Spit and Barrier Island Migration in the Southeastern Canadian Beaufort Sea

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ABSTRACT


The coastline of the southeastern Canadian Beaufort Sea is essentially composed of eroding bluffs of unconsolidated Quaternary sediments, complex embayments formed by the breaching of thermokarst lakes, and spits and barrier islands which are experiencing rapid landward migration. Comparison of air photographs shows that between 1950 and 1985 spits were retreating landward at an average rate of 1.7 m a⁻¹ while offshore barrier islands were migrating onshore at a rate of 3.1 m a⁻¹. “Detached spits,” which represent a type of barrier island almost attached to the mainland, migrated landward at a rate of 2.0 m a⁻¹. These differences in migration rates are explained in terms of sediment supply, morphology and physical processes responsible for the landward migration of the coastal landforms. Regression analyses of retreat rates as a function of longshore sediment supply revealed that sediment availability is a significant parameter controlling spit and barrier island landward migration. Analyses of retreat rates as a function of incoming deep-water wave power showed that barrier islands are retreating more rapidly than spits even if they are exposed to the same level of wave energy. Direct sediment supply from adjacent bluffs and the presence of coastal dunes effectively limit spit erosion and retreat. In the case of barrier islands, the lack of significant longshore sediment supply is favourable to a net sediment deficit and results in higher retreat rates. Spits are retreating in response to beachface erosion and storm overwashing where low crestal elevation permits swash incursion across the crest. Barrier islands are more often and more extensively overwashed and overwashing represents the main physical process responsible for their migration.

ADDITIONAL INDEX WORDS: Barrier islands, spits, landward migration, longshore sediment supply, overwash processes, Western Canadian Arctic.

INTRODUCTION

The Canadian Beaufort Sea coast consists mainly of bluffs developed in ice-bonded Quaternary sediments, and of barrier beaches, spits, and barrier islands enclosing, more or less completely, lagoons and complex embayments formed by the breaching of thermokarst lakes. Barriers, spits and barrier islands form approximately 20% of the length of the coastline, but along the coast east of the Mackenzie Delta (Figure 1), nearly 30% of the coastline consists of these types of coastal depositional landforms (HARPER, 1990). Several authors have reported retreat of barriers and spits at some specific sites (LEWIS and FORBES, 1975; RAMPTON and BOUCHARD, 1975; FORBES and FROBEL, 1985), but no detailed nor extensive work has been carried out so far on the mechanisms of onshore migration of these coastal accumulation features. The aim of this paper is to determine the migration rates of the spits and barrier islands along the southeast coast of the Canadian Beaufort Sea and to describe the major factors controlling their evolution. The study area includes the north coast of the Tuktoyaktuk Peninsula (Figure 2) and the south and east coasts of Kugmallit Bay (Figure 3).

METHODS

In addition to field observations and measurements, the primary data used in this study
are aerial photographs, wave energy data derived from a wave hindcast model, and to a lesser extent stratigraphic data from vibracore samples. Measurements of shoreline changes (accretion or retreat) were done by comparing 1950, 1972, and 1985 vertical aerial photographs, at scales varying from approximately 1:40 000 to 1:60 000. On two comparative photographs, a geographically common inland point such as a pingo was selected, and distances were measured to the water line. The measurements were used to calculate annual retreat or accretion rates of the coastal spits and barrier islands. Given the fact that many shoreline retreat measurements were in the order of 100 to 200 m between 1950 and 1985, and because relatively small tides occur in the area (about 30 cm), the possible error induced by tidal level variations is believed to be negligible. A simple test was undertaken to evaluate measuring error and photographic distortion. Distances were measured across more than twenty inland lakes and between ten pingos on the 1950, 1972, and 1985 air photographs and the range error between the photograph sets as always less than 5%.

The wave data used in this study are derived from a wave hindcast model (Pinchin et al., 1985). The wave hindcasts are based on fourteen years of hourly wind speed records at Tuktoyaktuk. Hindcasts were performed for offshore and nearshore sites extending from Herschel Island to Atkinson Point (Figure 1). The hindcast procedure included wind speed, wind duration and fetch length as input data and produced estimates of effective significant wave height ($H_s$), peak period ($T_p$) and direction of propagation. Because wave generating fetches in the Beaufort Sea are limited by the extent of the sea ice, weekly ice charts were used to define fetch lengths. A calibration of the procedure was performed by comparing wave hindcasts with measured wave data at two recording stations in the Beaufort Sea for limited periods. When the wave

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Figure 1. Location map showing wave power and wave frequency distribution in the southern Canadian Beaufort Sea. The wave power and wave frequency rose diagrams are based on hindcast data from Pinchin et al. (1985).
Barrier Island Migration

Figure 2. Location map of the study area showing the spits and barrier islands of the Tuktoyaktuk Peninsula considered in this paper.

For every site along the spits and barriers where retreat rates have been measured, incoming deep-water wave energy (E) and power (P) have been computed, using wave hindcasts as input data. For each site, incoming deep-water waves from a 90° sector centered normal to the coast were considered for the total fourteen years hindcast period. The wave energy density was found by:

\[ E = \frac{1}{8} \rho g H^2 \]  

where \( \rho \) is the density of water, \( g \) is the acceleration of gravity, \( H \) is the significant wave height in deep-water. Then, the deep-water wave power was calculated as:

\[ P = ECn \]  

where \( E \) is the wave energy density, \( C \) is the wave phase velocity in deep water, and \( n \) is the ratio of wave-group velocity to wave-phase velocity (\( n = 0.5 \) in deep water). Using SI units, \( E \) and \( P \) are expressed in N m\(^{-1}\) and in W m\(^{-1}\) per wave, respectively.

Potential longshore sediment supply has been estimated for every coastal depositional landform by calculating the volume of sediment provided by adjacent eroding headlands. In the absence of detailed longshore sediment transport calculations at every site, all the eroded material coarse enough to remain in the coastal system (sand and gravel) has been considered to represent potential sediment supply for the adjacent sandy depositional landform in the downdrift direction. The proportion of sand and
gravel in the bluffs was relatively easy to determine in most cases as virtually all the bluffs along the Tuktoyaktuk Peninsula are composed of sand. In this periglacial environment, ground-ice is also an important factor to take into consideration in any sediment budget calculation, so visual estimates of ground-ice content in the bluff sediments have been carried out. These estimates are proportions of massive ice in the bluffs which represent most of the excess ice per volume (i.e., volume of ice exceeding the volume of original voids in the sediment). Potential sediment supply per year has been calculated for each headland using bluff retreat rate, bluff height, proportion of sand and gravel, and mean ice content. Retreat rates were obtained from air photograph comparisons and bluff heights were measured in the field for most of the sites or estimated using low-altitude oblique airborne video imagery (FORBES and FROBEL, 1986). Although a part of the eroded sediment is likely transported away from the spits and barrier islands (e.g., offshore transport, deposition in lagoons), it has been assumed for purposes of analysis that the sediment supply remained constant along the entire coastal depositional landforms on the downdrift side of the headland. When a small inlet occurred, very little loss of sediment to tidal deltas has been assumed as their development is very restricted, so by-passing was considered predominant and thus the volume of potential sediment supply remained unchanged for the calculations.
REGIONAL SETTING

Surficial Geology

The study area lies to the east of the Mackenzie River Delta (Figure 1), the dominant depositional feature in the region. The coast consists of low-relief unconsolidated Quaternary deposits. The Tuktoyaktuk Peninsula (Figure 1) is principally composed of Pleistocene sands overlain by a variable thickness of glacial sediments of Wisconsinan age. The southwestern part of the peninsula is primarily formed of ice-contact deposits, moraines or morainal veneer overlain by lacustrine sediments of Holocene age, while the northeastern part consists of glacial outwash sands which are covered by eolian or lacustrine sediments in places (Rampton, 1988).

Cold climatic conditions during the Pleistocene have led to the formation of continuous permafrost to depths of several hundred metres. As a result, ground-ice is found throughout the region either in the form of pore ice or ice bodies of various dimensions (Mackay, 1971). Much of the topography in the area can be attributed to the presence or absence of subsurface ground-ice. Thermokarst, which is the process of ground-ice melting and the accompanying collapse of the ground surface to form depressions, has been an active process during the Holocene and the latter part of the Late Wisconsinan (Rampton, 1988). Thermokarst lakes are very common in the area. Nearly 40% of the northeastern part of the Tuktoyaktuk Peninsula is covered by lakes of various dimensions (Figure 4). The resultant topography consists of depressions separated by low elevated areas in which massive ice and icy sediments may be found.

The Canadian Beaufort Shelf extends offshore to 70 m water depth. In the eastern Beaufort Sea, the shelf is characterized by a very gentle gradient (in the range of 1:2000). Muds dominate the central and outer shelf while inshore of the 10 m isobath sand is generally abundant (Vilks et al., 1979). Subseabed permafrost underlies much of the Beaufort Shelf (Blasco, 1984). It is relic from periods during the late Pleistocene when the seabed was exposed to subaerial arctic conditions during periods of lower sea-level (Mackay, 1972).

Relative Sea-Level History

A late Quaternary sea-level curve, based on radiocarbon dates on peats discovered in shelf boreholes, has been proposed for the Canadian Beaufort Sea by Hill et al. (1985). According to this curve, a rise of 140 m in relative sea-level has occurred since ca. 27,000 years BP. During the Holocene, relative sea-level has risen approximately 70 m, but the rate of recent sea-level rise has not been clearly established. Forbes (1980), in a compilation of radiocarbon dates from the Yukon coast and from archaeological sites on Hershel Island (Figure 1), points to a slow sea-level rise of 1 to 2 m during the last 2000 years. Recent radiocarbon dates on peats from modern coastal marshes on the Tuktoyaktuk Peninsula also suggest a slow rise in sea-level during the last 1000 years (Hill et al., 1990). Although not statistically significant, tide-gauge data from Tuktoyaktuk suggest that relative mean sea-level is still rising at a rate of about 1 mm a\(^{-1}\) (Forbes, 1980). Geomorphological evidence also suggests a continuing rise of relative sea-level. The ubiquitous shoreline recession in the area and the fact that the Mackenzie Delta shows an aggrading rather than prograding morphology are positive evidence for contemporary sea-level rise.

Coastal Oceanography

Winter sea ice effectively limits wave energy in the region for nine months of an average year. The coastal ice regime is marked by four "seasons": open water, freeze-up, winter and breakup. Coastal ice forms and becomes intermittently stationary during the freeze-up season, usually from October to mid-January. The breakup season from June to mid-July is associated with deterioration of the fast ice. This period is followed by the open water season, from Mid-July to early October. During the open water season, winds mainly originate from the east, southeast and northwest quadrants. However, most of the higher energy waves originate from the northwest (Figure 1) in response to storm winds (Harper and Penland, 1982). Even during the ice-free period, wave energy is limited by the fetch-restricting pack ice offshore. As a result, the
Beaufort Sea is a moderate wave-energy environment and nearly 80% of deep-water waves are less than 1 m in height. Although storm waves in excess of 2 m in height occur less than 5% of the time, it is believed that they account for most of the coastal sediment transport (Pinnock et al., 1985).

The mean tidal range is 0.3 m at mean tides.
and 0.5 m at large tides. Consequently, the Canadian Beaufort Sea coast can be considered microtidal and wave-dominated (Hayes, 1979). Occasionally, the coastline is affected by positive storm surges up to 2.4 m in the Kugmallit Bay area (Harper et al., 1988).

**SPITS AND BARRIER ISLANDS OF THE SOUTHEAST CANADIAN BEAUFORT SEA**

The coast of the southeastern Canadian Beaufort Sea consists mainly of embayments formed by breached thermokarst lakes, spits and barrier islands, and low bluffs (usually less than 10 m high) containing a variable proportion of ground-ice. Although ground-ice can occur in the form of pore ice and ice veins, massive ice is common in the bluffs throughout the study area. The ubiquitous coastal erosion in the area favors the development of accretionary landforms by supplying significant volumes of clastic material to the shore zone. Recent studies conducted along the Canadian Beaufort Sea coast showed that bluffs are undergoing rapid regional retreat, with maximum retreat rates in excess of 10 m a\(^{-1}\) at some locations (Forbes and Frobel, 1985; Mackay, 1986; Harper, 1990). In addition to wave-induced erosion, thermal erosion at the bluff (thawing of ground ice) might favor rapid coastal retreat (Mackay, 1971). When ground ice occurs in the surficial sediments, coastal bluffs are affected by different types of erosional processes, depending on the type and proportion of ice, and on the textural composition of the bluff sediments (Hequette and Barnes, 1990). Bluff erosion results in the delivery of material to the coastal zone, but the actual volume of clastic material available for the beaches depends on the percentage of sediments coarse enough to remain in the littoral system as well as the proportion of ground ice present within the bluff.

Along the south and east side of Kugmallit Bay, the coast consists either of coastal bluffs essentially formed of glacial diamicton containing gravels and pebbles or of small embayments partially closed by small spits. The sediment size of the spit material is typically in the coarse sand to gravel range because of the relatively coarse lithology of the diamicton in the bluffs. The coast of Tuktoyaktuk Peninsula is quite different. Coastal bluffs are predominantly sandy and the coastline is regularized by long sandy spits and barrier islands. They isolate lagoons of various dimensions. Transverse bars are widespread on the landward margins of lagoons, aligned roughly perpendicular to the shoreline, with a crude rhythmic spacing (Figure 5). Such features are thought to form either as a response to a series of current gyres produced by wave refraction and interference (Nedoroda and Tanner, 1970) or under the influence of fairweather waves inducing a landward movement of previously eroded berm sediment on sheltered beaches (Bruner and Smosna, 1989).

The frost table occurs near the surface of all the spits and barrier islands in the area. Even late in the summer, vibracoring through the spits and barrier islands of the Tuktoyaktuk Peninsula revealed that the depth of ice-bonded sediments ranged from 1.0 to 1.6 m below the beach surface.

**Spits**

Along the eastern side of Kugmallit Bay, the coastline is highly indented and small spits have developed at the entrance of complex embayments formed by the coalescence of breached lakes. Southwest of Tuktoyaktuk, accumulation features are composed of sand and gravel and occasional coarser material, but north of Tuktoyaktuk, sandy features predominate. Usually they are linear features straightening the coastline, but some are more complex as at Topkak Point (Figure 3) where the distal section of the spit consists of relict recurved ridges (Figure 6A). Two different types of spit occur. One type is represented by narrow features (usually 100 to 150 m wide) of variable length (300 to 2000 m long). Some low coastal dunes (1 to 3 m high) may develop over the proximal part of these spits and sometimes along the central and distal parts (Figure 6B). The crests of these spits can reach an elevation of 3 m above mean sea-level, depending on the grain-size of the beach material, the exposure to waves and the presence or absence of dunes. The other type of spit is typically longer (3000 to 5000 m) and much wider. At Atkinson Point, for example, the width of the spit is in excess of 500 m (Figure 4). These wide spits are very low, their crest being rarely more than 1 m above mean sea-level. No dunes occur on these spits,
except in small areas where they are attached to the mainland.

The morphology and configuration of coastal spits show that the net wave-generated longshore sediment transport is generally oriented eastward along the coast of the southeastern Canadian Beaufort Sea, although local divergences in the direction of the littoral drift exist (FORBES and LEWIS, 1984). Numerical models of longshore sediment transport confirm the geo-
Figure 6. (A) Oblique aerial view of Topkak spit; note the relict recurved ridges in the foreground; (B) Coastal dunes near the distal part of Topkak spit. See Figure 3 for spit location.
morphological evidence. At Atkinson Point, the potential longshore sediment transport has been calculated to be in the range of $1.0 \times 10^5$ m$^3$ a$^{-1}$ northeastward (PINCHIN et al., 1985).

Elongated shore-parallel swash bars are common along the spits. Onshore migration of swash bars is a common mechanism along retrograding coasts (KING, 1972; SWIFT, 1976). In the study area, field evidence suggests that it represents an effective process of coastal sedimentation. Field observations point to a shoreward migration of the bars during post-storm conditions, until they eventually weld onto the beachface. These observations are consistent with laboratory experiments and field data under such conditions (SUNAMURA and TAKEDA, 1984). The sedimentary structures visible in a short core (1.2 m long) collected near the crest of Atkinson Point eastern spit (Core A1-87, Figure 4) support the field observations. X-ray radiography of the core revealed internal structures characteristic of landward migrating bars (DAVIS et al., 1972) with horizontal to gently-dipping basal beds thought to represent storm conditions overlain by high-angle landward-dipping laminae interpreted as the inner edge of a bar.

**Barrier Islands**

According to SWIFT (1975, p. 2), a barrier island is “a littoral sand body consisting of (1) a shoreface maintained by the prevailing hydraulic regime, and (2) attached washover fans whose surfaces are modified by aeolian and by biological activity.” More recently, OERTTEL (1985) defined a “barrier island” as the focal element of six depositional environments which together constitute the “barrier island system.” The six elements are: (1) mainland, (2) back-barrier lagoon, (3) inlet and inlet deltas, (4) barrier island (superstructure), (5) barrier platform (substructure), and (6) shoreface. The sandy islands of the southeastern Canadian Beaufort Sea are true barrier islands according to OERTTEL’s definition in that they contain these six elements (Figures 4 & 7), although tidal inlets and associated deltas are infrequent and poorly developed because of minor tidal activity. The barrier islands of the southeastern Canadian Beaufort Sea are however of modest dimensions in comparison with the classical examples of the eastern coast of North America (LEATHERMAN, 1979a).

The barrier islands occurring along the Tuktoyaktuk Peninsula are composed of well-sorted, fine to medium sand. Their elongated shapes (Figure 5) are typical of a micro-tidal environment (HAYES, 1979) and in most cases they face the northwesterly dominant wave approach. These barriers measure up to 10 km in length, are very low (< 1 m), generally wide (up to 450 m), and are extensively overwashed during storms. They usually form a uniform sand body, but some are linked to small remnants of the eroded mainland. Offshore barrier islands are completely detached from the mainland, stranded at some distance from the coastline (Figure 5). Because of the distance of these features to an eroding headland, sediment supplied from a longshore direction is likely restricted. As along the spits, swash bars are common on the seaward side of the barrier islands (Figure 5); they tend to migrate onshore during fair-weather conditions.

**Detached Spits**

Spit detachment appears to be the main mode of formation of barrier islands in the Canadian Beaufort Sea (RUZ et al., submitted for publication). Some barrier islands are just slightly detached from the mainland, only separated from an adjacent spit by a small inlet. In these cases, longshore sediment supply is likely to be more significant as sediment bypassing must occur across the inlets. West of Atkinson Point, for example (Figure 4), the morphology (elevation, width, backshore slope) and sedimentology of the barrier island are similar to those of the adjacent spit. This type of coastal feature, designated by the term “detached spit” in this paper, represents an intermediate morphological type of barrier between spits and “offshore barrier islands.”

**SPIT AND BARRIER ISLAND MIGRATION**

**Rates of Landward Migration**

During the Holocene, the coastline of the Beaufort Sea has undergone a regional recession in response to the rise in relative sea-level (HILL et al., 1986). At Atkinson Point, as on sev-
eral other beaches in the area, freshwater peat outcrops on the foreshore (Figure 8) because of beach erosion and landward migration of the spit. Radiocarbon dating of the peat revealed an age of 2950 ± 70 BP (Beta-28281). At the same location, a core has been collected about 500 m farther landward, near the edge of the lagoon (Core A2-87, Figure 4). The bottom of the core consists of freshwater peat and is overlain by an organic-rich silty sand unit occurring about 50 cm below present sea-level (Figure 9). This silty-sand deposit contains algae and brackish to freshwater dinoflagellates (*Naiadinium pallidium*, *Sigmopollis psilatus*, *Pediastrum boryanum* and *Ovoidites spp*) suggesting that it was probably deposited in a brackish environment with slight freshwater influence. We interpret this unit as representing a very shallow backbarrier lagoon environment with freshwater species input resulting from the erosion of surrounding terrestrial material. This unit has been dated at 1280 ± 70 BP (Beta-28282) and is covered by modern backbarrier sand. Our interpretation of the depositional facies suggests that the landward migrating spit began to bury the brackish backbarrier deposit sometime after that date while the sea-level was close to or slightly lower than present.

The study of the recent evolution of the spits and barrier islands of the southeastern Canadian Beaufort Sea, using aerial photographs, showed that these coastal features are still experiencing landward migration at various rates (Table 1). Between 1950 and 1985, the mean recession rate of the barrier islands was 3.1 m a\(^{-1}\) while it was 1.7 m a\(^{-1}\) for the spits and 2.0 m a\(^{-1}\) for the “detached spits.” Individual measurements along the coastline revealed retreat rates ranging from 0.9 to 3.3 m a\(^{-1}\) for the spits and 1.5 to 4.5 m a\(^{-1}\) for the barrier islands. Along the spits, erosion rates are usually higher in the proximal part and lower at the distal end. At Warren Point and Topkak Point, for example (Figure 2), retreat rates

Figure 7. Block diagram illustrating the sedimentary environments and the physical processes interacting in the barrier island system along the southeastern coast of the Canadian Beaufort Sea (after Ruz et al., submitted for publication).
Figure 8. Freshwater peat exposed on the foreshore of Atkinson Point spit. See Figure 2 for spit location.

Figure 9. Lithology and internal structure of core A2-87, collected in the backshore of Atkinson Spit. See Figure 4 for location.

decrease towards the tip of the spit, varying from 1.7 to 1.0 m a$^{-1}$ and from 1.3 to 0.9 m a$^{-1}$ respectively. This can also be seen at Mingnuk spit (Figure 10) where air photograph comparison shows that the most significant erosion occurred at the proximal part of the spit while accumulation took place at the extremity, this type of coastal evolution being classical along growing spits which show erosion in the proximal part and correlative accumulation at the distal end (GUILCHER, 1954).

Landward migration rates are generally higher along barrier islands (Table 1). The comparison of air photographs of the Cape Dalhousie barrier island system (Figure 2) between 1950 and 1985, gives an example of landward migrating barrier islands (Figure 11). This barrier island system is formed of sand bodies linked to small remnants of the eroded mainland (Pleistocene sands covered by tundra) which now constitute parts of the landward migrating barrier island. Their erosion provides some material to the beach. During this 35 year period, the mean landward migration rate was of 2.6 m a$^{-1}$, but substantial longshore differences in retreat rates along the seaward side of the barrier island have been measured (Table 1). Retreat rates, which varied from 1.5 m a$^{-1}$ up to 4.5 m a$^{-1}$, seem to be controlled by the exposure of the beach to the dominant
Table 1. Retreat rates, potential longshore sediment supply and exposure to incoming deep-water wave power along spits, detached spits and barrier islands of the southeastern Canadian Beaufort Sea (see Figures 2 and 3 for location).

<table>
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<th>Name of Coastal Feature</th>
<th>Location of Measurement</th>
<th>Type</th>
<th>Mean Retreat Rate (m a⁻¹)</th>
<th>Potential Longshore Sediment Supply (10³ m³ a⁻¹)</th>
<th>Incident Deepwater Wave Power (kW m¹)</th>
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<td>East McKinley South Spit S</td>
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<td>East McKinley Barrier Middle</td>
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<td>Atkinson Point Barrier Middle</td>
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Type: BI = Barrier Island, S = Spit, DS = Detached Spit.

northwesterly wave approach and by the availability of sediment eroded from the small headlands.

No significant longshore migration of barrier islands has been measured. Only tidal inlet migration has been observed. This has occurred when the progression of a spit has induced the erosion of the extremity of a barrier island on the downdrift side, for example west of Atkinson Point (Figure 4). Here the progression of the spit between 1950 and 1985 caused a southwestward migration of the tidal inlet with a correlative erosion of 150 m of the tip of the barrier island.

An Example of Spit Evolution and Sediment Budget

Mingnuk Spit is a low sandy barrier-spit extending across a small breached thermokarst lake (Figure 10). Between 1950 and 1985, this spit has retreated landward at a rate of 2.2 m a⁻¹ while, during the same period, it extended more than 300 m to the southeast across the embayment. A simple sediment budget calculation has been carried out for that coastal system for the period 1950-1985. The volume of the spit has been estimated for 1950 and 1985 by calculating the surface area, mean elevation above sea-level based on topographic profiles surveyed in 1986 (GILLIE, 1987), and assuming an average thickness down to 3 m below sea-level, based on water depths in nearby lagoons.
the spit thickness is an approximation, the possible error is the same in both cases, so it appears that the volume remained nearly constant or that some sediment loss possibly occurred. Potential sediment supply has been estimated by calculating the volume of sediments eroded in the adjacent bluffs during the same period. These bluffs are 1 to 5 m high and consist of massive ice overlain by about 1 m of mostly sandy sediment. Field measurements revealed very high retreat rates (up to 11.5 m between 1986 and 1988) due to large block failure. However, these rates appear to be high when compared with long-term erosion as measured on air photographs (2.1 m a\(^{-1}\)). The occurrence of massive ground-ice within the bluffs results in high inter-annual variability resulting from dramatic erosion during a single season and relative stability during the following years. The supply of sediment from the headland has been estimated from the 1950 and 1985 air photographs by dividing the coastline in sections of equal retreat rates. The resultant volume is \(8.2 \times 10^4\) m\(^3\). Because the air photograph comparison suggests that Mingnuk spit and the small spit to the northwest showed very little change in volume between 1950 and 1985 (Figure 10), other sediment sinks are needed for this material. A part of this sediment was distributed alongshore, contributing to nourish
both spits, but was probably also deposited in the lagoons and at the tip of the spits to build a subaqueous spit platform. The occurrence of small-scale flood deltas at the entrance of some shallow lagoons shows that tidal currents may also play a role in the littoral sediment transport pattern. In addition to longshore and landward sediment transport, there is also a seaward component of sediment transport. A detailed study carried out at Tibjak Beach, 11 km southwest of Mingnuk spit, showed the existence of strong storm-induced seaward-directed currents responsible for offshore sediment transport (Hequette et al., 1990).

The Role of Wave Energy and Longshore Sediment Supply

Least-squares regression analyses of retreat rate as a function of potential longshore sediment supply and exposure to deep-water wave power have been carried out. Because beach and nearshore sediment texture and shoreface slope, among other factors, are major controls on spit and barrier island behavior (Swift, 1975; Carter and Orford, 1984), only the spits and barrier islands of the Tuktoyaktuk Peninsula were examined as they are composed of similar material (generally fine to medium sand) and are associated with a very flat shoreface (gradient typically ranging from 1:750 to 1:1500 from the coastline to the 10 m isobath) composed of relatively homogeneous grain-size (mostly sand or silty sand) (Vilks et al., 1979).

In comparison, north of Richards Island, near the Mackenzie Delta (Figure 1), the shoreface bottom material consists of silt and clay (Hill and Nadeau, 1989), while the nearshore gradient can be as steep as 1:45 seaward of the Yukon coast where spits and barriers are commonly formed of coarse-grained sediment (pebble, gravel and sand) (Lewis, 1975; Hill, 1990).

Regression analysis showed a linear relationship between retreat rates and potential longshore sediment supply (Figure 12A) with a correlation coefficient \( r = 0.77 \), statistically significant at the 99.9% level, revealing the importance of sediment availability in the behaviour of spits and barrier islands. However, the regression analysis of retreat rates as a function of exposure to deep-water wave power revealed a poor correlation \( r = 0.31 \). The fact that the wave power data do not include the effects of refraction and other losses of wave energy across the shallow shelf may account for a part of the statistical variance. Consequently, depending on the site-specific nearshore bathymetry, the effective wave energy can vary substantially from one coastal site to another, even if they are exposed to the same deep-water wave climate. Despite these differences, it appears that for the same wave energy, spits and detached spits are retreating more slowly than barrier islands (Figure 12B).

Interestingly, when barrier islands only are considered, their retreat rates are more highly correlated to wave power (Figure 12C). Although only a small number of data points is
available, the regression analysis revealed a correlation coefficient of 0.70, significant at the 99% level. On the other hand, spits and detached spits retreat rates were not significantly correlated with incoming deep-water wave power ($r = 0.18$). These results show that the barrier islands not linked to the mainland seem to respond more directly to variations in wave energy, compared to spits or to barrier islands more closely linked to sources of longshore sediment supply (i.e., detached spits).

Statistical tests have been undertaken to assess the significance of difference between the retreat rates of barrier islands, spits and detached spits. Mann-Whitney U-test and Student’s t-test both showed no significance difference between retreat rates of spits and detached spits ($p > 0.1$). However, the same tests indicated that the difference in retreat rates between barrier islands and spits is significant at > 99% confidence level. These differences in coastal behaviour can be explained by the respective geomorphic and sedimentary processes responsible for the landward migration of these coastal features.

**DISCUSSION**

Because of their respective morphological characteristics, the spits and barrier islands of the Tuktoyaktuk Peninsula are retreating in response to specific combinations of physical processes. Two different types of processes contribute to the landward migration of the spits and barriers in the study area: these are (1) upper beach and foreshore erosion, accompanied by longshore sediment transport, and (2) overwash sedimentation with landward transfer of beach and backshore sediments.

In the southeastern Beaufort Sea, spit development is strongly controlled by the sediment input originating from the updrift direction, this supply of clastic material depending on the height and composition of the eroding bluffs near the proximal part of the spit. If the retreating bluffs provide a large sediment supply, coastwise progradation of the spit will occur, as air photograph comparisons showed, with little erosion of the beachface. However, if the amount of sediment entering the system is decreasing due to a reduction of available sediments at the source (e.g. lower bluff height, higher ice content, or bluff sediment too fine to remain in the littoral system), wave-generated erosion of the seaward side of the spit will occur. In that case, most of the sediments are transported alongshore leading to accretion at the distal part of the spit while the spit is progressively thinning as a result of beachface erosion due to the reduction of sediment input into the system. Foreshore and backshore erosion results in the landward migration of the spit crest and of the seaward edge of the foredune (if any) and thus in the landward displacement of the shoreline.

Overwash processes also play an important role in the landward migration of spits. Spits are affected by overwash processes in response to rising water levels and/or increasing wave height, usually during high-magnitude low-frequency storm surges. The crestal elevation of the spit will determine whether or not overwash will occur and if so, what type of backbarrier morphology will result from overwashing. Overwash is more common where the spit relief is low (absence of foredune, low foredune or low-lying parts of spits). A flow of sediment-charged water moving across a low crest will produce a sheet-like deposit over the backshore. When the spit shows higher relief, increase in overwash volume may generate unidirectional flows creating distinct channels through the crest which act as conduits in which sediments are transported landward. When incision of the crest occurs, a runoff channel and a washover fan develop (Figure 13); with increasing overwash activity, washover fans may merge laterally to form a washover flat. Whatever backshore morphology results from overwashing (i.e. fan or flat), the material is deposited on the landward slope as subhorizontal to very low angle laminae (Figure 14). At the terminus of the washover fan or flat, a small-scale washover delta develops characterized by prograding high-angle landward-dipping foresets. The process of overwashing constitutes a significant mechanism contributing to the shoreward migration of the spits of the study area by transporting landward nearshore and beach sediments.

The presence or absence of dunes on the spits is an important factor affecting the intensity of both beachface erosion and overwash processes. According to Leatherman (1979b), coastal dunes play at least three major roles during storms, functioning as sand reservoirs, energy
Figure 13. Small-scale washover fan on the landward side of Topkak spit (pencil in the center of the fan for scale). See Figure 3 for spit location.

Figure 14. Schematic illustration of internal structure of extensively overwashed spit at Atkinson Point showing beach cross-bedded sets, washover planar stratification, and prograding high-angle landward dipping washover delta foresets in the backbarrier lagoon. The stratification patterns are based on X-ray radiographs of two shallow vibracores (one through the crest and one near the edge of the lagoon; see Figure 4 for location) and on trenches across the backshore. Note that the stratification structures are not at scale and that the angle of dips is exaggerated.
dissipators and barriers to storm waves and swash. Dunes help to minimize beach erosion by serving as a stockpile of sand; they also act as natural barriers restricting overwash. The lower spit retreat rates have been measured at Tibjak and Topkak spits, north of Tuktoyaktuk (Figure 3), which are migrating landward at rates of 1.0 and 1.1 m a$^{-1}$ respectively. Well developed dunes and foredunes occur over a long portion of these two spits (Figure 6A & 6B), contrary to what we observe at the other spits which are retreating more rapidly despite the fact that they are exposed to a less energetic wave regime (Table 1). Therefore, in addition to the sediment supply from adjacent eroding bluffs, which enhances the stability of a spit, coastal dune occurrence helps to reduce the landward migration.

The barrier islands are more often and more extensively overwashed because of their low crest elevation and the virtual absence of dunes. Only a moderate storm surge will cause the water surface to rise to an elevation where waves are capable of moving water across the barrier crest. Depending on the magnitude of water level superelevation, overwash can be intermittent resulting only from runup of larger waves or may induce the complete submergence of the barrier island. Barrier submergence may lead to continuous current action and landward-directed sediment transport across the overwashed barrier. As a result, a morphology of coalescing washover flats will develop over the backslope of the barrier. This type of backshore morphology is the most common for the barrier islands of the study area with small-scale shallow runoff channels across the crest, probably formed by lower magnitude overwash events at the end of a storm.

Overwash is the main process responsible for the landward migration of the barrier islands of the southeastern Beaufort Sea. In areas where the tidal range is greater, tidal inlets and associated construction of flood deltas may account for most of the landward sediment transfers (Armon and McCann, 1979). However, in the micro-tidal Beaufort Sea, flood-tidal deltas are poorly developed and play an insignificant role in the landward migration of the barrier islands. In general, landward-retreating barrier islands lose sediment to the offshore through foreshore and shoreface erosion (Swift, 1975; Maurmeyer, 1978). However, despite their high retreat rates, the width of the barrier islands is similar on the 1950 and 1985 air photographs, suggesting a fairly constant sediment volume. Because there is no direct longshore sediment source nor river sediment supply, some onshore sediment transport seems to be necessary for explaining the relative maintenance of the barrier islands. In the eastern Beaufort Sea, sand is abundant in the nearshore and inner shelf zones as a transgressive sand sheet overlies Pleistocene glaciofluvial sands (Héquette and Hill, 1989; Blasco et al., 1990) (Figure 15). Under certain circumstances, waves and wave-generated currents are responsible for onshore sediment transport since the net bottom stresses due to waves are onshore, but sea ice processes may also contribute offshore sediment to the littoral system. It has been shown that onshore-directed ice push may represent a significant process supplying sediment to beaches in the Arctic environment (McLaren, 1982) and several examples have been documented along the Beaufort Sea coast (Reimnitz, et al., 1990).

As shown by the correlation analyses, the landward migration of spits and barrier islands is strongly controlled by sediment availability. The fact that a coastal feature is attached or almost attached to the mainland is significant in permitting longshore sediment supply which may even result in an excess of sand and spit progradation. The occurrence of sand dunes on several spits also contributes to coastline stability. However, offshore barrier islands rely only on their own sediment stock (barrier superstructure) and on possible sediment supply from the shoreface. Therefore, because of the relative scarcity of available sediments, the barrier island sediment budget will be in equilibrium at best and more likely in deficit (output of sand greater than input), resulting in higher retreat rates.

Poor correlation was obtained between spit retreat rates and wave power because the sediment supply can vary greatly from one spit to another depending on parameters like the height and composition of the nourishing bluff and the presence or absence of coastal dunes. This high variability in sediment supply results in more variable retreat rates for the same level of incident wave energy. A better correlation has been found for the offshore barrier islands because they all experience limited sediment
Figure 15. Conceptual geomorphic model of spit and barrier island migration in the southeastern Canadian Beaufort Sea, showing idealized plane view and cross-section with major sediment transport paths: (1) spit; (2) barrier island. The tentative representation of the stratigraphy is inferred from shallow vibracore samples in spits and inner shelf sand sheet and from high resolution seismic profiles on the inner shelf (Héquette and Hill, 1989). Arrow dimensions are proportional to the volume of sediment transport.
CONCLUSIONS

(1) Spits and barrier islands in the southeastern Canadian Beaufort Sea are experiencing rapid landward migration. Barrier islands migrate onshore at a mean rate of 3.1 m a⁻¹ whilst spits are retreating at an average rate of 1.7 m a⁻¹. Detached spits, which represent a type of barrier island almost attached to the mainland, migrate landward at a rate of 2.0 m a⁻¹.

(2) Spits are retreating in response to beach-face erosion and storm overwashing where low crestal elevation permits swash incursion across the crest; the main physical process responsible for barrier island migration is overwashing.

(3) Correlation between retreat rates and longshore sediment supply is significant for both spits and barrier islands. Landward migration rates are well correlated with incident deep-water wave power in the case of offshore barrier islands but not for spits and detached spits.

(4) Direct sediment supply from adjacent bluffs and the presence of coastal dunes effectively limit spit erosion and retreat. In the case of offshore barrier islands, the lack of significant longshore sediment supply is favourable to a net sediment deficit and results in higher retreat rates.

(5) The high variability in sediment supply from one spit to another explains the large statistical variance observed between retreat rates and wave power. Barrier islands are more strongly controlled by wave energy variations as the available sediments consist essentially of sand from the barrier itself and of possible sediment supplied from the shoreface.

ACKNOWLEDGEMENTS

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La côte sud-est de la Mer de Beaufort canadienne est essentiellement composée de falaises vives entaillées dans des sédiments meubles quaternaires, d'anciens lacs de thermokarst envahis par la mer et transformés en petites baies, et de flèches et îles barrières migrant rapidement vers la terre. Les mesures effectuées à partir de photographies aériennes ont révélé qu'entre 1950 et 1985, les flèches ont migré vers la terre à un rythme de 1,7 m a\(^{-1}\) alors que les îles barrières ont reculé à un rythme de 3,1 m a\(^{-1}\). Les "flèches tronçonnées", qui sont un type particulier d'îles barrières presque rattachées à la terre, ont reculé à un rythme de 2,0 m a\(^{-1}\). Ces inégalités entre les rythmes de migration sont expliquées par les variations dans les apports sédimentaires, les caractéristiques morphologiques des flèches et des îles barrières, et les processus responsables de la migration de ces formes d'accumulation littorale. Des analyses statistiques ont révélé que le rythme de recul de ces accumulations littorales est étroitement lié aux apports sédimentaires. L'analyse des rythmes de retrait en fonction de l'énergie en eau profonde des vagues incidentes montre que les îles barrières reculent plus rapidement que les flèches même lorsqu'elles sont exposées à des vagues de même énergie. L'érosion et le recul des flèches est limité par un apport direct de sédiments provenant de l'érosion des falaises meubles ainsi que par la présence de dunes côtières. Dans le cas des îles barrières, l'absence d'apport sédimentaire littoral important favorise un déficit sédimentaire net ce qui induit un recul plus rapide. Les processus responsables de la migration des flèches sont l'érosion frontale de la plage et les débordements de tempêtes là où la flèche est suffisamment basse pour permettre au jet de rive d'entaille la crête de la flèche. Les îles barrières sont plus souvent et plus complètement soumises aux débordements de tempêtes qui représentent le processus le plus important induisant leur recul vers la terre.

RESUMEN

La costa del Sudeste del Mar Canadian Beaufort está compuesta esencialmente por acantilados en erosión compuestos de sedimentos del Cuaternario no consolidados. Se formaron complejas entradas a bahías por la rotura de lagos temocarsticos y fléchas y barras han experimentado una rápida migración hacia tierra. La comparación de las fotografías aéreas entre 1950 y 1985 muestra que las flechas se retiraron en dirección a la costa del orden de 1.7 mm/año, mientras que las barras emigraron en dirección a la costa del orden de 3.1 m/año. Las fléchas desprendidas, las cuales representan un tipo de barras, casi alcanzaron la tierra, emigrando en dirección a tierra del orden de 20 mm/año. Estas diferencias en los rangos de emigración se explican en términos de aporte de sedimentos, morfología y procesos físicos. Un análisis de regresión de los rangos de retroceso como función del aporte longitudinal de sedimentos revela que la disponibilidad de sedimentos es un parámetro significante que controla la migración de las fléchas y barras. Analizando los rangos de retroceso como función de la energía en profundidad indefinida, se observa que las barras se retiran más rápidamente que las flechas, incluso si ellas están expuestas al mismo nivel de energía. El aporte directo de sedimentos de los acantilados adyacentes y la presencia de dunas costeras limitan la erosión de las fléchas y su retroceso. En el caso de barras, la carencia de un aporte significativo de sedimentos es favorable a un déficit neto de sedimento, dando lugar a mayores rangos de retroceso. Las flechas retroceden en respuesta a una erosión del frente de playa o el rebase en tormentas donde la baja elevación de las crestas ocasiona el rebase sobre ellas. Las barras son con más frecuencia y extensión sobrepasadas y el rebase representa el principal proceso físico responsable de su emigración.—Department af Water Sciences, University of Cantabria, Santander, Spain.