SEDIMENT TRANSPORT PROCESSES AND COASTAL VARIABILITY ON THE ALASKAN NORTH SLOPE

by

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ABSTRACT

Shoreline development and shore-zone sediment transport on the Alaskan North Slope are dependent upon levels of wave energy, sea ice conditions, and the ice-sediment characteristics of eroding tundra cliffs. Considerable variation exists between the coastal processes and the shore-zone morphology of the Chukchi and Beaufort Sea beaches, (respectively west and east of Point Barrow). The supply of coarse sediments (sands or gravels) and the volumes of material eroded from tundra cliffs are a function of the initial character of the cliff sediments and of the ice content of the exposed cliffs. As cliff heights decrease, the ice content of the cliff increases, erosion rates increase but the sediment supply rates decrease. Wave-energy levels are relatively high and maintain a constant level on the Chukchi coast. The transport system on this coast is continuous and is augmented by storm events. On the Beaufort coast, energy levels are much lower, transport processes discontinuous, and storm events are therefore more significant. Sediments supplied to the coastal zone on the Chukchi coast are derived largely from the erosion of tundra cliffs and the barriers are continuous, linear, and stable. Rivers are the primary source of coastal sediments on the Beaufort coast and the more variable energy levels produce unstable barriers that are subject to aperiodic transport processes.

INTRODUCTION

The shoreline processes and coastal form of the Alaskan North Slope between Cape Beaufort and Demarcation Point are characterized by considerable variability. These differences can be explained in terms of regional variations in geology, sediment supply, and sediment transport processes. This paper discusses the results and interpretations of work carried out since 1975 by the authors and by other workers in this area. The emphasis throughout is on the interaction between the sediments available for redistribution by shoreline processes and on the energy levels which control the redistribution of the littoral-zone sediments.

Although the same processes operate in the shore zone of the North Slope as in lower latitude regions, the role of ice is a key element in understanding the coastal geomorphology and the sediment dispersal patterns. The open-water season is less than 3 months each year and the shore zone is a low wave-energy environment due to the small fetch distances imposed by the perennial polar pack-ice. An additional role of ice is related to the ice content of the cliff sediments which is a critical factor in controlling the volume of sediments available to the shore zone for beach development. The ice content, which is a function of regional variations in cliff height, affects the rates of sediment supply and the construction of beach or barrier systems.

GEOLOGY

The geology of the Alaskan North Slope north of the Brooks Range is characterized by a series of thick (10-40 m) Quaternary sediments which form a low coastal plain. Outcrops of bedrock along the shoreline are limited to a few short sections of the Chukchi coast where Cretaceous sedimentary rocks outcrop at or near sea level. Apart from these relatively few sections of bedrock, the remainder of the Alaskan North Slope coast is composed of unconsolidated materials. Relief is higher along the Chukchi coast than on the Beaufort Sea coast (Table 1). On the Chukchi shorelines 44.3% of the relief is greater than 5 m, whereas, on the Beaufort Sea coast only 11.3% of the relief is greater than 5 m (Hartwell, 1973). The primary effect of this regional variation in relief is that the drainage is predominantly towards the northeast. Although approximately 40% of the North Slope is adjacent to the Chukchi coast, about 80% of the drainage is into the Beaufort Sea (Walker, 1974). This drainage pattern, which results from the greater relief in the western coastal plain, is dominated by the Colville system which drains the majority of the hinterland area.

In terms of the surficial sediments it is possible to distinguish two major units that are found to the east and to the west of Oliktok Point. To the east there is a series of predominantly coalescing alluvial or glacial-outwash fans (sandy, gravel material), or outcrops of the Flaxman Formation (Hopkins and Hartz, 1978). The latter is a sandy, mud Pleistocene deposit which contains pebbles, cobbles and boulders. West of Oliktok Point, the Cubik formation, a Pleistocene marine deposit, is a pebbley sand which contains up to 65% of silt-clay in some sections; elsewhere the stoney muds of the Flaxman Formation outcrop. In all areas, these post-Pleistocene surficial sediments are mantled by a 2-3 m thick layer of thaw-lake sediments, which are predominantly peats and muds (Hopkins and Hartz, 1978).

In terms of broad characteristics, the Chukchi Sea has a coast of relatively high relief and straight shorelines with no large river systems or deltas. The more irregular coast of the Beaufort Sea is a

TABLE 1. Summary of Relief and Tundra Cliff Characteristics

	CHUKCHI COAST	BEAUFORT COAST
Bedrock	• some coastal outcrops • often near surface	• no coastal outcrops
Relief >5 m (%)	44.3	11.3
Cliff Heights mean maximum	 10 m 18 m	 1 to 4 m 6 m
Average Retreat Rates (m/yr.)	0.3	1 to 3
Primary Cliff Sediments	clays gravels	silts
Estimated Overall Cliff Ice Content	≃25%	>90%

result of (i) shoreline erosion in this area of thaw lakes and low relief, and (ii) possible contemporary submergence (Hartwell, 1973). The Beaufort Sea coast has many sections of low cliffs, barrier islands, thaw lakes, and numerous large deltas.

The primary geological features of the North Slope that influence coastal zone processes and sediment transport systems are:

(i) the near-surface bedrock on the Chukchi coast that affects relief, drainage and thaw subsidence,

(ii) the variation in surficial sediments, with a higher fine fraction in the unconsolidated deposits on the Beaufort coast,

(iii) the greater coastal relief on the Chukchi coast, and

(iv) the greater number and size of the rivers that drain into the Beaufort Sea.

This geological background is essential to an understanding of the sediment sources and, therefore, of the sediment dispersal patterns on the North Slope.

The major sources of the sediments that accumulate in the beaches and in the lagoons of the North Slope are: (1) material eroded from tundra cliffs, and (2) sediments supplied to the littoral zone by rivers. Erosion of the barrier islands themselves may provide additional material to the nearshore system. The relative contributions from coastal and fluvial sources differ significantly between the Beaufort and Chukchi coasts. This difference can be attributed largely to: (a) the regional variation in tundra cliff characteristics and in the character of the unconsolidated deposits, and (b) the North Slope drainage pattern.

TUNDRA CLIFFS AND SEDIMENT SUPPLY

Tundra cliffs, comprised of unconsolidated Quaternary deposits and cemented by frozen interstitial pore water, are distributed widely along the Chukchi and Beaufort Sea coasts and are found on exposed outer shorelines as well as along lagoon shorelines. Estimates indicate that 50% to 75% of the coastline is backed by tundra cliffs.

Despite the geographical proximity of the two regions, fundamental differences in cliff morphology, stability and composition exist between the Chukchi and Beaufort Sea coasts. The major morphologic differences are caused by the regional variation in topography that has resulted from a stable to emergent coast with higher relief and near-surface bedrock, hence relatively high coastal cliffs, on the Chukchi Sea coast (Table 1) and from a submergent coast with widespread thaw subsidence, hence relatively low coastal cliffs, along the Beaufort Sea coast (Table 1). This regional variation in relief between the two regions has important consequences to the coastal stability and littoral sediment supply.

Sediments become enriched with pore ice at the tundra surface as a result of normal periglacial processes. Ice contents are typically 75% ice-by-volume near the surface and decrease exponentially with depth to values of 40% at the six-meter depth (Sellman et al., 1975). This means that near the tundra surface much of the bulk volume is actually comprised of ice, whereas, in sediments at lower depths only the normal void space is filled with ice. The important consequence of this phenomena is that the ice content of low cliffs is very high ("ice-rich") and of high cliffs is relatively low ("ice-poor"). Due to regional variations in topography (Table 1), the low, ice-rich cliffs are found primarily along the Beaufort coast and the high, ice-poor cliffs occur along the Chukchi coast.

The ice content of tundra cliffs is an important control on cliff stability, both in terms of rates of change and in terms of the mechanisms responsible for change. Surveys have shown that cliffs along the Chukchi coast are retreating at an average rate of 0.3 m/yr. (Harper, 1978), whereas along the Beaufort coast Lewellen's data (1977) indicate a mean cliff retreat rate of 2.7 m/yr. with local long-term retreat rates as high as 20 m/yr. Much of this order of magnitude difference in retreat rates can be attributed to the excess ice effect discussed above. In addition, large volumes of material may be eroded from low cliffs but these volumes would produce only small amounts of sediment for potential redistribution as these cliffs are largely comprised of ice. The effect of excess ice is illustrated in Figure 1 which shows the relationship between cliff height, retreat rates and the volume of sediment produced by erosion. From this figure, a 2-m high "ice-poor" cliff retreating at 0.5 m/yr, would supply one cubic meter of sediment to the littoral zone. An "ice-rich" cliff of the same height would have to retreat at a rate of 0.9 m/yr. to produce the same volume of sediment. An important point illustrated in this figure is that the effect of ice content on sediment supply rates is most pronounced for

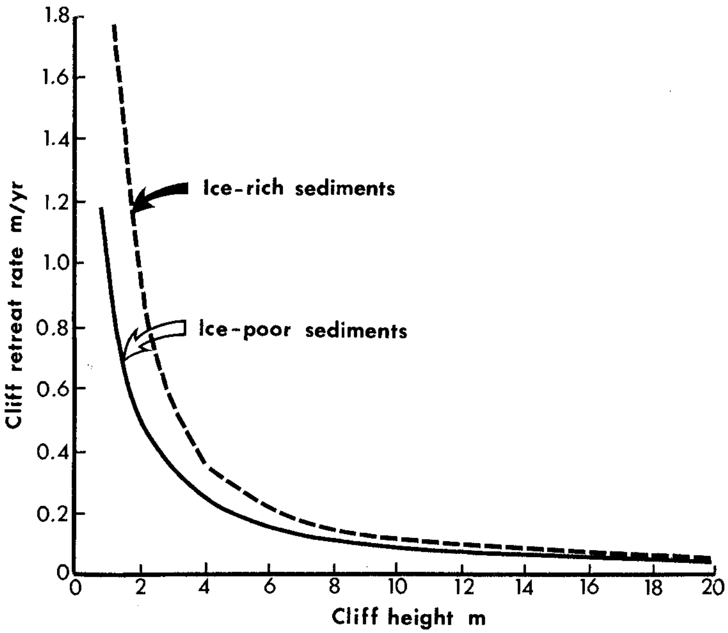

Figure 1. Cliff heights and cliff retreat rates required to produce 1 m^3/year of eroded sediment from "ice-rich" cliffs (dashed line) and from "ice-poor" cliffs (solid line).

low cliffs (less than 3 m in height). The second important effect of the ice content in cliff sediments is a disproportionately high retreat rate for the low-relief, ice-rich cliffs.

An additional factor contributing to the large differences in retreat rate is lithology (Table 1). The Beaufort Sea cliffs are comprised primarily of silt; the sediment produced by erosion of these unconsolidated, fine-grained materials is rapidly transported offshore and lost from the littoral system. By contrast the gravel component of the Chukchi cliffs forms protective beaches at the cliff bases and can be reworked into constructional spits and bars.

As a result of the differences in cliff heights, ice-contents, and lithology between the two coasts, the rate of sediment supply from cliff erosion also differs significantly. Along the Beaufort Sea coast low, silty, ice-rich, rapidly retreating cliffs yield small amounts of sediment for reworking into constructional landforms, whereas on the Chukchi coast, high, gravelly, ice-poor, slowly retreating cliffs yield relatively large amounts of material which is available for redistribution into beaches, bars, spits and barriers.

The other major sediment source is from river input; this also differs significantly between the two coasts. Although the Beaufort Sea coast is 50% longer than the Chukchi Sea coast (Chukchi, 811 km; Beaufort, 1343 km; Hartwell, 1973) over 80% of the drainage of the North Slope is into the Beaufort Sea (Walker, 1974). The major river systems on the North Slope are the Colville, Sagavanirktok and the Canning, all of which drain into the Beaufort Sea. Preliminary estimates (Cannon, 1978) for the Beaufort Sea coast suggest that 82% of the material deposited in the lagoon system is derived from fluvial input and that the remaining 18% is contributed from erosion of the tundra cliffs and of existing barrier islands. Sediment budget calculations for one section of the Chukchi coast indicate that less than 10% of the nearshore sediments are derived from fluvial input and that greater than 90% are contributed by erosion of the tundra cliffs (Harper, 1978).

Significant regional variations exist in terms of sediment sources. Material supplied from cliff erosion accounts for approximately 90% of the total sediment input to the Chukchi coast, whereas less than 20% of the sediment input on the Beaufort coast is from cliff erosion and over 80% is thought to be contributed by rivers. The effects of excess ice in the sediments and, to some extent, lithology are important in controlling these relative contributions.

No estimates are available on the absolute amounts of sediment input to the nearshore budget, however, knowledge of the relative contributions from cliff erosion versus fluvial input and observations of regional morphology suggest that total supply rates (in terms of reworkable material, i.e., sand or gravel) are much lower along the Beaufort than the Chukchi coasts. The net result is that: (1) erosion is exceeding supply along the Beaufort and the coastal system is experiencing a net sediment deficit, and (2) accretion is matching or exceeding erosion along the Chukchi and the coast is relatively stable. These regional variations in supply have important consequences to the stability and morphology of the constructional coastal landforms, particularly the barrier islands.

COASTAL PROCESSES

The single most important factor that controls shore-zone processes is the presence of sea ice on the adjacent coastal waters. The average open-water season on the North Slope decreases towards the northeast from Cape Beaufort to Point Barrow, from approximately 3 months to 1 month at Barrow, and increases to 2 months along the Beaufort Sea coast from Barrow towards Demarcation Point. In addition to open-water data, it is also important to consider the fetch distances and the presence of pack ice on the adjacent sea areas. Due to the location of the edge of the permanent polar pack the Chukchi Sea coast, which is exposed towards the west, has fetch distances in the order of 50-200 km during the open-water season. By contrast, fetch distances on the Beaufort Sea coast vary between 10 and a maximum of 200 km. Figure 2 presents the mean annual position of the 10% ice-cover line. The fetch areas adjacent to the coast are reduced from the southwest towards the northeast and into the Beaufort Sea area. In addition, pack ice assumes an increasingly important role in dampening existing waves. These factors combine to greatly reduce and limit the duration of the open-water period in the Beaufort Sea.

Although wave heights are low and wave periods are generally short throughout the entire area, there is a significant difference in shore-zone wave-energy levels between the Chukchi Sea and the Beaufort Sea due to the differences in potential wave generation. The coasts of the North Slope are low wave-energy environments and the role of storms is, therefore, significant as large pulses of energy are introduced to the shore zone in what would otherwise be relatively quiescent energy conditions. In particular, the southwest winds that affect the Chukchi coast are characterized by frequent short periods of high wind velocities (Short, 1979). Onshore winds on the Chukchi coast occur between 30% and 40% of the open-water season. The relatively short duration of these onshore winds is offset by the higher velocities during storms that occur on this coast and by the longer fetch distances when compared to the Beaufort coast.

Wind data from Barter Island on the Beaufort Sea coast indicates that northeast winds occur between 60% and 70% of the duration of the open-water season. Although the frequency of onshore winds is greater than on the Chukchi coast, the velocities are lower and the fetch distances are smaller, so that overall wave-energy levels at the shoreline are considerably reduced. Although data are scarce for this region,

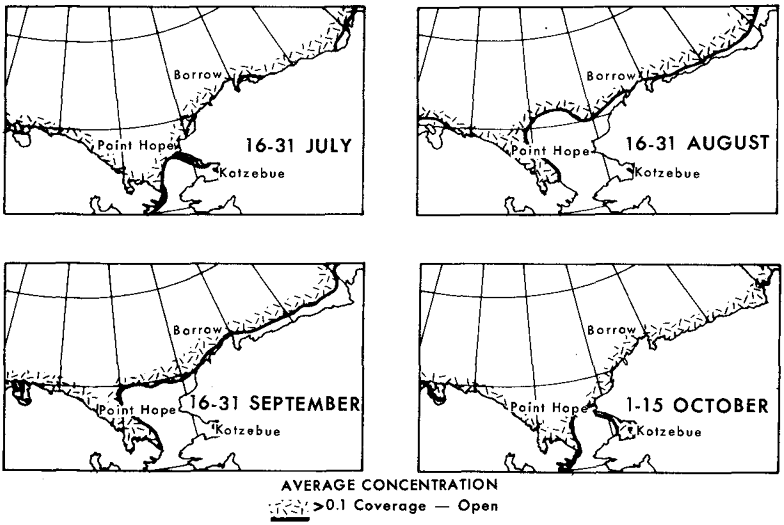

Figure 2. Mean position of the 0.1 (10%) ice-cover boundary for four different summer periods (from Selkregg, 1975).

wave heights greater than 1 m occur for approximately 10% of the open-water season on the Chukchi coast but for only 3% of the open-water season on the Beaufort coast. Brower et al. (1977) provide data on mean monthly wave heights for the Beaufort Sea which give values of 0.39 m for July, 0.48 m for August and 0.77 m for September. A secondary characteristic of the Beaufort Sea wave environment is that the angles of wave approach are generally high, due to the elongate nature of the wave generating zone. In addition to an increase in wave-energy levels from east to west along the Beaufort coast, which is a function of wind direction, the high-angle waves result in an east to west shore-zone sediment transport system.

Wave hindcasts for sites along the North Slope coast have been computed (Table 2) based on fetches derived from maps of the mean ice-margin position (Fig. 2). The wind speeds required to generate a fully arisen sea were determined for each of the fetch distances, based on Neumann (1953). The wave characteristics of the fully arisen sea were then related to wind velocities and the value $\bar{H}$ is the mean wave height of the spectrum. The wave heights are therefore the theoretical maxima possible for each of the onshore directions. These data are summarized diagrammatically in Figure 3.

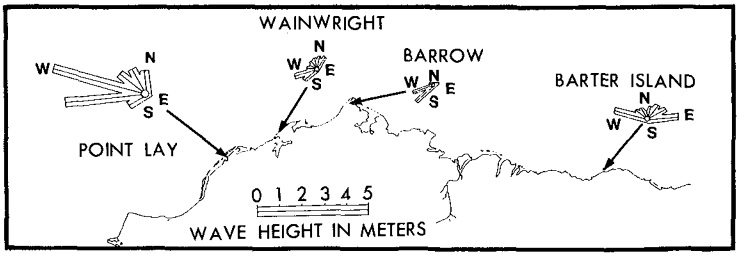

Figure 3. Hindcast maximum wave heights for September (data from Table 2).

TABLE 2. Measured fetch distances (F_m - in nautical miles) and mean wave heights ($\overline{H}$ in meters) hindcast by the Pierson-Neumann-James method, for typical summer ice conditions on the Alaskan shore of the Chukchi and Beaufort Seas.

	JULY		AUGUST		SEPTEMBER		OCTOBER
	F_m	$\overline{H}$	F_m	$\overline{H}$	F_m	$\overline{H}$	
Point Lay							
SW	38	.85	38	.85	38	.85	NONE
WSW	30	.58	229	3.78	218	3.66	
W	27	.49	290	4.57	272	4.36	
WNW	25	.43	245	3.96	76	1.58	
NW	22	.37	60	1.34	60	1.34	
NNW	30	.58	60	1.34	49	1.13	
Wainwright							
WSW	NONE		92	1.86	43	1.04	NONE
W			60	1.34	22	.37	
WNW			32	.61	16	.24	
NW			32	.61	16	.24	
NNW			27	.49	20	.30	
N			32	.61	19	.27	
NNE			38	.85	27	.49	
Point Barrow							
SW	NONE		NONE		50	1.16	NONE
WSW					43	1.04	
W					8	.15	
Barter Island							
WNW	NONE		21	.34	70	1.49	NONE
NW			11	< .15	32	.60	
NNW			10	< .15	27	.49	
N			9	< .15	22	.37	
NNE			10	< .15	27	.49	
NE			11	< .15	33	.67	
ENE			38	.85	28	.85	
E			~100	1.98	60	1.34	

As these are low wave-energy environments storms assume an important role on both coasts in terms of shoreline wave-energy levels and of sediment transport. Storm-induced water level changes are greater than the astronomical tides. The tidal range is less than 50 cm on all coasts, whereas, storm-induced water level changes can reach 3 m (Reimnitz and Maurer, 1978). Under normal circumstances the tidal range is slightly greater on the Chukchi than on the Beaufort Sea coast, whereas, the storm surges are greater on the Beaufort Sea coast.

The computation of shore-zone energy levels provides an approximate guide to relative variations alongshore. Short (1979) indicates that approximately twice as much wave energy acts upon the Chukchi as upon the Beaufort Sea coast (Table 3). Of equal importance to the higher energy levels is the fact that wave processes are more continuous on the Chukchi Sea coast due to higher wind velocities (Owens, 1977). Energy levels on the Beaufort Sea coast are lower and the frequency and intensity of storm-generated waves are also lower. Therefore sediment transport in the shore zone is a relatively continuous process on the more exposed Chukchi Sea coast and transport is more intermittent and more variable on the Beaufort Sea coast. These differences in energy levels are reflected in the character of the beaches and the barriers. On the more exposed Chukchi coast the beaches are both straighter and higher, with better defined berm systems. On the Beaufort Sea coast, beach sediments are generally poorly sorted and often the berm is either low or not present. These basic differences in the profile characteristic of the beaches can be attributed directly to variations in both the frequency and the magnitude of peaks in the wave-energy spectrum.

TABLE 3. Summary of North Slope Process Characteristics

	CHUKCHI COAST	BEAUFORT COAST
Open-Water Season (months)	2 to 3	1.5 to 2
Average Open-Water Fetch (km)	50 to 200	10 to 100
Prevailing Winds	SW	NE
Frequency of Wave Heights >1 m (%)	10	3
Total Open-Water Wave Energy * (ergs x 10^{14})	6.5	3.0

(*Wiseman et al., 1973)

SHORELINE DEVELOPMENT AND BEACH MORPHOLOGY

The regional variations in the geological and process parameters discussed above are clearly reflected in the character of the barrier beaches and in the sediment transport systems. Owens (1977) noted that the barriers of the Beaufort Sea coast have an irregular plan form, rarely have dunes, and are overwashed during storms. By contrast, the barriers between Point Hope and Barrow on the Chukchi coast are continuous, straight, and commonly have low dunes in the backshore. These differences are related directly to variations in both the frequency and magnitude of peaks in the wave-energy spectrum. Owens noted that longshore sediment transport processes on the more exposed Chukchi Sea coast are relatively continuous during the open-water season, whereas, energy levels on the Beaufort Sea coast are both lower and more variable.

The geometry of the barrier systems can be compared by referring to barrier height and barrier width values. Averages taken from survey profiles indicate that barrier heights on the Chukchi coast generally range between 1 and 3 m, whereas, barrier heights on the Beaufort coast greater than 1.5 m are rare. Similarly, barrier width values decrease from 150-350 m on the Chukchi coast to 100-200 m on the Beaufort coast. These morphological differences are a result of a combination of factors related to both wave-energy levels and sediment supply rates.

The paucity of sediments on the Beaufort Sea coast has given rise to a series of discontinuous and relatively unstable barriers which are generally crescentic in shape, are separated by wide tidal inlets, and are highly transgressive (Nummedal, 1979). Sediment transport on this coast takes place primarily as a series of storm-related pulses rather than as a continuous process. The Beaufort coast barriers are transgressive, with an average landward movement in the order of 3-5 m/yr. In response to the east-west sediment transport system (Short, 1979), many of the islands are also migrating towards the west at rates in the order of 20-30 m/yr. This overall sediment transport direction and migration pattern is not uniform, with frequent reversals related to storm winds. Due to the existence of wide inlets between many of the islands, many of the barrier islands are independent, self-contained systems rather than part of a longshore sediment transport continuum. This is in direct contrast to the long, continuous barrier systems of the Chukchi coast which form part of an integrated series of three large sediment transport cells.

The decrease in shoreline wave-energy levels towards the northeast and east along the coast of the North Slope results in an increasing complexity of beach profile morphology and in an increasing variability of beach plan morphology. These trends are a simple reflection of the changes in wave-energy levels alongshore and in the change from a continuous to an aperiodic sediment transport system. Overall sediment transport rates range from 5,000 to 20,000 m^3/yr. on the Chukchi Sea coast to 2,000 to 5,000 m^3/yr. on the Beaufort Sea coast (Wiseman, et al., 1973). Measured longshore sediment transport rates at Point Barrow (Nummedal, 1979) provide values in the order of 1,500 m^3 of sediment transport per day during a three-day storm in 1977 (Fig. 4). Thus this storm alone could have transported approximately 5,000 m^3 of sediment during that single event. Based on field observations and theoretical calculations, the entire annual sediment transport volume on the Beaufort Sea coast could be confined to one or several storm events.

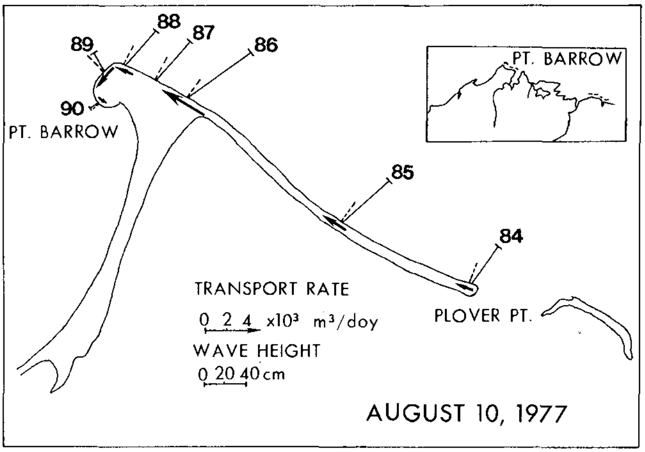

Figure 4. Sediment transport rates (arrows) based on measured longshore wave power and measured wave heights and wave orthogonal angles (bars) at Point Barrow. Numbers (84-90) refer to station codes (from Nummedal, 1979).

DISCUSSION

The assessment of the potential impacts of man's activities is important in engineering design studies. Sediment transport in the shore zone, cliff erosion rates, and the redistribution of beach materials are all critical and sensitive elements of the natural dynamics of the North Slope coasts. Many of the small, narrow, barrier islands of the Beaufort Sea coast are subject to major changes during large storms. The erosion and redistribution of sediments by overwash and by longshore transport can cause erosion and/or deposition on a large-scale during a period of only a few days. Site selection analyses for nearshore and onshore facilities must take into account the potential for such natural dynamic changes in morphology and in shoreline location on barrier islands as well as on the more obvious eroding tundra cliff coasts.

A knowledge and understanding of coastal processes can be used to advantage in the design process. For example, the orientation and shape of artificial islands placed in the nearshore zone can be varied to take into account local transport processes. Figure 5 provides a schematic example of this point. In this scenario an island oriented east-west would have a net shore-zone transport to the east, whereas, a 30° change in orientation to a northwest-southeast alignment would result in net transport towards the northwest. In both cases the calculated net transport rates are in the order of 10^5 m^3/yr. (Nummedal, 1979).

CONCLUSIONS

(a) The supply of sand-sized sediments from cliff erosion for barrier development on the North Slope is controlled by wave-energy levels, cliff lithology, cliff height, and by the ice content of the exposed cliffs. Ice plays an important role in coastal process and in sediment supply variations.

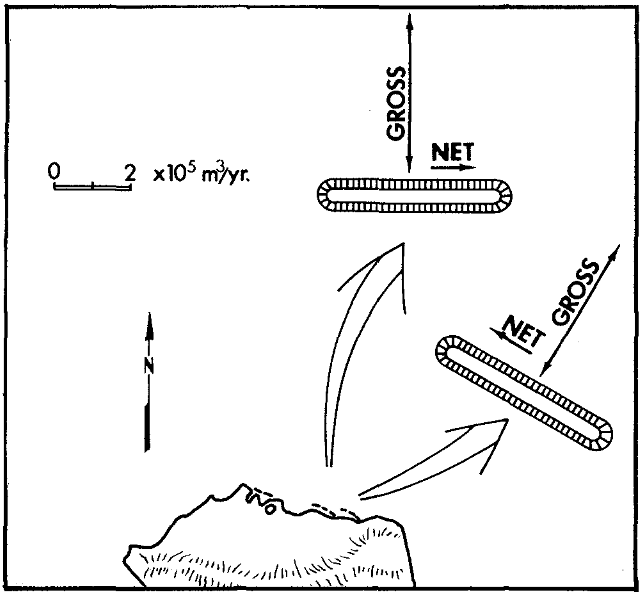

Figure 5. Sediment transport rates on hypothetical deep-water artificial islands.

(b) Shore-zone wave-energy levels are controlled primarily by the distribution of sea ice which limits fetch distances. The ice content of exposed cliff sections is a function of cliff height due to periglacial processes that concentrate ice near the surface.

(c) Variations in barrier and beach morphology between the Chukchi and Beaufort Sea coasts are dependent on the modifying effects of ice, both on the adjacent sea surface and, to some extent, within the cliff sediments.

(d) The Chukchi coast has high tundra cliffs which supply comparatively greater volumes of sediment to the shore zone. Wave-energy levels are higher and barriers are straight, continuous, and stable.

(e) Cliff heights, sediment supply rates and wave-energy levels are lower on the Beaufort coast. The barriers are more crescentic, complex, discontinuous, and transgressive.

(f) Previous studies of arctic coasts have noted the important effects of ice in limiting shore-zone physical processes. On the Alaskan North Slope the effects of variations in ice content within the tundra cliffs also play a critical role in limiting sediment availability for barrier beach development.

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