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A Review of Beach Nourishment From Ice Transport of Shoreface Materials, Beaufort Sea, Alaska

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ABSTRACT

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Ice encroachment onto land occurs mainly during the period of complete ice cover and takes two basic forms, both of which are associated with sediment transport to differing degrees. In ice ride-up, unbroken sheets slide over frozen to shallowly thawed beaches or barriers for distances from 1 to over 100 m, supplying to the beach sediments from the very shallow (<1.5m) shoreface but scraping into mounds mainly loose subaerial debris. In ice pile-up, the advancing sheets crumble, building rubble piles up to 20 m high that commonly contain a few percent of intermixed sediment entrained from as much as 50 m seaward and 5 m water depth; we hypothesize a likely entrainment mechanism of down-flexing of the thin (<.5m) floating ice sheet, of breaking at bottom contact and mixing with sediments, finally followed by extrusion of the mixture through the growing pile. The sediment contained by the ice settles onto the substrate within one to several summers of melting, forming melt lag deposits as opposed to the above push mounts. The lag mounds, usually within 20 m of the shoreline, may be 2 m high, and may add one m^3 of sandy gravel to each meter of coast line per pile-up.

Ice can stack sediments well above the elevation reached by waves, but in most areas the shoreline is receding fast relative to the recurrence rate of ice encroachment (~10yr), and the characteristic ice morphologies are shortlived. The materials added to beaches and barriers by ice encroachment remain, and are seen in barrier island pebble lithology and pebble size, pointing to offshore rather than alongshore sediment sources.

A stable barrier island we investigated apparently was elevated by repeated ice stacking to the unusual height of 4 m, as opposed to the 1–1.5 m height of wave-dominated barriers. A possible recent decrease in the rate of ice stacking versus wave reworking, or increased fetch, is seen in several other high, but rapidly disappearing barriers capped by coarse gravel to cobbles. Such a possible change in balance between the two processes may be related to a retreat of the summer ice edge during the last century. Recognition of wave- versus ice-dominated barrier islands should be possible along much of the circum Arctic Ocean shoreline, and may provide information about extent and severity of sea ice in the past or changes occurring today.

ADDITIONAL INDEX WORDS: *Ice push, ice shove, ride-up, pile-up, ice gouging, polar beaches, sediment supply, Arctic barriers, beach morphology, sea ice, northern Alaska.*

INTRODUCTION

Recent analyses of Beaufort Sea coastal processes pointed out that long stretches of Arctic shores retreat eight times faster than similar coasts that are ice-free, and showed that published littoral transport volumes, based on wave theory, are much too low to move the sand-size sediment thus released (REIMNITZ *et al.,* 1988; REIMNITZ and BARNES, 1987; REIMNITZ and KEMPEMA, 1987). These recent studies also suggest a fallacy in attributing a protective role to ice of polar seas, as has been done previously (for example ZENKOVICH, 1967, p. 170; SHORT, 1979). Ice, in fact, bulldozes, mobilizes, resuspends, and rafts sediments, although the processes have not been qualified largely because ice destroys any instrumentation deployed along ice-stressed coasts. A consequence of hostile conditions and a resulting lack of knowledge, for example, is that the Corps of Engineers' 2-volume Shore Protection Manual (U.S. ARMY, 1984) devoted only 2 pages to certain descriptive characteristics of coastal ice itself, and totally ignores the multitude of ice-related coastal processes. REIMNITZ and BARNES (1987) discuss qualitatively various means by which ice, either directly or indirectly, may augment shoreface and shoreline erosion. In the present study, we evaluate available information on the opposite effect of ice, that of beach nourishment.

Beach nourishment has long been recognized in the form of "ice-push gravel mounds and

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ridges" on high latitude beaches and coastal plains. REINHARD (1967) discusses names used for such ice produced mounds and ridges, and particularly mentions POHLE's (1922) use of the term "korga shore" (from Russian) for one marked by ice-supplied deposits. We discuss the processes forming these mounds and ridges, and show, with the aid of several case studies, the distance to and water depth of the offshore source areas. We also discuss how, under suitable conditions, the repeated addition of "ice-push mounds" results in unusual crestal elevations of barrier islands, and leaves its imprint on island chain lithologies and grain-size. We do not provide a thorough review of the abundant literature on ice-pushed coastal deposits (for example ALESTALO and HÄIKIÖ, 1976; CROASDALE, METGE and VERITY, 1978; DAVIS, 1973; GILBERT and GLEW, 1986; HARPER and OWENS, 1981; KING, 1969; NICHOLS, 1961; OWENS and McCANN, 1970; WISEMAN *et al.*, 1973; or the numerous publications of DIONNE *et al.*, *e.g.* 1972, 1978, 1979, 1988). The present study is largely restricted to cases from the Beaufort Sea, and to selected reports from elsewhere that may shed light on (1) mechanisms of shoreward sediment transfer and (2) elevating barrier islands by ice action above normal wave-washed forms.

Criteria for the recognition of old, high, ice-dominated barrier islands as opposed to low wave-washed forms prevalent today along Alaska's north coast should be applicable to circum-Arctic Ocean coastlines in general. Their study should lead to knowledge of past sea ice extent and severity, and an understanding of how future climatic warming may affect shorelines and coastal habitats in the Arctic.

SETTING

The low, gently sloping, and flat coastal plain of northern Alaska meets the Beaufort Sea typically in 3-m high, permanently frozen bluffs undergoing surficial summer thaw to depths of only about 0.2 m (REIMNITZ *et al.*, 1988; BARNES *et al.*, 1988). The bluffs are composed of mixtures of sand and finer material, with a very high organic content but almost no gravel. Coastal bluffs are commonly fronted by 1-m high, 10-m wide sandy gravel beaches. Several chains of barrier islands, 1–1.5 m high, also composed of sandy gravel, occupy 55% of this coast (SHORT, 1979) (Figure 1). Beaches and barrier islands, ice bonded in winter, thaw to only 1 m depth during summer (OWENS and HARPER, 1977). The shoreface also becomes ice bonded within the 2 m range of seasonal sea ice growth and only thaws to shallow depths during summer. While the normal tide range is only 10 cm, the 1-m-high barrier islands are commonly awash during storms accompanied by wind set-up, and therefore are dominated by overwash deposits (Figure 2). More extensive reworking occurs during major storm surges with a recurrence interval of 100 yrs, when sea level is elevated by as much as 3.5 m (REIMNITZ and MAURER, 1979a). The ever-present pack ice results in short summer fetches and low wave energy (NUMMEDAL, 1979), the marine energy to which traditionally coastal modifications or damage are attributed. Generally, for 9 months each year all motion in the coastal zone is totally arrested by a cover of immobile fast ice draped by drifting snow. In spite of this, the beaches and coast are retreating about 2 m/yr (REIMNITZ *et al.*, 1988), and many of the barrier islands are displaced southwestward at rates of 6 to 8 m/yr (for example, REIMNITZ and KEMPEMA, 1982).

Breakup and freezeup are the most dynamic periods for coastal encroachment by sea ice (KOVACS and SODHI, 1980). At these times, the land surface or shallow subsurface at the coast is commonly ice bonded, and is thus armored against deep bulldozing action by ice. The fact that landward thrusting sea ice can transport sediment to elevations not reached by waves has been observed along both inland waters and sea shores, as discussed later. No relative sea level changes affect the preservation of ice-encroachment scars in the study area (REIMNITZ *et al.*, 1988), in contrast to rapidly rising areas in parts of northern Canada (for example, KING, 1969).

BACKGROUND INFORMATION AND OBSERVATIONS

The occasional encroachment of ice onto land and its potential hazard to living things in the coastal zone has long been experienced and reported. The following descriptive account of ice closing in against the coast in the Beaufort Sea by STOCKTON (1890, p. 183) gives a good impression of nature's forces at work and

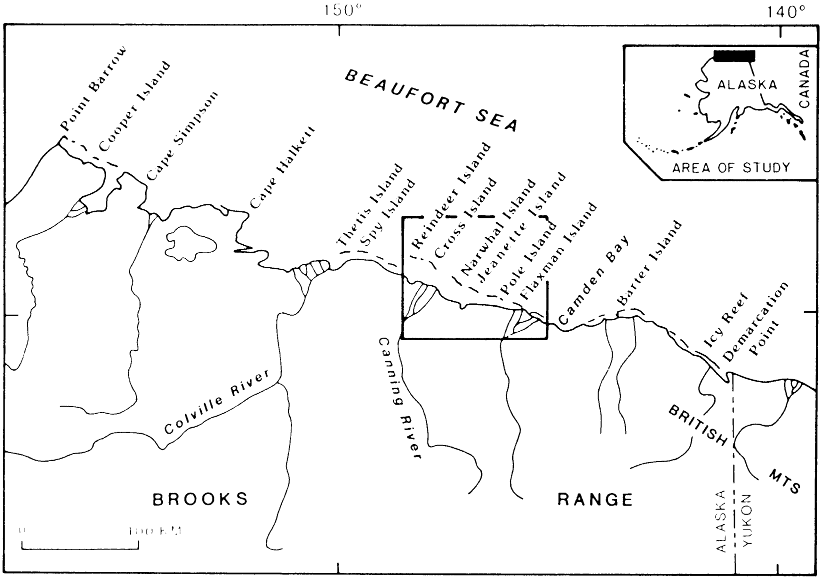

Figure 1. Location map of study area, with a box outlining the area of Figure 22.

implied sediment transport in this process: "Sometimes a long line of heavy floe-ice from the pack grounds in the shallow water near the shore during northerly winds, pressed from behind by the force and weight of the entire northern pack. It is gradually forced up, ploughing its way through the bottom, at the same time rising gradually along the ascent of the bottom toward the land. The effect of this solid wall of cold and relentless blue ice slowly rising and advancing upon those imprisoned between the ice and the shore (sailors) is one of the most sublime and terrible things that can be experienced."

In this section we review pertinent published information and our own observations necessary to provide the background for an evaluation of how ice encroachment onto land contributes sediment to beaches and islands, and how important this may be for littoral processes and the make-up of barrier islands.

Processes

A distinction is made between (1) ice ride-up and (2) ice pile-up in recent studies of the effects of sea ice encroachment onto land along the Alaskan coast (KOVACS, 1983, 1984) and global synopses of the phenomenon (KOVACS and SODHI, 1980; SODHI and KOVACS, 1983; and KOVACS and SODHI, 1988). The following description of the two mechanisms is largely based on work of these two authors. They review observations on the actual process of ice encroachment onto land, accompanied by surficial scraping and gouging, and by bulldozing of sediments ahead of the leading edge, and present accounts of the formation of pile-ups from the inhabited areas near Point Barrow, and a formerly inhabited area near Cape Halkett (Figure 1).

(1) Ice ride-up is the process in which a sheet of ice slides smoothly landward across a low-relief beach and steeper-relief areas beyond for distances as great as 800 m, but generally much shorter. Such sheets of ice generally conform to the land surface (Figure 3), starting from the submerged, sloping ice contact with the beach face. Ride-up is most likely to occur during the early ice-growth period, when the original submerged bottom contact and the subaerial surfaces transgressed are ice bonded. Ride-up also occurs in spring, when surficial ground-thaw has begun, and the bottom-fast ice has thinned to about 1.5 m and lifted free of the shoreface (for example, SHAPIRO *et al.*, 1984). In the Canadian Arctic Archipelago, shore ice ridging and encroachment is reported to occur in sum-

Figure 2. View north along lightly snow-covered, overwash-shaped surface of a rapidly migrating part of Cross Island. Observed over 15 years, a so-called ice push mounds are formed every 2–3 years here, but do not survive. Dark objects in 5-m wide white zone on right are pieces of brash ice on the active beach. (Photo E. W. Kempema).

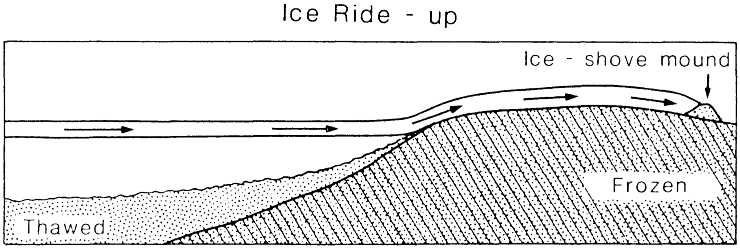

Figure 3. Ice commonly slides or scrapes over frozen ground in a ride-up. This results in true ice-shove mounds or ridges of mainly subaerial materials at greatly varying distances from the shoreline, sometimes even on lagoonal ice beyond a barrier island.

mer (TAYLOR, 1978). As documented below, however, summer ice encroachment so far is unknown for the study area.

(2) Ice pile-up is accompanied by buckling and crumbling of an advancing sheet of ice. The process may start in the vicinity of the tidal crack existing along the boundary between bottom-fast ice and floating fast ice. This ice failure then results in growing piles of broken ice, while the zone of failure moves progressively seaward into deeper water. Like ride-up, ice pile-ups also occur mainly in fall and less often in spring. The ice consumed in the building of rubble piles therefore is most commonly thin (<.5m), relatively undeformed and floating seasonal ice, moving nearly normal to shore. Important for the model developed later for shoreward sediment transfer by pile-ups, such undeformed, floating first-year ice rarely contains sand or coarser material. A cross section of a pile-up is shown in Figure 4. The internal structure and morphology of such a pile-up, and published reports of the mechanism (KOVACS and SODHI, 1980, among others), suggest that the pile grows by alternate ice-rubble production and by upward sliding of intact sheets that eventually break at the crest and tumble down on the landward and seaward face. Ice rubble piles may grow to over 20 m high, 10 to 30 m wide, and most of the ice comes to rest on and sometimes partly seaward of the beach. During the melting of such piles, thickening surficial drapes of sandy gravel form. After one or two summers, gravel mounds commonly as high as 2 to 4 m (KOVACS and SODHI, 1988), but possibly even 18 m high (NICHOLS, 1953) mark the former pile-up site. Despite the numerous detailed published discussions of pile-ups, the question of how sediment is excavated and brought ashore during the process, so important for our study, has never been raised.

In both ice ride-ups and ice pile-ups the

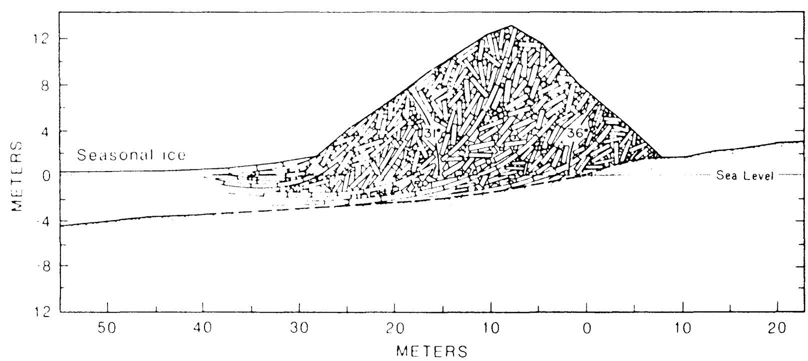

Figure 4. Conceptual cross-section of a pile-up, modified after Kovacs and Sodhi (1980). How sand and gravel is incorporated into such piles has never been addressed, even though it constrains the model.

encroachment is usually caused by extensive stretches of wind-driven pack ice, as noted long ago by Stockton (1890). The maximum keel depth of the pack is sorted to some extent by water depths across the continental shelf, so that scattered, grounded floes may occur across the width of the entire shelf. For this reason, the shoreward thrust of the pack is accompanied by ice gouging at a high angle to the coast. Such an event is shown by sonographs in Figure 5, which according to BARNES and SHAPIRO (*written communication,* 1988) are thought to record a shoreward ice movement of 250 m near Barrow (Figure 1). This resulted in as much as 20 m ride-up on the nearby beach in early July 1975, while the main portion of the thrust was taken up by offshore ice deformation (SHAPIRO *et al.,* 1984). Each individual ice keel that gouged shoreward in Figure 5 resulted in shoreward sediment displacement extending landward onto the beach, as discussed below. However, gouges are not seen in the nearshore region on these sonographs. This is one of many examples from our work with side-scan sonar, even under optimum conditions without ice obstacles and calm seas that this tool is unsuccessful to delineate ice-produced relief adjacent to the beach where ice had been thrust ashore. The primary reasons are (1) the coarse granular, and non-cohesive nature of shoreface materials which do not retain ice-produced shapes very well, (2) the short time required for obliteration of relief by currents and waves in very shallow water, and (3) the normal difficulty of defining morphologies by side-scan sonar on steep slopes blanketed by coarse material with high acoustic reflectivity.

Timing

Ice pile-up and ride-up, although frequent on a regional scale, are unpredictable for any particular site, and may be likened to a 50-year flood (SODHI and KOVACS, 1984). In the case of pile-ups, the event requires only 15 to 30 minutes at most, whereas ride-ups may proceed slowly for longer periods of time. After melting, such ice incursions commonly leave either gouges, striations, or "ice-push mounds and ridges."

The fact that ice ride-up and pile-up in the study area is restricted to the period of almost total ice cover is documented by our own summer observations, outlined below. We must point out, however, that these summer observations represent conditions of open, exposed coasts bordered by shallow water in which ice runs aground. This is very different from the restricted, deep-water settings reported by TAYLOR (1978).

Since 1970, the authors and a colleague (R.L. Phillips), worked a total of 40 months in small coastal vessels, from shore bases with skiff support, and made many low level reconnaissance flights, between Point Lay in the Chukchi Sea and the Mackenzie Delta in Canada, a distance of well over 800 km. Our experiences include 1975, the worst ice year on record, when the presence of coastal ice prevented shipping to the Prudhoe Bay oil field. These observations cover the period between July 10 and October 10. During this so called "open water season" loose pack ice almost always clutters the inner shelf. We therefore usually transit between different work areas by keeping within several hundred meters of beaches and barrier island chains. These transits permitted observations of long stretches of coastline on a daily basis. Night- and storm-anchorages are found in the shelter of low spits and gravel islands, as ice floes almost always are held by wind and waves against the seaward beaches within a hundred meters or so of the vessel. During these summer months we have commonly seen new evidence for recent ice encroachment, but never for summer encroachment.

Our direct observations of the lack of summer ride-up and pile-up are supported by many months of time-lapse photography during the summers of 1972, '79, '80, '81, '82, '83, and '85, covering seaward-facing beaches between Thetis and Narwhal Island (Figure 1). In these studies we have focused up to three cameras concurrently on vulnerable stretches of coast, in anticipation of summer ice encroachments. Not a single event has been recorded, but almost all storm scenes show ice floes wallowing on the shoreface. Thus, although heavy floe-ice is commonly seen pushed shoreward, as so vividly described by Stockton (1890), it is rarely shoved onto land during July, August, and September.

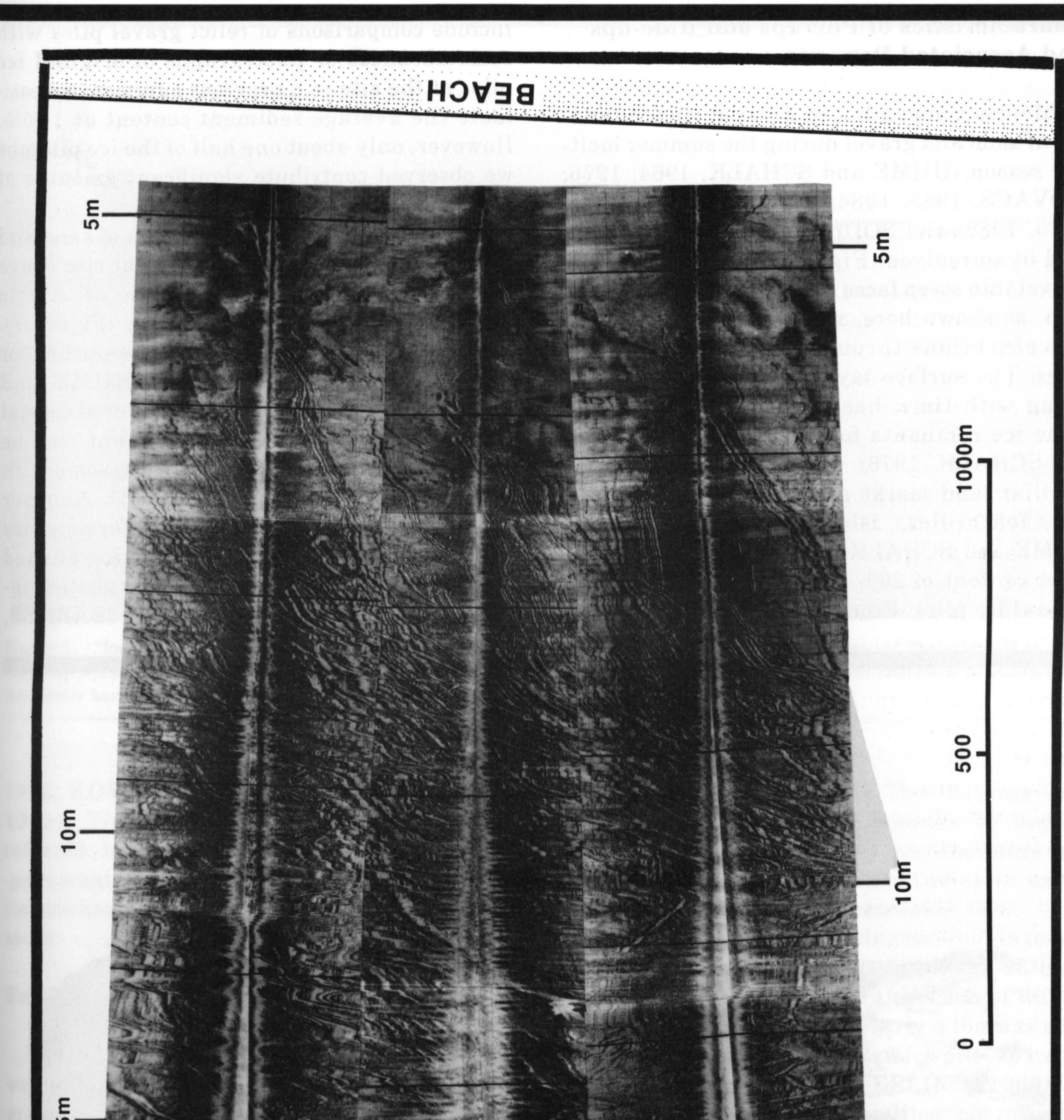

Figure 5. Extensive areas of polar pack thrusting ice and sediment onto land also bulldoze deeper shoreface and shelf sediment landward, as shown in this side-scan sonar mosaic from near Point Barrow in 1977.

Characteristics of Pile-ups and Ride-ups and Associated Deposits

Pile-ups commonly are covered with a blanket of sand and gravel during the summer melting season (HUME and SCHALK, 1964; 1976; KOVACS, 1983, 1984; KOVACS and SODHI, 1980, 1988; and SODHI and KOVACS, 1984), and by ourselves (Figure 6). Probing with a shovel into steep faces cut by summer wave erosion, as shown here, reveals uneven sediment concentrations throughout such covered ice piles. The surface layer, progressively thickening with time, has been noted to preserve some ice remnants for several years (HUME and SCHALK, 1976). Such major piles become familiar land marks and radar targets on the low, featureless island chains (Figure 7). HUME and SCHALK (1964) measured a sediment content of 20%, by coring the interior of several ice piles. From our observations, which include comparisons of relict gravel piles with remembrances or photographs of original ice piles at the site in a previous summer, we estimate the average sediment content at 1–5%. However, only about one half of the ice pile-ups we observed contribute significant amounts of sediment to the area they occupy.

The irregular mounds and ridges of sand and gravel are conspicuous features that rise above the otherwise smooth surfaces of Arctic beaches, spits, and barrier islands (Figure 7). They have been called ice-push, ice-pushed, or ice-shoved mounds or ridges (HUME and SCHALK, 1964). On the tundra-covered coastal plain, the limit of ice encroachment may be marked by ice-push tundra mounds, some with rotten driftwood (KOVACS, 1983). Another variation from the more common forms of ice push deposits is the 300-m long ice-pushed boulder ridge along the Camden Bay shore (Figure 1), described by several workers (BARNES,

Figure 6. From a distance (note two mounds in background), pile-ups look like mounds of sand and gravel. The mounds actually consist mainly of ice with interspersed sand and gravel throughout. During melting, sand and gravel settles vertically onto the beach surface, forming the so-called "ice-push mounds or ridges." Thetis Island, 1982.

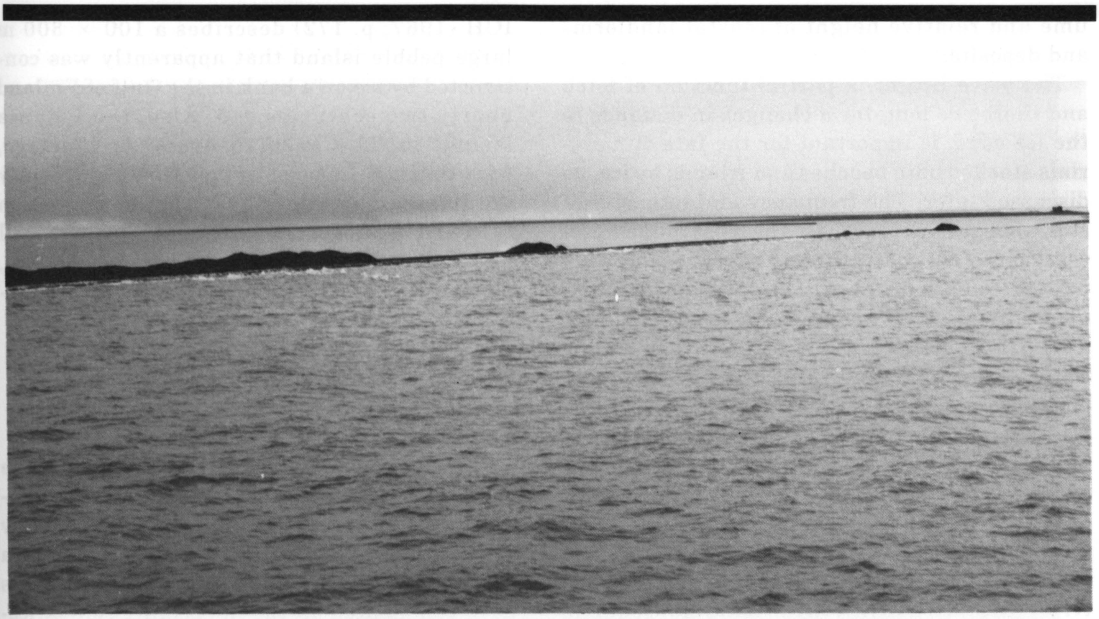

Figure 7. "Ice push mounds," better called ice-melt lag, constituted a large percentage of the volume of Thetis Island in 1982, but were winnowed and obliterated by fall storm-waves. Much of the gravel supplied by ice from the shoreface is incorporated into arctic barrier islands by alternating pile-ups and overwash.

1982; KOVACS, 1983; KOVACS and SODHI, 1988). This boulder-ridge, elsewhere also referred to as boulder-rampart, -barrier, or -pavement, is unique in the Beaufort Sea and its mechanism of formation is not well understood.

Factors Controlling the Fate of Deposits

When formed within the reach of storm waves, even 1-m high ice-produced sand-and-gravel ridges are smoothed out in a matter of hours (SCHALK and HUME, 1961). This smoothing, however, is not equal to removal of ice-supplied sediment, but may lead to increased beach elevation. HUME and SCHALK (1976), working mainly in the proximity of Point Barrow, report the largest mounds (over 2-m high) on Cooper Island (Figure 1), sometimes forming ridges over 50-m long as much as 100 m from the seaward beach. They further report that the youngest mounds are nearest the beach, and the oldest at the greatest distance (HUME and SCHALK, 1964). HOPKINS and HARTZ (1978) also report "ice-push ridges" as much as 2.5 m high and 100 m inland from the seaward beaches on Narwhal and Cross Island (Figure 1). This distance from the shoreline places such mounds far beyond the reach of waves, and they may therefore survive for decades or even centuries in areas where the rate of coastal retreat is slow.

Ice also is capable of raising sediments to elevations above the reach of waves, and of forming deposits inland beyond the reach of waves. Thus, a boulder weighing nearly a ton was seen 9 meters above sea level in an ice pile-up in the eastern Baltic Sea (KEYSERLING, 1863). In addition, ice has no difficulties mounting a 10-m high coastal bluff (KOVACS and SODHI, 1980). Gravel draped over tundra and over an archaeological site, at elevations up to 10 m near coastal bluffs south of Barrow (Figure 1), originally was believed to have been deposited there by storm-wave run-up over a previously formed ice ramp (DUGUID, 1971). KOVACS and SODHI (1988), however, report a recent thrust which directly laid gravel on top of a 5-m high bluff in the same area. The latter mechanism seems to us a more likely explanation for the elevated gravel deposits first reported by DUGUID (1971). The deposits could, under suitable conditions such as isostatic rebound, permanently increase the volume and relative height of coastal landforms and deposits.

The wave height, a partial function of fetch and therefore long-term changes in distance to the ice edge, is important for the fate of materials stacked onto beaches and islands by ice, as discussed later. The frequency and intensity of storm surges, however, are the most immediate, critical factors controlling the fate of materials put by ice onto beaches. The 1970 storm surge along the Alaskan Beaufort Sea coast, reaching a height of 3.5 m, was associated with conditions conducive to reworking the crests of some of the highest barriers in the study area (REIMNITZ and MAURER, 1979a). That type of surge, however, is likely to occur only once every hundred years, and therefore ice deposits above an elevation of 3 m are likely to persist for a long time. Surges reaching heights of 1–2 m seem to occur at least every decade (REIMNITZ and MAURER, 1979a, and subsequent field observations by the authors). Therefore, hummocky deposits made by ice at elevations of less than 2 m are likely to lose their identity quickly, but probably are not lost entirely from the beaches by these normal beach processes.

The grain size of shoreface materials thrust onland by ice is also very important in controlling their ultimate fate. No lag remains after storm overwash, and therefore there can be no net accretion or island construction where only fine grained sediment is transported onto low beaches by ice (Figure 8). As an example, the coast and inner shelf west of Cape Halkett (Figure 1) are composed of very fine grained sediments (REIMNITZ *et al.,* 1988). Here beaches are scant and no major island chain exists, although major ice incursions occurred there several decades ago and again in recent years (KOVACS, 1983, 1984). A series of elongated gravel bars, many of which rise above sea level, parallel the coast 250 to 1,000 m from shore (REIMNITZ and KEMPEMA, 1987). In 1984, surveyors located a small island of 'sticky clay' in the series of islets about 700 m from the nearest land, which apparently had been bulldozed by pack ice. All gravel islets were resurveyed the following year with little change, whereas the mud island had disappeared (REIMNITZ and KEMPEMA, 1987).

Many small islets apparently built by ice are found in subarctic lakes of Quebec (DIONNE, *written communication*, 1989), and ZENKOVICH (1967, p. 172) describes a 100 × 300 m large pebble island that apparently was constructed by ice on a bank in the Gulf of Finland nearly two centuries ago. Also, the Polynia Islands in the Canadian Arctic Archipelago, with unusual halos of gravel ridges, evidently are at least maintained by the bulldozing action of ice (HUDSON *et al.*, 1981), but may very well owe their origin to ice action. There is, however, no well-documented case history of island construction by ice.

The Nourishing Role of Onshore Ice Thrust

In the past, when boulders on beaches of the Baltic were blasted and hauled away for construction purposes, these were replenished by ice push (REINHARD, 1967), thus serving as a renewable natural resource. Various authors have commented on the nourishing role of ice-shove processes for high latitude beaches and barrier islands. As stated by SCHALK and HUME (1961, p. 2559), for example, "ice-shoved material makes an addition to the otherwise wasting beaches" in the Point Barrow area, and much later again by KOVACS (1983, p. 37): "Transport of offshore sediment onto the beach during shore ice movement appears to be a common phenomenon." HUME and SCHALK (1964) attempted to quantify the amount by measuring ice push-mounds on Cooper Island (Figure 1). They conclude that these at the time comprised 10% of the sediments above sea level but that a more typical figure for ice-push deposits in the beaches of the Barrow area was 11 or 22%. These authors also made the important observation that Barrow and Cooper Island receive ice push deposits over the majority of the beach almost every year, but that the deposits are temporary and are destroyed by the first storm. As pointed out earlier, wave reworking mainly destroys the identity of the mounds, but does not necessarily remove all of the material from the beach.

In two consecutive winters, 1981–1983, ice-push mounds and ridges dotted the surfaces of barrier islands extending from Thetis and Spy Island (Figure 1) eastward. From profiles measured in 1982 on Spy Island, one of us (J.H.) determined that at least 700 m^3 of coarse material was supplied by ice encroachment to a 350 m long stretch of the island. Material still ume and relative height of coastal landforms and deposits.

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In two consecutive winters, 1981–1983, ice-push mounds and ridges dotted the surfaces of barrier islands extending from Thetis and Spy Island (Figure 1) eastward. From profiles measured in 1982 on Spy Island, one of us (J.H.) determined that at least 700 m^3 of coarse material was supplied by ice encroachment to a 350 m long stretch of the island. Material still

Figure 8. Where only mud occurs on the shoreface and is transported by ice onto an island, subsequent overtopping and winnowing during storms will prevent net accretion. Photograph from western Camden Bay, with foot prints on lower right for scale.

incorporated within the ice pile-up at the time of measurement was not included. Figure 7 is a photograph of Thetis Island during mid summer 1982, when ice deposits in one area clearly comprised a significant portion of the islands' volume. The island again was converted to its normal, wave-washed appearance during the following fall storms. REIMNITZ *et al.*, (1988) estimated that a 42-km-long stretch of islands extending from Thetis Island eastward had received at least 1 m^3 of sediment per meter of shoreline through ice thrust after the fall storms of that same year. We note that, although these sandy gravel deposits may soon be winnowed and obliterated as recognizable morphological features, the gravel component may still contribute to the elevation of high storm berms on barrier islands and beaches.

McLAREN (1982), convinced of the gravel contribution by ice push to arctic beaches from his diving studies in the Canadian Arctic Archipelago, applied HUME and SCHALK's (1964) typical ice push contribution from the Barrow area to the entire Beaufort Sea coast. He estimated that the total volume of beaches will double through ice-shoved materials in 667 years (p. 4). HARPER *et al.*, (1985), in their study of the morphology and processes of the Canadian Beaufort Sea coast, speculated that the long, stable barrier islands of the western Yukon coast (Figure 1) receive their primary sediment supply through ice push from the nearshore.

Recognizing Coastal Ice Deposits?

Numerous workers have commented on the lack of ice-produced internal sedimentary structures, both in modern coastal deposits from ice-stressed environments (REX, 1964) and in ancient ones (TAYLOR and McCANN, 1983). As expressed by MARTINI (1980): "It is a common experience, and a rather annoying one, for geologists to realize that many ice-generated features observed on recent coasts are not readily recognizable in cross-sections of ancient deposits." This fact has made it difficult to properly evaluate the contribution of ice push to the sediment budget of coastal deposits after the surface-relief forms are smoothed by the sea. Possibly the only reliable characteristic to help identify high latitude beach deposits are (1) locally chaotic assemblages of all grades of sediments related to the former presence and melting of grounded ice (TAYLOR and McCANN, 1983), and (2) stratified beach sediments having distinct pods of material with distinct grain size distributions that are the result of erosion of a kaimoo (REINSON and ROSEN, 1982) or of anchor ice and ice-bonded sediments from the shoreface (REIMNITZ *et al.*, 1987).

DISCUSSION

The Mechanism of Landward Sediment Transfer

Our analysis of the mechanisms of sediment transport onto beaches by ice encroachment focuses on the two active processes in the study area: ride-up and pile-up. The processes that lead to the formation of so-called boulder ridges, -ramparts, -pavements, or -barriers, which may involve rolling and sliding, thereby concentrating cobbles and boulders in the littoral zone (for example GILBERT and AITKEN, 1981; BARNES, 1982), are of lesser importance here and will not be treated.

Sediment Transfer in Ride-Ups A growing sheet of sea ice riding up onto the beach in early or mid winter interacts mainly with ice-bonded surface sediments, including those in the narrow zone of pre-ride-up contact with the shoreface. From this narrow (3–5 m) zone, a layer of sediment frozen to the base of the wedge-shaped ice front is removed and transported up onto land (SHAPIRO *et al.*, 1984). Beyond this submerged contact zone, ride-up usually is only a surficial scraping process affecting the snow cover, a thin veneer of exposed and dry gravel, along with driftwood and other debris. A winter ride-up therefore results mainly in surface striations commonly terminating without substantial push ridges or mounds of sediment (Figure 9), and contributes little sediment from offshore. The push ridge of sediment will not be much higher than the ice-sheet thickness (50 cm) and, controlled by the angle of repose for coarse grained sediment, little under twice that wide at the base. The mechanism is shown schematically in Figure 3.

In a spring ride-up, the ice sheet typically has thinned from 2 m to 1.5 m by melting from the top and bottom, and therefore has lifted free of the bottom. The thin layer of sediment frozen to the base of the bottom-fast ice consequently has dropped back onto its former shoreface contact. By June 20 the beach surface has thawed to an average depth of 50 to 60 cm (OWENS and HARPER, 1977), whereas the shoreface may have thawed to only 20 cm. Thus, the advancing ice sheet could bulldoze onto shore a 20 cm layer starting from a water depth of 1.5 m. Once past the shoreline, the advancing ice sheet may bulldoze deeper into the subsurface. The mounds and ridges formed by spring ride-up may be over 2 m high, but are generally less than 1.5 m high and 3 to 4 m wide at the base. The deposits are composed mainly of subaerial material, including sticks, feathers, and vegetative debris. The resulting narrow and low push ridges, in either winter or spring ice ride-up onto land, most commonly come to rest within 20 m from the shoreline, infrequently as far as 50 m, and rarely 100 m inland, according to KOVACS (1983).

Sediment Transfer in Pile-Ups The mechanism of onshore sediment transfer seen in the abundant sediment in many pile-ups (Figure 6) has never been addressed, but certainly is very different from the simple sliding and bulldozing action in a ride-up. As will be seen, the term push-mound is misleading and obscures the mechanism of transport and deposition. One must consider the following facts when contemplating a mechanism for sediment entrainment into a pile-up that does not violate the conceptual cross-section in Figure 4 and similar ones published elsewhere: (1) buckling typically starts at the tidal crack, where the floating fast ice meets the bottom-fast ice, (2) buckling progresses from there seaward into deeper water as the rubble pile grows, (3) the floating ice sheet consumed in the formation of pile-ups contains no sand and gravel, (4) sediment is seen dispersed throughout the rubble pile, and (5) the continuous, concave-upward ice sheets, as shown in Figure 4, cannot disperse sediment throughout the pile. The suggested depression of the advancing ice sheets to over 2

Figure 9. Ice ride-up during winter faintly striates the ice-bonded island surface, but contributes little or no sediment to the island proper. Note the lack of push-ridges at the termination of 60-m long striae. Thetis Island, 1982.

m below sea level on the seaward edge of the pile in Figure 4 may hold the key to the question of sediment entrainment. The down-bending suggests to us that at this point ice rubble mixes with shoreface sediment and the advancing ice sheet pushes this mixture upward into the pile.

Several lines of evidence support this concept of downward bending of the advancing ice sheet by several meters, crumbling at bottom contact, and mixing with bottom materials before ascending upward into the pile. The supporting evidence is in form of field observations: of ice piles after the event, of a pile-up in progress, of observations of the interface between pile-ups and the sediment base, and of knowledge on the sediment source for pile-ups.

Numerous observations of pile-ups provide evidence that an ice sheet may be intruded into its own rubble pile and extruded from the top (for example KOVACS, 1984; HUDSON *et al.*, 1981). This mechanism was suggested in the pile-up depicted in Figure 4, prepared after KOVACS and SODHI (1980). KOVACS and SODHI (1988) present a photograph (their Figure 8) which shows that an ice sheet pushed up through its own, 8 to 10-m-high rubble, and note that the dirt in the rubble "was transported by ice having contacted the sea bed" (p. 117). Similar observations were made by DICKINS ASSOCIATES LTD. (1987, p. 19) in the Canadian Beaufort Sea, where the formation of a grounded rubble field was followed first by localized ice ride-up on the seaward side: "Eventually the resistance to further ride-up increased to the point where the advancing ice sheet was forced down into the seabed and extruded out the top in a dirty pulverized form." This pile-up occurred about 800 m from shore, at an approximate water depth of 5 m, suggesting downward deflection of 5 m. The most convincing evidence of this mechanism of subduction was presented by GRASS (1984) in a video movie of an ice pressure ridge formation in progress in Lake Erie at an approximate water depth of 20 m. The movie shows an extensive ice sheet, moving at a rate of 0.3 m/s against a growing ice rubble pile, being subducted under the pile, while ice rubble was extruded from the center of the pile. He reports that the water was turbid from the churning action of the ice sheet and that most blocks emerging were covered with silt and sand, suggesting mixing of ice and sediment at the lake-bed.

Very little is known about the ice/sediment interface below shore ice pile-ups, yet it is important for understanding not only sediment entrainment but the pile-up mechanism itself. Such interfaces were observed in early 1980 and again 1981 at small recurring pile-ups on Dinkum Sands, a gravel shoal midway between Cross and Narwhal Island (Figure 1). The pile-ups had formed from 20-cm-thick ice in early winter, at a time when the shoal is submerged by about 1 m and when the sediments presumably are thawed. A total of 6 excavations were made through the ice piles and penetrated between 30 and 53 cm into the frozen substrate. The gravelly substrate in all of these excavations contained large amounts of ice, ranging from gravel-size clasts, centimeter-thick layers, to 20-cm thick tilted slabs of pure ice. No decrease in ice content with depth into the substrate was observed. A representative sample of granulated ice and gravel collected 53 cm into the substrate from the wall of one of these excavations contained nearly 50% of ice by volume in excess of that occupied by loosely packed, saturated sediment after thawing. According to this evidence, moving ice sheets crumbling on bottom contact mix with sediments to a sub-bottom depth of at least one half meter, but possibly much deeper. KRAUS (1980) reported that some ice may remain buried in the substrate well into the summer, as it could be seen on the sea floor from a boat crossing the site of a major pile-up where notable depth changes also occurred.

HUME and SCHALK (1964) already recognized that most sediment transported ashore by sea ice is associated with pile-ups rather than ride-ups and explored the distance and water depth to the sediment source for pile-ups. In one instance, offshore sampling showed that the sediment contained in several "ice-push mounds" originated from a water depth as great as 3 m on the shoreface (HUME and SCHALK, 1976).

The following observations in two different years indicate even greater depths for the sediment sources. Numerous sediment-laden pile-ups, 2 to 4 m high and constructed of 40-cm thick ice, were observed in 1972 along the barrier islands from Reindeer to Narwhal Island (Figure 1), a distance of at least 20 km. We first noted these in July, before breakup was complete. On Cross Island, some piles contained 10-cm diameter cobbles among sand and gravel. Since the surrounding island surface had no cobble-size clasts, a submerged source was indicated. On August 17, while grounded floes in the offshore continued to prevent wave-reworking of the shoreface ever since formation of the pile-up, we made bottom observations along three diving traverses extending from a pile-up out to a depth of 8 m. Along these traverses, we found irregular, ice-produced relief, but none with a clear onshore trend. The first cobbles in a patchy sand and gravel substrate were noted at a depth of 5 m, about 50 m from the onshore pile-ups.

In 1983, sediment-laden pile-ups were common over a distance of more than 42 km extending from Thetis Island eastward, as mentioned earlier, and previously reported by KOVACS (1984). A 6-m high, 20-m wide, and nearly 1-km long pile composed of 50-cm ice slabs, occurred on Spy Island (Figure 10). The pile-up contained sediment throughout, which on July 28 already had formed a 10 cm thick surface layer. The sediment was mainly a mixture of sand and gravel, but included large pockets of well-sorted sand. We collected bottom samples in a restricted area of open water off the pile-up, at the time still protected from wave action by surrounding ice floes. From the pile seaward to 25 m, the bottom was pure gravel, changing to clean sand at 40 m distance, 4-m depth. In this case, bottom reworking by the sea cannot have occurred since the pile-up, and therefore its sand source, is reliably indicated. A similar sampling effort off the same ice pile by KOVACS (1984) also suggested a sediment source 50 m seaward and at 4-m depth.

The above evidence for ice extrusion through the growing rubble pile, for the occurrence of an

Figure 10. Aerial view of Spy Island in August 1983, showing a sediment covered pile-up. The sediment was derived from 50 m seaward of the pile at 4 to 5 m depth.

ice/sediment mixture at the base of pile-ups, and for a deep sediment source seaward of the pile-up, suggests a model for onshore sediment transfer mechanism shown schematically in Figure 11. Deposition from such ice rubble piles is very different from the onshore sediment movement into rubble piles, and occurs almost a year or more later. The mode of deposition is by vertical settling during melt-down of the pile. As might be expected, digging within the mounds reveals a lack of internal sedimentary structures.

The Role of Ice in the Development of Barrier Islands

Ice-dominated Barrier Islands One particular barrier island along the Beaufort Sea coast, unique in shape and structure, holds a convincing record of repeated pile-ups, and emphasizes the geological importance of the process affecting height and volume of islands. Icy Reef (Figure 1), a 26-km long, arcuate barrier island, was so named by John Franklin in 1826 because of severe coastal ice conditions encountered there by his party in mid-summer. The island fringes the Kongakut fan and delta, from which it is separated by a shallow (less than 1 m) lagoon, several hundred meter wide. The river is not now a sediment source for the island, because the Kongakut delta is composed of sandy mud, whereas the island consists of gravel (BARNES and REIMNITZ, 1988). The Icy Reef setting is unusual for several reasons: (1) The central part of the lagoon is seasonally occupied by a large naled (river icing), which seldom melts entirely; (2) With a crestal elevation of 4 m and a length of 26 km, the island is among the highest but also is the longest barrier island along the coast of the Alaskan Beaufort Sea. Typical island heights are 1–2 m; (3) The gravelly crest is hummocky, with over 1 m of relief (Figures 12, 13), as opposed to the current-washed surface of most islands (Figure 2);

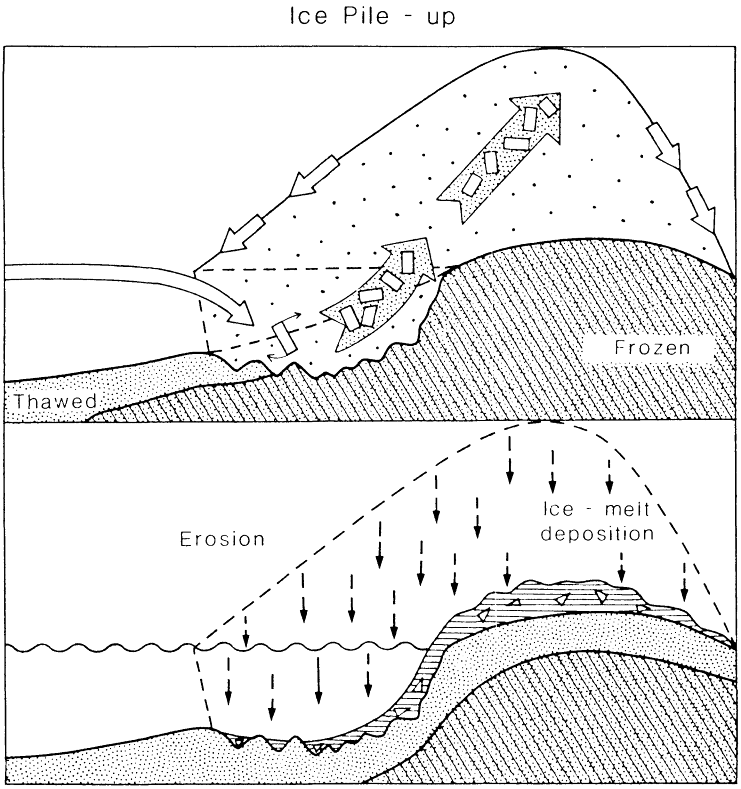


Figure 11. Conceptual model of landward sediment transfer during an ice pile-up, where slabs or granulated ice from the thrusting sheet mix with shoreface sediment, which then is extruded through the growing rubble pile. Upon melting, the sediment settles vertically onto the beach surface as much as a year or more later. This results in melt-lag deposits, formerly called "push mounds."

and (4) The central, 17-km-long stretch of the island has remained essentially unchanged in outline from 1951 to 1981 (REIMNITZ and BARNES, 1988), while other Arctic coastal features have undergone remarkable erosion or shifted positions (REIMNITZ *et al.*, 1988). The low (~1 m elevation) eastern and western extremities of Icy Reef are splayed to widths of a few hundred meters and are migrating onshore at rates of 1 m/yr or more, typical of many barrier islands along the coast further to the west (SHORT *et al.*, 1974; REIMNITZ *et al.*, 1988). The high, hummocky, and stable central third of the island (visited in 1981, 1987, and 1989) is presently dominated by piles of sandy gravel, 5 to 10 m long, cresting 1 to 2 m above the general surface (Figure 13). In 1987 the seaward side of this part of the island was truncated by an erosional scarp exposing three or more distinct horizontal beds about 25 cm thick (Figure 14). Laterally these beds vary in thickness and may pinch out. The base of the scarp at about 2 m above sea level was separated from the sea by a sloping, 15-m wide gravel beach typical of the arctic. The lagoonward flank of the island, sloping down to sea level over a distance of about 50 m, consists of a series of overwash deposits which originate at saddles in the hummocky island crest and are littered with driftwood (Figure 13). Aeolian sand accumulations are absent, as on nearly all Beaufort Sea barrier islands.

Observations of man-made structures suggest ice thrusting and overwash have been active since 1952 at Icy Reef. Eight of thirteen wooden towers erected there in 1952 for hydrographic survey control were destroyed by sea ice encroachment within the first 3 to 4 years (BARNES and REIMNITZ, 1988; REIMNITZ and BARNES, 1988), and apparently none of

Figure 12. Aerial view of unusually high Icy Reef, here considered an ice-dominated barrier island, in contrast to the wave-dominated barrier in Figure 2. (Photograph Ed Owens, 1976).

the towers remain standing today. Triangulation stations were placed along the highest part of the island at the same time (1952). One of these, station EASY, is shown in Figure 15 as it appeared in 1987, with the disc about 1 m below the average crestal height of the modern island. In 1972 the station could not be found. The inability to recover the markers around EASY in 1972 and their re-discovery in 1987, 1 m below the island crest, suggests that the station had been buried sometime before 1972, and was exhumed by the eroding sea since then. According to rough measurements, the net sediment accretion during the time interval would be 50 m^3 per meter length of island. A small amount of ice-push is seen in Figure 12, but we have seen no major pile-ups along Icy Reef in eight different summers since 1970. Similarly, KOVACS (1983) reported seeing no significant ice encroachment along that stretch of coast in two spring reconnaissance flights. Thus, ice incursions on Icy Reef may have been more severe or frequent in the past, as suggested by reports of a native who lived there many years ago (KOVACS, 1983, p. 33), and implied by the motives for naming the island in 1826.

Figure 16 shows the maximum elevations of recent storm overwash fans and terraces measured in 1977 by NUMMEDAL (1979) on barrier beaches from Barrow to the Canadian border (Figure 1). This figure also shows the approximate elevations of several other, problematically high, barriers discussed later. The 4 m height of Icy Reef, twice that of normal wave-dominated barrier islands, and its hummocky crest, to us indicate that the gravel has been stacked to such unusual heights by repeated ice encroachments. Much of this building process appears to have occurred since erection of survey monuments in 1952. Driftwood in saddles at 3.5 m above sea level, and the overwash channels extending from there, indicate that the

Figure 13. The 4-m-high crest of Icy Reef in 1981, dominated by ice-melt mounds from pile-ups, and overwash channel deposits dipping lagoonward (to the right) from saddles between the mounds.

island can still be overtopped by storm waves. Gravel stacking by ice seems to have alternated with smoothing and winnowing by storm waves to produce the horizontal layers of clean gravel. Since the last ice encroachment there has been no storm surge of adequate severity or duration to level the island top. The concept of an island dominated by ice stacking over wave action is shown schematically in Figure 17.

A number of barrier islands in the study area seem abnormal to us, partly because of their elevation (Figure 16) and lack of overwash during most storms (REIMNITZ and MAURER, 1979a). We suspect they may be relicts of a formerly more severe ice environment, when pile-ups were more frequent and larger. Narwhal Island (Figure 1) serves as one example of these islands to show reasons, other than elevation, that suggest a change in environment.

Today's Narwhal Island is a fragmented remnant of a formerly 3.5 km long barrier island (Figure 18A), and shows that we interpret as evidence for decreasing nourishment by ice. An old core of the island, approximately 3-m-high, was first separated from the rest by breaching about 1972 and by formation of a 3-m-deep channel. Since that time it has decreased in size by erosion mainly from the NE. The remainder of the island was fragmented into four 100- to 900-m-long islands by 1979 (Figure 18B). These four have shifted southwestward, and have taken on arcuate shapes, with the apex toward the dominant NE wind direction. The arcuate shape of these fragments indicates that the islands are disconnected from a longshore sediment transport system and that they now have their own separate budgets.

An erosional scarp at the east end of the old island core (Figure 18B) exposes a horizontally stratified section of sandy gravel (Figure 19). This section is capped by a thin layer of cobbles sufficiently smoothed by water that aircraft can land on it (Figure 20). The tower in the background of Figure 20 survives since the hydro-

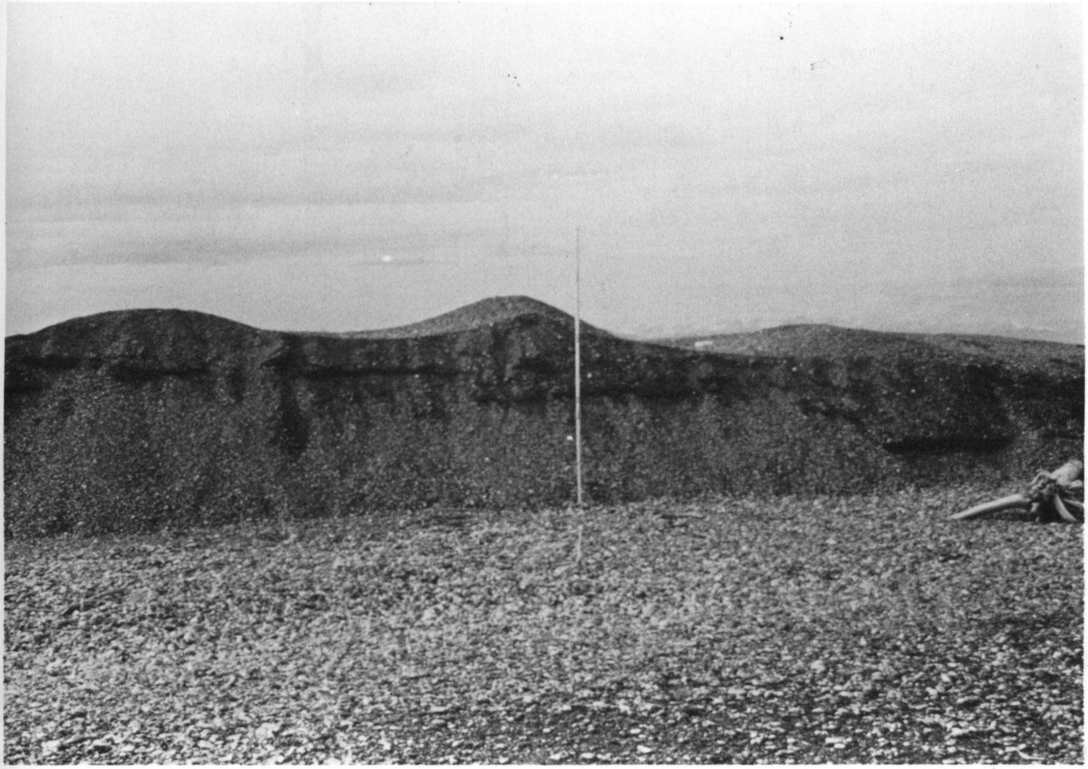


Figure 14. The active beach at the toe of 1.5 m high erosional scarp on Icy Reef in 1987. Horizontal gravel lenses suggest a succession of pile-ups alternating with storm over-wash constructed the island.

graphic surveys of 1949; remains of another labeled "Whal, 1949" on Figure 18A can still be seen. The sediments eroded from the seaward scarp are carried westward along the high, flat part of the island, where they accrete in a series of recurved spits (Figure 18B, 18C) at about 1 m above sea level; the typical height of active islands and beaches. This broad, low terrace commonly shows signs of ice action (Figure 21), in this case ice wallow, but we have seen no evidence for ice invading the old core of the island since 1970. We believe the old core was built by pile-ups alternating with overwash prior to 1949, during times when ice incursions were more frequent. Neither the scarp nor extensive digging, however, reveal sedimentary structures clearly documenting the stacking mechanism by pile-ups.

Other barrier islands in the Beaufort Sea have high, old, cores that presently are being displaced and are in the process of being reconstructed as wave-dominated forms, with strong similarities to Narwhal Island. Among those with which we are familiar are Cooper, Thetis, Cross, and Pole Islands (Figure 1); these also happen to be the only barrier islands with signs of former habitations. Todays more typical barrier islands are too vulnerable to flooding by storm surges to be suitable as long-term camp sites. In addition, only the old, ice-dominated island remnants provide suitable nesting habitats for such birds as eider ducks. Many of these formerly ice-dominated islands also have fragmented since 1950, and Dinkum Sands, a 1 m high island in 1949, now is a mere shoal between Narwhal and Cross Islands.

Onshore Transport by Ice Versus Longshore Transport by Waves In studies of ice-free environments, treating an inner shelf

Figure 15. The triangulation station EASY, with 4×4 inch witness post and bent reference mark in foreground, on the beach about 1 m below the modern crest of Icy Reef (1987). The island apparently was elevated by about 1 m through gravel stacking by pile-ups since 1952.

sediment budget within the constraints of the littoral cell, including sources, pathways, and sinks, has proven useful (INMAN and CHAMBERLAIN, 1960; INMAN and BRUSH, 1973). In its simplest form, the concept requires a dominant source, usually a major river, at the updrift end, and a major sink at the downdrift end of the cell. In the study area, the long island chain extending downdrift from the Canning River as a sediment source to Reindeer Island (Figure 1) plus any offshore sinks, is an obvious candidate for a simple littoral cell. If the concept were applicable, the lithology and longshore grain-size pattern in this island chain and in the offshore, should in some way reflect the Canning River as its main sediment source. Several lines of evidence indicate that the concept so simple and useful in ice-free settings is difficult to apply to this complex sedimentary regime where ice is the dominant geologic agent.

First, recent sediment budget studies have shown that the primary source in the study area is from coastal and shelf erosion, not from fluvial input (REIMNITZ *et al.*, 1988). Thus the sediment sources are rather evenly distributed along the entire coast, instead of being well defined at river mouths. In fact, the erosion products of several km of receding shoreline exceed the capacity of littoral drift from estimates using wave theory. Thus the system outlined by the box in Figure 1 would become choked by sediments without the help of ice as a transporter.

Secondly, the sediments so introduced to the sea find no sinks on the inner shelf. In the area of Figure 22, this has been shown from interpretations of high resolution seismic reflection data, supported by borehole studies (WOLF *et al.*, 1985). Several meters of Holocene sedimentary deposits exist only within the lagoons and along the island chain. These deposits cannot

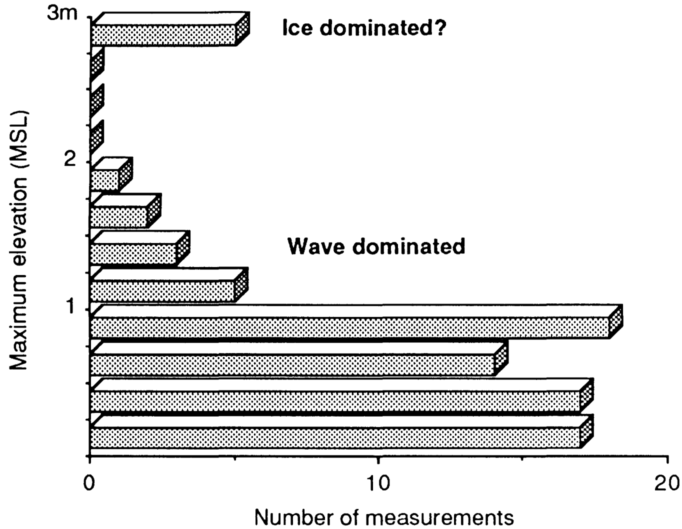


Figure 16. Maximum elevations of recent storm overwash fans between Barrow and the Canadian border, measured by NUMMEDAL (1979) in 1977. We believe the 5 islands with elevations of about 3 m (Cooper, Thetis, Cross, Narwhal, and Pole Islands), generally above the reach of waves, are disappearing relicts of formerly ice-dominated islands.

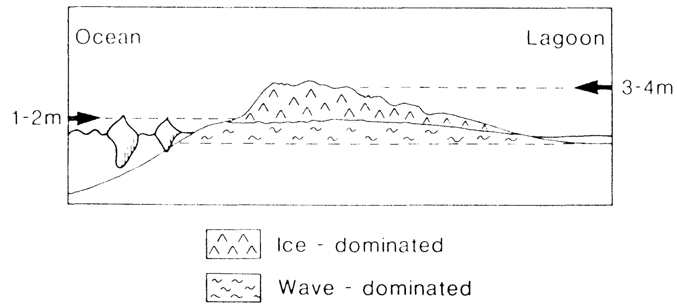
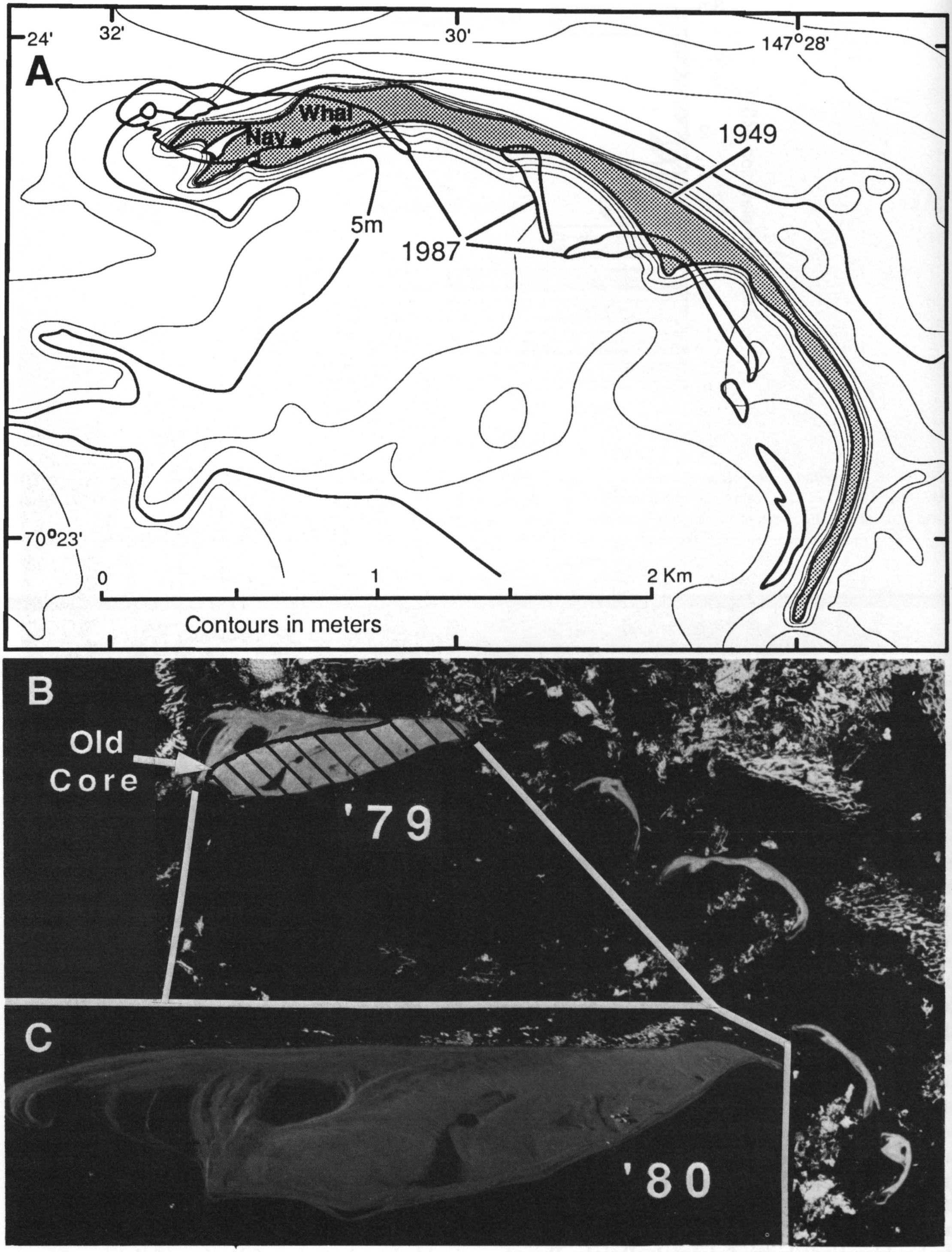


Figure 17. Schematic cross section of a normal wave-dominated barrier island (Reindeer Island) underlying an elevated cap constructed from alternating pile-ups and overwash (Icy Reef).

satisfy the need of long-term sinks for sediments, since islands and lagoons are migrating landward at the rate of the ongoing transgression (about 2 m/yr) and the islands in general are not growing in volume (REIMNITZ *et al.*, 1988).

Erosion of the open shelf has truncated former interglacial deposits, including the Pleistocene Flaxman Member of the Gubik Formation (DINTER, 1985). This unit is readily recognized by its lithologically distinct pebble- to boulder-size clasts, foreign to Brooks Range drainage systems (Figure 1), and which therefore call for ice rafting from the Canadian Arctic. Small, several-meter-thick patches of the unit remain only on Flaxman Island itself and locally along the mainland coast (HOPKINS and HARTZ, 1978). The erosional surface seaward of the island chain, and probably extending out to at least 40 m water depth, is totally replowed by ice every 200 yrs (BARNES *et al.*, 1978), a process that results in a several-meter-thick active layer called icekeel turbate (REIMNITZ and BARNES, 1987). The thickness of the icekeel turbate is a function of the maximum ice gouge incision depth, which in turn is


24'
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A
Whal
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1
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B
Old
Core
'79
C
'80

Figure 19. Three-meter-high erosional scarp exposing interbedded gravel and sandy gravel at the NE end of Narwhal Island's old core (Figure 18B) in 1979.

related to water depth (BARNES *et al.*, 1984). The replowing by icekeels results in current-winnowing of fine sediments and, consequently, in a concentration of pebbles and coarser clasts from the eroded section. The icekeel turbate in the study area therefore contains 2 to 10 percent pebbles and coarser clasts (BARNES and REIMNITZ, 1974). The North Slope rivers presently supply no gravel size material to the sea. RODEICK (1979), studying the lithologies of such coarse materials in the study area, found that most are akin to the Flaxman Member and therefore are foreign to Alaska. In summary, only a lag of locally derived materials blankets the shelf surface, and there has been a net, offshore loss of sediments, including those recently supplied by the Canning River.

Lastly, mapping of coastal gravel lithologies and clast sizes (Figure 22) also fail to support the concept of an alongshore source of fluvial, or Canning River origin, but rather suggest local derivations from the shelf surface lag. HOPKINS and HARTZ (1978) studied lithologies of 100 randomly chosen pebbles at many beach and island sites between the Canning River and Point Barrow. They divided pebble lithologies into four groups, two of which are of the same source as the Flaxman Member, one is indicative of sources in the Brooks Range, and one is of unknown source areas. Based on those studies, they concluded that pebble lithologies for islands and island groups in the three major chains covered by their work are not unified by littoral drift. Rather, certain groups, as for

Figure 18 (*facing page*). (A) Narwhal Island, traced from U.S. Coast and Geodetic Survey No. 7757 in 1949–50, and re-mapped by the National Ocean Survey in 1987. The tower labeled Nav remains intact (see Figure 22), broken remnants of the tower Whal were seen in 1971. (B) U-2 photograph of July 1979 shows the fragmented island, with remnants of the old, 3-m high, ice-constructed core at west end, enlarged in an oblique photograph of 1980 (C).

Figure 20. View south from same place as Figure 19, across current-smoothed cobble lag at +3 m, toward surviving "Nav" tower shown in Figure 18.

example Cross, Narwhal, and Jeanette Islands (Figure 1), either had in the past or still have today, their own sediment source on the open shelf. This conclusion is supported by both the varying clast size of pebbles along the island chain and the dominance of Flaxman- rather than upland-source lithologies in the islands' composition (Figure 22). Brooks Range lithologies, on the other hand, dominate the mainland beaches in the protected lagoon, where ice encroachment and associated sediment supply is comparatively rare. Thus, submerged source materials excavated and brought ashore by ice are far more important for the budget of this polar barrier island chain than classic longshore transport from an updrift source.

Transport associated with ice encroachment occurs not only in the narrow zone from the shoreface onto land. Some transport occurs from the deepest point on the shelf where ice floes can ground (50–60 m according to BARNES *et al.*, 1984; REIMNITZ *et al.*, 1984) during a shoreward thrust which ultimately terminates in encroachment. Recent model tests have shown that the forward displacement (D) of sedimentary particles during gouging is a function of gouge incision depth (d) and gouge incision width (w), with an average forward particle displacement of 2.3 times incision width (BARNES *et al.*, in press). These test results can provide an estimate for the shoreward sediment transport during the gouging depicted in sonographs of Figure 5, using assumptions for average values of w and d in that figure. BARNES *et al.* (in press) determined that the volume transport rate of sediment by ice bulldozing (T) equals the volume of material [cross sectional area of the gouge (wd), multiplied by the average displacement (D) across a line of unit length (l), oriented transverse to the transport path, in unit time (t), or

$$T = wDl^{-1}t^{-1}. \quad (1)$$

At 8 m water depth in Figure 5, where the seafloor is "saturated" by gouges trending about 25° from shore-normal, the number of gouges counted at right angle to that trend is about 100/km. The average gouge, including both incisions and flanking berms, therefore is 10 m wide. Based on extensive studies of gouges we

Figure 21. The 10-m wide, low, active beach with ice-wallow relief north of 3-m high, ice constructed remnant of Narwhal Island in background.

assume that a typical incision width is 60–70% of the total gouge width, in this case 6 to 7 m. An average incision depth of .2 m is reasonable for these gouges (BARNES and REARIC, 1985). Substituting these numbers in equation (1), the forward transport associated with the formation of each typical gouge obliquely crossing the 5-m isobath is 16.6 or 22.6 m^3, depending on whether we use an incision width of 6 or 7 m, respectively. From this number, the volume of sediment bulldozed directly shoreward across the 8-m isobath during the disturbance is calculated to be 1.5 to 2.0 m^3/m. The gouges shown in Figure 5 probably represent less than one year (t) of work. At this rate, the shoreface sediment stacked onto beaches and islands every few years by ice encroachment is replaced from deeper water at a similar rate by ice gouging, thus explaining the pebble lithologies and clast size on barrier island chains. The arctic coast, of course, is receding rapidly rather than accreting. Therefore, the net effect of ice on the coastal and shelf sediment budget has to be cross-shelf transport of mainly fines to the deep Arctic Basin (REIMNITZ and BARNES, 1987).

The Balance Between Ice and Marine Processes Energy generated over the Arctic Ocean and transmitted for long distances through ice to surrounding coastlines, if not previously expended by gouging shelf surfaces and by ice deformation, is ultimately consumed during ice encroachment onto land. The net effect of ice encroachment, in the form of ride-up or pile-up, is an addition of sea bed material to beaches and barrier islands. This transport is unidirectional, without the seaward component in wave action. Except for areas where boulders protrude substantially above the bed, little sorting occurs during this onshore sediment transfer. Sorting occurs during occasional storms aided by year-round eolian deflation

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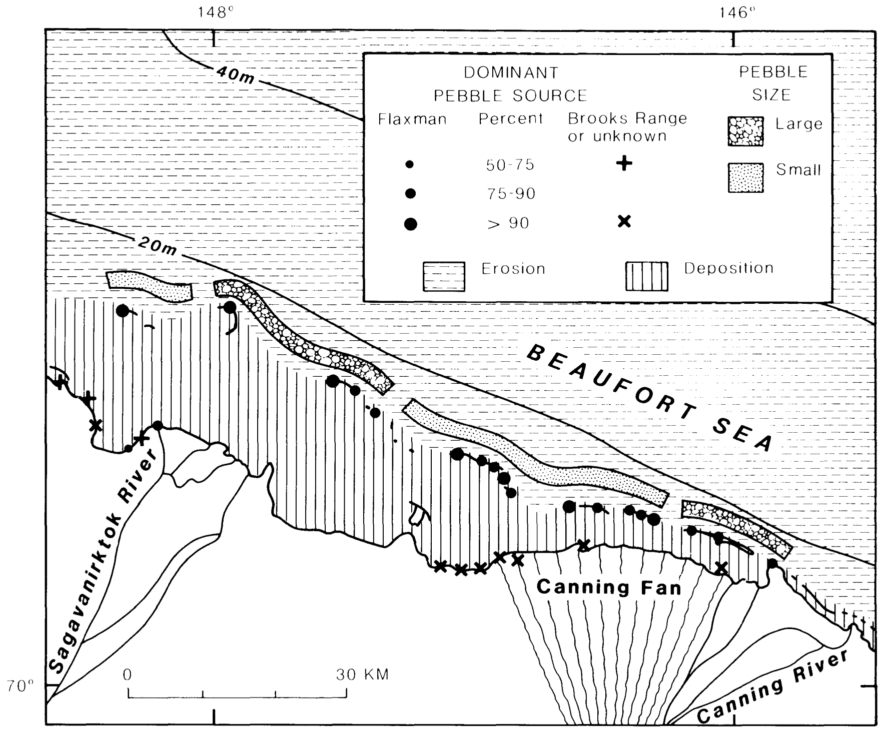

Figure 22. The erosional shelf surface, and patterns of pebble size and lithologies (from counts of 100 pebbles at each site) show that this island chain is not dominated by the up-drift Canning River as sediment source (as in a littoral cell), but instead by onshore ice transport from submerged sources. After Hopkins and Hartz (1978).

(REIMNITZ and MAURER, 1979b), which removes the finer sediment. These interactions of water and wind with materials contributed by ice encroachment are largely responsible for the gravelly composition of arctic barriers. We have shown that ride-up and pile-up in the study area are largely restricted to the period of total ice cover, or to transitions between that period and the season of open water. Ice rarely encroaches during the navigation season with open water and wave action. Of the two basic types of ice encroachment, pile-up is evidently more nourishing for arctic barriers and beaches than ride-up. Sediment additions to the beaches from pile-up should not be called ice push-mounds, since ultimately the mounds form from sediment settling vertically onto land from a mixture of ice, with less than 5% sediment. Bottom sediment is entrained into the advancing ice sheet from the shoreface to water depths as great as 5 m, and 50 m distant from the beach. This sediment typically consists of sand and gravel. Hummocky melt-lag deposits derived from pile-up, according to our observations, may form on the average once every 10 years at a site, and generally within a narrow zone (less than 20 m) paralleling the shoreline. The short horizontal distance from the shoreline does not prevent obliteration of the mounds by storm waves. The resulting subaerial deposits are temporary and soon reworked by the sea in most areas. Alaskan beaches and barrier islands today are dominated by low, wave-washed forms, because of the present low recurrence rate of ice encroachment relative to the general 2-m/yr coastal retreat rate. However, the ice-supplied sand and gravel is important for the sediment budget of barrier islands and beaches and the local offshore sources are reflected in pebble lithologies and pebble size on beaches. Segments of coast with fine-grained sediments on the shoreface, as at Cape Halkett, cannot benefit from nourishment by ice thrust, because the mud is soon removed by waves and current. As a consequence, such coastal segments cannot have any barrier island chains (Figure 1.)

The balance between the rate of sand-and-gravel contribution by ice and its removal or smoothing by waves can change for various reasons so that coastal features become strongly ice-dominated. In the case of Icy Reef, 30-yr comparative stability of the shoreline and recurring ice encroachment, possibly with temporarily reduced interference by storms, have resulted in stacking of gravel to heights beyond reach of any but the most severe storm waves. Icy Reef could theoretically continue to accrete vertically, because pile-ups can raise sediments to 10 meters or more above sea level. Less frequent pile-ups or increased fetch for the generation of storm waves, on the other hand, could change the balance so that Icy Reef assumes the wave-dominated form of most Beaufort Sea barrier islands. Pile-ups apparently were more frequent and larger several decades ago than in recent years, and the wave fetch shorter. The balance for most of the barriers in this study, therefore, may have recently changed in favor of reworking by overwash.

The changing setting of the Arctic coastline during historical times, suggested by certain aspects of its barrier islands, is not out of line with evidence for changes in temperature and ice cover in the Arctic during the last century. LACHENBRUCH (1985) interpreted temperature logs from 24 wells on the North Slope of Alaska to show a 1–3°C warming over the coastal plain, foot hills and the Brooks Range since the middle of the last century. Soviet evidence for variations in Arctic coastal ice conditions and their causes, summarized by ARE (1988), indicates that changes in ice-cover lag behind changes in atmospheric circulation by 10 to 20 years. In the 1920's and 1930's the ice cover in coastal shipping lanes decreased to half of what it occupied at the end of the 19th century. This is supported by logs of captains sailing in Alaskan coastal waters, dating back to 1860, which show that the ice edge for July and August was much closer to shore in the years before 1940 than since (Figure 23A, after HUNT and NASKE, 1979). This change is further supported in the memory of natives, who believe that todays ice conditions are less severe (probably also referring to improved navigation conditions) than several decades ago (KOVACS, 1983). During the last 35 years, or since the time that the summer ice edge in Figure 23A has retreated to its greatest distance from the coast, however, summer ice-conditions seem to have stayed rather constant. This is shown by the ice severity index (BARNETT, 1980), which considers such factors as the August and September distance north of Barrow to the ice edge, or to $5/10$ ice cover, as well as conditions in the coastal shipping lane to Prudhoe Bay (Figure 23B). Such overall decrease of ice cover would not necessarily decrease the intensity of ice encroachment onto land, as suggested by natives. A retreat of the summer ice edge, however, would increase the fetch for summer wave generation. Increased wave activity, in turn, may have changed the balance between beach-nourishing pile-ups and wave reworking towards the latter, and, therefore, towards barrier island destruction. Such subtle climatic changes affecting coastal processes and morphology would certainly also affect biology by diminishing available nesting habitats of shore birds.

In past studies, the barrier island chains of the Beaufort Sea coast have been viewed as classic examples and abnormal elevations, now suggesting to us fundamental differences from temperate-region barriers, were not addressed (for example NUMMEDAL, 1979; SHORT, 1979). Those local crestal elevations above the reach of storm waves, in this case clearly not due to differential vertical crustal movement (REIMNITZ *et al.*, 1988), nor to eolian sand accumulations, may some day be useful as criteria for recognizing beaches and barriers in the geologic record of ice stressed environments. Such abnormally high coastal features should locally be capped by coarse, ice pile-up and ride-up materials, and should contain lenses of melt-down lag gravels marking locations of former pile-ups.

CONCLUSIONS

Our analysis of available information on beach nourishment by ice encroachment onto the Beaufort Sea shores leads to the following conclusions:

(1) Sediment transport by ice onto land occurs during the period of ice cover in the

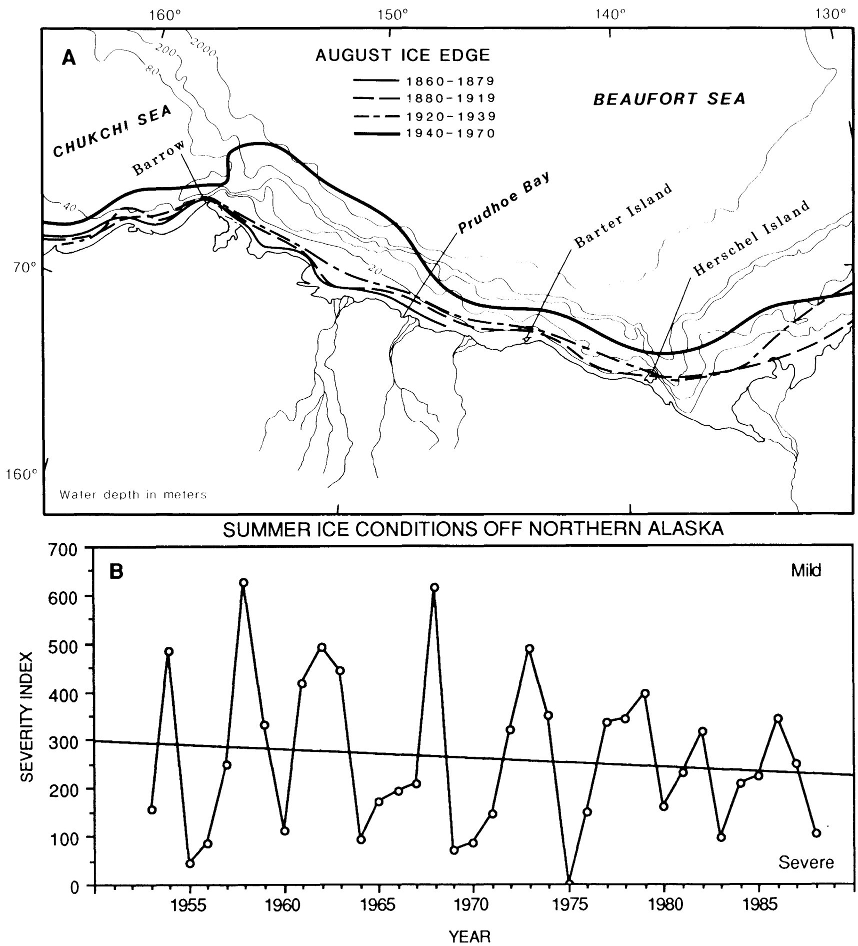

Figure 23. (A) The summer ice edge, reconstructed from captains logs dating back over 100 years (from Hunt and Naske, 1979), suggests increasing fetch and wave action. (B) The ice severity index (Barnett, 1980, up-dated from written communication), indicates slightly decreasing fetch since 1953.

coastal zone, and almost never during the period of wave action.

(2) Pile-up is more effective in supplying sediment to beaches than ride-up, which usually only scrapes across frozen surfaces.

(3) The sediments occurring throughout many, if not most pile-ups, are derived mainly from the shoreface seaward of the bottom-fast ice and of the ice pile, from water depths ranging to 5 m and distances to 50 m or more from the beach.

(4) This shoreward sediment transfer requires offshore down-bending of the advancing ice sheet, mixing of ice rubble with bottom sediments, and subsequent extrusion of the mixture through the ice pile.

(5) Ice can transport and stack shoreface sediments to 10 m height or more, beyond the reach of wave reworking, and has the potential for building abnormally high, "ice-dominated" barrier islands.

(6) Today, barriers and beaches generally migrate too rapidly to become ice dominated, because ice-supplied sediments are deposited within 10 to 20 m of the shoreline. However, eroding remnants of formerly ice-dominated barrier islands can still be identified.

(7) Evidence suggests that the balance

between gravel stacking by ice and winnowing by waves has changed during the last century, with ice conditions less severe now than at the beginning of this century.

(8) Pebble lithologies and clast size in island chains record the dominance of shoreward transport by ice versus longshore transport by littoral processes.

Although the onshore transport by ice is important for the nourishment and maintenance of retreating beaches, we believe that the overall effect of ice on the inner shelf sediment budget is erosive through cross-shelf transport to the deep Arctic Basin.

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