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COASTAL MORPHOLOGY, COASTAL EROSION, AND BARRIER ISLANDS OF THE BEAUFORT SEA, ALASKA

By

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COASTAL MORPHOLOGY, COASTAL EROSION, AND BARRIER ISLANDS OF THE BEAUFORT SEA COAST, ALASKA

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INTRODUCTION

The discovery of large oil and gas reserves in the Prudhoe Bay region, and the quickening pace of petroleum exploration elsewhere onshore and offshore along the Beaufort Sea coast brings a need for a better knowledge of the geomorphic processes, erosion rates, permafrost conditions, and availability of sand and gravel along the coast and on the continental shelf of the Beaufort Sea. This report attempts to meet part of that need with a summary of present knowledge of coastal morphology, coastal erosional processes, and the dynamics of the barrier islands of the Alaskan segment of the Beaufort Sea.

Although visited by a scattering of Arctic explorers during the 19th Century and by a great many whaling vessels during the latter part of that century, the Beaufort Sea coast has, until recently, remained remote, inaccessible, and scientifically little studied. A classical study of the geography, geomorphology, and geology of the entire Alaskan segment of the Beaufort Sea coast resulted from E. de K. Leffingwell's residence and travels in the region between 1906 and 1914 (Leffingwell, 1919). Exploration and the search for oil within Naval Petroleum Reserve No. 4 (now National Petroleum Reserve, Alaska) included some attention to the Quaternary geology of the western/coastal plain (Black, 1951, 1964). Establishment of the Naval Arctic Research Laboratory

(NARL) at the former NPR-4 exploration camp near Barrow led to a number of studies of permafrost, coastal geology, coastal processes, and nearshore oceanography during the 1950's and 1960's. Especially significant for this report are discussions of coastal erosion and beach processes by MacCarthy (1953), Hume and Schalk (1964a, 1964b, 1967), Lewellen (1965, 1970, 1972a, 1972b) and early studies of the effects of ice upon the sea floor on the continental shelf (Carsola, 1954; Rex, 1955). During this period, researchers from the Coastal Studies Institute, Louisiana State University, mounted a series of studies of the Colville River and its delta (Arnborg and Walker, 1964; Arnborg and others, 1966, 1967; Walker and McCloy, 1969; Walker, 1969, 1974). Interest in the Beaufort Sea coast east of the Colville River remained dormant, however, from 1916 until the early 1960's.

The discovery of oil at Prudhoe Bay, followed by the development of roads, airfields, drilling pads, construction camp sites, and port facilities, and the extension of petroleum exploration to the continental shelf led to a new series of studies of the coast of Beaufort Sea east of the Colville River. These include reports, cited elsewhere, by P. W. Barnes and Erk Reimnitz and their Geological Survey associates; W. M. Wiseman and associates from Louisiana State University; A. S. Naidu, J. A. Dygas, and associates from the University of Alaska; P. V. Sellmann and Jerry Brown and associates from the U.S. Army Cold Regions Research and Engineering Laboratory; and R. E. Lewellen of Arctic Research, Inc. Meanwhile, renewed interest in the potential resources of the National Petroleum Reserve has led to renewed and more systematic studies of the Quaternary geology and geomorphic processes of the western coastal plain by L. D. Carter and J. R. Williams and associates from the U.S. Geological Survey.

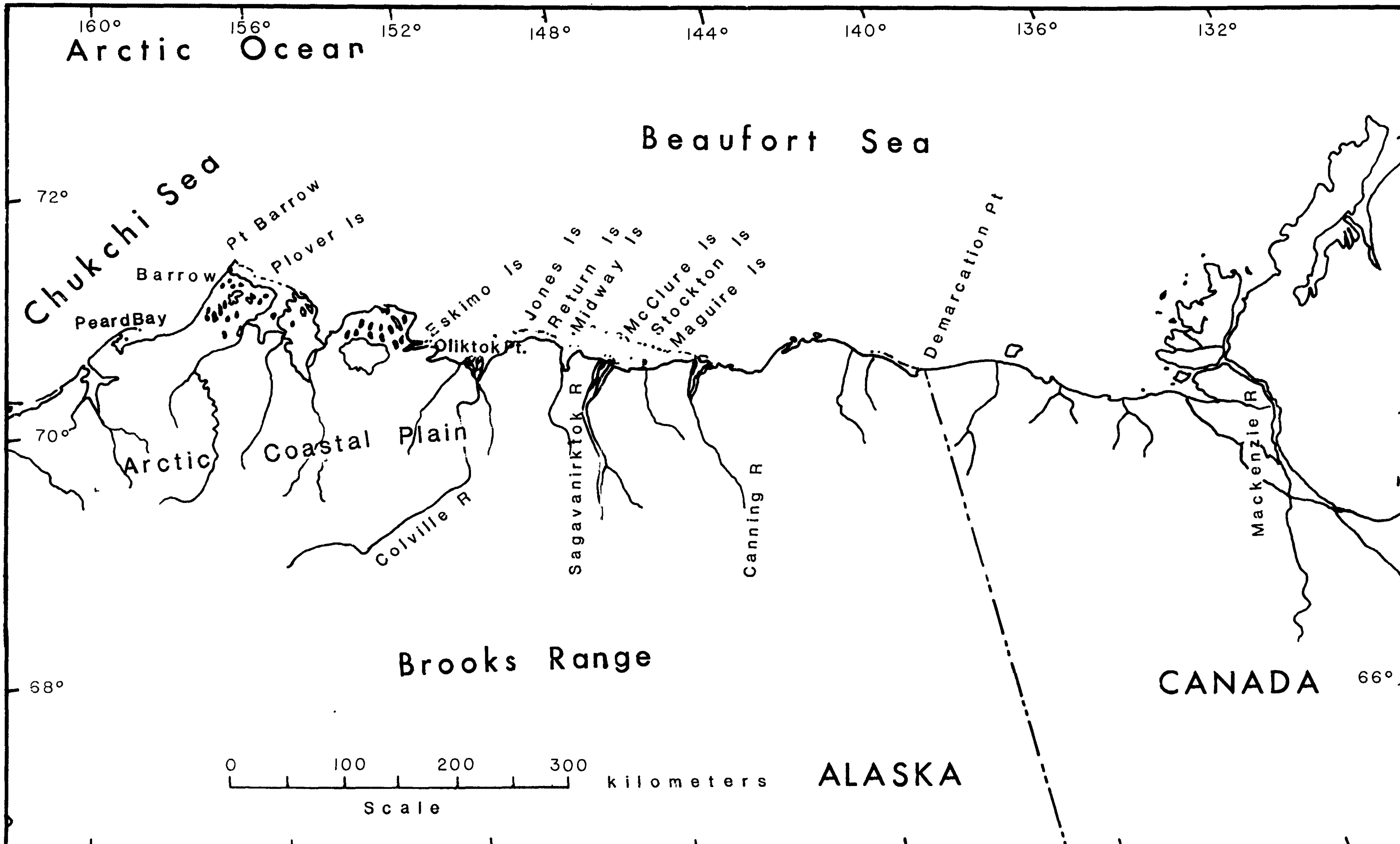
Our study of the Beaufort Sea coast was conducted during the summers of 1976 and 1977. The primary objectives were to ascertain the relationship of coastal geology and geomorphology to shoreline history and the occurrence of offshore permafrost and to determine the potential impact of gravel mining on beaches and barrier islands. Special attention was given to such critical problems as the origin and renewability of barrier islands, gravel distribution and longshore transport, coastal stratigraphy, and coastal erosion. The study was supported jointly by the Bureau of Land Management and the U.S. Geological Survey through interagency agreement with the National Oceanic and Atmospheric Administration as part of the Outer Continental Shelf Environmental Assessment Program (OCSEAP). We were assisted in the field by R. E. Nelson, P. A. Smith, and C. J. Stanley. During planning and preparation of the paper, we benefited from discussions with P. W. Barnes, L. D. Carter, John Harper, A. S. Naidu, Dag Nummedal, Erk Reimnitz, W. J. Wiseman. P. W. Barnes and T. D. Hamilton reviewed the report and assisted us with many painful comments and agonizing suggestions.

COASTAL REGIME--THE SEASONAL ROUND

The Beaufort Sea (fig. 1) is ice-covered most of the year; the open-water season is variable in length, but in general it extends from mid-July to mid-September (Barnes and others, 1977a). The Alaskan segment has a microtidal regime; astronomical tides amount to only about 15 cm (U.S. Dept. Commerce, 1978), and their effects are subordinate to changes in barometric pressure and wind direction. Wave energy is limited. Even during the open season, the arctic ice-pack generally lies only a few tens of kilometers offshore, and consequently, potential fetch is small. However, the frequent strong northwest winds of late summer and the barometric lows with which they are associated can result in storm surges as much as 3 m above normal sea level with wave heights reaching 6 m (Hume and Schalk, 1967 ; Wiseman and others, 1973).

In autumn, Beaufort Sea beaches become sheathed in ice and ice-cemented gravel, and later covered by snow. Growing sea-ice and the impinging pack-ice are pushed onshore by the prevailing northeasterly winds, disrupting offshore islands and beaches to varying degrees and creating furrows tens of meters long and ridges a meter or more high on some exposed outer beaches. During the remainder of winter and spring beaches are protected from further effects of waves or moving ice (Wiseman and others, 1973). When the ice breaks up in late June or July, low coastal bluffs begin to thaw, creating mudflows which ooze down over adjoining beaches or over the snowbanks that continue to cover them.

Figure-1 Index Map



In late summer, beginning commonly in mid-August but sometimes as early as late July, low-pressure cells associated with Pacific storms begin to cross Alaska, reaching the Arctic coast (Wiseman and others, 1973). The lowered barometric pressures result in higher sea level. Wave energy is intensified, and sea ice may once again be driven onto the outer beaches. Most of the coastal changes--bluff retreat, spit elongation, and island migration--and most of the sediment transport is accomplished during this late summer and early autumn period.

COASTAL GEOLOGY

Recent studies of the Beaufort Sea coast by L. D. Carter, O. J. Ferrians, Jr., R. W. Hartz, D. M. Hopkins, and R. E. Nelson indicate that east of Oliktok Point, the Arctic coastal plain is underlain by a series of coalescing alluvial and glacial-outwash fans extending northward from the Brooks Range (fig. 2c and d). They consist mostly of sandy gravel. The alluvial fans generally extend to the coast, but in some places, the immediate coastal area is occupied by the Flaxman Formation, a marine sandy mud of Pleistocene age which contains abundant glaciated pebbles, cobbles, and boulders foreign to Alaska and quite different in lithology from the gravel of Brooks Range origin in the alluvial fans (Leffingwell, 1919, p. 142-149).

The Flaxman Formation contains a suite of pebble types almost completely different from the pebble types found in the alluvial and glacio-fluvial deposits of streams draining the Brooks Range. Consequently, pebble-lithology counts can be used to identify the relative importance of Brooks Range alluvial deposits relative to the Flaxman Formation as sources of Beach sediment (Rodeick, 1975). Gravel derived from alluvium

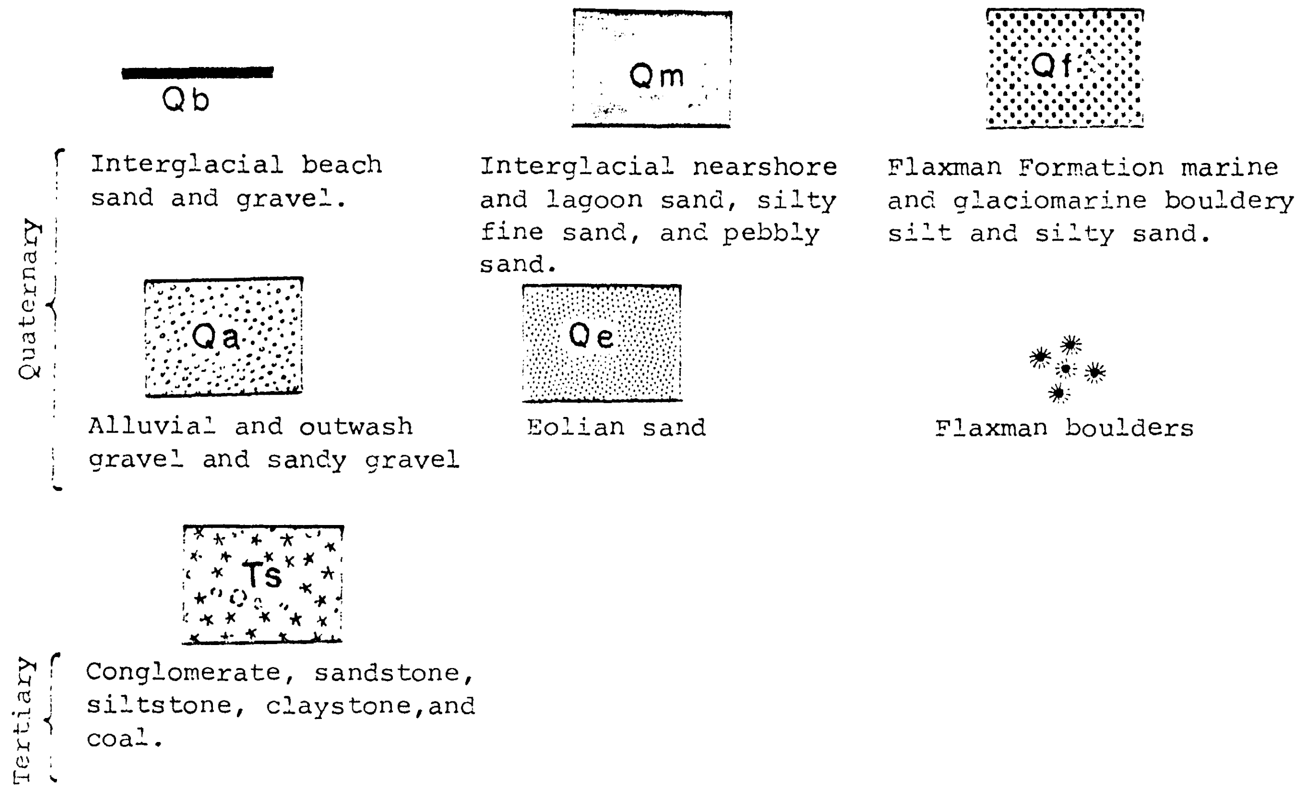


Figure 2; Geologic map of the Arctic coastal plain west of the Canning River.

Figure-2a

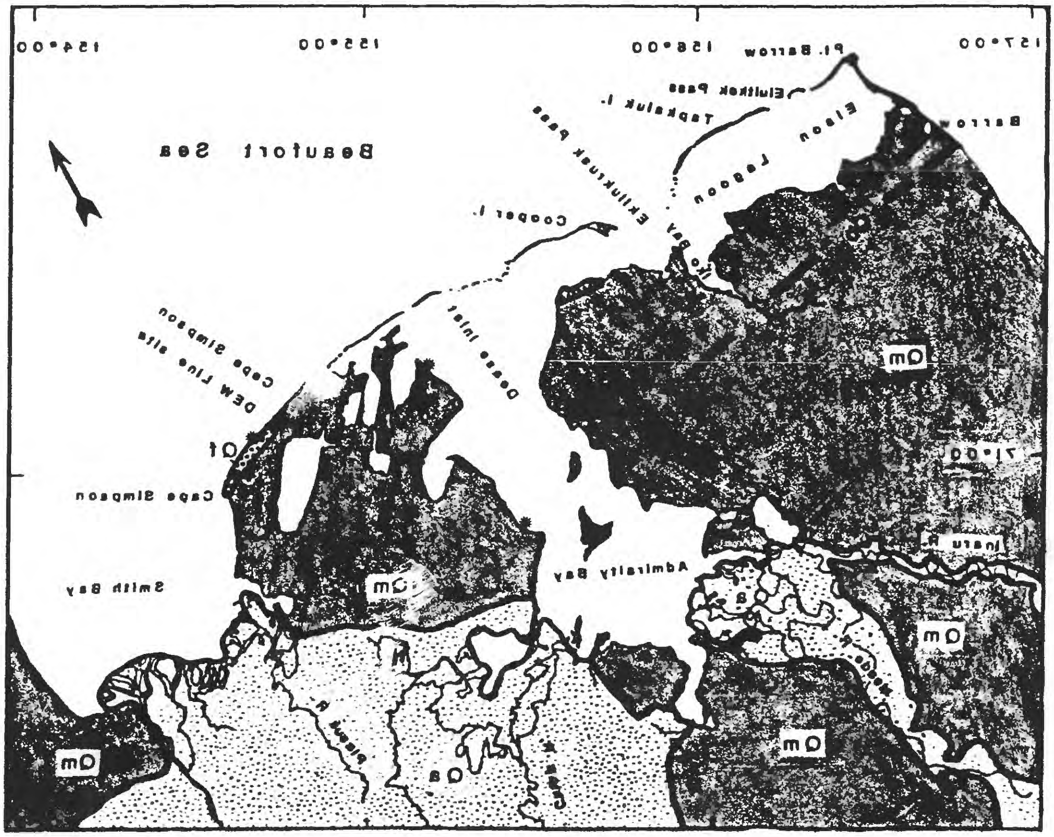


Figure-2b

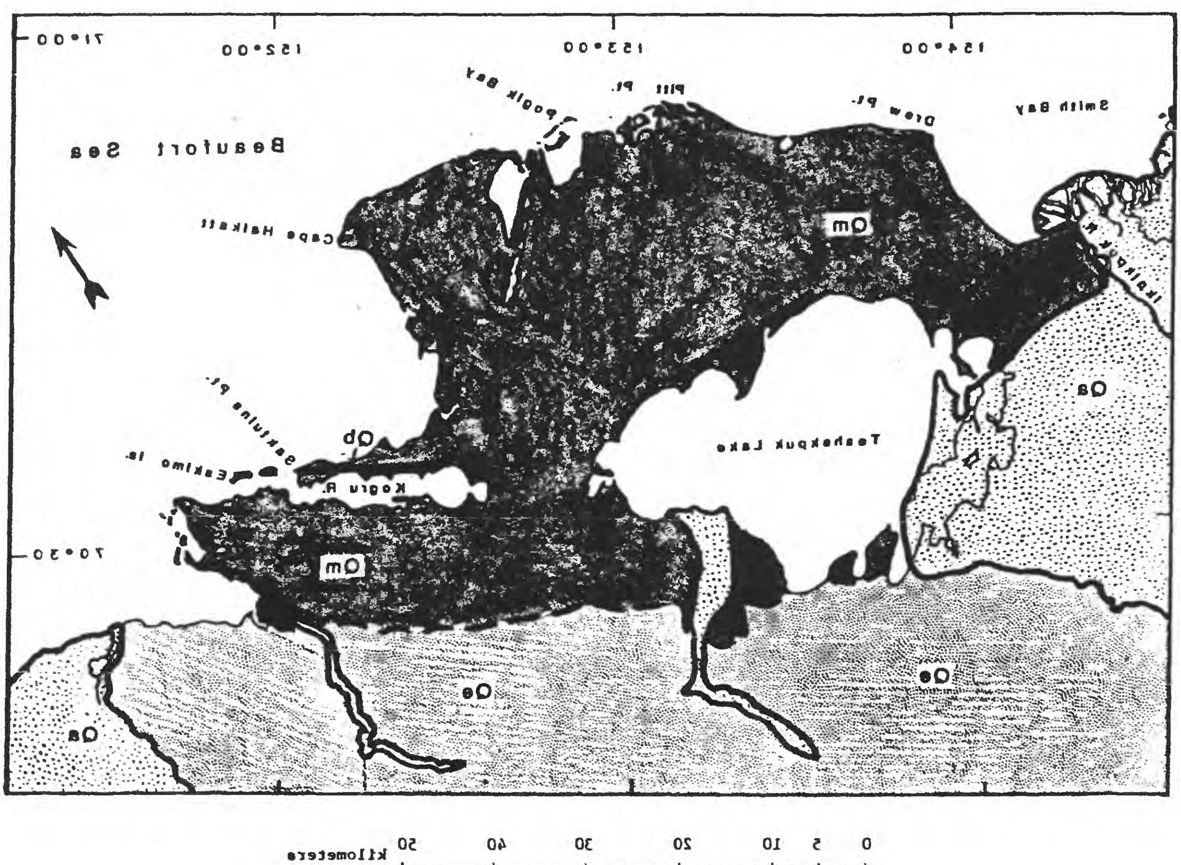


Figure-2c

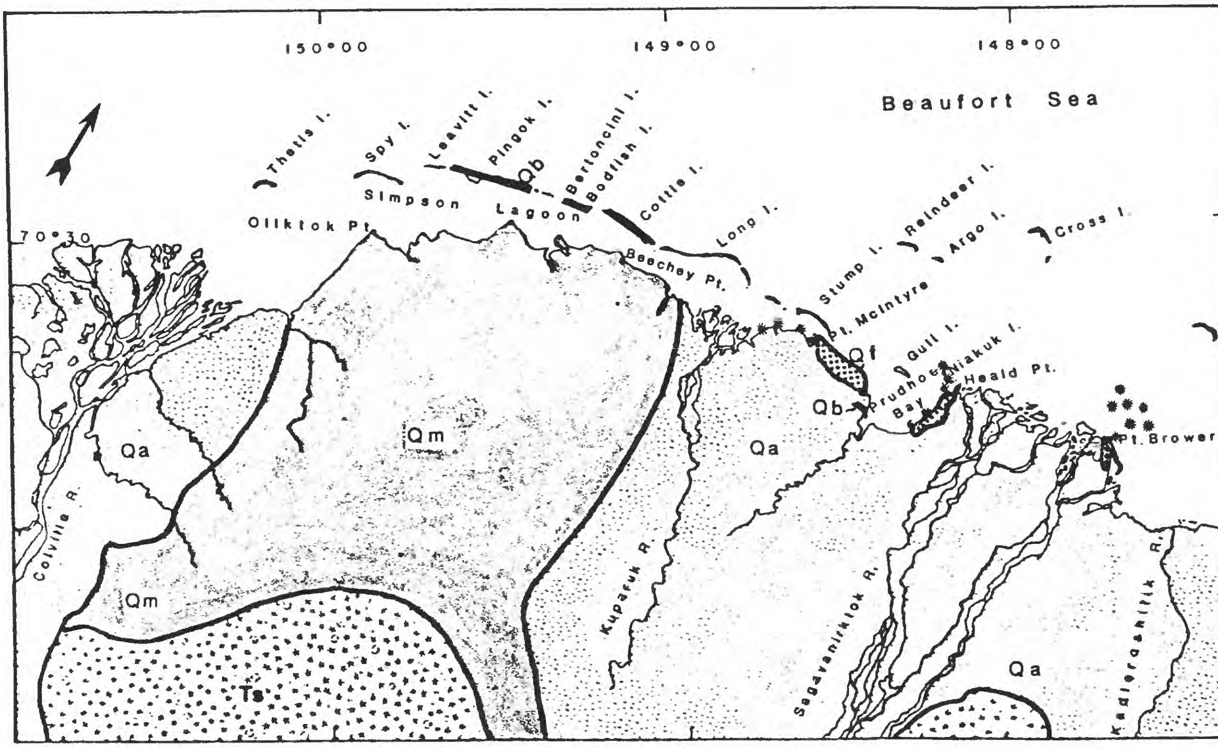
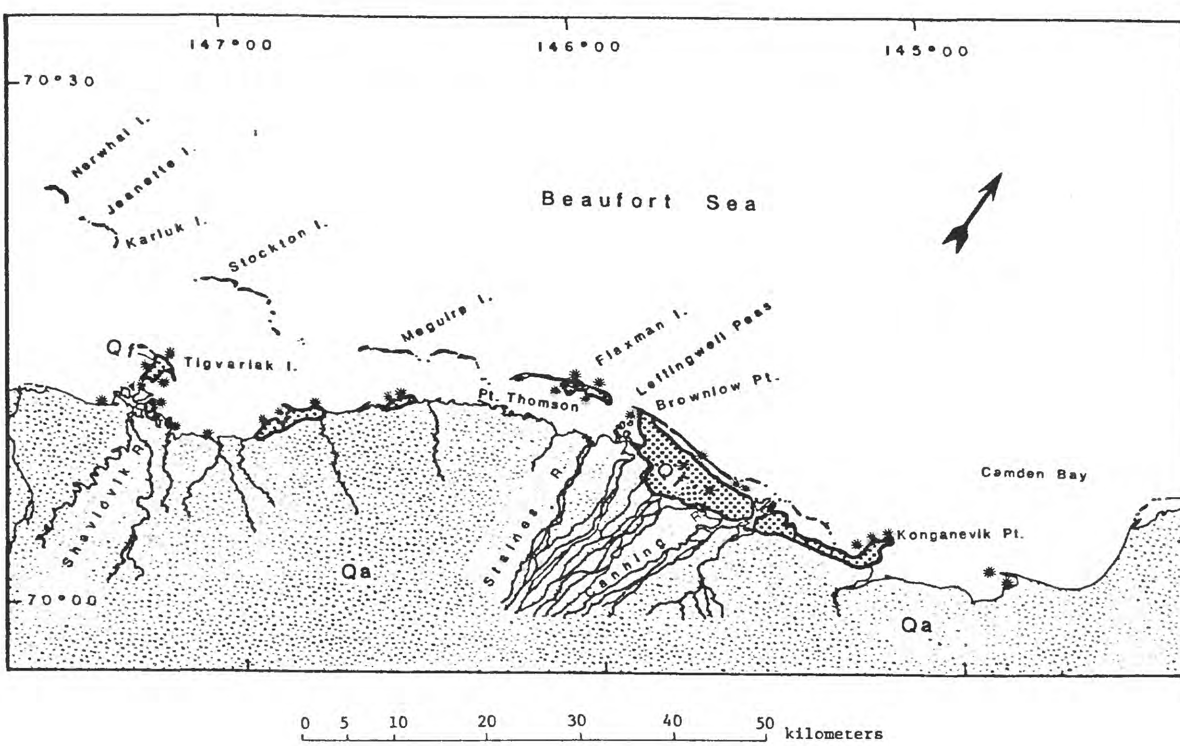


Figure-2d



and outwash of streams draining the Brooks Range consists largely of chert, graywacke, and grit, and includes notable quantities of vein quartzite, while gravel derived from the Flaxman Formation consists largely of dolomite and also includes notable quantities of red quartz, red granite, pyroxenite and diabase. The Flaxman Formation underlies most of Tigvariak Island, Flaxman Island, and large mainland areas between and to the east of the distributaries of the Canning River, as well as smaller areas near Point McIntyre, Heald Point, and Point Brower and some still smaller coastal areas farther west (fig. 2). Extensive areas of the continental shelf that are littered with boulders resting on overconsolidated clay (Rodeick, 1975; Mowatt and Naidu, 1974; Barnes and Reimnitz, 1974; Chamberlain and others, 1978; Sellmann and Chamberlain, 1978) also seem to represent outcrops of the Flaxman Formation.

Most of Pingok, Bertoncini, and Bodfish Islands and two small high-standing areas on Cottle Island are underlain by sandy pebble gravel interpreted here as representing remains of an ancient island chain probably formed during the last interglacial interval, about 120,000 years ago. This ancient beach gravel contains a mixture of Brooks Range and Flaxman pebbles.

The Arctic coastal plain west of Oliktok Point is divided into two belts separated by a line of low mounds and ridges generally less than 10 m in altitude (figs. 2a, 2b). The inner Arctic coastal plain is a mosaic of areas underlain by Pleistocene marine pebble sand of the Gubik Formation, of Pleistocene dune fields, and of Pleistocene and Holocene sandy alluvial plains and deltas (Williams and others, 1977;

Carter and Robinson, 1978). Gravel is found on the western inner coastal plain only beneath the floodplain and terraces of the Colville River. The outer coastal plain is underlain by compact stoney mud of the Flaxman Formation which probably extends onto the sea floor to the north. The mounds and ridges that separate the inner from the outer coastal plain extend from Barrow southeastward along the north side of Teshekpuk Lake through the peninsula north of Kogru River, to Saktuina Point and the Eskimo Islands (figs. 2a and b). This high ground is underlain by beach sand and fine gravel of the Gubik Formation, and contains a mixture of pebbles of Brooks Range and Flaxman origin, and represents, in our opinion, a westward continuation of the former Pliestocene island chain which forms the cores of modern Pingok, Bertoncini, Bodfish, and Cottle Islands.

Throughout the region, the Pleistocene marine, alluvial, and glacio-fluvial sediments are mantled by 2 or 3 m of late Pleistocene and Holocene thaw-lake sediments consisting of peat and mud, commonly with a minor admixture of pebbles, cobbles, and boulders redeposited from the underlying Pleistocene sediments. Much of the Beaufort Sea coast is so low that the Pleistocene deposits lie below sea level, and only the mantle of Holocene peaty thaw-lake deposits can be seen in the coastal bluffs. Throughout the region, the Pleistocene and Holocene sediments are perennially frozen at depths greater than a few tens of centimeters, and the near-surface sediments contain variable but generally large quantities of ground ice.

COASTAL GEOMORPHOLOGY

The mainland coast of the Beaufort Sea is crenulated and deeply embayed, especially in the segment west of the Canning River, the region to which our studies were confined. A series of en echelon island chains resembling barrier chains serve to provide a relatively straight outer coast in some regions, but other deeply embayed coastal segments, notably Harrison Bay and Smith Bay, lack protective island chains. Even where offshore islands are present, they may offer little wave shelter to the mainland coast, because they commonly enclose lagoons so wide as to allow considerable wave fetch. Furthermore, the sheltered waters become freed of floating ice relatively early in the summer, and so the lagoon shores are exposed to wave action for longer periods.

Some details of the form of the Beaufort Sea coast are inherited from a coastal morphology created during the next previous high-sea-level episode, 120,000 years ago. Simpson Lagoon, Kogru River, Teshekpuk Lake, and perhaps Admiralty Bay all occupy the former positions of interglacial lagoons that lay behind the ridge of Gubik sand and gravel marking the position of an interglacial barrier chain. A few thousand years ago, the sites of these shallow water bodies were low-lying but dry; thermokarst collapse of ice-rich lagoonal sediments allowed the sea to invade.

BEACHES AND LONGSHORE TRANSPORT

The mainland shores are characterized by narrow, low-lying beaches backed by coastal bluffs generally less than 10 m and commonly only 2 or 3 m high. The beaches are rarely wider than 20 m and commonly are only a few tens of centimeters thick. Gravel predominates in beaches between the Canning River and Point McIntyre and sand in beaches farther west. Gravel sources are scarce, and in many places the mainland beaches are obviously starved. It is not uncommon to see beaches which consist of low ridges of sand and gravel perched on a seaside bluff 1.0 to 1.5 m high carved in peat and mud (fig. 3).

Most, if not all, of the coarse sediment comprising the beaches is derived from erosion of coastal bluffs. Rivers deliver no coarse material to the mainland or island bluffs; they drop their load of sand and gravel a few kilometers inland and only easily resuspended fine sand, silt, and clay reaches the lagoons and estuaries (Arnborg and others, 1966; Barnes and Reimnitz, 1974).

However, sand and gravel reaches the beach in small quantities from coastal bluffs carved in alluvial and glacial-outwash fans away from the immediate vicinities of the river mouths. Larger quantities of sand and gravel are delivered to beaches in areas where coastal bluffs are carved in the Flaxman Formation or into the pebbly sand of the hillocks and ridges marking the sites of the Pleistocene island chain. Nevertheless, large segments of the Beaufort Sea coast, especially in the stretch extending from northwestern Harrison Bay to Barrow village, are backed by coastal bluffs in which gravel-sized particles are lacking, and sand-sized particles are scarce.

A minor amount of sand and gravel is provided to some beaches by ice push. Ice-plowed gravel ridges on Cross and Narwhal Island (figs. 4 and 5) and along the low-lying coast near Cape Simpson DEWLine

Figure 3 Section through a starved and inverted beach near Cape Simpson. No vertical exaggeration.

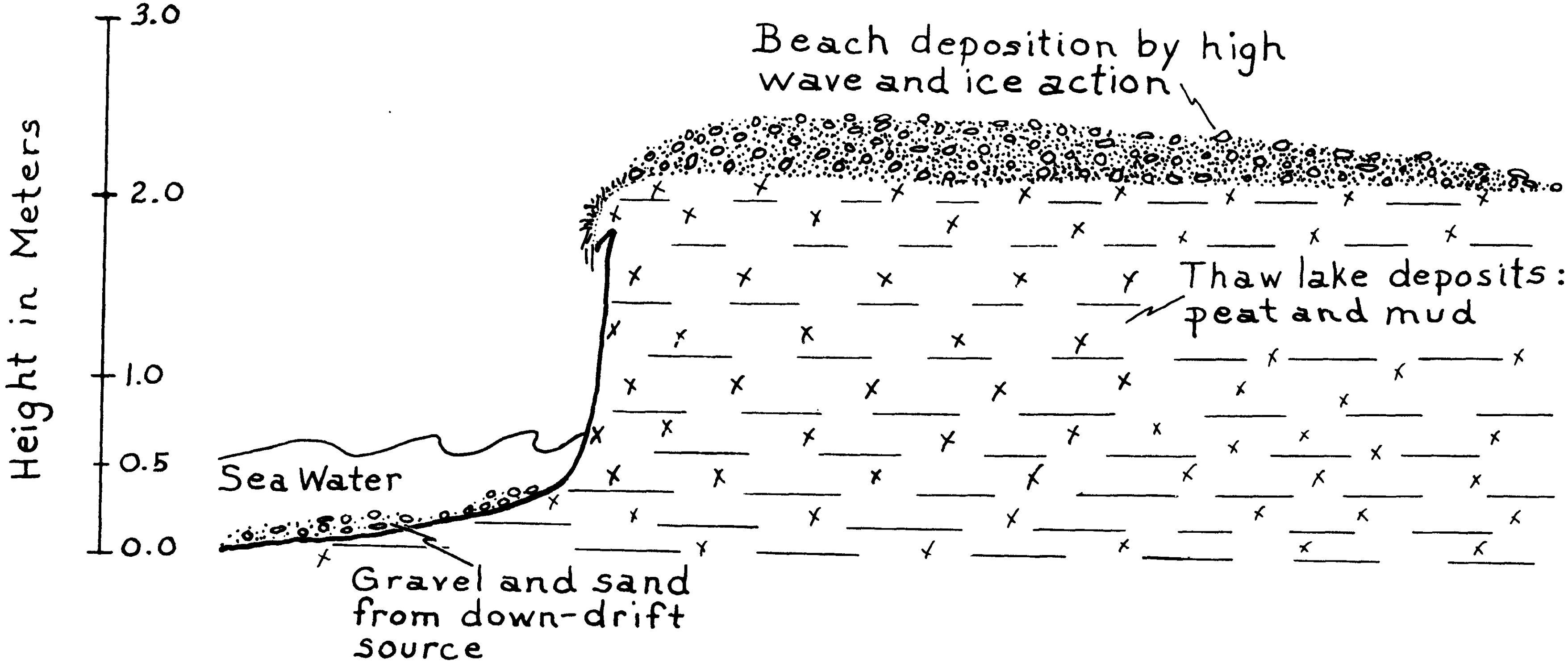


Figure 4 Ice-plowed gravel ridges on Cross Island, July, 1977

Figure 5 Ice-plowed gravel ridges on Narwhal Island, July, 1977

station, among other places, contain cobbles and boulders coarser than any that can be found onshore nearby, indicating that grounded ice is plowing gravel to the beach from a submerged nearshore source.

The direction of littoral sediment drift is generally westward, but wave refraction induces many local reversals along the crenulate mainland coast and also on the more arcuate offshore islands. The mainland coast is thus divided into many small littoral transport cells, mostly shorter than 10 km. Some of the island chains form slightly longer west-drifting transport cells, but others, as we shall show later, seem to consist of isolated slugs of sand and gravel migrating southwestward without interchange with other islands or with the mainland coast.

Because wave energy is low and the open season short, total amounts of sediment transport along the beaches are small. The rate of longshore drift of sediment has not been estimated for points on the mainland coast, but Wiseman and others (1973) estimate longshore transport on the outer coast of Pingok Island at 10,000 m^3 during the summer and autumn of 1972. The observed rate of lengthening of western Pingok and Leavitt Islands between 1955 and 1972 (Wiseman and others, 1973) suggests that this rate has been sustained over a long period. A lower rate of mass transport is indicated for the Maguire Islands; the observed rate of island migration, there (Wiseman and others, 1973), indicates mass transport of slightly more than 5,000 m^3/yr. The mass transport rate is probably lower along those parts of the mainland coast protected by nearby island chains.

THERMOKARST COLLAPSE, THERMAL EROSION, AND COASTAL RETREAT

Despite the short open season and the prevalence of a low wave-energy regime, the coast of the Beaufort Sea is retreating at a spectacular pace. Rates of coastal erosion observed there are, for example, an order of magnitude faster than those reported for the Chukchi Sea coast (table 1). The rapid retreat of the Beaufort Sea coast is governed by the involvement of the distinctively Arctic processes of thermokarst collapse and thermal erosion[1/] acting upon bluffs composed of perennially frozen and predominantly fine-grained sediment.

The arctic coastal plain and those Beaufort Sea islands that are composed of ice-rich Pleistocene sediments are affected by thermokarst collapse. Localized thawing in onshore areas results in subsidence due to the melting-out of excess ground ice, and the resulting subsidence basins become occupied by rapidly growing thaw lakes. On the higher or steeper parts of the arctic coastal plain, there is enough relief so that thaw lakes tend to break through and drain to lower ground before reaching diameters larger than 1 or 2 km. Near the coast, however,

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[1/] Thermokarst collapse is defined here as collapse or loss of volume due to melting out of ground ice in excess of normal porosity of the sediment. Thermal erosion is defined here as lateral erosion resulting from melting out of ground and interstitial ice accompanied by lateral current-transport of resulting fine materials.

Table 1. Rates of Coastal Retreat, Beaufort Sea Coast and Chukchi Sea Coast North of Peard Bay

Section of Coastline	Composition of Bluffs	Period of Observation (yrs.)	Number of Data Points	Average Yearly Rate of Retreat (M)	Source of Information
Mackenzie Bay to Demarcation Pt.	Quaternary alllluvium, silts, sands, and gravels	+50	Unknown	±2.5	MacKay, 1963
Demarcation Pt. to Camden Bay	Quaternary alluvium and Quaternary Flaxman Formation. Overlain by thaw lake deposits	23	23	1.5	Lewellen, 1977
Camden Bay to Brownlow Pt.		23	4	1.6	Lewellen, 1977
Flaxman Island	Quaternary Flaxman Formation	87	8	9.2	Leffingwell, 1919
	Overlain by thaw lake deposits	19		3.5	Lewellen, 1970
Brownlow Pt. to Point Thomson	Quaternary alluvium and Quaternary Flaxman Foration	6	Unknown	9.0 (Brownlow Pt. only)	Leffingwell, 1919
		23	2	6.8	Lewellen, 1977
	Overlain by thaw lake deposits	28	7	3.5	Hartz, unpublished data
Point Thomson to Tigvariak Island		28	6	2.0	Hartz, unpublished data
Tigvariak Island to Heald Point		28	4	3.0	Hartz, unpublished data
Heald Point to Point McIntyre		20	5	1.5	Lewellen, 1977
		20	Unknown	2.0	Barnes & Reimnitz, 1977
Point McIntyre to Beechey Pt.	Quaternary marine silts and fine sands plus Quaternary Flaxman Formation plus Quaternary alluvium. Overlain by thaw lake deposits	20	5	0.9	Lewellen, 1977
		20	Unknown	1.0	Barnes & Reimnitz, 1977
Beechey Pt. to Oliktok Pt.	Quaternary marine silts and fine sands. Overlain by thaw lake deposits	22	58	1.4	Dygas and others, 1972
		23	19	1.6	Lewellen, 1977
Colville R. Delta	Deltaic silts and fine sands	24	8	0	Toimil, 1977
Oliktok Pt. to Kogru River	Quaternary marine silts and fine sand plus Quaternary eolian sands plus Quaternary alluvium, overlain by thaw lake deposits	28		2.0	Hartz, unpub. data
Kogru River to Cape Halkett	Quaternary marine silts and fine sand overlain by thaw lake deposits (Williams & Carter, 1977)	28	12	3.2	Hartz, 1978
Cape Halkett to Pitt Point		23	7	12.0	Lewellen, 1977
		28	5	13.4	Hartz, 1978
Pitt Point to Cape Simpson		6	Unknown	30.0 (Drew Pt. only)	Leffingwell, 1919
		23	14	.0	Lewellen, 1977
		28	9	11.4	Hartz, 1978
Cape Simpson to Admirality Bay		6	Unknown	30.0 (Cape Simpson only)	Leffingwell, 1919
		23	6	4.6	Lewellen, 1977
		28	10	4.3	Hartz, 1978
Admirality Bay to Iko Bay		23	21	3.1	Lewellen, 1977
		28	7	3.0	Hartz, 1978
Iko Bay to Point Barrow		2	6	2.1	MacCarthy, 1953
		21	149	3.3	Hume & Schalk, 1972
		23	19	2.	Lewellen, 1977
		28	10	2.5	Hartz, 1978
Point Barrow to Peard Ba	Quaternary marine silts and sands underlain by Cretaceous bedrock	27	101	0.31	Harper, 1978

lakes can coalesce into shallow water bodies of scalloped outline, tens of kilometers across; Teshekpuk Lake is the largest example. Abrupt changes in the outline of the coast can result when the retreating shoreline breaks through into a lake whose bottom lies below sea level. Prudhoe Bay seems to have originated in this manner (Hopkins and others, 1977).

The sea coast and, to a lesser extent, lake shores, are also affected by thermal erosion. Thermal erosion is most rapid and effective along coastal segments where the bluffs are composed of ice-rich, frozen mud, silt, or fine sand containing few or no stones. Thawing and erosion of bluffs composed of pebbly sand or sandy gravel releases enough coarse sediment to thicken the beach and minimize undercutting. The fibrous, interlacing structure of arctic peat and turf makes these materials also somewhat resistant to wave attack; thick peat accumulations thus tend to persist as minor promontories on actively retreating coasts. Where thick peat is missing, surficial turf may drape like a robe over the face of an actively retreating bluff cut in fine sediment (fig. 6).

As Leffingwell (1919) and Lewellen (1977) have pointed out, most of the bluff erosion takes place during late summer and autumn. Drifting snow accumulates in the lee of the shore bluffs during winter, and the resulting snow drifts tend to persist well into July (fig. 7). Where snow is lacking, mudflows and slumps regrade the coastal bluffs and partly cover the narrow beaches. During late summer and autumn, when the weather is dominated by the passage of cyclonic low-pressure systems with easterly winds, sea level rises above the tops of the low

Figure 6 Turf draped over deeply undercut silt and fine sand bluff south of Cape Halkett, late August, 1977

Figure 7 Persistent snowbanks on the beach south of Icy Cape (Chukchi Sea), July, 1976

beaches. The remaining snow and much of the slumped material is quickly removed, and waves begin to attack the exposed bluffs. Even when the sea is nearly calm, the cold salt water thaws the frozen mud, releasing small particles to be carried away by lonshore currents. Such bluffs can be quickly undercut to depths as great as 6 or 8 meters (fig. 8). When frost cracks extending along the axes of ice wedges are intersected (fig. 9), blocks as large as houses collapse onto the beach (fig. 10). Destruction of the collapsed blocks by continued lapping of the waves may require several years.

Rates of coastal retreat (table 1) differ in different sites, depending not only upon differences in the composition of the coastal bluffs, but also upon exposure and upon morphology of the adjoining sea bottom. The highest rates of coastal retreat are recorded on promontories and points, probably because these areas are affected by rapid coastal erosion from opposing directions. Nevertheless, many bays and estuaries have persistently cuspate outlines, evidently indicating that thermal erosion and thermokarst collapse tend to cause parallel retreat of the shoreline, regardless of coastal orientation. As Lewellen (1977) observes, promontories and points tend to persist in the same general areas, and the morphology of the coast tends to remain similar over periods of many decades, in spite of the observed rapid rates of erosion and apparently preferentially high short-term rates of erosion on promontories.

Mainland shorelines adjoined by narrow lagoons tend to retreat more slowly than do open coasts. However, as we have noted, many lagoons and embayments are so wide that the island chains afford little

Figure 8 Thermal niche carved in bluffs of Flaxman Formation during a period of temporary high sea level. Bluffs east of Cape Simpson Dewline Station, September 1, 1977

Figure 9 Large tilted blocks of frozen silt and sand undercut by thermal erosion and broken along median cracks in ice wedges near Benchmark Samuel, west of Cape Halkett, late August, 1977.

Figure 10 Undercut blocks of Flaxman Formation near Cape Simpson Dewline Station, September, 1977.

protection to the mainland coast. Furthermore, rates of retreat observed on the lagoon sides of some of the high-standing islands are as rapid as the retreat rates on the sewaward coasts. It may be important that the protected waters of lagoons and bays warm up and become free of ice much earlier than waters adjoining the outer coast.

Coastal bluffs that are adjoined by water shallow enough for shoals to be exposed during the early summer low-water periods retreat much less rapidly than do similar bluffs adjoined by deeper water. For this reason, high-standing remnants of Pleistocene sediments tend to be preserved in promontories adjoing the mouths of large rivers, being protected, there, by pro-delta shoals. Conspicuous examples are Heald Point and Point Brower on either side of the mouth of the Sagavanirktok River. Tigvariak Island seems to persist because pro-delta shoals of the Shaviovik River refract waves and reduce wave energy in the surrounding waters.

Rates of coastal retreat also vary dramatically from one year to another, depending upon the time of breakup of sea ice, variations in size of open-water areas, and timing and intensity of late summer and autumn storms.

Coastal retreat is so rapid as to pose a serious hazard in many areas to man-made structures near the coast. Rates of coastal retreat have consequently been measured in many places and on many occasions (Leffingwell, 1919; MacCarthy, 1953; MacKay, 1963; Hume and Schalk, 1967; Lewellen, 1970; Dygas and others, 1972; Hume and others, 1972; Wiseman and others, 1973; Lewis and Forbes, 1975; Barnes and others, 1977b; Hartz, 1978; P. J. Cannon, unpublished report to OCSEAP, 1978).

Coastal retreat proceeds at an average rate of about 2.5 meters per year along the Canadian Beaufort Sea coast between the MacKenzie River delta and Demarcation Point (MacKay, 1963; Lewis and Forbes, 1975). Coastal retreat along the mainland coast between Demarcation Point and the Colville River averages about 1.6 m/yr, although local short-term rates may be much higher; at Oliktok Point, for example, shoreline retreat of 11 m was observed within a single two-week period (Dygas and others, 1972). Rates of shoreline retreat on the Pleistocene remnants of Pingok Island are also on the order of 1.5 m/yr, with lagoon shores reported to be retreating more rapidly than the seaward coast which is well protected by a wide sand beach (P. J. Cannon, unpub. rept. to OCSEAP, 1978).

The high-standing areas of Flaxman Island are disappearing much more rapidly. Lewellen (1977) reports that the seaward coast retreated about 3.5 m/yr between 1949 and 1968 and that the lagoon shore retreated almost as rapidly. Erosion evidently progressed at similar rates between 1911 and 1949 and possibly at a much greater rate between the visit by the Franklin Expedition in 1826 and Leggingwell's observations in 1911 (Leffingwell, 1919; Lewellen, 1977).

Average rates of retreat are highest from Harrison Bay eastward to Barrow, reflecting the paucity of coarse sediment in the material composing the low bluffs along this segment of the coast. Lewellen's (1977) 68 data points indicate an average retreat rate of 4.7 m for the Harrison Bay-Barrow segment, and Leffingwell reported short-term erosion rates as great as 30 m/yr at Drew Point and Cape Simpson (table 1).

The exceptional nature of the high retreat rates measured along the Beaufort Sea coast is dramatized by retreat rates generally an order of magnitude lower along the Chukchi Sea coast immediately to the southwest (Harper, in press) (table 1). Causes of this difference are not yet entirely clear, but are probably related to the fact that most segments of the coast of Chukchi Sea between Peard Bay and Barrow consist of bluffs 10 to 30 m high, to a greater abundance of sand and gravel in the Chukchi coastal bluffs, and to the fact that much of that segment of the coast is carved, at beach level, in relatively compact, ice-poor clay of Cretaceous age with a few interbeds of firmly cemented sandstone (our unpub. data).

Areas of progradation are almost entirely restricted to the immediate vicinity of the mouths of the larger rivers. The Canning, Shaviovik, Sagavanirktok, Kuparuk, Colville, Ikpikpuk, Topagoruk, and Meade Rivers all have prograding deltas at their mouths, and actively prograding deltas are probably present at the mouths of the larger streams east of the Canning River, as well[2/].

OFFSHORE ISLANDS

Several OCSEAP studies have focused upon the description and origin of the Beaufort Sea islands west of the Canning River and upon

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[2/] Rates of progradation are evidently very slow. A comparison of coastal charts shows no progradation of the delta strand nor of the submerged 2-meter delta front bench of the Colville River during the last 25 years (Toimil, 1977).

the shoreline processes affecting them. The islands are obviously prime candidates for siting petroleum exploration and production facilities, or, alternately, prime candidates for gravel quarrying. On the other hand, they profoundly affect water circulation and sediment movement on the inner shelf, anchor sea ice and widen the zone of shorefast ice, offer shelter to large shorebird populations during the late summer resting period or molt, and, in a few exceptional areas, provide important nesting habitat. Thus, it has become important to obtain a clearer idea of their origin, sources of sediment, and probable future.

Low-lying islands at the mouths of the major rivers are simply emergent depositional shoals of fine river sand representing the outer fringes of deltas; they will not be discussed further in this report. Some other islands are erosional remnants of the coastal plain that have become isolated form the mainland by thermokarst subsidence and rapid thermal erosion. Still other islands are recent constructional features resembling barrier chains. Some of the constructional islands, however, have cores of Pleistocene sediment. The situation is complicated further by the fact that some of the Pleistocene remnants originated as ancient barrier islands formed tens of thousands of years ago during a Pleistocene interglacial episode of higher sea level.

Islands representing erosional remnants of the coastal plain generally stand 4 m or more above sea level and lie within a few kilometers of the mainland shore. Most are rather broad and have length:width ratios no less than 1:4; some are more or less equidimensional. The remnant islands commonly have cuspate outlines and resemble the form of erosional remnants left between mutually interfering thermokarst-lake basins. Some remnant islands are composed of pebbly mud of the Flaxman Formation and others of Pleistocene beach sand and gravel of the Gubik Formation; both types typically have a cover several meters thick of ice-rich peat, thaw-lake deposits, and wind-blown sand. Tigvariak and Flaxman Islands are composed of Flaxman Formation. The Niakuk Islands off Point McIntyre consisted of Flaxman Formation in the early 20th Century (Leffingwell, 1919) and now are low-lying lag deposits of Flaxman boulders (P. W. Barnes and Erk Reimnitz, oral commun., 1977). The Eskimo Islands and the Pleistocene cores of Pingok, Bertoncini, Bodfish, and Cottle Islands consist of Pleistocene beach deposits of the Gubik Formation. Pogik Island is a Pleistocene remnant that has not yet been examined.

Most of the predominantly construction islands lie within one of three chains resembling barrier chains (fig. 2). The eastern chain extends from Brownlow Point through Flaxman Island to Reindeer Island; the central chain from Pt. McIntyre through Stump Island to Thetis Island; and the western chain from Cape Simpson DEWLine Station through the Plover Islands to Point Barrow. All three chains diverge northwestward from the mainland coast. The eastern and central chains are open westward so that both Reindeer and Thetis Islands lie about 14 km offshore. The Plover Island chain is closed on the west by Point Barrow spit which extends the Chukchi Sea coast 7.5 km northeastward from the mainland.

The islands are mostly recent constructional accumulations of sand and gravel, although, as we noted above, Flaxman Island in the eastern chain and several islands in the central part of the central chain have cores of Pleistocene sediments. These erosional remnants stand 3 to 6 m above sea level and support a continuous cover of non-halophytic tundra vegetation. All are disappearing rapidly by wave erosion and thermokarst collapse.

The constructional parts of the islands may be as long 9 km and are nowhere higher than 3 m. They generally range from 90 to 110 m in width but may be as wide as 460 m in the rare areas of accretionary beach ridges and spits. The island chains consist of broadly arcuate or bow-shaped groups of islands separated from one another by major passes. The passes differ greatly in width and depth; most are several kilometers wide but only 2.5 to 3.0 m deep; a few are only a few hundred meters wide, but these may be 10 m or more in depth. The passes are sites of strong currents and major water exchange. Leffingwell Pass has deepened steadily and dramatically during the past 150 years (Leffingwell, 1919; Lewellen, 1977), and in 1976 had reached a depth of 10.5 m (Reimnitz and Toimil, 1977). Other passes may be undergoing similar dynamic changes.

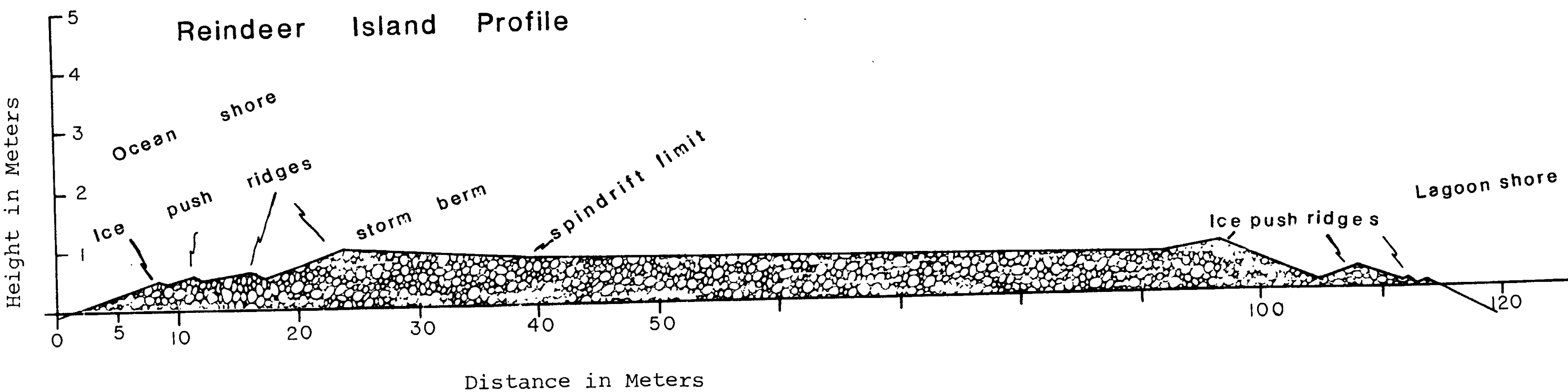
The bow or arcuate shape of the island groups is caused by deflections as much as 2 or 3 km landward at eastern and western ends. Within the groups, individual islands are sinuous and are separated by ephemeral passes generally only a few hundred meters wide and no more than one to two meters deep. Migration of islands, filling of old passes, and development of new ones (Wiseman and others, 1973) results in such rapid changes in morphology that maps and air photos 20 years old are almost useless for locating oneself during an overflight.

Typical profiles across the islands show a central depression that may contain a small pond adjoined by a high berm about 20 m wide and as much as 2 m high on the ocean side and by a low berm 10 or 15 m wide and less than 1.5 m high on the lagoon side (fig. 11). A more complex morphology may be seen at the western termini of island groups; there, successions of storms have commonly built recurved accretionary spits consisting of small areas of ridge and swale topography (fig. 12A). Exceptional storms occasionally extend the western terminus of an island group westward past a previously formed recurved spit, and the old spit then persists as a claw-like spur on the lagoon sides of the island group (fig. 12B). Bypassed spits are the most persistent and commonly the highest parts of the constructional islands. Some spur-like protuberances mapped by Leffingwell in 1912 could still be recognized in 1977, although they had been truncated, and their relative positions had changed because of the continuing westward migration of more active parts of the islands.

The constructional islands are extensively inundated, every few years, during autumn storm surges. The most extreme storm events, such as the storm surge of 1970, can inundate the islands almost completely (Erk Reimnitz, oral commun., 1977).

Ice-push affects different islands to different degrees. Most affected are Cross and Narwhal Islands in the eastern chain. These islands lie far offshore, near the shear zone between shorefast ice and the Arctic ice pack. Narwhal and Cross Islands feature belts of ice-push ridges as much as 2.5 m high extending as much as 100 m inland from the ocean beach. Three separate generations of ice-push

Fiqure 11 Barrier Island Profiles



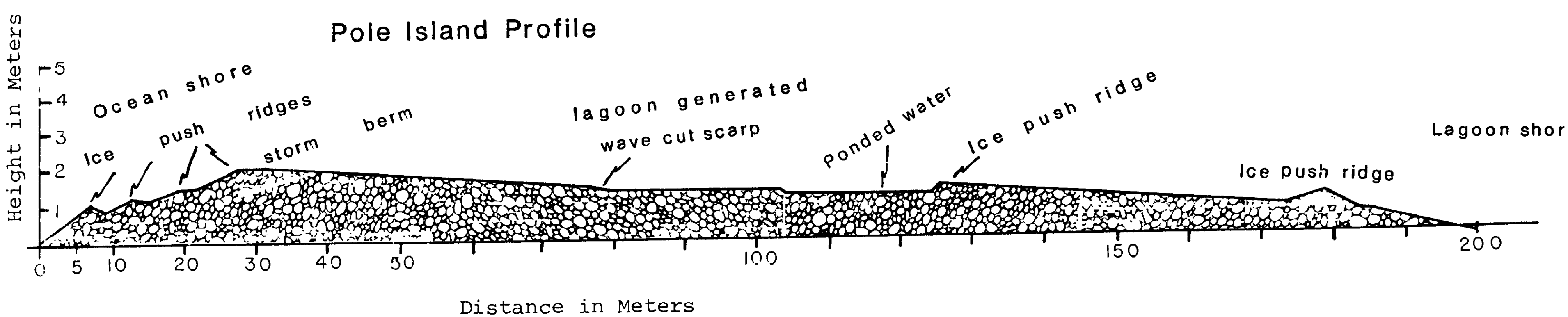


Figure 12-A Pole Island, 1955: Successional storm built recurved spits consisting of small areas of ridge and swale topography.

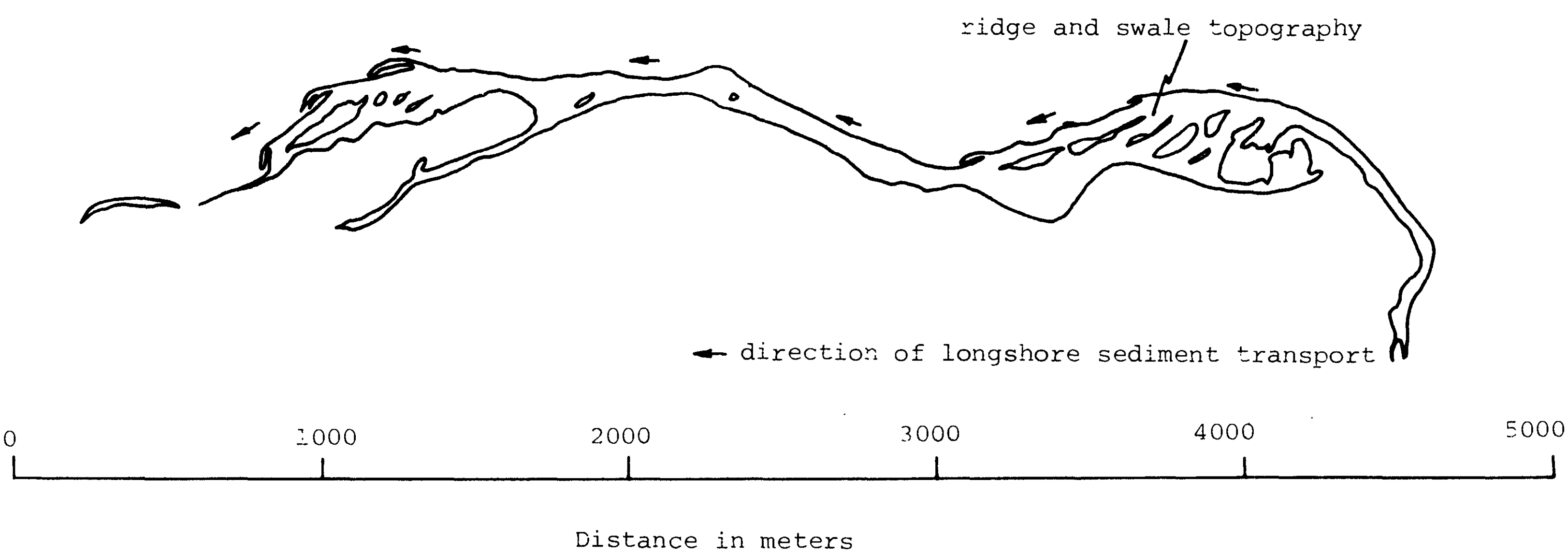
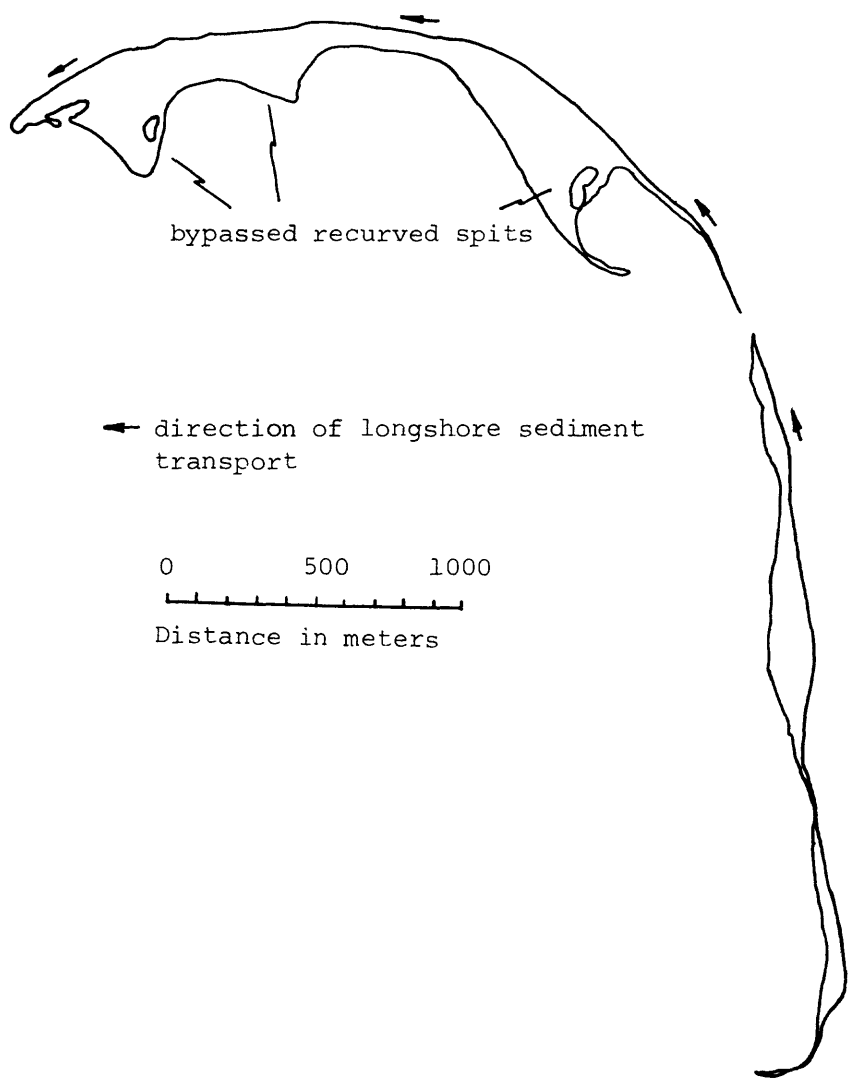


Figure 12-B Thetis Island, 1971: Extended western terminus past previously formed recurved spits.



ridges could be recognized during our visit to the island in 1977. Well preserved ridges at least a year old could be distinguished by the presence of vehicle tracks left by researchers camped on the island during the winter of 1976-77.

The constructional islands are migrating westward and landward at a rapid pace. Migration rates ranging from 19 to 30 m/yr west and from 3 to 7 m/yr landward have been established for various islands in the eastern and central chains (Lewellen, 1970; Wiseman and others, 1973). The more arcuate and isolated islands, such as Narwhal, Cross, Spy, and Thetis Islands and also Stump Island appear to be migrating southwestward en masse at rates of 4 to 7 m/yr (Barnes and others, 1977b, c. The pace of southwestward migration is such that most parts of the constructional islands require only 30 or 40 years to cross a given point on the sea floor.

The constructional islands are mostly devoid of vegetation of any kind, reflecting their short history, but a sparse cover of halophytic plants is present in those few constructional areas (i.e., truncated or inactive spits) that are older than 30 or 40 years. Because vegetation is generally lacking, the constructional portions of the islands typically lack dunes. However, dunes are extensive on the rear of beaches and on the adjoining tundra of Pingok, Bertoncini, and Bodfish Islands. Small dunes are also present in an area of sparse halophytic vegetation at the west end of Cooper Island, and they probably can be found in the sparsely vegetated areas that are present on a few of the other constructional islands.

Firmly ice-bonded permafrost is present beneath the older, sparsely vegetated recurved spits and spurs (Rogers and Morack, 1977). These areas can be recognized by the presence of frost cracks extending across ancient wave-constructed ridges and swale. Most areas on the constructional parts of the islands, however, lack firmly bonded permafrost (Rogers and Morack, 1977), although interstitial ice was found in the sediment in a borehole on Reindeer Island; the interstices in the sediment beneath the younger parts of the islands must be filled with a two-phase mixture of brine and ice. Evidently 40 or 50 years are required for freezing to progress to a point where brine is either excluded or frozen and the sediment becomes bonded firmly enough to crack when subjected to the extremely cold winter temperatures[3/].

Recent work by Rogers and Morack (1978), indicates ice-bonded materials are present 2 m below the surface of Stump Island, although this data apparently contradicts our generalization that constructional islands lack ice-bonded permafrost except in by-passed spits. We conclude, as did Rogers and Morack, that these ice-bonded materials represent relic permafrost.

Pebble lithology differs from one island group to another, reflecting differences in the sources of material making up the islands (fig. 13). The sand and gravel in all island groups within the eastern

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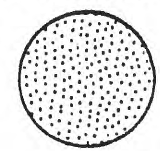
[3/] P. W. Barnes (written commun., 5/78) points out that gradual accumulation of fresh rain and snow-melt water in a Ghyben-Herzberg lens may contribute to the gradual elimination of interstitial brine in the constructional islands.

Figure 13-A,B,C,D Pebble lithologies of barrier islands and mainland beaches, Point Barrow to Brownlow Point.

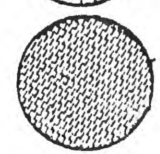
In order to ascertain sources of nourishment of beaches and barrier islands and to determine directions of sediment transport we collected random samples of of 100 pebbles at various points along the Beaufort Sea coast. Pebble lithology counts were then conducted and the results are graphically presented on the following maps.

EXPLANATION OF MAP SYMBOLS

Flaxman Formation Lithology: Dolomite

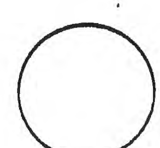


Other



Brooks Range Lithology:

Unknown Source:



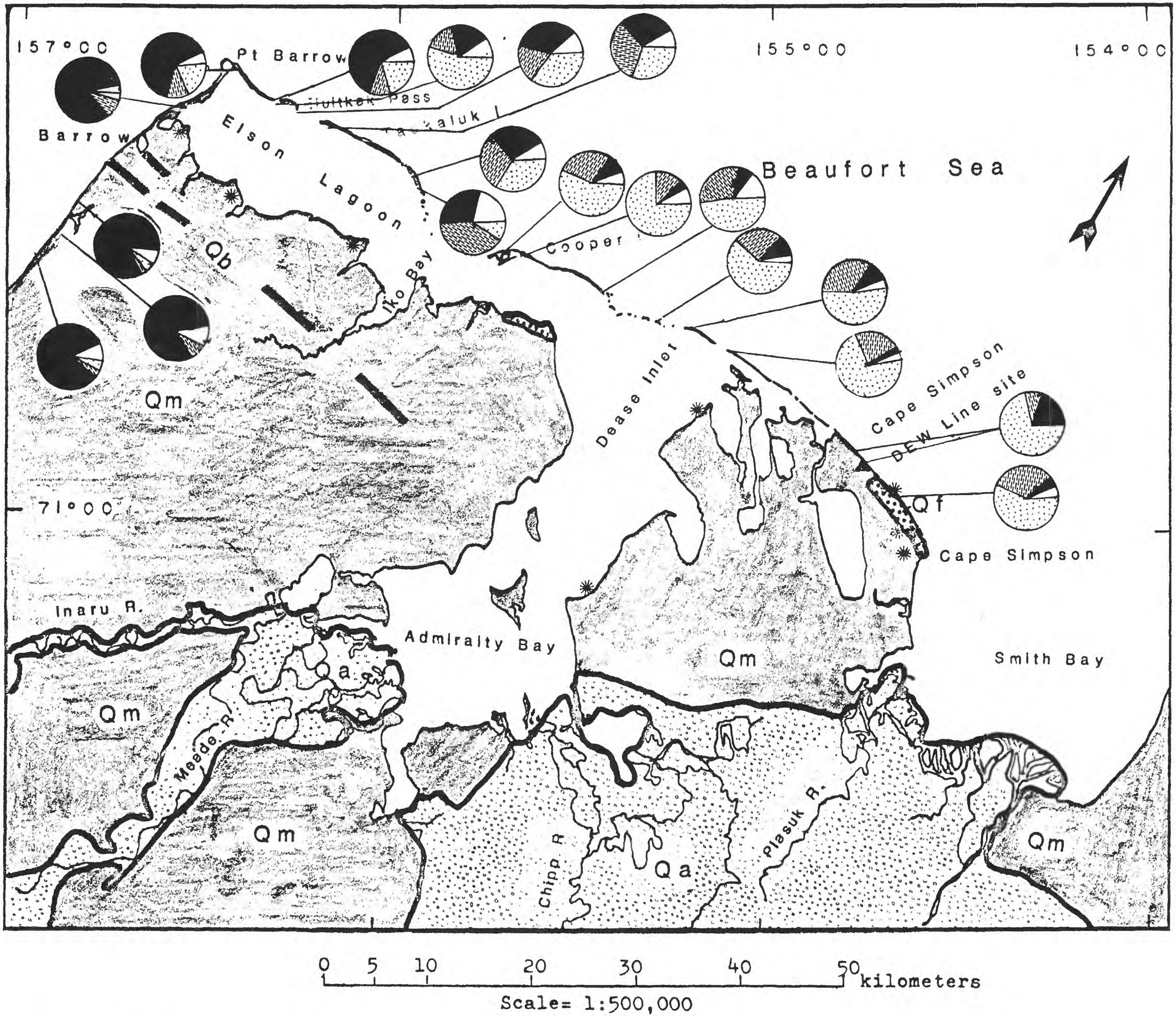
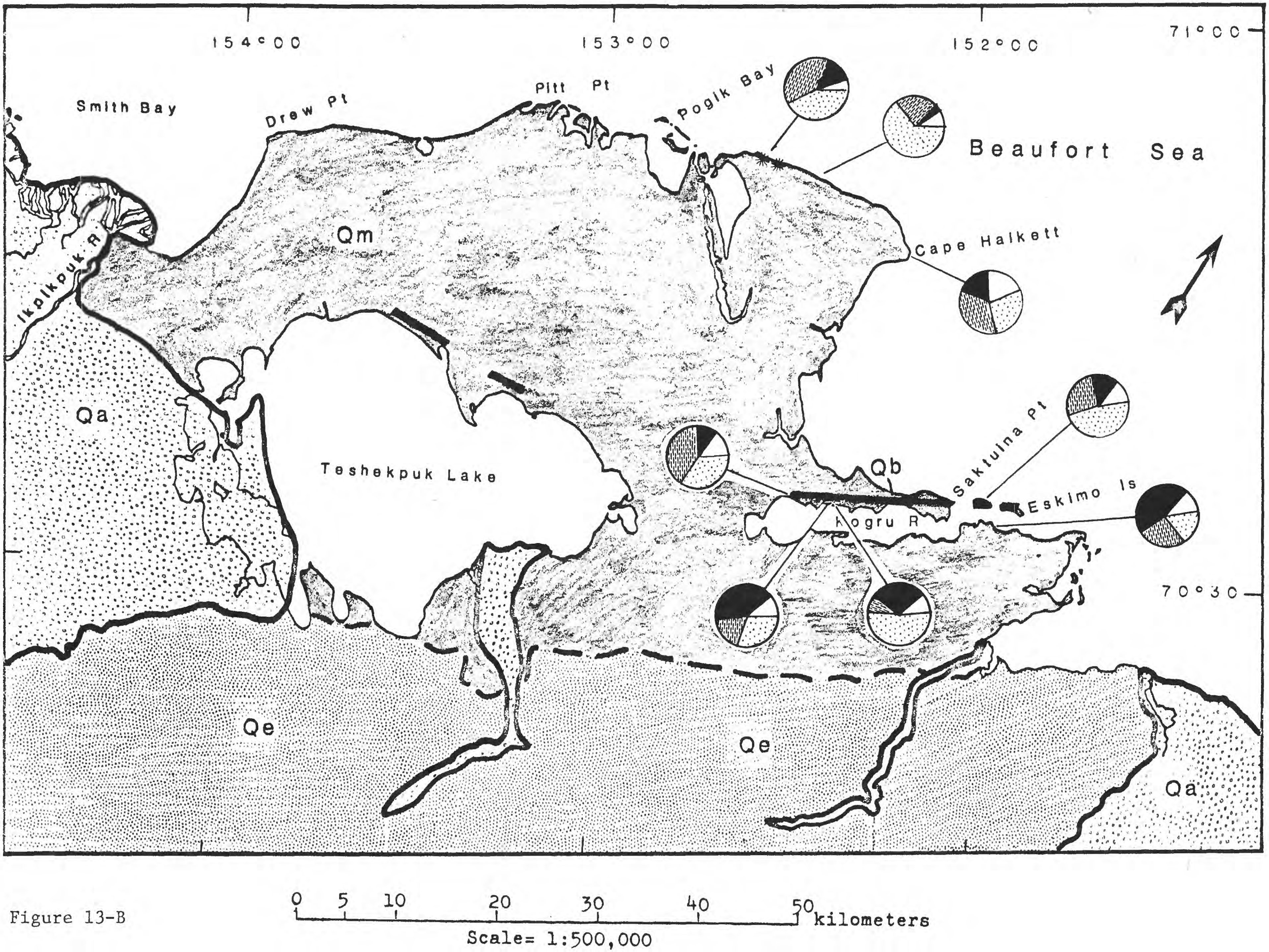
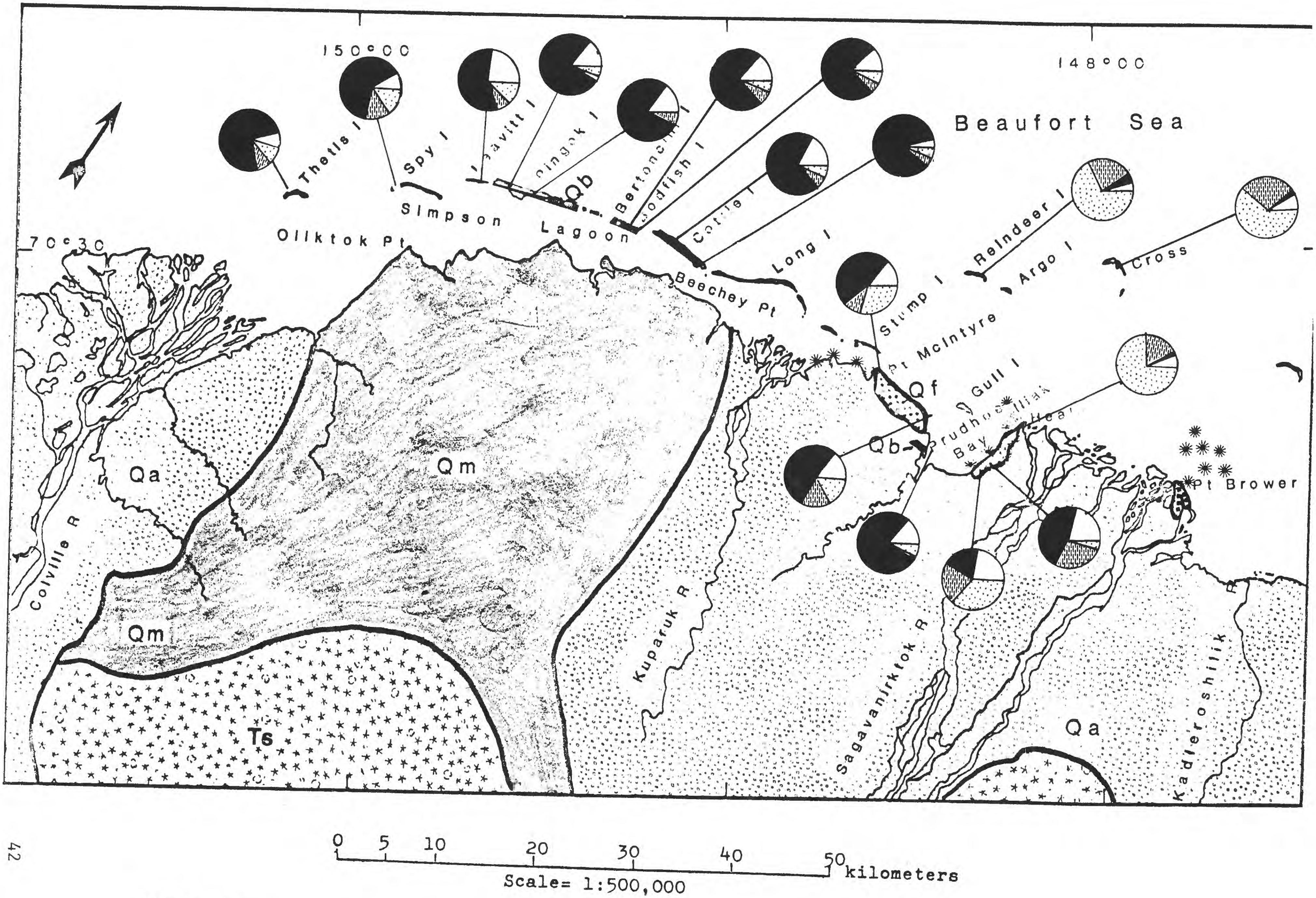

157°00
155°00
154°00
71°00
Pt Barrow
Barrow
Elson
Lagoon
Iko Bay
Cooper I
Beaufort Sea
Dease Inlet
Cape Simpson
DEW Line site
Qf
Cape Simpson
Qb
Qm
Qa
Inaru R.
Meade R.
Admiralty Bay
Chipp R.
Piasuk R.
Smith Bay
0 5 10 20 30 40 50 kilometers
Scale= 1:500,000

Figure 13-A



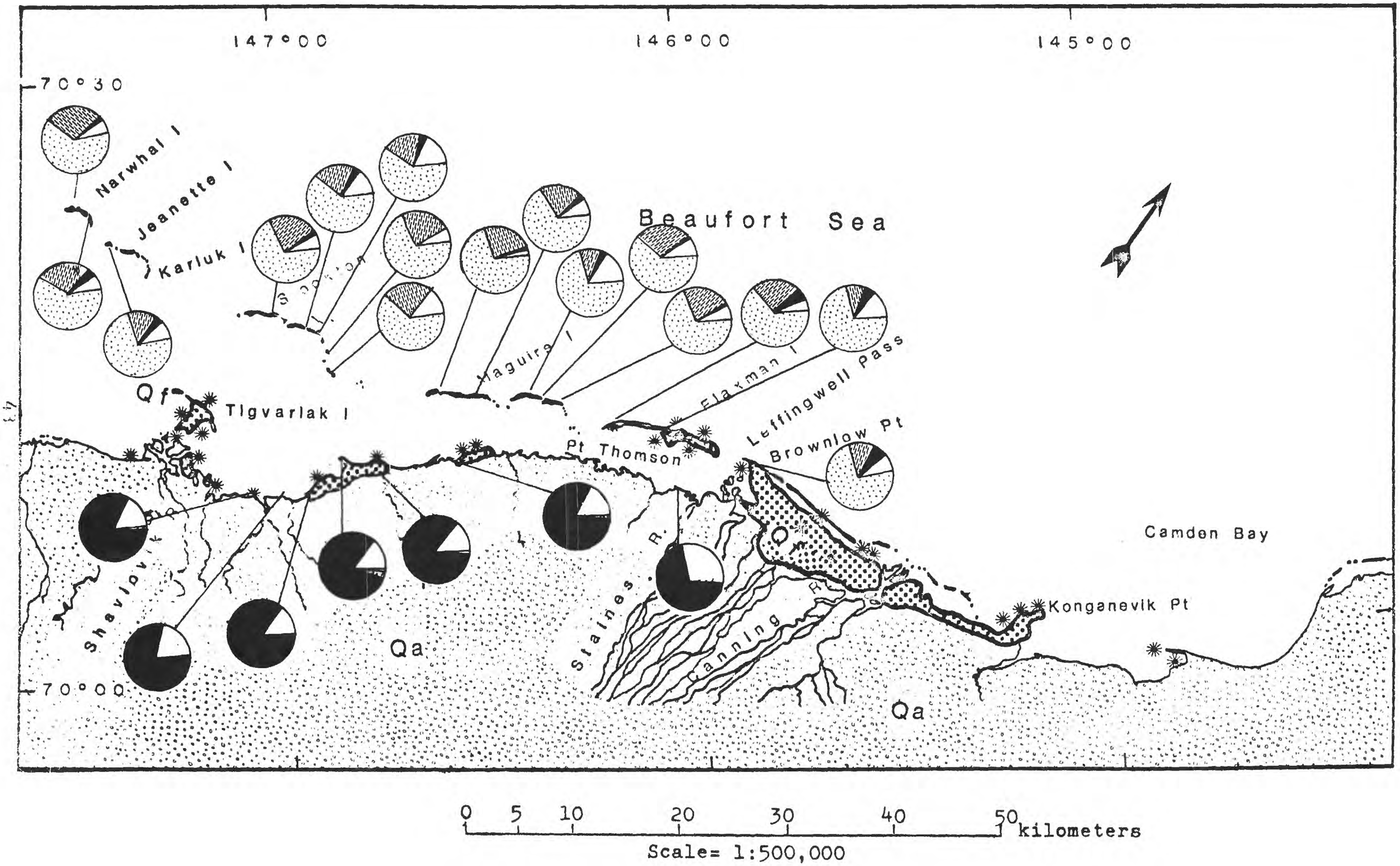
154°00
153°00
152°00
71°00
70°30
Smith Bay
Drew Pt
Pitt Pt
Pogik Bay
Beaufort Sea
Cape Halkett
Ikpikpuk R
Qm
Qa
Teshekpuk Lake
Qb
Saktuina Pt
Eskimo Is
Kogru R
Qe
Qe
Qa
0 5 10 20 30 40 50 kilometers
Scale= 1:500,000

Figure 13-B



150°00
148°00
70°30
Beaufort Sea
Thetis I
Spy I
Simpson Lagoon
Oliktok Pt
Qb
Bertoncini I
Codfish I
Cottle I
Long I
Beechey Pt
Reindeer I
Argo I
Cross
Stump I
Pt McIntyre
Gull I
Qf
Qb
Prudhoe Bay
Pt Brower
Qa
Qm
Ts
Colville R
Kuparuk R
Sagavanirktok R
Kadleroshilik R
0 5 10 20 30 40 50 kilometers
Scale= 1:500,000

Figure 13-C



147°00
146°00
145°00
70°30
70°00
Beaufort Sea
Narwhal I
Jeanette I
Karluk I
Maguire I
Flaxman I
Leffingwell Pass
Brownlow Pt
Pt Thomson
Tigvarlak I
Qf
Qa
Shaviovik
Staines R.
Canning R.
Konganevik Pt
Camden Bay
0 5 10 20 30 40 50 kilometers
Scale= 1:500,000

Figure 13-D

chain (figs. 13C and 13D) is entirely derived from the Flaxman Formation. In this island chain, coarse gravel with large cobbles is found on not only on Flaxman Island but also on westernmost Jeanette, Narwhal, and Cross Islands, while the islands between Flaxman and Jeanette Islands, as well as Reindeer and Argo Islands at the western end of the chain are composed of much finer material. It is notable that the core of Flaxman Island consists of Flaxman Formation and that widely distributed lag gravel and overconsolidated silt and clay (Rodeick, 1975; Reimnitz and Toimil, 1977; Chamberlain and others, 1978) suggest that the Flaxman Formation crops out on the sea floor from Cross through Narwhal and Jeanuette to Karluk Island.

Gravel in the central island chain (fig. 13C) consists mostly of Brooks Range pebble types with a 10 to 25% admixture of Flaxman lithologies. The Pleistocene beach gravel that forms the cores of several islands in the central part of the chain is a similar mixture. There is little difference in coarseness of gravel from one island group to another, but the coarsest gravel on strongly arcuate Spy and Thetis Islands is found at the northern, trailing edges of these islands.

Gravel lithology in the western chain (fig. 13A) differs from one island group to another, as a consequence of a series of stepwise changes at Ekilikruak and Eluitkak Passes. East of Ekilikruak Pass, Flaxman lithologies comprise more than 90% of the gravel, and it seems clear that this island group consists of material transported by westward beach drift from outcrops of Flaxman Formation near Cape Simpson. Between Ekilikruak and Eluitkak Passes, the gravel contains a 30% admixture of Brooks Range lithologies; and west of Elitkak Pass, Brooks Range lithologies make up more than 60% of the gravel.

It is clear that the major passes within the Beaufort Sea island chains are barriers to sediment transport and serve to isolate the different island groups from one another. Barnes and others (1977c) concluded, for example, that "various types of evidence indicate that Cross Island is not receiving gravel from an outside source". The arc- or bow-shape of the island groups and their frequent terminations in compound recurved spits confirms that the passes are sediment sinks, not sediment transmission belts. Further confirmation comes from the observation by Reimnitz and Toimil (1977) that the deepest part of Leffingwell Channel is floored with compact, current-scoured mud, not sand and gravel, and that Flaxman boulders litter the bottom of the pass east of Karluk Island and from our observation that relative proportions of Brooks Range and Flaxman pebble types change in stepwise fashion across two passes in the western island chain. Some of these observations come from passes that seem to be nowhere deeper than 2.5 m, indicating that sediment cannot bypass a trough deeper than 2.5 m in this low-energy sea.

Several additional lines of evidence demonstrate that the island chains are not unified sediment-transport systems, but rather that many of the island groups have or once had their own sediment sources. The presence of gravel on Jeanette, Narwhal, and Cross Islands much coarser than the gravel comprising islands that lie eastward and updrift establishes that a source of sediment lies or once lay somewhere seaward on the continental shelf. The eastern islands within the Plover chain are or once were fed from the bluffs east of Cape Simpson DEWLine Station, while the peninsula leading from Eluitkak Pass to Point Barrow may be fed by sediment moving northward up the Chukchi Sea coast and eastward around Point Barrow, but the islands between Eluikrak and Eluitkak Passes differ enough to indicate that they originated from a sediment source that has now disappeared. Leavitt Island, in the central part of the central chain, is obviously fed by the erosion of Pingok Island and other Pleistocene remnants that lie eastward and updrift, but Long, Egg, and Stump Islands lie still further updrift and must have originated from a different source. Thetis and Spy Islands, like Cross Island, seem to "represent the dying phase of the barrier island system off northern Alaska" (Barnes and others, 1977c) and to be drifting southwestward from sources that have longsince disappeared.

The island passes themselves seem to be of diverse origin. Our study of Flaxman Island establishes that the Leffingwell Channel is the site of a former distributary of the Canning River which was drowned by rising sea level at some time within the last few thousand years.[4/] Other passes have probably originated in similar manner.

[4/] Holocene thaw-lake deposits on eastern Flaxman Island are overlain by a wedge of wind-blown sand which thickens eastward to about 4 m at the west shore of Leffingwell Channel. There is no present-day source for this wind-blown sand, but similar wedges are actively accumulating along the west banks of the broad channels of all of the major streams draining northward from the Brooks Range to the Beaufort Sea. Reimnitz and Toimil did not find alluvial gravel during their dive in the deepest part of Leffingwell Channel. Evidently the original river channel lay further east, beneath the area now occupied by the spit that extends westward from Brownlow Point.

Still others may originally have simply been low areas between Pleistocene hillocks. Some of the deep passes, however, may have originated much more recently as breaches formed in a low-lying bar during a storm surge which were subsequently deepened by winter and summer tidal scour to the point where sand and gravel could no longer bypass them.

We conclude that despite their superficial resemblance to barrier chains, the island chains of the Beaufort Sea are of much more complex origin.

The constructional area of Flaxman Island is, indeed, fed by coastal drift of sediment eroded from the Pleistocene remnants that form the island core. The Maguire Islands and possible the Stockton Islands may originally have been westward continuations of this barrier chain which became isolated as a result of storm-breaching and tidal deepening of intervening channels; if this speculation is correct, then Flaxman Island would have once been a much larger and more adequate source of sediment.

Karluk, Jeanette, and Narwhal Islands, however, seem to be lag deposits resulting from the erosion and eventual destruction of areas of Flaxman Formation that are now preserved only as outcrops of Pleistocene sediment on the sea floor. Ice-push may continue to add new coarse material to the seaward beaches of these islands. Cross Island originated from another area of Flaxman Formation, as did Reindeer and Argo Islands, but Reindeer and Argo Islands have migrated at least a kilometer or more landward from areas of boulder-littered sea floor suggestive of outcrops of Flaxman Formation (Rodeick, 1975).

The central chain of islands originated by erosion of a row of hillocks representing a Pleistocene island chain. Erosion has completely destroyed the original hillocks that were the source of the eastern islands and western islands in the chain. The source hillocks for Spy and Thetis Islands disappeared many centuries ago and these two islands have subsequently moved several kilometers landward from their initial positions.

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

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

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