams, J. R., in prep. The Flaxman Member of the Gubik Formation of northern Alaska.

Hopkins, D. M., and Hartz, R. W., 1978, Shoreline history of Chukchi and Beaufort Seas as an aid to predicting offshore permafrost conditions: Annual Reports, v. 12, p. 503-574.

Hopkins, D. M., Sellmann, P. V., Chamberlain, E., Lewellen, R. E., and Robinson, W. W., 1979, Buried valleys as a possible determinant of the distribution of deeply buried permafrost on the continental shelf of the Beaufort Sea, In: Smith, P. A. and Hopkins, D. M., 1979, Offshore permafrost studies and shoreline history of Chukchi and Beaufort Seas as an aid to predicting offshore permafrost conditions: Annual Report to NOAA, Environmental Assessment of the Alaskan Continental Shelf, Principal Investigators report for year ending March 1979; v. IX, p. 116-163

Howitt, F., 1971, Permafrost geology at Prudhoe Bay: World Petroleum, v. 42, no. 8, p. 28-32.

Jahns, H. O., 1979, Overview of design procedure. In: Technical seminar on Alaskan Beaufort Sea gravel island design: Exxon Production Research Co., Houston, Tex.

Jones, H. P., and Speers, R. G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska: American Association of Petroleum Geologists Memoir 24, p. 23-50.

Leffingwell, E. dek., 1919, The Canning River region, northern Alaska: U. S. Geological Survey Prof. Paper 109, 251 p.

Mowatt, T. C., and Naidu, S., 1974, Gravels from the Alaskan continental shelf, Beaufort Sea, Arctic Ocean: petrographic character and implications for sediment source and transport: Alaskan Geol. and Geophys. Survey Open-File Report AOF43, 40 p.

Norton, D. W., and Sackinger, W. M., (eds.), 1981, Beaufort Sea Synthesis-Sale 71, U. S. Dept. of Commerce, NOAA, Office of Marine Pollution Assessment, Juneau, Alaska, 175 p.

Osterkamp, T. E., and M. W. Payne, 1981, Estimate of Permafrost thickness from well logs in northern Alaska. Cold. Reg. Sci. Tech. (in press).

Payne, T. G., and others, 1952, Geology of the Arctic slope of Alaska: U. S. Geological Survey Oil and Gas Inv. Map OM-126.

Rearic, D. M., and P. W. Barnes, 1980, Reassessment of ice gouging the inner shelf of the Beaufort Sea, Alaska - A progress report. Environmental assessment of the Alaskan continental shelf. NOAA OCSEAP Ann. Rep. 4:318-332.

Rearic, D. M., Barnes, P. W., and Reimnitz, E. 1981, Ice gouge data, Beaufort Sea, Alaska, 1972-1980: U. S. Geological Survey Open-File Report 810950, 8 microfische cards.

Reimnitz, E. and Barnes, P. W., 1974, Sea Ice as a geologic agent on the Beaufort Sea shelf of Alaska: in Reed, J. C., and Sater, J. E., (eds,) The Coast and Shelf of the Beaufort Sea, Proceedings of the Arctic Institute of North America Symposium on Beaufort Sea Coast and Shelf Research, Arlington, Virginia, Arctic Institute of North America, p. 301-351.

Reimnitz, E., Barnes, P. W., Forgatsch, T. C., and Rodeick, C. A., 1972a, Influence of grounding ice on the Arctic shelf of Alaska: Marine Geology, v. 13, p. 323-334.

Reimnitz, E., Barnes, P. W., and Melchior, J., 1977a, Changes in barrier island morphology--1949 to 1979, Cross Island, Beaufort Sea, Alaska: U. S. Geological Survey Open File Report, 77-477, p. F1-F14.

Reimnitz, E., Barnes, P. W., Minkler, P. W., Rearic, D. M., Kempema, E. W., and Reiss, T., 1982, Marine Geological Investigations in the Beaufort Sea in 1981 and Prelinminary Interpretations for Region from the Canning River to the Canadian Border, National Oceanic and Atmospheric Administration, Environmental Assessment of the Alaskan Continental Shelf: Principal Investigators Reports for 1981, 46 p.

Reimnitz, E., Barnes, P. W., Toimil, L. J., and Melchior, J. 1977b, Ice gouge recurrence and rates of sediment reworking, Beaufort Sea, Alaska: Geology, v. 5, p. 405-408.

Reimnitz, E., and E. W. Kempema, 1981, Pack Ice interaction with Stamukhi Shoal, Beaufort Sea, Alaska. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Reimnitz, E., and E. W. Kempema, C. R. Ross, and P. W. Minkler, 1980, Overconsolidated surficial deposits on the Beaufort Shelf. U. S. Geological Survey Open-File Report 80-2010, 37 pp.

Reimnitz, E., and D. K. Maurer, 1978, Stamukhi shoals of the Arctic - some observations from the Beaufort Sea. U. S. Geol. Sur. Open-File Report. 78-666, 17 pp.

Reimnitz, E., and Maurer, D. K., 1979, Eolian sand deflation - A cause for gravel barrier islands in Arctic Alaska?, Geology, v. 7, pp. 507-510.

Reimnitz, E. Maurer, D. K., and Barnes, P. W., 1977c, Preliminary results of Kogru River Studies, in National Oceanic and Atmospheric Administration, Environmental Assessment of the Alaskan Continental Shelf; Principal Investigators Reports, March 1977, v. 17, p. 54-62.

Reimnitz, E. and Melchior, J. and Toimil, L. J., 1976, Shoal migration under the influence of ice: A comparison study, 1950-1975: National Oceanic and Atmospheric Administration, Environmental Assessment of the Alaskan Continental Shelf: Principal Investigators Reports, April 1976, v. 12, p. 583-590.

Reimnitz, E., and P. W. Minkler, 1981, Finger Shoal survey: An unusual field of bedforms in Harrison Bay. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Rep. (in press).

Reimnitz, E. and Ross, C. R., 1979, Lag deposits of boulders in Stefansson Sound; Beaufort Sea, Alaska: U. S. Geological Survey Open-File Report 79-1205, 26 p.

Reimnitz, E. Toimil, L. J., and Barnes, P. W., 1978, Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska: Marine Geology, v. 28, p. 179-210.

Reimnitz, E., Wolf, S. C., and Rodeick, C. A., 1972b, Preliminary interpretation of seismic profiles in the Prudhoe Bay area, Beaufort Sea, Alaska: U. S. Geological Survey Open-File Report 72-548.

Rodeick, C. A., 1979, The origin, distribution, and depositional history of gravel deposits on the Beaufort Sea continental shelf, Alaska: U. S. Geological Survey Open-File Report 79-234, 87 p.

Rogers, J., and Morack, J., 1977, Beaufort Sea coast permafrost studies; National Oceanic and Atmospheric Administration, Environmental Assessment of the Alaskan Continental Shelf: Annual reports of principal investigators for the year ending March, 1977, v. 17, Hazards, p. 467-510.

Rogers, J. C., and J. L. Morack, 1981, Beaufort and Chukchi seacoast permafrost studies. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Report (in press).

Sea Technology Staff Report, 1982, Gulf Canada's Beaufort, Sea Technology, April, pp. 20-23.

Sellmann, P. V., and Chamberlain, E., 1979, Delineation and engineering characteristics of permafrost beneath the Beaufort Sea: Quarterly Report to U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Arctic Projects Office, Fairbanks, Alaska.

Sellmann, P. V., and K. G. Neave, and E. J. Chamberlain, 1981, Delineation and engineering characteristics of permafrost beneath the Beaufort Sea. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP Ann. Report (in press).

Smith, P. A., and Hopkins, D. M., 1979, Offshore permafrost studies and shoreline history of Chukchi and Beaufort Seas as an aid to predicting offshore permafrost conditions: U. S. National Oceanic and Atmospheric Administration, Environmental Assessment of the Alaskan Continental Shelf, Annual Reports of Principal Investigators, March 1979, v. IX, p. 116-163.

Tailleur, I. L., Pessel, G. H., Levorsen, J. A., and Engwicht, S. E., 1978, Maps showing land status and well locations and tables of well data, eastern North Slope petroleum province, Alaska: U. S. Geological Survey Miscellaneous Field Studies Map MF928A, 5 sheets.

Trefethen, 1950, in Pettijohn, F. J., 1957, Sedimentary Rocks, New York, Harper and Brothers, p. 24.

Vilks, G., Wagner, F. J. E., and Pelletier, B. R., 1979, The Holocene marine environment of the Beaufort Shelf: Geological Survey of Canada, Geological Survey Bulletin 303, 43 p.

Weller, G. E., D. W. Norton, and T. M. Johnson (eds.), 1978, Interim Synthesis, Beaufort/Chukchi. Environmental assessment of the Alaskan continental shelf. NOAA/OCSEAP. Boulder, Colo. 362 p.

Wentworth, C. K., 1922, A sacale of grade and class terms for clastic sediments. Jour. Geol., v. 30, no. 5, pp. 377-392.

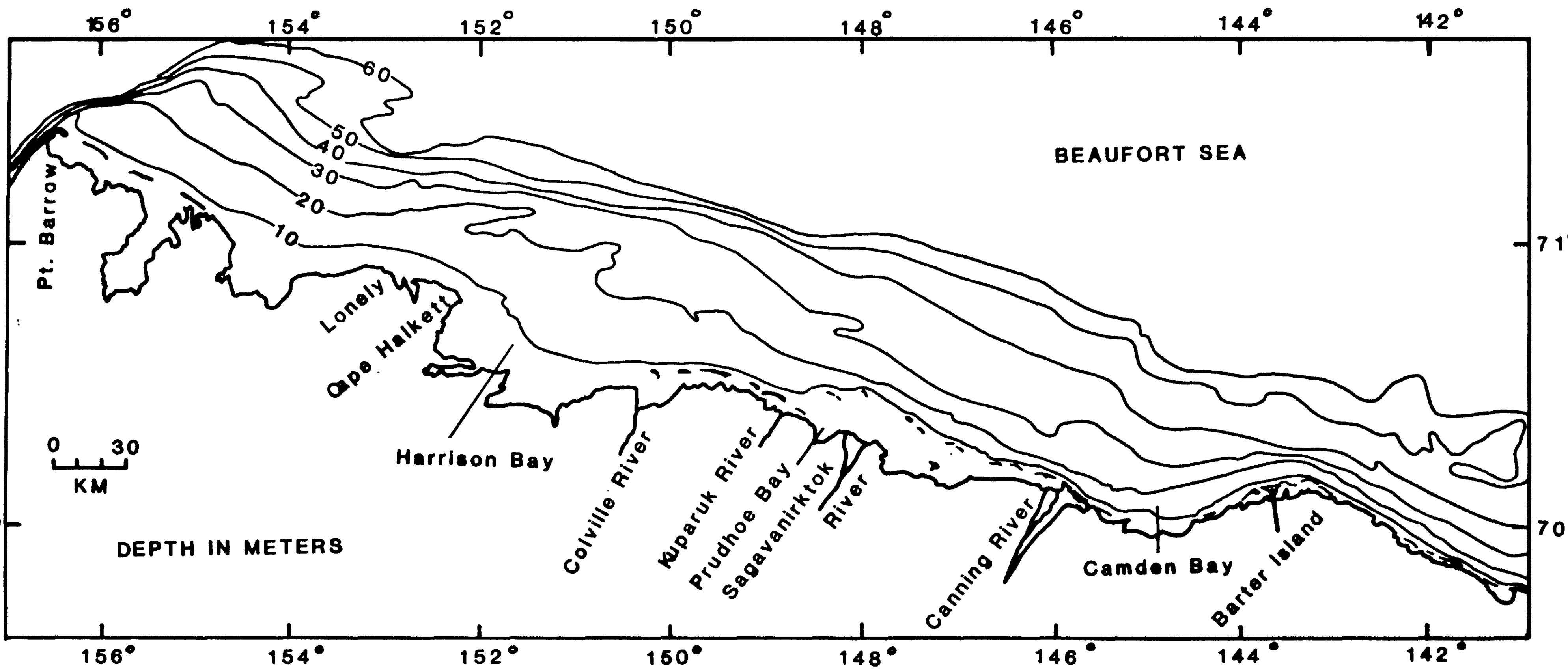


Figure 1. Beaufort Sea shelf from Barrow to the Canadian border. Bathymetry west of 145° from Rearic et al., 1981; east of 145° from Greenberg et al., 1981.

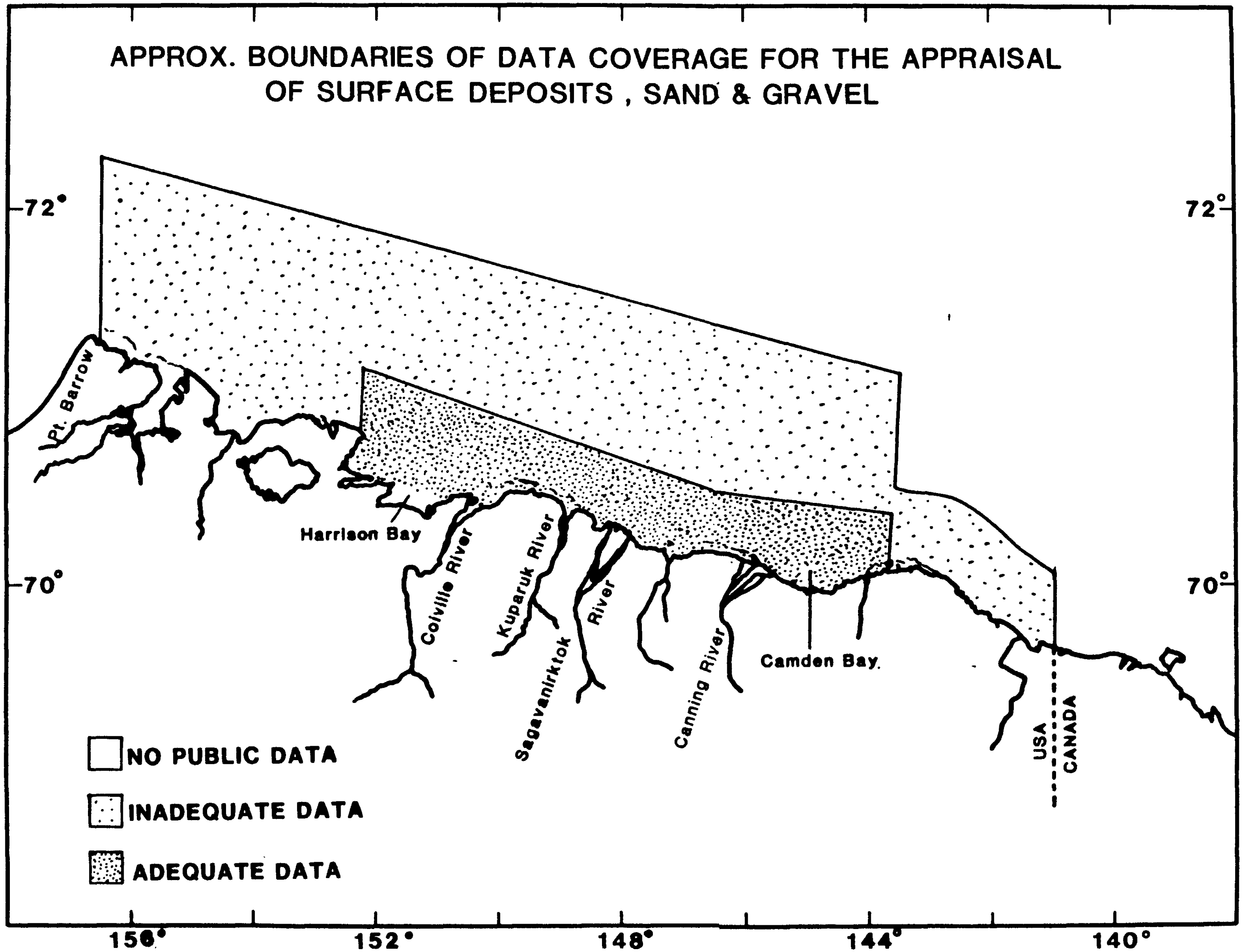

APPROX. BOUNDARIES OF DATA COVERAGE FOR THE APPRAISAL OF SURFACE DEPOSITS, SAND & GRAVEL
72°
70°
156°
152°
148°
144°
140°
Pt. Barrow
Harrison Bay
Colville River
Kuparuk River
Sagavanirktok River
Canning River
Camden Bay
USA
CANADA
NO PUBLIC DATA
INADEQUATE DATA
ADEQUATE DATA

Figure 2A

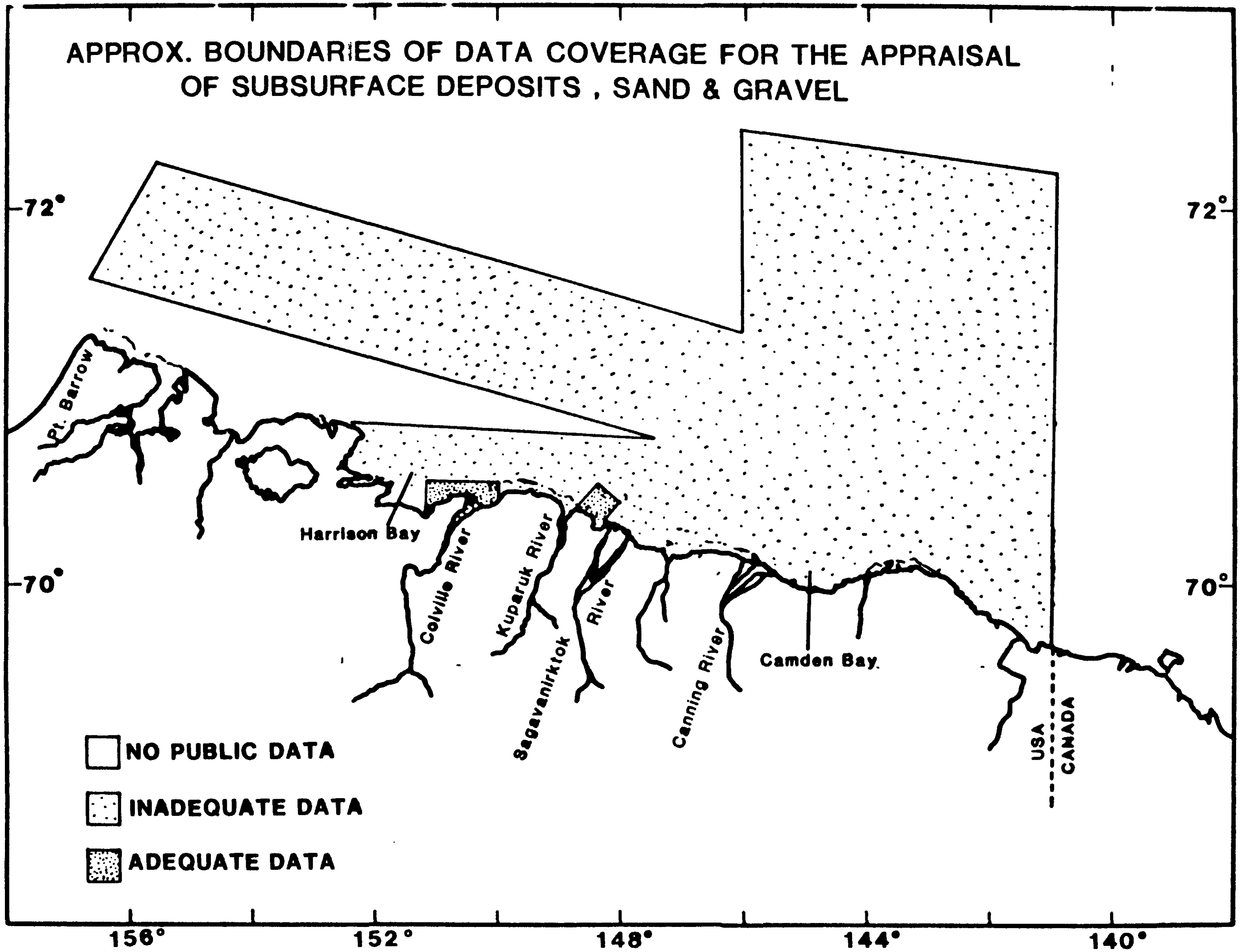

APPROX. BOUNDARIES OF DATA COVERAGE FOR THE APPRAISAL OF SUBSURFACE DEPOSITS, SAND & GRAVEL
72°
70°
Pt. Barrow
Harrison Bay
Colville River
Kuparuk River
Sagavanirktok
River
Canning River
Camden Bay
USA
CANADA
NO PUBLIC DATA
INADEQUATE DATA
ADEQUATE DATA
156°
152°
148°
144°
140°

Figure 2B

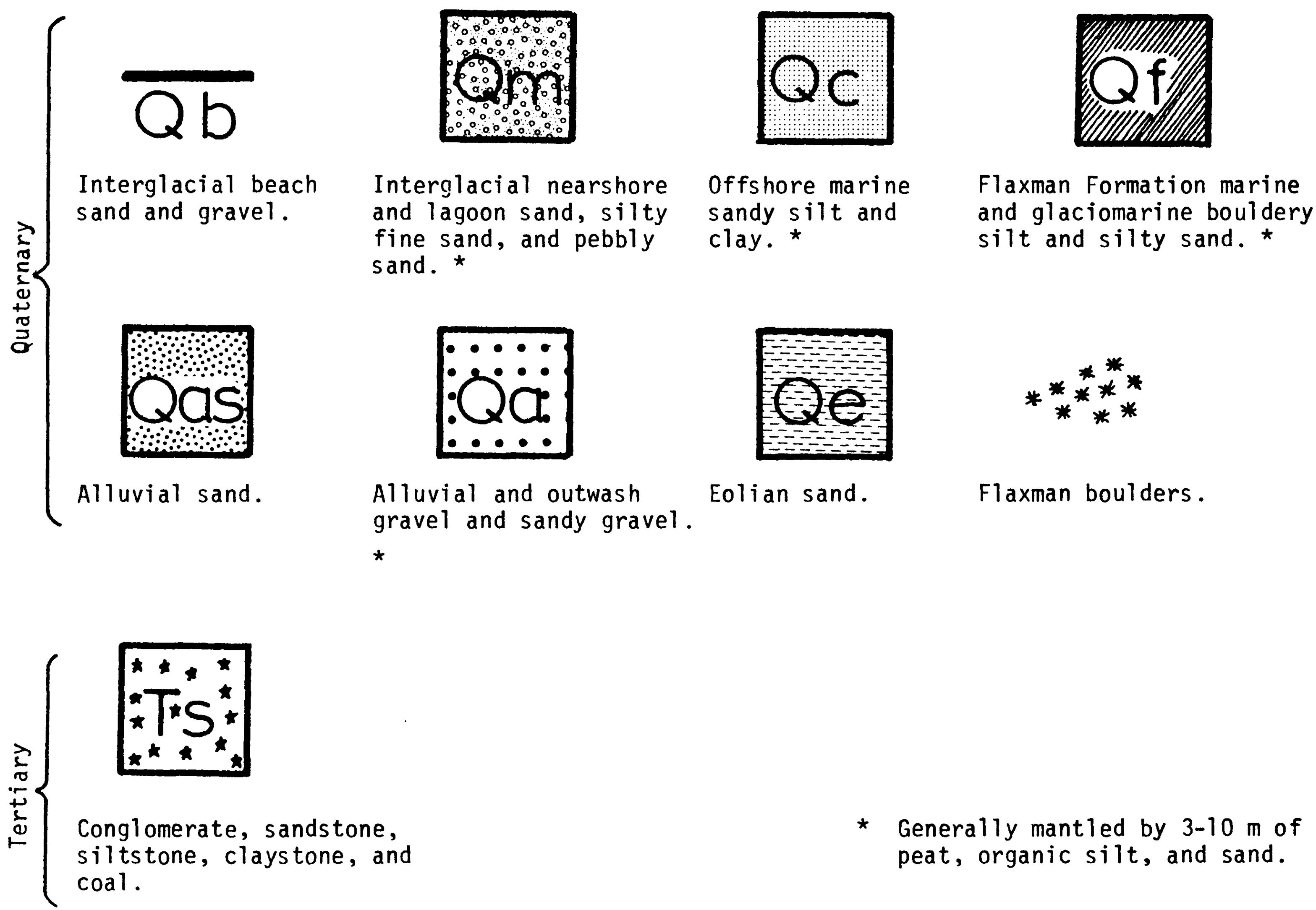
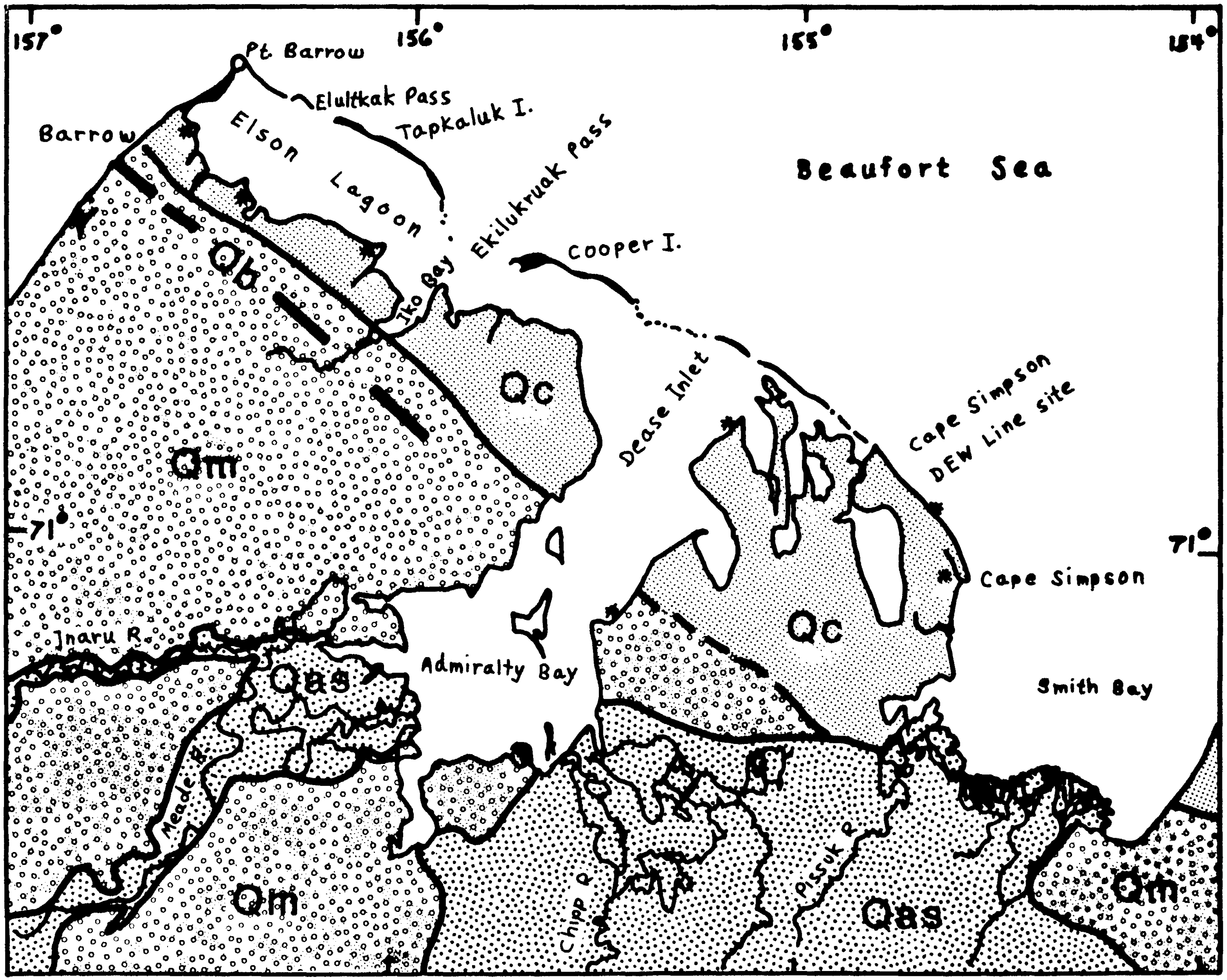
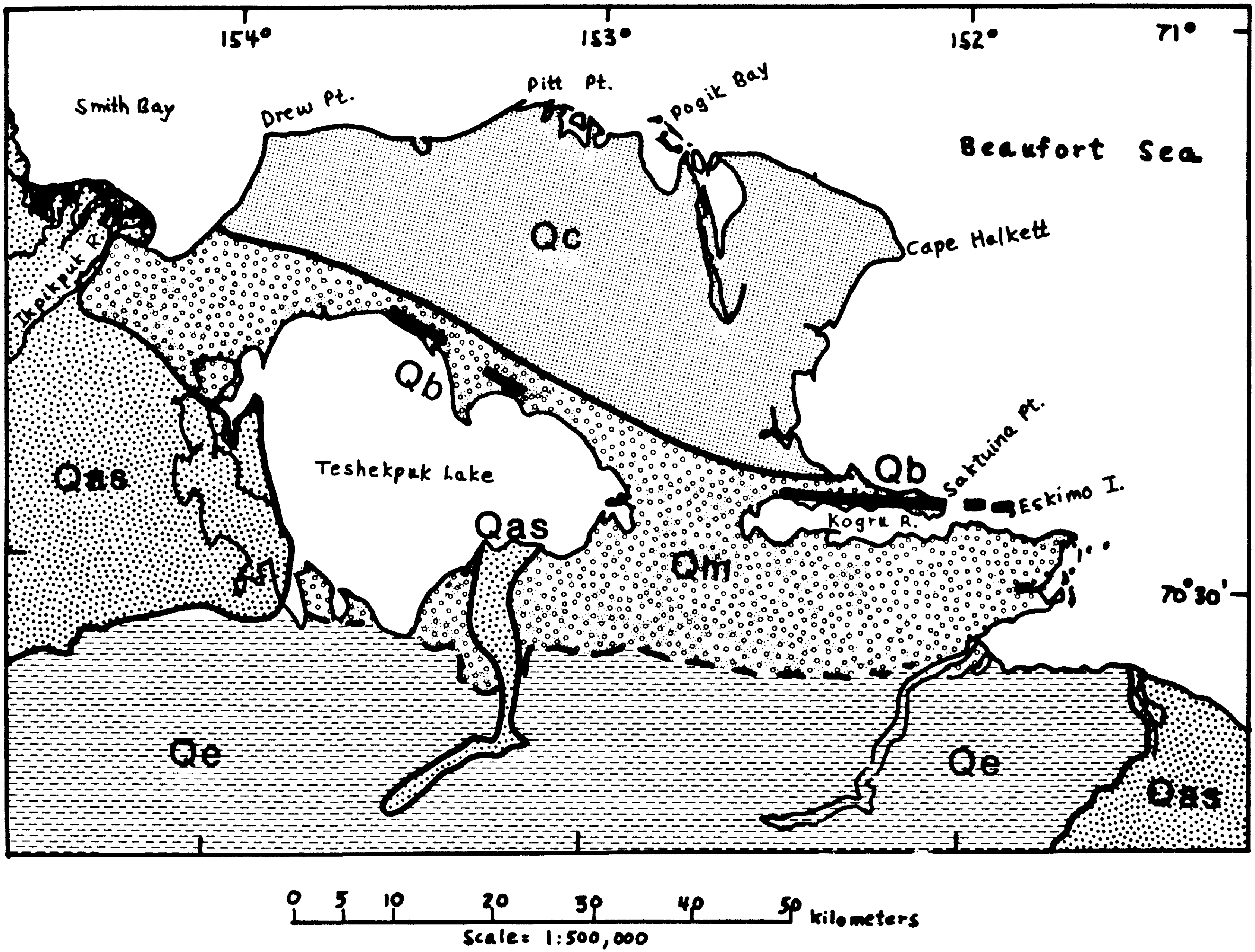


Figure 3. Geology of Arctic Coastal Plain, Barrow to Camden Bay (after Hopkins and Hartz, 1978).



157°
156°
155°
154°
Pt. Barrow
Elultkak Pass
Tapkaluk I.
Barrow
Elson Lagoon
Ekilukruak pass
Beaufort Sea
Cooper I.
Iko Bay
Qb
Qc
Dease Inlet
Cape Simpson DEW Line site
Qm
71°
Cape Simpson
Jnaru R.
Qas
Admiralty Bay
Smith Bay
Meade R.
Chipp R.
Pissuk R.
0 5 10 20 30 40 50 kilometers
Scale = 1:500,000

Figure 3A



154°
153°
152°
71°
70°30'
Smith Bay
Drew Pt.
Pitt Pt.
Pogik Bay
Beaufort Sea
Cape Halkett
Ikpikpuk R.
Teshekpuk Lake
Kogru R.
Saktuina Pt.
Eskimo I.
Qc
Qb
Qb
Qm
Qas
Qas
Qas
Qe
Qe
0 5 10 20 30 40 50 kilometers
Scale= 1:500,000

Figure 3B

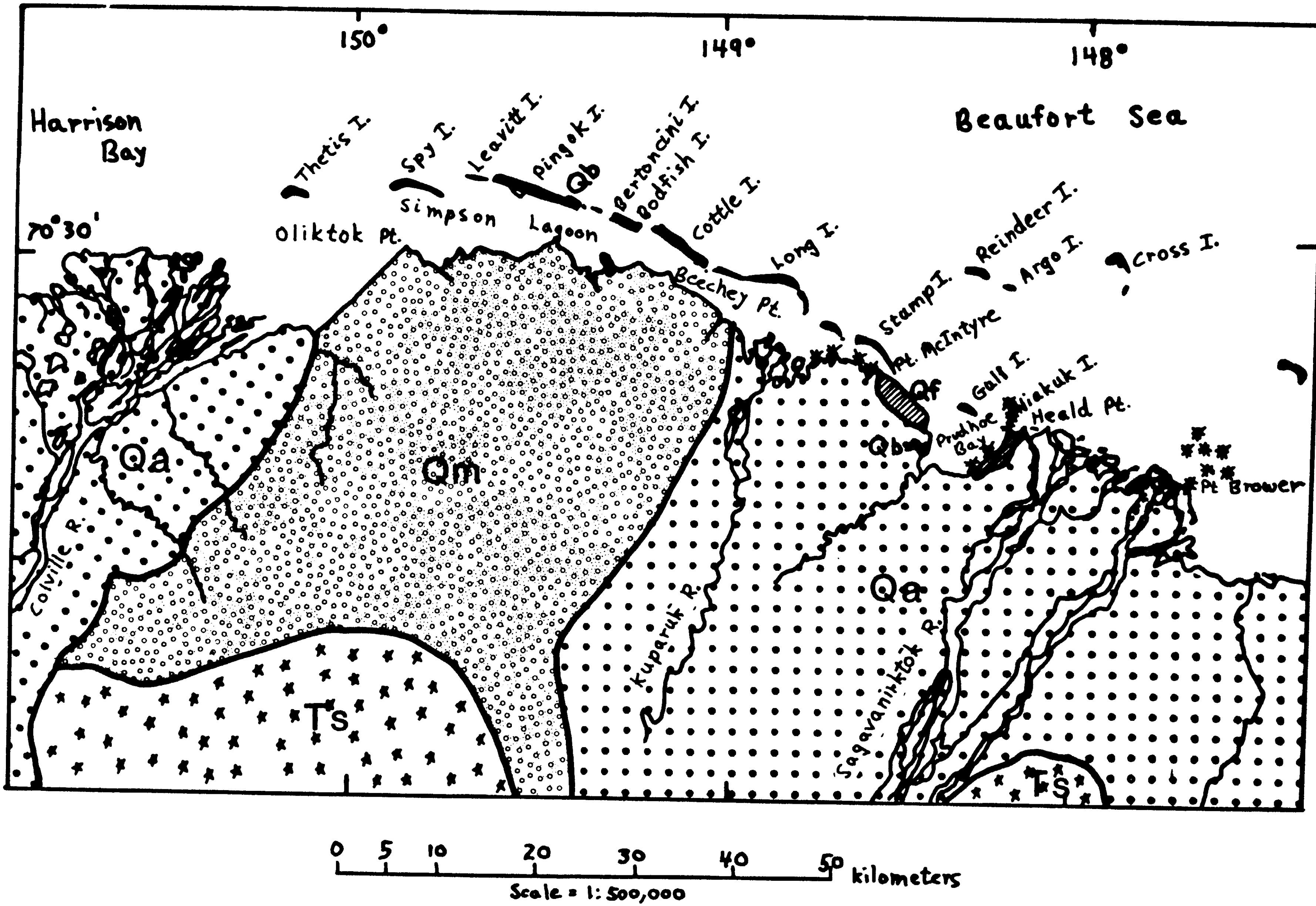

150°
149°
148°
Harrison Bay
Beaufort Sea
70°30'
Thetis I.
Spy I.
Leavitt I.
Pingok I.
Qb
Bertoncini I.
Bodfish I.
Cottle I.
Long I.
Reindeer I.
Argo I.
Cross I.
Stamp I.
Pt. McIntyre
Gull I.
Niakuk I.
Heald Pt.
Qf
Qb
Prudhoe Bay
Pt Brower
Simpson Lagoon
Oliktok Pt.
Beechey Pt.
Qa
Qm
Qa
Ts
Ts
Colville R.
Kuparuk R.
Sagavanirktok R.
0 5 10 20 30 40 50 kilometers
Scale = 1: 500,000

Figure 3C

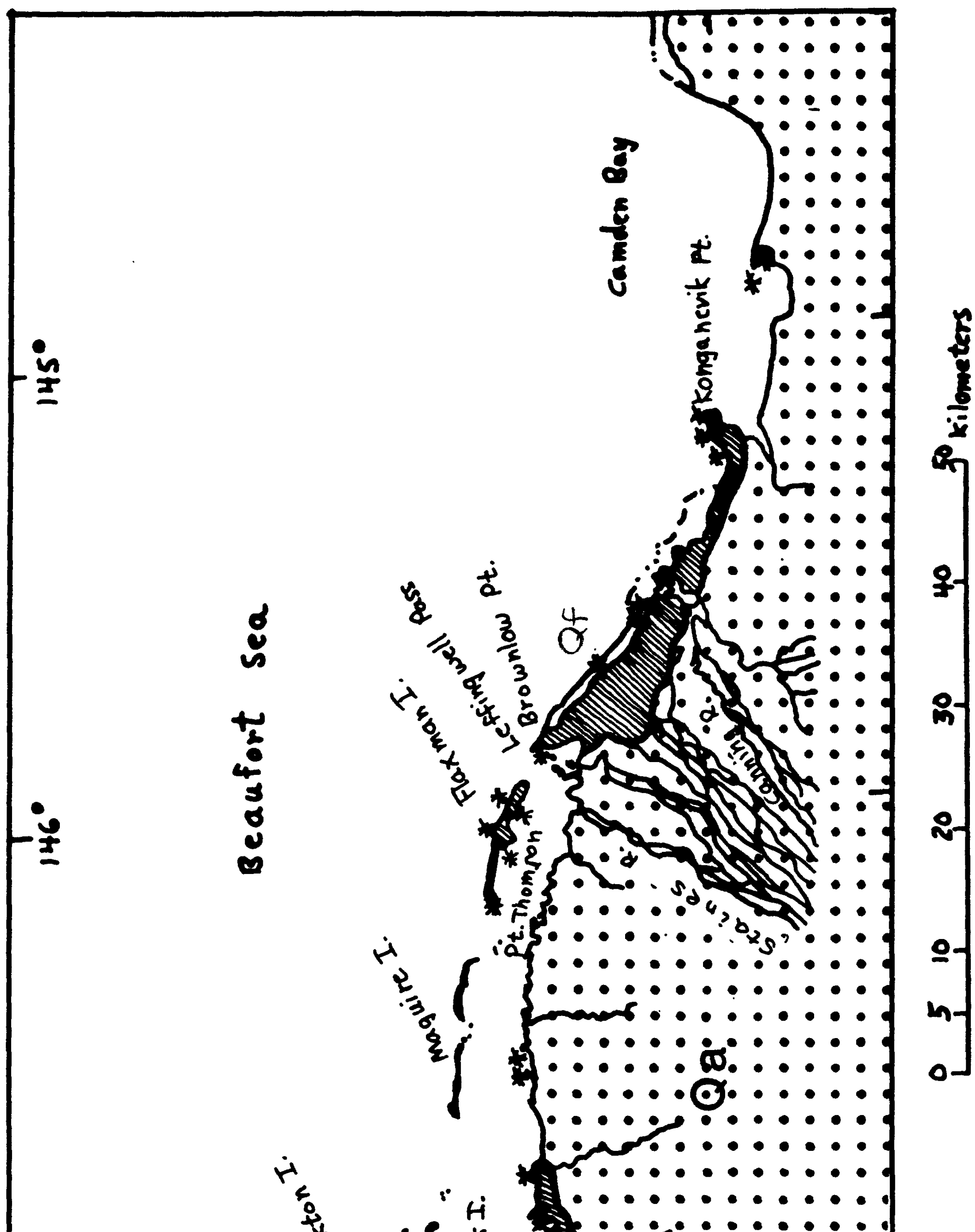

Beaufort Sea
Camden Bay
Konganevik Pt.
Flaxman I.
Leffingwell Pass
Brownlow Pt.
Pt. Thompson
Maguire I.
Stockton I.
Tigvariak I.
Karluk I.
Jeanette I.
Narwhal I.
Qf
Qf
Qa
Canning R.
Staines R.
145°
146°
147°
70°30'
70°
0 5 10 20 30 40 50 Kilometers
Scale = 1:500,000

Figure 3D

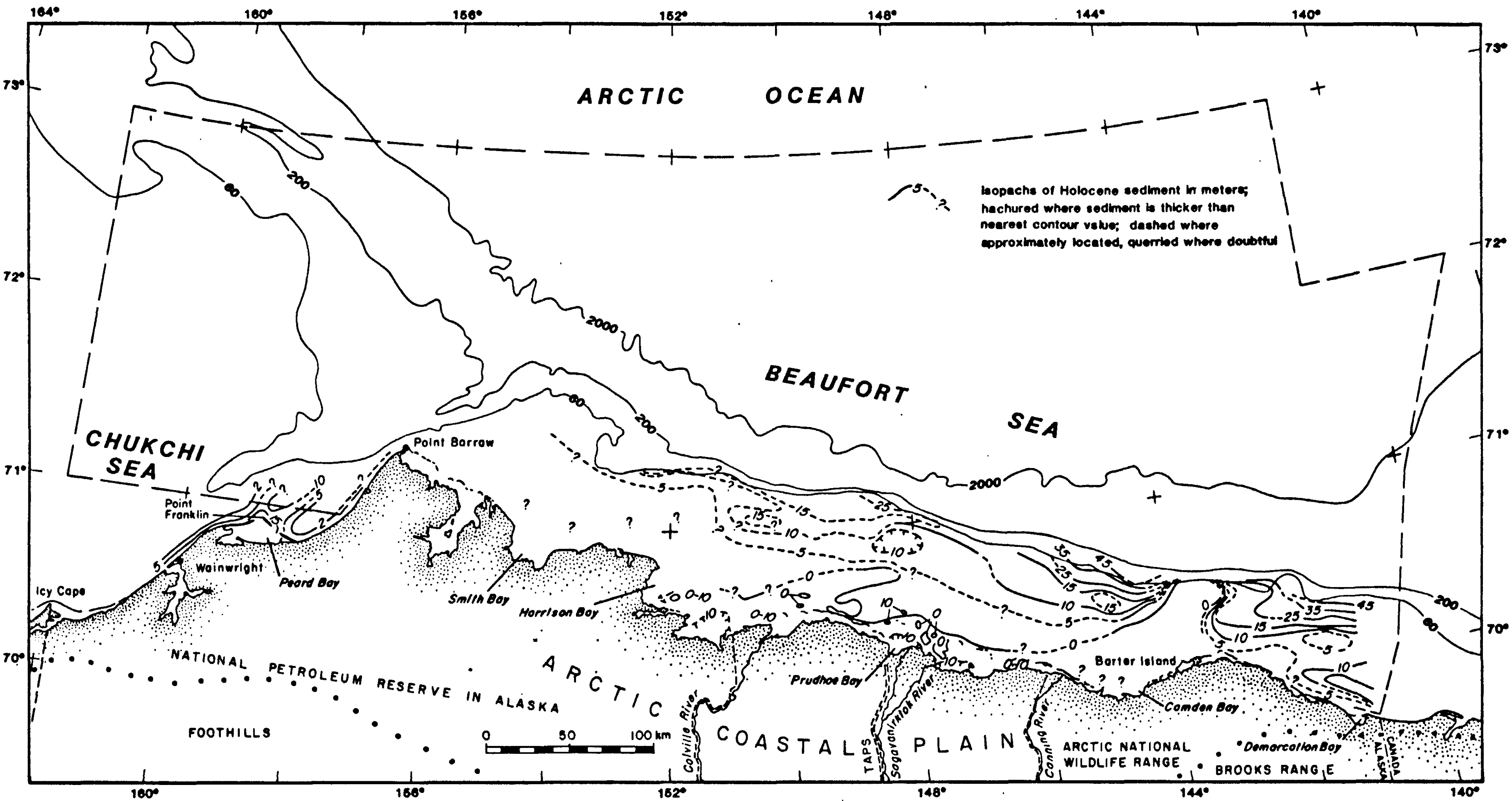


Figure 4a. Holocene marine sediment thickness on the Alaskan Beaufort and northeast Chukchi shelves. (from Grantz and others, 1982).

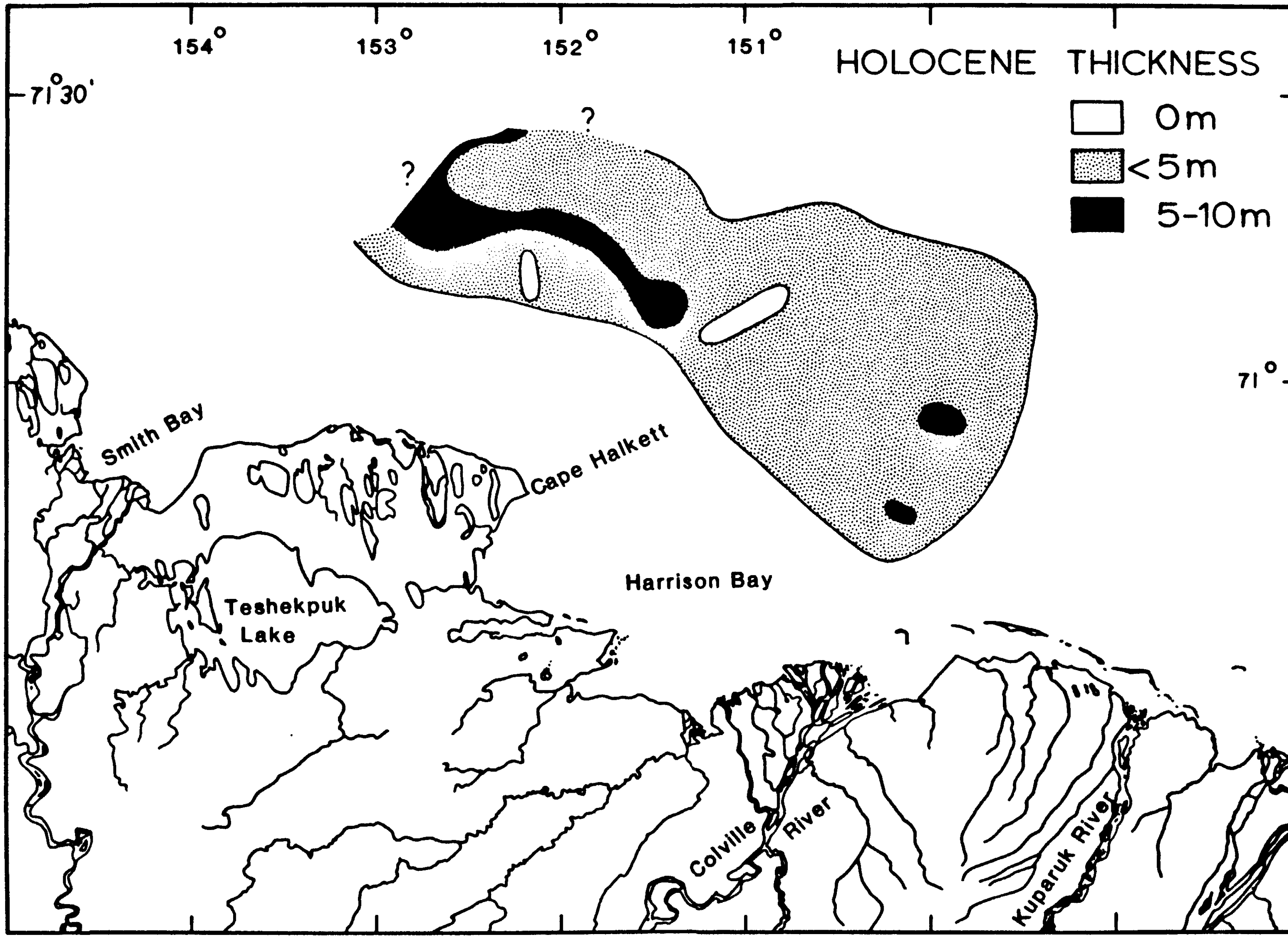


Figure 4b (from unpublished data of Reimnitz and Rodeick)

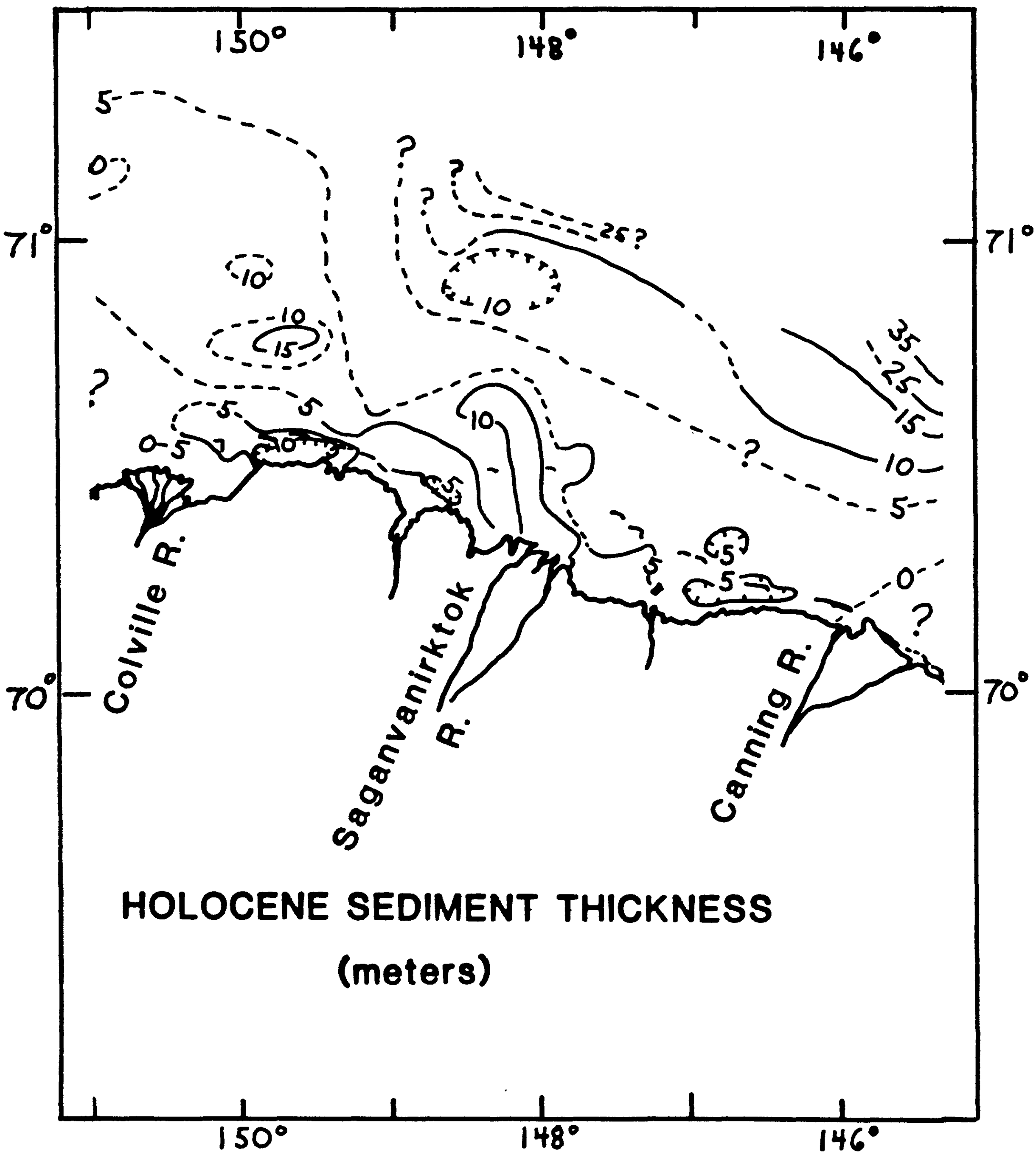


Figure 4c (based on Reimnitz et al., 1972, Hartz et al., 1979, Boucher et al., 1981)

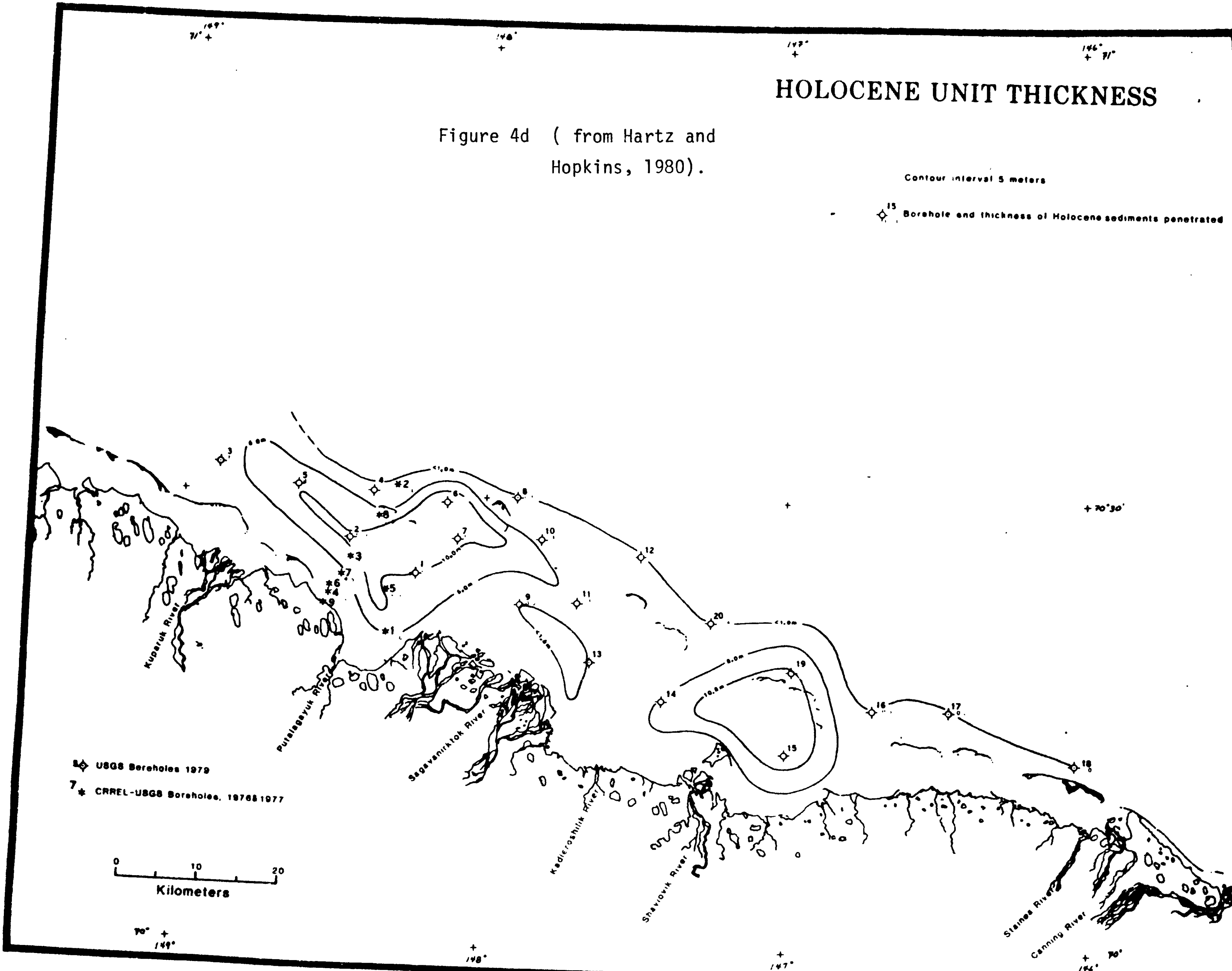


Figure 4d (from Hartz and Hopkins, 1980).

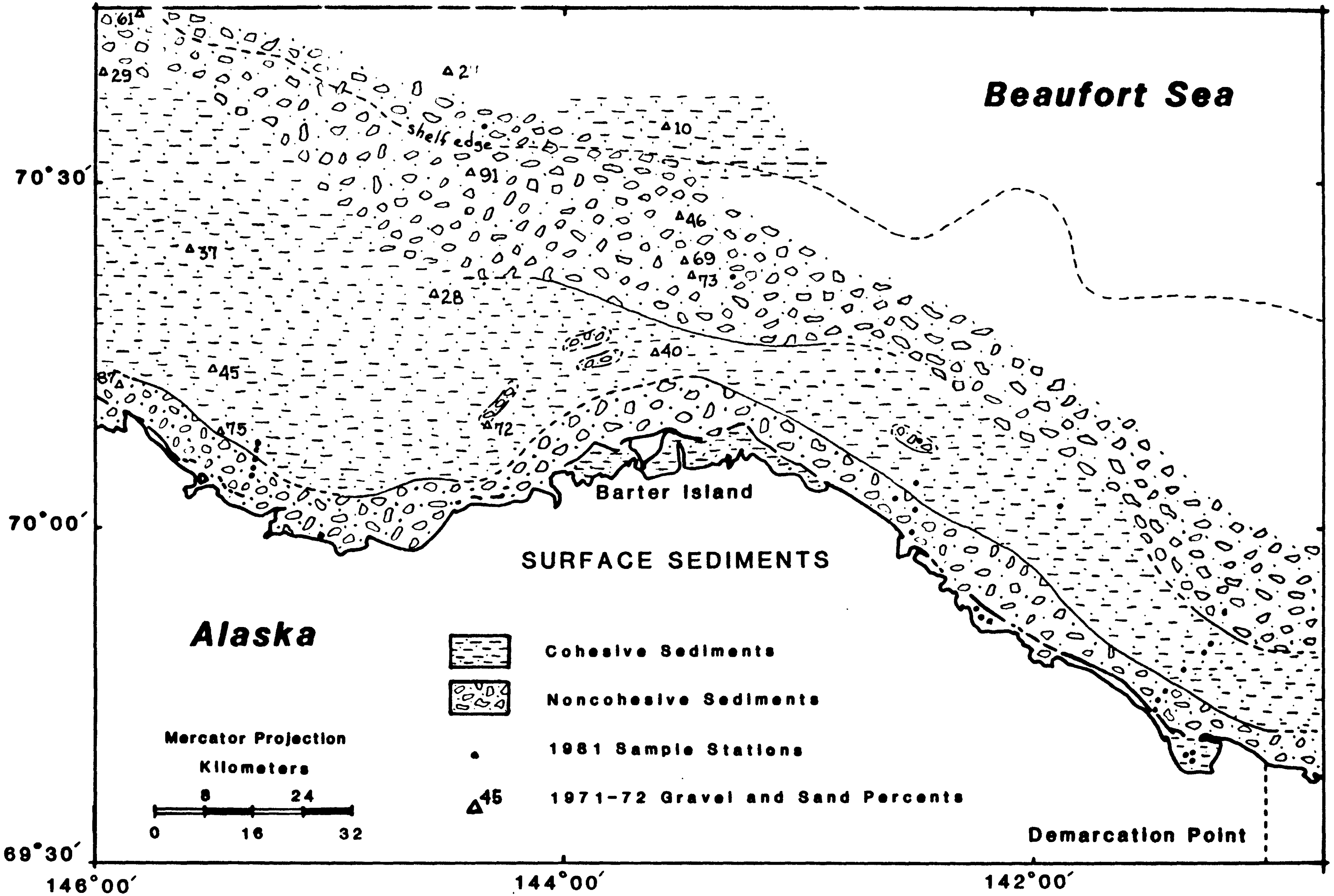


Figure 5.- Map of surface sediment textures, as interpreted from geophysical records and sediment samples. Percentages of combined sand and gravel are next to the old sample stations of Barnes (1974).
(from Reimnitz and others, 1982).

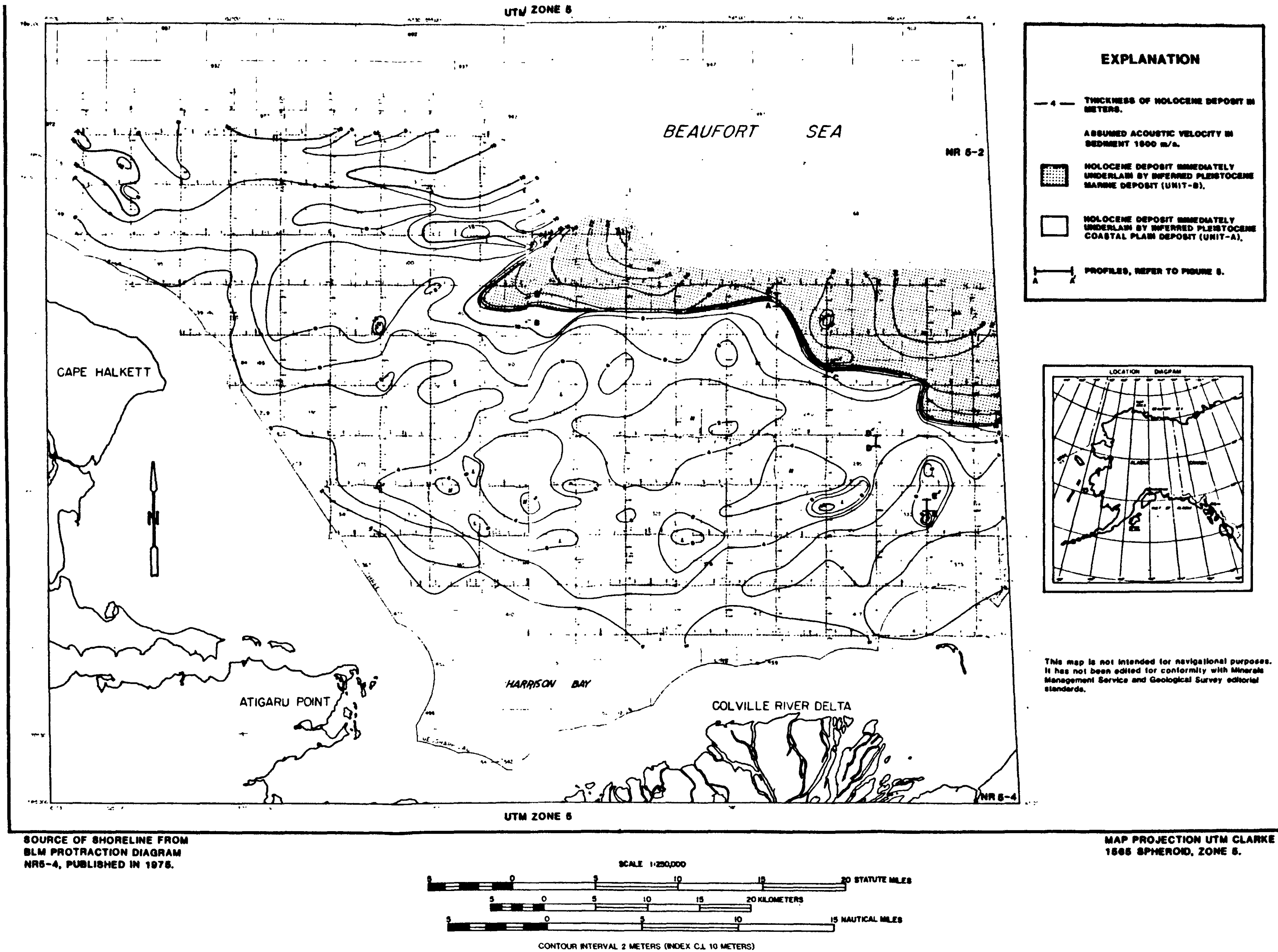


Figure 6. Map of Harrison Bay showing areas underlain by inferred Pleistocene marine and non-marine sections (from Craig and Thrasher, 1982).

Cross Section of Prudhoe Bay based on Boreholes

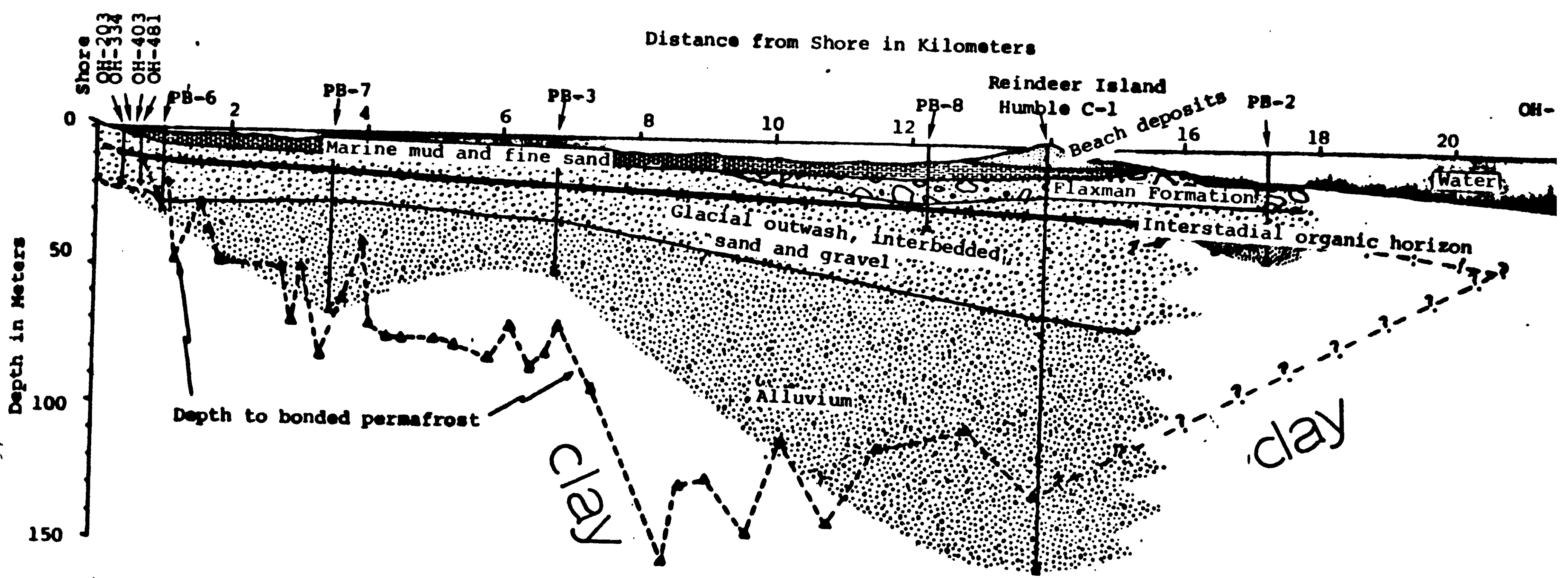


Figure 7. (from Hopkins, 1979)

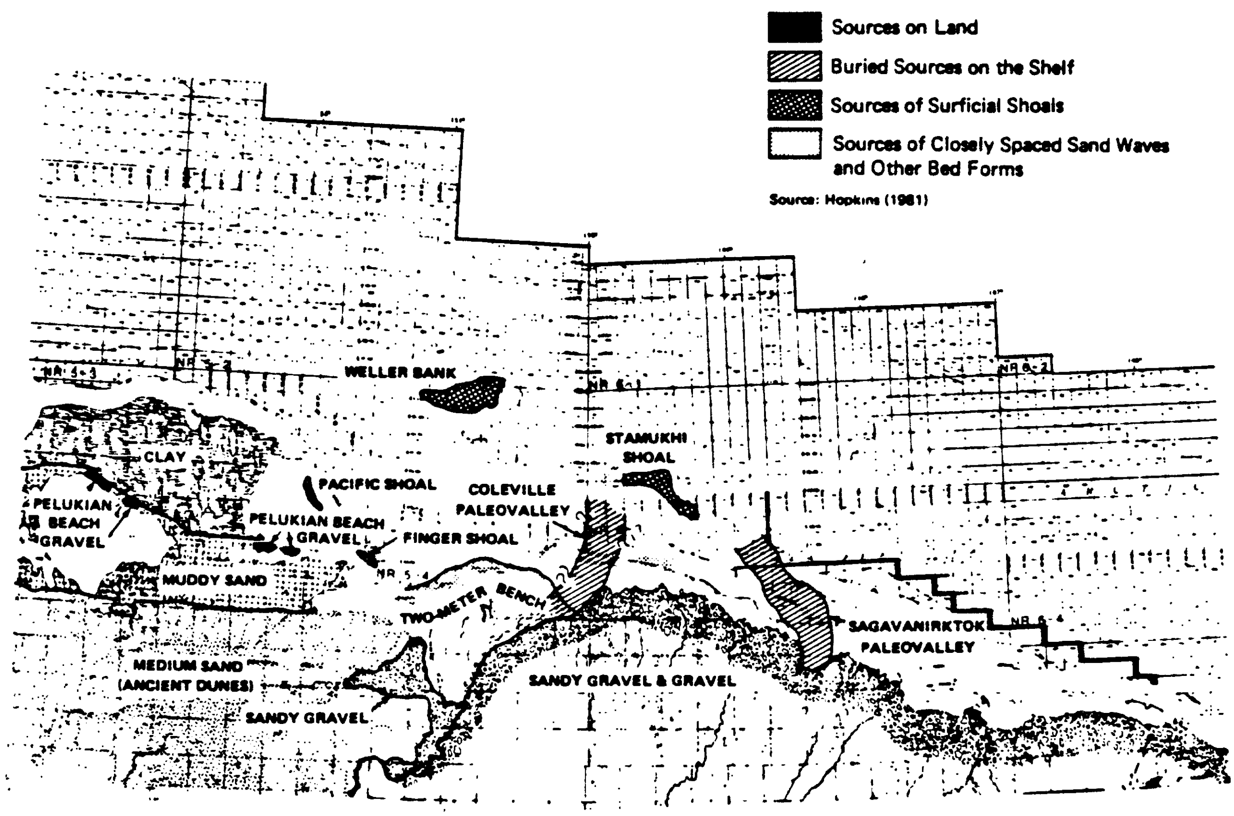


Figure 8. Sources of fill in and near Sale 71 area (from Norton and Sackinger, 1981).

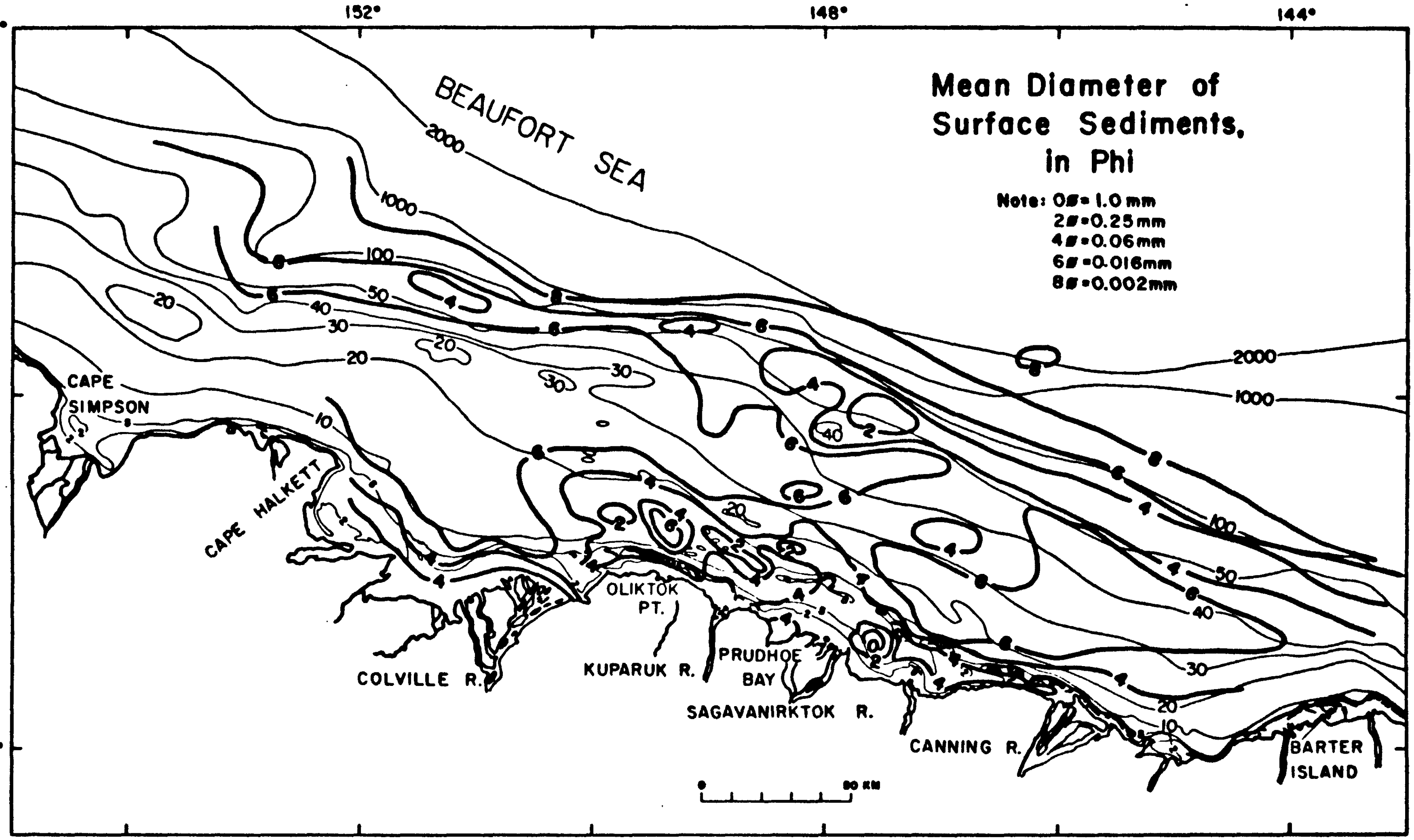


Figure 9. Mean diameter of surface sediments from Cape Simpson to Barter Island (from Barnes, 1974).

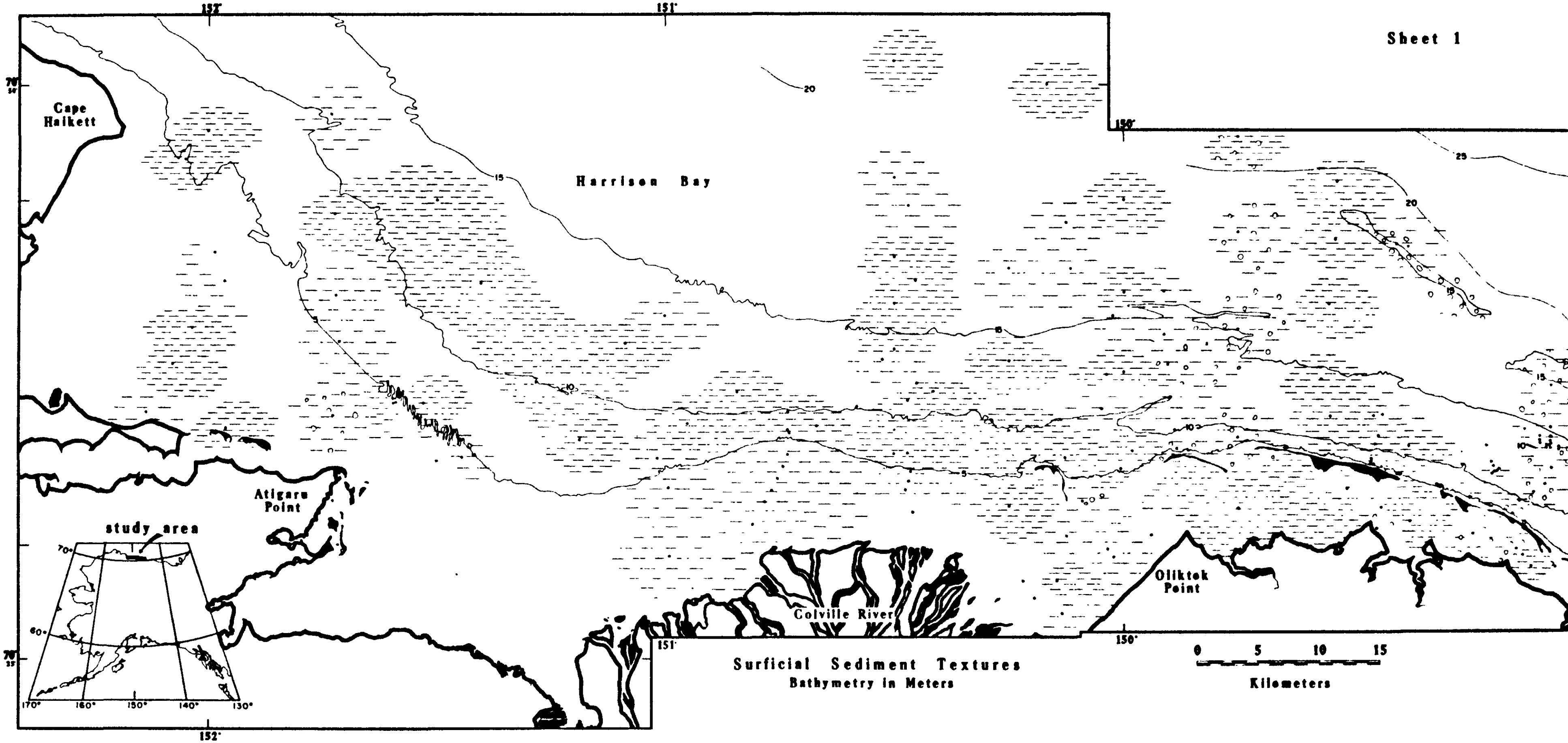


Figure 10, sheet 1. Surface sediment texture,
Cape Halkett to Brownlow Point
(from Barnes et al., 1980).

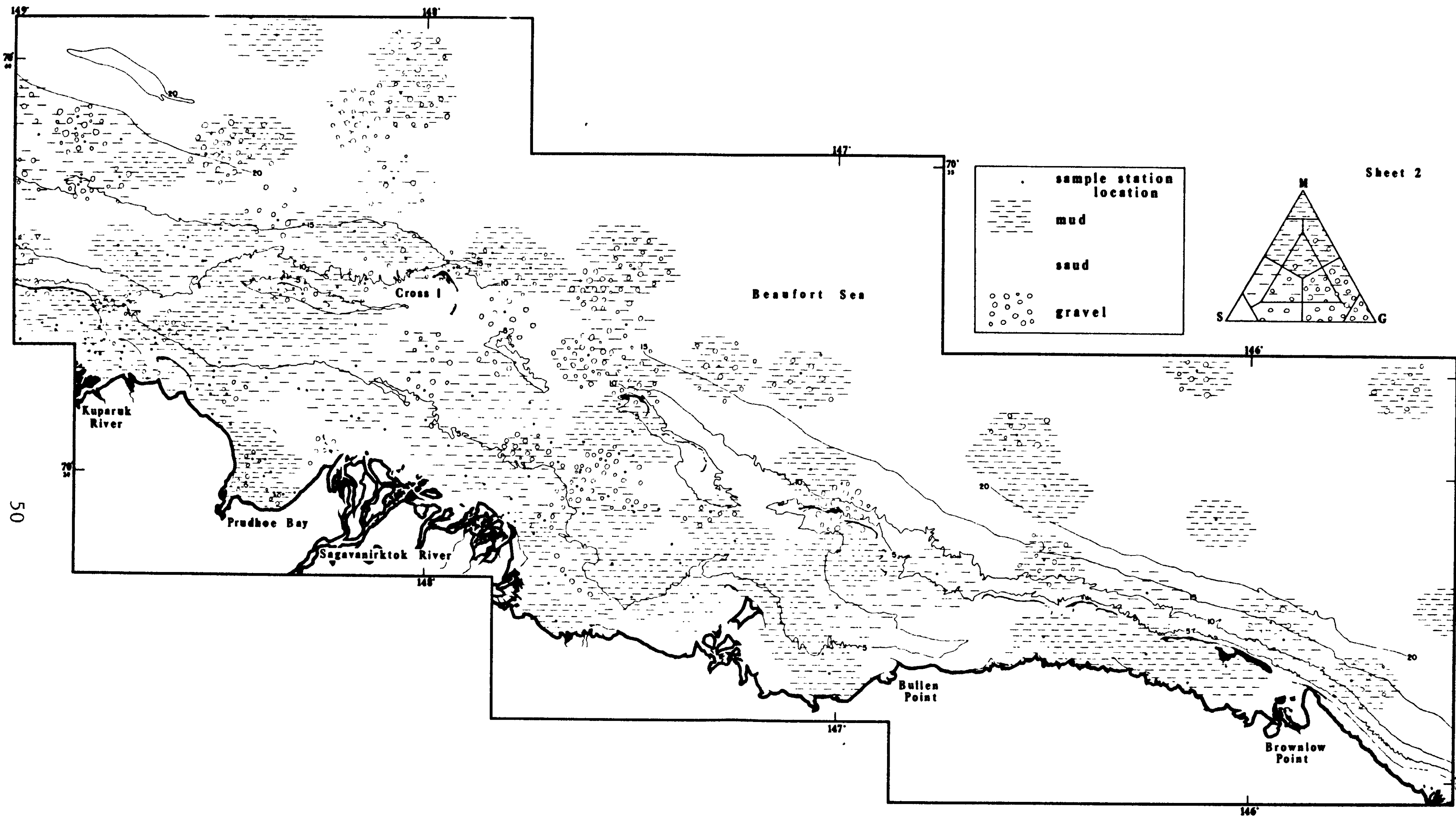


Figure 10, sheet 2 (from Barnes et al., 1980).

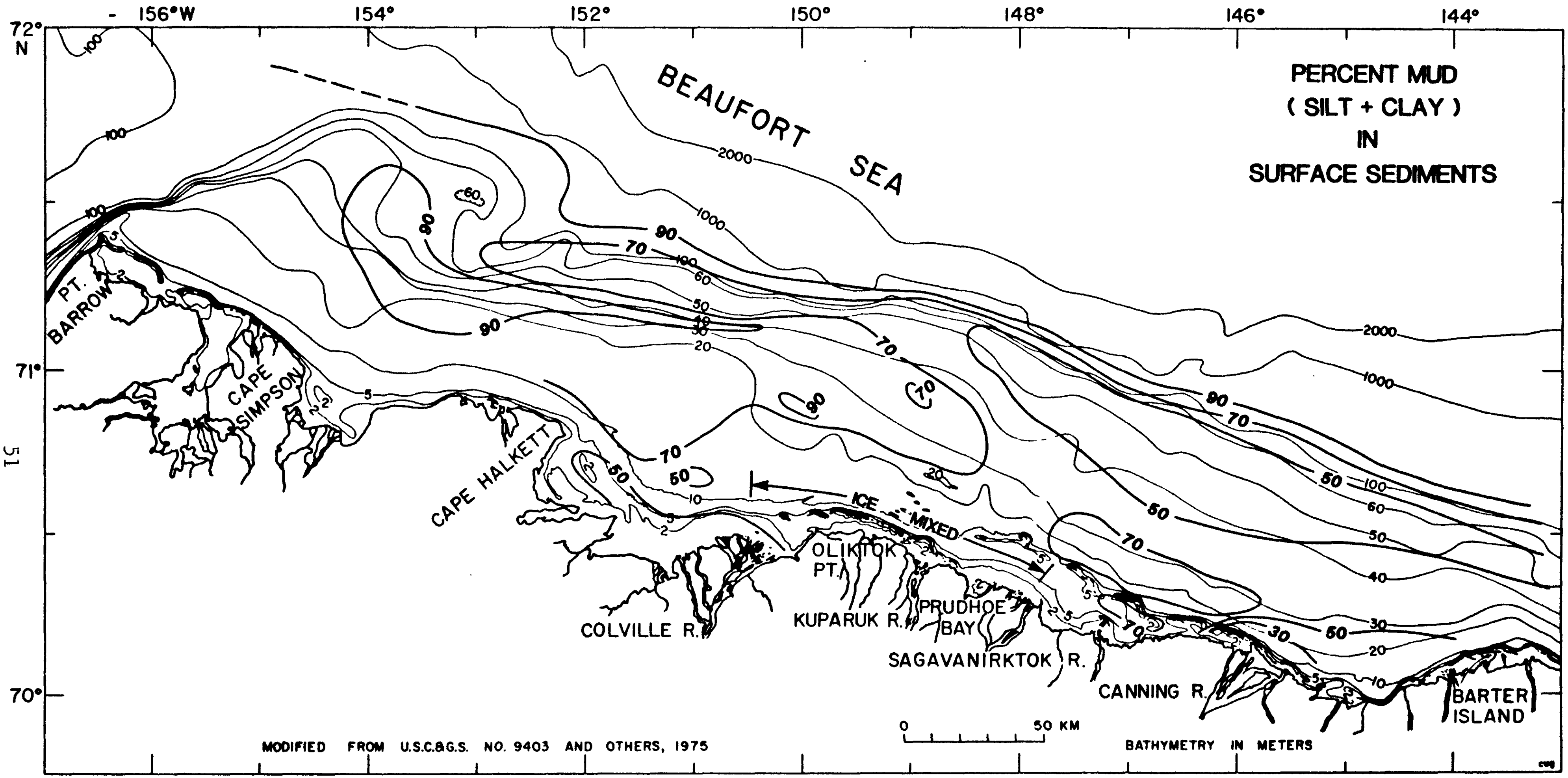


Figure 11 . Percent mud (mean diameter less than 0.0625 mm) in surface sediments. (from unpublished work of P. Barnes).

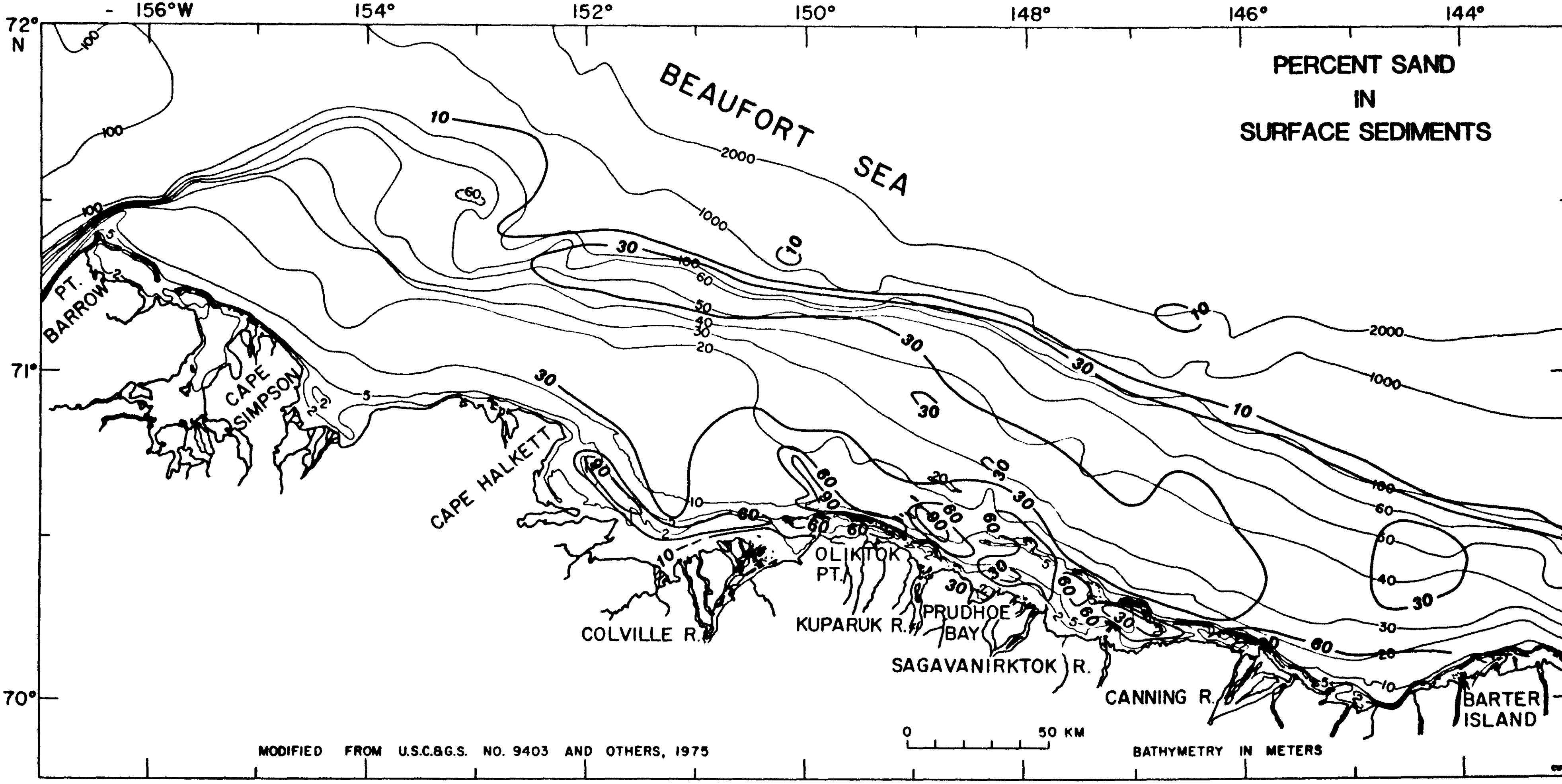


Figure 12 . Percent sand (0.0625 - 2 mm) in surface sediments (from unpublished work of P. Barnes).

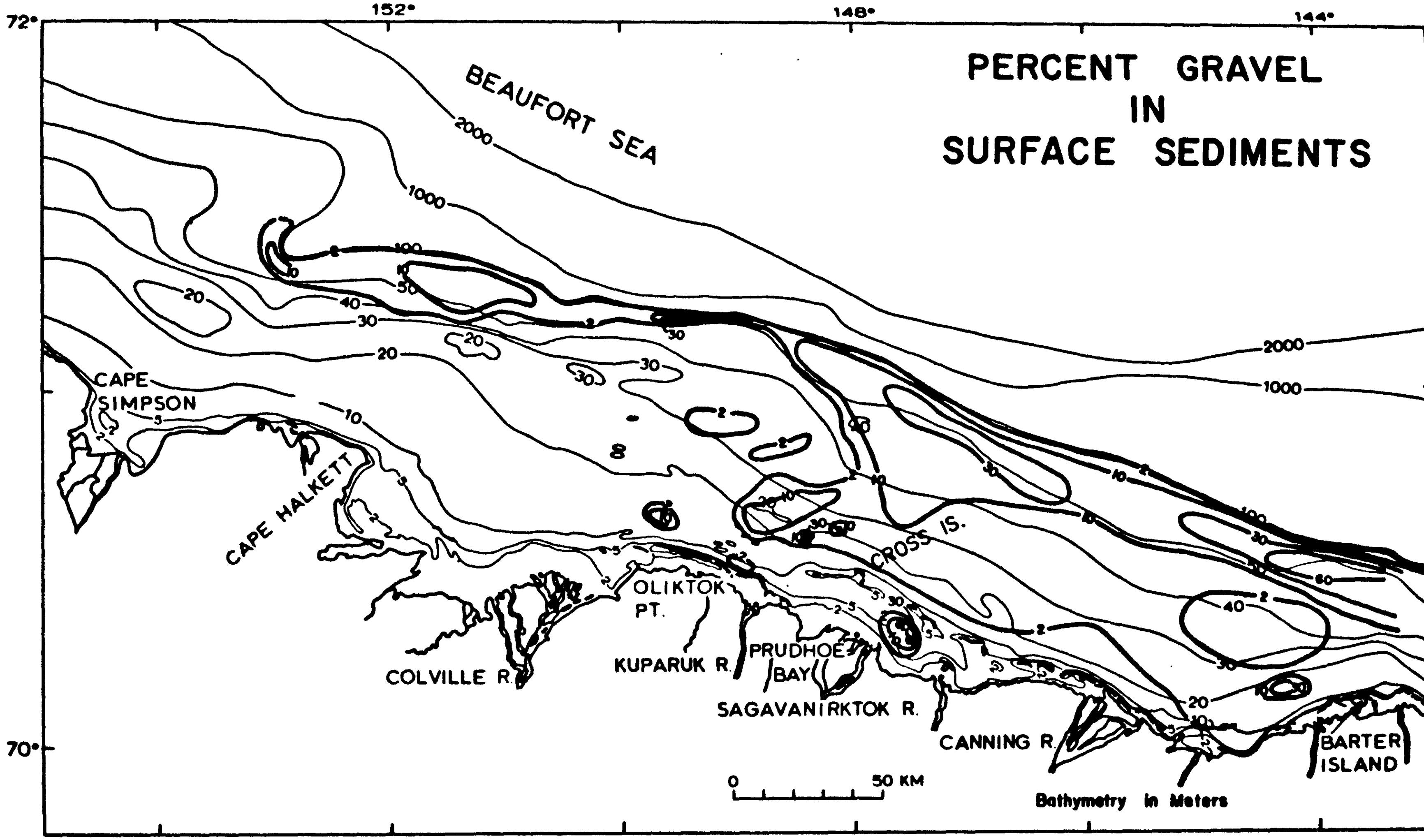


Figure 13 . Percent gravel (greater than 2 mm) in surface sediments (from Barnes, 1974).

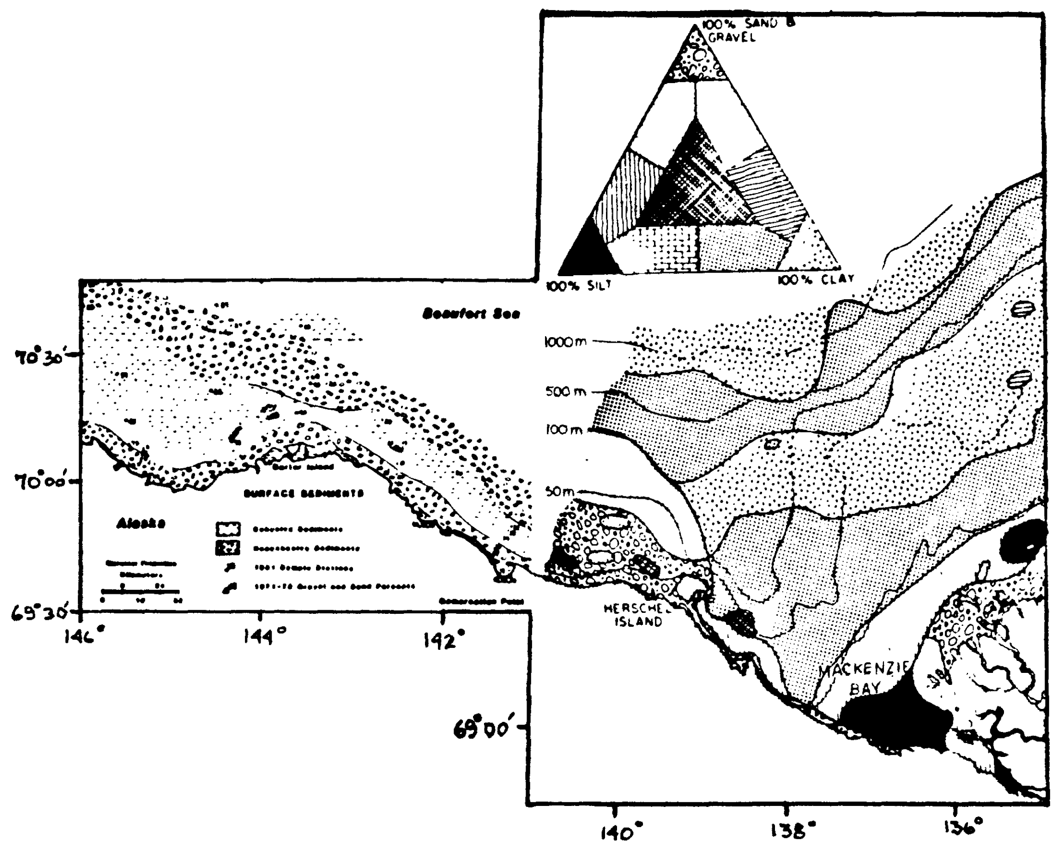


Figure 14. Surficial sediment texture from the Canning River to the Canadian border (from Reimnitz and others, 1982).

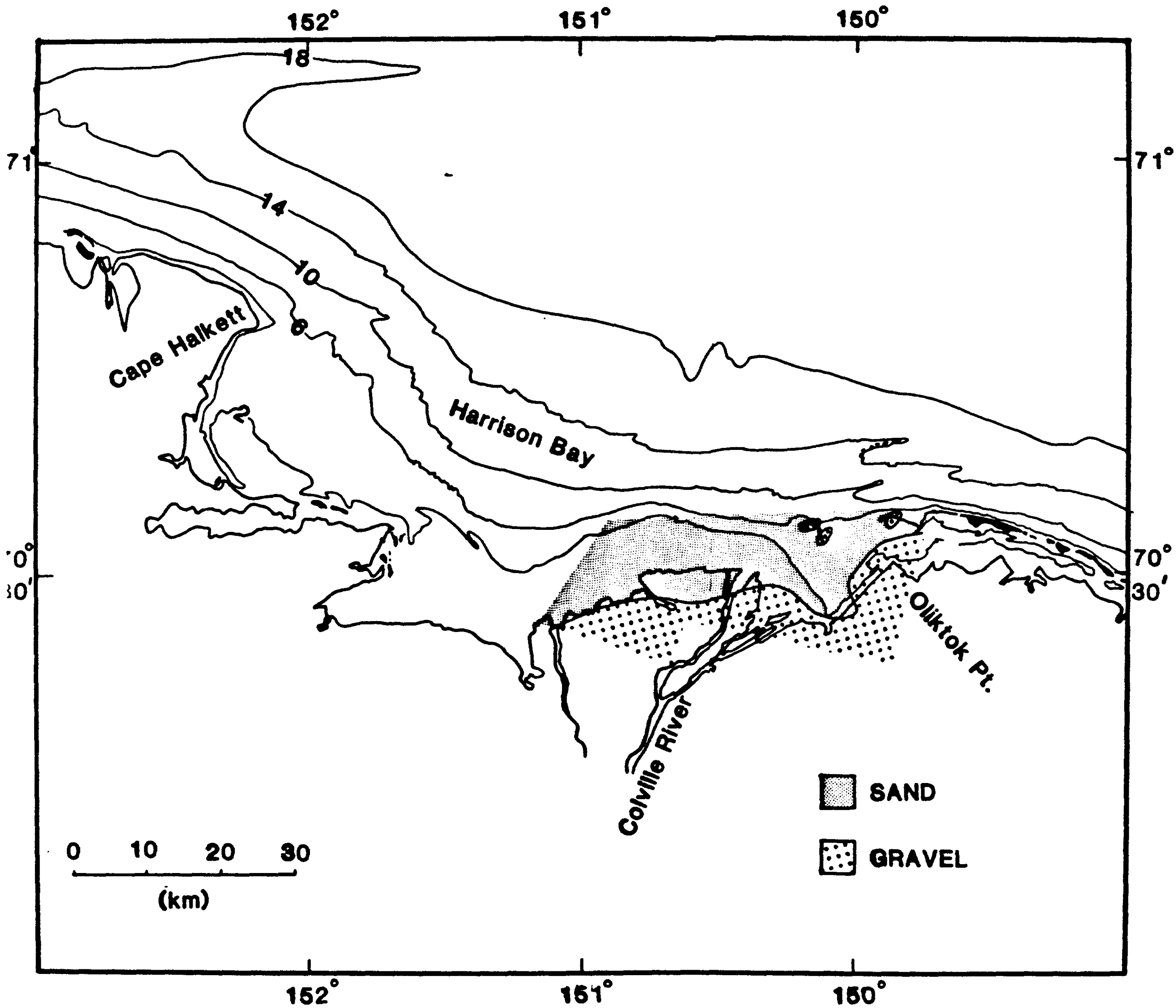


Figure 15. Subsurface sediment type (to depths of a few tens of meters) based on industry shot-hole driller logs made available to E. Reimnitz.

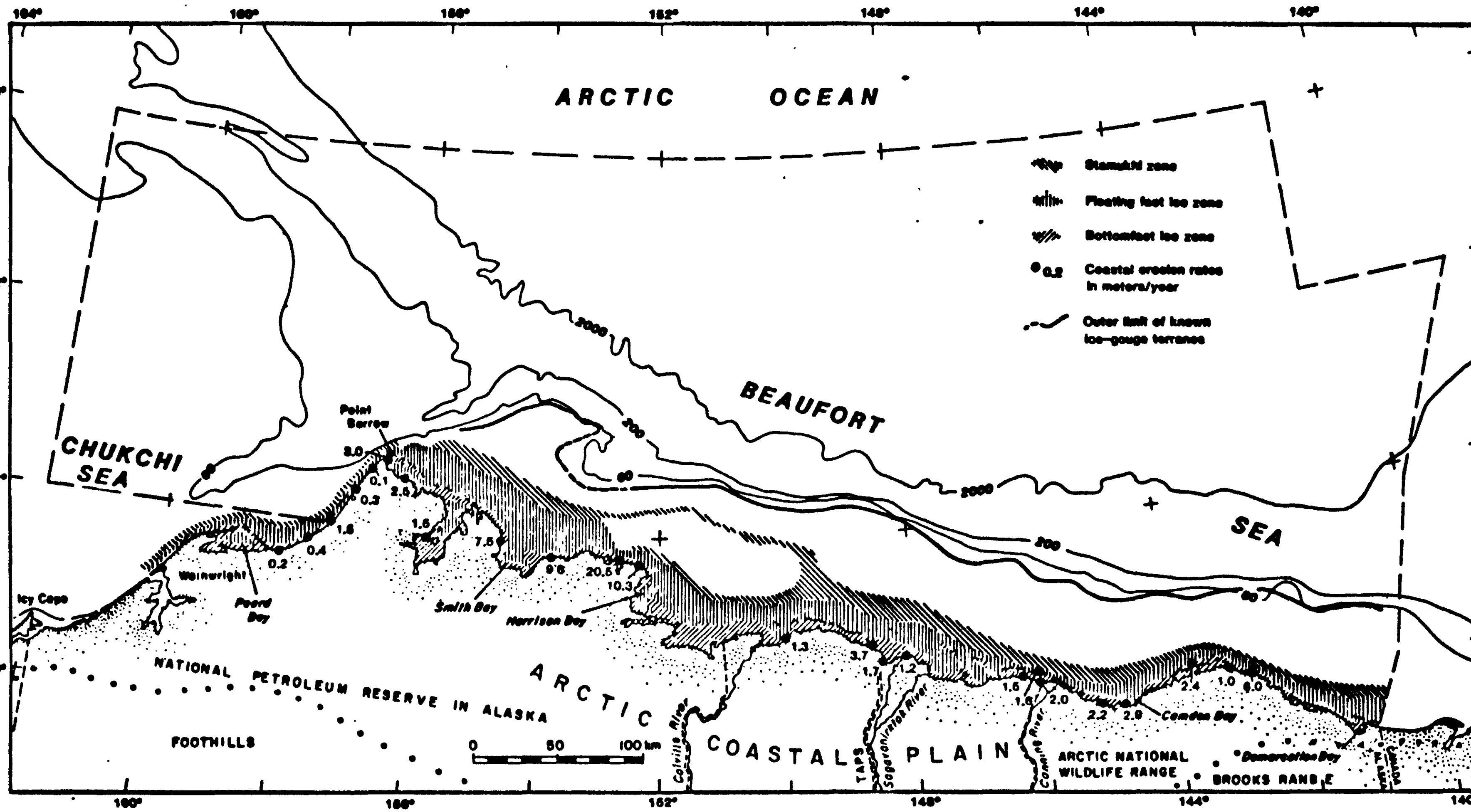


Figure 16. Ice zonation, Beaufort Sea shelf (from Grantz and others, 1982).

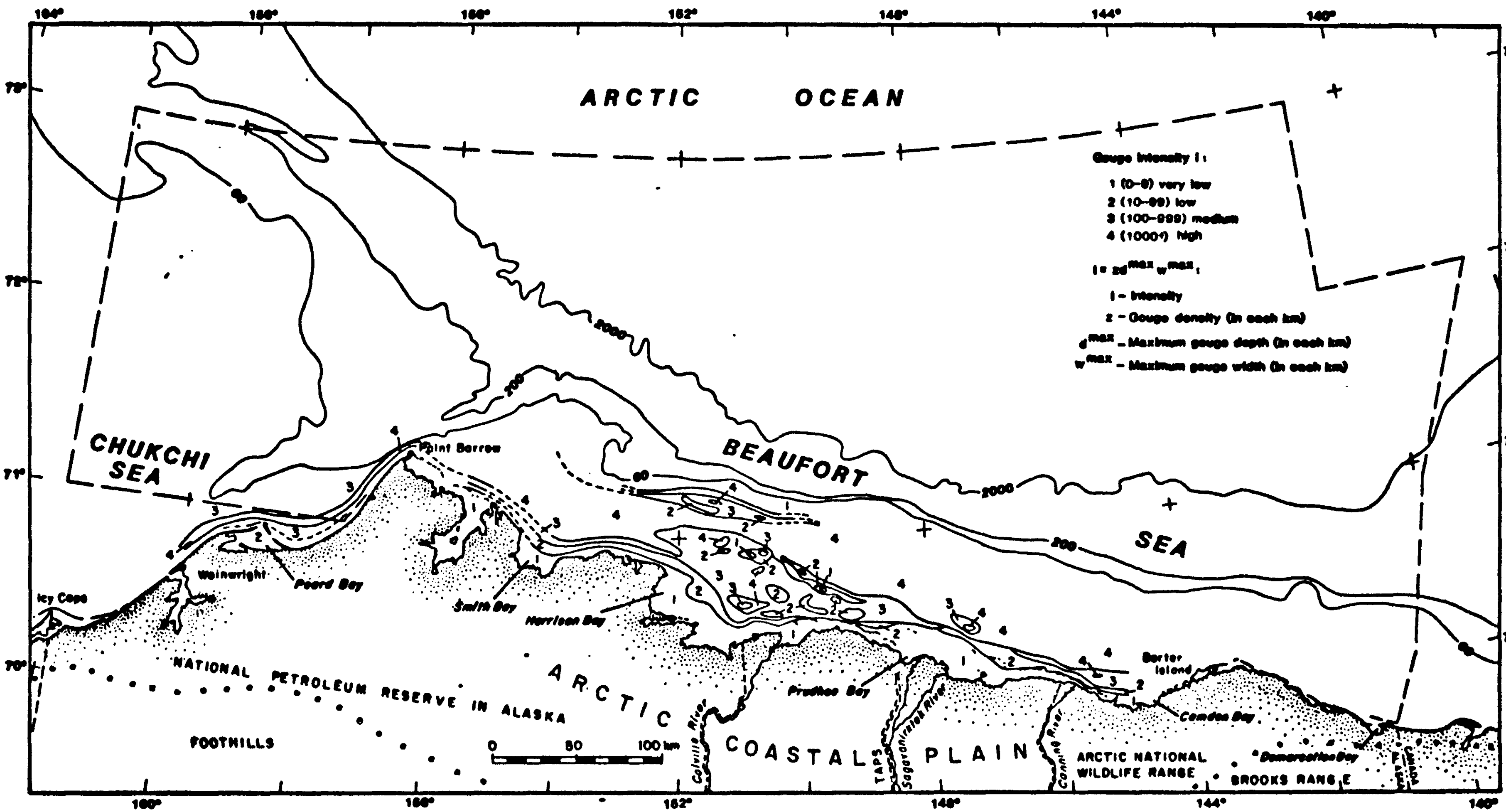


Figure 17. Contours of ice-scour intensity
(from Grantz and others, 1982).

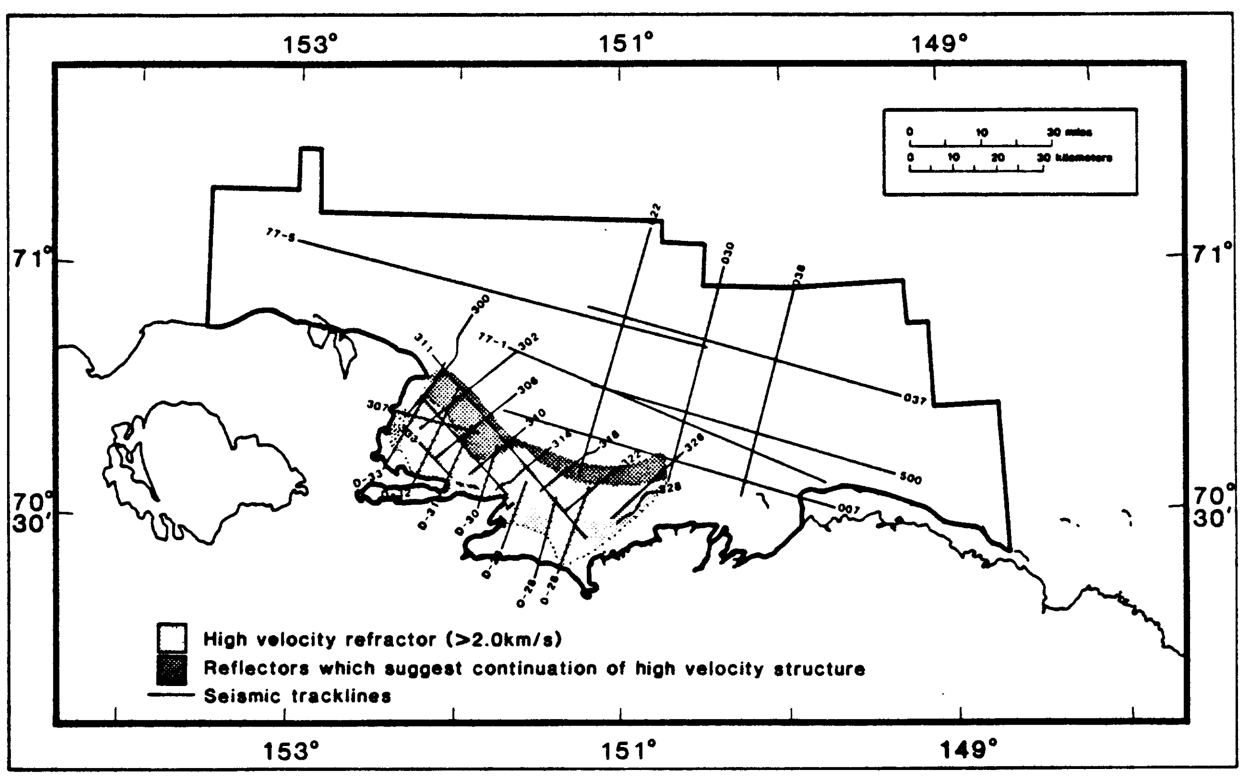


Figure 18. Preliminary map showing known distributions of high-velocity material, from study of industry seismic records (Sellmann et al., 1981), (from Norton and Sackinger, 1981).

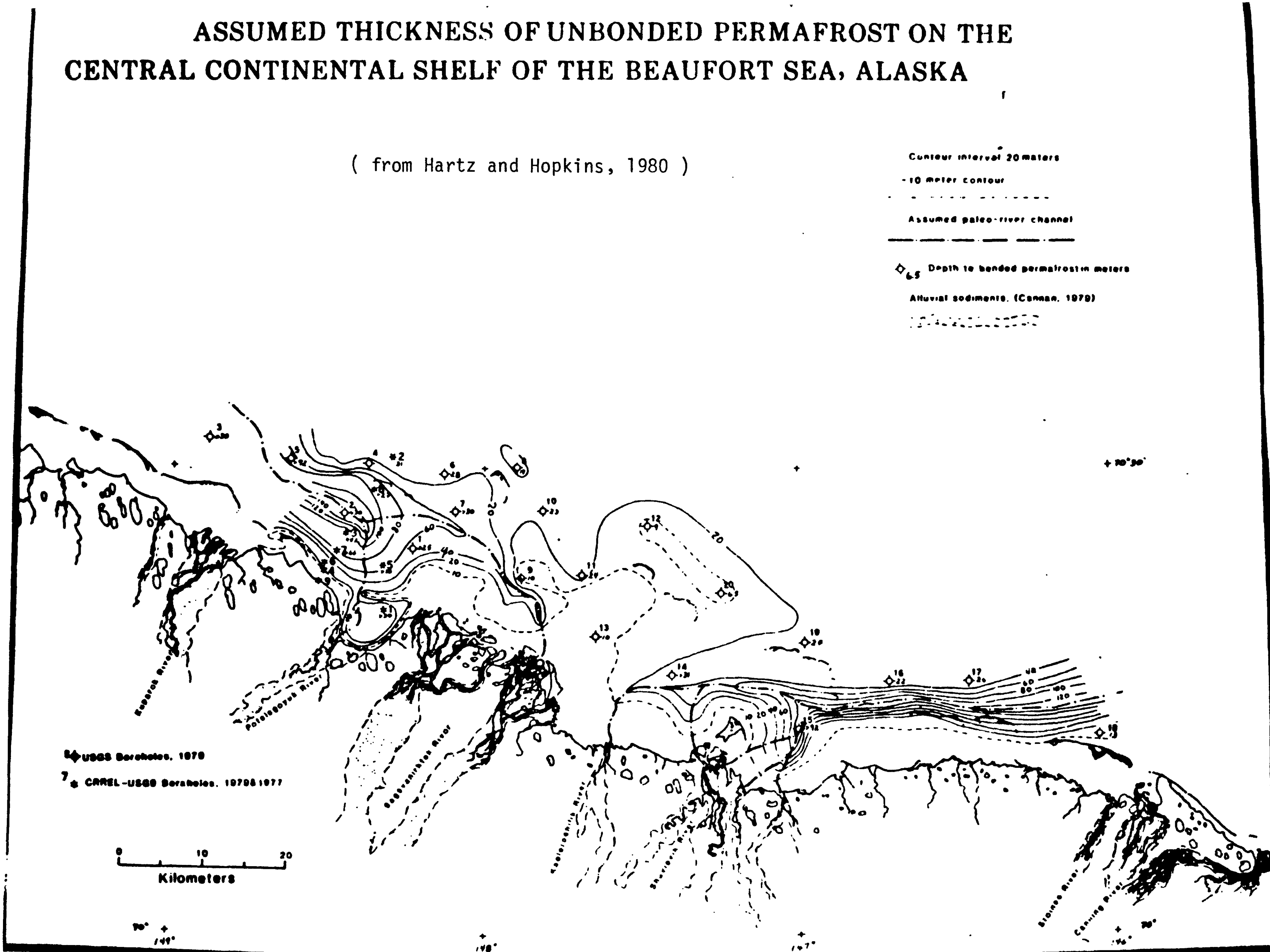


Figure 19. Assumed thickness of unbonded permafrost.

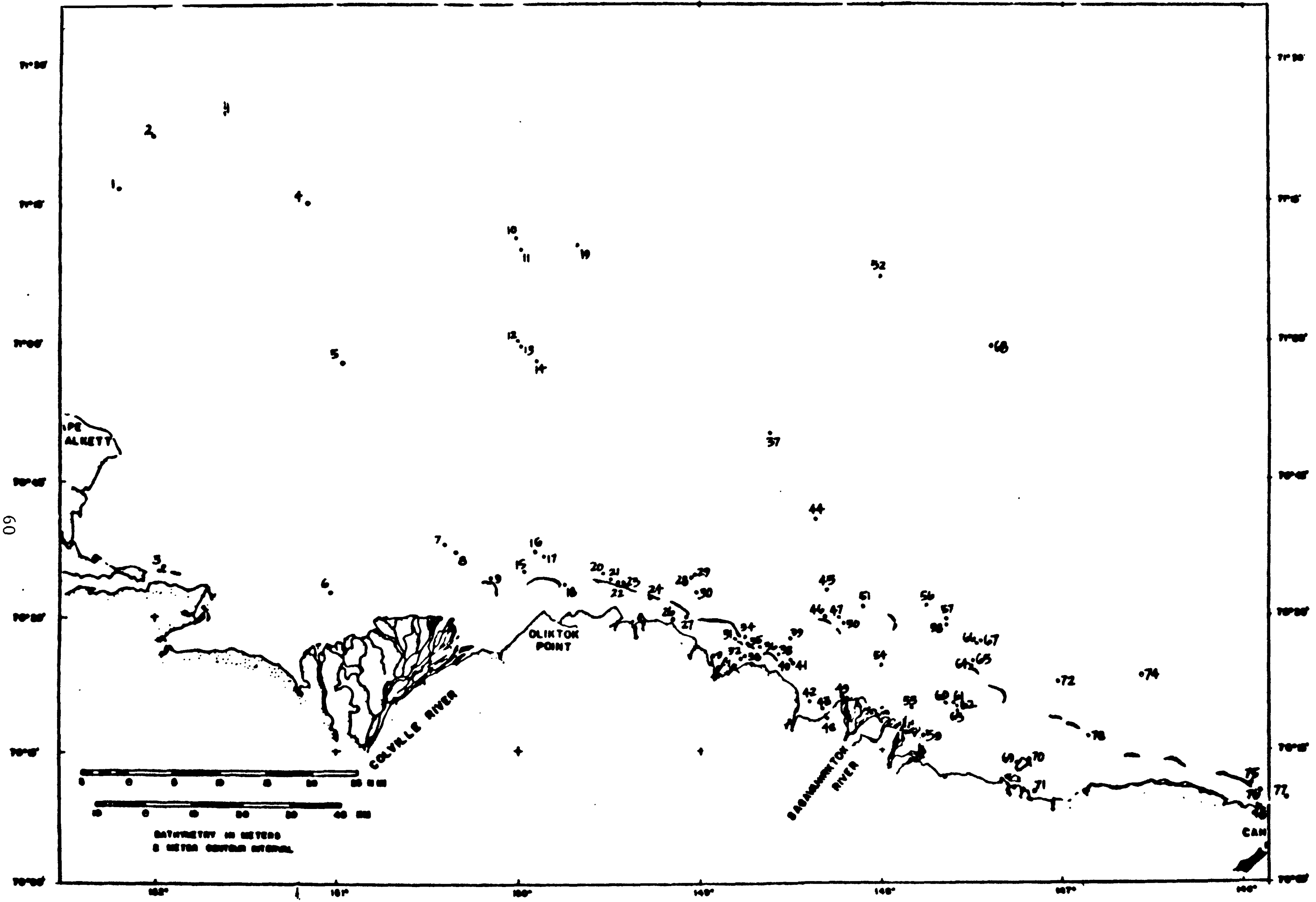


Figure 20 . Known locations of overconsolidated clay (from Reimnitz and others, 1980).

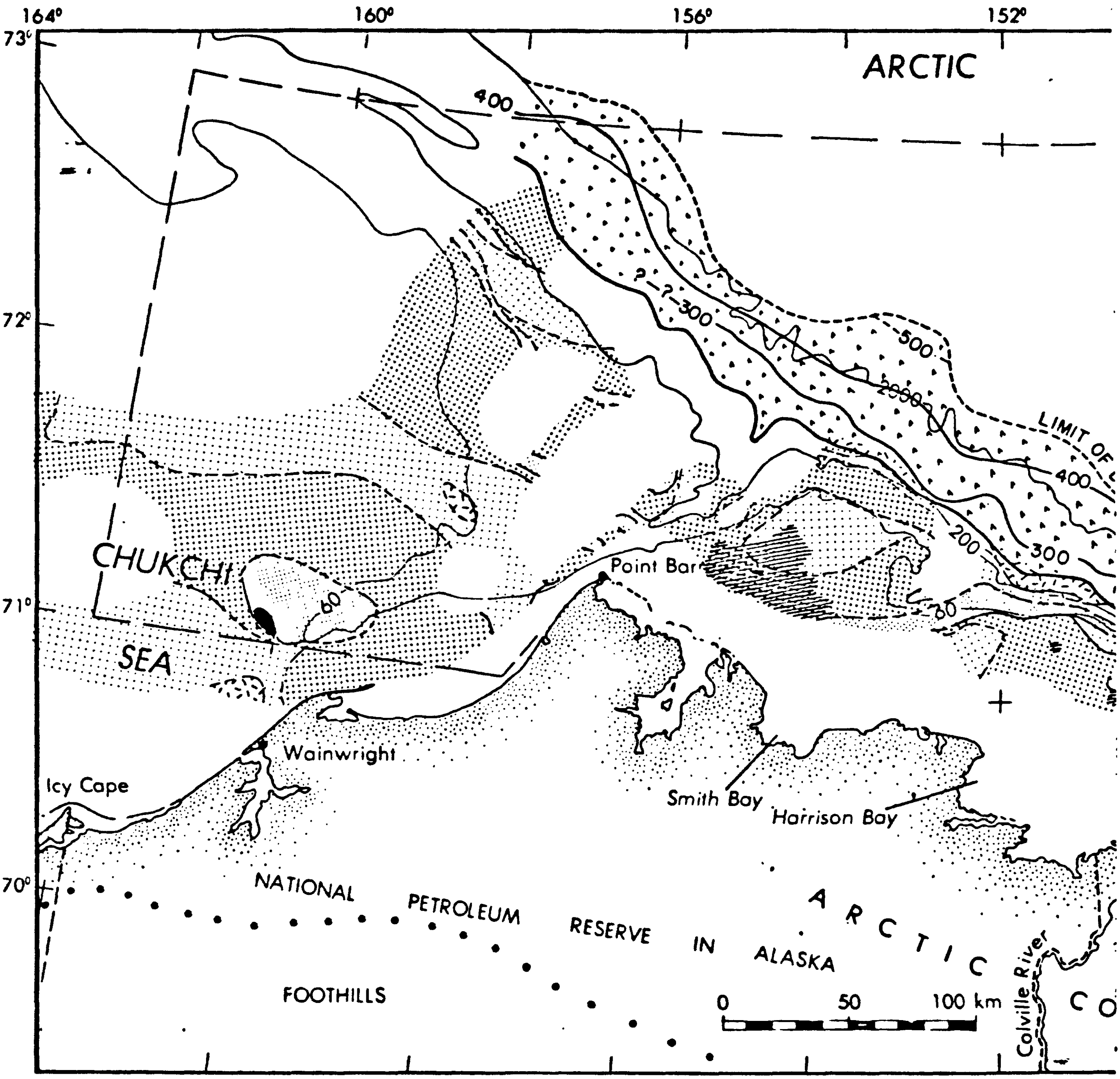


Figure 21, sheet 1. Areas of shallow gas (from Grantz and others, 1982).

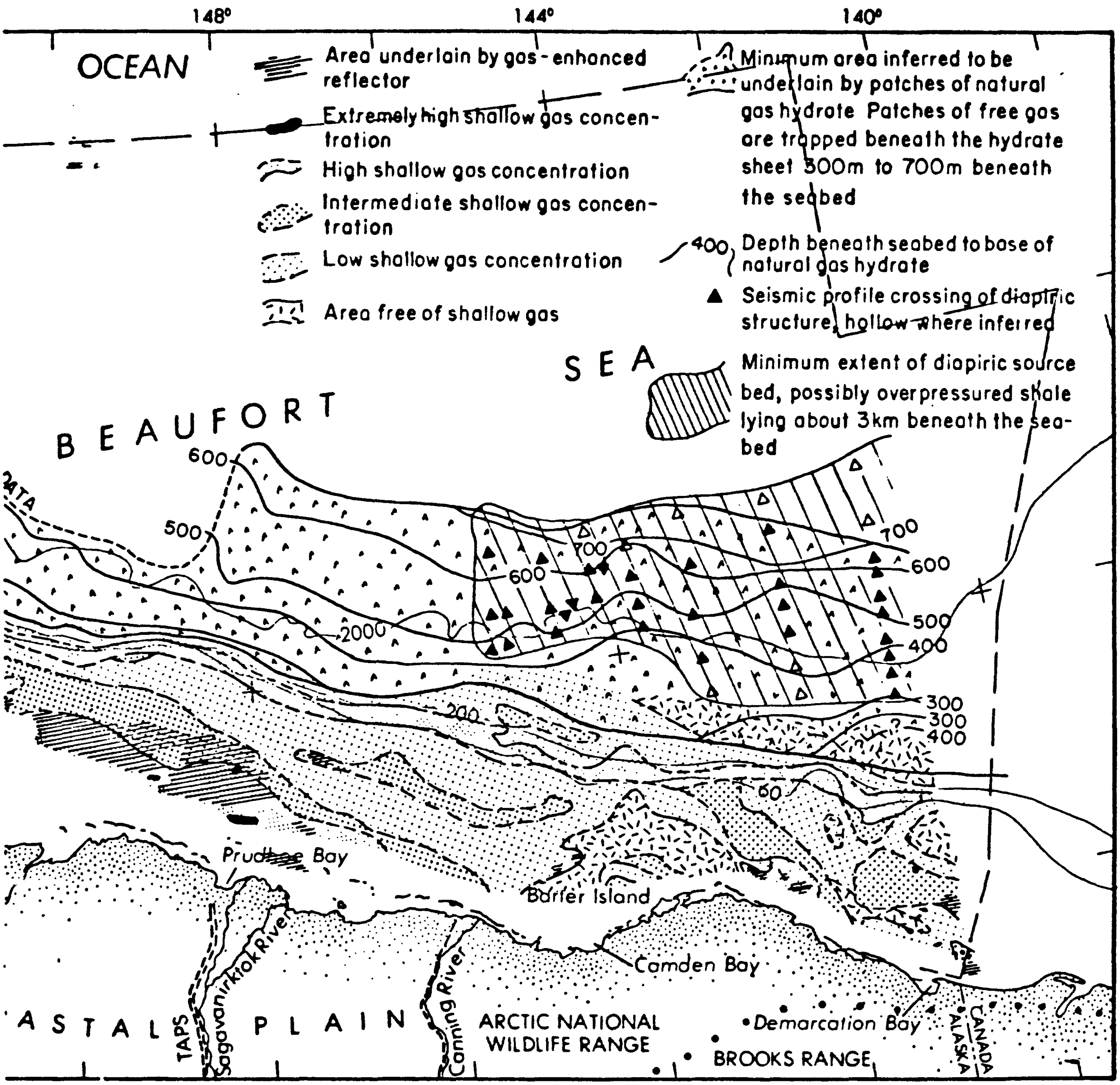


Figure 21 , sheet 2.

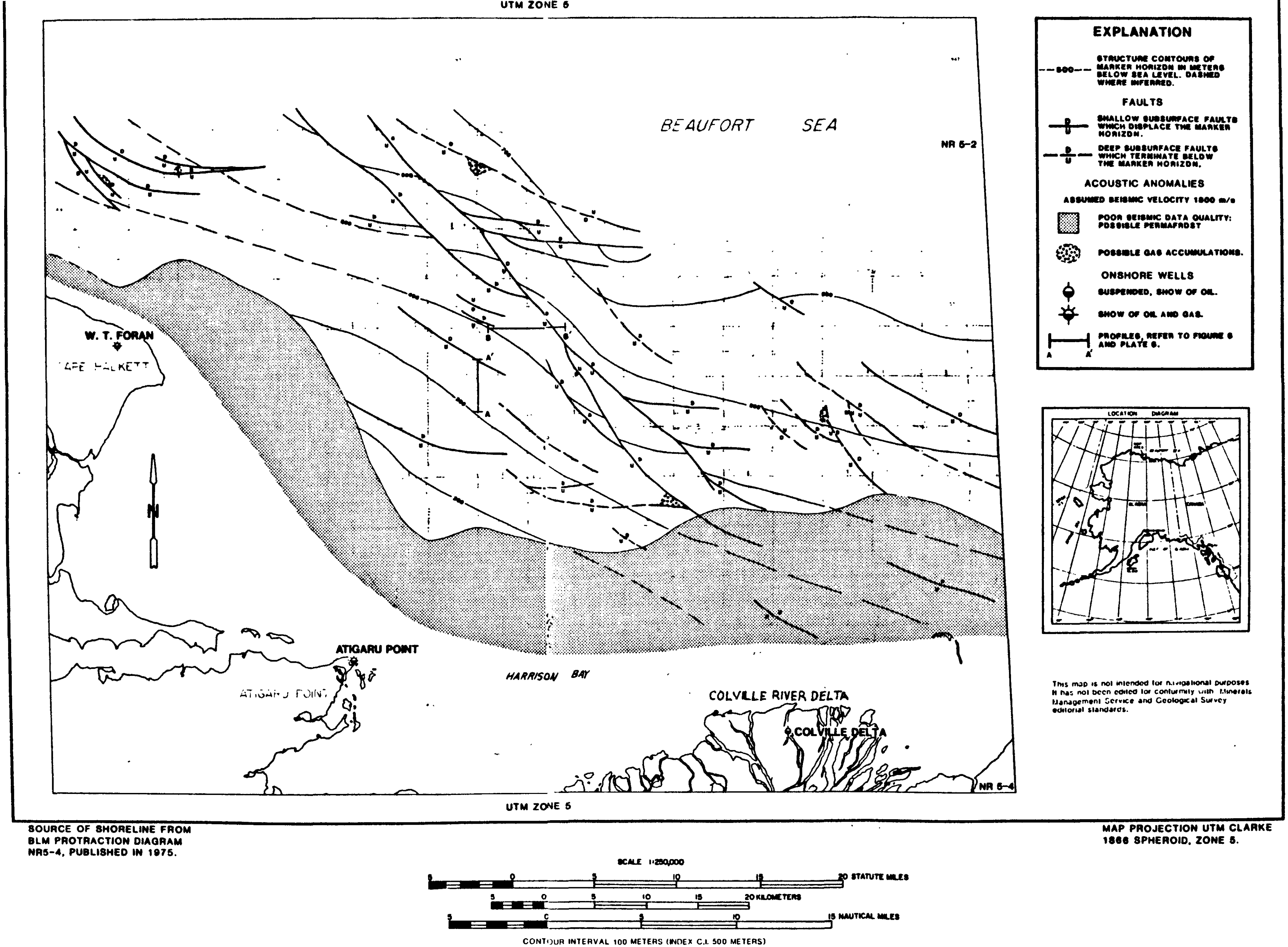


Figure 22. Map of Harrison Bay showing areas of inferred shallow gas and permafrost. Structure shown is for inferred Late Cretaceous to Tertiary section

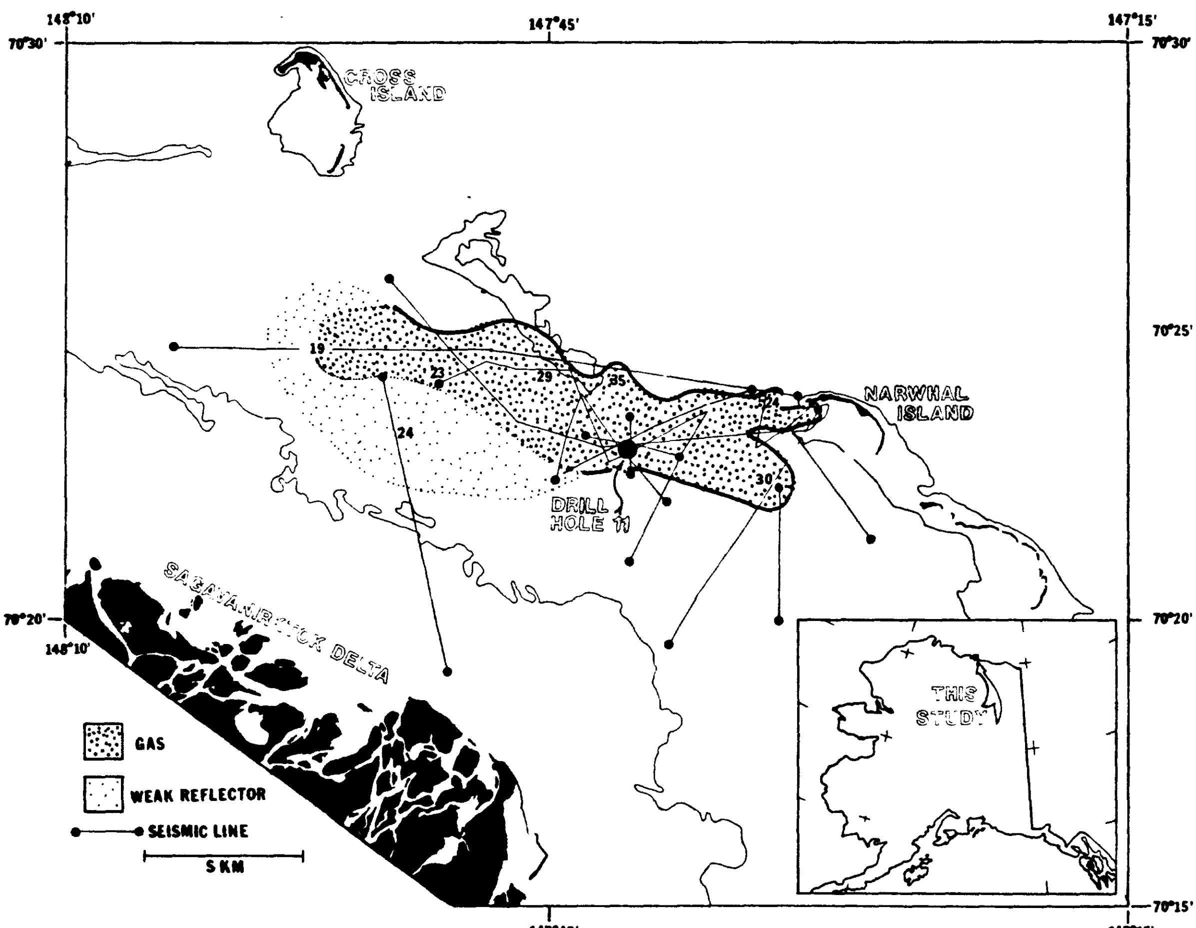


Fig. 23. Seismic trackline coverage showing the extent of the gas reflector in Stefansson Sound. The indicated reflector depths below the mudline in meters (small numbers within the gas area) are based on reflection time, assuming an average velocity of 2000 m/sec in the sub-bottom.
The 5-meter isobath is shown. (from Boucher et al., 1981).

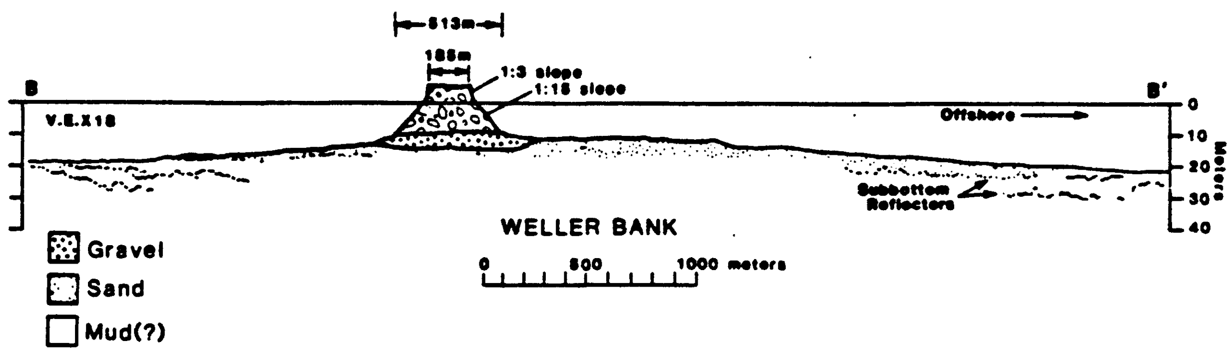


Figure 24. Hypothetical dredged production island sited on Weller Bank(see Fig. 7 for location). The dimensions and slopes of the island are according to industry designs for this type of island, drawn at a vertical exaggeration of 15 x. Sub-bottom traces are from 7 KHz seismic records. Thickness and extent of gravel and of sand at Weller Bank are estimated from surface samples (from Norton and Sackinger, 1981).