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EFFECT OF SEA ICE ON BEAUFORT SEA COASTAL PROCESSES

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Submitted to

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PROJECT TEAM

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EXECUTIVE SUMMARY

The consideration of shoreface developments for the Canadian Beaufort Sea makes it important to understand the prevailing coastal processes. This northern environment is unique in that sea ice is a major component. This study has been conducted to investigate the significance of sea ice for Beaufort Sea shoreline processes and to identify critical information gaps to guide the planning of future research efforts.

The study was conducted by reviewing available data on coastal morphology, sediment transport and sea ice to develop conceptual models for shore/ice interaction processes, and developing first approximation numerical estimates of their significance in the Canadian Beaufort. Assessments were then made of their potential significance for coastal development at King Point and North Head.

A number of processes were identified by which sea ice may affect the littoral zone. These fall into two general classes, as follows:

(a) Modification of marine-related sediment transport mechanisms (e.g. waves).

(b) Interactions in which sea ice directly works the beach or is responsible for sediment transport.

Processes in the former category include the limitation of the annual duration of open water conditions; the limitation of wave energy produced in the coastal environment; and the attenuation of wave energy reaching the beach.

The latter category above includes ice scour and ice push; ice override of shorelines; ice wallowing; strudel scour; and the transport of sediment adhered to, encapsulated in and deposited on the ice sheet; and abrasion by frazil ice.

On a regional scale, the predominant effect of sea ice is believed to be its effect on marine-related sediment transport. First cut approximations suggest that ice-related processes could be responsible for a large percentage of the Beaufort Sea sediment budget.

Ice action may significantly affect local sites both by modifying marine-related sediment transport mechanisms and by reworking the beach.

At North Head, entrapment of sediment in or on the ice cover are the most likely processes, although it is believed that their effects on coastal development are minor. As the beach slope is very shallow, both ice incursions and wave energy in this environment are limited. It is believed that the predominant effect of sea ice here is to limit the duration of the open water season.

At King Point, sea ice is more likely to affect coastal processes as the beach slope is steeper. Thus, ice incursions are more likely. On a local scale ice scour, ice push, and ice override may significantly rework the beach. On a regional scale, ice push has the potential to supply a significant volume of sediment to the littoral zone.

Table 1 summarizes the results of the general assessments which were made. Table 2 summarizes the information gaps at present which are considered most critical.

Field reconnaissance surveys at break-up and field beach profile surveys are recommended to investigate ice push. Efforts to build up a historical database on sea ice-related shoreline processes should continue. Physical model studies are recommended to assess the effects of specific engineering developments on these processes. (These projects are described in detail in Section 8).

TABLE 1

IMPORTANCE OF SEA ICE FOR COASTAL PROCESSES

SEA ICE-RELATED SHORELINE PROCESS	LOCAL SITE INVESTIGATIONS	REGIONAL COASTAL SURVEYS
I. MODIFICATION OF MARINE-RELATED SEDIMENT TRANSPORT MECHANISMS:		
(a) Limitation of annual duration of open water conditions.	High	High
(b) Limitation of wave energy in coastal environment.	Not considered to be a local process	Low-High (depends on prevailing conditions)
(c) Attenuation of wave energy reaching shoreline.	Unknown (has potential to be significant for specific local conditions)	Unknown (has potential to be significant for specific local conditions but is suspected to be less significant on a regional basis)
II. SEA ICE - SHORELINE INTERACTION PROCESSES:		
(a) Ice scour and ice push	Unknown (Ice scour and ice push have potential to be highly significant).	Unknown (Ice push has potential to be highly significant)
(b) Ice override	Unknown (possibly important at some sites)	Unknown (believed to be of low significance)
(c) Ice wallow	Unknown (ice wallow has the potential to be significant at specific sites)	Believed to be of low significance.
(d) Strudel scour	Unknown (strudel scour has the potential to be significant for local specific sites).	Believed to be of low significance.
(e) Sediment content of ice cover	Believed to be of low significance	Believed to be of low significance.

TABLE 2
SUMMARY OF GENERAL RESEARCH REQUIREMENTS

SEA ICE-RELATED SEDIMENT TRANSPORT PROCESS	LOCAL SITE INVESTIGATION	REGIONAL COASTAL STUDIES
I. MODIFICATION OF MARINE-RELATED SEDIMENT TRANSPORT MECHANISMS:		
(a) Limitation of annual duration of open water conditions.	Further research believed to be important to aid in understanding possible effects of man-made changes in ice cover regime.	
(b) Limitation of wave energy produced in coastal environment	Not considered to be a local process	Further research efforts have only been generally defined as this study has focussed on direct sea ice-shoreline interactions. Improvements are required in present capabilities both for the operational definition of field environmental conditions and for understanding the basic processes involved.
(c) Attenuation of wave energy reaching shoreline	No further research recommended as this process will not contribute to shoreface development problems. Also see (a) above.	No further research recommended due to difficulties in defining the local environment, (which is extremely variable). This process will not contribute to shoreface development problems.
II. SEA ICE - SHORELINE INTERACTION PROCESSES:		
(a) Ice scour and ice push	Determination of the depth of disturbed beach sediments.	Determination of probable relative nearshore movement directions between ice keels and the shoreline.
	Determination of the local scour frequency.	Coastal mapping of shoreline susceptibility to these processes.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of several people in the preparation of this report.

Dr. John Harper of Dobrocky Seatech Ltd., was part of the project team. He conducted several of the personal interviews listed in Section 3 and also provided some field observations which he made personally. Finally, his review of this report is acknowledged.

Valuable discussions were held with Dr. Phillip Hill and his input is acknowledged.

Finally, a large number of prominent investigators were interviewed during this study (as listed in Section 3). Their information and assistance is acknowledged.

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1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

The consideration of shoreface developments for the Beaufort Sea makes it important to understand the prevailing coastal processes of this environment. This northern coastline, (see Figure 1.1), is a unique environment which poses particular problems for development.

In general, the Beaufort Sea coastline is presently retreating. Based on an extensive survey of the Beaufort Sea coastal morphology, Harper (1985) observed that the majority of the coastline is comprised of erosional shoreline landforms.

High rates of retreat have been observed in some areas (i.e. up to 29 m/a - Hill et al (1986). Lewis (1975 reported a general trend of shoreline retreat of up to 90 m over a 16 to 18 year period.

Sea ice is an important component of this environment. The effect of sea ice on coastal processes has not previously been documented in a systematic manner, and is the subject of this study.

During the long winter period, sea ice probably has a beneficial effect as it protects the shoreline against marine-related sediment transport mechanisms (e.g. waves).

The effect of sea ice during the short open water season and at freeze-up and break-up, however, is less clear. A number of sea ice-related shoreline processes (e.g. ice wallow, strudel scour) which have been observed in the Alaskan Beaufort Sea may contribute to shoreline erosion. Also, sea ice ridges commonly scour the littoral zone and may contribute a net sediment transport.

A study has been conducted to investigate the significance of sea ice as a coastal agent. Detailed recommendations are provided to investigate critical knowledge gaps.

1.2 Objectives

The objectives of this study were to investigate the various ice-related shoreline processes which are active in the coastal and near shore areas of the Canadian Beaufort Sea.

This study was aimed at:

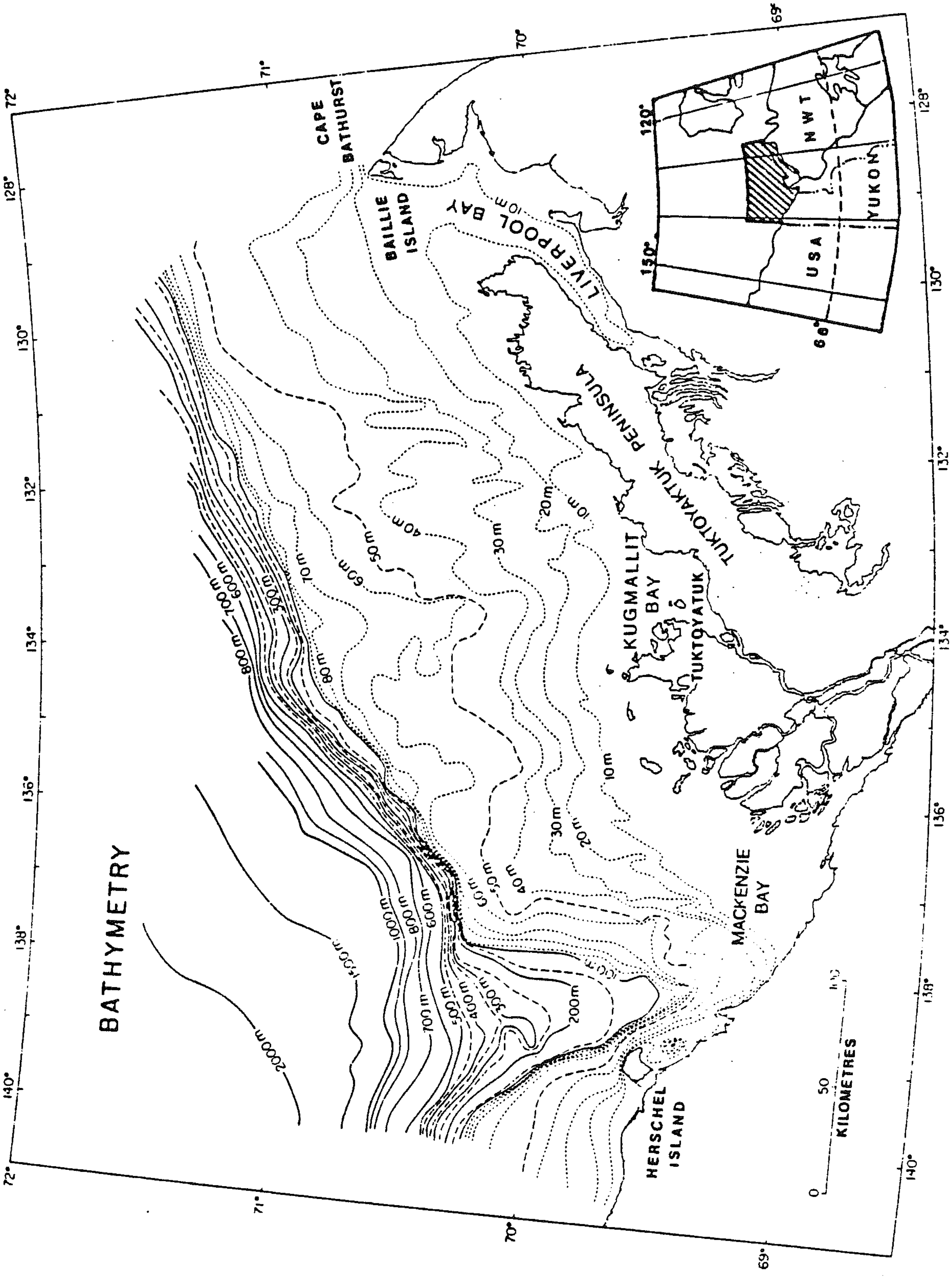
(a) evaluating the probable significance of sea ice as a coastal erosion/accretion agent.

(b) identifying critical knowledge gaps and making recommendations aimed at filling these gaps.

Figure 1.1

BEAUFORT SEA SHELF BATHYMETRY

(after Pelletier, 1974)



2. STUDY APPROACH AND SCOPE

An extensive survey of the information presently available to evaluate the probable significance of sea ice with respect to Beaufort Sea shoreline processes was carried out. This survey provided information on a range of topics which contribute to the understanding of sea ice as a geologic agent, including:

- Beaufort Sea shoreline environmental conditions.
- Beaufort Sea shore-zone ice conditions.
- Sea ice - shoreline interaction processes (e.g. ice scour, ice push, ice wallow, strudel scour, anchor ice, and frazil interaction with waves and beaches).
- Sea ice - related sediment transport.

This survey was accomplished both by reviewing the available literature and by conducting a series of meetings and discussions with prominent investigators and arctic operators.

By surveying both of these sources, a wide range of information was assembled which contributed to the overall study. The personal interviews were particularly useful for providing insights regarding sea ice - shoreline interaction processes which have not been extensively reported in the literature.

The results of this survey are summarized in the following sections. Appendix A provides summary sheets which describe the most relevant reports reviewed. Table 2.1 lists the contacts made.

From this survey, some understanding of the probable significance of sea ice as a sediment transport agent was obtained. Also, this survey allowed an assessment of the significance of the various sea ice - shoreline interaction processes which were identified, at King Point and North Head. These sites have been proposed as locations for shipping or offshore exploration terminals involving the alteration of the natural shoreline by man-made structures. It was desirable to obtain an understanding of the effects of sea ice here in order to assess possible effects of the developments on the shoreline environment.

The results of this survey were supplemented with exploratory sediment transport calculations for key sea ice processes such as ice scour.

From this work, the key knowledge gaps were identified. Using this basis, a long term two phase research program was planned and defined to improve present knowledge.

TABLE 2.1

ORGANIZATIONS AND INVESTIGATIONS CONTACTED

ORGANIZATION	INVESTIGATOR
Atlantic Geoscience Centre	S. Blasco ; D. Forbes
United States Geological Survey	E. Reimnitz; P. Barnes
Canadian National Research Council	B. Pratt (Hydraulics Division) R. Frederking (Building Research) M. Sayed (Building Research) L. Goodrich (Building Research)
Department of Indian Affairs and Northern Development	H. Young
Esso Resources Canada Ltd.	G. Spedding
Gulf Canada Resources Inc.	J. Low
Can Dive Services Ltd.	M. Atherton
B.C. Ministry of Environment	P. Lewis
Geological Survey of Canada	B. Pelletier; S. Dollimore
Louisiana State University	B. Wiseman
Berkley University	Dr. Harms
PRIVATE CONSULTANTS:	
- J. Shearer	
- J.R. MacKay	
- Arctec Offshore Corp. (East)	J. Cox
- Arctec Offshore Corp. (West)	I. Collins; T. Johnson
- Terrain Analysis & Mapping Services Limited	V. Rampton
- P.F.L.	M. Fernandez

3. BEAUFORT SEA ENVIRONMENTAL CONDITIONS

3.1 Beaufort Sea Coastal Environment Regional Setting

A large number of studies and surveys have been carried out to date to characterize the coastal environment of the Beaufort Sea. Recent comprehensive works include an atlas of sediments and coastal landforms (Pelletier, 1984), terrestrial quaternary geology (Rampton, 1982; 1987), sediment transport mechanisms and shoreline profile adjustment (Philpott, 1985), and an analysis of shore-zone dynamics (Harper, 1985). A summary of the parameters relevant to sediment transport is provided in this section to provide a background understanding.

3.1.1 Physiography and Bathymetry

The Beaufort Sea coast falls within three physiographic zones; the Yukon Coastal Plain, the Mackenzie Delta and the Interior Plains (Rampton, 1982; 1987).

The Coastal Plain includes the land area northeast of the Bristol, Barn and Richardson mountains. It slopes gently toward the Beaufort coast where bedrock is overlain by ice-rich clay estimated at 60 m thick. Land along the coast is very flat with prominent stream valleys incised from 3 to 15 m below the surrounding plain and thermokarst lakes incised from 1.5 to 6 m. Other prominent features include Herschel Island which rises to 185 m above sea level, a ridge of glacial till between Kay Point and King Point with maximum elevation of 80 m, and a coastal scarp with elevation between 9 and 30 m. Higher relief is found along the western edge of the delta, with hills reaching 155 m.

The Mackenzie Delta is a very flat deltaic plain extending over 100 km into the Beaufort Sea but rising only a few meters above sea level. The Delta has numerous channels, most of which drain to the east into Shallow Bay.

The interior lowlands region includes the Tuktoyaktuk Peninsula, offshore islands and Cape Bathurst. Recent geological surveys indicate it to be underlain by pre-glacial and glacial sand and till deposits and colluvium (Rampton, 1987). It is predominantly a poorly drained lowland area with thick ground-ice and numerous thermokarst lakes. It is also noted for ice-cored mounds known as pingoes.

The Beaufort Sea includes five bathymetric components (Harper and Penland, 1982) (Figure 3.1):

- **the Coast**, which consists largely of rapidly eroding, ice-rich tundra cliffs and discontinuous barrier island systems,
- **the Mackenzie River and Delta**, a major contributor of sediment to the Beaufort Sea,
- **the continental shelf**, which extends from the coastline to approximately the 100 m depth and ranges in width between 30 and 130 km,
- **the Mackenzie Canyon**, which cuts across the shelf near the western channel of the Mackenzie River, bringing water depths of 200 m to within 50 km of the coast,
- **the continental slope**, which is seaward of the self and extends to water depths of approximately 1000 m.

3.1.2 Sediment Transport

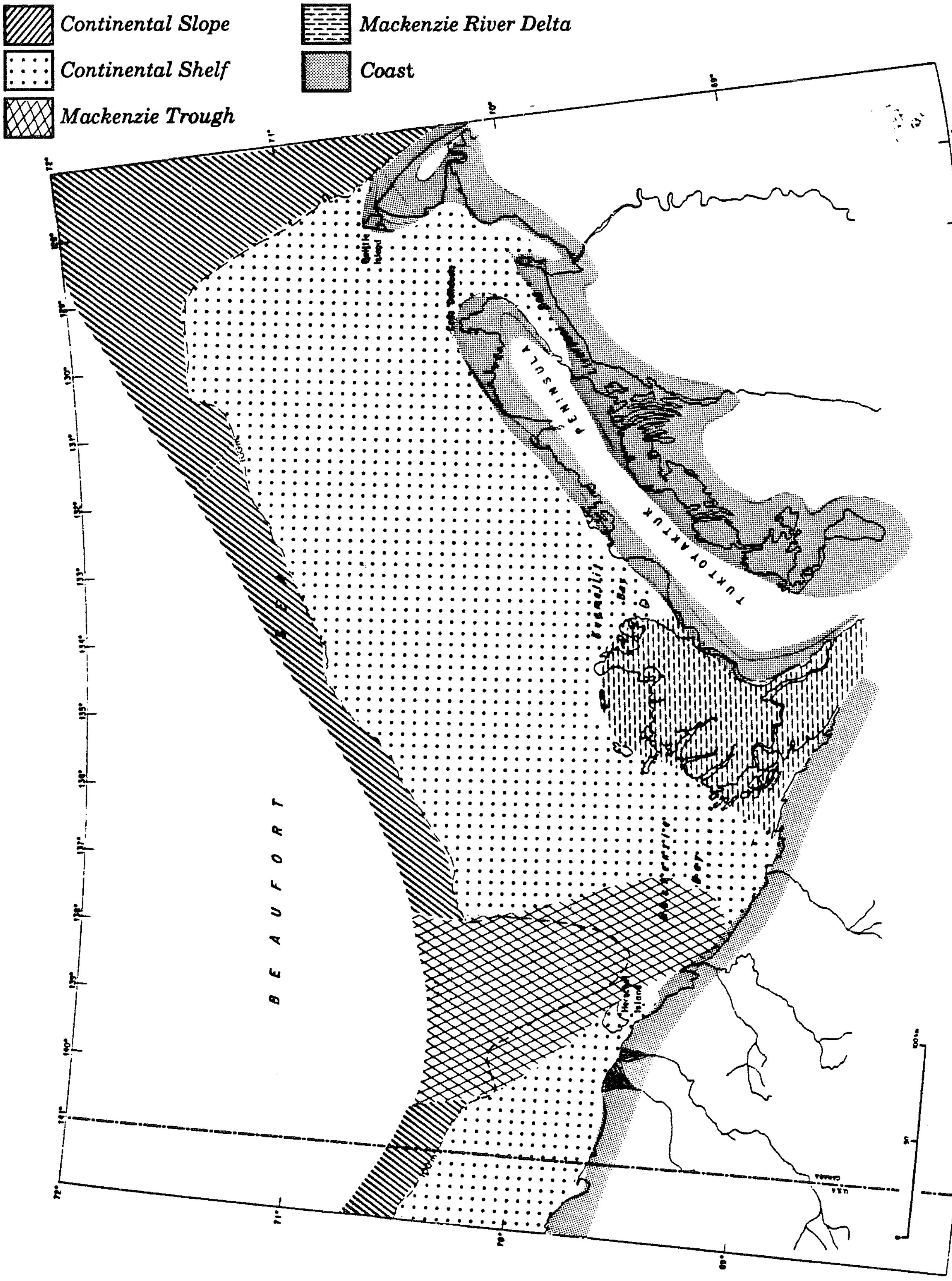
Sediment sources and sinks in the Beaufort Sea coastal zone are described by Harper and Penland (1982), Pelletier (1984), Bornhold (1975), Lewis (1975), Davies (1975) and Lewis and Forbes (1975). By far the biggest source of sediment is the Mackenzie River, with estimated contribution of 86 x 10^6 m^3/yr. The peak discharge of the Mackenzie is in late May or early June, but the maximum sediment discharge is believed to be in mid-summer (Harper and Pentland, 1982). The Mackenzie discharges through three principle channels, with 34% of the discharge eastward into Kugmallit Bay, 38% westward into Mackenzie Bay and 28% northwestward, to the north of Mackenzie Bay (Davies, 1975).

Other sediment sources include rivers of the western Yukon, contributing about 4.5 x 10^5 m^3/yr and coastal erosion, contributing 3 x 10^6 m^3/yr (Harper and Pentland, 1982). Seasonal aspects of these sources have not been examined in detail, although Harper (1985) notes the importance of storm events during the ice-free season in erosion of the ice-rich cliffs. The rate of volumetric retreat of the cliffs may be greater than the rate of contribution to the sediment budget, since a significant volume of the cliffs is composed of ice.

Predominant sediments types and sediment dispersal patterns are mapped by Pelletier (1984) (Figure 3.2). Generally, fine sediments are found seaward of the 10 m isobath. Exceptions to this are explained by the sediment transport patterns shown. Clearly, the Mackenzie River discharge and longshore drift east from Kugmallit Bay have an important effect on sediment patterns.

Figure 3.1

BATHYMETRIC COMPONENTS OF THE BEAUFORT SEA



3.1.3 Coastal Morphology

Coastal sediments and morphology have been mapped extensively by Forbes and Lewis (1984) and Harper (1985). Harper conducted an extensive mapping program to identify significant features along the Beaufort Sea coast. His analysis shows that the coastline consists of four predominant erosional and two accretional types plus three additional modifiers (Table 3.1). On the basis of the relative importance of each of these features he mapped twelve geographic zones along the coast (Figure 3.2, Table 3.2). His analysis shows that the coastline is dominated (63%) by erosional landforms.

Harper (1985) also presents a process oriented analysis of coastline types in the Beaufort. Two conceptual models are presented to describe dominant processes (Figure 3.3).

Model 1 is generally applicable to the coastline east of the Mackenzie River. This produces a coastal topography which is typified by relatively low but steep coastal cliffs fronted by narrow beaches. The cliffs consist of mainly unconsolidated material, often containing significant amounts of ground ice. In some areas, a short distance seaward of the beach, spits or barriers have developed from the deposition of eroded sediments (Lewis, 1975). These spits, once formed, tend to protect the beaches from wave energy which assists in stabilizing the shoreface and often produces a shallow beach slope.

Harper proposed Model #2 (see Figure 3.3) to describe shoreline processes along the western Yukon coast, where barrier spits and islands, and shoreward lagoons are more common. One principal difference between this area and the coastal regions to the east is the relative effect of the Mackenzie River. (Significantly less sediment is supplied to the western Yukon coast by the Mackenzie River). Harper speculated that sediment supplied by onshore ice push may be significant for this region.

Harper's analysis shows that approximately 60% of the coastline is erosional, 20% is deltaic of an unusual, erosional type and 20% is accretional. Erosion rates are estimated at > 1 m/yr for most areas and > 2 m/yr in the delta. North Head is an important exception to the general pattern, being an apparently stable landform with neither erosion nor accretion occurring.

TABLE 3.1

DESCRIPTION OF COASTAL TYPES AND MODIFIERS
(after Harper, 1985)

EROSIONAL COASTAL TYPES

Ice Poor Cliffs - coastal cliffs, usually low to moderate relief fronted by narrow beaches (< 15 m) of sand/gravel material; mass-wasting dominated by debris slides and surface wash erosion; cliff materials usually sands or gravelly sands capped by peat; moderate to low retreat (< 1 m/yr).

Ice-Rich Cliffs - coastal cliffs, usually moderate to high relief (5 - 15 m) fronted by narrow gravelly sand beaches; upper cliff sections typically show retrogressive thaw failures indicating ice-rich material; mudflows from failures frequently flow across beaches; retreat rates are moderate (0.5 to 1.0 m/yr).

Low Tundra Cliffs - low coastal cliffs (< 1 m relief) fronted by narrow sand or sand and gravel beaches; cliffs commonly show a veneer of sediment on tundra; log lines common landward of cliff edge; retreat moderate to high (1 to 2 m/yr).

Inundated Tundra - submerged tundra extending into nearshore and foreshore areas; low relief areas from highly crenulated coastlines; beaches are narrow to non-existent although wide intertidal and subtidal flats commonly found in association; organic-rich areas common; high coastal retreat.

ACCRETIONAL LANDFORMS

Barrier Beaches and Spits - sand to gravelly sand barrier beaches of variable width depending on wave exposure (widths 20 - 200 m); wider spits usually associated with high wave exposure; multiple recurved spits cause local width increases; relief low (< 1.5 m); with lagoons and/or estuaries which commonly contain a wetland fringe; dunes are rare; spit stability determined by retreat of anchoring headlands; barrier islands comparatively stable.

Intertidal Flats, Wetland and Channel Complexes - usually associated with deltas; flats are typically very wide (up to several kilometers) and comprised of sands, muddy sands and/or organics; commonly low erosional scarp cut into peat at or near the high water line; coastlines are complex and highly crenulated with flats on the outer coast, and channels and wetlands to landward.

COASTAL MODIFIERS

Multiple Nearshore Bars/Flats - low gradient nearshore areas; usually sandy; often with multiple low amplitude nearshore bars; commonly associated with low wave exposure areas.

Figure 3.2

PHYSIOGRAPHIC AND COASTAL REGIONS

(after Hill et al, 1986)

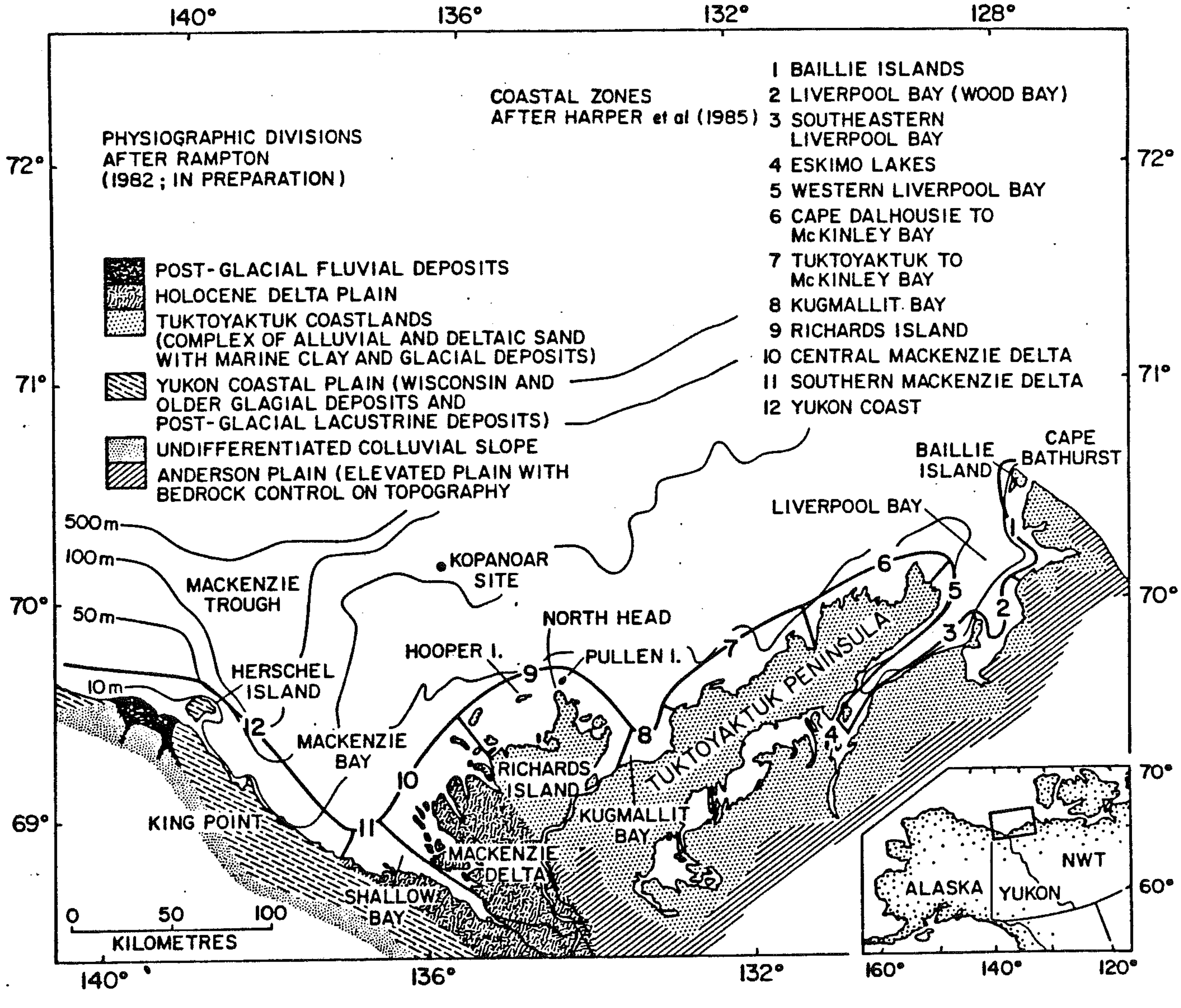


TABLE 3.2

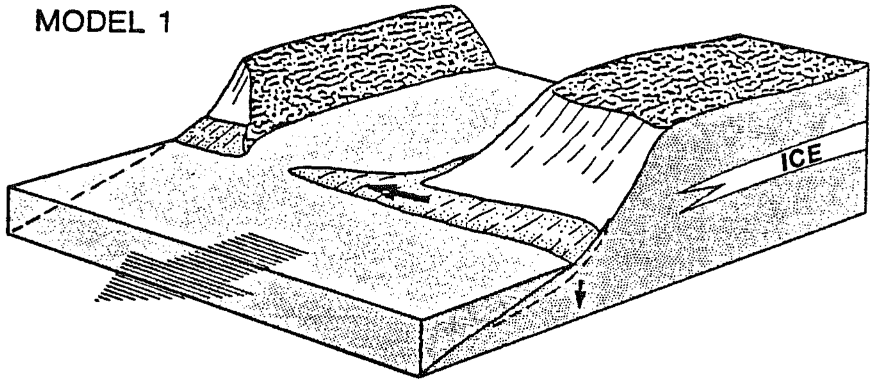
OCCURRENCE OF COASTAL TYPES AND MODIFIERS
(after Harper, 1985)

	LOGALITY[1]											
Coastal Type	1	2	3	5	6	7	8	9	10	11	12	TOTAL
Ice poor cliffs	37	14	28	74	64	9	21	67	20	-	70	404 (19%)
Ice rich cliffs	77	57	54	66	-	1	4	26	36	-	83	405 (19%)
Low tundra cliffs	1	8	-	1	144	50	31	27	3	-	18	283 (14%)
Inundated tundra	4	3	-	19	40	42	16	18	8	-	10	161 (8%)
Barrier spits islands	58	34	5	6	36	104	23	39	30	-	87	422 (20%)
Flat, wetland, channel complexes	4	17	-	-	-	-	4	4	216	128	31	403 (19%)
Coastal Modifier												
Multiple bars, flats	21	25	82	116	131	139	5	64	-	-	7	590 (28%)
Active retrogressive	-	3	1	2	-	-	1	6	5	-	13	31 (2%)
Stable thaw failures	-	3	10	16	-	-	2	6	9	-	6	53 (3%)
TOTAL COASTLINE MAPPED	180	133	87	165	285	205	98	183	314	128	299	2077
UNMAPPED[2]			24	3		46	32	254	166		1	526

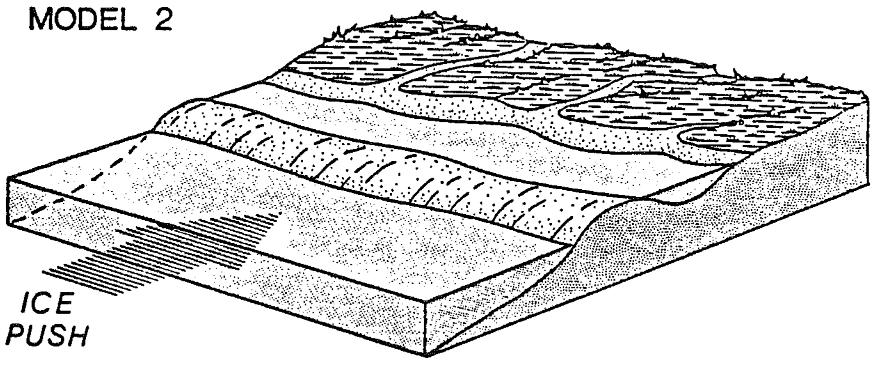
Figure 3.3

CONCEPTUAL COASTAL PROCESS MODELS

(after Harper, 1985)



Conceptual model for coastal processes along most sections of the Beaufort Sea coast. Melting of ice in the coastal sediments contributes to the steepening of the nearshore gradient (indicated by downward arrow), coarse sand and gravel is transported primarily alongshore and is deposited in barrier spits or beaches and fine material is transported offshore in suspension. The net result is a rapidly retreating shore with ephemeral accretional sediment deposits (beaches and barrier spits).



Conceptual model for coastal processes along the western Yukon coast. The main component of sand and gravel sediment in the barrier islands is supplied by offshore ice push. Lagoons are prevented from infilling by a possible relative sea level rise.

3.2 Beaufort Sea Shore-Zone Ice Conditions

3.2.1 Introduction

An analysis of the effects of sea ice on Beaufort Sea coastal processes requires an understanding of the properties and dynamics of sea ice in the coastal region. This section presents a general review of ice conditions and features which are found in the Canadian Beaufort Sea, and of specific features relevant to coastal processes.

3.2.2 Seasonal Occurrence of Sea Ice

The seasonal occurrence of sea ice in the Beaufort is illustrated in Figures 3.5 through 3.7 (Markham, 1981). These figures are based on the median concentration of all ice types as observed from air and satellite reconnaissance over a period of more than 15 years. Winter conditions are similar to those shown for October.

Winter ice usually dissipates along the coast in mid-June, with break-up progressing along three fronts; westward from the Cape Bathurst area, shoreward from the outer ice edge and seaward from Mackenzie Bay. The last area to break up is Liverpool Bay, which does not clear until early July. Freeze-up begins in the Mackenzie Bay area close to the low salinity river discharge, and spreads uniformly over the ocean surface elsewhere. Ice formation begins in early October and is complete by the end of the month.

3.2.3 Ice Morphology and Dynamics

The ice cover is composed of several types of ice, and can be categorized into four main morphological zones on the basis of predominant type, dynamics and features present. The main types of ice present in the Beaufort Sea are first year and old sea ice, and ice island fragments. First year (FY) ice grows on the water surface as it cools below the freezing point, and melts completely in the following summer. It forms as a skim on the water surface, and thickens by growing downward into the water. First year ice has several sub-classifications depending on its thickness (A.E.S. 1980), and reaches a maximum of about 2 meters in the Canadian Arctic. The limitation on maximum thickness is the rate of ice growth; the thicker the ice gets, the slower is the rate of heat loss from the bottom surface where growth takes place. A typical growth curve for the Beaufort Sea region is shown in Figure 3.8.

If the ice does not melt completely during the following summer but grows anew, it is called second year ice and in subsequent years is called multi-year ice. Together, second and multi-year ice are termed old ice. Old ice reaches a maximum thickness of about 4 meters in the Beaufort Sea.

Figure 3.5

MEDIAN TOTAL ICE CONCENTRATION - May 28

(after Markham, 1981)

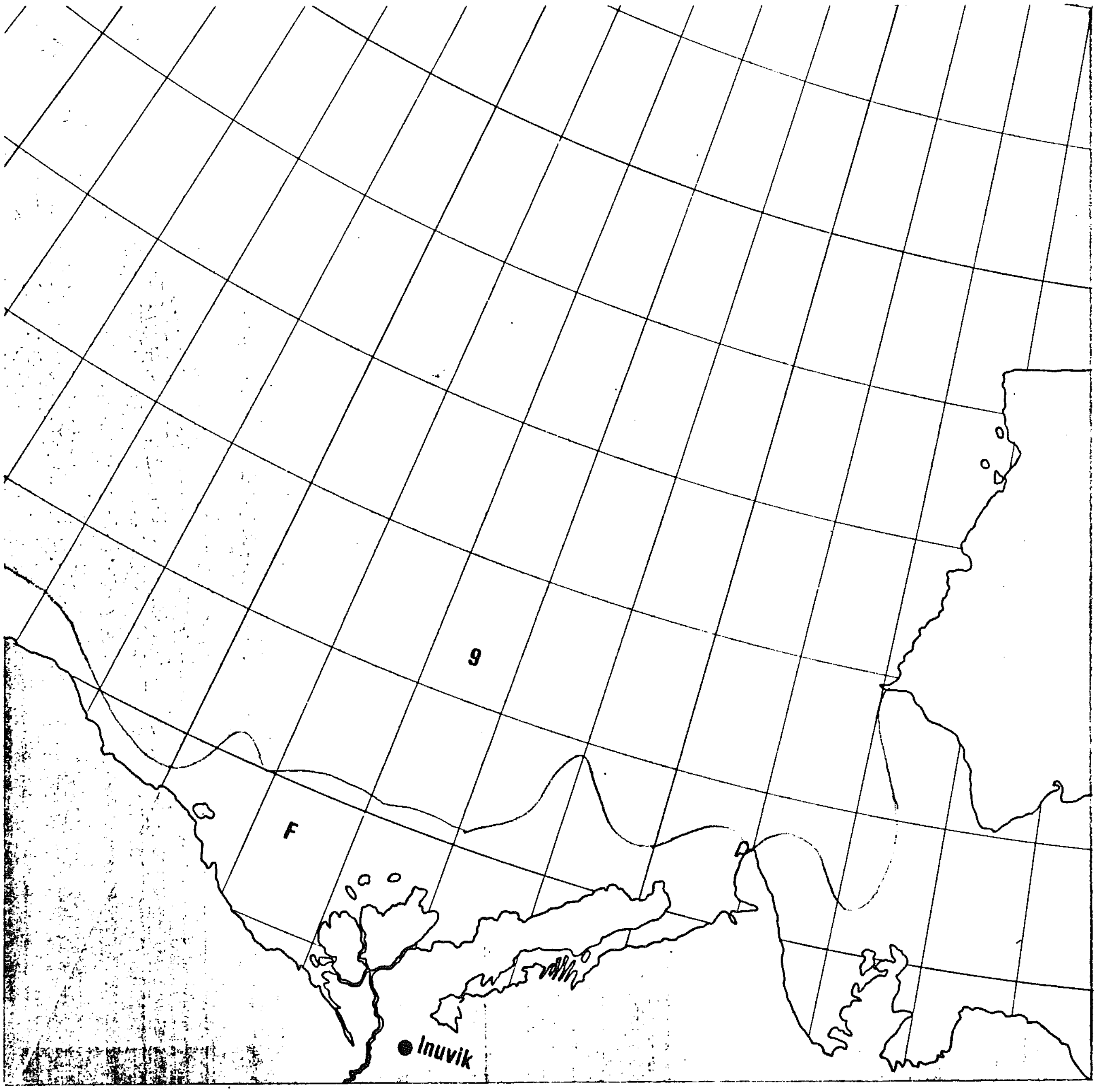


Figure 3.6

MEDIAN TOTAL ICE CONCENTRATION - July 30

(after Markham, 1981)

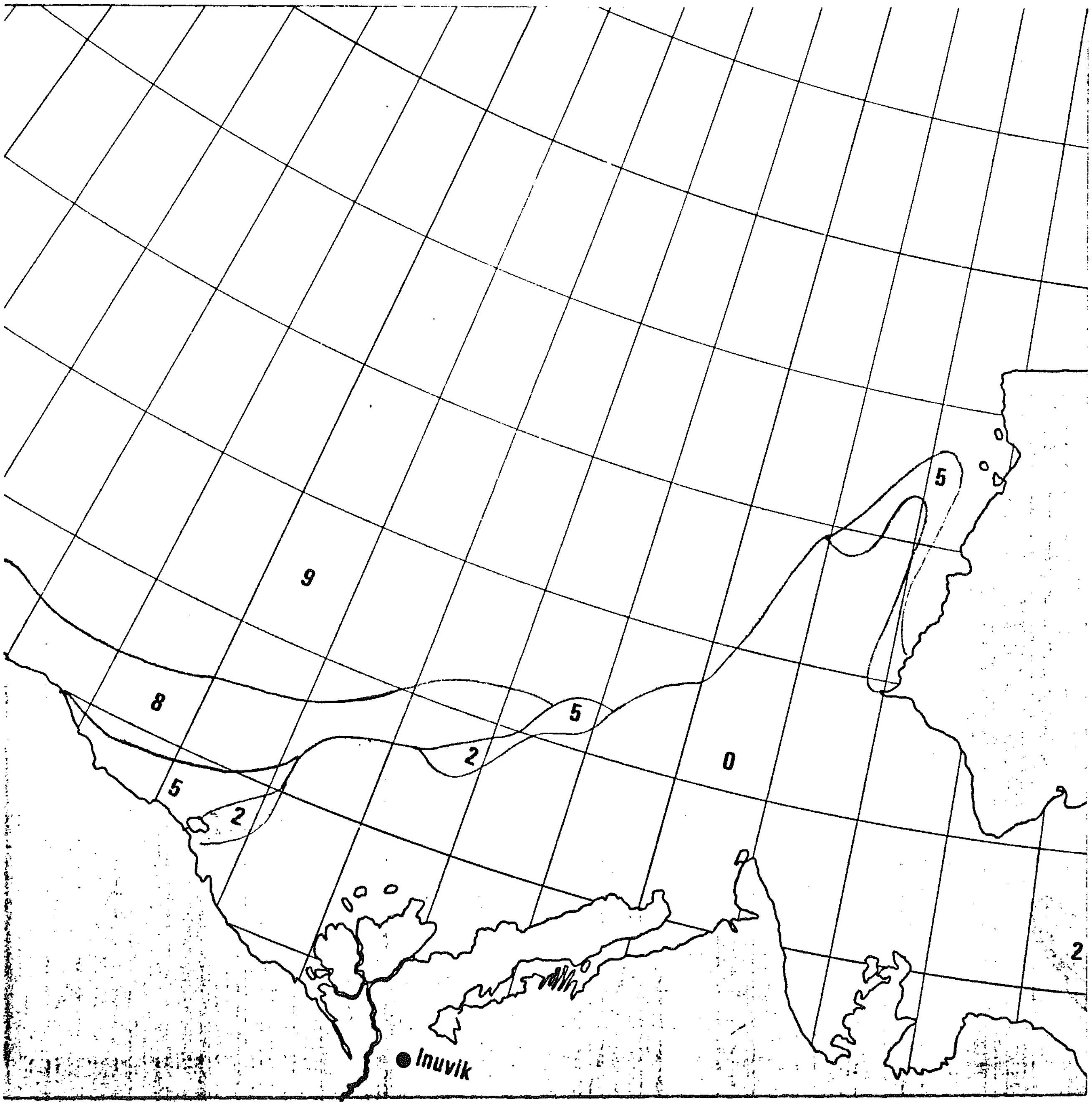


Figure 3.7

MEDIAN TOTAL ICE CONCENTRATION - Sept. 24

(after Markham, 1981)

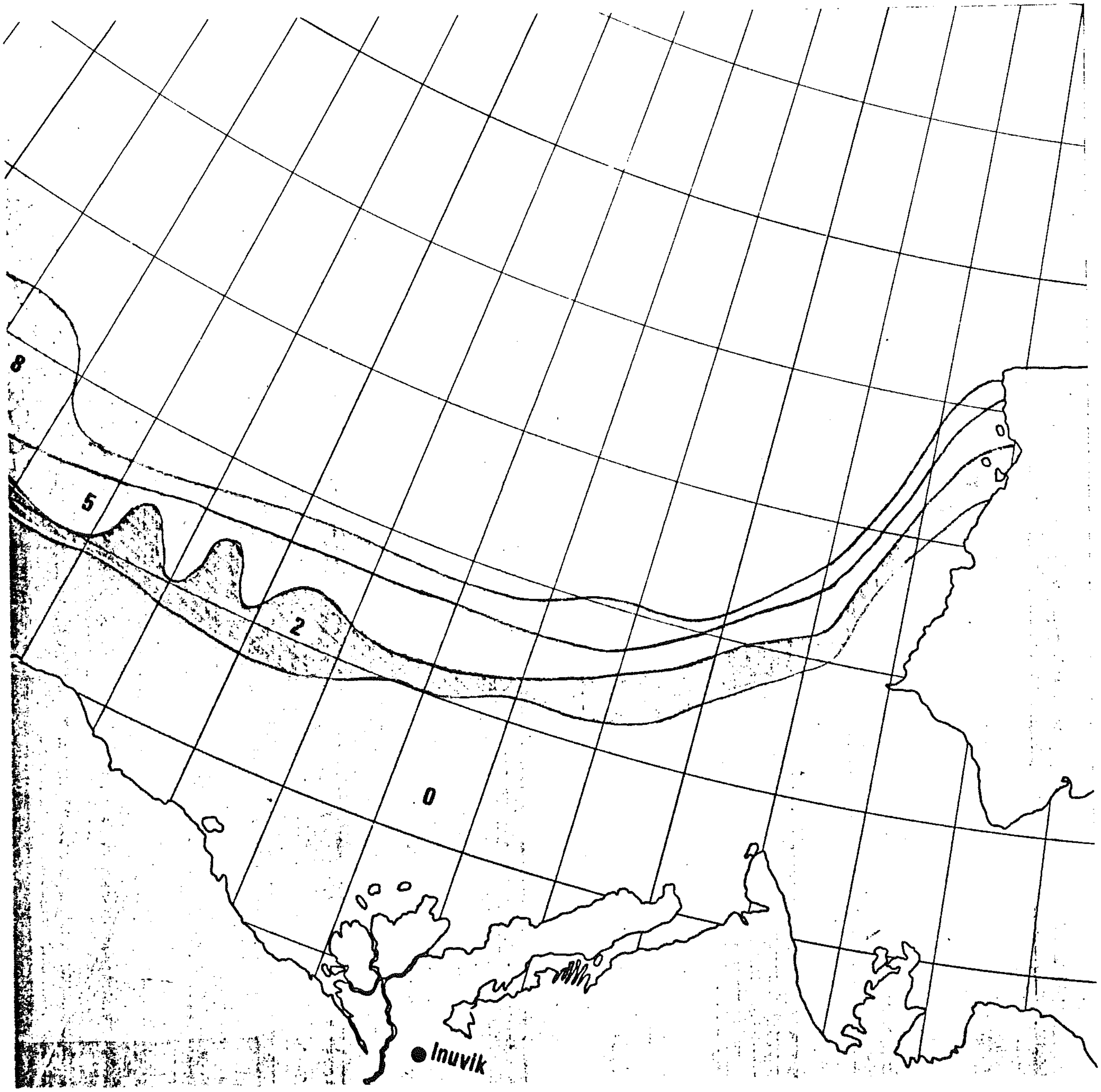
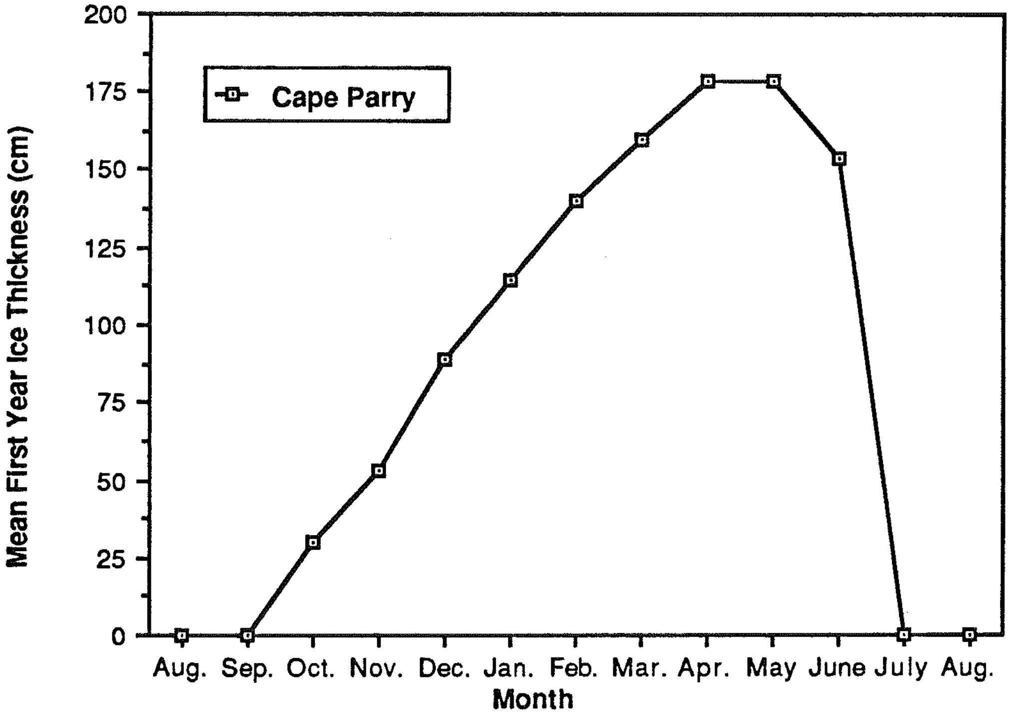


Figure 3.8

BEAUFORT SEA ICE GROWTH CURVE



Source: AES

A third ice type which may be present is ice island fragments. Ice islands originate from ice shelves on the north coast of Ellesmere Island (Markham, 1981). They are composed of floating glacier ice plus thick, multi-year sea ice which has frozen to the perimeter. Several times in this century, pieces of ice shelf up to 50 m thick and kilometers across have calved off and drifted westward with the Arctic Gyre. Fragments of these ice islands have on occasion (i.e. 1970, 1971) drifted into coastal regions and become grounded along the shore (Dome et al, 1982).

Each of the ice types is present in a concentration and form controlled by the processes of ice growth, deformation, drift and melt. These processes result in four morphological zones in the Beaufort region as illustrated in Figure 3.9. These are the polar pack, the seasonal or transition zone, the shear zone and the landfast zone.

The polar pack ice zone refers to ice in the central region of the Beaufort Sea. This region is subject to a year round, clockwise circulation known as the Beaufort Gyre. The Gyre, driven by an atmospheric high pressure system, carries the pack ice westward at an average rate of 2 km per day (Dome et al, 1987). Ice concentrations are always high in this zone and predominantly of old ice. Its southern limits normally lie at about 72°N, but on at least five occasions in the past thirty years it has approached the shore (Dome et al 1982). The pack ice zone is important to coastal processes mainly in that it is a source area for old ice which drifts shoreward.

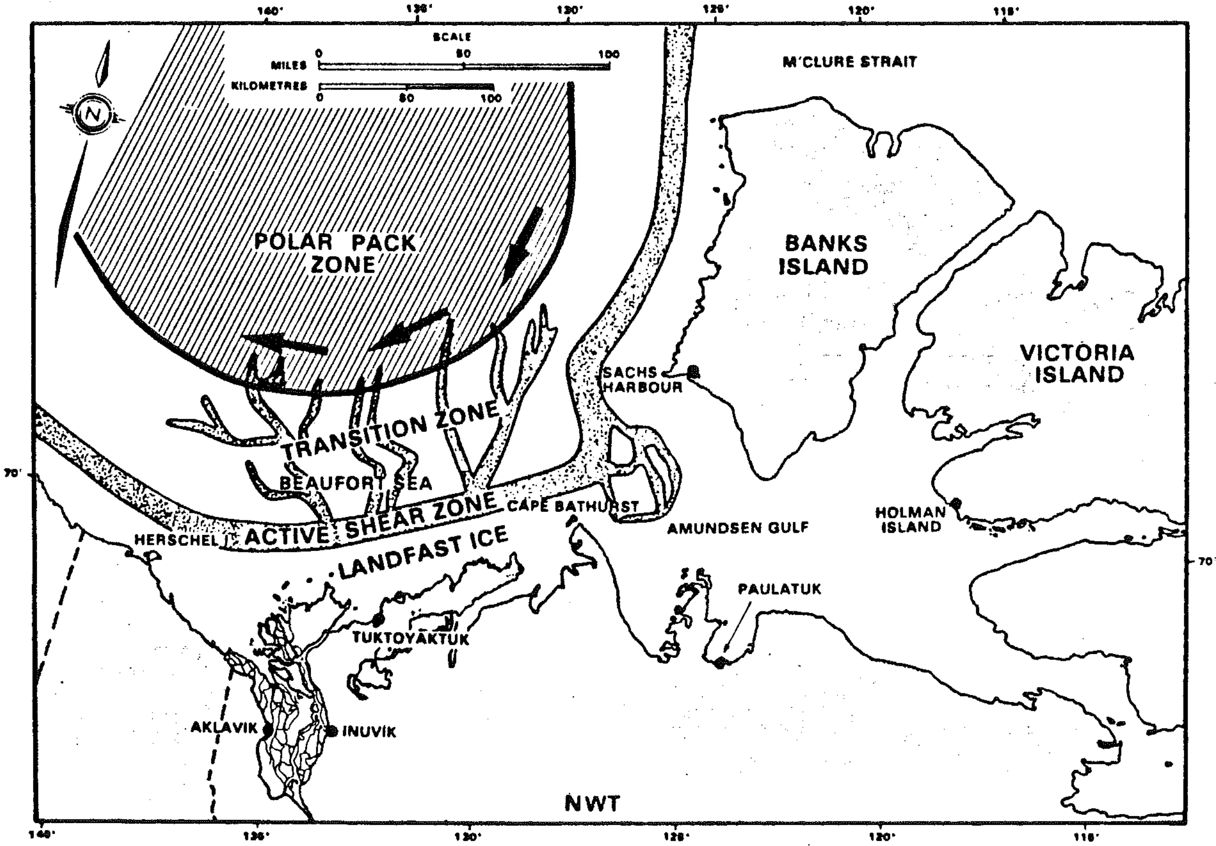
The transition zone is distinguished from the polar pack by its higher concentration of first year ice. Like the polar pack, it drifts with the Beaufort Gyre. It is a highly dynamic zone with dimensions depending on the effect of prevailing winds on the offshore polar pack, and the seaward growth of the landfast zone. Measured ice floe velocities in this zone range from 3 to 30 km/day.

The shear zone identifies the area of contact between the drifting polar pack or transition zones and the stationary landfast ice zone. It is characterized by mixed ice types, severe ridging and variable amounts of open water. Subject to prevailing wind direction, the ice contact zone may be either opened as a flaw lead between the landfast and drifting ice, or heavily ridged as the ice pack is compressed or sheared seaward of the grounding depth. Its relevance to shoreline processes is in the production of ridge keels which tend to anchor the landfast ice in winter and may drift onshore to interact with the seabed in summer.

Figure 3.9

BEAUFORT SEA ICE MORPHOLOGICAL ZONES

(Dome et al, 1982)



The landfast zone is of most relevance to this study. It is located adjacent to the shore along most of the Beaufort Sea coast, and has open water conditions through the summer. The first year ice cover which forms here in the fall becomes anchored in place by grounding and by contact with surrounding shorelines, and does not drift with the Beaufort Gyre.

Movement in this zone during winter is primarily due to thermal expansion of the ice sheet in the direction of open water. Individual movement events up to 100 m have been recorded, but typical displacements are in the order of 1.5 m with net displacement over the winter of 10 m (Dome et al, 1982). Larger movements associated with ice drift occur only during freeze-up in this zone.

Ice features typically present within the landfast and shear zones are shown schematically in Figure 3.10. These include bottom fast ice, a tidal crack, floating first year and multi-year ice, floating and grounded ridges, grounded ice and a flaw lead.

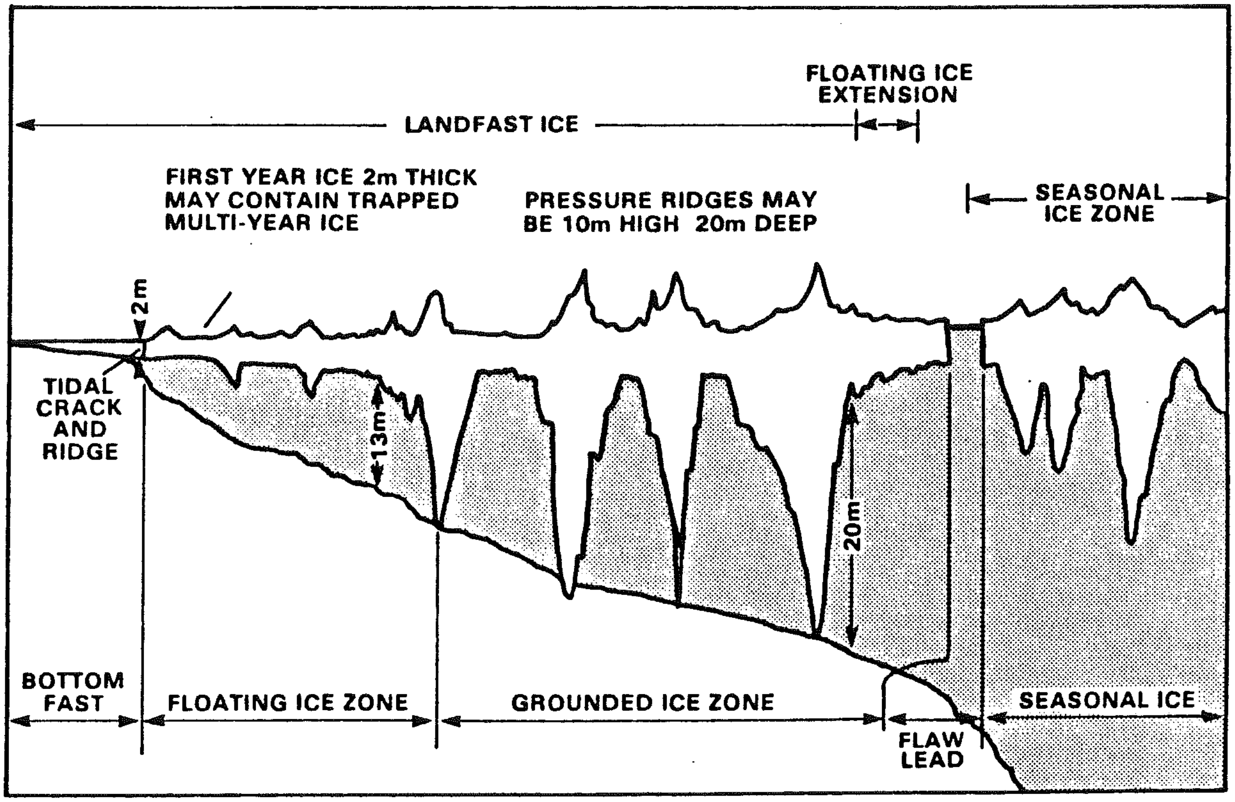
The grounded ice zone forms along shore out to the maximum depth of first year ice. This is frozen to the seabed and protects the shore from wave, current and ice abrasion during the winter period. A tidal crack occurs at its seaward edge where significant tidal motion occurs and a small ridge of broken ice builds up as the crack is repeatedly refrozen and broken.

The floating ice zone is composed mainly of first year ice which freezes in situ, plus any grounded old ice pieces which drifted to shore during summer and did not melt. Relatively small ridges may be formed here by offshore winds during the freeze-up season. In winter, the zone is protected from further deformation by grounded ice further offshore.

Larger ridges occur somewhat further offshore, seaward of 13 m depth (Dome et al, 1982). Here, the ice remains mobile later into the freeze-up season and the ridges are characteristically bigger and grounded. Once a ridge becomes grounded it provides an obstacle to drifting ice, resulting in the rapid build-up of more ridges until the ice surface can be described as "rubbled". This is the condition at the seaward edge of the landfast zone. Once grounded ridges are present the landfast zone is extended, and thus it grows seaward during freeze-up. The seaward limit is reached when water depths exceed that of the ridge keels. This occurs at about the 20 m isobath, after which the water deepens more quickly.

Figure 3.10

LAND FAST ICE MORPHOLOGY



The summer condition in the landfast zone is open water, with periodic incursions of wind-blown ice from the transition or polar pack zones, plus any remaining multi-year ice or ridges from the winter. Ice drift speeds in open water are roughly 2 to 4% (Dickins, 1986) of the prevailing wind speed, and values based on hourly measurement intervals are shown in Figure 3.11.

The importance of landfast features to coastal processes are primarily in protection of the shore zone throughout the winter period, and in the development of deep ice keels which can drift onshore as they ablate during the summer. The effects of these features at specific locations along the shore are investigated in the following sections.

3.2.4 **Coastal Sub-Zones**

Detailed historical analyses of ice conditions at a level of detail which would help to explain variations in coastal morphology in the Canadian Beaufort Sea are not reported in the open literature. For purposes of discussion, four sub-zones are hypothesized on the basis of conditions described elsewhere in this report (Table 3.3).

The Western Yukon region has the most severe ice conditions along the coast. There, the Beaufort Gyre tends to force the polar pack transition and shear zone ice closer to shore than at other locations. In addition, the relatively steep beach profile permits incursions of deep draft ice features. Barrier splits in some areas (e.g. at King Point) protect shoreward bays and lagoons from ice action.

The Mackenzie Delta coastline has a significantly shallower beach profile which protects this zone from extensive ice action. This region is affected by the outflow of the Mackenzie River which accelerates both freeze-up (due to the freshwater input of the river) and break-up (due to the advanced break-up of the river).

The Liverpool Bay area is the region least exposed to ice action as it is protected by Tuktoyaktuk Peninsula. Consequently, pack ice incursions are rare in this region.

The exposure of the Nicholson Peninsula area to ice action is generally similar to that of Tuktoyaktuk Peninsula as both regions have relatively shallow beach slopes. Ice movements in the Beaufort Sea follow a general east-west pattern along the Beaufort Gyre and consequently, it might be argued that the Nicholson Peninsula area is more protected. However, it is believed that the sea ice movements which have the greatest implication for coastal processes are those in which pack ice, or an ice feature, is driven into the shoreline. This usually occurs as a result of local wind, current and pack ice conditions and consequently local ice movements are considerably more random. Since the local ice movement directions necessary to cause incursions of pack ice are similar for both the Nicholson Peninsula and the Tuktoyaktuk Peninsula areas, these two regions may be reliably considered to have equivalent exposure to ice action.

Figure 3.11

ICE FLOE DRIFT SPEEDS

(Dickins, 1986)

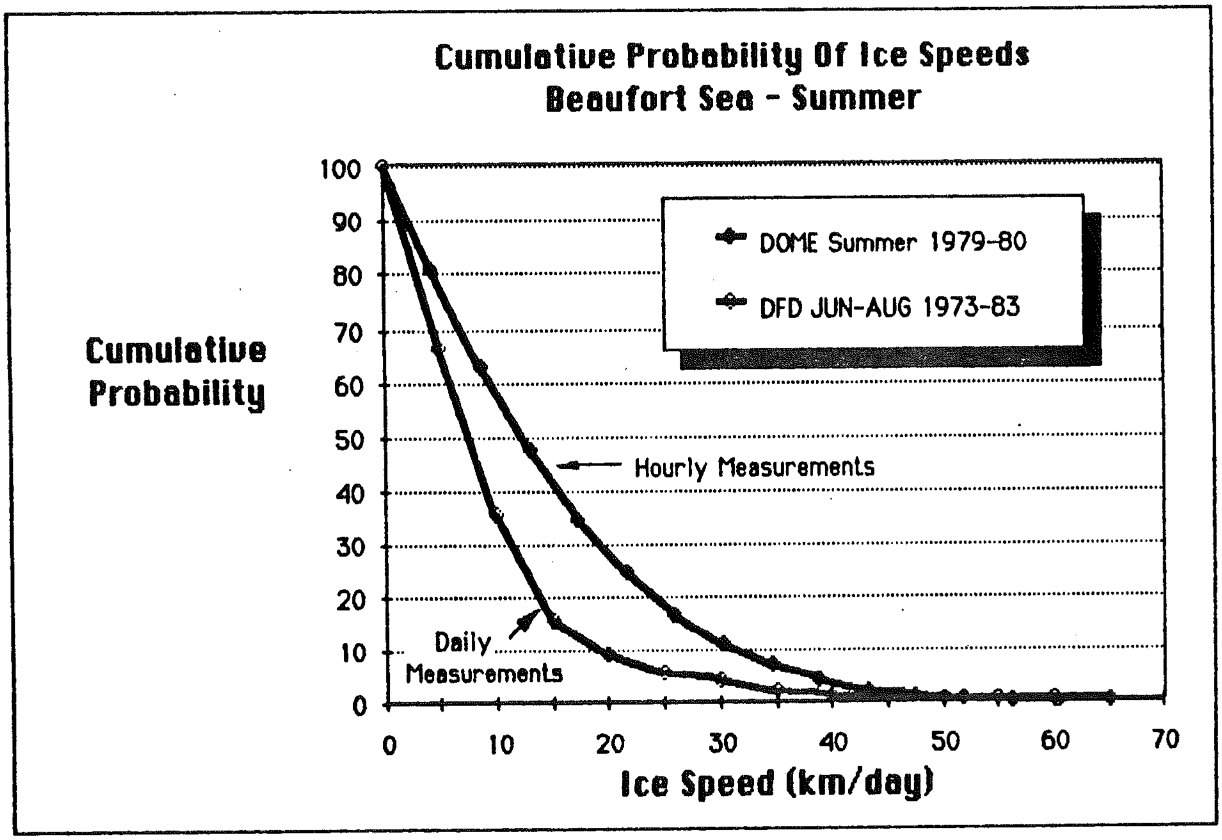


TABLE 3.3

BEAUFORT SEA COASTAL ICE SUB-ZONES

ICE SUB-ZONE	CORRESPONDING GENERAL PHYSIOGRAPHIC REGION (AS IDENTIFIED BY RAMPTON, 1982 - SEE FIGURE 3.2)	CORRESPONDING COASTAL ZONES (AS IDENTIFIED BY HARBER, 1985 - SEE FIGURE 3.2)
Western Yukon	King Point (Western Yukon)	12
Mackenzie Delta	Shallow Bay, Mackenzie Delta, Richards Island, Tuktoyaktuk Peninsula	6 - 11
Liverpool Bay	Liverpool Bay	3 - 5
Nicholson Peninsula	Baillie Island and Cape Bathurst	1 - 2

4. THE INTERACTION OF SEA ICE WITH THE SHORELINE

There are a number of sea ice-shoreline interaction processes which occur that need to be considered for an assessment of the significance of sea ice for coastal processes. These are summarized in Table 4.1.

These fall into two general categories, as follows:

(a) Modification of marine sediment transport mechanisms.

(b) Direct interaction of sea ice with the shoreline.

4.1 Modification of Marine Sediment Transport Mechanisms

The presence of sea ice may affect shoreline processes by modifying the coastal regime. There are three general methods by which sea ice affects marine sediment transport processes, as follows:

(a) limitation of annual duration of open water conditions.

(b) limitation of the wave energy which can be produced in the coastal environment.

(c) attenuation of the wave field which limits the wave energy reaching the shoreline.

During the winter period, sea ice stabilizes the coastline by protecting against marine sediment transport mechanisms. As the Beaufort Sea coast is icebound for about eight to nine months of the year, the significance of this effect is obvious.

During the break-up to freeze-up period, the effect of offshore sea ice on marine sediment transport mechanisms is also important through the limitation of wind fetch. Fetch is the distance over which wind stress can act on the ocean surface to produce waves. In most situations this is limited by the geometry of land features but in the Arctic, pack ice has a similar effect to land (Maxwell, 1980). The geometry of the pack ice edge in relation to wind direction is thus very important in limiting the development of waves along the Beaufort Sea coast.

The important effect of the offshore ice pack was included in Philpott's (1985) hindcast of wave climate at sites along the Beaufort Sea coast. He used estimates of the daily ice edge location to limit fetch in a fourteen year wave hindcast study.

TABLE 4.1

SEA ICE-RELATED COASTAL PROCESSES

SEA ICE-RELATED PROCESS	PERIOD OF OCCURRENCE DURING "ICE YEAR"
I: Modification of marine sediment transport mechanisms:	
• Limitation of annual duration of marine sediment transport mechanisms	Winter
• Limitation of the available wave energy in the coastal environment(by limiting the fetch available for wave generation)	Break-up; Summer; Freeze-up
• Wave energy attenuation (through pack ice and nearshore frazil)	Break-up; Summer; Freeze-up
II: Direct Interaction of Sea Ice with the Shoreline:	
• Ice scour, ice push and ice override – these terms refer to the bulldozing or ploughing of seabed material which results when a moving deep draft ice feature contacts the seabed.	Break-up; Summer; Freeze-up
• Ice wallow – localized erosion and deposition around floating and grounded ice blocks which occurs due to localized high water velocities produced by the motion of an ice feature in a wave field.	Summer; Freeze-up
• Strudel scour – localized erosion resulting from drainage of surface meltwater from the ice sheet.	Break-up
• Transport of sediment adhered to the ice bottom.	Break-up
• Encapsulation of sediment in the ice sheet.	Freeze-up; Break-up
• Transport of sediment deposited on top of the ice sheet.	Break-up

Another problem in the understanding of the effect of sea ice on wave erosion is in defining the "ice edge" as it affects fetch. Typically the southern limit of the Beaufort ice pack is not a solid boundary, but is a zone of gradually decreasing ice concentration, frequently with streamers or projections towards the coast. Philpott (1985) defined the ice edge as the southern limit of three tenths ice cover and others have used values as low as one tenth, while Canadian wave forecasting practice is to define the ice edge as the limit of six tenths ice cover. This arbitrary practice has been in use for many years (METOC, 1987).

Sea ice and frazil ice near the shoreline will also attenuate the wave field thus limiting the wave energy reaching the beach. In the case of sea ice, this is a process which has been both observed in the field (e.g. Taylor, personal communication; Dr. Wiseman, personal communication), studied in the laboratory (e.g. Harms, 1986; Grande et al, personal communication), and modelled theoretically (Rao and Vandiver, 1987). Similar studies have not been conducted for frazil ice.

Several models have been developed for wave attenuation in a continuous ice cover which treat the problem as one of coupling between the waves and the ice cover. The important properties are incident wave lengths and flexural properties. In a broken ice cover, energy is lost primarily through scattering and floe collisions. Rao and Vandiver (1987) developed a model to estimate the wave field at a given distance from the ice edge and within a specified range of ice conditions, but additional work is needed to utilize this approach to derive wave attenuation factors for different ice concentrations. As stated above, current practice is to define an arbitrary concentration at which the ice ceases to affect wave generation or attenuation. While this process is usually temporary (as the waves often erode or reconfigure the ice field), it is nevertheless an important limitation on the wave energy applied to the beach.

This process is most significant at break-up and freeze-up when pack ice is most common in the shore-zone area.

Frazil ice also has a noticeable, attenuating effect on waves but this process has not been modelled or studied experimentally. It is analogous to the effects of fluid mud which has received some scientific study. Wells and Coleman (1981) for instance measured wave height and fluid mud concentration off the coast of Surinam and found that ocean waves were almost fully attenuated by mud concentrations of 1000 mg/l. Their approach might usefully be applied to an examination of the attenuating effects of frazil along the Beaufort Sea coast.

4.2 Direct Interaction of Sea Ice with the Shoreline

The following direct seabed-sea ice interaction processes have been identified from the information survey conducted:

- ice scour, ice push, and ice override
- ice walloving
- strudel scour
- adherence, encapulation and/or surface transport of sediment.

This section provides a summary discussion for each of these processes.

4.2.1 Ice Scour, Ice Push and Ice Override

Sea ice features may interact directly with the shoreline in a number of ways. For clarity of discussion in this report, these processes have been subdivided as follows:

(a) **Ice scour** events in which a deep draft ice feature such as an ice keel ploughs or gouges into the seabed (see Figure 4.2).

(b) **Ice push** events in which a deep draft ice feature or ice floe is driven 'broadsides' into the beach or where ridging occurs along a specific isobath or nearshore ice feature (see Figure 4.2).

(c) **Ice override** events in which the ice sheet overrides the beach (see Figure 4.2).

The actual field sea ice - shoreline interactions are complex and often involve a combination of the above. However, the events delineated above span the continuum of field cases and provide a useful means for understanding ice scouring processes in the coastal zone.

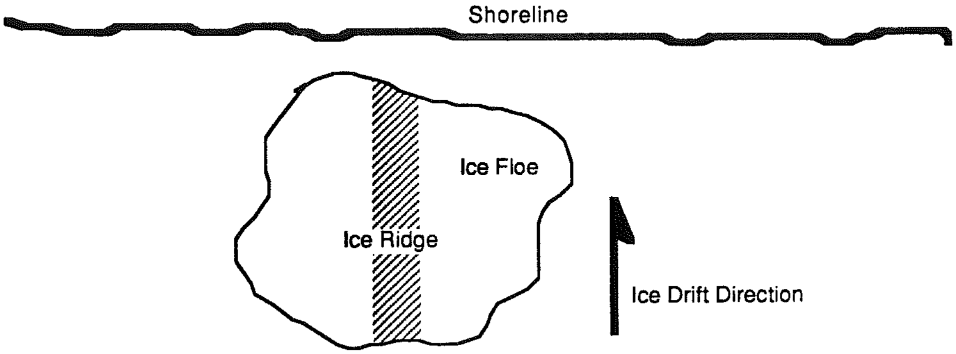
Scouring occurs when a moving ice feature contacts the seabed and/or when ridge-building extends to the seafloor.

Moving ice floes drifting into the shoreline will come to rest when the available kinetic energy is totally expended in doing work to scour the soil. As well, other driving forces (e.g. winds, waves, currents and adjacent pack ice) are likely to act on the ice floe during this event and further contribute to the scour created.

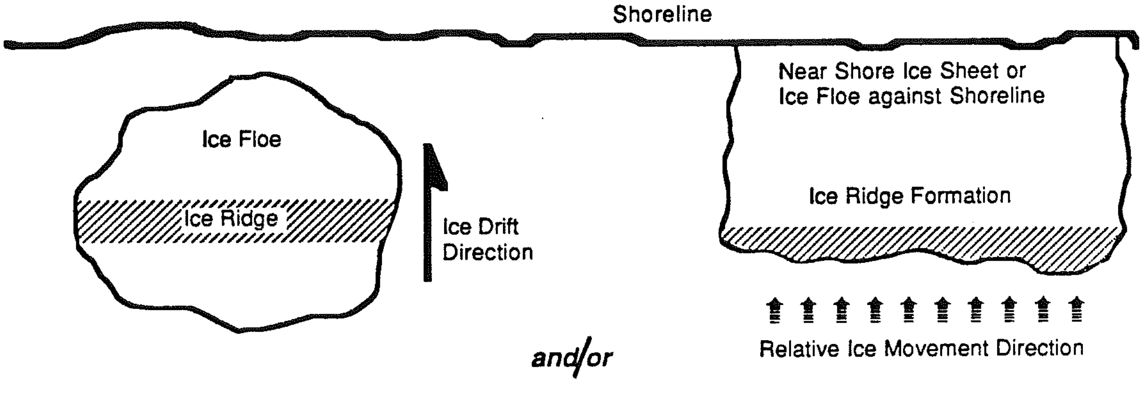
Figure 4.2

SCHEMATIC OF ICE SCOUR, ICE PUSH AND OVERRIDE EVENTS

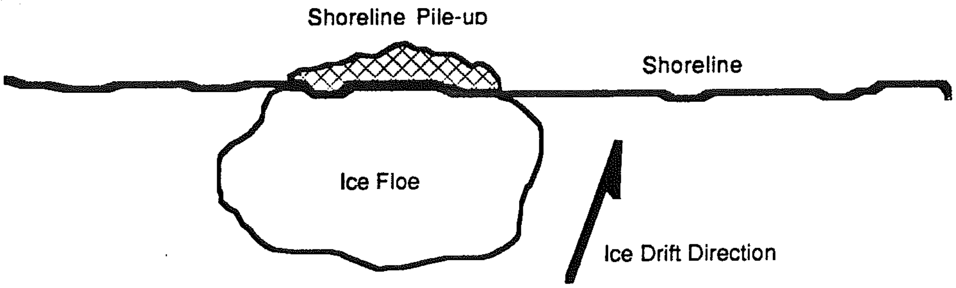
Ice Scour



Ice Push:



Ice Override



Ice scour and ice push events were separated as the potential for sediment movement is significantly greater for ice push. On the other hand, ice scour is a more common occurrence. (This is discussed further in subsequent sections.)

Ice override is essentially a special case of the ice push category. However, this event case is significant as it has the potential to move sediment above the mean waterline. Also, it is an event which has been quantified to some extent in the literature using historical data.

The **grounding** of ice features associated with each of the above ice-shoreline interaction events also affects coastal processes by producing high water velocities near the bottom of partially grounded ice features. This affects sediment deposition and erosion by waves and may produce pits and mounts in the beach when the ice blocks melt or leave the area. Any pits thus formed are a local increase in depth near the shore, and have a potential for indirectly accelerating coastal erosion by increasing the susceptibility of the shore face to wave attack. This is especially true for a coastline like the Beaufort which is in general, sediment starved.

4.2.1.1 Ice Scour and Push

A wide range of projects have been undertaken to date to understand seabed scouring by ice features for offshore Beaufort Sea and eastern Canadian locations. However, most of this research has been conducted with the general objective of investigating the suitability of various offshore seabed oil and gas production installations and consequently is not directly applicable to understanding shoreline processes.

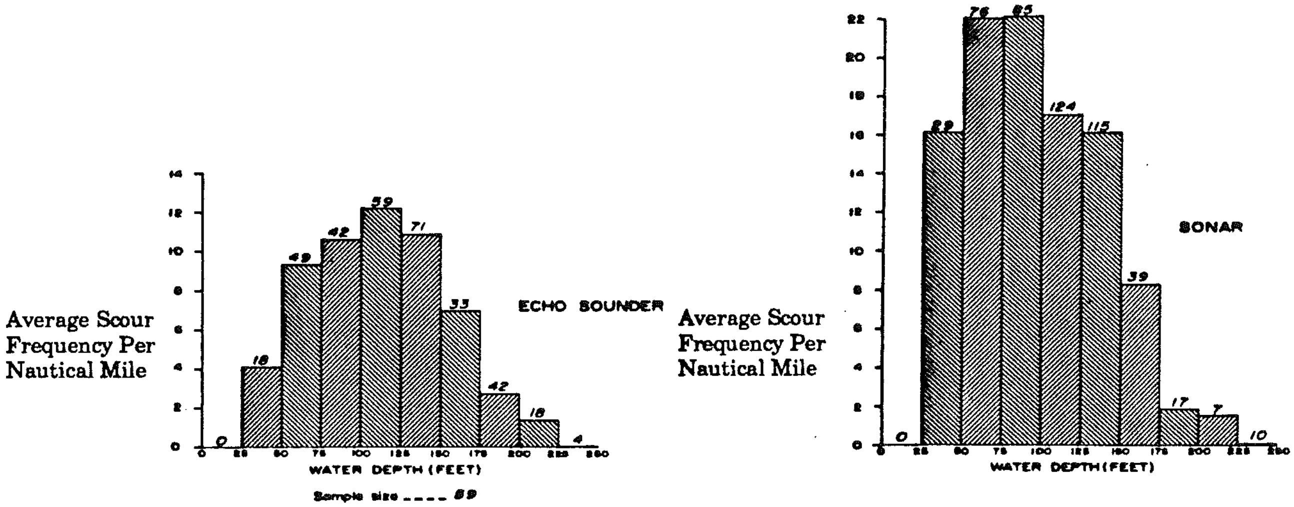
The work to date has predominantly addressed the stochastic portion of this problem. Several field surveys have been conducted to define temporal and spatial scouring frequencies and probable scouring depths (e.g. Pilkington and Marcellus (1981); Weeks et al (1983)). These data provide useful background information for shoreline processes.

However, these surveys have typically been conducted offshore of the littoral zone and unfortunately, cannot be relied upon for quantitative shore-zone analyses. The available data indicate that seabed scouring is more common offshore than nearshore for the Canadian Beaufort Sea (See Figure 4.3). However, it is well known that the nearshore area is quickly reworked by wave action, particularly for cohesionless soils. For example, field observations by Barnes and Reimnitz (1979) showed that extensive infilling of scours (of up to 13 m depth) occurred during storm conditions in the Alaskan Beaufort Sea in 1977. Although data are not available to quantify the frequency of recurrence of these 1977 storm conditions, they are relatively common. Weeks et al (1983) suggested that a return period of 25 years would be a reasonable estimate. As higher frequency events will cause obliteration of the smaller (and much more common) scours, the reliability of nearshore field scour surveys becomes even more questionable.

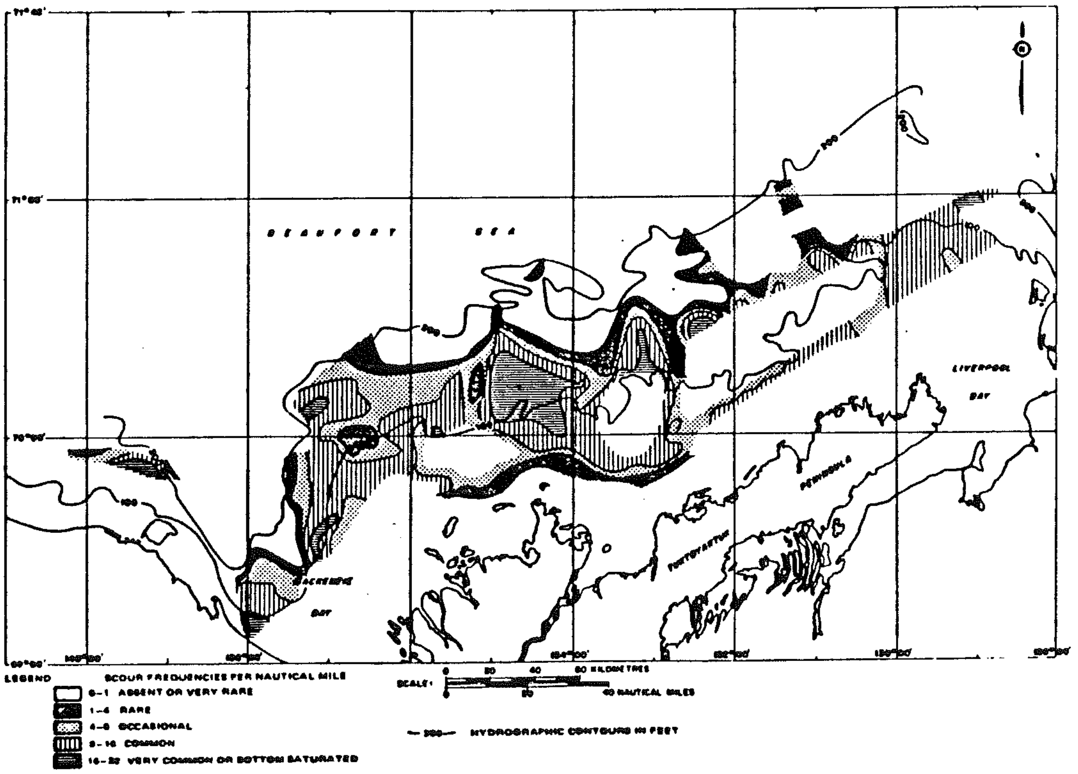
Figure 4.3

BEAUFORT SEA SCOUR FREQUENCIES

(after Hnatiuk and Brown, 1982)



Histograms Showing Frequencies of Scouring in Relation to Water Depths



Frequency of Scouring From Echo Sounder Records

Pilkington and Marcellus (1981) have suggested that the nearshore zone may be considered to be in a steady-state equilibrium with new scours being created at about the same rate as old scours being obliterated. This would provide some confidence in the collected field data. However, Weeks et al (1979) discount this theory for water depths less than 20 m based on the facts that only short term observations are available and that nearshore hydrodynamic and ice conditions are very variable.

In short, it is believed that the available field scour data greatly underestimate nearshore scouring frequencies.

Furthermore, scour data have not been systematically gathered to date over the long-term and consequently, statistical analyses are difficult to apply with confidence. The available information in this area is improving with the recent establishment and monitoring of repetitive scour mapping grids by the ESRF. (These grids however are offshore of the littoral zone.)

Thus it is believed that present field survey information on shore-zone ice scour is inadequate for reliable quantitative analyses.

Work has also been conducted towards understanding the deterministic portion of the ice scour problem. This work has some application for shoreline processes. A number of analytical models have been developed to predict the size of scour created by various ice features for various environmental conditions. These may be divided into the following general categories:

(a) models which balance the available energy of the ice feature with the work done in deforming the soil (e.g. Chari (1979); Fenco (1975)).

(b) equilibrium analyses which balance the forces acting on the ice feature (e.g. Fenco, 1975).

(c) limiting scour depth analyses in which the depth of scour is limited by failure of the ice feature (e.g. Comfort et al (1982); Fenco (1975)).

All of the available models are relatively simplistic at present and suffer from an inadequate knowledge of the processes involved. A limited number of small scale laboratory tests (e.g. Chari (1979); Abdelnour (1980)) have been conducted to investigate basic scouring mechanisms in support of these models. Recently, Comfort and Graham (1986) have conducted a calibration study for some of these analytical models using the available field data sets. Unfortunately, the results of this work must be considered preliminary as the available field data sets are incomplete.

Recently field measurements have been made as part of the Dynamic Iceberg Grounding Study (DIGS) offshore of Labrador to improve basic understanding of scouring mechanisms. This study is the first effort to conduct dedicated field tests and represents a useful resource for the development of more reliable deterministic ice-seabed interaction models. This ESRF-funded project has not yet been publicly reported.

Of relevance to this study, McLaren (1982) has conducted diver observations of ice-shore interaction for Byam Martin Channel in the high Arctic.

McLaren's (1982) observations indicated that ice scouring of nearshore sediments is a common feature for the Byam Martin Channel area. Furthermore, he noted that the vast majority of scouring had a significant onshore-directed component, which produced a net onshore-directed sediment movement. He estimated that 90 to 100% of the shore materials were contributed by ice scour and ice push. He noted that wave energy, which is very low in that area, provides only minor reworking of those sediments. McLaren also re-interpreted observations made by Hume and Schalk (1964) and concluded that ice-pushed sediment piles on Alaskan Beaufort Sea barrier islands could cause almost total replenishment of these islands in less than 1000 years.

Care must be taken in applying McLaren's observations to the Beaufort Sea coast. Although the ice scour shoreline sediment transport processes which he observed also occur along the Beaufort Sea, their overall effect on the total sediment transport budget is expected to be less significant as the wave energy of the Beaufort Sea coast is greater than for Byam Martin Channel. Thus, the contribution of ice scour to the overall transport of shoreline sediment may be masked by normal marine processes, such as wave-related transport.

This theory has received recent support by E. Reimnitz and P. Barnes at the USCG who believe that the bench which occurs at the 18 m isobath almost continuously along the Alaskan Beaufort Sea coast is formed by ice-related transport.

The critical parameters governing sediment transport by ice scour and ice push for the Beaufort Sea include:

(a) The relative movement directions of the ice feature and its keel, and the beach (see Figure 4.2).

(b) The spatial and temporal scouring frequency.

(c) The size and shape of the scouring ice feature.

(d) The size of the scour (e.g. scour depth, geometry and width).

(e) The properties of the soil and the bedslope.

It is clear that onshore movements where the scouring ice keel is oriented 'broadside' to the beach (i.e. "ice push" as shown in Figure 4.2) will move large volumes of sediment up the beach. On the other hand, ice floe movements in the direction of the keel (i.e. "ice scour" as shown in Figure 4.2) will move significantly less sediment.

Exploratory calculations of the average upslope sediment transport due to ice push and ice scour along a typical 1 km wide section of the Beaufort Sea coastline are given in Table 4.2. They suggest an annual upslope movement **per event** of 5000 m^3 due to ice push and 424 m^3 due to ice scour. The calculations are exploratory and have wide margins of error, but clearly indicate the significance of the direction of floe motion in relation to the shoreline and the ridge keel (i.e. ice push is more important than ice scour).

A very crude approximation of the total upslope transport due to these processes can be obtained from a measure of the total length of coastline subject to these processes. This is approximately 650 km (length of Canadian Beaufort Sea coast directly exposed to ice action, excluding Liverpool Bay at 1:5,000,000). Thus the total **annual** upslope sediment transport due to ice push could be approximately 3.2×10^6 m^3 and due to ice scour is 2.8×10^5 m^3 **for the Canadian Beaufort Sea.** For comparison, the annual sediment input to the Beaufort Sea is estimated as 85.5×10^6 m^3 from the Mackenzie River, 3×10^6 m^3 from wave erosion along the coast and 4.5×10^5 m^3 from several rivers in the Yukon. These predictions span a wide range and are considered preliminary (see Table 4.2).

Ice scouring events (in which the ice feature ploughs into the seabed) are likely to move small volumes of sediment and are thus relatively insignificant as direct agents of sediment movement.

On the other hand, ice push events (where an ice feature is driven 'broadside' up the beach profile) are capable of moving significant sediment volumes. These events are expected to be rare, however, as there must be sufficient driving forces and/or floe momentum to drive the floe onto the beach. Also, it is unlikely that the floe would be driven up the beach without rotating.

Data are required to quantify the probability of these events. Some understanding may be gained from available statistics for shoreline ice override frequencies (which are presented in the next section). These statistics indicate that shoreline override is relatively rare. However, these statistics are expected to underpredict the frequency of shoreline ice push events as ice features often ground nearshore without overriding the beach.

Consequently, it is believed that the first priority of research activities in this area should be to investigate ice motions and directions in the shoreline area. Both ice push and ice scour require that relatively thick floes drift close to the shore and are therefore most likely to be found to the east of Mackenzie Bay, where nearshore slopes are steepest. Coincidentally, summer ice incursions to the shore area are most frequent here.

TABLE 4.2

FIRST ORDER ESTIMATES OF SEDIMENT TRANSPORT BY ICE SCOUR

PREDICTED UPSLOPE SEDIMENT TRANSPORT VOLUMES FOR A 1 KM WIDE FRONT:

1. Ice Push (as per Figure 4.2): 5,000 m^3/yr
2. Ice Scour (as per Figure 4.2): 424 m^3/yr

ASSUMPTIONS COMMON FOR BOTH CASES:

1. Scouring occurs to a depth of 1 m in both cases on the assumption that permafrost is encountered at this depth which prevents further scouring.
2. A relatively small ridge 1 km long contacts the seabed.

ASSUMPTIONS SPECIFIC TO ICE PUSH CASE:

1. The bed slope is 1:500.
2. The ridge keel is rectangular in cross-section.
3. The ridge keel is oriented parallel to the shoreline and the ice floe drifts perpendicular to the shoreline.
4. An annual spatial scouring probability of 2% was assumed based on the fact that this event will be rarer than Case 2, which was assumed to have a 20% probability of occurrence (see notes for ice scour case and Appendix B).

ASSUMPTIONS SPECIFIC TO ICE SCOUR CASE:

1. The scour width is 3 m (see Appendix B).
2. The ridge keel drifts at 45° to the shoreline. As discussed in Appendix B, this is a rare event, as the available scour statistics indicate that alongshore scouring is predominant. This assumption however produces a maximum predicted sediment transport volume.
3. Sediment particles are displaced at an angle of 45° to the drift direction (see Appendix B).
4. An annual spatial scouring probability of 20% was assumed (see Appendix B for further discussion).

4.2.1.2 Ice Override

Shoreline ice pile-ups created during override events may contribute a net sediment movement by bulldozing soil ahead of the pile-up. An exhaustive historical review of these events has been undertaken by Kovacs and Sodhi (1980) who analyzed aerial photography for the Alaskan Beaufort Sea. As well, Harper and Owens (1981); also Harper (1980) reviewed aerial photographs to estimate the frequency of ice override events. Summary results are presented in Table 4.3 below which suggest that ice override and associated scouring are relatively rare along the Chukchi and Beaufort Sea coasts of Alaska. The results are biased to some extent in that the analysis only evaluated override features and associated ice scours that were visible on aerial photographs (i.e., large events) and smaller events may have gone undetected.

TABLE 4.3

SUMMARY OF ICE OVERRIDE EVENTS FROM THE ALASKAN CHUKCHI AND BEAUFORT SEA COASTS (After Harper and Owens, 1981)

	LENGTH OF SHORELINE SURVEYED	NUMBER OF EVENTS OBSERVED	NUMBER OF SEVERE EVENTS OBSERVED
Beaufort Sea Coast	611 km	11	4
Chukchi Sea Coast	970 km	9	6
TOTAL	1,581 km	20	10

Similar ice override statistics are not publicly available for the Canadian Beaufort Sea. However, the available historical photographic data has been informally reviewed by J. Harper during the conduct of a recent shore-zone analysis for the Canadian Beaufort Sea, (Harper (1985)). During this study, no evidence of ice override events was observed (J. Harper, personal communication).

There are no systematic statistics on shore-zone scour depths, but 1 m is probably a maximum scour depth (J. Harper, personal communication). Overrides that occur between fall freeze-up and spring break-up are unlikely to cause significant scours because beach sediments are frozen below the surface. Even during summer months, backshore areas along arctic coasts have a permafrost table close to 1 m below the beach surface (Owens and Harper (1978)).

In 1982, J. Harper made observations and measurements of an ice ride-up event along Spy Island on the Alaskan Beaufort Sea coast (Figure 4.3A). His observations are summarized in Appendix C of this report. They provide valuable insight towards the probable significance of ice override and shoreline pileup as it is one of the few data sets where measurements have been made of the sediment pile associated with the ride-up.

That event is estimated to have moved a total sediment volume of approximately 700 m^3 (over the 350 m of shoreline over which the ride-up event occurred)

This amount is small in relation to estimates of longshore transport for that area (of approximately 5000 to 10,000m^3/yr). Furthermore, it should be noted that ice override is a relatively rare event (as demonstrated by Table 4.3) and consequently the net annual sediment contribution on a long-term basis will be significantly less. These first order approximations suggest that ice-pushed sediment provides only a small part of the total sediment budget for Spy Island. As ice-push has been observed to be less common in the Canadian Beaufort Sea, one expects an even smaller contribution there.

It is probably reasonable to assume a similar rate of override if non-susceptible areas such as Liverpool Bay are ignored. Assuming an average rate of 0.01 events per km of susceptible coastline (see Table 4.3), 650km of susceptible coast on the Canadian Beaufort and 700 m^3 of sediment movement per event (see Section 4.2.1), the annual upslope movement due to ice override can be estimated at 4.5 X $10^3 m^3$.

Thus, it can be seen that some information is available to allow an assessment of the significance of this transport mechanism. This information however is preliminary.

The critical information gaps are considered to be:

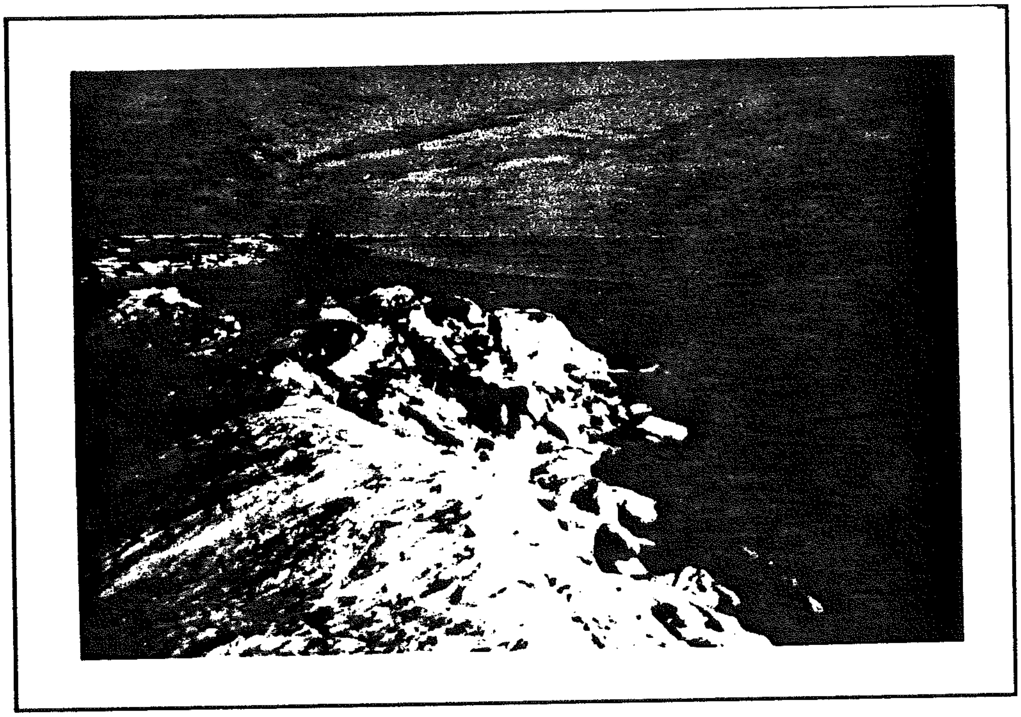
(a) the temporal and spatial frequency of ride-up events.
(b) the net quantity of material moves up the beach during an event.
(c) the fate of the reworked material.

4.2.2 Ice Wallowing

"Ice wallow" relief has only been reported by Reimnitz and Kempema (1982) who carried out accurate beach surveys near Reindeer Island, Alaska. It has not been observed for the Canadian Beaufort Sea. Reimnitz and Kempema (1982) measured numerous closed depressions and mounds about 50 to 100 m in diameter and 2 to 3 m in relief. They also observed that these features were obliterated over the course of two to three years; however, new ice wallow features had formed during this period.

Figure 4.3A

ICE OVERRIDE EVENT AT SPY ISLAND, ALASKA, August 1982



Sediment on Ridge Crest

Deposition of Gravel as Ridge Melts

Figure 4.3B

ICE OVERRIDE EVENT AT SPY ISLAND, ALASKA, August 1982

Remnant Override Ridge Along North Shore of Spy Island

It is worth noting that they used very accurate navigation control to make these measurements. Therefore, the relative paucity of observations in the literature is not believed to be necessarily indicative of the significance of this ice-related sediment transport mechanism.

Ice wallow relief is believed to be caused by intensified flow patterns around nearshore ice blocks in a wave field. Reimnitz and Kempema (1982) collected time lapse movies at the field site in which ice blocks 4 to 5 m in thickness were observed to heave continuously in a wave field. This wave field also produced pulsating and rocking ice block motions. (This time lapse movie is available for viewing at the United States Geological Survey.)

Ice wallow relief may be formed both under ice blocks which are grounded on the beach and under ice blocks floating nearshore. Figures 4.4 and 4.5 describe the formation of ice wallow relief schematically for each of these cases.

The process commences with high local flow rates at the base of the ice block which scour the beach material. A crater is produced which eventually allows the ice block to become free floating. At the same time, the ice block may heave in response to the prevailing wave conditions. This produces a pumping action that further contributes to the local scour of the beach material. Erosion will stop when the water depth beneath the ice block is sufficiently large that local currents are below the critical soil erosion velocity.

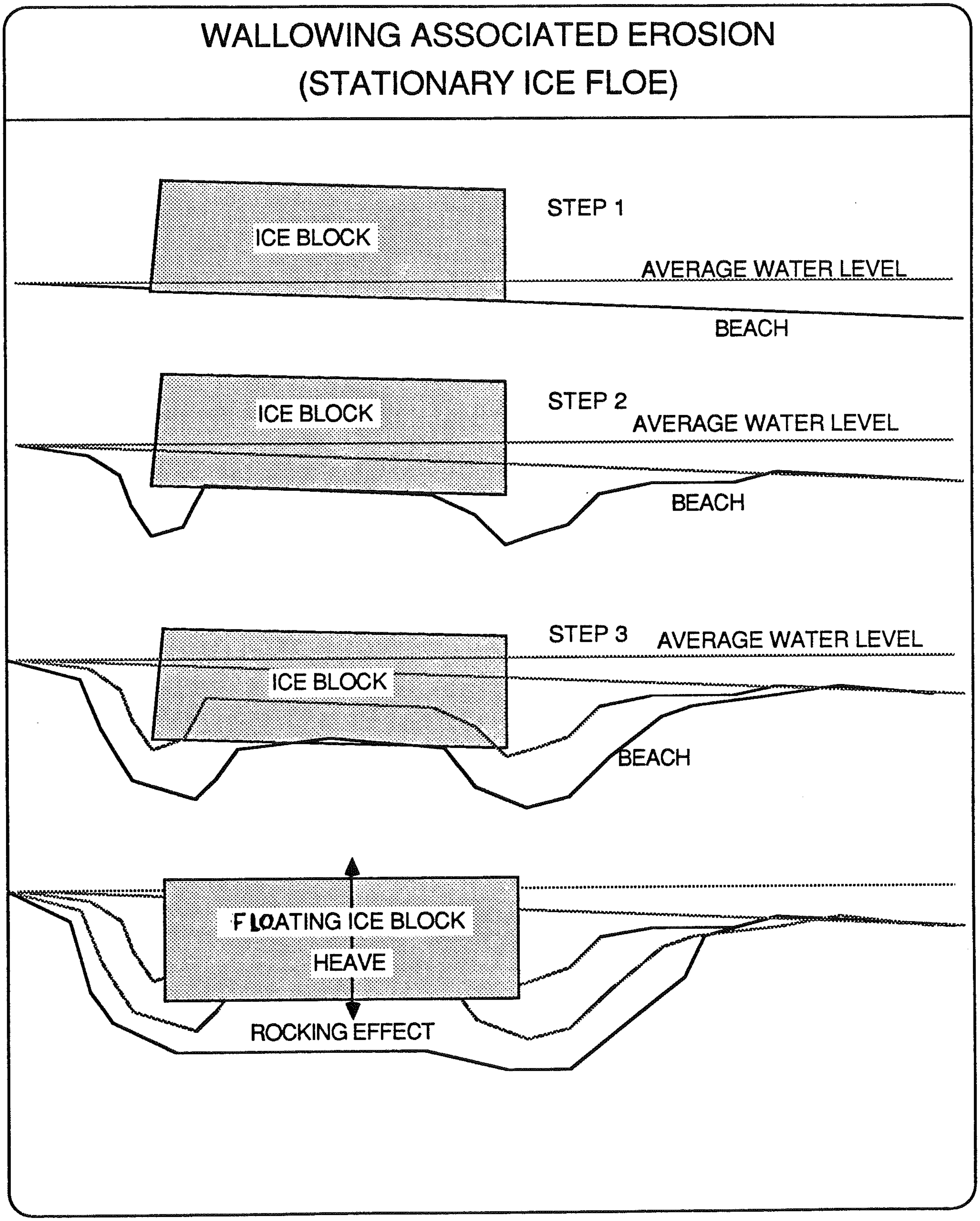
The amount of scouring which occurs due to ice wallowing is dependent upon several factors including:

- local ice conditions
- wave characteristics and the occurrence of storm surges
- bench slope and water depth
- soil type.

Local Ice Conditions: Important ice parameters include the draft and number of grounded ice blocks; and the size, thickness and coverage of ice floes in the local nearshore area.

The depth of ice block exposed out of the soil affects the amount of scour that is possible. If the ice block is only lightly grounded, then little scouring is necessary before the ice block becomes free-floating. This may limit the quantity of scour either by allowing the ice block to drift offshore or by reducing flow velocities to below the critical scour velocity under the ice block. Deeper scours will be produced under ice blocks that are heavily grounded as these blocks are likely to be trapped in the craters produced and unable to move away.

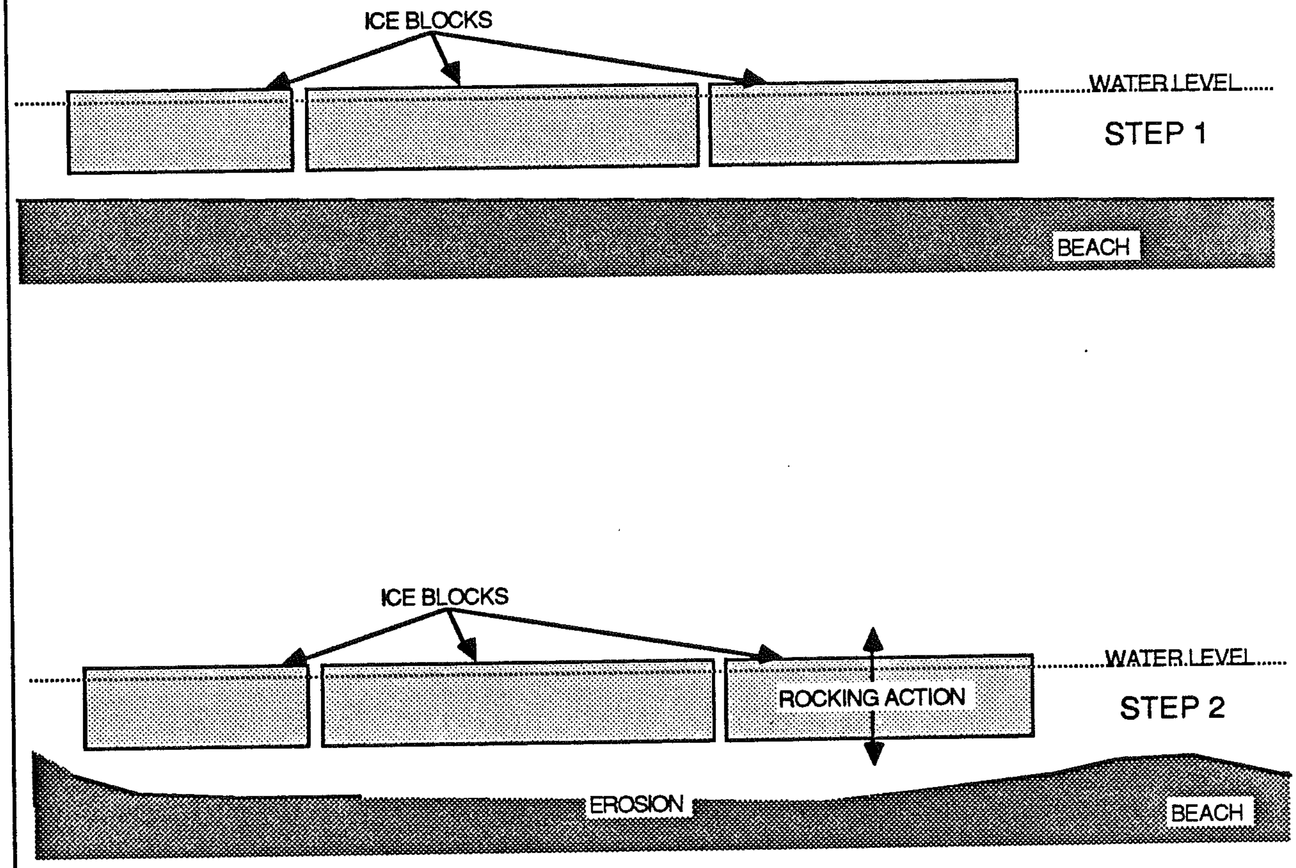
FIGURE 4.4



WALLOWING ASSOCIATED EROSION
(STATIONARY ICE FLOE)

FIGURE 4.5

WALLOWING ASSOCIATED EROSION (FLOATING ICE FLOES)



The size, thickness and coverage of ice floes in the local nearshore area affect the quantity of scour both by governing the amount of wave energy which reaches the shoreline (and the wave attenuation that occurs) and by governing the motions of the individual ice blocks in the wave field. Also, the ice coverage affects the area of beach over which ice wallow relief may be produced.

One case which has the potential to affect large beach areas is that of an ice floe ensemble drifting alongshore in a wave field.

Wave characteristics and the occurrence of storm surges: Storm surges are one mechanism by which ice blocks may become grounded on the beach. Ice blocks driven onshore at high storm surge levels may be heavily grounded after the storm surge subsides. Ice wallowing may then occur around these ice blocks.

The wave characteristics are important as they affect the motion of the ice block in the wave field. Small ice blocks in a long period wave field will follow the water particle motions. On the other hand, only small ice block motions will result for large ice pieces in a short period wave field. Figure 4.6 shows the heave response amplitude operator for cubical, spherical and cylindrical ice blocks for deep-water conditions. This figure shows that a dynamic amplification of more than four times is possible for cubical ice blocks.

Beach slope and water depth: The beach slope and the water depth affect the wave energy that reaches the littoral zone and the local flow velocities beneath the ice block.

The presence of a shallow beach provides a natural defense which reduces the wave energy reaching the beach by attenuation and the formation of breaking waves. Thus, greater ice wallow relief is to be expected for steeper beach profiles.

Sediment type: The sediment type is important for a number of reasons. One is that it governs the critical water velocity necessary to cause sediment transport.

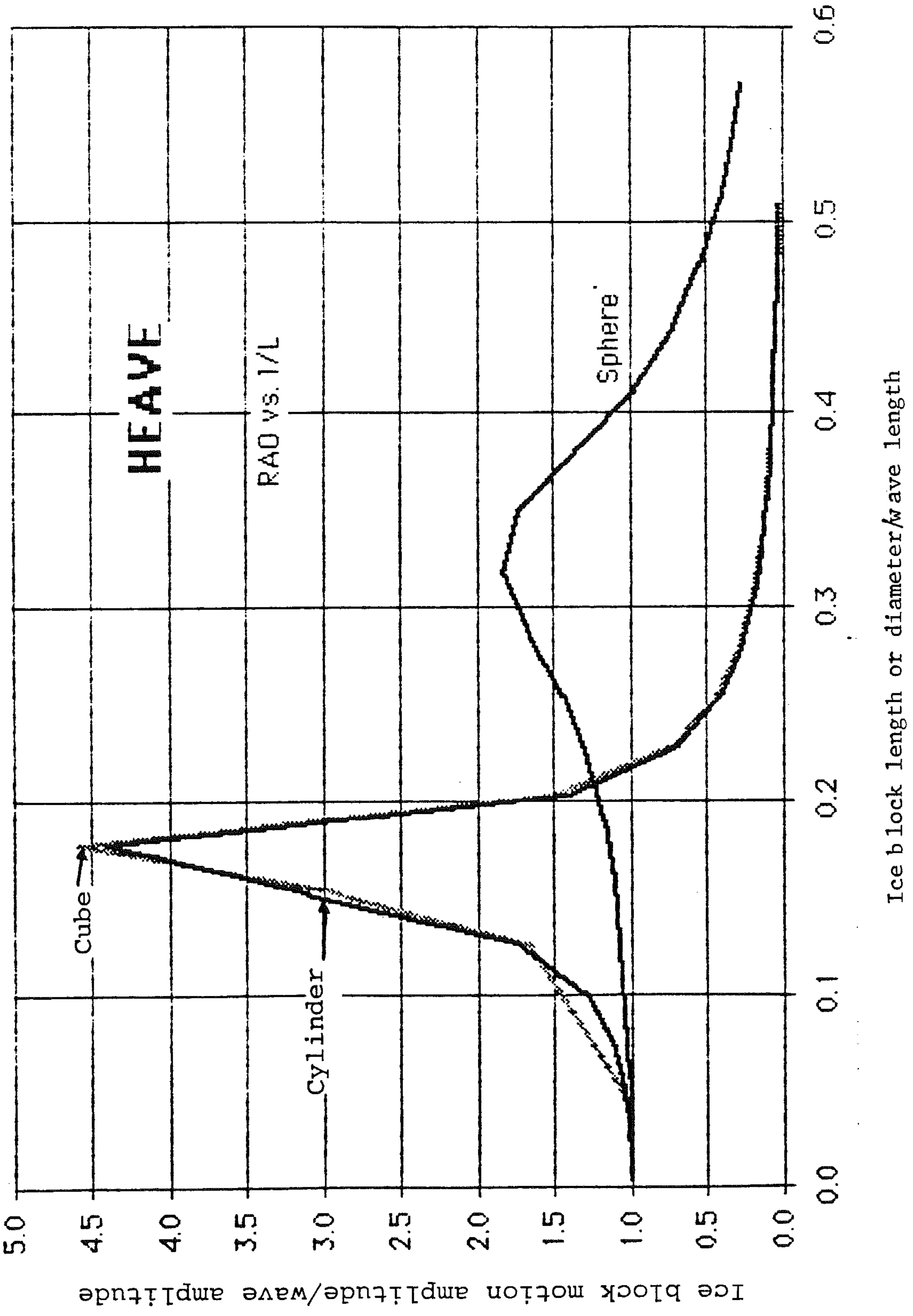
The sediment type also greatly affects the possibility that sediments may be placed in suspension by ice wallowing actions and then moved out of the littoral zone by the prevailing wave and current conditions. This scenario is most likely with fine-grained sediments.

4.2.3 Strudel Scour

The phenomenon of strudel scour has been recognized as a uniquely arctic offshore process that affects the nearshore area of the Beaufort Sea in relatively shallow water near river mouths.

Figure 4.6

ICE BLOCK HEAVE MOTIONS IN A WAVE FIELD



NOTE: This figure applies to the deepwater case.

This phenomenon has been observed and studied for the Alaskan Beaufort Sea. Most observations of strudel scours have been made seaward of the Sagavanirktok River in conjunction with the oil industry's concentrated efforts in that area. Grantz et al (1982) mapped surface current patterns at break-up and regions of strudel scour for the Alaskan Beaufort and northeast Chukchi Sea shelves (see Figure 4.7).

Strudel scours have been observed and monitored on sonar records by the United States Geological Survey (e.g. Reimnitz and Bruder (1972); Reimnitz, Roderick and Wolf (1974)). Measurements have been made of the infill rate of strudel scours to provide a basis for estimating annual sediment transport (Reimnitz and Kempema, (1982)).

For the Canadian Beaufort Sea, less information is available regarding this phenomenon. Strudel scours have not been observed by S. Blasco (personal communication). G. Spedding (personal communication) of Esso Resources Canada has noted that overflow occurs out to approximately 15 km from shore in Mackenzie Bay. However, he has never seen any large strudels as most of the above-ice water appears to be drained through relatively small cracks. He has never found any seabed strudel scour craters but he believes they would fill in quickly in the delta.

P. Lewis (personal communication) has observed strudel scour holes in the ice cover at the Babbage River; however, no strudel scour craters have been found. It is likely that strudel scours are filled quickly there as the soil material is cohesionless.

Strudel scours are a by-product of the annual arctic break-up cycle and are produced when relatively warm river spring overflow is drained through the nearshore sea-ice canopy (see Figure 4.8 for schematic). As peak spring runoff from these northward-flowing rivers discharging into the Beaufort Sea occurs in advance of break-up of the nearshore ice cover, flooding results at the river mouths. This floodwater eventually drains into the sea water below through thaw holes, seal breathing holes and cracks in the ice sheet. The resulting vertical discharge scours the seabed and may create large local depressions. (Depressions up to approximately 10 m in depth and 3 m in diameter have been reported (Reimnitz and Kempema, 1982)).

Strudel scours appear on sonographs as distinct features quite different from those related to ice scour. Strudel scours generally appear either as solitary roughly circular depressions with a ridge around part or all of their rims or they may be arranged in linear groups where floodwater has drained through cracks in the ice cover.

Figure 4.7

ALASKAN BEAUFORT SEA STRUDEL SCOUR PATTERNS

(after Grantz et al, 1982)

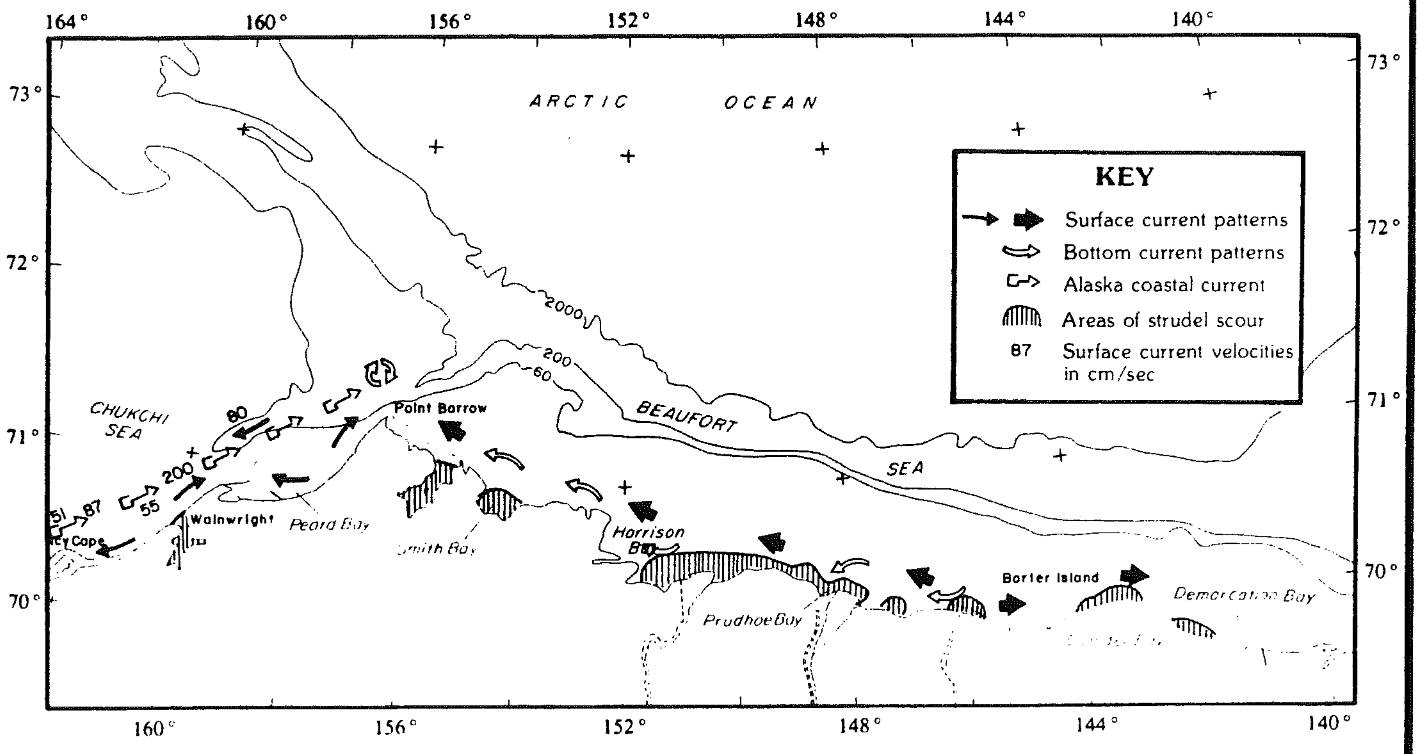
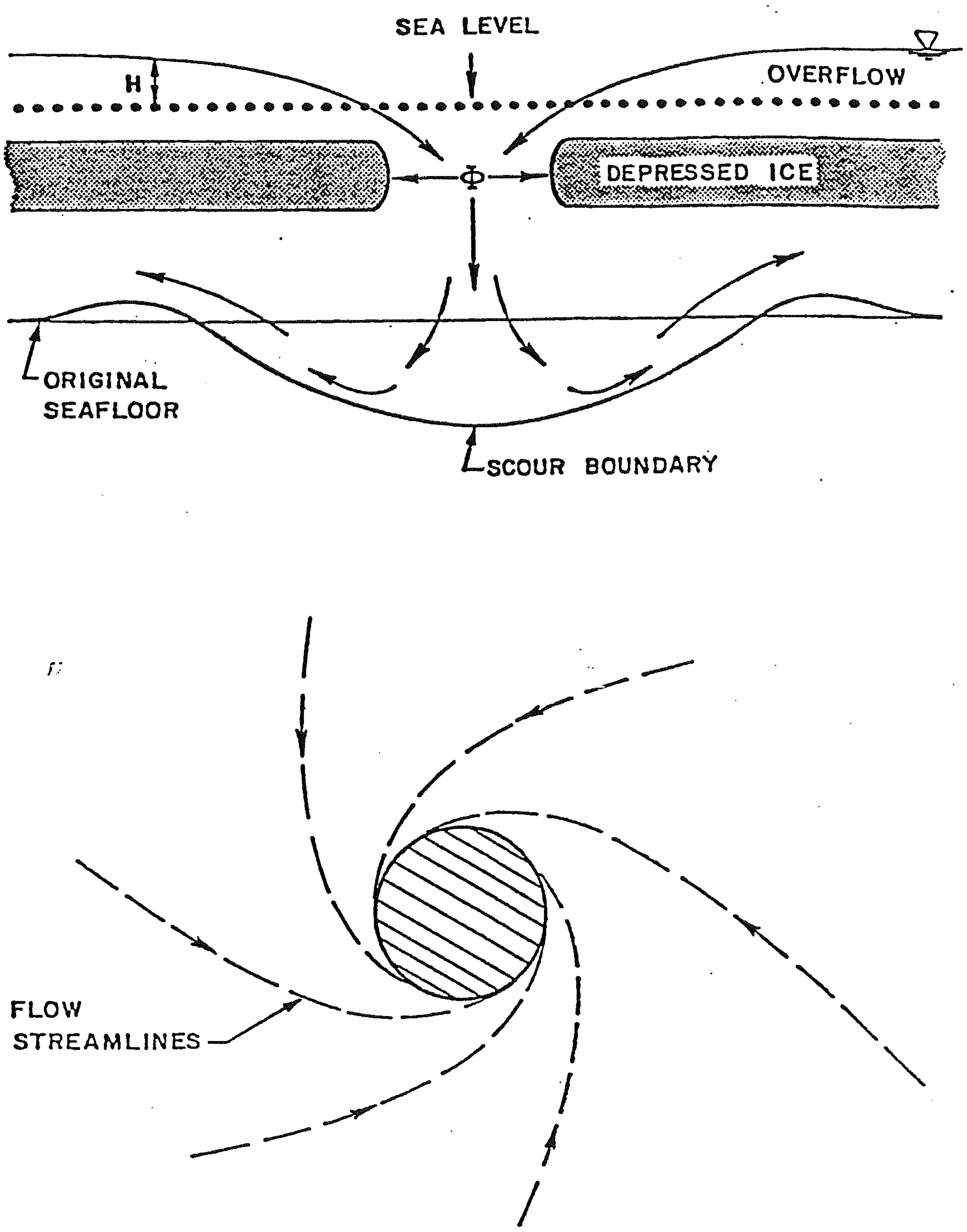


FIGURE 14. Current patterns and regions of strudel scour on the Alaskan Beaufort and northeast Chukchi shelves. (Source: Grantz et al. 1982.)

Figure 4.8

SCHEMATIC OF STRUDEL SCOUR PHENOMENON



Strudel scour patterns vary from year to year. In 1971, Walker (1974) found that approximately two-thirds of the 140 strudels counted were in the eastern one-third of the overflow band for the Sagavanuktok River. However, in 1973, the bulk of the drainage occurred at pressure ridges along the seaward edge of the delta.

Most strudel scours have been observed in water depths ranging from 1.5 m to 5 m. For deeper water, the frequency of strudel scour drops significantly probably reflecting the reduced scouring efficiency of the strudel jet in deeper water.

Annual observations of strudel scour sites at the Sagavanuktok River delta (along the Alaskan Beaufort Sea Coast) by the United States Geological Survey indicate that strudel scours infill quickly. By the third year, the seabed was restored to its original flat surface (Reimnitz, USCG, personal communication).

It is not clear why strudel scours have only been observed and reported to date for the Alaskan Beaufort Sea. West of the Mackenzie River, in the western Yukon region, shoreline conditions are similar to those along the eastern portion of the Alaskan Beaufort Sea and consequently some strudel scours are expected there (e.g. at the mouth of the Babbage River). It is suspected that the lack of observations here reflect a combination of relatively infrequent contact with this region during the critical spring runoff period (when strudel scours are visible on the surface) and the fact that strudel scours infill quickly. (To date, oil exploration activities have been largely concentrated in areas east of this zone).

Erosion Due to Strudel Scour: The amount of strudel scour which occurs is dependent upon a number of factors, including:

- the discharge head
- the size of the strudel hole in the ice cover
- the discharge rate and duration
- the seabed soil properties
- the water depth.

Basic laboratory tests have been conducted by Rajaratnam (1981) who investigated the problem of a vertical water jet impinging on a plane horizontal sediment surface.

Figure 4.9 schematically describes Rajaratnam's (1981) vertical jet model and the predicted strudel scour depth.

His analysis predicts that a jet diameter of 0.3 m with a head of 0.6 m will produce a strudel scour 4.5 m deep in 2.5 m of water for fine-grained sand seabed material (of 0.1 mm diameter).

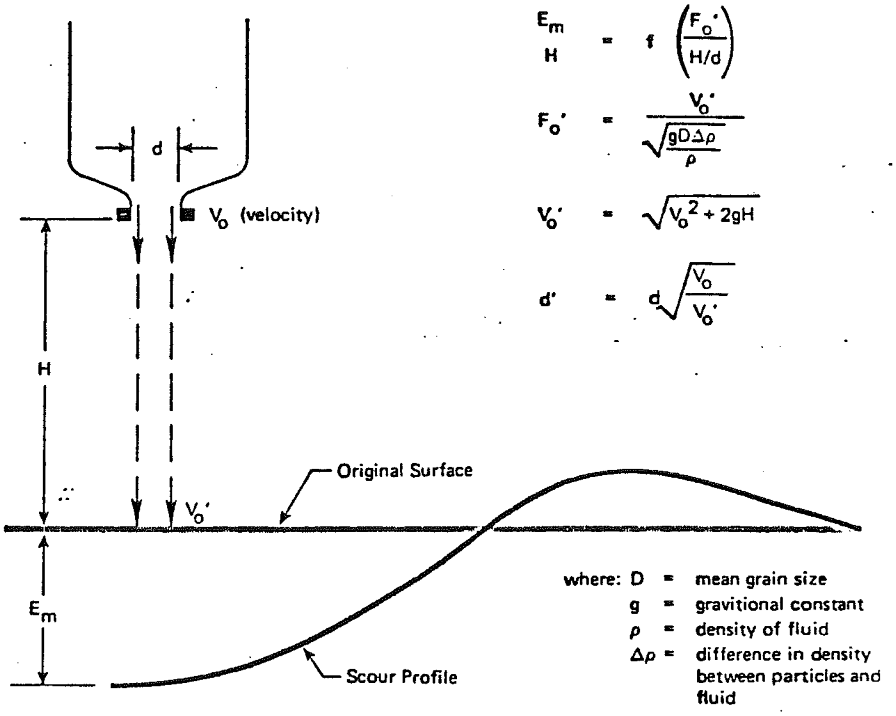
These exploratory calculations are considered preliminary for a number of reasons. Firstly, field values for critical model input parameters (e.g. hole size, discharge head) are not available

Figure 4.9

VERTICAL JET MODEL AND ASSOCIATED SCOUR DEPTH

(after Rajaratnam, 1981)

Note: Shield's Curve criterion used to define critical shear stress for sediment transport for this model (see Figure 4.10)



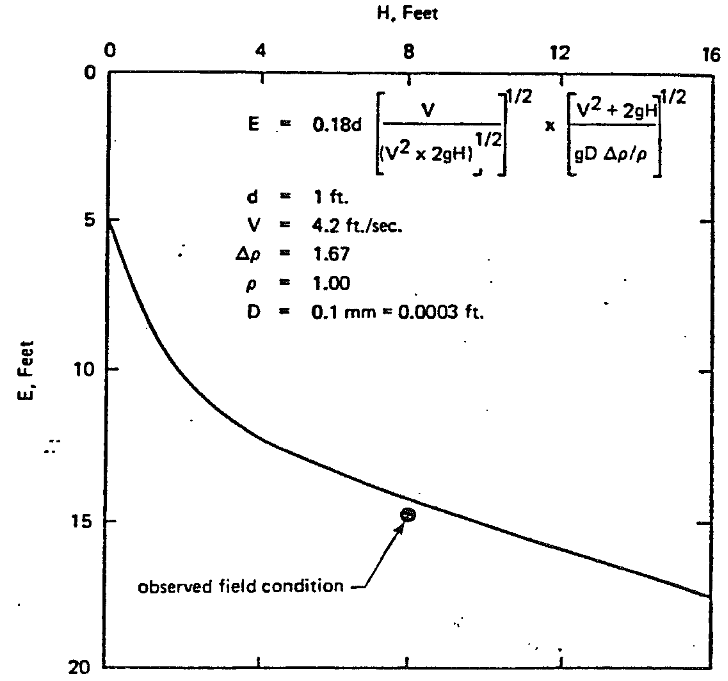
$$\frac{E_m}{H} = f\left(\frac{F_o'}{H/d}\right)$$

$$F_o' = \frac{V_o'}{\sqrt{\frac{gD\Delta\rho}{\rho}}}$$

$$V_o' = \sqrt{V_o^2 + 2gH}$$

$$d' = d\sqrt{\frac{V_o}{V_o'}}$$

where: D = mean grain size
g = gravitional constant
ρ = density of fluid
$\Delta\rho$ = difference in density between particles and fluid

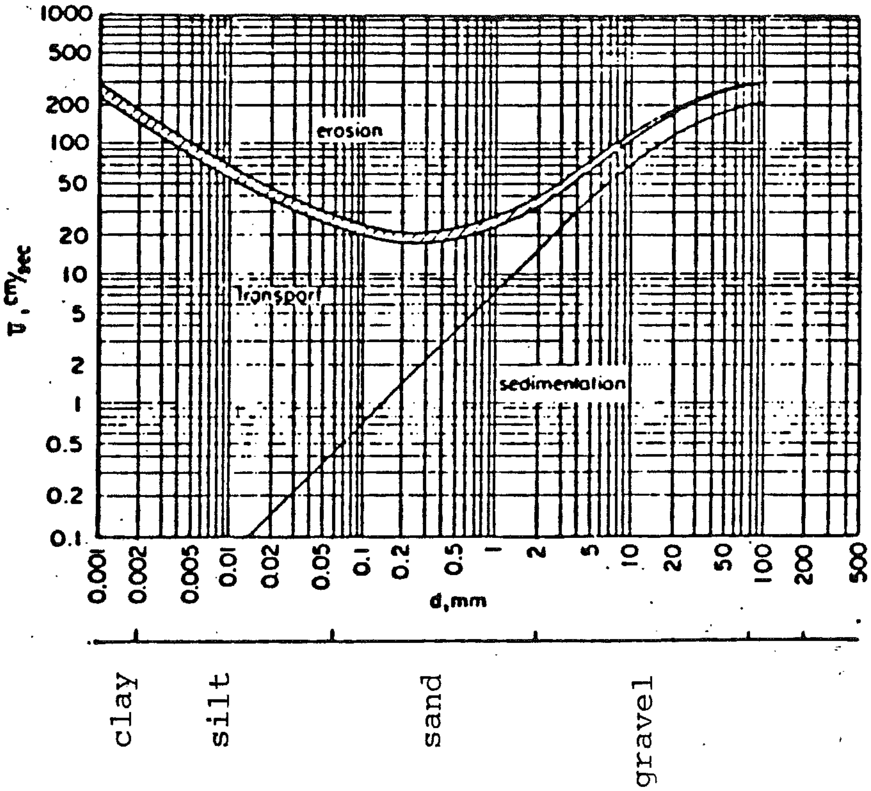


$$E = 0.18d\left[\frac{V}{(V^2 \times 2gH)^{1/2}}\right]^{1/2} \times \left[\frac{V^2 + 2gH}{gD\,\Delta\rho/\rho}\right]^{1/2}$$

d = 1 ft.
V = 4.2 ft./sec.
$\Delta\rho$ = 1.67
ρ = 1.00
D = 0.1 mm = 0.0003 ft.

Figure 4.10

SHIELD'S CURVE CRITERION FOR SEDIMENTATION AND EROSION



and were assumed. Nevertheless, the general agreement between the predicted strudel scour depths and the strudel scours measured in the field is encouraging.

Rajaratnam's analysis is relatively simplistic and is a first cut at the problem. Most critically, the model considers only the hydrostatic head which drives the jet and ignores the vortex flow which accompanies the jet. This will lead to an underestimation of the total discharge which will result in an under prediction of the strudel scour depth. (A more detailed discussion and treatment of this problem is provided in Appendix E.)

The relationship of the static scour depth (i.e. the scour depth measured after the jet was stopped which is predicted by Rajaratnam's analysis) and the dynamic scour depth (which occurs when the jet is discharging) is another uncertainty. During Rajaratnam's test, the dynamic scour depth was two to three times greater than the static scour depth.

Other uncertainties include the selection of appropriate values for the discharge head (as the ice cover will deflect downwards due to the weight of the surface floodwater) and the ice hole size (as the hole is likely to rapidly erode and increase in size during the strudel scour process).

Nevertheless, Rajaratnam's analysis is useful for first-order calculations and for understanding the significance of the various parameters affecting strudel scour.

4.2.4 Sediment Transport by Bottomfast Ice, In-Ice Encapsulation, and On-Ice Surface Transport

Sediment transport may result from three general ice sediment content mechanisms:

(a) On-ice sediment transport. Fluvial sediments may be deposited by rivers discharging over the sea ice at break-up (e.g. Taylor (1976)).

(b) In-ice sediment transport. At freeze-up, wave action may mix and trap sediments in the frazil and subsequently, the sheet ice which is formed.

(c) Bottomfast ice formation. In the nearshore area, the ice sheet will freeze to the seabed. At break-up sediment adhering and frozen to the ice bottom may be carried out of the littoral zone if the ice sheet does not melt in-place.

On-Ice Sediment Transport: At break-up, flooding of the nearshore ice cover is common for areas at the mouths of rivers. Typically break-up of the northward flowing rivers occurs before the sea ice cover breaks up resulting in overflooding. Also major rivers such as the Mackenzie River are relatively shallow and consequently, the presence of an ice cover over the river channel(s) severely restricts the flow.

This mechanism may result in the deposition of fluvial material on the ice surface at the river mouth. These sediments may be either carried out of the littoral zone if the ice sheet moves intact or may be deposited on the seafloor if the ice sheet melts in place.

There is little information available with which to evaluate the significance of this transport mechanism. Few operators or researchers active in this field have observed this process. This may give some insight into the significance of this mechanism; however, it should be remembered that no observation programs have been undertaken specifically to investigate this process.

G. Spedding (personal communication) has noted that the Mackenzie River overflow is 'comparatively clean' in the delta and that the ice surface is clean after the overflow has drained.

On the other hand, Taylor et al (1976) reported that a significant quantity of sediment was deposited on the ice cover for the Somerset Island area of the Canadian high Arctic.

The Mackenzie River carries a large sediment load which significantly affects coastal process and thus this mechanism has the potential to be important.

However, there are some important differences between the Beaufort Sea and the high Arctic.

Typically the nearshore ice cover in Shallow Bay melts in place and therefore most of the on-ice fluvial sediment is expected to remain in the littoral zone on the seabed (excepting that which is kept in suspension until marine-related sediment transport can occur). On the other hand, break-up in the high Arctic rarely occurs by in-situ melting. Generally, the nearshore ice cover melts away from the shoreline and the ice sheet is then driven offshore by winds, waves and pack ice. This mechanism has more potential to move sediment out of the littoral zone.

Consequently, this mechanism is not expected to transport large volumes of sediment for the Canadian Beaufort Sea.

In-Ice Sediment Content: Sediments suspended by wave action at freeze-up are likely to be trapped in the frazil, and subsequently the sheet ice, which is formed. If large movements of this nearshore ice occur, then sediment may be transported out of the littoral zone.

Furthermore, on the basis of freeze-up observations at Pt. Lay, Alaska, Dr. J. Wiseman speculated that the observed attenuation and steepening of incoming waves may produce a net onshore sediment transport above the mean water level (personal communication). On the other hand, it is well known that waves may be significantly attenuated by frazil and consequently the net effect of this mechanism is unclear.

There is little information with which to evaluate the significance of this transport mechanism. Isolated quantitative data have been collected for the Alaskan Beaufort Sea; field survey data are not available for the Canadian Beaufort Sea.

Qualitative observations of 'dirty' ice in nearshore ice cores are relatively common for the Alaskan Beaufort Sea (e.g. Exxon, 1979).

During the 1978 and 1979 winters, Barnes et al (1982) measured in-ice sediment concentrations of 243 t/km^2 and 800 t/km^2 in the coast to stamukhi zone area along the Alaskan Beaufort Sea. They then estimated the total in-ice sediment content in this region as 0.79 x 10^6 tons in 1978 and 2.6 x 10^6 tons in 1979 using the mapping work of Reimnitz et al (1978) to determine the area of the coast to stamukhi zone. They found the in-ice sediment to consist mainly of silt and clay during the 1978 field measurements; in 1979, sediment samples were found to contain 30% sand.

For the nearshore Mackenzie Bay area (i.e. out to approximately 15 km), sediment has not been observed in ice cores (G. Spedding, personal communication). Ice in this area is believed to form relatively quickly (reflecting the freshwater input of the Mackenzie River) which may prevent or reduce sediment entrapment.

However, relatively high in-ice sediment contents for the upper 0.5 m of the ice sheet have been observed in the Mackenzie Delta further offshore at about 80 km from the coast (M. Atherton, personal communication).

It is clear that this mechanism has the potential to affect a significant quantity of sediment in relation to the net longshore Beaufort Sea sediment transport budget (which is estimated to be of the order of 20,000-40,000m^3/year (Harper et al, 1985)). A simple calculation shows that a small in-ice volumetric sediment concentration of only 5 x 10^{-4}% (i.e. 1 x 10^{-5} tonnes/m^2 for material with a specific gravity of 2) would be required over a 1 km wide nearshore zone along the 2000 km long Beaufort Sea coast for only a 1 m thick ice sheet to match this quantity.

However, the importance of this transport mechanism is unclear as the fate of the entrapped sediments is a major uncertainty.

Since the bottom fast nearshore ice (where in-ice sediment concentrations will be highest) often melts in place, it is not clear that significant sediment transport will result. Further offshore, movements of the nearshore ice are more common; however, the movement of these floes is often restricted by grounded nearshore ridges. In any case, movement does not usually occur until the ice floes are deteriorated at which time the sediment load of the ice sheet is expected to be greatly reduced (as compared to mid-winter concentrations).

Consequently, most of this material is expected to be locally released into the water and hence this mechanism is unlikely to transport large volumes of sediment.

Bottomfast Ice: In the nearshore area, the ice sheet will freeze to the seabed. At break-up, sediment transport may result if ice movement occurs while material is adhered to the ice bottom.

Observations of bottomfast ice to date are very limited. Most operators and researchers who were interviewed had not made observations of anchor ice.

For the Adgo Island area, sediment has been observed attached to the ice bottom for areas which were bottom fast during the winter. However, this ice is 'usually pretty clean' (G. Spedding, personal communication).

The movement of sediment attached to bottomfast ice at break-up has the potential to be significant in relation to the net longshore Beaufort Sea sediment transport budget (which is estimated to be in the order of 10,000 m^3/year (Harper et al (1985)). A thin sediment layer of only .02 mm of uniform thickness over the nearshore bottom fast ice zone (which is typically of the order of 0.5 km wide) over the 1000 km long Beaufort Sea coastline would be required to match this quantity.

However, the importance of this transport mechanism is unclear as the amount of sediment which adheres to the ice bottom is uncertain.

Typically the nearshore ice melts inplace at break-up or drifts offshore only after significant deterioration has occurred. Consequently, this mechanism is not expected to transport large volumes of sediments.

4.2.5 **Summary**

The above discussion introduces eight possible effects of sea ice on nearshore processes in the Beaufort Sea. Very little research has been done in Canada on these processes and only the crudest estimates can be made of their rates, of the effects of different variables on them, or as to their significance in the Beaufort sediment budget.

The main results of the literature review are summarized in Table 4.4, which lists the conditions which are required for each of the processes to occur. It provides a framework for the assessment of the importance of ice related processes at specific sites.

TABLE 4.4

SUMMARY OF LITERATURE REVIEW RESULTS

PROCESS	REQUISITE CONDITIONS/LIMITATIONS	POTENTIAL MAGNITUDE IN CANADIAN BEAUFORT SEA
Ice Scour	Ice ridge must contact the seabed; ridge perpendicular to shore.	3.8 X 10^5m^3/year
Ice Push	Ice ridge must contact the seabed ridge parallel to shore.	3.2 X 10^6m^3/year
Ice Override	Steep profile to allow ice floes to contact the onshore contact with surrounding ice floes to provide momentum for ride-up soft shore sediments (i.e. non-frozen), shallow-sloped fore shore but relatively steep below water level.	4.5 X 10^3m^3/year
Wallowing	Relatively deep offshore (to allow floes to drift near shore) but shallow near-shore zone (for grounding); tidal fluctuation or exposed to storm surge fine grained sediment.	Unknown
Strudel Scour	River overflow onto sea ice; shallow water at strudel hole (1.5 - 5.0 m).	Unknown
Surface Entrainment	River overflow	Unknown
In-Ice Entrapment	Suspended sediment during freeze-up; shallow water with current or wave-action during freeze-up.	Unknown
Bottom Fast Ice Entrapment	Shallow water; freezing to seabed.	Up to 10,000m^3/year

The estimated magnitudes of sediment movement by ice scour, ice push and bottom fast ice entrapment are potentially larger than the total sediment transport budget estimated by Harper (1985) for the Beaufort Sea. The significance of the other processes cannot be measured with available information. These data indicate the importance of ice related processes in the Beaufort Sea sediment regime and emphasize the importance of obtaining more observational data for sites in Canada.

5. RELATIVE SIGNIFICANCE OF ICE-RELATED SHORELINE EROSION PROCESSES FOR TWO PROPOSED BEAUFORT SEA SHOREFACE DEVELOPMENTS

Shoreface developments are presently proposed at King Point and North Head on Richards Island along the Beaufort Sea coast.

King Point is located in the western Yukon ice zone while North Head is located in the Mackenzie Delta-Richards Island ice zone (as outlined in Section 3.2). A harbour facility has been proposed for King Point while North Head is one site under consideration for a shoreface pipeline crossing.

The regional setting and coastal environment of these two sites has been studied in some detail. Hill et al (1986) provides a summary of the prevailing coastal and physiographic conditions at these two sites. Excerpts from their paper are included in Appendix F of this report to provide general background information.

The following sections provide a brief discussion of the probable effect of sea ice on coastal processes for these developments.

5.1 King Point

Site Description - King Point is the proposed site of a marine terminal on the Yukon coast. It is a barrier beach enclosing a lagoon between Kay Point and Shingle Beach, along a coastline that is dominated by ice-rich coastal cliffs, Pelletier (1984). It is unusual in being an accretionary landform in this region.

The physiography of King Point is well documented in air photographs and surveys. The barrier is composed of gravel and sand which prograded progressively in the direction of longshore drift, Pelletier (1984), from a spit in 1954 to a barrier beach by 1968 [Sailing Directions, Volume III]. Continued progradation is presently widening the newer, east end of the barrier, Hill (1986). Current drift is to the southeast.

The seaward slope of the prograding barrier is relatively steep (slope of .15) down to the 3 m water depth (Appendix F). Below 3 m the slope near shore is shallow and convex at the north end, but steep and concave at the south end.

Winter ice in the vicinity is predominantly first year, and is landfast for several miles offshore. It begins to form in October, Markham (1981), and typically grows to a maximum thickness of 1.8 m, A.E.S. (1982). The ice cover is dynamic during the freeze-up period, and ridges are often formed as the ice is freezing in the littoral zone. The extent of ice motion in winter is very minor along shore, since the landfast zone extends 10 to 30 miles offshore in this region. This protects the shore region from the heavy ridging prevalent in the transition and polar pack ice zones.

Break-up and clearing of ice occurs in mid-July, about the same time as in the offshore zone. Large, intact floes may be present near shore during the break-up period. The pattern of summer clearing is often such that the pack lies relatively close inshore off King Point, but farther offshore to the east, leaving open water between King Point and Banks Island (Figures 3.5 - 3.7). In mid-summer prevailing winds can blow the ice onshore at any time (Figure 5.1).

Potential Effects of Sea Ice: The potential for direct sea ice related shoreline processes is summarized in Table 5.1. The site has a high potential for ice override because the shoreface is deeper than the level ice but the beach slope is shallow. Ice scour and ice push are both likely during the open water season since it is susceptible to summer incursions of both first year and old ice, and ridge keels could easily reach the seabed. Bathymetric records shows that ice scour has occurred here, Hill (1986), but the frequency of such events along the coast has not been investigated. Scour and push would be unlikely during the winter season because the extensive landfast zone precludes most ice movements.

The depth of water makes wallowing and ice bottom entrainment unlikely, and no river discharge is present to cause strudel scour or surface entrainment of sediment.

The landfast ice cover would indirectly affect coastal processes here as everywhere along the coast, reducing wave action during the winter. Since the landfast ice does not persist into summer, wave action would not be affected in the open water season.

Effects of Proposed Developments: Six types of marine terminals have been proposed for this site. These include a dredged channel through the barrier into the lagoon, dock or breakwater structures extending from the barrier face out to sea, or a combination of these (Figure 5.2).

The effects of each type of development on shore/ice interaction processes can be hypothesized.

Dredged Channel: This would have no effect on strudel scour, surface entrapment, in-ice entrapment or ice bottom entrapment, or on ice override. It could increase the likelihood of ice scour, ice push and wallowing because the deeper channel would allow deeper ice keels to enter the near shore area. The keels could then scour along the sides of the channel. Wallowing would also be encouraged since thick ice could become grounded at the sides of the channel or within the lagoon. In summary, a dredged channel would increase the likelihood of ice-induced coastal erosion at King Point.

TABLE 5.1

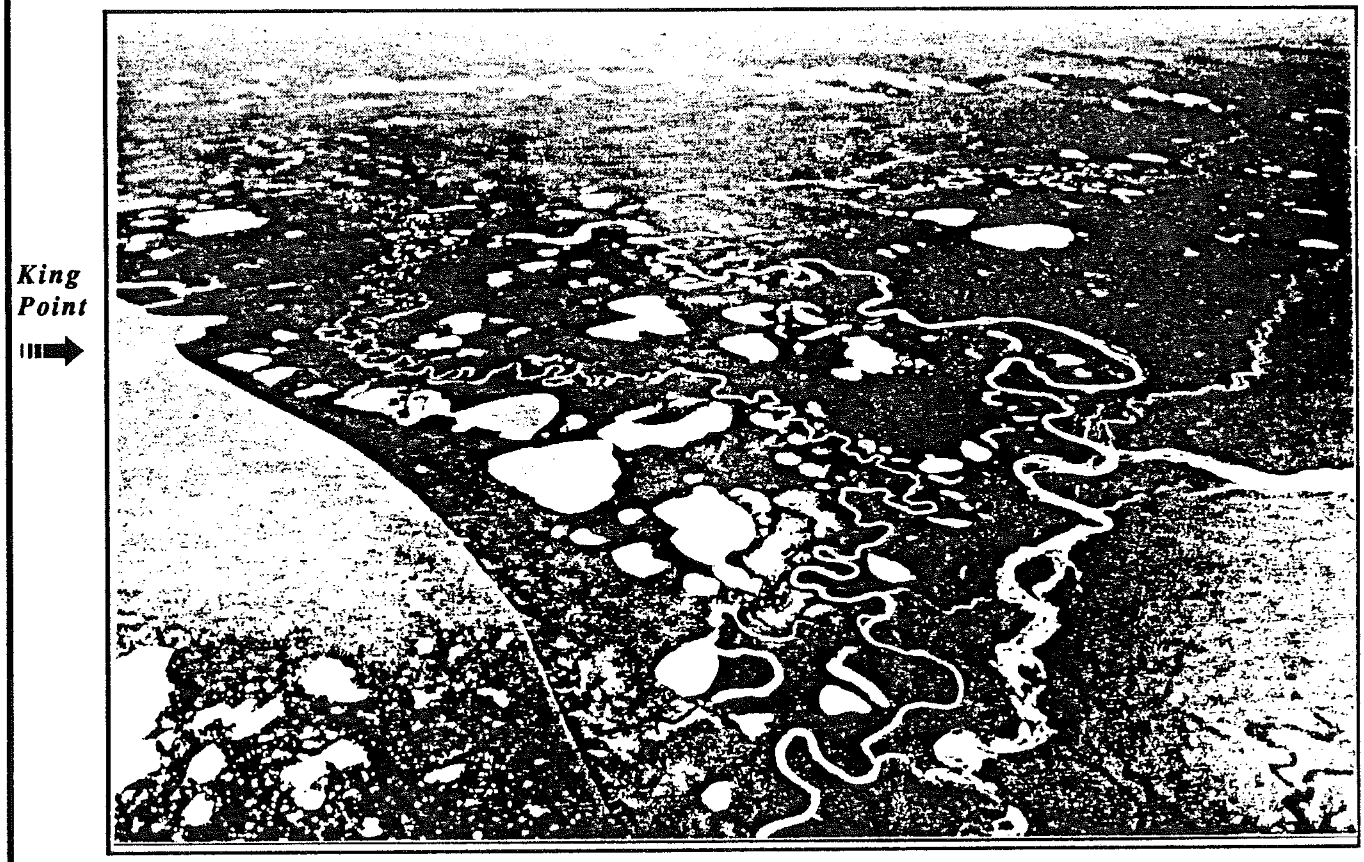
SEA ICE RELATED COASTAL PROCESSES

PROCESS	LIKELIHOOD OF OCCURRENCE KING POINT	 NORTH HEAD
Ice Scour	++	-
Ice Push	++	-
Override	++	-
Wallowing	+	+
Strudel Scour	-	+
Surface Entrapment	-	++
In-Ice Entrapment	+	++
Ice Bottom Entrapment	-	++

++	matches requisite conditions, or observed
+	possible
-	does not match requisite conditions.

Figure 5.1

AERIAL VIEW OF KING POINT AT EARLY STAGE OF BARRIER FORMATION

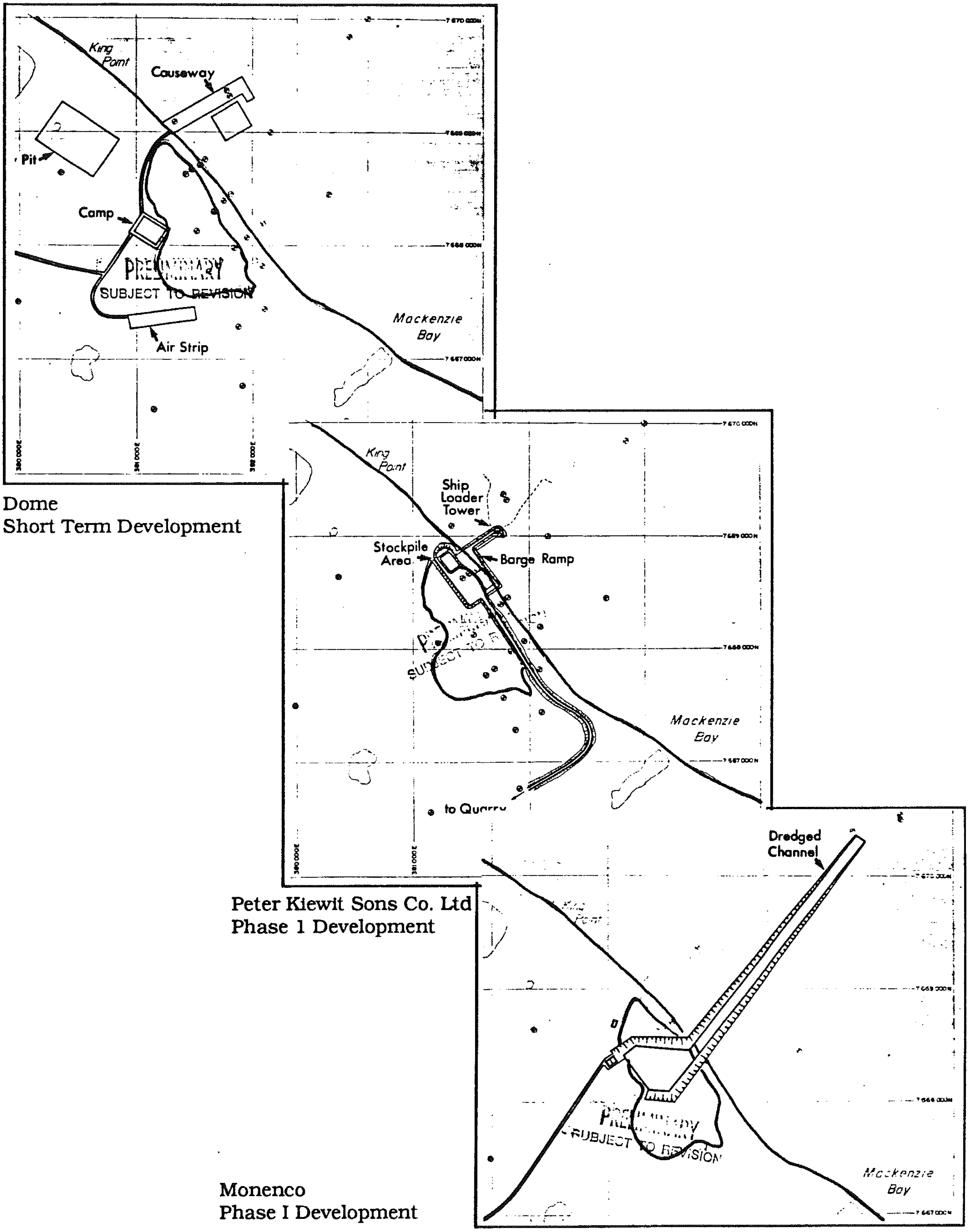


Yukon coastal plain, looking south from the Beaufort Sea coast, Aug. 22, 1944. King Point is shown on the left, prior to formation of a barrier across the lagoon in about 1968. Numerous ice floes can be seen along the shore.

(Photo from Dunbar and Greenway, 1956)

Figure 5.2

PROPOSED DEVELOPMENTS AT KING POINT



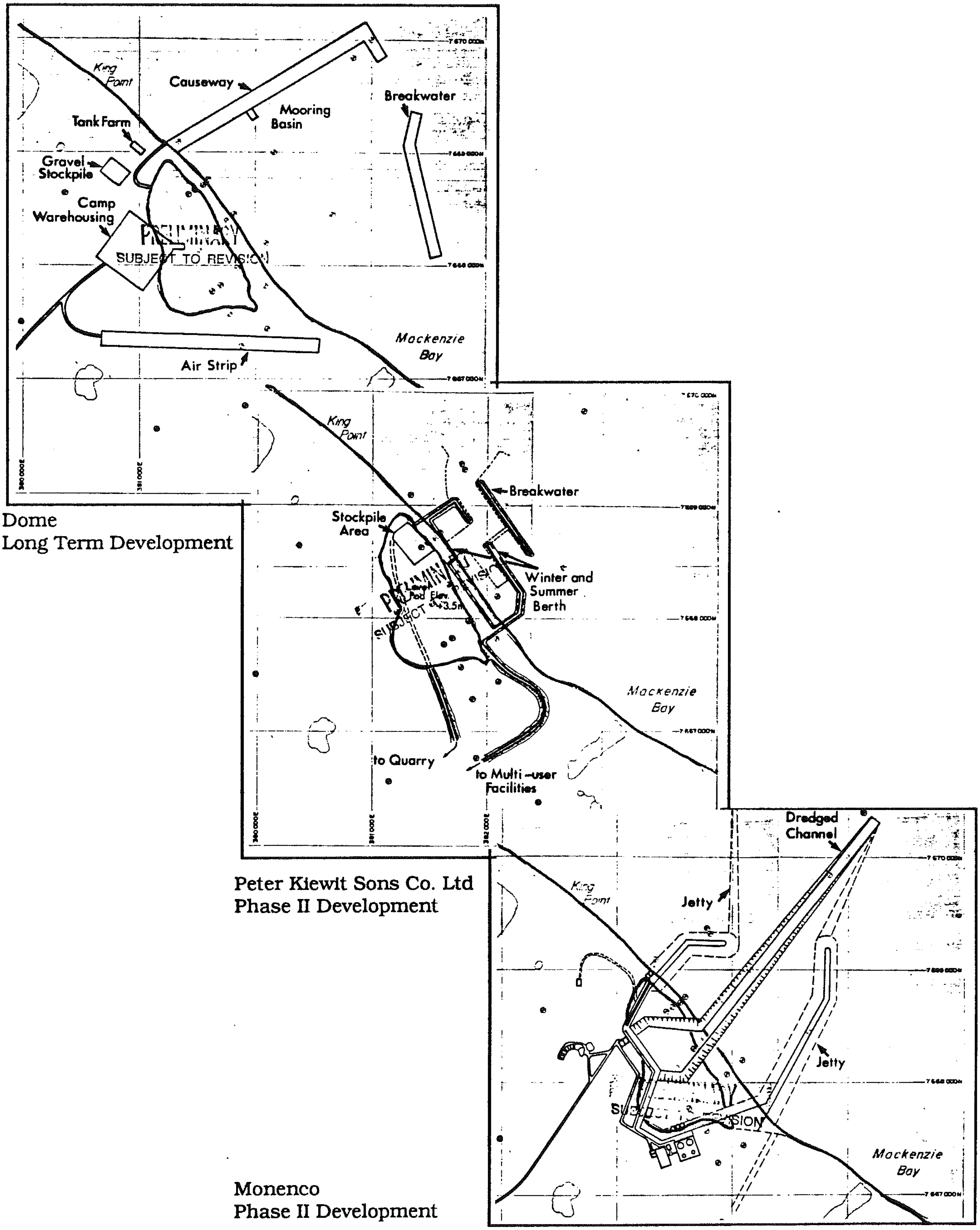
Dome
Short Term Development

Peter Kiewit Sons Co. Ltd
Phase 1 Development

Monenco
Phase I Development

Figure 5.2 a

PROPOSED DEVELOPMENTS AT KING POINT



Dome
Long Term Development

Peter Kiewit Sons Co. Ltd
Phase II Development

Monenco
Phase II Development

Dock Structure: A dock or breakwater structure extending seaward from the barrier would be likely to have a beneficial effect with regard to ice scour and push and detrimental with regard to ice override, wallowing and sediment entrapment.

The structure would act as an anchor during the freeze-up and break-up periods, reducing ice drift motion and act as a shield to the shore during the open water period. It likely would encourage freeze-up and retard break-up locally and this would reduce wave erosion during these periods. The beach behind the structure would be shielded from ice override thus reducing a sediment source for the beach.

Ice wallowing would likely be increased by the presence of a shore-face structure for two reasons. First, ice growth would begin earlier in the fall since the ice cover would protected from wave action and anchored by the seaward projection, thus resulting in a thicker ice cover and a larger extent of contact with the seabed. Second, an ice bustle would develop on the face of the structure and this would have a deeper keel than surrounding, level ice. Tidal action would bring the keel in contact with the seabed and encourage wallowing and ice entrapment.

Conclusion: The conceptual understanding of the effects of sea ice on coastal processes suggests that a man-made structure would have a beneficial effect in terms of reducing wave erosion early in the fall and later in the spring and a detrimental effect in terms of reducing the likelihood of ice override onto the shore and increasing the likelihood of ice wallowing. The net effect cannot be calculated at this time because the relative importance of each of the processes at this site is not known. In the absence of extensive field data on the magnitude and frequency of data on shore/ice interaction events at this site, it is recommended that possible effects be studied using a scale model approach.

5.2 North Head

Site Description: North Head has been proposed as the shoreline crossing site for a subsea pipeline. It is situated at the north end of Richards Island in the Mackenzie Delta region in close proximity to man-made gravel islands and offshore drilling structures. Its maximum elevation of about 10 meters is much lower than southern parts of the island. Superficial materials here are complex, including sand over lain by glacial till, lacustrine sediments, colluvium and organic deposits, Hill et al (1986). Thermokarst lakes attest to the presence of ground ice.

Shoreline features at North Head are varied. As shown in Figures 5.3 and 5.4, shoreline complexes include simple barrier beaches, wave-cut cliffs fronted by bars,cliffs without bars, breached thermokarst lakes with associated thaw failures and inter-tidal flats, and inundated tundra, Harper et al (1985).

Bathymetry surrounding the Head is regular and extremely shallow, with depths less than 5 m found 5 to 10 km offshore. Measured sediment concentrations indicate that the west side of North Head falls within an area of fine sediment deposition from the east flowing Mackenzie River plume, Harper et al (1985), and this sediment source likely adds to that from the wave-cut cliffs in making this a stable coastline.

The prevailing storm direction is westerly (Philpott, 1985), and this is reflected in the coastal landforms. Areas of North Head which are directly exposed to the northwest have a wave-cut shoreline, while areas to the north and south which are protected from direct wave action by Hooper and Pullen Islands have bars fronting the cliffs (see Figure 5.4). It is possible that the extensive shallows off North Head play an important role in attenuating the waves and in turn contributing to the supply of suspended sediment along the shore, but more study is needed to confirm this, (Hill et al, 1986).

The ice cover at North head begins to form in early October and is generally complete by the end of the month, Markham (1981). Freeze-up is hastened by the input of fresh water from the Mackenzie River. Some minor ridging of new ice and on-shore movement of second year ice floes occurs during the freeze-up period but the ice is generally level and very stable during the winter, when it is well within the landfast zone. Ice roads have been used along the coast out to Hooper and Pullen Islands, which are seasonal staging areas for the oil exploration companies. Winter ice grows to a thickness of about 1.8 meters, suggesting that it becomes bottom-fast near the shore.

Figure 5.3

MORPHOLOGICAL FEATURES AT NORTH HEAD

(Hill, 1986)

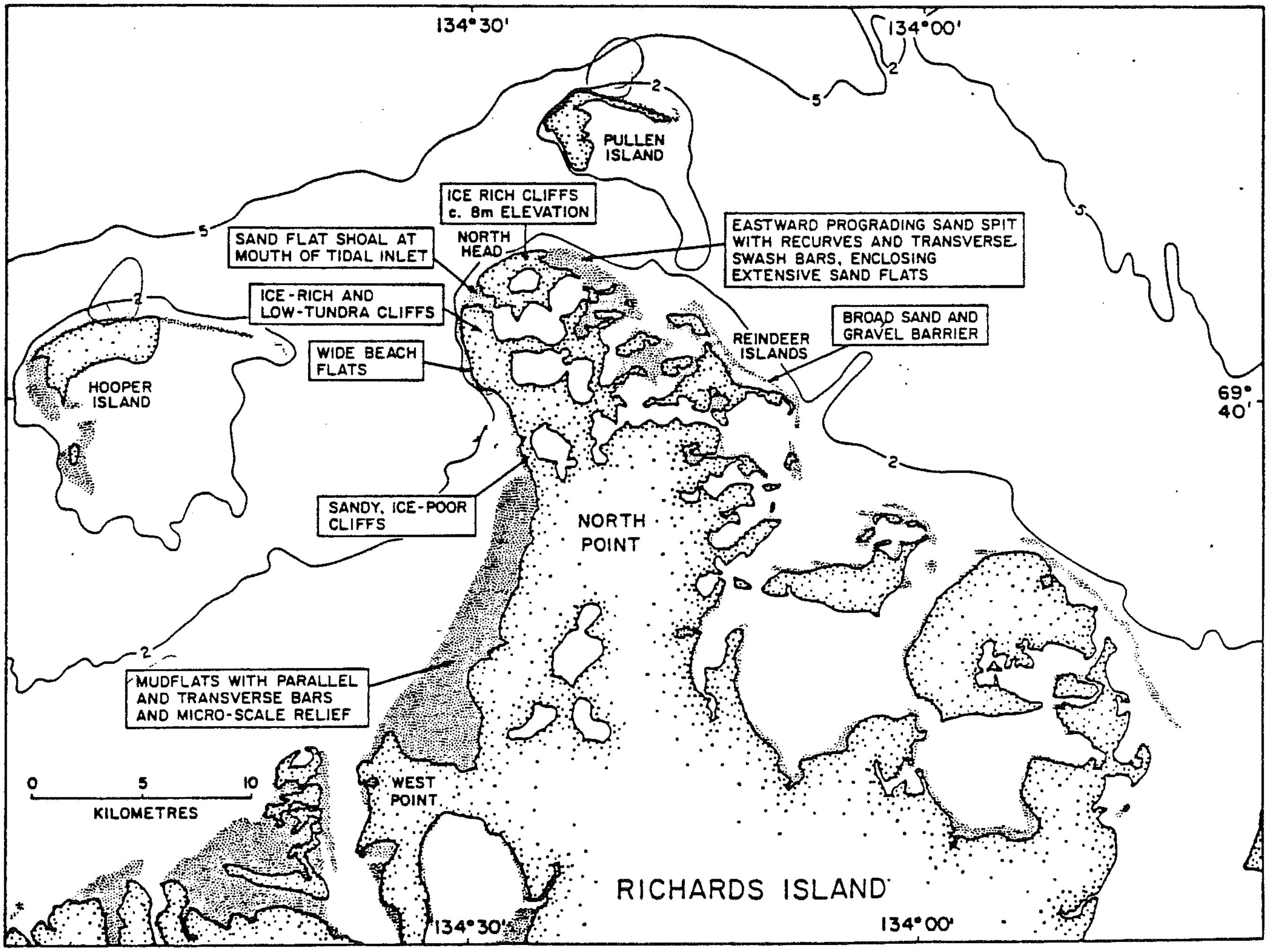


Figure 5. 4

NORTH HEAD SHORE - ZONE TYPES

(Harper, 1985)

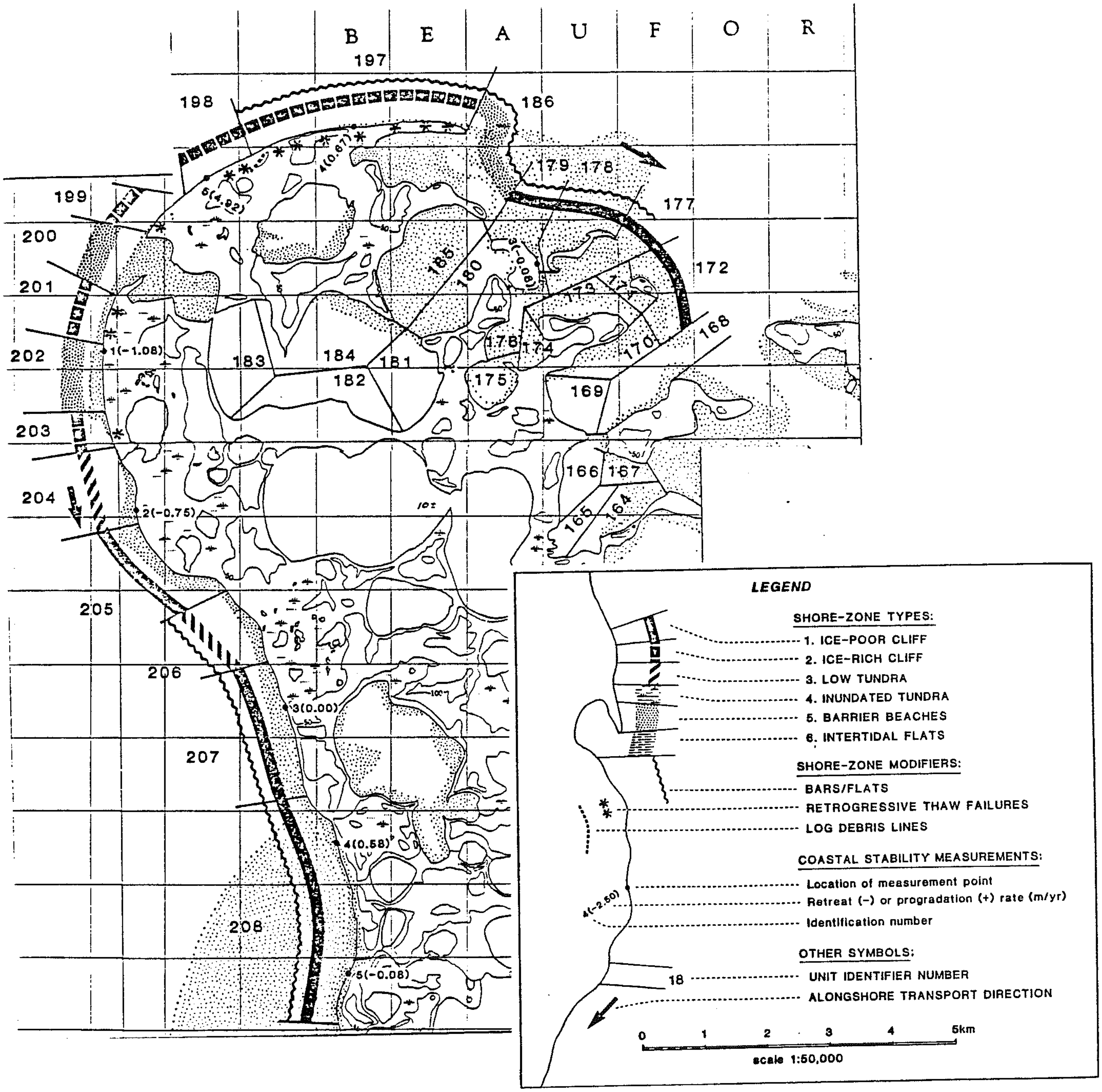
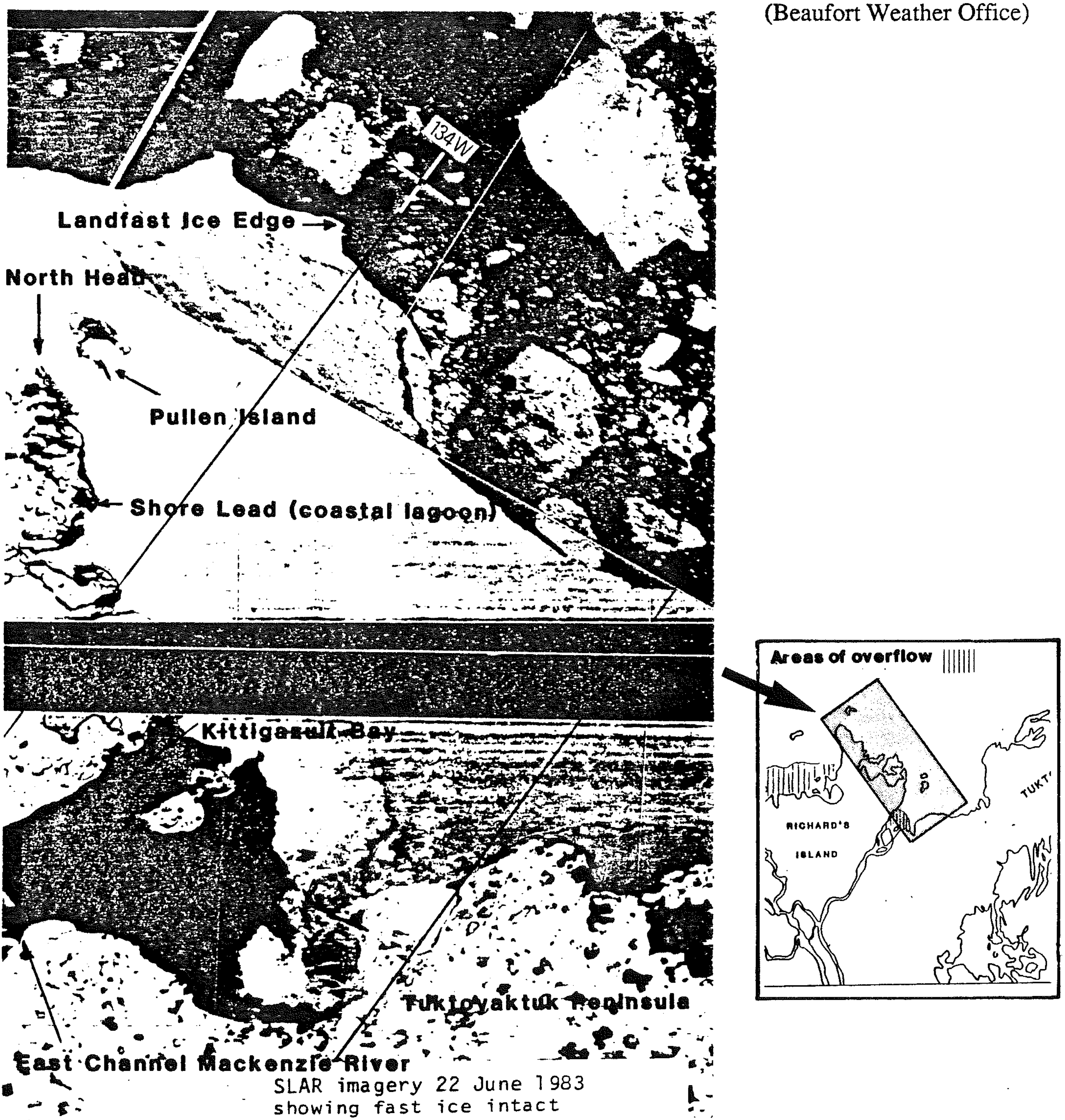


Figure 5.5

LANDFAST ICE, SHORE LEADS AND SITE OF MACKENZIE RIVER OVERFLOW NEAR NORTH HEAD,June, 1983

(Beaufort Weather Office)



SLAR imagery 22 June 1983
showing fast ice intact

Landfast ice persists locally near shore until after the offshore pack has begun to break up in June, thus affording protection from drifting pack ice during the break-up season. The development of leads or 'lagoons' along the shore, as well as overflow from Mackenzie River channels contributes to the decay of the fast ice on northern Richards Island (see Figure 5.5). During summer, pack ice lies about 60 miles to the northwest and farther off to the northeast, although this is affected by prevailing winds, Markham (1981). Summer ice incursions to the shoreline are rare due to the prevailing east to west ice drift, plus the shallow bathymetry and protection by Pullen and Hooper Islands.

Potential Effects of Sea Ice: Table 5.1 summarizes the potential effects of sea ice on shore related processes at North Head. The presence of lagoons and Mackenzie River overflow suggest that strudel scour and entrainment of sediment on the ice surface may occur to the south of North Head, depending on the extent of overflow beyond the river channels. Strudel scour could be important near North Head where flow is concentrated between the ice cover and the shallow seabed. Entrainment within the ice cover is possible because early winter storms are likely to stir up bottom sediment during the ice growth period, and entrainment into the ice bottom is likely as the ice cover freezes to the seabed in the coastal shallows. Ice wallowing is likely to occur, especially early in the summer when decaying landfast ice is stranded along the shore.

Ice scour has been extensively documented seaward of Pullen Island, Shearer (1985), but is unlikely to be important at North Head. The shallow depths preclude significant ice scour or push since most ridges and thick floes would be grounded far offshore. Ice override is unlikely due to grounding of floes offshore, and to the presence of cliffs along much of the shoreline.

The late break-up and somewhat early freeze-up of landfast ice here, no doubt, significantly reduces wave erosion during the early summer and early fall periods.

Effects of Proposed Developments: Gulf Canada has proposed North Head along with Tuktoyaktuk as alternative sites for a buried pipeline to their offshore production fields. No detailed planning has been undertaken as yet, and no engineering drawings or design information is available (person communication with J. Low, Gulf Canada). Mason Bay on Richards Island has also been suggested as a possible site but again, no further information is available (personal communication with H. Young, Department of Indian and Northern Affairs).

A buried pipeline at North Head would result in minimal permanent disruption to the ice, wave or current regimes of the North Head areas unless it was not back filled to grade. In that use, thicker floes or deeper ridge keels could gain access to the coastal area during the freeze-up or summer periods, and ice scour or push could become more prevalent along the pipeline corridor.

Backfilling above the surrounding seabed level would provide an additional anchor point for landfast ice, promoting earlier freeze-up and later break-up. This would tend to reduce the duration of marine related sediment transfer processes during the seasons of highest wave energy.

Conclusions: The hypothesized effects of a buried pipeline at North Head on shore/ice interaction are an increase in push and scour, and a general decrease in the annual duration of marine related sediment transfer processes. These are based on very preliminary information and conjecture regarding the proposed development and on the processes involved at the site.

A more rigorous assessment of the effects of a pipeline development at this site could be obtained using a scale model simulation of sediment transport and shoreline/ice interaction.

6. DISCUSSION OF RESEARCH REQUIREMENTS

6.1 General

A description of the observed effects of sea ice on coastal processes in the Beaufort Sea is provided in Section 4 and of possible effects at specific sites in Section 5. This section further discusses the gaps in understanding which were identified in these sections and presents general recommendations for further study. Section 7 describes specific projects which will help to fill the knowledge gaps.

The gaps in understanding include understanding of the mechanics and local effects of the ice-related processes and of the regional significance on the Beaufort Sea sediment budget as a whole (Figure 6.1). The processes involved include modification of marine-related sediment transport processes by sea ice, and direct sea ice-shoreline interaction.

6.2 Modification of Marine-Related Sediment Transport Processes by Sea Ice

As outlined in Section 4, the presence of sea ice may affect marine sediment transport processes by:

(a) limiting the annual duration over which marine-related sediment transport processes are active.

(b) limiting the wave energy which can be produced in the coastal environment.

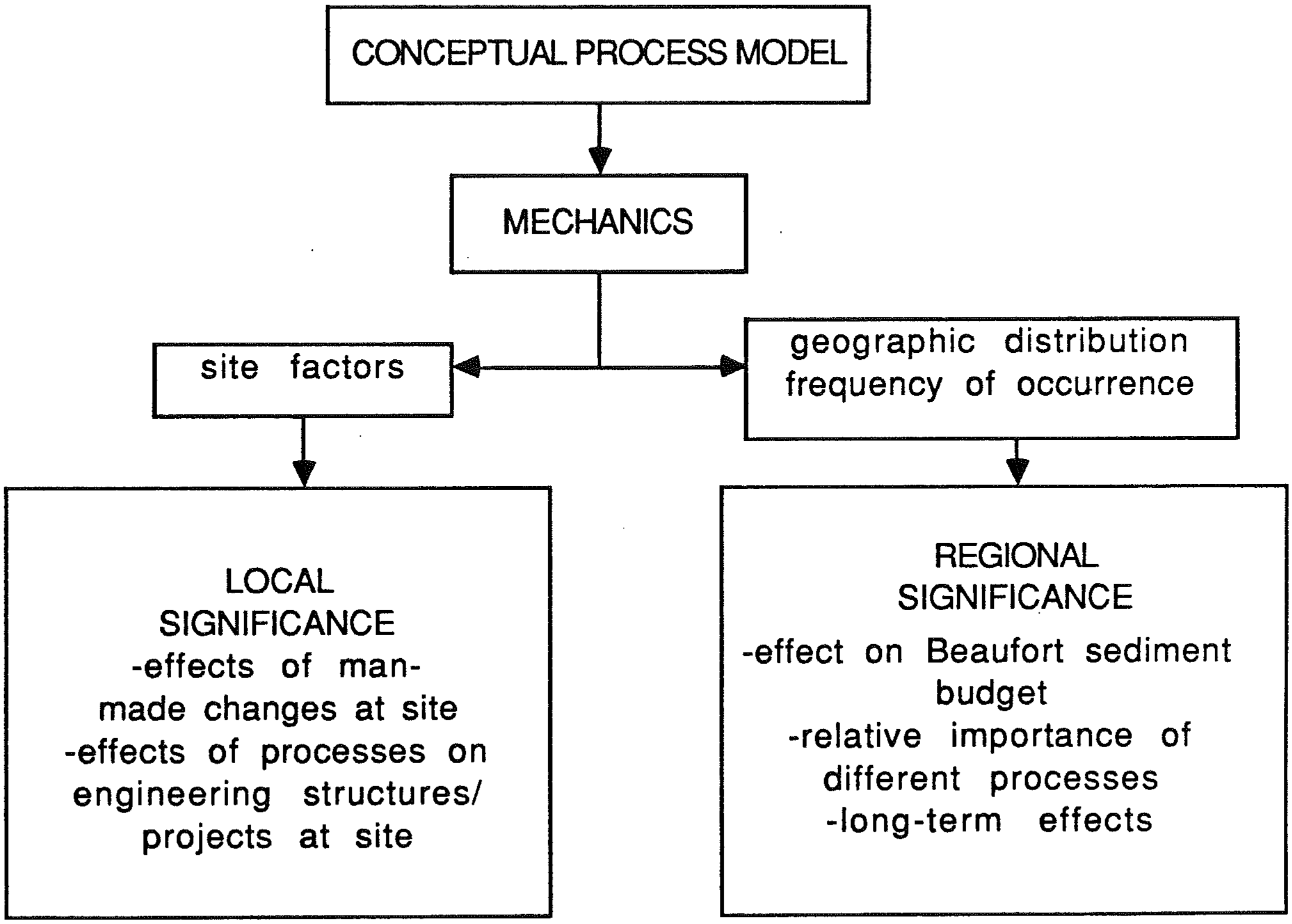
(c) limiting the wave energy which reaches the coastal zone.

This section further considers these processes and makes general recommendations towards further research. In general, the above processes are beneficial at erosional sites in that they reduce the frequency or magnitude of shoreline erosion and thus will not contribute to problems for shoreface developments.

The main recommendations for further research, summarized in Table 6.1, relate to possible changes in the existing sea ice seasonal regime. These could significantly change the degree to which sea ice affects marine related sediment transport.

Figure 6.1

EFFECT OF SEA ICE ON BEAUFORT SEA COASTAL PROCESSES
GENERAL RESEARCH REQUIREMENTS AND OBJECTIVES



6.2.1 Limitation of Annual Duration of Marine-Related Sediment Transport Processes

As the Beaufort Sea coast is ice-bound for about eight to nine months of the year, the annual duration over which marine-related sediment transport can occur is limited.

This effect could be altered significantly by engineering developments or artificial ice management associated with oil company or shipping operations, as well as long term climatic changes. It is no doubt responsible in part for regional differences in the Beaufort Sea sediment budget. The general concept is well understood however, and further research in this area is therefore of secondary interest as compared with other processes which more directly affect coastal processes.

6.2.2 Limitation of Production of Wave Energy

As outlined in Section 4, sea ice clearly limits the amount of wave energy that is produced by limiting the fetch available for wave generation, but parametric models are not available to quantify this effect.

Treatment of ice covered water as a land surface and arbitrary selection of a particular concentration in delineating the ice edge is a satisfactory treatment of the problem for operational wave forecasting. This arbitrary approach does not provide a model with which the significance of wave-ice effects can be evaluated. Philpott's use of fetch limitation in a hindcast clearly recognizes its importance but does not separate its effects as a parameter in the results.

Two types of research would assist here. First, a better theoretical understanding is required of the wave generation in a broken ice cover. Second, an analysis should be undertaken to estimate the significance of fetch limitation by sea ice, on coastal processes. Since fetch is generated over a large area, its limitation by sea ice is unlikely to cause significant differences in shoreline processes on a local scale. It would be more significant climatologically, for instance in comparing the influence on sediment transport in the Canadian Beaufort Sea versus the Alaskan Beaufort Sea (Table 6.1).

6.2.3 Attenuation of Nearshore Wave Energy

It is clear that the understanding of the interaction of waves with ice floes and attenuation of a wave field in an open pack situation has recently advanced dramatically, (Rao and Vandiver, 1987), but has been modelled only in a situation which is not applicable to the study of shoreline erosion. Attenuation in a complete ice cover (such as landfast ice) is reasonably well understood, (Squire and Moore, 1980).

TABLE 6.1

RECOMMENDED RESEARCH ON MODIFICATION OF SEDIMENT TRANSPORT PROCESSES BY SEA ICE

TOPIC	RESEARCH	RESULTS
Limitation of Annual Duration of Sediment Transport Processes	Effects of engineering structures, ice management activities, and climatic changes on duration of ice cover.	Improved understanding of possible changes in sediment transport processes due to changes in ice cover durations at a particular site
		Better chronology of coastal geomorphology due to non-constant rates of erosion or accretion through time.
		Understanding of regional differences in the sediment budget.
Limitation of Production of Wave Energy	Improved theoretical understanding of wave generation in broken ice cover.	Prediction of ice cover effects on wave energy and resulting sediment transport.
	Occurrence of fetch limitation by sea ice.	Improved understanding of regional or temporal differences in sediment transport.
Attenuation of Near shore Energy	Process and climatology of wave attenuation by sea ice and frazil ice.	Improved understanding of regional or temporal differences in sediment transport.

The application of available models to specific localities is impracticable. During the wave generation season, the shoreline ice cover is either in the late stages of deterioration or is fully dispersed (Figures 3.5 to 3.7), and a wave generating storm event would tend to accelerate this process at a rate which is, for all practical purposes, random. Thus, the effects of wave attenuation would be difficult to model in a deterministic fashion.

It is possible however, to estimate the extent and duration of an ice cover along the shore from a climatological perspective. This could be used with storm wave hindcast information to quantify the effects of wave attenuation along the shore in reducing erosion on a long term, climatological basis.

6.3 Sea Ice - Shoreline Interaction Processes

As outlined in Section 4, the interaction of sea ice with the shoreline may involve a number of processes, including:

(a) ice scour and ice push
(b) ice override
(c) ice wallow
(d) strudel scour
(e) sediment transport by anchor ice, in-ice encapsulation and on-ice surface transport.

Another process which may be important is mechanical erosion by frazil ice. Frazil ice abrasion is believed to be an agent of mechanical erosion of the seabed but no literature was found to describe this process.

The significance of these processes is further assessed in this section and general recommendations are provided for further research.

6.3.1 Ice Scour and Ice Push

As outlined in Section 4, a large number of studies have been conducted to investigate ice scour in the Beaufort Sea, including scour depths and spatial and temporal scouring frequencies.

The process is well understood conceptually, and research which is now in progress will provide a validation for existing numerical models and an improved understanding of scour mechanics.

The significance of ice scour and push at the shoreline is not well understood because most of the reliable field data have been collected offshore where scours infill much less rapidly. Exploratory calculations in this study suggest that ice scour events are unlikely to move large volumes of sediment whereas ice push events (in which a scouring ice keel is driven 'broadsides' up the beach) have the potential to significantly affect the littoral zone. (See Section 4 for a definition of these two events.)

The critical parameters governing ice scour include the relative movement directions of the scouring ice keel and the shoreline; the size and shape of the ice keel; the bedslope and water depth; and the soil properties. Of these, an improved understanding of the probable relative movement directions between the scouring ice keel and the shoreline is the most critical research requirement. (The exploratory calculations show that the ice-related sediment transport volume was extremely sensitive to this parameter).

Since the process mechanics are now understood, further research should be directed toward understanding the local and regional occurrence. This can be obtained through site studies of the direction of movement of ice keels in relation to the shoreline (spatial and temporal aspects) and of the depth of disturbed sediments. Recommended research is outlined in Table 6.2

TABLE 6.2

RECOMMENDED ICE SCOUR AND ICE PUSH RESEARCH

PROGRAM OBJECTIVES	GENERAL RECOMMENDED APPROACH
LOCAL SITE INVESTIGATIONS (SEE NOTES BELOW):	
1. To determine the depth of the disturbed beach sediments	a) Field beach sonar surveys immediately after break-up. b) Use or duplication of presently ongoing laboratory testing to determine the stress field in the soil beneath the scour. (see notes below)
2. To determine the local spatial and temporal scour frequency.	Field beach sonar surveys immediately after break-up (when ice action is essentially complete but wave action has not yet been extensive).
REGIONAL COASTAL SURVEYS (SEE NOTES BELOW):	
1. To determine the probable relative spatial and temporal frequencies of ice push and ice scour events.	a) Field beach surveys after break-up at sites where grounded ridges were located the previous winter (to determine the size of the underwater berm produced). b) Frequent aerial reconnaissance surveys using aerial photography and SAR (to provide all weather capability) to observe ice movement directions.

NOTES:

1. The above research projects are listed in the considered order of priority. As an investigation of ice ridge movement directions is considered to be most critical for global coastal surveys, only this research work is recommended at present.

2. The Exxon Corporation is presently undertaking large scale laboratory tests to measure the soil stress field under a scour. The results of this work, unfortunately, will be proprietary to Exxon.

6.3.2 Ice Override

Only preliminary information is available to assess the significance of ice override for Canadian Beaufort Sea coastal processes.

The override of ice onto the beach is an event which has been observed in the field and studied using historical aerial reconnaissance data. This work has been conducted for the Alaskan Beaufort Sea coast; similar observations are not publicly available for the Canadian Beaufort Sea although the available data have been informally reviewed (J. Harper, personal communication).

Thus some data are available to assess the significance of this process for sediment transport in the coastal zone in a preliminary manner.

Ice override is relatively rare for the Alaskan Beaufort Sea. Similar frequencies of occurrence are expected for the western Yukon coast of the Canadian Beaufort Sea as this region is generally similar in bedslope to the Alaskan Beaufort Sea. Also, the offshore pack ice is generally relatively close to shore for both regions.

For the more easterly coastal zones of the Canadian Beaufort Sea, the bedslope is typically shallower and the pack ice is generally further offshore in the break-up to freeze-up period. Consequently, the frequency of ice override events for these regions is expected to be lower.

Preliminary measurements of ice-pushed sediment volumes also indicate that ice override is unlikely to move large quantities of material in relation to the overall sediment transport budget. It is important however, because it has the potential to both push material out of the littoral zone and to rework the beach. Consequently, it may be of concern for both local site and regional investigations.

The critical information gaps regarding this process are believed to be:

(a) the spatial and temporal frequencies of occurrence.

(b) the quantity of material moved during override events and the volume of sediment pushed out of the littoral zone.

(c) the area and distance back from the shoreline which is affected during an ice override event. (This is of concern primarily for local site investigations where the required shoreline setback distance is a design parameter).

Table 6.3 summarizes the recommended research activities regarding this process. As present information indicates that ice override is unlikely to be a major factor for coastal sediment transport, preliminary studies are recommended local surveys only. More detailed studies are recommended subsequently pending the results of this preliminary work.

TABLE 6.3

RECOMMENDED ICE OVERRIDE RESEARCH

PROGRAM OBJECTIVES	GENERAL RECOMMENDED APPROACH
LOCAL SITE INVESTIGATIONS (SEE NOTES BELOW):	
1. To determine the local spatial and temporal frequencies of occurrence	Assembly of historical database using local aerial reconnaissance surveys and other remotely-sensed imagery (e.g. SLAR, SAR, LANDSAT).
2. To determine the area and distance back from the shoreline which is affected by ice override events.	(a) Assembly of historical database. (b) Field measurements at ice override sites identified from aerial reconnaissance surveys and remotely-sensed imagery.
3. To determine the depth of beach zone sediment which is affected by an override event.	Field beach profile surveys at ice override sites.
REGIONAL COASTAL STUDIES (SEE NOTES BELOW):	
1. To determine the spatial and temporal frequencies of occurrence.	Assembly of historical database of aerial reconnaissance survey imagery and analysis of other remotely-sensed imagery.
2. To determine the quantity of beach material moved during ice override events.	Field beach profile surveys at ice override sites.

NOTE: The above research projects are listed in the considered order of priority. For both local and regional surveys, an investigation of the frequency of occurrence is considered to be of highest priority. If these surveys indicate that ice override may be significant, then further studies of the magnitude and geographical distribution of this process are recommended.

6.3.3 Ice Wallow

Only preliminary field observations for the Alaskan Beaufort Sea are available for an assessment of the significance of this ice-related sediment transport mechanism. These observations indicate that ice wallow may produce significant reworking of the beach material. However, since the shoreline relief produced by ice wallow infilled relatively quickly (within three years), this process is not expected to transport large volumes of sediment into or out of the littoral zone.

Although ice wallow relief has only been reported once to date in the literature, it is believed that the process is probably widespread along the Beaufort Sea coast as it occurs due to the interaction of waves with grounded and nearshore floating ice blocks. These environmental conditions are relatively common in the break-up to freeze-up period.

Basic theory is also available to numerically analyze ice wallow problems although no quantitative analyses have yet been specifically developed or performed. The principal impediments to this approach are difficulties in defining the site environment (which is highly variable both in space and in time during an ice wallow event) and an imprecise knowledge of the mechanics involved.

The major information gaps regarding ice wallow are:

(a) the spatial and temporal frequency of ice wallow events.
(b) the fate of the reworked beach material.
(c) the basic process mechanism.

As the field conditions producing ice wallow are complex and highly variable, it is believed that quantitative deterministic analyses of ice wallow will be difficult, and probably intractable. Consequently field observations are recommended at present. If these studies show that further detailed study is warranted, then a combination of detailed field observations (to characterize ice wallowing events), basic laboratory testing, and numerical modelling (taking into account the hydrodynamic and sediment transport portions of the interaction) is recommended.

Table 6.4 summarizes the recommended research activities.

TABLE 6.4

RECOMMENDED ICE WALLOW RESEARCH

PROJECT OBJECTIVE	GENERAL RECOMMENDED APPROACH
LOCAL SITE INVESTIGATIONS:	
1. Spatial and temporal frequency of occurrence.	(a) Analyses using historical data (e.g. Landsat satellite imagery, air photos and storm reports) to define the combined probabilities of occurrence for the conditions necessary to produce ice wallow relief. (b) Aerial reconnaissance surveys during the freeze-up to break-up period, particularly before and after storms.
2. Fate of reworked material.	Beach surveys before and after storms.
3. Investigation of ice wallowing mechanism.	Laboratory tests and numerical modelling of the process.
REGIONAL COASTAL STUDIES (SEE NOTE):	
1. Spatial and temporal frequency of occurrence.	Analyses using historical data (e.g. Landsat satellite imagery, air photos and storm reports) to define the combined probabilities of occurrence for the conditions necessary to produce ice wallow relief.
2. Fate of reworked material.	Beach surveys before and after storms.

NOTE:

As ice wallow is considered likely to only rework the beach, only preliminary studies are recommended initially to evaluate the frequency of occurrence of this process.

6.3.4 Strudel Scour

As discussed previously, some field data, laboratory test results and numerical analyses are presently available for strudel scour. It has been observed to occur during spring break- up at the mouths of rivers discharging into the Alaskan Beaufort Sea. Preliminary field mapping and measurements of strudel scours have been done.

Strudel scours have not yet been reported in the Canadian Beaufort Sea. (However, it must be remembered that no field surveys have yet been undertaken with this objective.)

Basic laboratory test results and numerical analyses are also available to provide a first order understanding of the strudel scour process.

Strudel scour is a local process which is of greatest significance for the local investigation of sites near river mouths.

For more global sediment transport investigations, it is believed that strudel scour will not be a major shoreline process for two reasons:

(a) strudel scour is a local phenomenon.
(b) strudel scours will infill relatively quickly.

Table 6.5 summarizes the critical gaps in present understanding of strudel scour and makes general recommendations for further research in this area.

TABLE 6.5

RECOMMENDED STRUDEL SCOUR RESEARCH

PROJECT OBJECTIVE	GENERAL RECOMMENDED APPROACH
LOCAL SITE INVESTIGATIONS (SEE NOTES BELOW):	
1. Frequency of occurrence.	Aerial reconnaissance surveys at break-up.
2. Investigation of strudel scour infill rate.	Sidescan sonar surveys at observed at strudel scour sites.
3. Investigation of strudel scour mechanism.	Laboratory tests, numerical modelling and field sampling of strudel scour sites.
REGIONAL COASTAL STUDIES:	
Strudel scour studies are believed to be of low priority.	

NOTES:
1. Strudel scour studies are only recommended if the local site is near a river mouth.
2. The projects identified above are listed in the considered order of priority.

6.3.5 Sediment Transport by Bottomfast Ice, In-Ice Encapsulation and On-Ice Surface Transport

Information on these potential ice-related sediment transport mechanisms is largely qualitative. However, some relevant information is available.

As coastal freeze-up and break-up processes and patterns are relatively well understood, preliminary statements regarding the probable importance of the above processes can be made. Also preliminary measurements of in-ice sediment content are available for the Alaskan Beaufort Sea.

Although exploratory calculations indicate that each of the above ice-related sediment transport processes have the potential to be important (as shown in Section 4), the significance of these interactions for coastal processes is unclear. The principal information gap producing this uncertainty is the fate of the sediment at ice break-up.

As the nearshore ice typically does not move until it is deteriorated, much of the sediment which was adhered to the ice bottom and/or entrapped in the sheet during the winter is expected to be locally released into the water. As well, little on-ice surface transport of sediment is considered likely to occur as the nearshore ice cover close to river mouths typically melts inplace before large scale ice sheet movements occur. (This is particularly true for the Mackenzie River which is the most significant source of fluvial sediment.)

Consequently, further research into these ice-related sediment transport processes is given a low priority.

If further investigation of these processes is undertaken, then it is recommended that these research efforts focus on understanding the fate of the sediment at break-up. Table 6.6 recommends a general approach for these observations.

6.3.6 Frazil Ice Erosion

Very little information is available to evaluate the significance of frazil ice with respect to sediment transport.

The presence of frazil ice may affect sediment transport in two general ways:

(a) it may alternate wave action at the beach, thereby reducing the wave energy reaching the littoral zone (see Section 4.1). This would have the effect of reducing sediment transport.

(b) it may abrade the shoreline. This would tend to increase sediment transport.

Thus, it is unclear whether the presence of frazil ice will tend to increase or decrease sediment transport. The frazil concentration and wave field in the littoral zone are two important parameters affecting sediment transport by frazil ice.

It is recommended that preliminary studies be carried out initially to investigate both the sediment transport mechanisms which occur in the presence of frazil ice and the probable significance of these mechanisms.

TABLE 6.6

RECOMMENDED APPROACHES FOR ICE SEDIMENT CONTENT RESEARCH

PROJECT OBJECTIVES	GENERAL RECOMMENDED APPROACH
Fate of sediment encapsulated in the ice and adhered to the ice bottom at break-up	Field coring and measurements of in-ice sediment content during the ice melt period, before and after movement of the nearshore ice sheet has occurred. Monitoring the drift and fate of sediment-laden floes after break-up.
Fate of fluvial sediments deposited on the ice surface at break-up	(a) Field observations and sampling of the sediment quantity remaining on the ice surface near river mouths after surface drainage has occurred. (b) Field observations and mapping of the area of sediment-laden ice which undergoes large movements at breakup.

7. RECOMMENDATIONS

Section 6 outlined the general information gaps and provided an assessment of the significance of the various sea ice - shoreline interaction processes from existing information.

Table 7.1 summarizes the results of this assessment of the significance of sea ice for coastal processes. Table 7.2 summarizes the general information gaps which are considered most critical.

On a regional scale, the greatest effect of sea ice is its reduction of the annual duration of open water conditions. This process, however, is relatively simple and well understood and its importance lies in possible long-term changes from the existing sea ice regimes which could have significant consequences for Beaufort Sea coastal processes. It would be useful therefore to study historical changes in average duration of the seasonal ice cover as an aid in understanding coastal morphology and possible effects of future changes in ice cover.

The limitation of wave energy produced and attenuation of wave energy reaching the shoreline may also be important; however, the significance of this effect of sea ice is strongly dependent on local and dynamic environmental conditions. Consequently, this effect of sea ice will be difficult to quantify in a general manner and further research is expected to be inconclusive.

Sea ice is believed to be most important on a local scale (as many of the interaction processes observed to date have the potential to significantly rework the beach). Thus investigations for local sites need to be carried out specifically for the locations under consideration.

As noted in Section 5, available field data and numerical models are insufficient for assessing the effects of frazil ice and of specific engineering developments on ice related coastal processes. Physical modelling is therefore recommended for these purposes.

Follow-on projects with the highest priority are described in the following tables. Six projects are described in Tables 7.3 to 7.8 with the following respective objectives:

TABLE #	**PROJECT TITLE**	**PROJECT OBJECTIVES**
7.3	Field Reconnaissance	1) Investigation of ice movement directions at break-up. 2) Investigation of ice override events.
7.4	Berm and Ridge Field Survey	Investigation of effect of alongshore grounded ridges on seabed bathymetry.
7.5	Continued assembly of Historical Database	1) Investigation of typical near-shore ridge patterns. 2) Investigation of ice override events. 3) Documentation of ice action. 4) Documentation of near-shore landfast ice drift after break-up.
7.6	Long term changes in Beaufort Sea Ice Cover	1) Investigate changes in ice cover due to climatic change. 2) Assess effects on annual duration of ice cover and on rates of sediment transport processes.
7.7	Sediment Dynamic Physical Model	1) Model sediment processes at King Point. 2) Assess effects of proposed developments.
7.8	Effect of Frazil Ice on Erosion	1) Determine potential significance of frazil ice for sediment transport 2) Improve present understanding of sediment transport mechanisms in frazil ice

TABLE 7.1

IMPORTANCE OF SEA ICE FOR COASTAL PROCESSES

SEA ICE-RELATED SHORELINE PROCESS	LOCAL SITE INVESTIGATIONS	REGIONAL COASTAL SURVEYS
I. MODIFICATION OF MARINE-RELATED SEDIMENT TRANSPORT MECHANISMS:		
(a) Limitation of annual duration of open water conditions.	High	High
(b) Limitation of wave energy in coastal environment.	Not considered to be a local process	Low-High (depends on prevailing conditions)
(c) Attenuation of wave energy reaching shoreline (sea ice or frazil ice).	Unknown (has potential to be significant for specific local conditions)	Unknown (has potential to be significant for specific local conditions but is suspected to be less significant on a regional basis)
II. SEA ICE - SHORELINE INTERACTION PROCESSES:		
(a) Ice scour and ice push	Unknown (Ice scour and ice push have potential to be highly significant).	Unknown (Ice push has potential to be highly significant)
(b) Ice override	Unknown (possibly important at some sites)	Unknown (believed to of low significance)
(c) Ice wallow	Unknown (ice wallow has the potential to be significant at specific sites)	Believed to be of low significance.
(d) Strudel scour	Unknown (strudel scour has the potential to be significant for local specific sites).	Believed to be of low significance.
(e) Sediment content of ice cover	Believed to be of low significance	Believed to be of low significance.
(f) Effect of frazil ice on corrosion	Unkown	Believed to be of low significance.

TABLE 7.2
SUMMARY OF GENERAL RESEARCH REQUIREMENTS

SEA ICE-RELATED SEDIMENT TRANSPORT PROCESS	LOCAL SITE INVESTIGATION	REGIONAL COASTAL STUDIES
I. MODIFICATION OF MARINE-RELATED SEDIMENT TRANSPORT MECHANISMS:		
(a) Limitation of annual duration of open water conditions.	Further research believed to be important to aid in understanding possible effects of man-made changes in ice cover regime.	
(b) Limitation of wave energy produced in coastal environment	Not considered to be a local process	Further research efforts have only been generally defined as this study has focussed on direct sea ice-shoreline interactions. Improvements are required in present capabilities both for the operational definition of field environmental conditions and for understanding the basic processes involved.
(c) Attenuation of wave energy reaching shoreline	No further research recommended as this process will not contribute to shoreface development problems. Also see (a) above.	No further research recommended due to difficulties in defining the local environment, (which is extremely variable). This process will not contribute to shoreface development problems.
II. SEA ICE - SHORELINE INTERACTION PROCESSES:		
(a) Ice scour and ice push	Determination of the depth of disturbed beach sediments.	Determination of probable relative nearshore movement directions between ice keels and the shoreline.
	Determination of the local scour frequency.	Coastal mapping of shoreline susceptibility to these processes.

TABLE 7.2 (CONTINUED)
SUMMARY OF GENERAL RESEARCH REQUIREMENTS

SEA ICE-RELATED SEDIMENT TRANSPORT PROCESS	LOCAL SITE INVESTIGATION	REGIONAL COASTAL STUDIES
(b) Ice override	Assembly of historical database for assessment of the frequencies of occurrence using field reconnaissance data, aerial photographs and satellite imagery.	Continued assembly of historical database for assessment of the geographical distribution frequencies of occurrence using field reconnaissance data, aerial photographs and satellite imagery.
	Determination of area and distance back from the shoreline which is affected by ice override. Determination of depth of beach zone sediment affected by ice override.	Determination of quantity of beach material moved during ice override events Note: As the available information indicates that ice override is unlikely to move large volumes of sediment, only preliminary studies are recommended initially.
(c) Ice wallow	Determination of local frequency of occurrence Determination of fate or reworked material.	Determination of geographical distribution and frequency of occurrence. Determination of fate of reworked material. Note: As ice wallow is considered likely to only rework the beach, only preliminary studies are recommended initially.
(d) Strudel scour	Determination of strudel scour depth, frequency of occurrence and infill rate.	Further research believed to be of low priority as strudel scours are expected to be local and to infill quickly.

TABLE 7.2 (CONTINUED)
SUMMARY OF GENERAL RESEARCH REQUIREMENTS

SEA ICE-RELATED SEDIMENT TRANSPORT PROCESS	LOCAL SITE INVESTIGATION	REGIONAL COASTAL STUDIES
(e) Sediment content of ice cover	Determination of volume of sediment and distance moved.	Estimation of magnitude. Could be very important in terms of volume transported, but may re-deposit it locally.
(f) Effect of frazil ice on erosion	Study of mechanics of erosion by frazil ice.	Estimation of frazil ice concentration in shore zone.

TABLE 7.3

PROJECT DESCRIPTION - FIELD RECONNAISSANCE

STUDY OBJECTIVES:

1. To investigate ice movement directions at break-up for an assessment of the frequency of ice push events.
2. To investigate the occurrence of ice override events. (Note: this is a secondary objective of the field reconnaissance program.)

PROJECT SUMMARY:

An aerial reconnaissance program is suggested for the break-up period when ice movements in the nearshore area are most common.

Both visual and photographic data should be collected during the reconnaissance. There are a number of logistical options for this project.

A project involving visual observations and relatively simple photographic documentation (e.g. continuous video photography and handheld or aircraft hatch-mounted 35 mm or 70 mm still cameras) is the minimum requirement. Large format mapping cameras are not recommended here as they will severely restrict the weather window within which the reconnaissance program may operate. (Low visibility conditions often occur in this area during the break-up period.)

The use of aircraft with SAR capability would greatly reduce the dependence of the project on weather conditions and should be considered at the planning stage. (This option however would involve significantly greater costs.)

The use of AES ice observation aircraft is one option that was considered but rejected. This aircraft is fitted with SLAR which provides all-weather capability; however, the resolution of this imagery is believed to be insufficient for this project. Also the use of this aircraft may involve high cost (depending on the cost recovery policies adopted by the AES).

The reconnaissance should be directed by observers who accompany the flight and have general experience with sea ice processes and the southern Beaufort Sea coastline and nearshore topography.

Ideally, this reconnaissance should be carried out along the complete Beaufort Sea coast. However, this would involve significant costs. Consequently, it is recommended that reconnaissance surveys be carried out at two different sites which span a range of conditions. The western Yukon and Richards Island areas are two candidate sites for this survey.

TABLE 7.3 (CONTINUED)
PROJECT DESCRIPTION - FIELD RECONNAISSANCE

The timing of reconnaissance flights should be structured to observe ice movement events. Thus, flights should be flown before and after storms. If the reconnaissance aircraft has all-weather capability, then surveys should also be conducted during the storm. Reconnaissance missions should be undertaken only if ice is in the nearshore area and should be planned using input from available satellite imagery and other data (e.g. ice maps prepared by the AES).

Ideally, this reconnaissance program should be undertaken over a number of years to gain an understanding of the annual variation that is possible. However, this would involve significant costs. Consequently, this detailed reconnaissance program is only recommended for one year pending the results obtained.

In addition it is recommended that present efforts by the Atlantic Geoscience Centre to build up a historical reconnaissance survey database be continued. Thus a long-term reconnaissance program should be maintained at a relatively low level of effort. For evaluation of ice override events, a program involving one flight on approximately five year intervals is considered sufficient. For more general investigations, a program involving one to two flights per year, just before and after break-up is recommended. This will contribute data for the build-up of a historical database which may be used to assess ice action at future candidate sites.

PROJECT OUTPUT

1. Observations of ice movement directions in the nearshore zone and an understanding of the frequency of ice push events.
2. Observations of ice override events.
3. Improved general understanding of the overall effect of sea ice on coastal processes.
4. Survey data contribution for historical database.

POTENTIAL DIFFICULTIES

1. Nearshore ice conditions may be light at break-up.
2. The frequency of missions will be limited by poor weather conditions (if the reconnaissance aircraft does not have all- weather capability).

APPROXIMATE COST

$50,000.00 to $500,000.00 per annum (depending on scope).

EVALUATION

High cost, medium risk, high payoff.

TABLE 7.4

PROJECT DESCRIPTION - BERM AND RIDGE FIELD SURVEY

PROJECT OBJECTIVE

To observe and measure the effect of nearshore grounded ridges on seabed bathymetry to investigate the probable amount of soil moved during ice push events.

PROJECT SUMMARY

A field measurement program involving ridge and seabed bathymetry surveys is proposed during the late winter and break-up period. The project scope should involve seabed surveys both at grounded ridge sites and at control sites in the same water depth where ridging is not present.

During the late winter period, a number of grounded ridges should be located and surveyed topside and bottomside (using standard sonar and land surveying techniques). Diver observations of the ice - seabed interaction should also be performed.

Immediately after break-up (after the ridges move) seabed bathymetry surveys should be undertaken.

This project should be undertaken for a range of water depths both to obtain information on the effect of this parameter and to reduce the probability that an early season storm will rework the seabed before it can be surveyed.

PROJECT OUTPUT

1. Quantitative measurement of soil moved during ice push events.
2. Improved general understanding of ice - seabed interactions.

POTENTIAL DIFFICULTIES

1. An early season storm may rework the seabed before it can be surveyed.
2. It may be difficult to quantitatively determine the soil volume moved due to local variations in bedslope.

APPROXIMATE COST

$100,000 to $300,000 (depending on scope).

EVALUATION

High cost, medium risk, high payoff.

TABLE 7.5

PROJECT DESCRIPTION - CONTINUED DEVELOPMENT OF HISTORICAL DATABASE

PROJECT OBJECTIVE

1. To build up a database which may be used to assess ice action at future candidate sites, and to map shoreline susceptibility.

PROJECT SUMMARY

A large amount of historical data has been collected to characterize Beaufort Sea ice and coastal conditions. Some of this information is publicly available such as LANDSAT satellite imagery, air photographs and weather and storm reports. Other imagery such as air photographs, and SAR imagery have been collected by the offshore oil industry; while this information is proprietary to the oil industry, it is believed that access could be obtained for general environmental studies.

A project is proposed in which this historical data would be formally catalogued and archived into one data set which may be used to investigate ice action at future candidate sites.

Additional data which is collected should be added to the database as it becomes available. For example, the field reconnaissance data collected as described in Table 7.3 is one data set which should be added to the database.

PROJECT OUTPUT

1. Historical database for assessing ice action at future candidate sites.

POTENTIAL DIFFICULTIES

Data record may be incomplete or poorly archived.

APPROXIMATE COST

$50,000.00

EVALUATION

Low cost, medium risk, medium payoff.

TABLE 7.6

PROJECT DESCRIPTION - EFFECT OF LONG-TERM CHANGES IN BEAUFORT SEA ICE COVER

PROJECT OBJECTIVE

1. To develop a method for investigating possible effects of long-term changes in Beaufort Sea ice cover and its effects on sediment transport processes.

PROJECT SUMMARY

Changes in the average annual ice cover duration can be caused by slight climatic changes or by man-made changes due to engineering developments or ice management practices. Such changes are likely to have occurred over geologic time and may have occurred within restricted areas since offshore exploration began here in the 1960's.

Changes in the average duration of ice cover no doubt affect sediment transport processes and may have significantly altered erosion and accretion rates through the recent epoch. This would have a serious bearing on any estimates of the rates and significance of these processes.

The project will develop a research plan and methodology to investigate (see objective). It will be conducted by reviewing the literature on climatic change and on climatic and sea ice modelling.

PROJECT OUTPUT

1. Methodology for modelling climatic change.
2. Methodology for modelling effects of climatic change on sea ice extent and duration in Beaufort Sea.
3. Methodology for investigating effects of changes in ice cover on sediment transport processes.

POTENTIAL DIFFICULTIES

Limited availability of models.

APPROXIMATE COST

$50,000.00

EVALUATION

Low cost, low risk, medium payoff.

TABLE 7.7

PROJECT DESCRIPTION - SEDIMENT DYNAMICS PHYSICAL MODEL

PROJECT OBJECTIVE

1. To use a physical, scale model in a hydraulic tank to assess the possible effects of shoreline developments at King Point, Yukon Territory, on coastal sediment transport processes.

PROJECT SUMMARY

This project involves two major tasks. The first is to develop a physical model of sediment transport processes and coastal erosion at King Point, calibrated against measured data.

The second task is to simulate the coastal environment after each of the proposed developments is in place, to assess the effects of the developments.

PROJECT OUTPUT

1. Working model of King Point coastal environment.
2. Improved understanding of coastal processes.
3. Rigorous assessment of potential effects of coastal developments at King Point.
4. Data for future development of numerical models.

POTENTIAL DIFFICULTIES

1. May be difficult to model the existing environment.
2. Additional survey data may be required to develop the model.

APPROXIMATE COST

$250,000.00

EVALUATION

High cost, medium risk, high payoff.

TABLE 7.8

PROJECT DESCRIPTION - EFFECT OF FRAZIL ICE ON EROSION

PROJECT OBJECTIVE

1. To determine the potential significance of frazil ice for sediment transport.

2. To improve present understanding of sediment transport mechanisms in the presence of frazil ice.

PROJECT SUMMARY

This project will use a hydraulic testing basin to simulate erosion of a shoreline by frazil ice. Several different shoreline materials, bed slopes, wave and current conditions will be simulated. Wax or plastic beads will be used to simulate frazil ice, as properties can be controlled this way.

Videotapes and visual observations will be used to document the mechanical processes involved, and measurements will be made of the following properties under the controlled test conditions:

1. Attenuation or steepening of waves by frazil ice.
2. Rate of sediment erosion.
3. Rate of sediment transport.

PROJECT OUTPUT

1. Improved understanding of effects of frazil ice on shoreline erosion.

2. Numerical models of sediment erosion by frazil ice.

3. Data with which to model effects of frazil on waves.

POTENTIAL DIFFICULTIES

1. Experimentation required to model frazil ice properties.

2. Need to develop methods for measuring wave slope in laboratory.

APPROXIMATE COST

$75,000.00

EVALUATION

Medium cost, low risk, medium payoff.

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APPENDIX A

LITERATURE REVIEW SUMMARY SHEETS AND INTERVIEW REPORTS

LITERATURE SEARCH

Title:	MARINE GEOLOGICAL INVESTIGATION IN THE BEAUFORT SEA IN 1981 AND PRELIMINARY INTERPRETATION FOR REGIONS FROM THE CANNING RIVER TO THE CANADIAN BORDER		
Author:	Reimnitz, E., Barnes, P., Rearic, D. et al		
Source:	U.S. Geological Survey	Date:	1982
Subject:	SEA BED MAKE UP AND SCOUR FREQUENCIES IN ALASKAN BEAUFORT		

Abstract:

The USGS vessel R/V KARLUK ran approximately 1000 km of geophysical tracklines on the inner shelf of the Beaufort Sea, Alaska from July 14 to August 20, 1981. In addition to the trackline surveys, 37 sediment grab samples were collected, one area was investigated by scuba divers, and 5 sites were monitored with Ocean Bottom Seismographs (OBS), three per site. The R/V KARLUK left the Beaufort Sea on August 20 to support investigations by Drs. Ralph Hunter and Larry Phillips in the Chukchi Sea.

In our 1981 field efforts, the emphasis was on reconnaissance data collection from the eastern sector, between the Canning River and the international border. This work was accomplished in two legs, the first one under P.W. Barnes, the second under Erk Reimnitz. Ice and weather conditions were about average to favourable for inner shelf navigation during the first half of the available open-water season. In this report we outline the general scope of our 1981 field efforts in the Beaufort Sea, the types of equipment used, list much of the data gathered, present those parameters and relationships already extracted from the geophysical records, and give preliminary interpretations of our findings.

Comments:

Report details events in Alaska Beaufort. Does give a figure showing composite of sea bed in Canadian Beaufort.

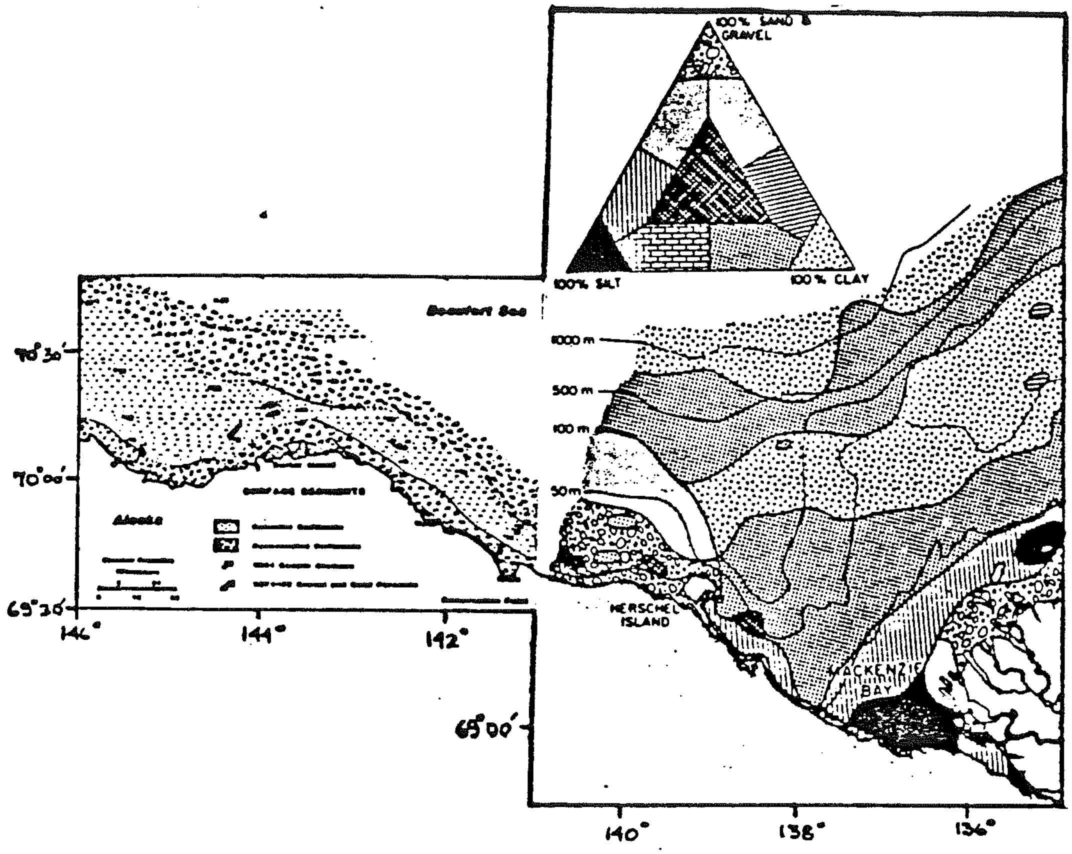

Figure 28.- Composite of surface sediment textures from the present study, and east of the Canadian border (Vilks et al., 1979).

LITERATURE SEARCH

Title:	A NUMERICAL SIMULATION OF THE ICE GOUGE FORMATION AND INFILLING ON THE SHELF OF THE BEAUFORT
Author:	Weeks, W.F. and Tucker (III), W.B.
Source:	Date:
Subject:	SCOURING

Abstract:

A simulation model for sea ice-induced gouges on the shelf of the Beaufort Sea is developed by assuming that annual occurrence of new gouges is given by a Poisson distribution, locations of the gouges are random, and distribution of gouge depths is specified by an exponential distribution. Once a gouge is formed it is subject to infilling by transport of sediment into the region and by local movement of sediment into the region and by local movement of sediment along the sea floor. These processes are modelled by assuming a sediment input based on stratigraphic considerations and by calculating bedload transport using methods from sediment transport theory. It is found that if currents are sufficient to transport sediment, rapid infilling of gouges occurs. In that these threshold currents are small for typical grain sizes on the Beaufort Shelf, this suggests that the gouging record commonly represents only a few tens of years.

Comments:

Sedimentation rates on the Beaufort shelf approximately 0.05 to 0.2 cm/year. Based on observations that 3 m of recent sediment has accumulated since the Beaufort was created, 5000 years ago. Water motion during storms in the ice free open periods is sufficient to rapidly erase gouges in shallow water. In deep water bed load transport of medium to coarse sand is possible results in rapid gouge infilling. Majority of gouge found during winter month when ice is thick, strong and large lateral stresses can be transited. Coring of the subsea have shown sediment props highly variable; all holes showed fine-grained surface sections of marine sediments 2 - 12 m thick.

LITERATURE SEARCH

Title: ESTIMATION OF THE FREQUENCY AND MAGNITUDE OF DRIFT-ICE GROUNDINGS FROM ICE SCOUR TRACKS IN THE CANADIAN BEAUFORT

Author: Lewis, C.F.M.

Source: 4th International Conference on Port and Ocean Engineering under Arctic Conditions

Date: Sept. 1977

Subject: ICE SCOUR

Abstract:

This paper describes a study of the morphology of ice scours in the Canadian Beaufort Sea and their variation with water depth. Within specific bathymetric zones scour depth frequencies are distributed exponentially and Gumbel's extreme-value distribution is used to describe maximum scour depths. When combined with related information on sedimentation, the drift-ice regime, and sea level change, the statistical nature of ice scour tracks is used to: (1) differentiate areas of contemporary and relict scouring, and (2) build a theory for estimating the rate of scour additions for various depths of ice keel penetrations beneath the seabed. Scour additions measured over periods of a few years by repetitive seafloor mapping are described also.

Comments:

The report states "the seaward limit for the hazard zone due to the bottom impact by drift ice is inferred to be the 50 m depth contour". A similar maximum keel depth was given by Lyon, 1967.

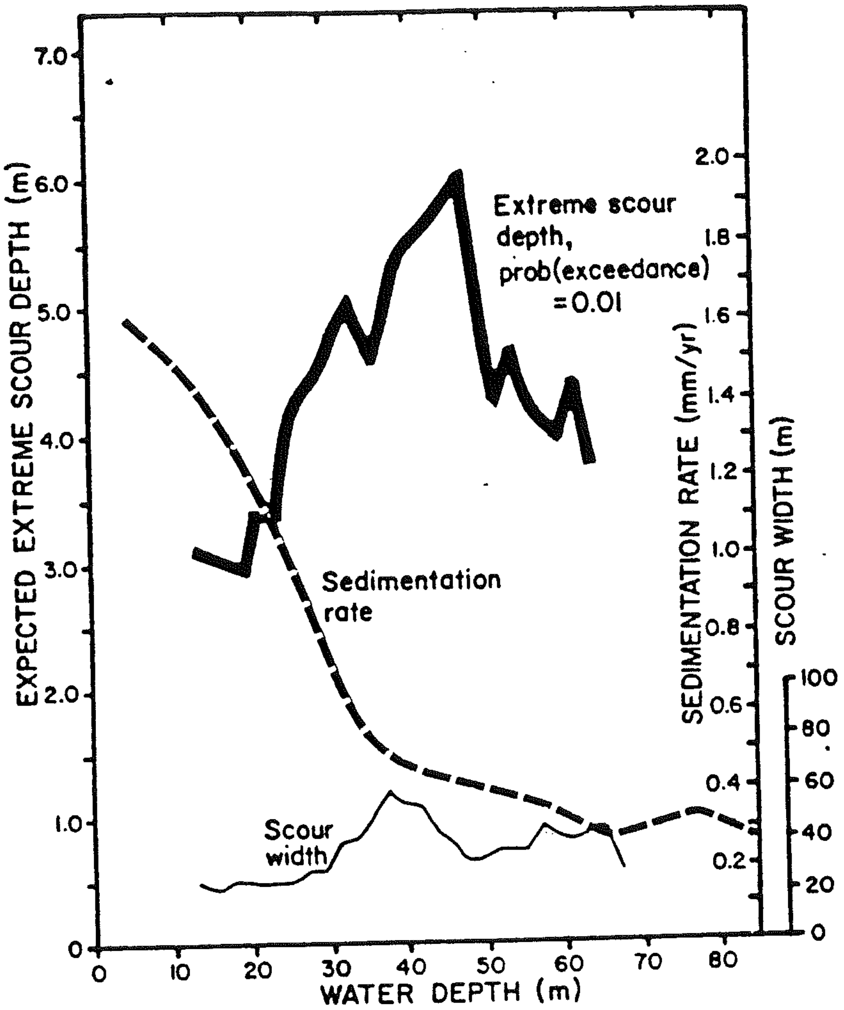

Figure 6. Extreme scour depth, mean scour width, and average sedimentation rates vs water depth for the Beaufort Sea Continental Shelf, Canada.

LITERATURE SEARCH

Title: SUSPENDED MATTER IN THE SOUTHERN BEAUFORT SEA

Author: Bornhold, B.D.

Source: Beaufort Sea Project Tech. Report #25b

Date: Dec. 1975

Subject: MATERIAL IN BEAUFORT

Abstract:

Concentrations of suspended matter measured in the southern Beaufort Sea in Aug. and Sept., 1975 ranged from less than 0.1mg/l to more than 17mg/l. The highest concentrations were recorded at stations off Kugmallit Bay. Mid-water and near-bottom zones of turbid water are common, though their exact causes are not clear. The distributional pattern of suspended matter reflects closely the physical oceanography of the area. As seen from satellite photographs, the sediment plume from the Mackenzie River is carried eastwards along the inner shelf while the plume emanating from Kugmallit Bay remains as a distinct band of turbid water along the SW Tuktoyaktuk Peninsula. The small basin southeast of Herschel Is. receives considerable suspended sediment from longshore drift produced by a small clockwise eddy and the easterly flow past Herschel Is. The anticlockwise gyre which flows south and southeastward into Mackenzie Bay, brings little suspended matter into the shelf waters west of Herschel Is. The major components of the suspended matter include fine inorganic particles, organic aggregates of plankton and inorganic particles, and phytoplankton. Throughout the area the clay minerals display distinct differences.

Comments:

The Mackenzie River contributes 15×10^9 tons of suspended matter per year into the Arctic Ocean.

LITERATURE SEARCH

Title: THE CLIMATE OF THE MACKENZIE VALLEY - BEAUFORT SEA	
Author: Barns, B.M.	
Source: Environment Canada	Date: 1973
Subject: CLIMATE	

Abstract:

The study presents a broad overview of climatic factors pertinent to the Mackenzie Valley - Beaufort Sea. Emphasis is on probability estimates of extremes of precipitation, temperature and winds, as well as duration of critical weather types. Energy exchange, snow cover, wind-chill, inversion frequencies and elements which individually or in combination are important in the resolution of heat flow and environmental quality problems were treated as completely as data permitted.

Comments:

Mean summer temperature in Tuktoyaktuk is approximately 45°F (June - September). The length of winter in coastal areas of Beaufort in the Mackenzie Bay area is 250 - 275 days (mean temperature < 32°F). Mean sea temperatures: July ≃ 36°F; August ≃ 40°F; September ≃ 34°F. Coastal waters around the Tuktoyaktuk area are usually ice free from late June until September.

LITERATURE SEARCH

Title:	MACKENZIE RIVER INPUT TO THE BEAUFORT SEA
Author:	Davies, K.F.
Source:	Beaufort Sea Project, Tech. Report #15
Date:	Dec., 1975
Subject:	WATER AND SEDIMENT INPUT

Abstract:

This report contains a summary of the findings under the study, "Mackenzie River Input to the Beaufort Sea," one of a series of studies comprising the Beaufort Sea Project.
Comprehensive descriptions of the gauging sites and methods used are included in the report. Distribution of flow in the main channels as a percentage of total flow has been determined on a month-by-month basis for the period July 1974 to June 1975.
Suspended sediment transport, ice thickness, and water temperature in the Delta are also discussed and the results shown.
All data contained in the report are provisional, subject to correction, pending publication in the Annual Departmental Reports.

Comments:

Suspended sediment measurements collected during the open water periods showed that on average of one million tons per day of sediment was transported into the delta, for the June to September 1974 period. The peak during this period was 26 million tons per day recorded on August 12, 1974. Average water temperatures shown on Figure 5. Ice thickness measurements made during the winter months are given in Figure 6.

LITERATURE SEARCH

Title:	STORM SURGES		
Author:	Henry, R.F.		
Source:	Beaufort Sea Project, Tech. Report #19	Date:	Dec., 1975
Subject:	CHANGE IN SEA LEVEL		

Abstract:

Storm surges, that is storm induced increases in sea level, of about 1 m in amplitude and lasting for some hours are not uncommon on the Beaufort Sea coast in ice-free summers. Surge levels may even exceed 2 m in some embayments, for instance at Tuktoyaktuk. This report describes a study involving numerical models, designed to permit prediction of surge levels between Herschel Island and Cape Bathurst and also to check if surge magnitudes at sites well off-shore are ever large enough to pose hazards to drilling operations. At the coast, surges cause flooding and accelerated beach erosion and are a factor which should be considered in the design of artificial islands. The nesting sites of thousands of seabirds, of economic importance to the native population, can be inundated, and it is conceivable that the bird population might not survive contamination of the nesting grounds due to a surge carrying oil inland from a spill offshore. The accuracy of numerical storm surge models has to be verified by simulation of a number of actual surges. Too few surges have been successfully recorded in the Beaufort Sea to permit full quantitative model verification at the present time. It can be concluded that storm surge amplitudes are much smaller at sites well offshore.

Comments:

Coast land from Mackenzie Bay to Cape Dalhousie at the eastern tip of the Tuktoyaktuk Peninsula stands barely above sea level. Most of the Beaufort coast line is subject to fairly rapid erosion. Storm surges greatly accelerate this process and at some points the retreat of the shoreline during a major surge - as much as 20 m - is equivalent to several normal years of erosion. Summer surges up to 3 m, winter surges (rare) up to 1 m.

LITERATURE SEARCH

Title:	NEAR BOTTOM CURRENTS AND OFFSHORE TIDES
Author:	Huggett, W.S. and Woodward, M.J. et al
Source:	Beaufort Sea Project, Tech. Report #16
Date:	Dec., 1975
Subject:	CURRENTS OF TIDES

Abstract:

The studies carried out in the Beaufort Sea and described in this report are part of our overall baseline environmental study which will provide background information to the Federal Government. This information could be used to assist in drawing guidelines for offshore drilling. Our specific objective was to gain some understanding of the bottom currents and offshore tides in the southern Beaufort Sea, their relationship to wind and ice conditions, and to measure storm surges along the coast in the Mackenzie River Delta area. The data obtained in this study, and particularly those on storm surges, are to be used in the fine adjustment of the numerical model described by Henry (1975). The Beaufort Sea is the traditional name applied to the waters off the northern coasts of Alaska and Canada. It is an integral part of the Arctic Ocean and cannot be separated oceanographically. The Beaufort Sea extends from the Chukchi Sea on the west, to Banks Island of the Canadian Archipelago. The southern portion of the sea overlies the continental shelf off the northern coasts of Alaska and Canada, which extends northward approximately 150 kilometers and is generally shallower that 65 meters. It then drops off rapidly into the Canadian Basin, reaching a depth of 3940 meters in the Beaufort Deep.

Comments:

- Tides are very weak, measured between 2-3 cm/sec and are semi-diurnal.
- Changes in mean sea level are often larger than the tides. Storm surges of up to 3m have been observed (rarely).

LITERATURE SEARCH

Title: HIGH RATES OF BED LOAD TRANSPORT MEASURED FROM INFILLING RATE OF LARGE STRUDEL-SCOUR CRATERS IN THE BEAUFORT SEA ALASKA

Author: Reimnitz, E., Kempema, E.W.

Source: U.S. Geological Survey, Open File Report 82-588

Date: 1982

Subject: STRUDEL SCOUR

Abstract:

Strudel scours are craters as much as 20 m wide and 4 m deep, that are excavated by vertical drainage flow during the yearly spring flooding of vast reaches of fast ice surrounding Arctic deltas, they form at a rate of about 2.5 km^{-2} yr^{-1}. Monitoring two such craters in the Beaufort Sea, we found that in relatively unprotected sites they fill in by deposition from bedload in 2 to 3 years. Net westward sediment transport results in sand layers dipping at the angle of repose westward into the strudel scour crater, whereas the west wall of the crater remains steep to vertical. Initially the crater traps almost all bedload: sand, pebbles and organic detritus; as infilling progresses, the materials are increaseingly winnowed, and bypassing must occur. Over a 20 m wide sector, an exposed strudel scour trapped 360 m^3 of bedload during two seasons; this infilling represents a bedload transport rate of 9 m^3 m^{-1}. This rate should be applicable to a 4.5 km wide zone with equal exposure and similar or shallower depth. Within this zone, the transport rate is 40,500 m^3 yr^{-1}, similar to estimated longshore transport rates on local barrier beaches. Vibracores typically show dipping interbedded sand and lenses of organic material draped over very steep erosional contacts, and an absence of horizontal continuity of strata - criteria that should identify high latitude deltaic deposits.

Comments:

Paper describes the use of strudel scour pits as natural bedload transport samples:
- large diameter - gives good average
- can collect all particles involved easily.
- should not alter bedload discharge by changing local flow plants.
- allows particles to enter from any direction.
- sampler is stable
- sampling period would be long - should give value close to actual rates of transport.

LITERATURE SEARCH

Title: THE EFFECTS OF SEA AND NEARSHORE ICE ON COASTAL PROCESSES IN CANADIAN ARCTIC ARCHIPELAGO.

Author: R.B. Taylor and S.B. McCann

Source: Larevae de Geographic de Montreal, Vol. XXX

Date: 1976

Subject:

Abstract:

Field investigations at five different coastal locations within the Canadian Arctic Archipelago have shown that, although Arctic beaches are characteristically low energy environments, pronounced differences in the magnitude of wave energy occur between different coastal locations. Nearshore ice has a temporary inhibitive role of delaying the onset of wave action on beaches but the overriding factors in producing variation in wave energy are the length of fetch and presence or absence of sea ice, i.e., length of open water season. An examination of sea ice cover at each of the five coastal areas indicated the longest average period of open water occurred off the northern coast of Somerset Island. A further indirect measure of wave energy was obtained by analyzing the degree of sorting and roundness of the beach sediments from each of the five beaches. The nearshore ice also has a positive role, when subjected to sea ice pressures or storm waves, of creating ice-push and ice-melt features across the beach.

Comments:

Shorefast ice protects the beach from grounding sea ice and prevents waves from reworking the sediment of the lower beach. Sediment can be removed from a beach by ice two ways (1) frozen to the base of shorefast ice and (2) on top of the ice for fluiral sediments. Predominate effect of ice is to limit wave generation and wave action. However ice can produce sinking formations, but only to 2% of the local beach material is involved in this.

LITERATURE SEARCH

Title: THE EFFECTS OF ICE ON THE LITTORAL ZONE AT RICHIBUCTO HEAD EASTERN NEW BRUNSWICK

Author: E.H. OWENS

Source: La Revue de Geographie de Montreal, Vol XXX, Nos 1-2

Date:

Subject: EFFECTS OF ICE ON SHORELINE

Abstract:

Regular monitoring of a barrier beach in a microtidal area (tidal range < 1m) on the west coast of the southern Gulf of St. Lawrence during winter of 1973-74 provided on ice morphology and the effects of ice on the littoral zone. Wave action on the beach was limited for a 3 month period due to the presence of an icefoot for 12-13 weeks and of sea ice for 10 weeks in the adjacent nearshore area. 3 distinct ice zones were studied by means of trenches: the icefoot near high-water level; a hinge zone, 10-25 m wide consisting of broken ice, which grounds at low tide and is characterized by tidal cracks trending parallel to the icefoot; sea ice zone forming an unbroken ice cover, 40-60 cm thick, which grounds on nearshore bar or in intertidal zone at spring low tides. Small amounts of material were incorporated into the ice in these zones by swash action, freezing at the base of the ice, aeolian action, and by freezing in situ of suspended sediment. The main effect of grounding ice floes during breakup is formation of small ice-push ridges at or above the high-water level. Little sediment was redistributed by the ice, and sedimentary features resulting from ice action were destroyed soon after breakup by storm waves. The most important effect of ice in this environment is to limit wave action and consequently to reduce net annual volume of longshore sediment transport in the littoral zone.

Comments:

Little sediment was incorporated in ice during the formation of the icefoot. In the hinge zone some sediment adhered to the base of the ice. Because little material was incorporated into the ice, little material was removed from the littoral zone by ice action. Sea ice tends to diminish or reduce the wave action on the littoral zone. Ice limits wave action during winter months when storm conditions are more prevalent.

LITERATURE SEARCH

Title: SEA ICE GENERATED FEATURES OF COASTAL SEDIMENTS OF JAMES BAY, ONTARIO.

Author: I.P. Martin

Source: Canadian Coastal Conference 1980, Burlington

Date: 1980

Subject: ICE ENHANCED EROSION

Abstract:

The importance of sea ice in shaping and reworking arctic shores and sediments has been well documented in qualitatively descriptive terms. Most studies analyze surficial expressions of cyrogenic phenomena. Not much work has been done in trying to determine which features are more likely to be preserved in ancient deposits, thus more suitable for paleoenvironmental and paleoclimatological reconstructions. Indeed, few ice generated structures observed along the shores are preserved unmodified. Those environments that are acted upon primarily by sea ice are subsequently exposed to intense storm wave action. Materials are reworked and characteristics of water laid sediments remain in geological record. In James Bay such a reworking is not complete and some cryogenic characteristics are preserved, generating a series of typical textural-structural inversions. Such inversions illustrate the juxta-position in the same environment (deposit) of two or more energy states of contrasting processes. Examples of inversions consist of the presence of thick (3m) boulder ridges in fine, thin (50-300 cm) sedimentary sequences; presence of rounded boulders of solid igneous and metamorphic rocks in sorted fine sands and silts; presence of deep, straight walled cuts made into cohesive bedrock or fine deposits of high tidal flats, filled by coarse unsorted sand and fine gravel.

Comments:

Paper more interested in historical determination of ice activity, not ice enhanced beach erosion. Sea ice can erode coastal areas by bulldozing directly into the substructure, by pushing boulders along the bottom or by freezing into the bottom and removing parts of substratum when the ice blocks are refloated at high tides. Sea ice may also foster intense local erosion by funnelling and focussing tides, currents and waves along temporary ice walled bays and breakers.

LITERATURE SEARCH

Title: SHORE ZONE ICE SCOUR STATISTICS: IMPLICATIONS TO COASTAL DEVELOPMENT

Author: J.R. Harper

Source: NRC Workshop on Ice Scouring, Montebello, Quebec

Date: 1982

Subject: ICE SCOUR

Abstract:

Shore-zone ice-scour statistics are available for some sections of the arctic coast, and these statistics provide some preliminary design constraints for coastal development in areas of ice invested waters. The statistics suggest that ice override and associated ice scour may be a process occurring frequently enough to dictate minimum set back distances of coastal structures; the risk of damage by scouring to buried structures, such as pipelines or cables, appears to be of comparable magnitude to other hazards such as coastal erosion, thaw settlement, storm surge, strudel scour and ice "wallowing". These hazards may pose more serious design problems.

Comments:

Scouring of the shore zone may accompany both ice push and ice override. Ice push - ice/shore interaction limited to areas seaward of the high water line. Ice override - sea or lake ice penetrating substantial distances into the backshore (greater than 20 m). Overrides that occur between fall freeze-up and spring break-up are unlikely to cause significant scours because bench sediments are frozen below the surface. Even during summer months, backshore areas along arctic coasts have a permafrost table close to 1 m below the beach surface.

LITERATURE SEARCH

Title: ICE SCOUR ON THE CANADIAN BEAUFORT SEA CONTINENTAL SHELF

Author: C.F.M., Lewis, S.N., Blasco, P. McLaren, B.R., Pelletier

Source: Discussion

Date: June 2/86

Subject: ICE SCOUR

Abstract:

Long curvilinear grooves or scours formed by impingement of drifting sea ice are common features on muddy seafloor of the Beaufort Sea continental shelf. The phenomenon is reviewed, based on existing and new investigations using side scan sonar, profiling, coring, SCUBA, and submersible diving. Scours are best preserved in cohesive silt and clay sediments that blanket the Mackenzie canyon and Beaufort Shelf from Herschel to Baillie Islands. These sediments are generally soft where undisturbed (30-200 kg/m^2 shear strength). The less cohesive sands may be ice-scoured but appear to be smoothed out seasonally by wave and current action. Seafloor is virtually saturated with scour from 3-50 m water depth. Scour frequency diminishes rapidly in deeper water and reaches zero by 80 m. The direction such as embayments and depressions. A dense sub-bottom sand rising close to the seabottom may limit scour depth. Scour widths range from a few meters to hundred of meters; the widest are multiple (parallel) scours. Scour depths on the average range 1.0-1.5 m but maximum depths range up to 6 m below the sea floor. Present results on the rate of scour addition from rate of burial considerations are preliminary and speculative. On the other hand comparison of selected areas from 1971-1975 by means of seabed mosaics constructed from side scan sonar imagery have been highly successful.

Comments:

Mackenzie Canyon and Beaufort Shelf from Herschel to Baillie Islands is blanketed with cohesive silt and clay sediment and soft where undisturbed. Scour depths - average 1 to 1.5 m but can go up to 6 m. Highest scour densities occur in mid range water depths. Probably due to extreme mobility and tendency for pressure ridge development in the shear zone of the winter ice cover. Most scours are produced by keels in pressured ice under the influence of onshore storm winds. The influence of currents, such as the arctic gyro circulation are much less effective in producing scour.

LITERATURE SEARCH

Title: SEA BOTTOM SCOURING IN THE CANADIAN BEAUFORT SEA

Author: J. Hnatiuk, B.D. Wright

Source: 15th OTC, Houston, Texas

Date: May 1986

Subject: SCOURING IN CANADIAN BEAUFORT SEA

Abstract:

Echo sounding, side scan sonar and seismic profiling records have shown that the continental shelf of the Canadian Beaufort Sea has been subjected to extensive scouring by ice features. The scouring phenomena is important in design and protection of offshore wells and future pipelines. Analyses of records collected by industry and government in the early 1970's and reported by Hnatiuk and Brown in 1977 have been refined with the inclusion of additional data collected by industry and government in 1975 and 1976. Here, the results of the information synthesis are presented in terms of regional maps showing relevant scouring parameters and their variation with location and water depth. A quantitative evaluation of scour return period is also presented on the basis of sedimentation assumptions. This information is compared with a recent analysis of sidescan scour mosaics collected repetitively over four areas ranging in water depths from 45 to 150 feet and with time intervals ranging from 2 to 7 years between the repetitive seafloor maps. The rate of addition of new scours determined from the repetitive mosaic approach supports the regional assessment of Beaufort Sea scour but suggests more episodic and a really frequent scour events along with more active scouring in water depths approaching 150 feet. This information is discussed in terms of the Beaufort Sea ice regime.

Comments:

Paper discussed scour in Beaufort sea mainly in deeper water > 20 feet. Scour depths vary from 3 - 5 feet normally. 97% of scours between 2 - 7 feet deep. Scouring most common in water depths from 50 to 150 feet.

LITERATURE SEARCH

Title: FURTHER OBSERVATIONS OF THE SCOURING PHENOMENA IN THE BEAUFORT SEA

Author: J. Shearer, S. Blasco

Source: Geological Survey of Canada, Paper 75-1/A

Date: May, 1975

Subject:

Abstract:

Comments:

Paper mainly concerned with scour in deeper water not on beaches. Scours in the Beaufort thought to be caused during winter months when large pieces of ice are frozen in the polar pack ice. This gives the ice sufficient momentum to scour the bottom. Typically scours are not found inside the 10 m depth contour.

LITERATURE SEARCH

Title: THE OCCURRENCE OF PERMAFROST AND FROZEN SUB SEABOTTOM MATERIAL IN THE SOUTHERN BEAUFORT SEA

Author: J.A.M. Hunter, et. al.

Source: Beaufort Sea Project, Tech. Report #22

Date: April 1976

Subject: PERMAFROST IN BEAUFORT AREA

Abstract:

Permafrost conditions exist beneath most of the Beaufort Sea Shelf area. As a result of large changes in the surface thermal regime in the recent geological past, non-equilibrium conditions are probably found in most areas; hence permafrost is both aggrading and degrading. Permafrost is generally at much higher temperatures offshore than the equivalent permafrost conditions onshore and as a result is much more susceptible to thawing by a thermal disturbance. The occurrence of ice-rich sub-seabottom sediments over large areas of the shelf has been interpreted from seismic data. Such sediments are potentially susceptible to hazardous thermal degradation. Because of low sediment temperatures, natural gas in shallow sediments may be found in the form of clathrate hydrates, which may cause additional technical problems for exploratory drilling. No such shallow occurrences have been documented in offshore drilling done to date; however, these deposits are seismically indistinguishable from ice-bonded sediments.

Comments:

Sub seabottom permafrost exists owes much of the Beaufort Sea Shelf.

LITERATURE SEARCH

Title: PERMAFROST BENEATH THE BEAUFORT SEA - NEAR PRUDHOE BAY, ALASKA

Author: P.V. Sellman, E.J. Chamberlain

Source: 1979 OTC, Houston, Texas

Date: May, 1986

Subject: PERMAFROST

Abstract:

Occurrence and properties of subsea permafrost near Prudhoe Bay, Alaska, were investigated by drilling and probing. Nine holes were drilled and 27 sites were probed with a cone penetrometer. The deepest drill hole was 65.1m below the seabed, while a depth of 14.1m was reached with the cone penetrometer. Engineering and chemical properties were determined from core samples and point penetration resistance data were obtained from the penetrometer. Thermal profiles were acquired at both the drill and probe sites. Temperatures below 0°C were observed in all the drill and penetrometer holes logged, although frozen sediments were encountered only occasionally. Seasonally frozen sediments were observed near the seabed at each site. The degree of ice bonding, or strength could be related to seabed temperature and was greatest in shallow water (<2m). The penetrometer resistance and thermal data indicated that deeper ice-bonded sediments occur, for example approximately 12.7 m below the seabed in 2 m of water off the Sagavanirktok delta. Of eight holes drilled offshore, it appeared that four encountered bonded permafrost. In general, the position of the ice-bonded permafrost interface was extremely irregular. The depth below the seabed to this interface at various distances from shore along the line studied was 28.8 m at 1 km, 65.1 m at 3.5 km, 44.1 m at 6.8 km, and 29.5 m at 17.2 km.

Comments:

"Wherever the highly over consolidated silt or clay is preserved in the sea bottom, ice-bonded permafrost lie close to the sea floor, the dense sediments inhibiting the infiltration of more saline waters into the deeper sands and gravel". Sediment temperature increases with depth to depth ranging from 4 to 10 m, then decrease with depth, indicating that perennially frozen sediments occur at all sites.

LITERATURE SEARCH

Title: ICE GOUGE CHARACTERISTICS RELATED TO SEA-ICE ZONATION, BEAUFORT SEA

Author: P.W. Barnes, E. Reimnitz, D.M. Rearic

Source: NRC Ice Scour Workshop, Montebello, Quebec.

Date: Feb.1982

Subject: ICE SCOUR

Abstract:

Gouging of the sea floor by ice is an ongoing process that disrupts and modifies the seabed, affecting sedimentologic processes, ice zonation, and petroleum development activities. The sea ice off northern Alaska is not smooth but broken by ridges of ice on its surface, expressed as keels below the surface. Gouging occurs where these keels come into contact with, and plow into, the seafloor. Sediments are disrupted, atmospheric and oceanic energy is absorbed, ice movement is arrested, stabilizing the ice and affecting ice zonation. Development activities that place pipelines and subsea structures on the sea floor are affected by the plowing and forces involved in ice gouging. In this report we summarize 8 years of bathymetric and side-scan sonar data regarding the character and variability of ice gouging on the shelf of the Beaufort Sea of northern Alaska. A description of the character of ice gouging is presented to describe the regional character of gouging on the shelf without regard to yearly variability. Regional and process-related variability are then discussed to show general ice, seabed-sediment relationships in a reassessment and updating of our earlier work (Reimnitz and Barnes, 1974).

Comments:

Most gouges occur in water 15 to 30 m deep. Greatest gouge depth in water 18 to 25 m, commonly 1 m deep and often more than the 2 m. In water less than 10 m and over 45 m deep maximum depths are less than 1 m.

LITERATURE SEARCH

Title: STATISTICAL ASPECTS OF ICE GOUGING ON THE ALASKAN SHELF OF THE BEAUFORT SEA

Author: W.F. Weeks, P.W. Barnes, D.M. Rearic and E. Reimnitz

Source: No source

Date:

Subject: ICE SCOUR

Abstract:

Statistical characteristics of ice produced gouges that occur on the sea floor along a 190 km stretch of the Alaskan coast of the Beaufort Sea between Smith Bay and Camden Bay are studied. Data set is based on 1500 km of precision fathometry and side-looking sonar records that were obtained between 1972 and 1979 in water depths to 30 m. The probability density function of the gouge depths into the sediment can be represented by a simple negative exponential over 4 decades of gouge frequency. The exceedance probability function is, therefore, $e^{-\lambda d}$ where d is the gouge depth in meters and λ is a constant. The value of λ shows a general decrease with increasing water depth from 9 m^{-1} in shallow water to less than 3 m^{-1} in water 30 to 35 m deep. The deepest gouge observed was 3.6 m from a sample of 20,354 gouges that have depths of greater or equal to 0.2 m. The dominant gouge orientations are usually unimodal and reasonable clustered, with the most frequent alignments roughly parallel to the general trend of the coastline. The value of $\bar{N}1$, the mean number of gouges (deeper than 0.2 m) per kilometer measured normal to the trend of the gouges, varies from 0.2 for the protected lagoons and sounds to 80 in water between 20 and 30 m deep in the unprotected offshore regions. Distribution of spacings between gouges as measured along a sampling track is a negative exponential.

Comments:

Sedimentary structures are dominated by wave and current related processes inshore of 10 m, by ice and wave and current related processes between 10 and 20 m and by primarily ice related processes to water depth of 50 m or more. Spring breakup occurs in June and refreezes in October.

LITERATURE SEARCH

Title:	SEA ICE GOUGE STATISTICS
Author:	J.D. Wheeler and A.T. Wang
Source:	Proceedings of POAC '85
Date:	Sept. 1985
Subject:	SCOUR

Abstract:

Information on sea-ice gouging of the seafloor is needed whenever pipelines are to be buried for protection against impact from keels that are moving from the Arctic ice canopy. This paper discusses four topics that are of interest in making use of gouge data. First, two procedures for representing gouge-depth data, with reasons for a preferred approach. Second, statistical criteria for selecting a probability function to represent gouge data. Third, a procedure for estimating pipeline burial depths where gouge statistics vary appreciably with water depth along the pipeline length. Fourth, data needs for improving assessment of the statistics of the gouging processes.

Comments:

Paper concerned primarily with the use of gouge statistics to predict the minimum burial depth for pipelines. Author suggests gouging statistics in the actual area of interest should be used rather than a geographically large area to predict minimum burial depths.

LITERATURE SEARCH

Title:	SHORE ICE RIDE-UP AND PILE-UP FEATURES		
Author:	A. Kovacs		
Source:	CRREL Report 83-9, March 1983	Date:	May 1986
Subject:	ICE DAMAGE		

Abstract:

Recent observations of shore ice pile-up and ride-up along the coast of the Alaska Beaufort Sea are presented. Information is given to show that sea ice movement on shore has overridden steep coastal bluffs and has thrust inland over 150 m, gouging into and pushing up mounds of beach sand, gravel, boulders and peat and, inland, the tundra material. The resulting ice scar morphology was found to remain for tens of years. Onshore ice movements up to 20 m are relatively common, but those over 100 m are very infrequent. Spring is a dangerous time, when sea ice melts away from the shore, allowing ice to move freely. Under this condition, driving stresses of less than 100 kPa can push thick sea ice onto the land.

Comments:

This report dramatically shows the power and extent of damage to shore lines due to ice. Also documents the erosion of the coast line at Rsoak. Since 1949 the shore line has receded 410 m, this represents an average of 12.8 m of erosion per year.

LITERATURE SEARCH

Title: ICE AND WAVE ACTION ON ARTIFICIAL ISLANDS IN THE BEAUFORT SEA

Author: K.R. Croasdale, R.W. Marcellus

Source: Canadian Journal of Civil Engineering V.5(1)

Date: March 1978

Subject: ARTIFICIAL ISLANDS

Abstract:

Artificial islands are being used in the Beaufort Sea to conduct exploratory drilling for hydrocarbons. By May 1977, 15 islands had been built in water depths ranging to the 5 fathom isobath (8.5 m). Ice up to about 7 ft (2 m) thick covers the Beaufort Sea for 9 months of the year and has a considerable influence on construction methods and island design. The islands need sufficient sliding stability to withstand the forces generated by the moving ice and the possibility of ice ride-up has to be considered. Islands can be built either during the winter by trucking gravel over the ice or in the short arctic summer dredges. Temporary slope protection is needed to avoid beach erosion during the short summer months. Slope protection is designed to match the measured and predicted sea state, which also influences the island freeboard needed to avoid wave over- topping. Slope protection methods include anchored poly filter cloth, sandbags and sacrificial beaches. Optimum island designs have to account for constructional constraints, working area needed, ice action, wave action and geotechnical factors.

Comments:

Report deals with artificial islands for exploratory drill in the Beaufort. Briefly describes 2 measures used to reduce or eliminate erosion of the island: (1) sacrificial beaches - long gently sloping sand beaches; (2) sandbag on the beach - this system does not require such large quantities of material. Both ideas work. Either system is used based on supply of raw materials and depth of water.

LITERATURE SEARCH

Title:	MARINE GEOLOGICAL INVESTIGATION IN THE BEAUFORT SEA IN 1981 AND PRELIMINARY INTERPRETATION FOR REGIONS FROM THE CANNING RIVER TO THE CANADIAN BORDER
Author:	Reimnitz, E., Barnes, P., Rearic, D. et al
Source:	U.S. Geological Survey
Date:	1982
Subject:	SEA BED MAKE UP AND SCOUR FREQUENCIES IN ALASKAN BEAUFORT

Abstract:

The USGS vessel R/V KARLUK ran approximately 1000 km of geophysical tracklines on the inner shelf of the Beaufort Sea, Alaska from July 14 to August 20, 1981. In addition to the trackline surveys, 37 sediment grab samples were collected, one area was investigated by scuba divers, and 5 sites were monitored with Ocean Bottom Seismographs (OBS), three per site. The R/V KARLUK left the Beaufort Sea on August 20 to support investigations by Drs. Ralph Hunter and Larry Phillips in the Chukchi Sea.

In our 1981 field efforts, the emphasis was on reconnaissance data collection from the eastern sector, between the Canning River and the international border. This work was accomplished in two legs, the first one under P.W. Barnes, the second under Erk Reimnitz. Ice and weather conditions were about average to favourable for inner shelf navigation during the first half of the available open-water season. In this report we outline the general scope of our 1981 field efforts in the Beaufort Sea, the types of equipment used, list much of the data gathered, present those parameters and relationships already extracted from the geophysical records, and give preliminary interpretations of our findings.

Comments:

Report details events in Alaska Beaufort. Does give a figure showing composite of sea bed in Canadian Beaufort.

LITERATURE SEARCH

Title:	ICE INDUCED EROSION
Author:	N.F. Allyn, J. Tseng, F.B. Caridge
Source:	Canadian Coastal Conference, St.John's,Nfld.
Date:	1985
Subject:	EROSION

Abstract:

Sea-ice and lake-ice formations are formidable erosion agents through scour. In the Beaufort Sea, ice floes, ice ridges and ice rubble fields scour the seabed and artificial islands. In the Great Lakes, off the East Coast of Canada, as well as in the Beaufort Sea, seabed scours from ice ridges and rubble fields formed in situ have been documented. These environmental hazards are amenable to evaluations by deterministic models which quantify erosion for a given ice feature. For those ice features whose attributes have empirical probabilities of occurrences, the erosion caused by these ice features can be evaluated probabilistically. This paper presents two numerical solutions to quantify ice induced erosion, on seabed scour and floe induced berm erosion, with examples for the Great Lakes and Beaufort Sea, respectively.

Comments:

Paper deals with ice scour in deeper water not in areas close to the shore. The paper also presents equation to calculate forces and pressures involved in scouring process. Presents a probabilistic erosion model.

LITERATURE SEARCH

Title: RAPID SHORELINE EROSION AND RETREAT AT ICY BAY, ALASKA - A STAGING AREA FOR OFFSHORE PETROLEUM DEVELOPMENT

Author: B.F. Molnia

Source: 9th OTC, Houston, Texas, 1977

Date: May, 1986

Subject: ILLUSTRATION OF EROSION PROBLEMS

Abstract:

Icy Bay is the only sheltered bay near many of the offshore tracts that were leased for petroleum exploration in the April 1976 northern Gulf of Alaska OCS lease sale. Consequently, it has been selected as a primary onshore staging site for support of offshore exploration and development. The environment of Icy Bay has many hazardous features, including a submarine moraine at the bay mouth and actively calving glaciers at the bay's head which produce many icebergs. But most significant from the point of view of locating onshore facilities and pipeline corridors are high rates of shoreline erosion and sediment deposition. The glacier that once filled Icy Bay has receded more than 40 km since 1904, when the bay was completely ice-covered. A large hooked spit, Point Riou Spit, has developed on the eastern shore of the bay mouth within the limits of the terminal morraine and has grown to a length of 6.6 km (average growth rate of 92 m/6). The Gulf of Alaska shoreline on the east side of Icy Bay, which includes the Malaspina Foreland and Point Riou Spit complex, has been steadily eroded northward by waves and longshore currents. Analysis of ten sets of aerial photographs taken since 1941 indicate that the eastern shoreline has receded as much as 1.3 km in this 35 year period, an average rate of retreat of 37 m/y.

Comments:

Case history of changes in an area due to erosion and deposition of material due to wave action.

LITERATURE SEARCH

Title: SEA ICE AS A GEOLOGIC AGENT ON THE BEAUFORT SEA SHELF OF ALASKA

Author: Reimnitz and Barnes

Source: The Coast and Shelf of the Beaufort Sea, Proc

Date: 1974

Subject: ICE INFLUENCE ON SEDIMENT

Abstract:

A study of the processes and effects of sea ice as a geologic agent on the Beaufort Sea shelf north of Alaska has been conducted during four years of data collecting under both summer and winter conditions. A variety of techniques was used, including bathymetric, high resolution seismic, and sidescan sonar surveys; surface and diving observations; bottom photography; sediment sampling; oceanographic measurements and remote sensing. During the winter season, the ice cover is nearly complete. In the summer season, drifting ice occurs in concentrations up to 100%. A dominant movement of ice from east to west is evident at all seasons. Gouges are generally 0.5 to 1.0 m deep, but incisions up to 5.5 m deep have been measured. Lowest densities are in regions landward of such highs and landward of islands and areas adjacent to river deltas. At depths shallower than 20 m, seasonal gouges may be abundant, but they can be smoothed over by the waves and currents of a single summer. In shallower water, where currents are strong, the flow around grounded ice is intensified and turbulent, producing current scour depressions at the ice bottom contact. Periodic adfreezing of sediment to the bottom adds thin layers of sediment to the nearshore ice. Since most of this ice melts in place, ice rafting of sediments away from the coast is negligible.

Comments:

Comments based on observations on the Beaufort Sea Shelf north of Alaska. Measurement taken on the inner shelf show temperatures of bottom water are highly variable from 1.5 to -1.5° because of salinity of pore water, sediments are not solid. Very little of the sediment on an in the fast ice is rafted away during sea ice breakup. Grounded ice creates a rough bottom and physically unstable deposits. Gouging suspends the bottom sediments by stirring the bottom, which commonly is associated by intensified and turbulent flow near the contact area. All of these factors aid the transport regime in making sediment available for transport by current.

LITERATURE SEARCH

Title: COASTAL SEDIMENTARY PROCESS AND SEDIMENTS, SOUTHERN BEAUFORT SEA

Author: C.P. Lewis and D.L. Forbes

Source: Beaufort Sea Project, Tech. Report #24

Date: Dec.1975

Subject: COASTAL ERROSION

Abstract:

Comments:

Physical conditions (a) steep coastal cliffs, often containing significant amount of grounding ice and fronted by narrow beaches; (b) spits and barners; (c) deltas of coastal plains river. Fine material is moved offshore and beaches, spits and barners contain reminant gravel and sands. Cliffs retreat up to 90 m in 16-18 years has occurred. Significnat sediment transport occurs during spring break-up and storm flood. Direct effect of sea ice on the stability of the coastal features appear small. Indirect effects, particularly the influence of the amount and location of ice in storm surges and wave activity are more important.

LITERATURE SEARCH

Title: PHYSICAL OCEANOGRAPHY OF THE SOUTH EASTERN BEAUFORT SEA

Author: R.N. Herlinueaux, B.R. deLange Boom

Source: Beaufort Sea Project, Tech. Report #18

Date: Dec.1975

Subject: BEAUFORT OCEANOGRAPHY

Abstract:

In the Beaufort Sea meteorological and ice conditions play a major role in the distribution of oceanographic properties. Field studies were conducted during the summer of 1974 ("worst ice conditions on record") as well as during the spring and summer of 1975 ("good ice conditions"). The discharge from the Mackenzie River dominates the surface waters of the southern Beaufort Sea, especially during bad ice years. The density distribution of salinity, temperature, tubridity and currents are described for summer and spring conditions of westerly or easterly winds together with the resulting temperature and salinity distribution. During the spring, tidally induced movements of water column were observed only at mid- depth off Kugmallit Bay, and these movements are not considered to be a major factor in the study area. The movement of Mackenzie River water in the Beaufort Sea is predictable to some degree and can be followed by satellite imagery. Although teh behaviour of oil is not identical to that of water, the flow of surface water could involve the movement of either crude oil from a blow out or other pollutants.

Comments:

Bottom Topography: in the Mackenzie Bay region the nearshore water is very shallow, deepening gradually, with the 10 m isobath lying as far as 35 km offshore. Only ice scours and underwater purges over the flatness of the continental shelf. **Land Drainage:** discharge waters from the Mackenzie River constitute the major source of brackish water in the north coast of Canada; summer flow (May to August) reach a peak flow of approximately $2.3x10^4 m^3$/sec. By December the discharge is reduced to the winter months of approximatley $2.5x10^3 m^3$/sec. **Winds:** during the summer months winds generally blow from the northwest and south- west gradients about equal amounts of time. Strongest winds are generally westerly. **Salinity:** in Mackenzie Bay the salinity has been measured as low as 0% at the surface. The salinity increases with depth reading normal sea levels at depths of approximately 15m (August). **Temperature:** surface water temps have been recorded at approximately 0°C-13°C (August).

LITERATURE SEARCH

Title:	SEDIMENT DISPERSAL IN THE SOUTHERN BEAUFORT SEA
Author:	B.R. Pelletier
Source:	Beaufort Sea Project Tech. Report #25a
Date:	Dec.1975
Subject:	SEDIMENT TRANSPORT AND DISTRIBUTION
Abstract:	

Comments:

Except for the area northwest of Herschel Island which is though to be receiving ice-rifted deposits, sediments on the floor of the Beaufort Sea are mainly fine grained and consists predominately of clay and silt in the western and central areas and somewhat coarser types in the eastern part. In the delta arc and its immediate offshore, this dispersal pattern is partly a result of the fine-grained sediment discharge from the Mackenzie River.

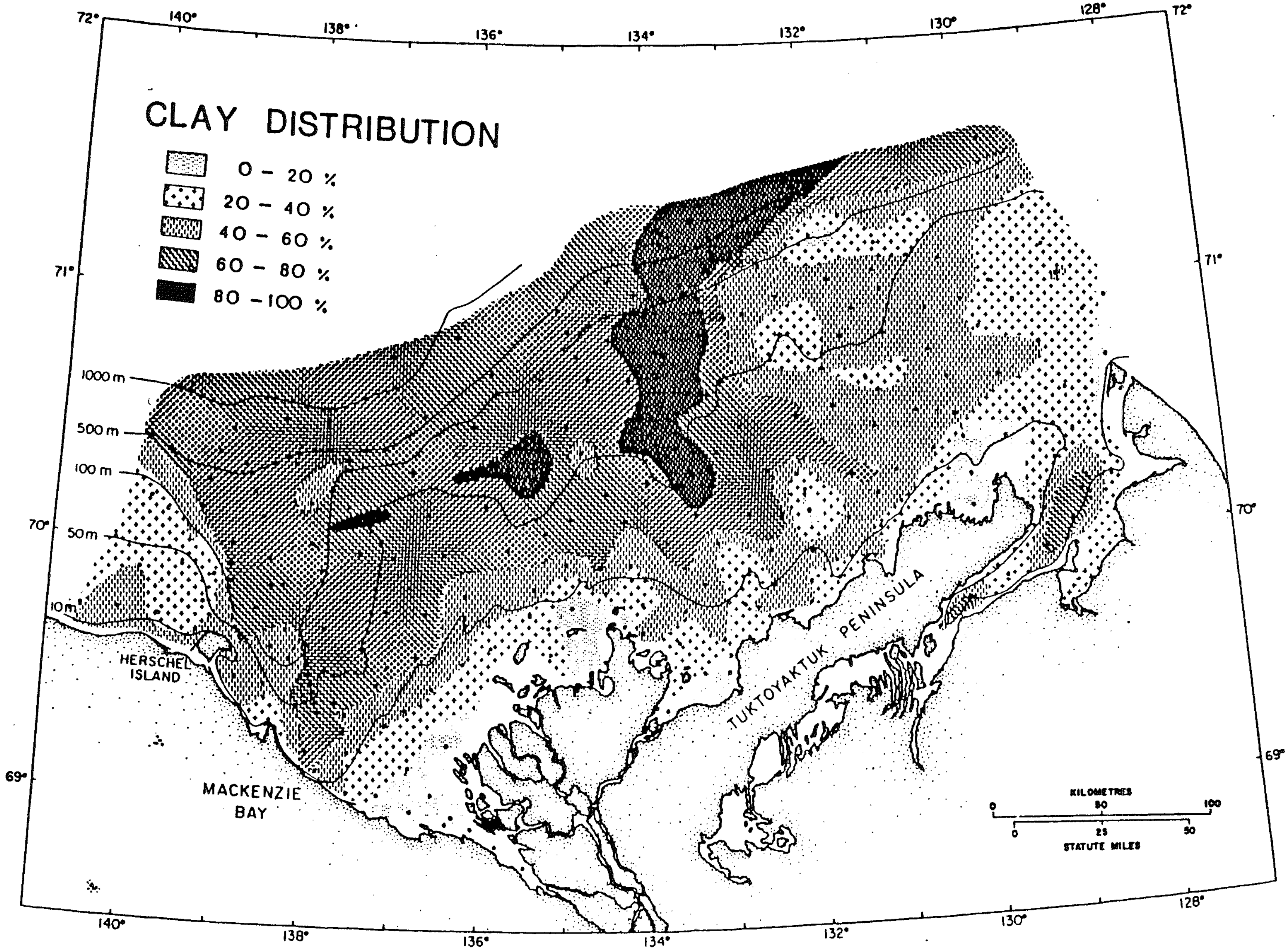

Figure 9. Distribution of clay showing minor amount in the delta areas and heavy concentration offshore.

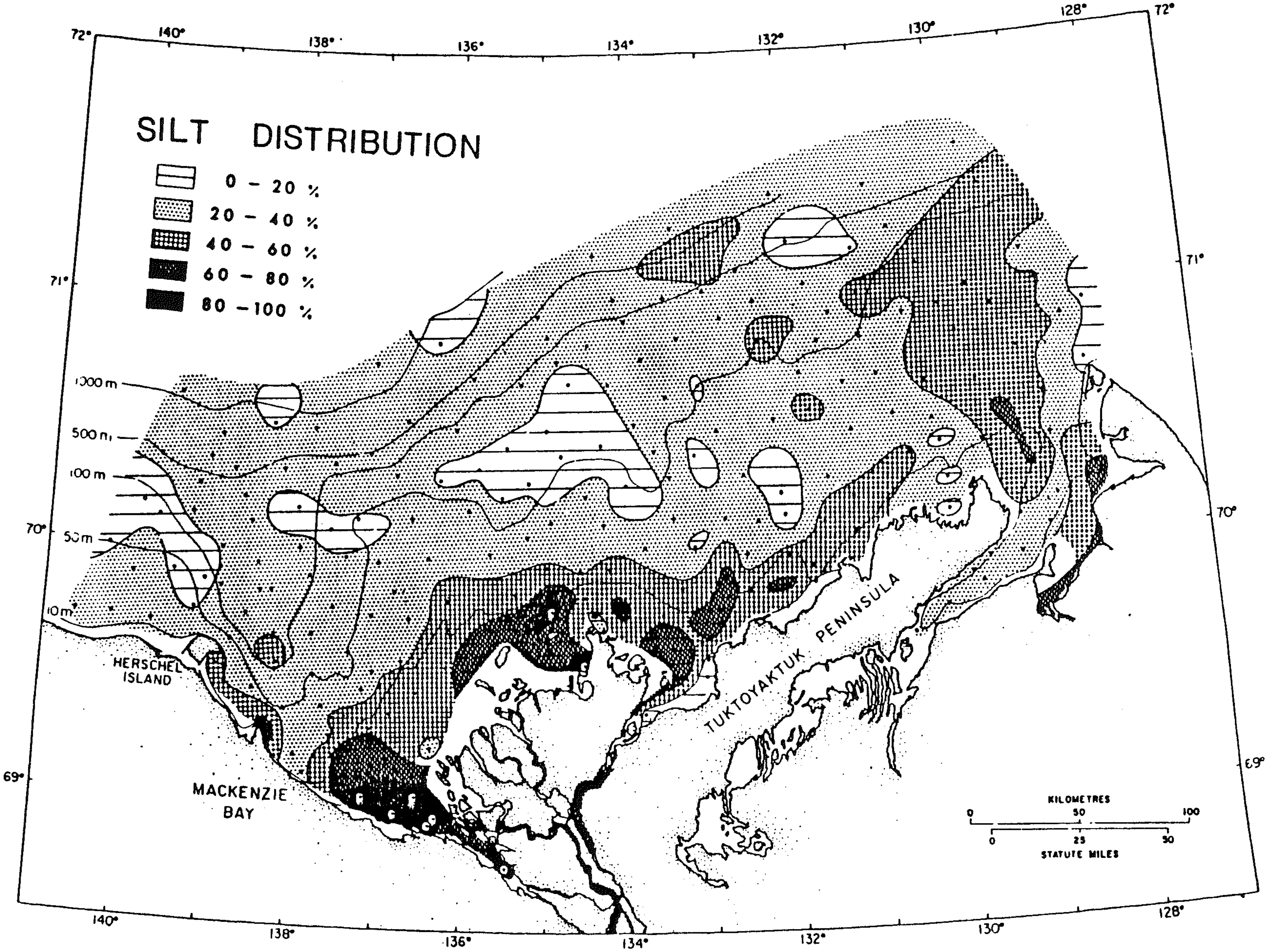

Figure 6. Distribution of silt showing heavy concentration in the delta area, and minor content offshore.

LITERATURE SEARCH

Title: BEACH THAW DEPTH AND EFFECT OF ICE-BONDED SEDIMENTS ON BEACH STABILITY

Author: R.B. Taylor

Source: Canadian Coastal Conference, 1980

Date: May, 1986

Subject: ERROSION OF ARCTIC BEACHES

Abstract:

Fluctuations in beach that were monitored on northern Somerset Island, N.W.T., during 1974 to 1976. The progression of seasonal thaw was similar to that previously reported for other Arctic beaches. Mean annual thaw across gravel beaches was only 50 cm. Beneath the foreshore, the surface of ice-bonded sediment fluctuated in response to changing beach morphology and to changing salinity of the pore water. When exposed, ice boned sediment thawed at 10 to 16 cm/day, a rate similar to the initial beach thaw after melt; however, concentrations of high wave energy eroded the ice-bonded sdediment 30 to 50 cm/day.

Comments:

Paper indicated that the shores of the Beaufort coast are composed of fine grained sediments having ice rich frozen ground containing massive ice denses beneath it. Significant variation in seasonal thaw occurred between beaches of different sediment composition, i.e. thaw was earlier and deeper beneath sand than gravel beaches: better thermal conductivity of the moist sand and less interstial ice. Beneath the foreshore the depth of thaw is deeper than the backshore, can be attributed to the salt content in the water. Ice bonded material can be eroded by waves, but compared to unbonded material the erosion is much slower. Therefore exposed ice bonded material does provide considerable stability to the coast.

LITERATURE SEARCH

Title: SHORE APPROACH ENGINEERING FOR ARCTIC OFFSHORE PIPELINES

Author: R. Nielsen, C. Smith, L.A. Gebhart

Source: Offshore Mechanics and Arctic Engineering Speciality Symposium, New Orleans

Date: 1986

Subject:

Abstract:

The environmental criteria in the Beaufort Sea, Chukchi Sea, and Canadian Arctic Islands impose unique constraints on the design and construction of pipeline shore crossings. These criteria include ice scour, strudel scour, permafrost, subsea soil characteristics, and erosion and deposition patterns. The design of a pipeline shore approach must include protection from these enviironmental factors. Both the burial depth and the way the pipeline is constructed contribute to this protection. Gravel causeways, trenched pipelines, and subterranean pipelines, including both tunneling and directional drilling, are the three most viable pipeline protection techniques for shore approaches in the Arctic regions.

Comments:

Three types of ice sea floor interactiion that may damage pipelines: (i) Scour - depth approximately 1 m in water up to 2 m; depth 3-5 m in water 20-30 m deep; width usually greater than depth; difficult to estimate scour frequency in near shore area. (ii) Strudel Scour - water flowing over holes in ice cause vortex that erodes the sea floor occurs only to edge of bottom first ice i.e. to 2 m isobath. (iii) Ice Pounding ice bangs ice due to variations in water level. Permafrost - at or near the sea floor surface in 2 m water depth; past 2 m depth the upper boundary of ice bonded permafrost is at a variable depth; where permafrost exposed to the atmosphere or shallow water there is usually a surface layer which alternately thaws and refreezes which leads to thaw settlement and frost heave. Wave conditions - generally moderate in Beaufort; shallow water, limited fetch; short open water season; storms do generate large waves (3m); tidal fluctuations small 0.2 - 0.3 m; storm surges significant, up to 2 m.

LITERATURE SEARCH

Title: THE EFFECT OF ICE ON THE BEACH AND NEAR SHORE, POINT BARROW, ARCTIC ALASKA

Author: Hume, J.D., M. Schalk

Source: La Revue de Geographie de Montreal, Vol. XXX Nos. 1-2, P. 105-114

Date:

Subject: EFFECT OF ICE ON ERROSION

Abstract:

Net annual longshore transport at Barrow is approximately 8000 m^3, about 3% of that found in topographically similar temperature areas. Artificial removal of beach sediments can be especially critical with such a low transport rate. Source material available to wave action is unconsolidated gravel, sand, silt, and clay which, except for the annually thawed layer, is frozen to depths exceeding 300 m. The presence or absence of ice offshore determines thefetch available to generate waves. Sea ice on the beach may also act to slow or stop beach processes. Storms occurring during ice-free periods control the rate of erosion of shorelines composed of the fine grained, ice rich sediments. Ice-shove reshapes beaches and adds up to a maximum of 10% to the sediment above sea level. Ice buckling results in depressions up to 3 m deep in the beach and offshore bottom. In waters shallower than 6 m, wave action smoothes such depressions within a few years. Arctic lagoons formed by barrier island chains show a seasonal cycle of salinity ranging from about 28% in the late summer, to a probable 100% in spring, and to 2% in early summer.

Comments:

Ice substantially reduced wave action and resulting transport of particles along the beach. During 'ice free' periods, scattered ice floating near the shore or unmelted in and on the beach also decrease wave action. Frozen sediments on the beach cannot be removed until it is melted. Fine grained silts and clays are susceptable to frost heave, this rarely occurs in sands or gravel. Vertical mass of ice, called frost wedges can occur in sediments of any size. More ground ice occurs in fine sediments (ice-rich); therefore melting of this material influences errosion, for coarser material wave action is more important. Floating ice and/or grounded ice reduce wave action.

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27 July 1986

Razek Abdelnour
Arctec Newfoundland Limited
330 Portugal Cove Road
P.O. Box 5040
St. John's, Newfoundland
A1C 5V3

Dear Razek,

As promised in my telex of 16 May 1986, I am enclosing miscellaneous information components for the ice/shore interaction project. These include:

Item 1 - Review of Exxon gravel island report.

Item 2 - Review of Patrick McLaren's report on ice/shore interaction from the high arctic.

Item 3 - Interview summaries with Mark Atherton (CanDive), Peter Lewis (B.C. Ministry of Environment), Geoff Spedding (Esso), and Bill Wiseman (LSU).

Item 4 - Review of observations of an ice ride-up event along Spy Island, Alaska.

Item 5 - Review of the Arctic Sciences B.C. Hydro report on the proposed Liard River damn site and the potential effects on Mackenzie River breakup.

Item 6 - Development of an ice scour transport model.

Two items that were not completed were (1) the interview with J. Ross Mackay because he is in the field for the entire summer and (2) the development of a ice-wallow conceptual model because you have already made most of the appropriate calculations.

....2

Should you require any additional information, please let me know. I will be looking foward to reviewing the draft report in the near future.

With regards,

John R. Harper, Ph.D.
Manager West Coast Region
Dobrocky Seatech Ltd.

Enc.

Item 1 - Review of Exxon Ice Island Report

This report[1] was prepared by the Exxon Production Research Lab to provide an overview of Exxon's experience with artifical islands in the Beaufort Sea of Canada and Alaska. The report was reviewed to see if they had had any specific experience with ice/shore interaction around their artificial islands.

There is no specific information related to ice related transport of sediment material. Apparently there have been no really detailed measurements of shore-face morphology on artificial islands that would indicate effects of ice on the shore face. Ride-up events have occurred on several of the Canadian Beaufort Islands but are discussed only in an engineering context. Noteably a ride-up event occurred in Mackenzie Bay on Kannerk Island in March of 1977 and acheived an elevation of 22 feet above the sea surface, although no penetration onto the island proper occurred.

The only other mention with relavance to our study was the dirty ice which was commonly noted in Exxon's Prudhoe Bay drilling areas. Several pictures indicated that dirty ice in the ice canopy could be up to five feet in thickness.

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[1] Exxon Company U.S.A., 1979. Technical seminar on Alaskan Beaufort Sea gravel island design. Exxon Production Research Company, Houston, Texas.

Item 2 - Review of Pat McLaren's Paper

This paper[1] is of interest because in describes diver observations of ice/shore interaction and presents a model of how this interaction is important in controlling coastal morphology. Although the observations are from the High Arctic, the processes probably occur within the Beaufort Sea and the conclusions are therefore relavent to this study.

Morphogical observations by McLaren (1982) indicated that ice scouring of nearshore sediments is a common feature in his study areas. Furthermore, the vast majority of scouring has a significant onshore-directed component to it, so that ~~a~~ there is a net onshore-directed sediment movement due to ice scouring. McLaren esti~~a~~mated that 90 to 100% of the shore materials are contributed to ice scour and ice push. Wave energy, which is very low in that area, provides only minor reworking of these sediments. McLaren also reinterpreted observations made by Hume and Schalk (1964) and concluded that ice push sediment piles on Alaskan Beaufort Sea barrier islands could cause almost total replenishment of the islands in less than 1000 years.

The observations of McLaren are significant and suggest that the processes he observed at Byam Martin Channel are likely to occur in other areas of the arctic but may be masked by normal marine processes such as wave-related transport. This theory has received recent support by E. Reimnitz and P. Barnes at USGS who believe that the 18-m bench that occurs almost continuously along the Alaskan Beaufort Sea coast is formed by ice-related transport.

The theory advocated by McLaren (1982) is not new and was originally proposed by Nichols (1961).

Hume, J.D. and M. Schalk, 1964. The effects of ice-push on arctic beaches. Amer. Journ. Sci. 262:267-273.

[1] McLaren, P., 1982. The coastal morphology, sedimentology and processes of eastern Melville and western Byam Martin Islands, Canadian Arctic Archipelago. Geol. Surv. Can. Bull. 333, 39p.

Nichols, R.L., 1961. Characteristics of beaches formed in polar climates. Amer. Journ. Sci. 259:694-708.

Item 3 - Interview Summaries

Mark Atherton

Technical Manager

CanDive

The main reason to interview Mark was because of the numerous under ice dives conducted by CanDive. Major observations:

- not much observation of ice/sediment interaction
- provided photo indicating high sediment ice content in upper 2 feet of ice canopy (80 km offshore) indicating frazel ice may be important in Mackenzie Delta area
- no observations of any offshore anchor ice
- pressure ridges age - on new ridges it is easy to dislodge blocks of ice from keel and create underwater avalanches (ice blocks float up!), however, on "older" ridges it was impossible for divers to dislodge ice blocks even with mechanical assistance
- frazel ice definitely shows preferential ice growth on plastics (photo provided)
- have noted the growth of stalactites under ice (photo provided) which can be as long as 3 m with 15 cm/day growth. These are "soft" however and disintegrate when touched
- divers have noted freshwater/saltwater interfaces immediately below the ice surface

Peter Lewis
Ministry of Environment
Victoria, B.C.

The reason for interviewing Peter Lewis was because of his many years of experience in nearshore areas of (a) the Mackenzie Delta and (b) the Yukon coast

1. Overflow and Strudel Scour

   - has taken pictures of strudel holes in Babbage River
   - never saw a strudel scour crater, presumably because sediment materials are cohesionless (same for nearshore ice scour).
   - doesn't believe there are any channels from the Mackenzie greater than 2 m deep so overflow must occur in most areas of the delta out to the 2 m isobath
   - P.L. has observed overflow on Babbage, Firth and Blow rivers

2. Other Observations

   - no observations of frazel ice
   - no observations of anchor ice in nearshore
   - has observed ice push event on Kay Point but not any substantial ride-up features
   - suggested contacting - Jim Hunter re anchor ice
     - Nicky Cooper re ice observations
   - no observations of freeze up

Geoff Spedding
Esso Resources Canada Ltd.
Calgary, Alberta

Spedding is presently in charge of Esso's oceanographic and ice observation programs.

1. Overflow and Strudel Scour

   - most extensive at mouth of Middle Channel, out to 10-15 miles offshore
   - overflow occurs around the ADGO Islands
   - he has never seen any really large strudels - mostly smaller cracks
   - no strudel scour craters noted but believes they fill in quickly in the delta
   - overflow is comparatively clean (low SSC) in delta; ice clean after overflow
   - no overflow noted in Kugmallit Bay, possibly because of deeper channel
   - "pop up" channels common during early flood; he had seen very good examples on this years LANDSAT

2. Sediment in Ice

   - G.S. has not noted sediment layers in ice cores
   - he feels freshwater freezes quickly in delta area, thus preventing this (most ice out 10-15 miles off delta is freshwater ice)
   - ADGO ice usually pretty clean but has seen sediment attached to bottom of ice where ice is bottom fast.

3. Ice Ride-up

   - has not seen any ride-up features along coast eventhough he has many overflight miles.

William Wiseman
Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana

Dr. Wiseman conducted a coastal freeze-up at Point Lay, Alaska (Chuckchi Sea) in 1975.

- frazel ice very common near the shore - it forms in lagoons and is transported to the shore

- frazel thickens noticeably towards shore

- when waves come through frazel the radiation stress due to waves results in a strong onshore movement of the frazel such that material is pushed up above MWL on the beach face; creates steep ice foot

- they had pressure sensors in, but all failed

- thought there was considerable merit in the hypothesis that frazel reduces wave steepness and as such may contribute to a net onshore sediment transport

2. No observations of overflow

3. No observations of ride-up

Item 5 - Liard River Report

This report[1] was reviewed because it contained the most detailed description of breakup in the Mackenzie River Delta. In particular, it was reviewed with respect to the area of overflooding and the potential for strudel scour formation.

The major conclusions of the report were that the construction of the Liard River dam~~s~~ would retard breakup in the Mackenzie River delta from 2 to 9 days and that vertical mixing within the shallow delta area would be increased by some unknown amount.

The sequence of breakup in the delta is illustrated by a series of TIROS satellite images from 1980 and is as follows:

30 May 1980 - some overflow present in the eastern channels; some moat areas open.

8 June 1980 - breakup in the eastern delta much later than western delta.

24 June 1980 - major moats open except at North Head where the landfast ice sheet appears to be very stable, especially to the north of Pullen Island.

LANDSAT images illusrtated some additional aspects of breakup:

4 June 1978 - some moats; some "pop-up" channels.

10 June 1980 - deeper channels appear to be melted out as moat forms, so overflow may not occur (?); some overflow on Kugmallit Bay but none on North Head.

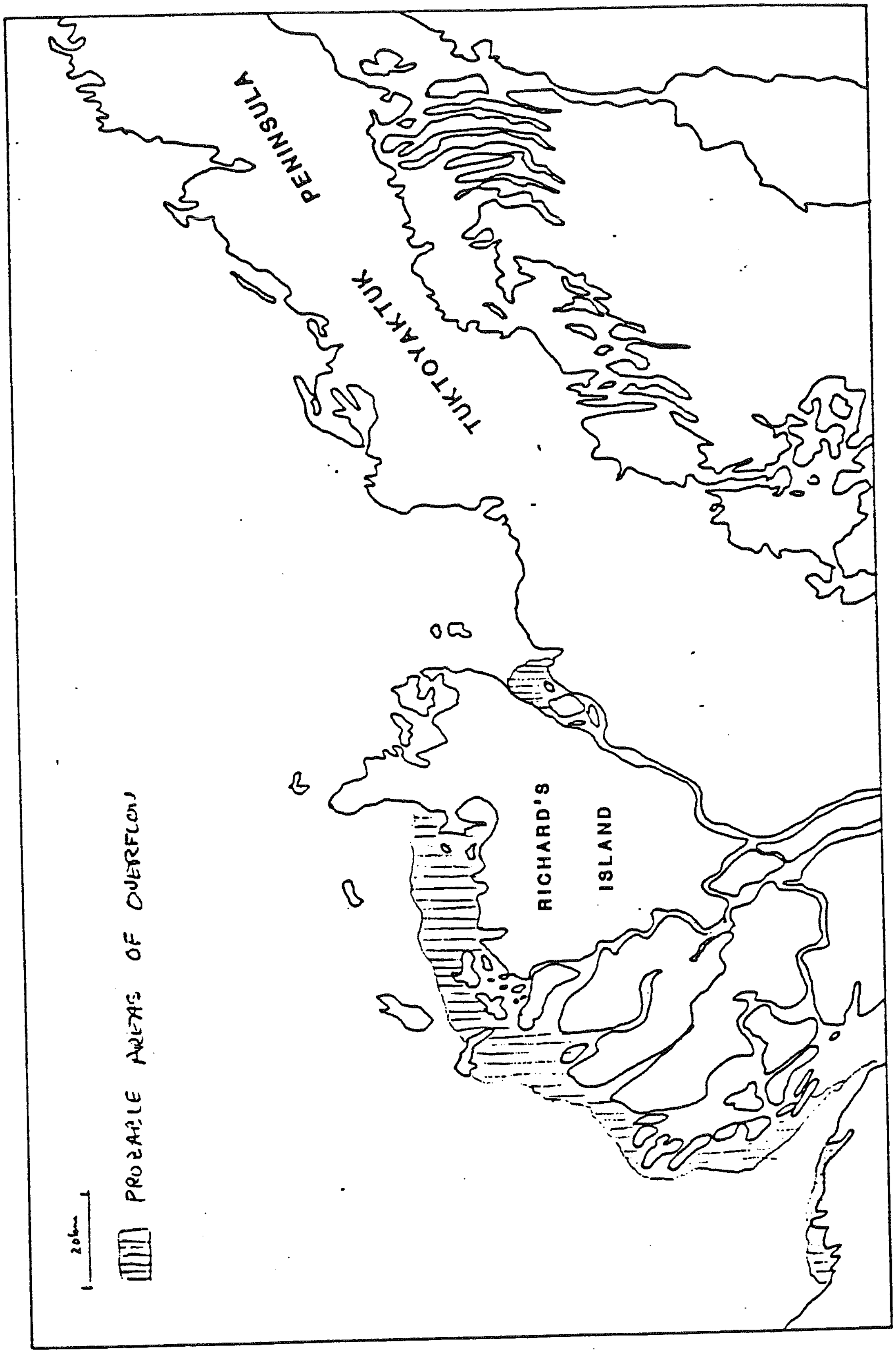
1 July 1976 - landfast ice sheet is attached to Pullen Island only.

Some other miscellaneous information was included within the report as was a complete catalog of images (appropriate images were photographed and are provided as an attachment to this Item). The report mostly cited Alaskan reference relative to overflow phenomena; however, on the 25 May 1976 image there is a grey band off of the eastern delta indicating overflow. This band is between 10 to 15 km in width. Analysis of the images from the report and discussion with Geoff Spedding were used to construct the map of probable overflooding areas shown in Figure 2.

Freezeup appears to occur in a stepwise fashion from the shore outward and the authors suggest that the ice may be slightly thicker in the nearshore because of the freshwater flow that continues througout the year.

---

[1] Marko, J.B., D.B. Fissel, M.A. Wilson and D. Huston, 1983. Background and evaluation of impacts of the Liard River hydroelectic development in the southeastern Beaufort Sea. Unpuplished proprietary report prepared for B.C. Hydro Authority, Vancouver, B.C. by Arctic Sciences Ltd., Sidney, B.C., 81 p with appendices.


TUKTOYAKTUK
PENINSULA
RICHARD'S
ISLAND
20km
PROBABLE AREAS OF OVERFLOW

APPENDIX B

ICE SCOUR SEDIMENT TRANSPORT ESTIMATES

Item 6 - Ice Scour Transport Model

This model was developed to make a first approxiamtion of the amount of onshore sediment movement created by ice scouring. The development of the model was essentially to test the hypothesis that there is a significant quantity of sediment material moved in the onshore direction due to ice scouring. The net onshore movement results from the fact that most scour events have a net movement vector that is slightly onshore.

The basic assumptions of the model are indicated in the attached calculation sheets. The first approxiamtions indicate that:

- net displacements are small, in the order of a few centimeters per year.
- net displacements during an event can be large, in the order of a few metres.
- if onshore directed sediment movement due to ice scour is thought to be significant, then it is clear that ice must be directed at the coast at high angles (i.e. angle of incidence greater than 20°.

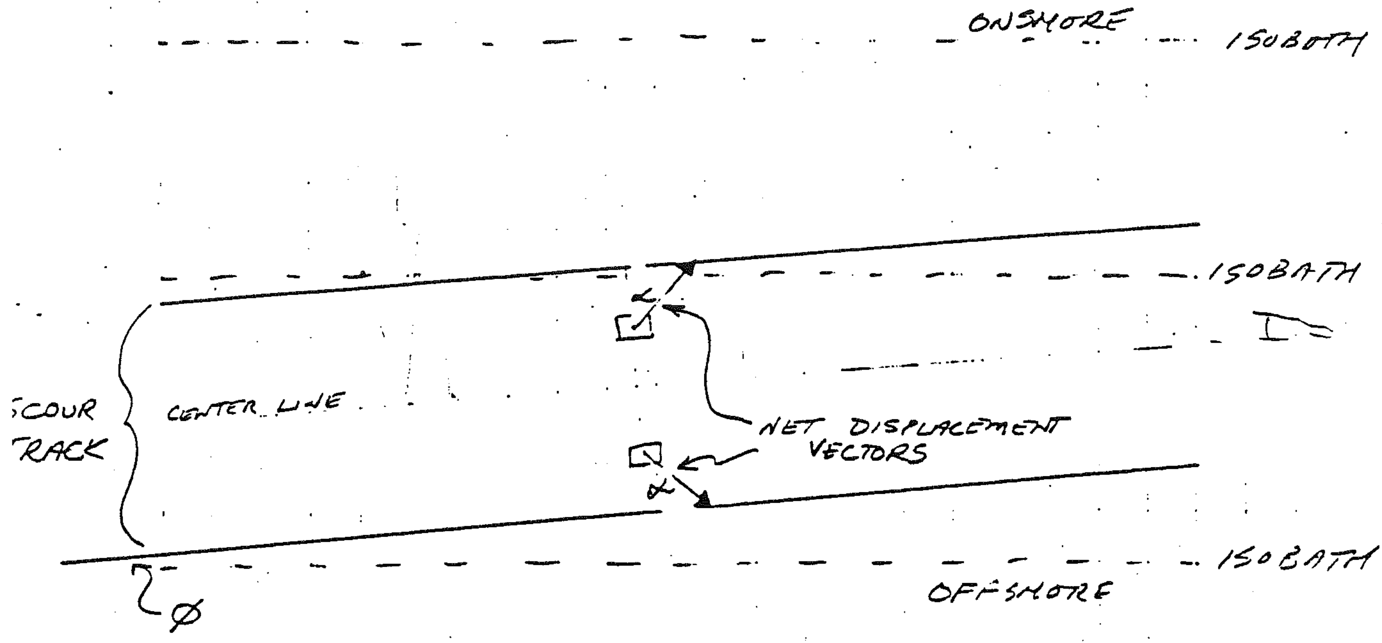
The data used to make the above computations is taken from offshore ice scour statistics in the Beaufort Sea (Lewis, unpublished Beaufort Sea Project Report). It is possible, and in fact probable, that these statistics are not appropriate for shallow, nearshore areas. In shallower water near the coast (<10 m) it is suggested that the following assumptions can be made:

- gouges are narrower, probably an average of 3 m wide, ~~(i.e. 1 = 25m)~~,
- gouge events are more frequent, probably an order of magnitude more frequent
- angle of incidence with the shore is slightly greater than in offshore areas (about 10 - 15°).

With these assumptions, the net onshore displacement values do not change significantly (see section 6 of calculations).

As a first approximation, it appears that seabed ice scouring has a very minimal effect on the net transport of material. Although arguments by McLaren (1982) are convincing as to the net transport due to ice scour, the preliminary calcualtions suggest that little net onshore displacement will result from ice scour.

CONCEPTUAL SCOUR TRANSPORT MODEL



① ASSUME NET DISPLACEMENT OF MATERIAL IN EACH "HALF TRACK" IS 45° THEN

$$D \sin 45 = R/2$$

$$D = R/2 \sin 45$$

$$D = 0.707R$$

WHERE D : DISPLACEMENT DISTANCE
R : SCOUR WIDTH

② DISPLACEMENT UP SLOPE

$$\cos(\overset{45^\circ}{\alpha} - \phi) = D+/D$$

$$D \cos(\alpha - \phi) = D+$$

$$\boxed{0.707R} \cos(\alpha - \phi) = D+$$

→ Assumes $\alpha = 45°$

where $D+$ is the onshore displacement component

③ DISPLACEMENT DOWNSLOPE

$$\cos(\alpha + \phi) = D-/D$$

$$D \cos(\alpha + \phi) = D-$$

$$\boxed{0.707R} \cos(\alpha + \phi) = D-$$

where $D-$ is the offshore displacement component!

[illegible] $\alpha = 45°$

④ NET DISPLACEMENT

$$\Delta D = D_+ - D_-$$

$$= \left[0.707 R \cos(\alpha - \phi)\right] - \left[0.707 R \cos(\alpha + \phi)\right]$$

$$= 0.707 R \left(\cos(\alpha - \phi) - \cos(\alpha + \phi)\right)$$

where ΔD is the net displacement per event.

ΔD	R	α	ϕ
0.9	10	45	5
1.7	10	45	10
3.4	10	45	20
0.43	5	45	5
1.7	20	45	5
7.1	10	45	45

⑤ PROBABILITY

Given than the probability of an event at a particular location is about <u>2%</u> then

ΔF = net displacement per year

$$= \Delta D \times 0.02$$

$\Delta F \times 1000$	ΔF	R	α	ϕ
18 m/1000 yr	0.018/yr	10	45	5
34 m/1000 yr	0.034/yr	10	45	10
68 m/1000 yr	0.068/yr	10	45	20
140 m/1000 yr	0.14 m/yr	10	45	45

⑥ Shallow Water Assumption

	ΔF	ΔD m/yr	R	α	ϕ
0.1	~~0.05~~	~~0.26~~ 0.52	~~1.5~~ 3	45	10
0.16	~~0.08~~	~~0.39~~ 0.78	~~1.5~~ 3	45	15
0.42	~~0.21~~	2.12	~~1.5~~ 3	45	45

where probability of scouring is 20%

APPENDIX C

ICE SEDIMENT TRANSPORT FOR AN OVERRIDE EVENT AT SPY ISLAND, ALASKA

Item 4 - Observations along Spy Island, Alaskan Beaufort Sea

In 1982, J. Harper made observations and meausurements of an ice ride-up event along Spy Island on the Beaufort Sea coast of Alaska. It is included here because it is one the few sites where measurments were made of the sediment push pile associated with the ride-up. As such, the measurements permit a very crude approximation of total amount of material contributed to the island due to the ice ride-up.

Spy Island is a low (<2 m above MWL) sand and gravel barrier island. The island is devoid of vegetation and is frequently washed over by storm surges. The island has been breached and now consists of distinct east and west components.

The ice ride-up occurred at two distinct locations along the islands. The two ride-up features differed in morphology although they almost certainly originated during the same ice movement. Approximately 500 m of shore were affected by the ride-up. Representative profiles across the pile-up and sediment push pile are shown in Figure 1.

From measurements taken from Figure 1, an average of about 2 m^3/m of shoreline were contributed during the event. Push piles occurred along approximately 350 m of shoreline so that a total of 700 m^3 were contributed to the island during the event.

These volumetric estimates provide a basis for evaluating the long-term effect of ice on the islands. Given that this event probably occurs an average of once each 10 years along the entire coast of the island, then the net contirbution due to ice push would be:

0.2 m^3/yr

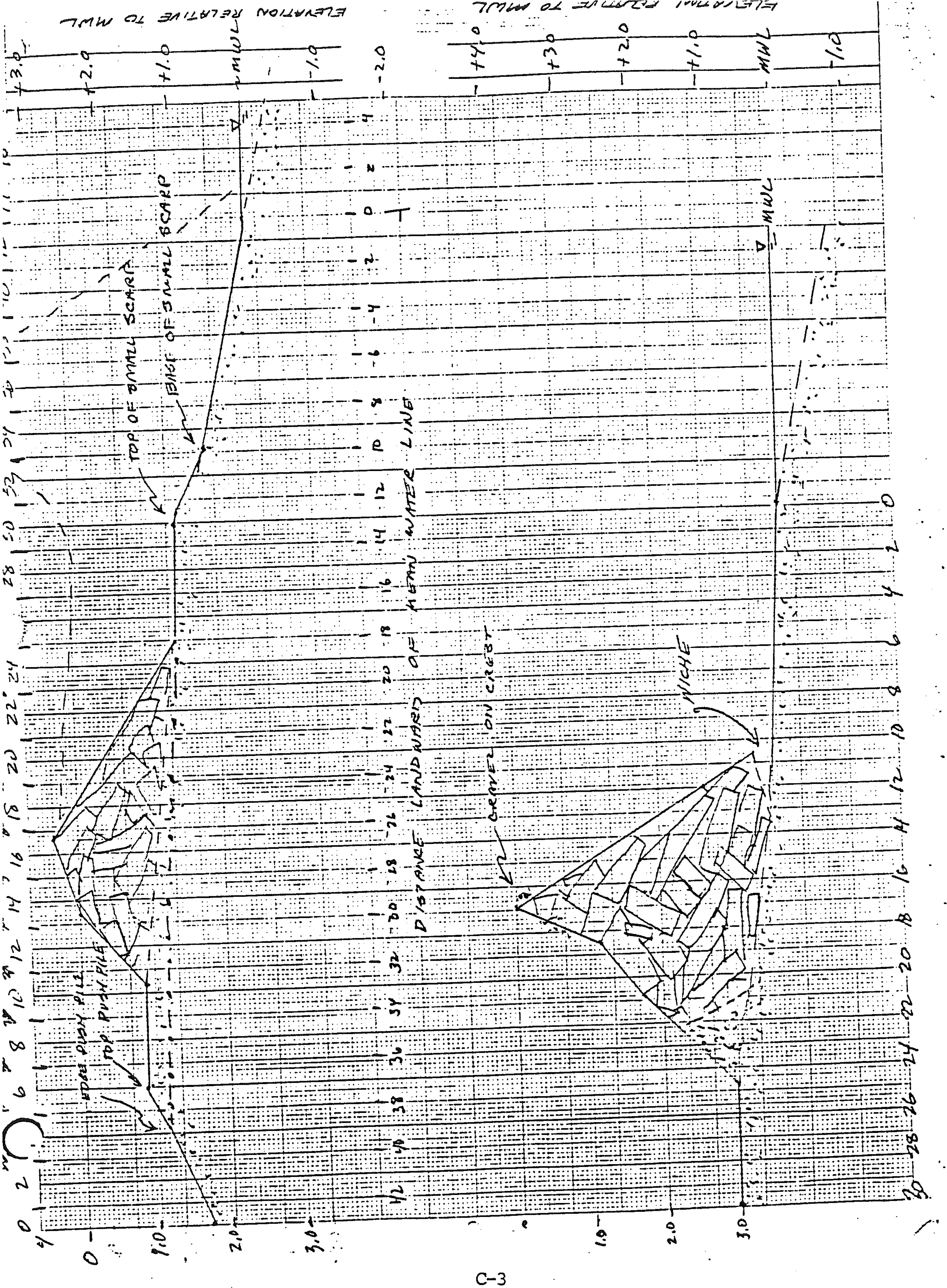
2 $m^3/$ 10 years

20 $m^3/$ 100 years

200 $m^3/$ 1000 years.

Given that estimates of longshore transport are in the range of 5,000-10,000 m^3/yr for this section of coast, the amount of material contributed by ice push appears very small. It is also estimated that the amount of onshore transport that occurs during storm overwash would be much larger than 2 m^3/event. The one unknown factor is: how much material may have been contributed by ice push but is not accounted for in the sediment push piles? This unaccounted for material would be the thin layers of material that were not readily identifiable from the wave-transported beach material.

These first order approxiamtions suggest that ice-pushed sediment provides only a small part of the total sediment budget for Spy Island; given that ice push has been observed to be less common in the Canadian Beaufort Sea, one expects even a smaller contribution there.


ELEVATION RELATIVE TO MWL
+3.0
+2.0
+1.0
MWL
-1.0
-2.0
ELEVATION RELATIVE TO MWL
+4.0
+3.0
+2.0
+1.0
MWL
-1.0
TOP OF SMALL SCARP
BASE OF SMALL SCARP
EDGE PUSH PILE
TOP PUSH PILE
DISTANCE LANDWARD OF MEAN WATER LINE
4
2
0
-2
-4
-6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
GRAVEL ON CREST
NICHE
MWL
0
2
4
6
8
10
12
14
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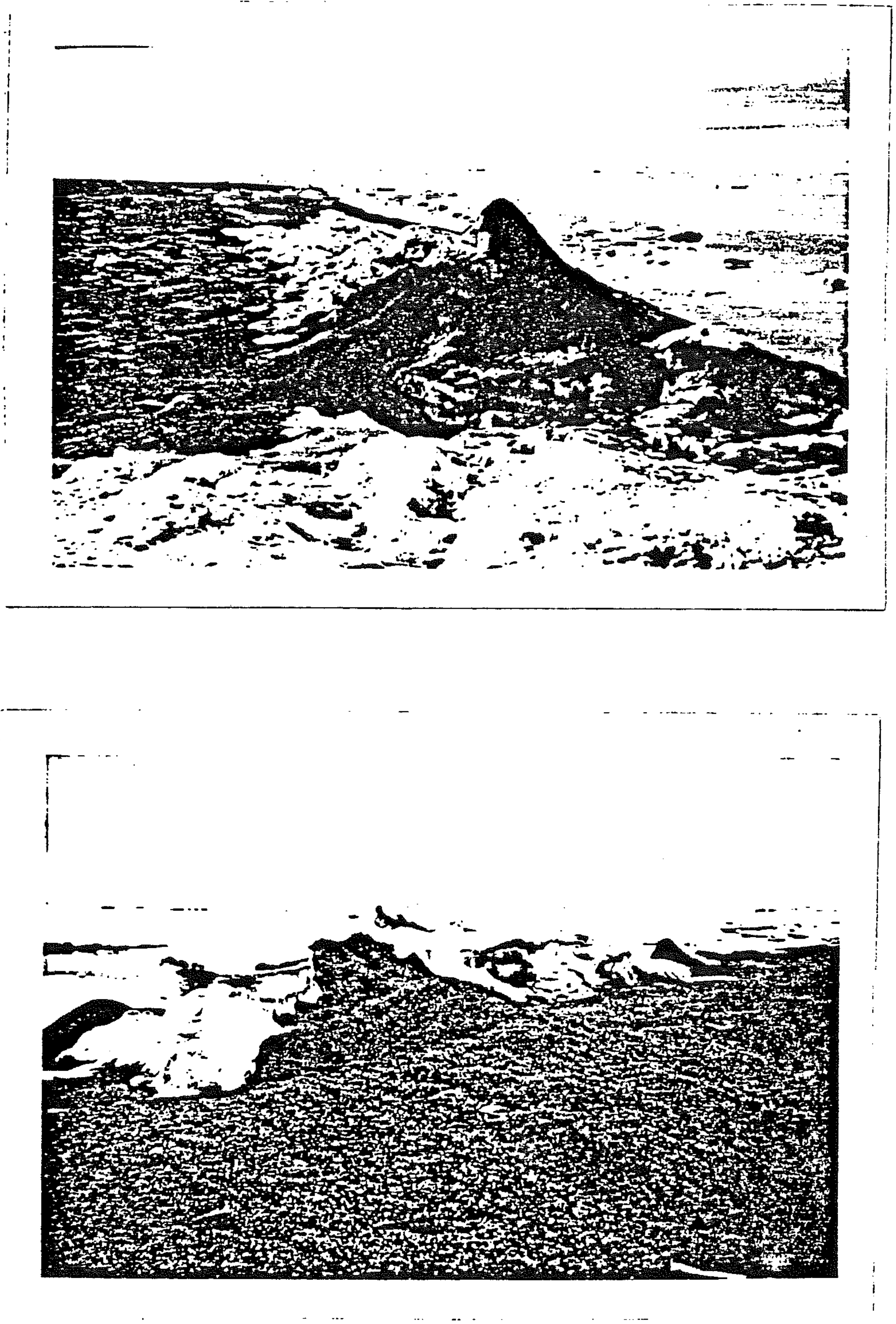


PHOTOGRAPHS OF SPY ISLAND OVERRIDE EVENT (AUGUST 1982)

APPENDIX D

SHORELINE LANDFORM MAPS (AFTER HARPER, 1985)

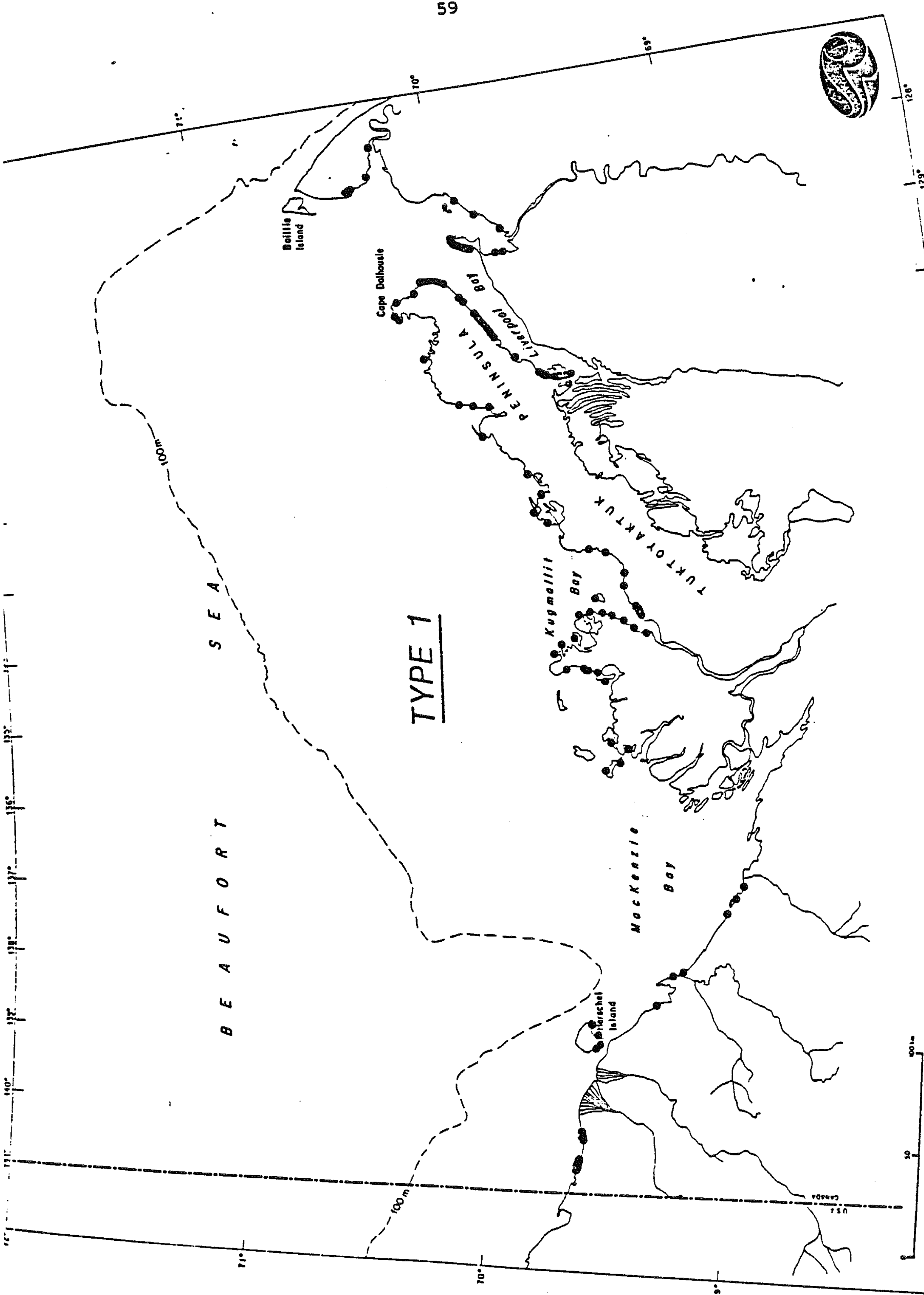


Figure 5.10 The distribution of ice-poor cliffs.

Dobrocky
SEATECH

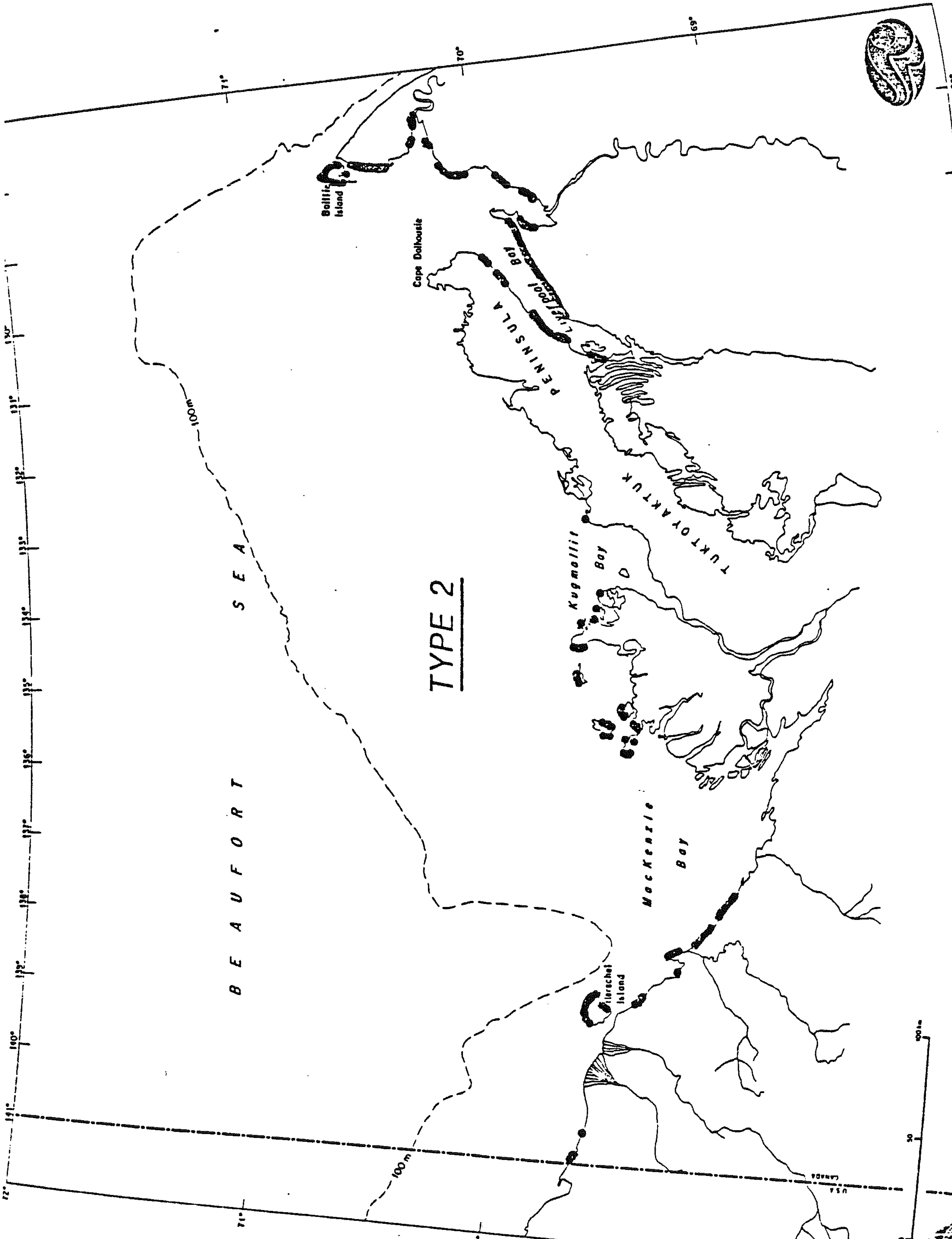


Figure 5.11 The distribution of ice-rich cliffs.

Dobrocky
SEATECH

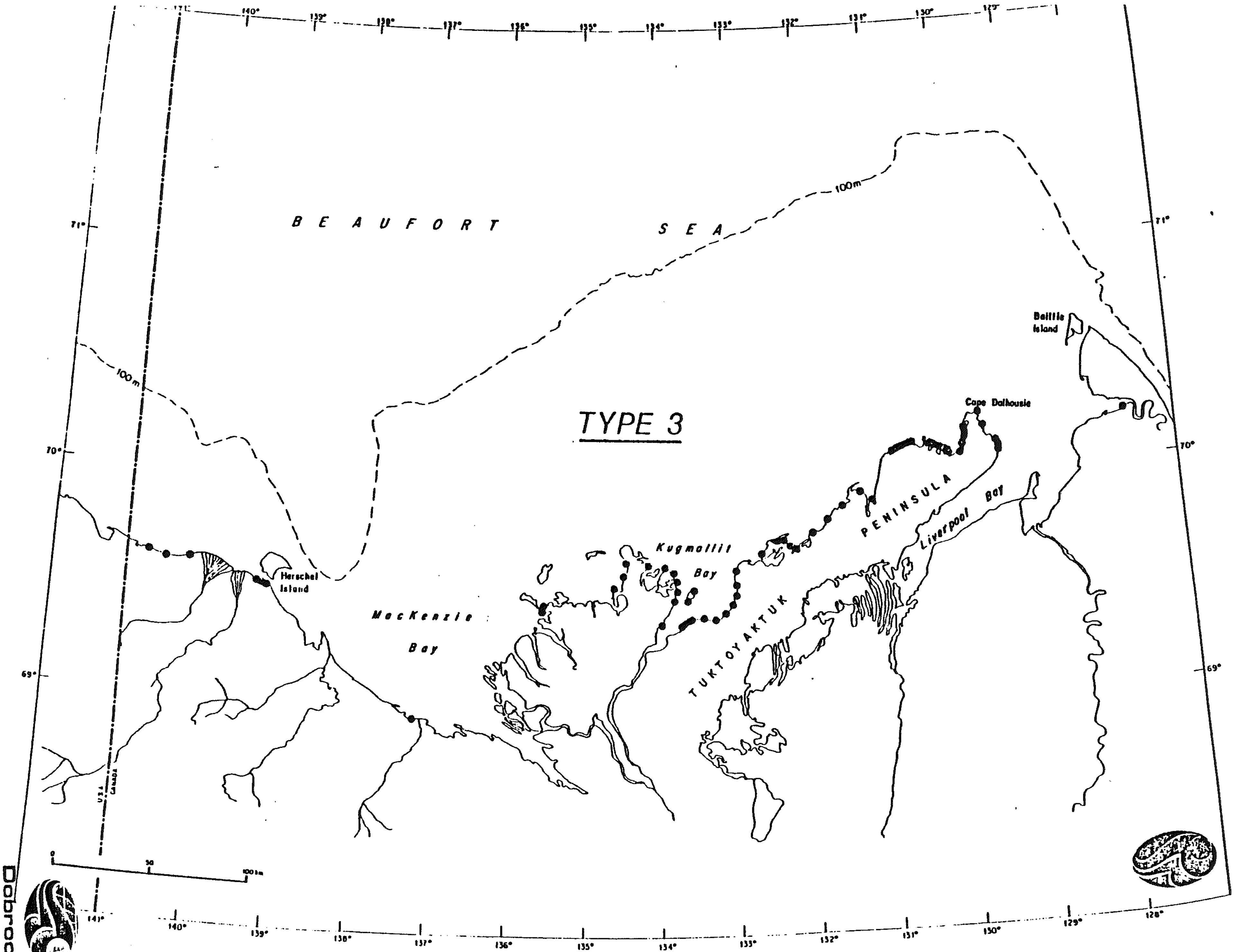


Figure 5.12 The distribution of low tundra cliffs.

Dobrocky
SEATECH

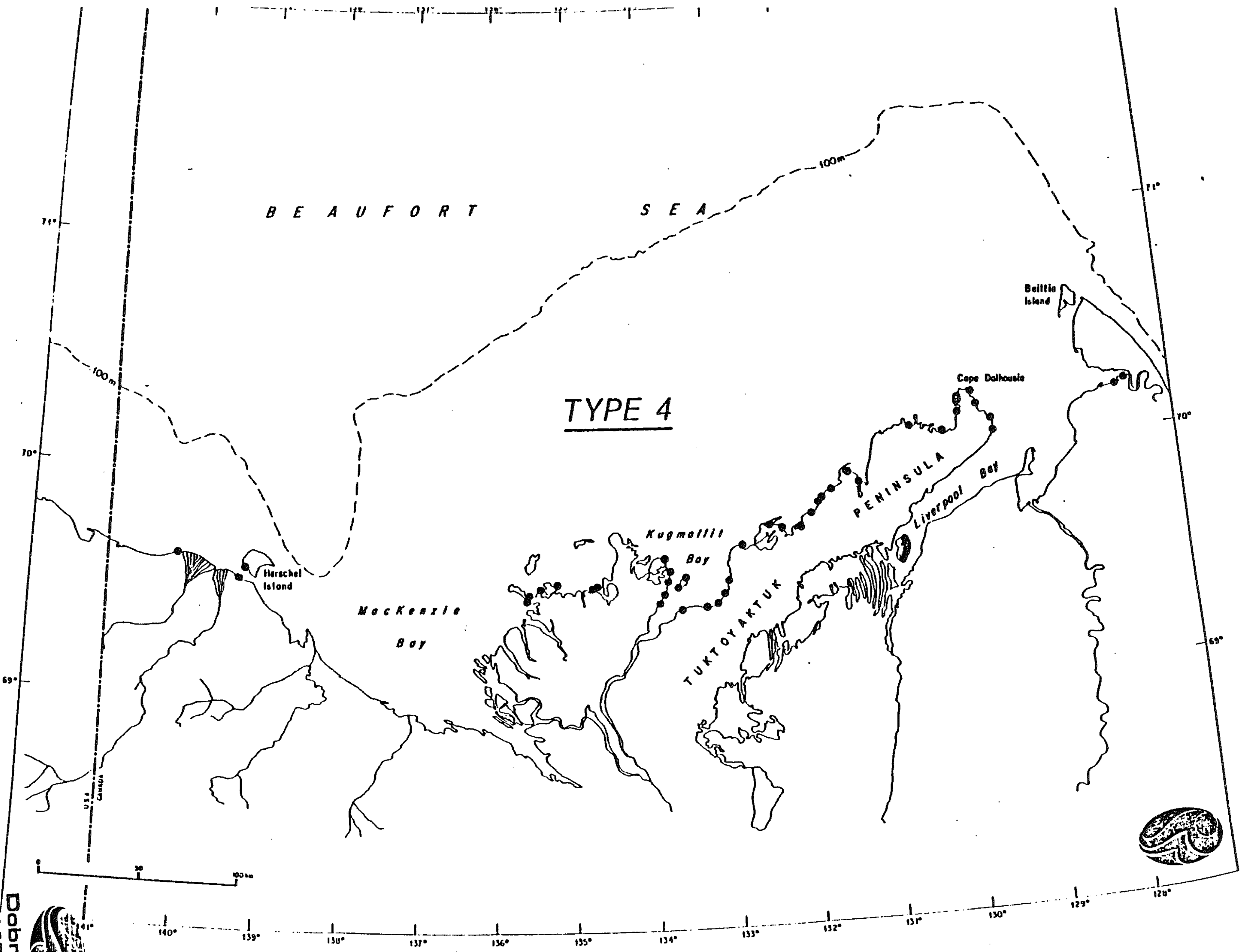


Figure 5.13 The distribution of inundated tundra.

Dobrocky
SEATECH

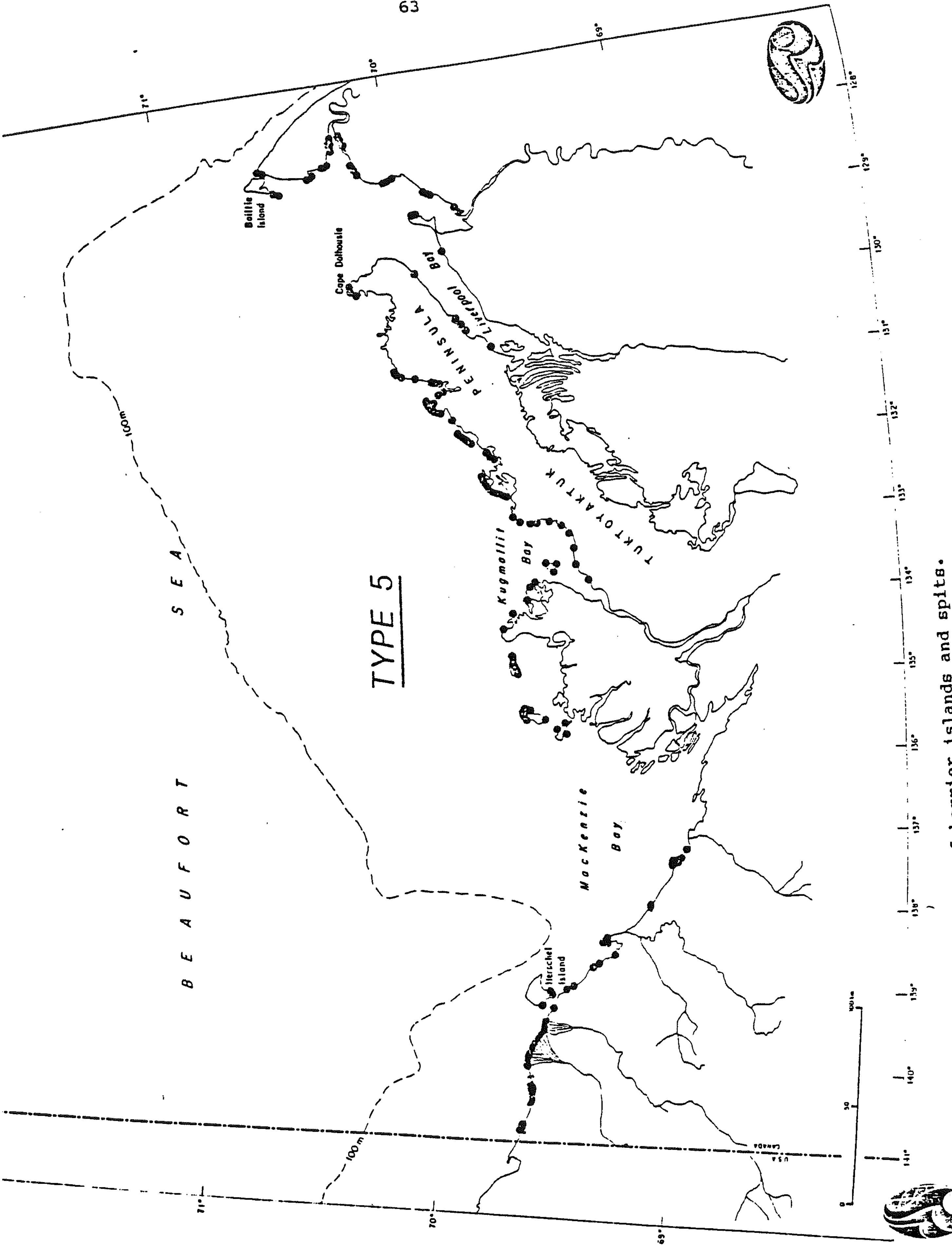


Figure 5.14 The distribution of barrier islands and spits.

---- wetland-channel complexes.

Dobrocky SEATECH

SEATECH

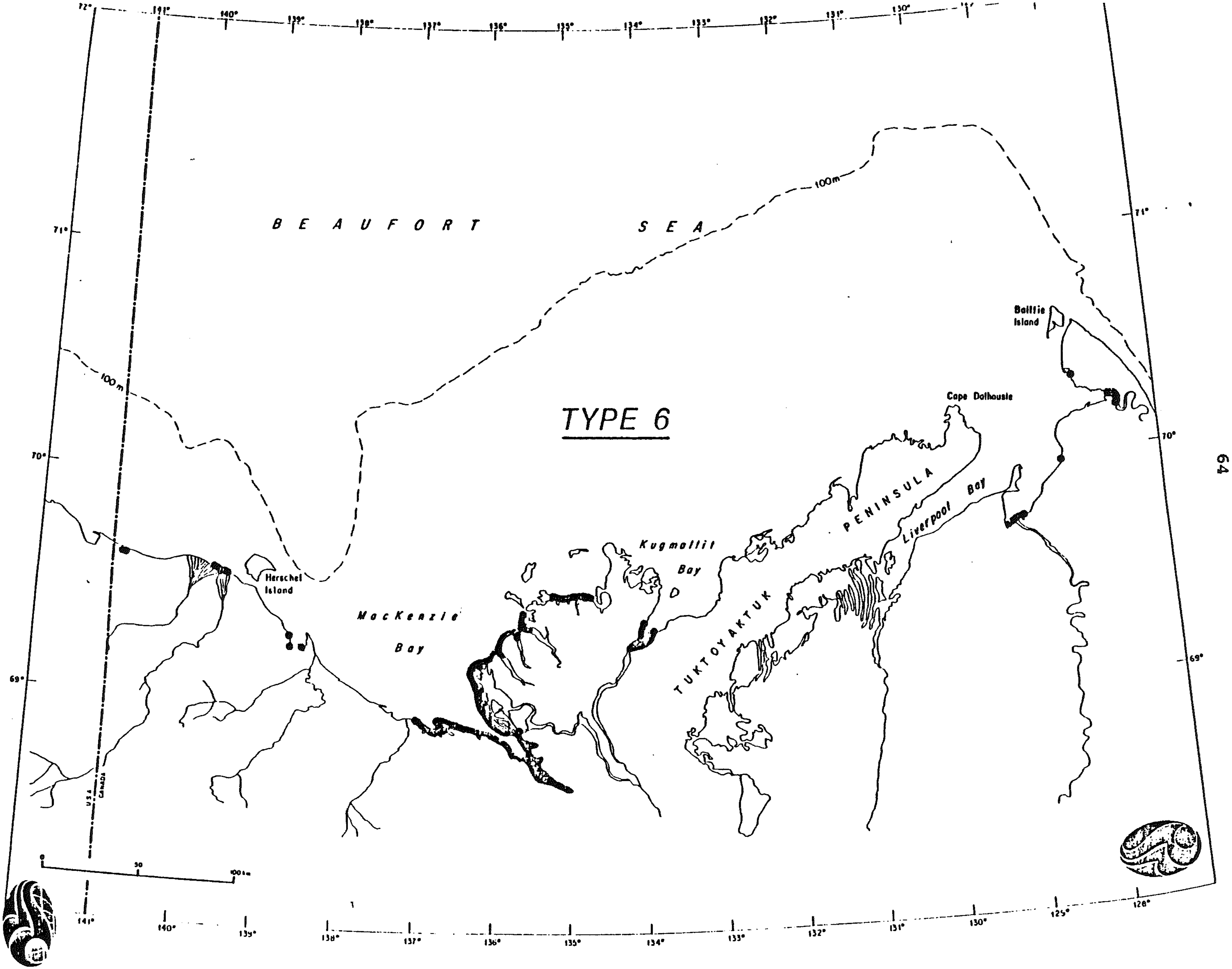


Figure 5.15 The distribution of flat-wetland-channel complexes.

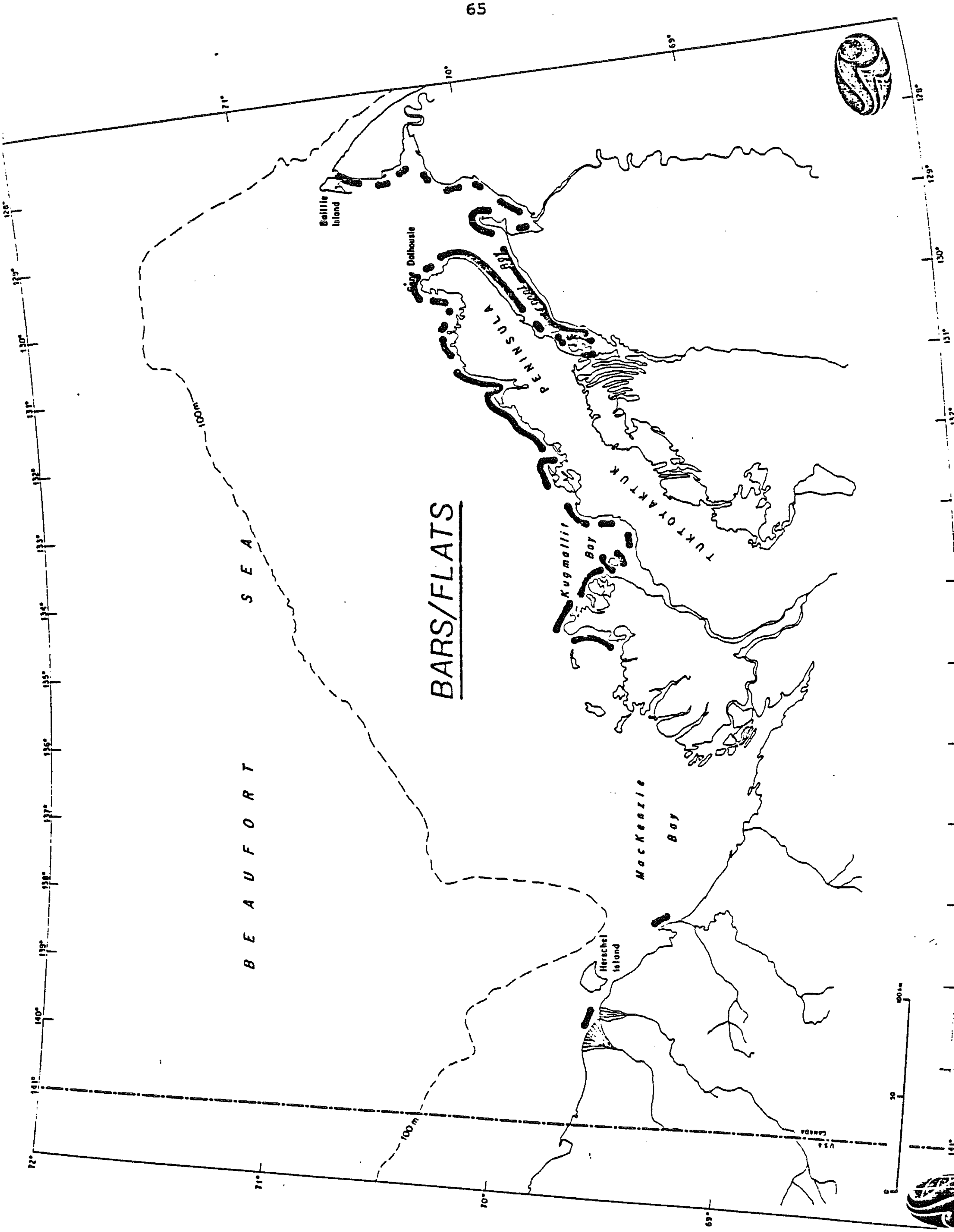


Figure 5.16 The distribution of multiple nearshore bars and flats.

Dobrocky
SEATECH

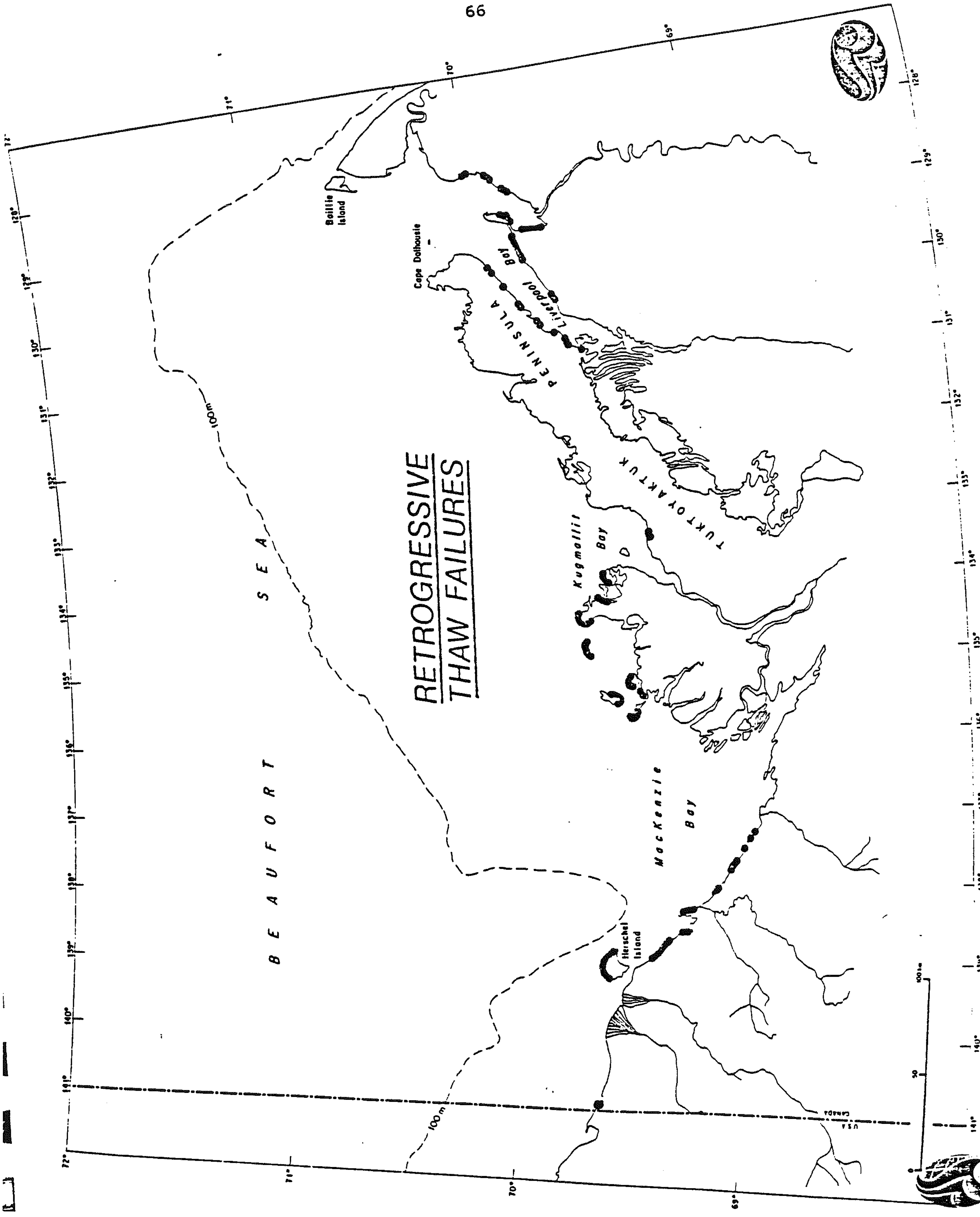


Figure 5.17 The distribution of retrogressive thaw failures.

Dobrocky SEATECH

APPENDIX E

NUMERICAL ANALYSIS OF STRUDEL SCOUR

(Personal communication from J. Cox, Arctec Engineering Inc.)

A very simplistic model for strudel scouring for which there is laboratory data involves the scouring of a sediment surface by a submerged water jet. Recent model tests by Rajaratnam (1981a, 1981b) have established relationships between particle size and resulting scour geometry in sand beds for circular water jets. The scale of the model tests is small in comparison with the field problem; the model jet varies from 1/2 to 1 inch diameter. However, using similitude methods, the maximum scour depths were found to be mainly a function of the densiometric Froude number (F) and height and diameter of the jet for large Reynolds numbers. Figure 1 shows the geometry and equations used by Rajaratnam. The model tests for the no tailwater condition resulted in the following dimensionless relationship: $E_m/d' = 0.13F'_0$ Rajaratnam states that for the condition with tailwater the value E_m/d' would be about 40 percent larger.

To apply this solution to the strudel scour problem still requires several major assumptions:

a. The velocity of the flow into the seawater is assumed to be similar to the maximum velocity (V in feet per second) for a broad-crested weir where H is the height of water in feet above the weir crest (King and Brater, 1963):

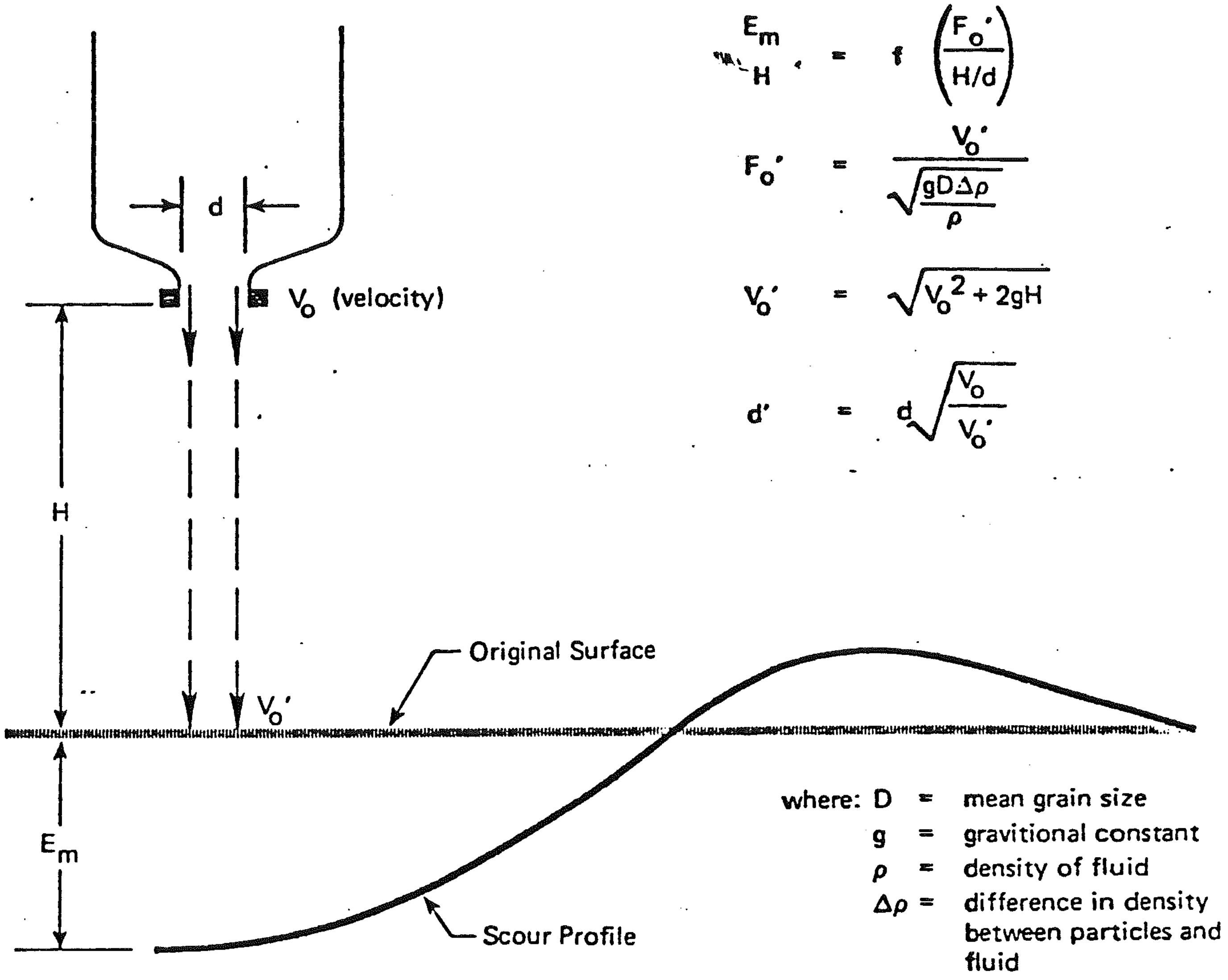
$$V = 3\sqrt{H}$$

b. Reimnitz, Rodeick and Wolf (1974) have reported water depths above the ice of about 4 feet. However, the weight of water this deep should depress the surface of the ice so that the head difference between the overflow water and sea level is only 1 to 2 feet. We have used a head of 2 feet in our calculations, which results in an entrance velocity of 4.2 feet per second.

c. The jet diameter, d, and impingement height, H, do not directly relate to the field problem. However, if H is assumed to be the water depth, an equivalent jet diameter can be estimated from the maximum observed scour depths.

A jet diameter of about 1 foot is found to correspond to a scour depth of 15 feet for a water depth of 8 feet as shown in Figure 2.

The scour depth for a gravel backfill can be estimated by keeping all variables in Figure 2 constant except for the mean grain size. Typical Prudhoe Bay area gravel has a mean grain size of about 3/8 inch or 0.03 foot which results in a predicted scour depth of 1 to 2 feet below the sea floor.



$$\frac{E_m}{H} = f\left(\frac{F_o'}{H/d}\right)$$

$$F_o' = \frac{V_o'}{\sqrt{\frac{gD\Delta\rho}{\rho}}}$$

$$V_o' = \sqrt{V_o^2 + 2gH}$$

$$d' = d\sqrt{\frac{V_o}{V_o'}}$$

where: D = mean grain size
g = gravitional constant
ρ = density of fluid
$\Delta\rho$ = difference in density between particles and fluid

Figure 1. Vertical Jet Model
(after Rajaratnam, 1981)

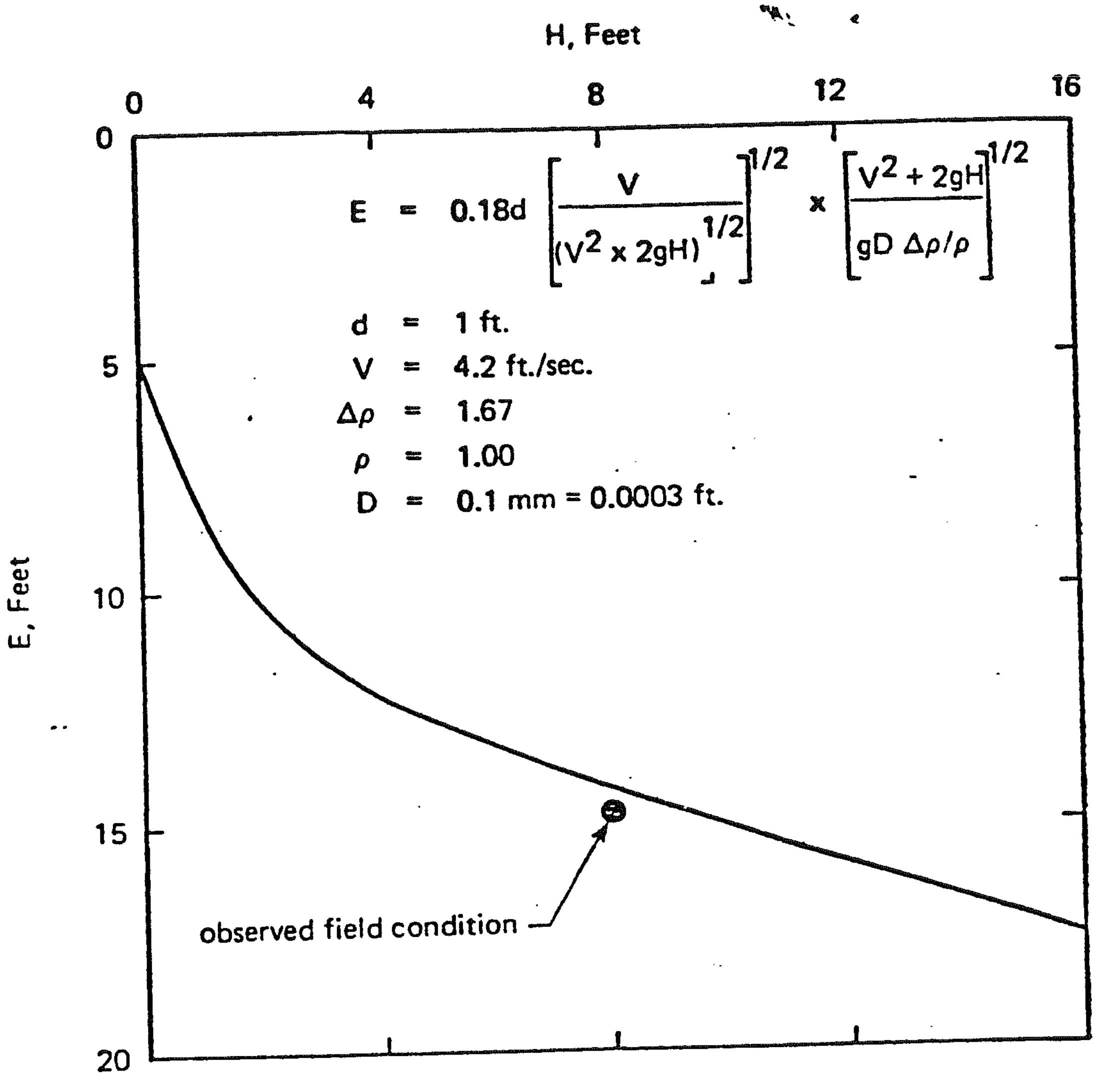


Figure 2. Scour Depth Versus Scour Jet Impingement Height

The predicted scour depth is referred to by Rajaratnam as the static scour depth, the depth measured after the jet is stopped. The dynamic scour depth which occurs when the jet is discharging is deeper; in the tests by Rajaratnam the dynamic scour depth was two to three times greater than the static scour depth. If we assume the ratio of dynamic to static depths observed in the laboratory is applicable to the field condition, the gravel thickness would have to be four to six feet above the pipe to isolate the pipe from any turbulence during scour.

Obviously, the above analysis is approximate. Although the analysis is based on strudel scour depths observed in the field for fine sands, the process has not been verified by field or laboratory observations in sandy gravel or, more importantly, for silts (particularly overconsolidated silts) or clays. If the pipeline is protected by a six-foot-thick layer of typical Prudhoe Bay gravel, a four-foot-thick layer of coarse material is expected to remain after a strudel scour occurrance. The four- to six-foot thickness appears to be reasonable for pipeline protection but annual monitoring after construction would be needed to verify the effectiveness of the sandy gravel backfill.

Earlier laboratory work on a jet of water discharging from an orifice and impinging on a sand bottom (Doddiah et al., 1953) resulted in an alternate expression for the ultimate depth of scour:

$$\frac{h}{b} = \frac{0.023\sqrt{A}}{b} \log \left[\frac{W_m T}{b}\right] \left(\frac{V}{W_m} - 1\right) - 0.022 \frac{b}{\sqrt{A}} + 0.4$$

where h is depth of scour, b is depth of sea water under the ice, V is the velocity of the jet, A is the area of the jet, T is time, and W_m is the fall velocity of the sediment. The lateral extent of scour is not predicted by this method.

The main problem with both simple models of submerged jets is that they ignore the vortex flow which accompanies the drainage of river overflow through a hole in the ice. A more sophisticated model of the hydrodynamic phenomenon which leads to strudel scour combines both a source and vortex flow. Figure 3 depicts the flow pattern of water as it approaches and drains through a hole in the ice. A spiralling behavior is induced by the Coriolis effect and local environmental effects. In two dimensions the flow can be described through a complex flow potential given by Milne Thompson, 1969

$$w = \left(- m + i \frac{\Gamma}{2\pi A}\right) \log_n z$$

where Γ is the circulation and m is the intensity of the source. The Stream Function is

$$\psi = m\theta + \frac{\Gamma}{2\pi} \log_n r$$

The radial and tangential velocity components can then be determined from

$$V_\theta = \frac{\partial \psi}{\partial r} \text{ and } V_r = \frac{1}{r}\frac{\partial \psi}{\partial \theta}$$

If a longitudinal velocity is superimposed on this system, the equations then can describe the swirling discharge of the jet of water as it escapes out through the opening in the ice.

The strength of the jet of water issuing from the opening in the ice can be predicted from analogous motion in a "swirl atomizer". In vortex flow, the swirl velocity is inversely proportional to the distance from the axis, i.e.

$$V = \Gamma/2\pi r$$

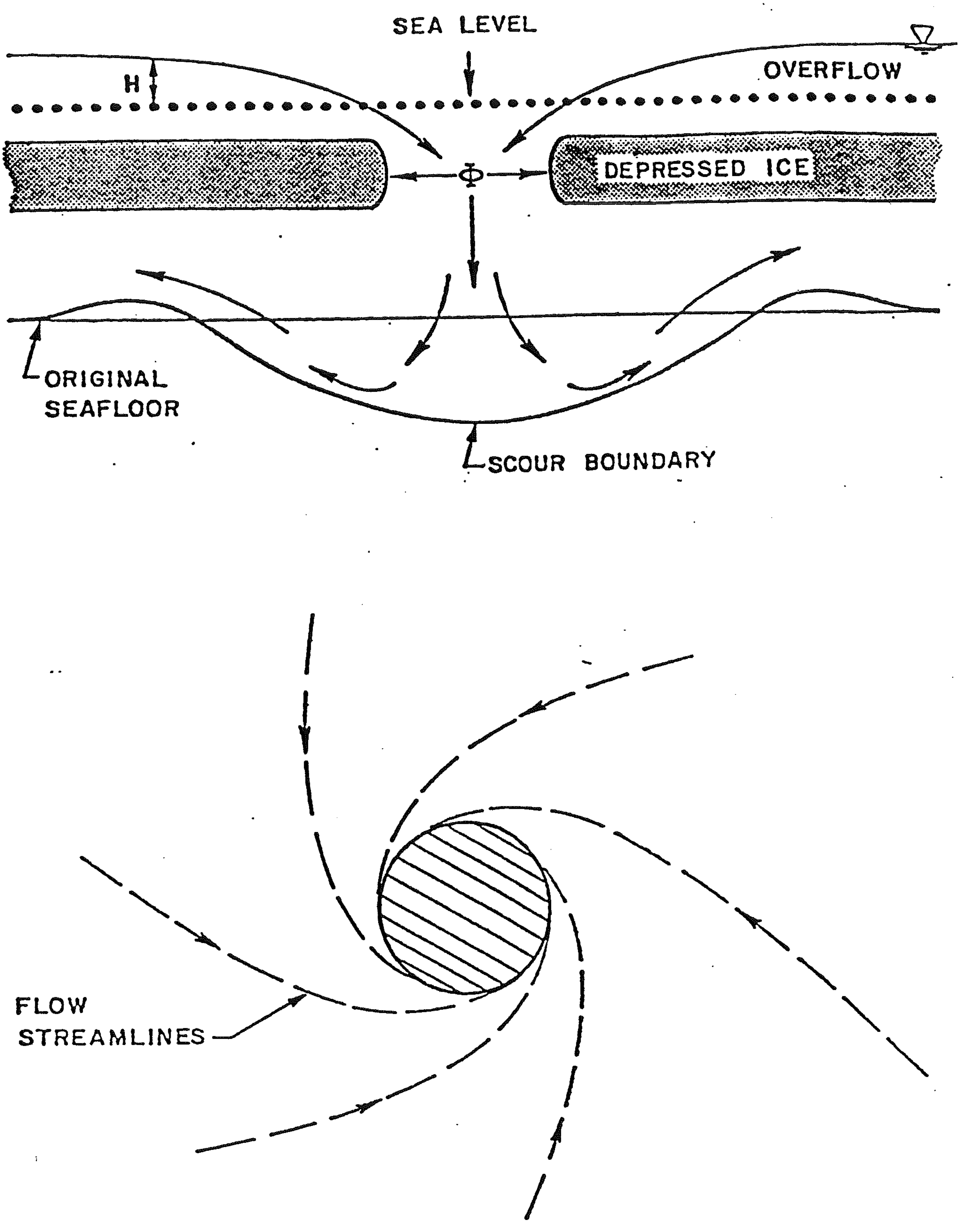


Figure 3

SCHEMATIC OF STRUDEL SCOUR PHENOMENON

Consequently, the pressure acting is obtainable from Bernoulli's equation as

$$p = p_{\infty} - \frac{\rho \Gamma^2}{g \pi^2 r^2}$$

and will diminish toward the vertex. The flow will therefore be driven by the pressure gradient toward the vertex causing an effective outflow through the orifice (Moore, 1964). The total discharge will therefore exceed that contributed by assuming hydrostatic head of water only driving the strudel jet.

Johnson (1983) has shown that the hydrostatic head of flooding water over the ice is <u>not</u> necessarily given by the total depth of water on the ice, but rather must be determined by considering the buoyancy and density of the ice and fresh water versus the underlying seawater. As an example, consider ice 2 meters thick flooded with 1.5 meters of fresh water. The ice cover will sink until hydrostatic equilibrium is established. It can be shown then that the actual driving head for this example is only 0.225 meter, and the bottom of the 2-meter-thick ice cover is 3.27 meters rather than 1.80 meters below the original water level.

The rotational nature and intensity of the scouring jet will determine the actual breadth and geometry of the strudel scour hole. For tantential flow along the bottom Bretschneider (1969) indicates that the scour hole size can be predicted by the expression:

$$\frac{h\ (x,t)}{b} = 0.075\ \left(\frac{x}{b}\right)^{0.85} [\omega v t - \omega v\ (t_o / \frac{x}{b} = 1 * \left(\frac{x}{b}\right)^{\ 2.5})]$$

where h is the depth of scour, x is the distance to depth h, t_o represents a time factor that determines the scaling process, and b is the water depth. This relation is relatively independent of flow conditions and material characteristics.

It is evident that scour develops only when the velocity of the waer exceeds the critical velocity V_{crit}, at which the bed material starts moving. Information on the relationship between the critical shear stress and the average grain size diameter is available from various sources. Typically, the Shield's criterion is used and incipient motion is expressed in terms of critical shear stress. This relation is shown in Figure 4. Results can be adequately expressed if turbulent fluctuations are considered by the parameter (Bretschneider, 1969)

$$V_{local} = V\ (1 + 3\varepsilon)$$

where V is the average flow velocity, ε is the turbulence intensity level, and V_{local} is the equivalent scouring velocity. If V_{local} exceeds V_{crit} then scouring will insue until the local velocity falls below V_{crit}, ceasing the scour process through scour hole formation.

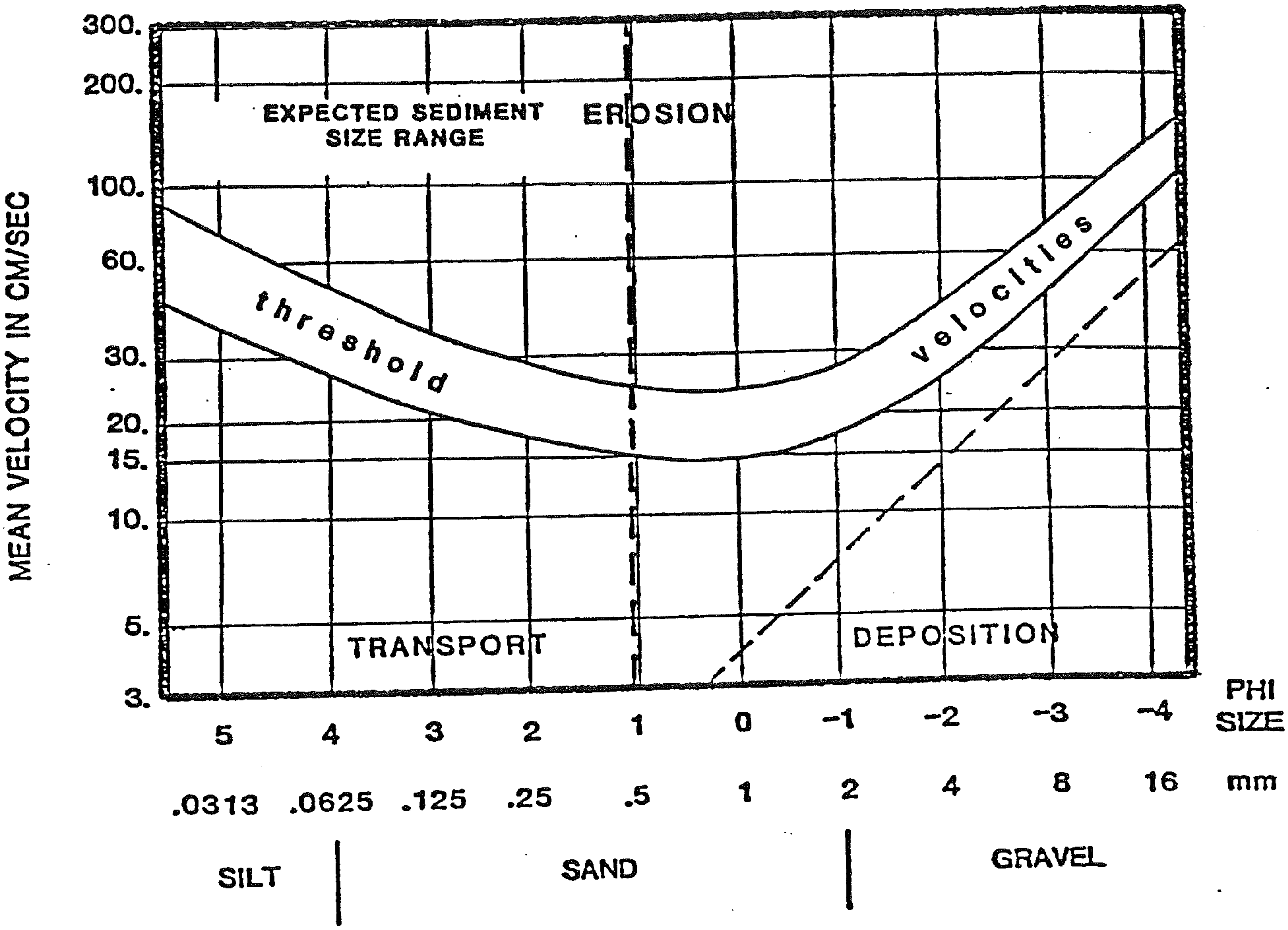


Figure 4

RESPONSE OF SEDIMENT TO A CURRENT

APPENDIX F

REGIONAL SETTING OF KING POINT AND NORTH HEAD

(Excerpt from Hill et al, 1986)

Table 1
Effective wave height exceedance values for deep- and shallow-water conditions at King Point and North Head, based on 14-year hindcast analysis by Pinchin et al. (1985).

King Point

Deep water		Shallow water refracted	
1%	2.0 m	1%	1.2 m
10%	1.2 m	10%	0.8 m
50%	0.5 m	50%	0.1 m

North Head

Deep water		Shallow water hindcast	
1%	2.6 m	1%	0.5 m
10%	1.3 m	10%	0.3 m
50%	0.1 m	50%	0.0 m

Table 1 presents an overview of deep and shallow water wave conditions at King Point and North Head, based on the wave hindcasting study of Pinchin et al. (1985). The table presents 1%, 10%, and 50% exceedance values of effective wave height for all open-water days during the 14 seasons 1970-1983. The mean open water season at both deep water locations over the 14 years was approximately 3.3 months.

The estimated 1% and 10% exceedance wave heights off King Point are approximately 2.0 m and 1.2 m respectively. The equivalent values off North Head are slightly higher at 2.6 and 1.3 m. Modal peak periods at both sites are comparable, in the 3-4 s range. Inshore refracted wave data at King Point are reduced to 1.2 m (1%) and 0.8 m (10%). Although the shallow-water statistics for North Head are not strictly equivalent, being separately hindcast for the shallow fetch area south of the outlying islands, these results indicate much lower wave energy levels in that area (Table 1). Modal peak periods are 2-3 s.

The hindcast data indicate substantial differences in the directional distribution of incident wave power. Off King Point, the distribution is bimodal, with peaks out of the northwest and northeast. Off North Head, the energy is concentrated in the west-northwest octant for both deep water and shallow water data sets.

KING POINT

King Point is located on a relatively straight segment of the Yukon coast, facing northeast onto Mackenzie Bay. Brief discussions of coastal evolution in the area have been provided by Mackay (1963) and McDonald and Lewis (1973). A fuller description of the site appears in M.J. O'Connor and Associates (in preparation).

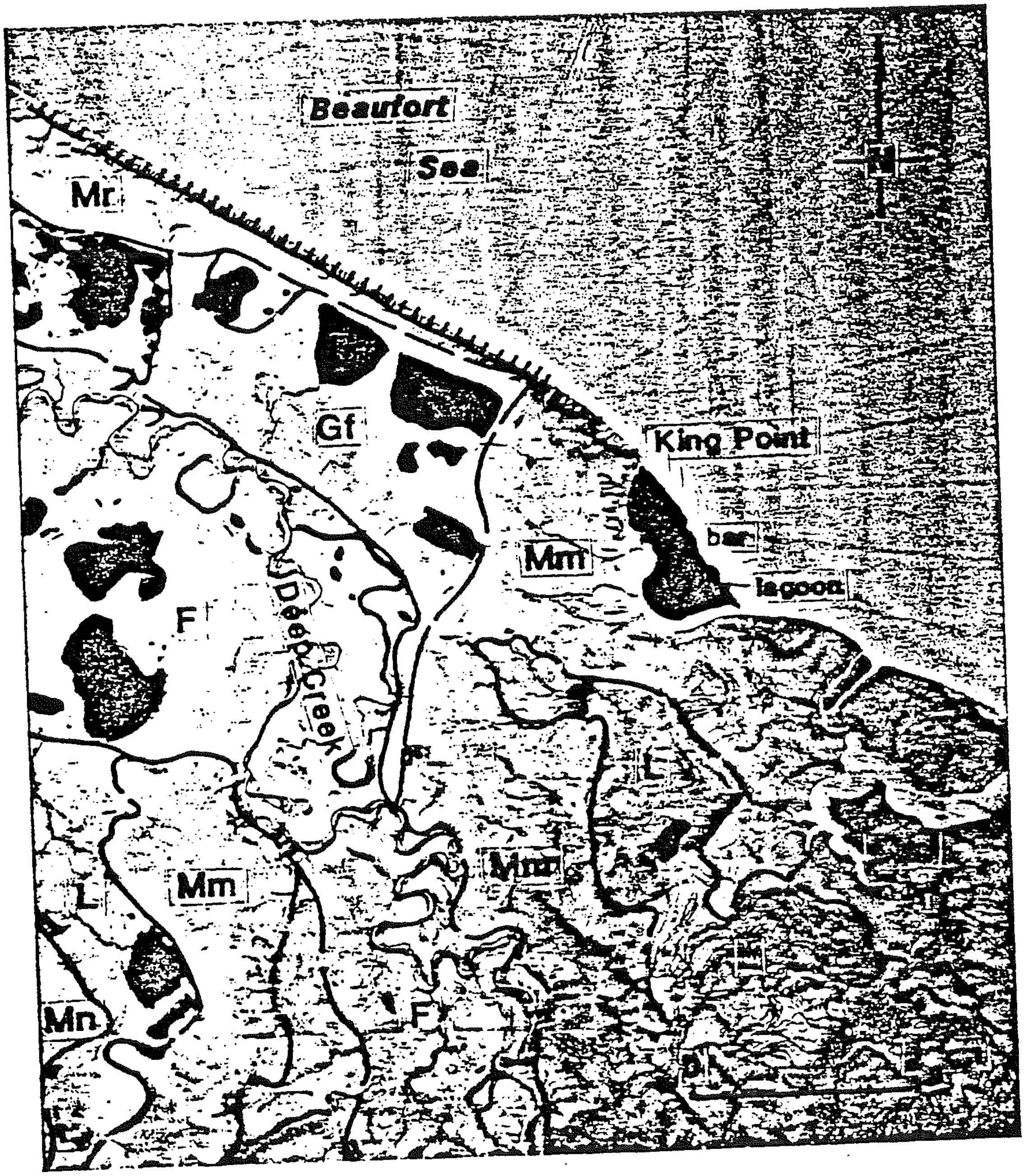


Figure 2. Annotated airphoto showing the distribution of surficial soils near King Point, Yukon. Mm - glacial till; Mr - ice-thrusted ridge of glacial and pre-glacial sediments; Gf - glaciofluvial sand and gravel; F - fluvial sand; L - lacustrine silt and clay.

Terrain Setting

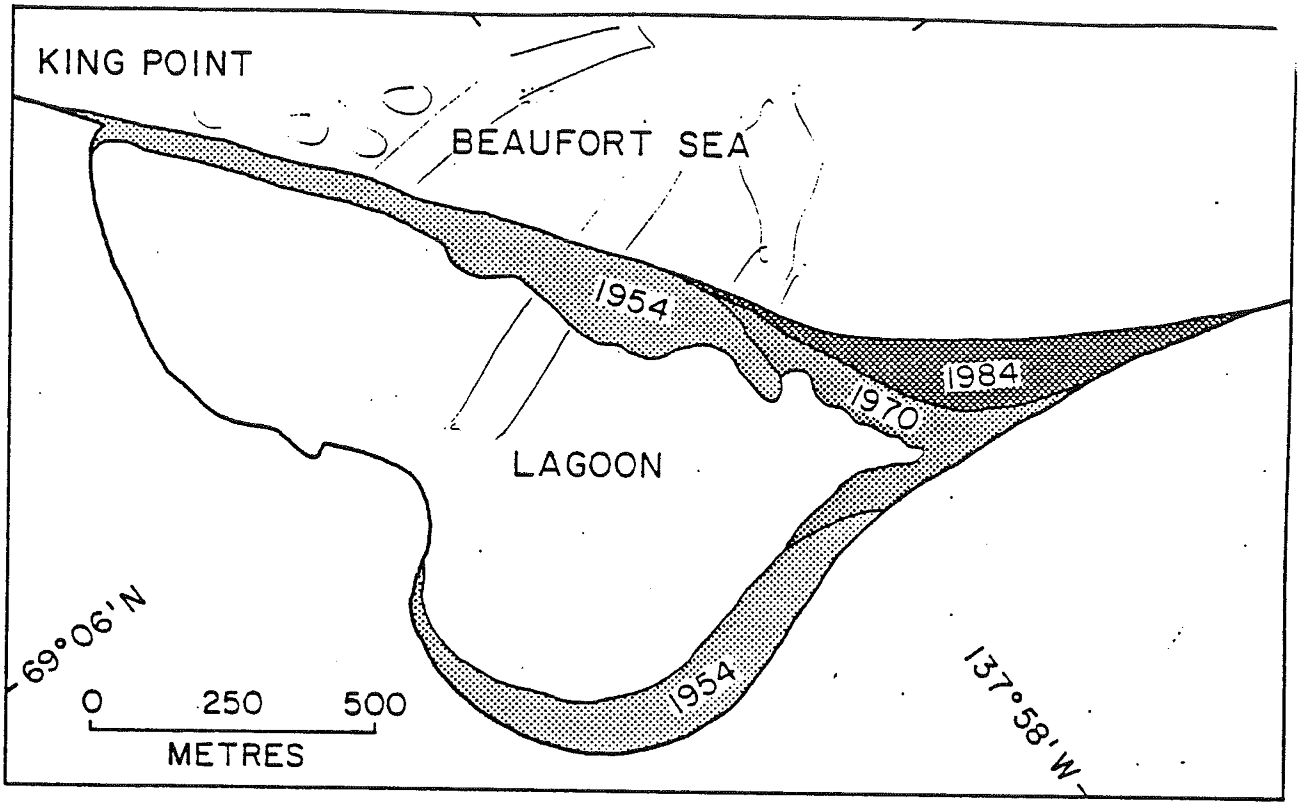
The onshore topography in the vicinity of King Point is gently rolling with relief generally less than 30 m. The distribution of subaerial materials is shown in Figure 2. The oldest surficial material in the area is a sequence of pre-glacial sands and silts which are found exposed in the lower part of cliffs to the southeast of King Point and in a sequence of ice-thrusted sediments to the northwest. These sediments are covered by a variable thickness of clay-rich glacial till (Mm) deposited by ice flowing to the northwest from a source near the present Mackenzie River. Rampton (1982) refers to the period of regional ice cover which deposited the till as the Buckland Glaciation, of probable early Wisconsinan age. The high ice-thrusted ridge (Mr) running northwest from King Point is thought to have formed during a possible stillstand of the Buckland Glaciation called the Sabine Phase (Rampton, 1982). Glacial outwash (Gf) sands and gravel were deposited on the down-ice side of the ridge at this time. Variable thicknesses of more recent lacustrine silts and clays (L), fluvial sands (F), clay rich colluvium and organic deposits are superimposed on top of the older glacial and pre-glacial sediments.

A variety of ground-ice forms are present in the surficial deposits near King Point. Fine-grained sediments such as the glacial till and lacustrine material often contain substantial amounts of excess ice as vertical ice-wedges (Harry et al., 1985), horizontal lenses, veins and coatings on particles. Generally the coarser grained sands and gravels have relatively low excess ice content. Massive ice or discrete bodies of nearly pure ice are also present. Recent drilling (M.J. O'Connor and Associates, in preparation) and field mapping indicates that massive ice is associated with upland areas of glacial till and with the glacial-fluvial deposit west of King Point. The broad slope between the barrier and the high cliffs west of the point and the segment of coast on the right of Figure 2 are areas of polycyclic retrogressive thaw failures.

Shoreline and Shoreface Development

Two major morphological components of the coastal system are recognised (Fig. 2): (1) the ice-rich mud, sand, gravel and till cliffs, rising to 50-60 m just west of King Point, and (2) the sand-gravel barrier beach extending 2 km southeast from the point across the front of a shallow lagoon. Sediment forming the King Point barrier was originally derived primarily from erosion of cliffs to the northwest. Photogrammetric analysis of 1954-1970 airphotos showed no measurable retreat of the high cliffs immediately west of King Point (McDonald and Lewis,1973), although erosion rates averaging up to 1 m/a or more occur further west and somewhat higher rates may have prevailed at the point (Mackay, 1963). Since closure of the barrier sometime prior to 1970, beach sediment may also have been derived from the southeast, where retreat rates of 1-2 m/a were measured over the 1954-1970 interval (McDonald and Lewis, 1973).

The subaerial width of the barrier ranges from less than 50 m near King Point to more than 200 m in the vicinity of the former inlet at the east end. The barrier has shown significant morphological change since1954 (Fig. 3; McDonald and Lewis, 1973; M.J. O'Connor and Associates, in preparation). At that time, the barrier extended as a narrow spit southeast from King Point. The distal end of the barrier exhibited multiple recurved spit deposits. A 400-m wide inlet was present at the east end and an extensive beach was developed on the south side of the lagoon. By 1970, the barrier had completely enclosed the lagoon, forming a 100-m wide neck at the southeast end. Oblique aerial video surveys in 1984 (Forbes and Frobel, 1986) and ground observations (Gillie, 1985; Morgan, in press) indicate that the southeast end of the barrier has prograded seaward by a further 100 m or more since 1970.



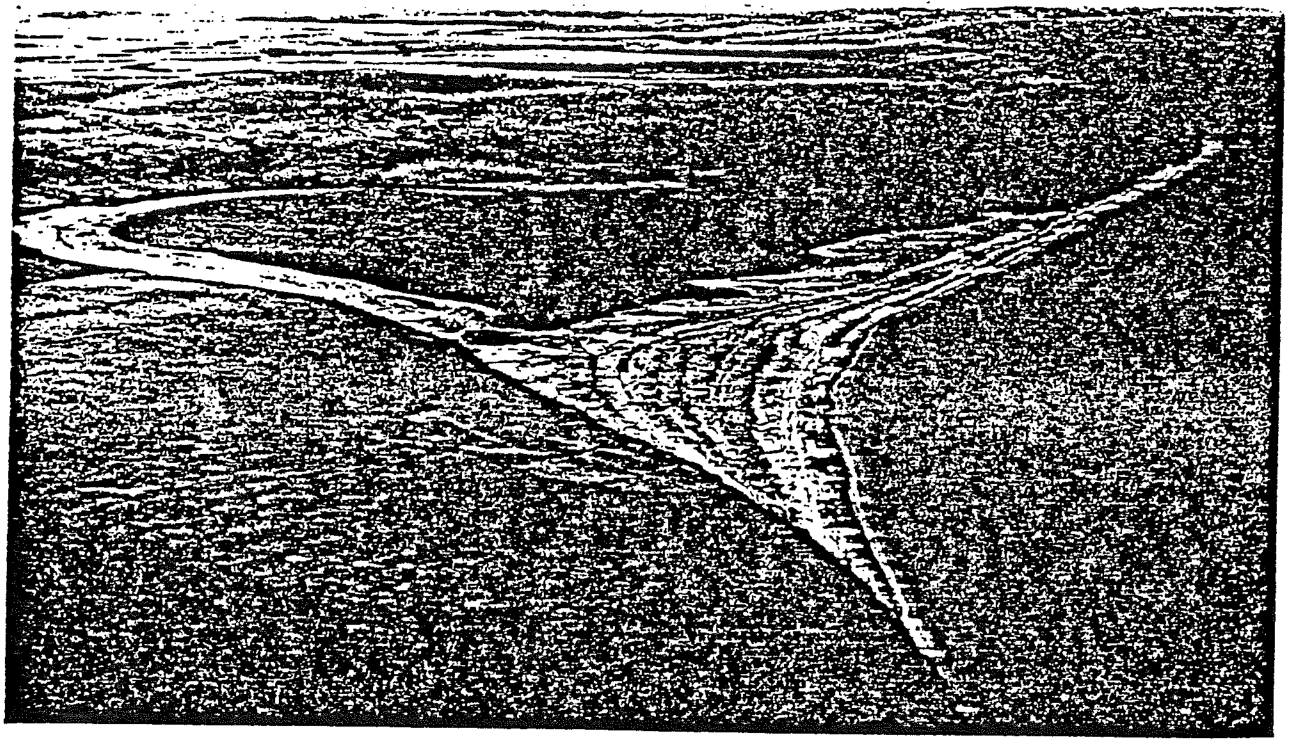


Figure 3. Top: King Point barrier evolution 1954-1984 (From M.J. O'Connor and Associates Ltd., in preparation). Bottom: oblique aerial photograph of the barrier taken in September 1985.

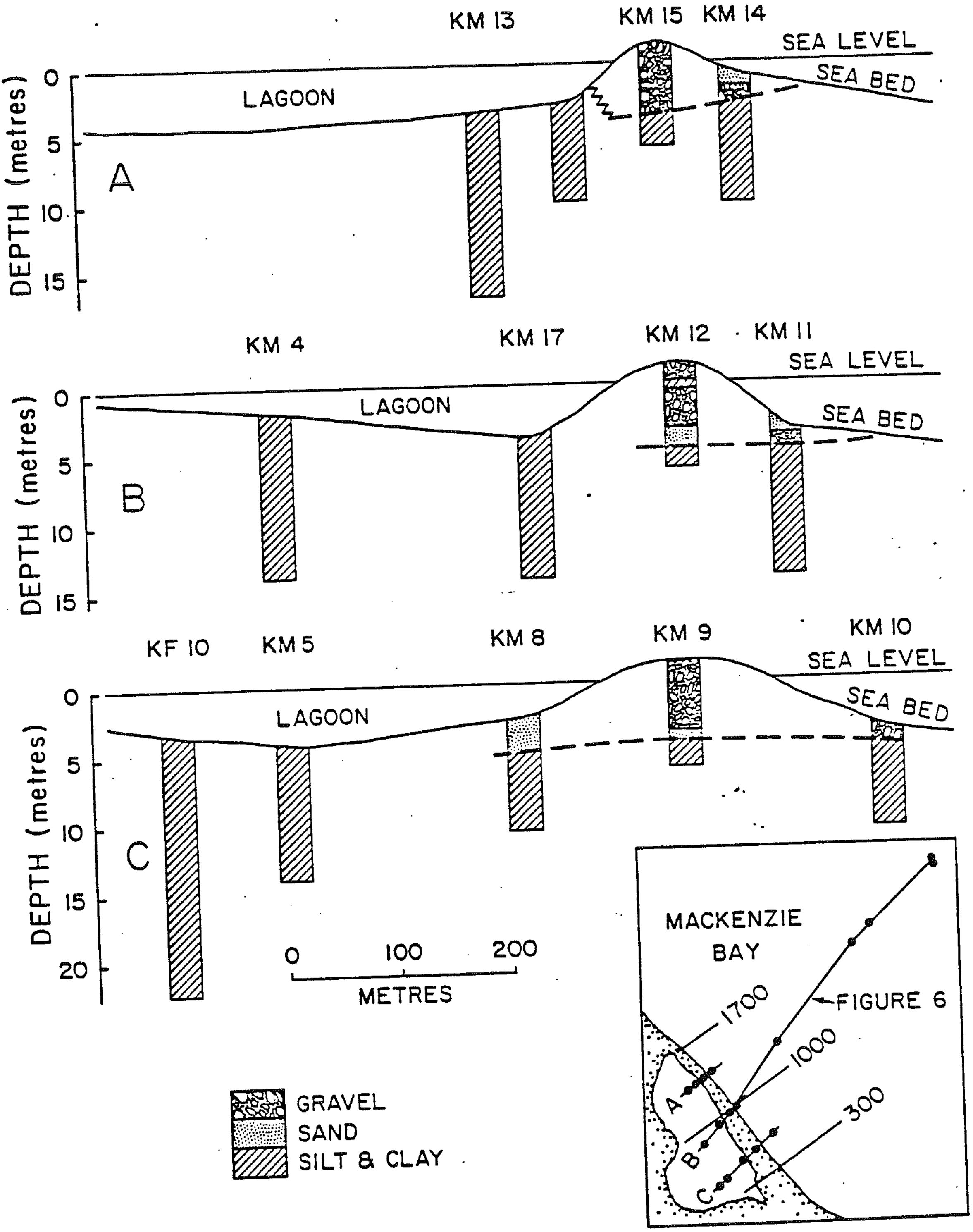


Figure 4. Borehole transects across the barrier, King Point. Insert map shows location of transects, profiles shown in Figure 5 and borehole transect shown in Figure6.

The present structure and morphology of the barrier reflect this history. Borehole transects across the deposit show that it is approximately 5-6 m thick and composed of interbedded gravel and sand (Fig. 4). At the narrow northwest end, washover deposits extend to the barrier backshore, reflecting the transgressive nature of the system in that area. Preserved recurve ridges underlying beach and washover deposits in the middle portion of the barrier show that inlet-fill took place by spit extension to the southeast. The east end of the barrier shows accretionary upper-beachface deposits reflecting offshore progradation.

The lower beachface morphology (Fig. 5) is consistent with the foregoing pattern. At the northwest end of the barrier (profile 1700, Figs. 4, 5), the lower beachface and upper shoreface show a smooth concave-up profile extending from the upper foreshore out to depths of 7 m or more. The slope decreases monotonically from 0.09 in less than 2 m to 0.01 beyond 7 m depth. In contrast, the nearshore morphology at the southeast end of the barrier (between profiles 300 and 1000, Figs. 4, 5) is marked by an abrupt discontinuity at 3 m depth. The lower beachface above this point is a steep front (with a slope of about 0.15) prograding seaward over the lower-angle (slope <0.01) shoreface surface. This morphology indicates that sand and gravel beach sedimentation is largely confined above the 3 m isobath at the southeast end of the system.

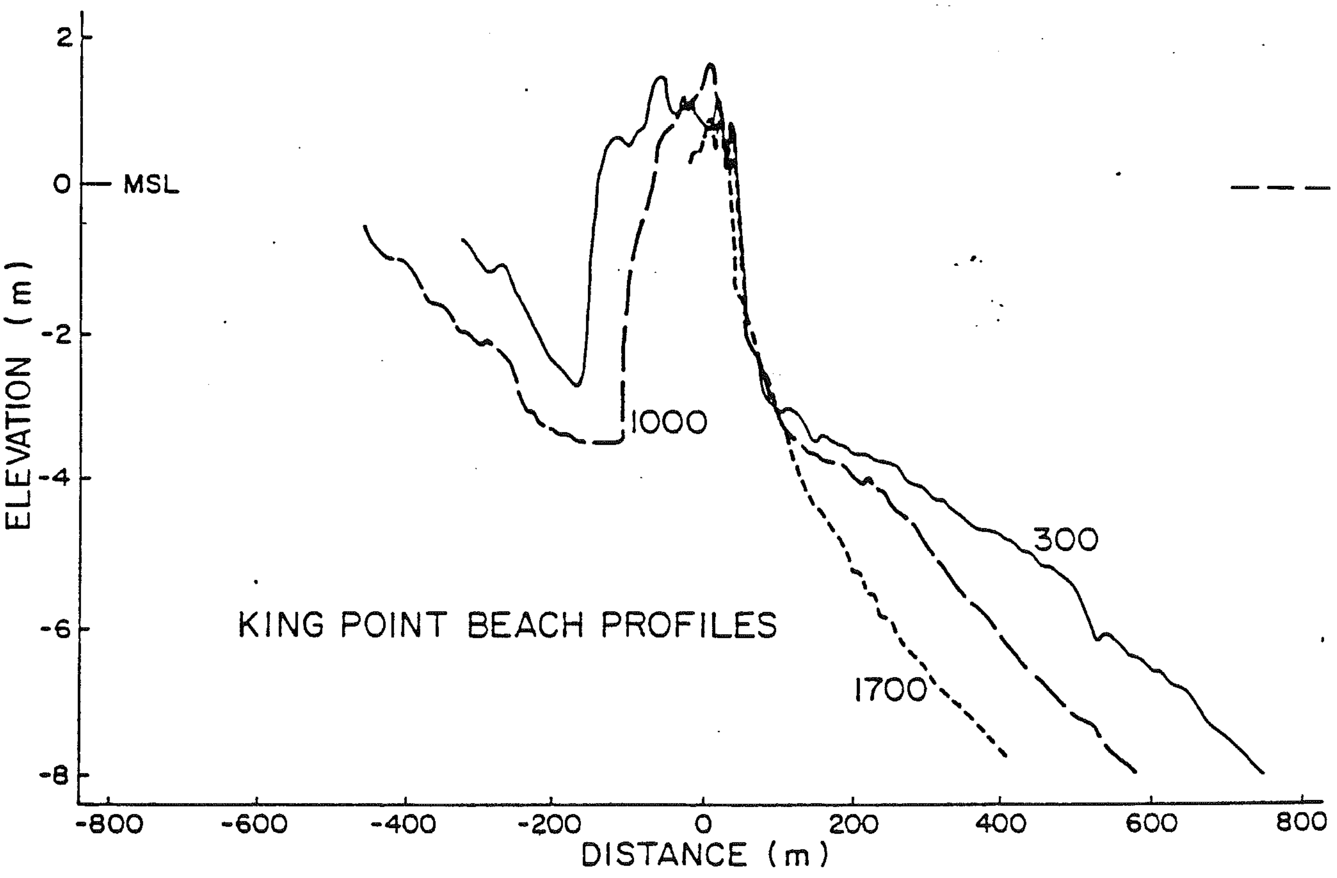


Figure 5. Beach and shoreface profiles for three 1985 survey lines (shown in Figure 4).

The borehole data (M.J. O'Connor and Associates, in preparation) indicate that the barrier sequence at King Point overlies stiff black silt and clay containing visible ice. This fine-grained lithology can be traced offshore to adjacent boreholes, where it in turn overlies diamicton. The silt and clay may also correlate with similar deposits, in onshore boreholes, which are interpreted as lacustrine sediments and which also commonly overlie diamicton. These stratigraphic relationships and the ubiquitous presence of ice within the lithology indicate that the black silt and clay represent terrestial deposits, with the diamicton being glacial in origin and early Wisconsinan or older in age (Rampton, 1982).

Sand and gravel deposits associated with the beach/ barrier complex extend offshore to at least 50 m, beyond which sand occurs as a very thin (< 1 cm) surficial and discontinuous layer (Gillie, 1985). The sand overlies the stiff black silt and clay described above. From the borehole data, these older sediments were interpreted to outcrop at the seabed between 5 and 17 m water depth (M.J. O'Connor and Associates Ltd., in preparation). Acoustic profiles along the central borehole transect (Fig. 6) show the presence of a distinct reflector which marks the unconformity

example
: material below
sand

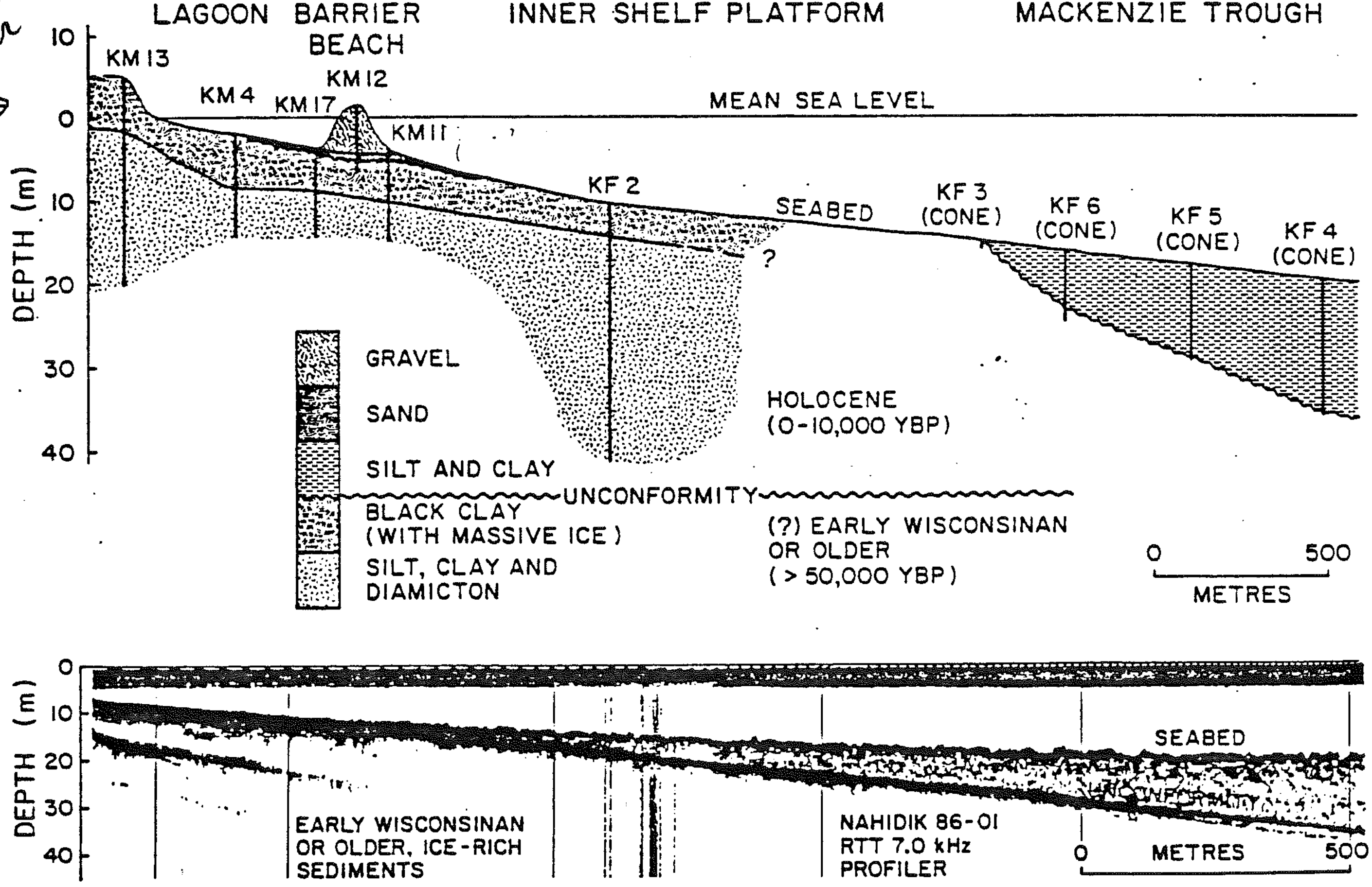


Figure 6. Top: borehole transect off the middle part of the King Point barrier (see Fig. 4). Bottom: RTT 7.0 kHz profile along the same transect.

Terrain Setting

The North Head area is low-lying, with relief generally less than 20 m. The distribution of subaerial materials is shown in Figure 8. The entire area is underlain by a brown sand interpreted by Rampton (in preparation) to be deltaic in origin. The sand is commonly exposed in cliffs particularly in the eastern and northern areas of the peninsula. The sand is overlain by a clay-rich glacial till (M) which appears to be more or less continuous in extent to the west but becomes a discontinuous veneer (Mv) to the east and north. The till is thought to be of early Wisconsinan age associated with the Toker Point Stade (Rampton, in preparation), an equivalent of the Buckland glaciation. Recent surficial materials in the area include lacustrine sediments (L) which in some cases have been inundated by the sea, fine grained colluvium and organic deposits.

Figure 8. Annotated airphoto showing the distribution of surficial sediments near North Head, Richards Island, N.W.T. M - glacial till; Mv/m - veneer of glacial till over marine sand; L - lacustrine sand, silt and clay.

By comparison with the surficial sediments of the King Point area, it is expected that significant amounts of excess ice may be present, particularly in the fine grained sediments. The occurrence of massive ice is not well documented, although the presence of numerous retrogressive thaw flow slides associated with areas of till cover suggests substantial excess ice content in these sediments.

Shoreline and Shoreface Development

The shoreline around North Head shows a complex mix of erosional and depositional morphologic types (Fig. 7). At North Head itself, cliffs up to 8 m high are composed of fine-grained and ice-rich cohesive till, underlain by sand. Estimated recession rates (based on 1950-1974 airphoto comparison) averaged 0.7 to 5 m/a (Harper et al., 1985). Sediment supplied from this source has contributed to beach sedimentation around the headland. Sand spits and extensive sand flats have built out to the southeast and southwest of North Head. To the southeast, the spit shows former recurved surfaces and pronounced sandy transverse swash bars. Further south along the peninsula, the coastline is highly irregular as a result of the breaching of numerous thaw lakes. The outlying islands act as point sources for numerous small spits and areas of sand flat. A broad sand and gravel barrier has enclosed a lagoon along the coast of the Reindeer Islands.

Southwest of North Head, the coastline is more continuous and is made up of fine-grained, ice-rich and sandy ice-poor cliffs (Fig. 7). Small tidal inlets with extensive submerged shoals and intertidal flats connect the relatively small number of breached lakes to the ocean. Much of the cliffed shoreline is fronted by wide beach flats which to the south show multiple nearshore bar development (Fig. 8). The broad embayment between North Point and West Point (Fig. 7) consists of a very wide sand and/or mud flat.

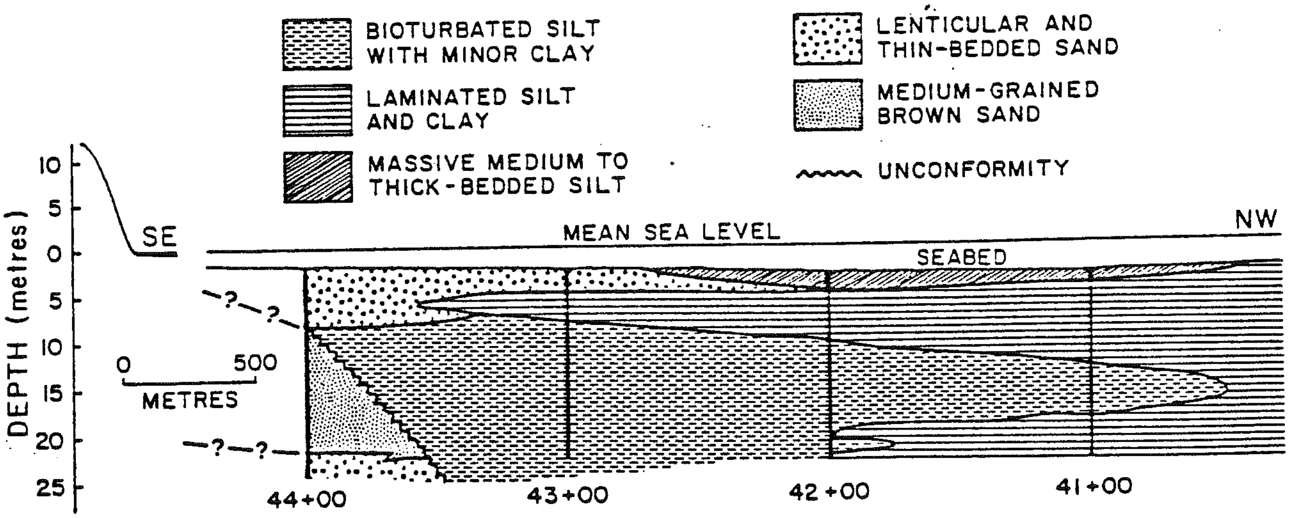


Figure 9. Borehole transect, offshore North Point. Facies descriptions after Hill et al. (in press).

The offshore boreholes extend from the area of ice-rich cliffs to the southwest of North Head (Fig. 7, 9). This area is most exposed to waves from the dominant northwesterly direction, not being sheltered from this direction by either Hooper or Pullen Island. Shoreface profiles in the North Head area show much lower gradients than at King Point (Fig. 10). The shoreface forms a gentle ramp out to 5 m water depth, 5-10 km offshore, and slopes even more gently beyond the 5 m isobath.

In the borehole closest to shore, in 2 m of water (44+00, Fig. 9), frozen sand was encountered (Hill et al., in press). This sand is similar in character to the brown sands of pre-Early Wisconsinan age (Rampton, in preparation) found onshore. Overlying this sand sequence is a series of Holocene marine silt and clay facies which have been described by Hill et al. (in press). The Holocene sediments thicken rapidly seaward and are at least 20 m thick within 2 km of the 2 m isobath (Figs. 7, 9). Radiocarbon dates from these sediments indicate a net sedimentation rate of at least 3 mm/a over the last 3000 years (Hill et al., in press).