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The Coastal Morphology and Sedimentology of Cape Hatt Peninsula

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ABSTRACT. A small peninsula located on northern Baffin Island was selected as the site for an experimental oil spill. The experiment required three similar bays, one to serve as control and two to compare the fate and behaviour of oil and an oil-dispersant mix spilled in the nearshore zone. Geomorphic and sedimentologic observations indicate that (1) the shoreline sediments of Cape Hatt are reworked glacial deposits, (2) bays facing Eclipse Sound are the most exposed to wave and ice action and those of Z-Lagoon are the most sheltered, (3) there is a westerly sediment transport direction in the bays of Eclipse Sound, a winnowing of fines from the most exposed bays of Z-Lagoon and several transport directions in Ragged Channel and (4) ice action is the most important process at Cape Hatt. Qualitative assessment of these features was used to recommend that Bay 10 be used for control, Bay 9 for the oil-alone experiment and Bay 11 for the oil-dispersant mix experiment. Geological features, however, reflect the integration of all processes operating at Cape Hatt over long periods of time and do not warrant as high a priority as meteorological and oceanographic criteria in the final selection of bays for the BIOS Project.

Key words: Eastern Arctic, Cape Hatt, shoreline morphology, sedimentology

RÉSUMÉ. Une petite péninsule située à l'extrémité nord de l'île de Baffin, a été choisie pour y conduire un déversement expérimental d'hydrocarbure. L'expérience nécessita trois baies semblables, une devant être utilisée comme témoin, et deux pour comparer les conséquences d'un déversement d'hydrocarbure et d'un mélange d'hydrocarbure et d'un agent de dispersion. L'étude géomorphique et sédimentologique du cap Hatt démontra que (1) les sédiments des plages du cap Hatt sont constitués d'ancient dépôts glaciaires modifiés par l'action des vagues et de la glace, (2) les plages adjacentes à Eclipse Sound sont les plus exposées à l'action des vagues et des glaces, et ceux du lagon "Z" les plus abritées, (3) les sédiments des plages adjacentes à Eclipse Sound se déplacent vers l'ouest; les sédiments les plus fins du lagon "Z" sont remis en suspension et en mouvement; et dans Ragged Channel, il existe plusieurs directions de transport des sédiments, et (4) le glaciel est le facteur et le processus le plus important du cap Hatt. Une évaluation qualitative de ces facteurs permit de choisir trois baies parmi les 13 disponibles et de recommander l'usage préférable pour chacune de ces baies. Toutefois, les facteurs géologiques étudiés représentent l'intégration des processus géologiques de la région sur de longues périodes de temps et ne méritent pas autant d'emphase dans le choix final des baies que celui accordé aux facteurs météorologiques et océanographiques.

Mots clés: Arctique de l'est, cap Hatt, morphologie des côtes, sédimentologie

INTRODUCTION

A small peninsula that extends into southwestern Eclipse Sound (Fig. 1) was selected in 1979 as the site for the Baffin Island Oil Spill (BIOS) Project (Thornton, 1979). This project had two principal objectives: to determine if the use of a chemical dispersant would increase or decrease the environmental effects of spilled oil in the arctic nearshore; and to determine under field conditions the relative effectiveness of various shoreline protection and cleanup techniques. An important requirement related to the first objective was the selection of three small bays with similar physical and biological characteristics. Of these three bays, one was to remain uncontaminated and serve as control, one was to receive a mixture of oil and dispersant and the third was to receive oil alone as a surface slick.

Field work during 1980 and 1981 was designed to determine the coastal morphology, sedimentology and processes of Cape Hatt Peninsula. It included three major components: (1) during late May and early June 1980 nearshore zones were sampled using the sea-ice cover as a working platform (Fig. 2); (2) during late July and early August 1980 the foreshore and backshore zones of all potential bays were profiled and sampled (Barrie *et al.*, 1981); and (3) coring and trenching of the ice overlying the backshore and foreshore zones of selected bays were performed in early May 1981 to determine the interaction of ice and sediments. Geomorphic and sedimentologic features of Cape Hatt were then evaluated with respect to the objectives of the BIOS Project (McLaren *et al.*, 1981), and the most suitable bays for the experimental spills were selected.

FIELD METHODS

In late May and early June 1980 permanently marked profiles were established by driving steel rods into the shore zone of all bays (Fig. 1). Beginning from a point on the beach face, ten equally spaced holes were augered through the ice and used as sampling locations to obtain bathymetric and geologic information. Sediment cores for geological and chemical analyses were obtained using a vibracoring device designed and fabricated after a version developed at the Bedford Institute of Oceanography (Fowler *et al.*, 1977). Cores obtained for geological purposes were separated lengthwise into two halves, photographed, described and subsampled for grain size analyses and biological examination. Cores for hydrocarbon analyses were obtained using sections of chemically cleaned plexiglass tubing as liner inside the core barrel. Both ends of the plexiglass tube were protected from contamination by capping them with chemically cleaned Teflon sheeting prior to freezing. Bottom samples were also obtained using a Foerst-Peterson grab lowered sideways through the ice hole.

In late July and early August 1980 all beaches were profiled using a method described by Emery (1961). Elevations along each profile were measured approximately every 1.5 m and at intervening topographic inflections or facies changes. The top

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15-20 cm of sediment in each facies encountered was sampled and retained for grain size analysis. Nearshore sampling and observations of the sea floor to a depth of 20 m were also carried out in Bays 9, 10, 11 and 13 using scuba equipment. Altogether, 54 cores, 74 grabs, 29 diver-collected samples and 114 beach samples were obtained for chemical and grain size analyses (Barrie *et al.*, 1981).

In order to understand the freeze-up of beaches, four thermocouple probes were inserted approximately 1.8 m into the intertidal zone along the profile of Bay 106. Each probe contained eight underground and one or two aboveground evenly spaced sensors. These sensors were used on an opportunity basis to measure the air and ground temperatures from 7 August to 15 September 1980.

During May 1981 a portable auger was used to core the ice overlying the backshore, beach face and nearshore zone of Bays 10, 11, 12 and 106. The ice cores were examined with respect to salinity, solids content and crystallography. The foreshore of Bay 11 was also trenched to observe the distribution of sediments in ice.

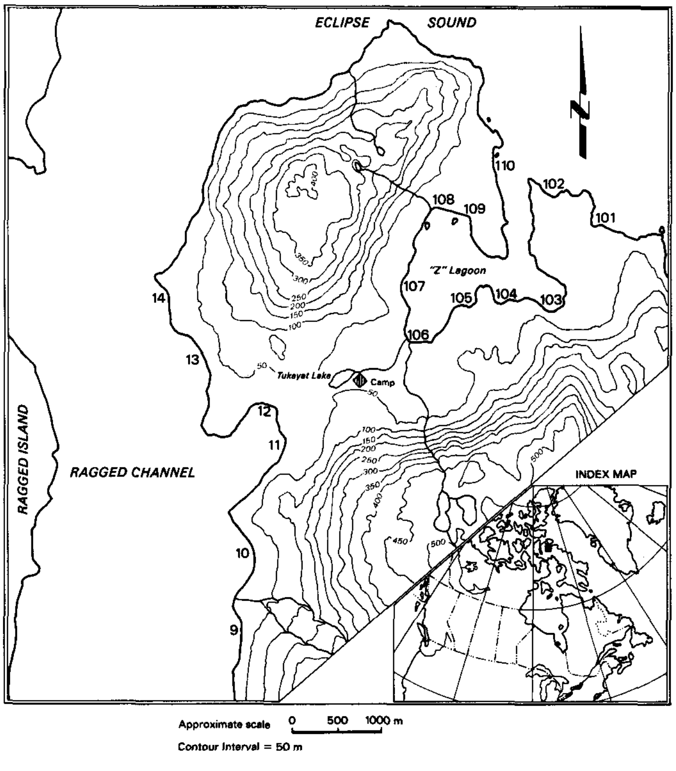

FIG. 1. Bay numbers, general topography and location of Cape Hatt.

GEOLOGICAL SETTING

Cape Hatt is located on the northern tip of a small peninsula that extends into southwestern Eclipse Sound on northern Baffin Island (Fig. 1). The peninsula itself is roughly oval in shape, with an average radius of about 3 km. It is bordered on the north by Eclipse Sound and on the east and west by two northerly trending fiords.

Two elongated hills, both trending northeasterly, are present at the northwest and southeast parts of the peninsula. Reaching elevations of 400 m and 500 m respectively, they are separated by a northeasterly trending saddle-shaped valley that extends between an embayment on Ragged Channel (Bays 11 and 12) and the southwestern end of Z-Lagoon. This valley does not exceed 50 m in elevation.

The peninsula is divided geologically by the White Bay Fault, which trends southeast from the southern end of Bay 10, where it is expressed morphologically by a deeply incised drainage valley. The continuation of this fault across Ragged Channel forms the northeast coast of Ragged Island.

North of this fault, the peninsula is composed of Archean and Aphebian migmatites and a few ultramafic bodies. The migmatites are made up of alternating layers of medium-grain quartz monzonite, granodiorite, amphibolite and paragneiss. These migmatites are presumably the result of the introduction of granitic material into metavolcanic and metasedimentary rocks (Jackson *et al.*, 1975).

The area south of the fault includes two Neohelikian sedimentary sequences: the Victor Bay Formation, composed of thinly bedded black shale, siltstone, limestone, dolomite and sandstone; and the Athole Point Formation, composed principally of thinly bedded argillaceous limestone, calcareous shale and siltstone. The Athole Point Formation overlies conformably the Victor Bay Formation and, south of Bay 9, it forms the core of a northwesterly plunging syncline.

Cape Hatt lies near the northeastern limit of the Laurentide Ice Sheet. The peninsula was completely covered by glacier ice during the early part of the last glaciation (Klassen, 1981). Later, during Late Wisconsinan time, the northern extent of glacier ice was limited to the mouth of Milne Inlet and Oliver Sound. Glacial deposits on upland surfaces are coarse grained and form a thin (<0.5 m) discontinuous cover over bedrock. These deposits are composed of locally derived debris as well as rock fragments known to have travelled more than 100 km from north-central Baffin Island and Foxe Basin to the south. The lower parts of slopes adjacent to Milne Inlet and Ragged Channel are blanketed by glaciofluvial and glaciomarine deposits bounded at their upper margin by moraine ridges and kame-terraces. Two moraine ridges extend in a northeasterly direction on the east side of Ragged Channel and one curves around the embayment of Bays 11 and 12 toward Z-Lagoon (Hodgson and Haselton, 1974). South of Tukayat Lake (Fig. 1), the water-lain sediments terminate in a large glaciomarine delta, with its upper surface at an elevation of 80 m above sea level. This delta marks the Late Wisconsinan terminus of the Laurentide Ice Sheet some 9500 years ago, as indicated by radiocarbon dating of shells found *in situ* (Klassen, pers. comm. 1982).

Bays on the peninsula are generally separated by steep, rocky promontories or headlands, with the exception of a small delta between Bays 9 and 10. The coarse sand, gravel and cobbles that make up the beach and nearshore sediments of the outer bays are all derived from older glacial and glaciofluvial sediments by the action of winds, waves, tides, currents and ice. Modern processes, however, are not necessarily responsible for all morphologic and textural characteristics of the present marine deposits. For example, the sediments of Z-Lagoon, exceptional in that they consist mainly of poorly sorted mud, could represent a distal facies of the Cape Hatt glaciomarine delta. A more likely possibility is that they are a relic feature modified by the sedimentary processes that have been active during the course of Holocene emergence.

CLIMATIC AND OCEANOGRAPHIC CONDITIONS

The climatic and oceanographic conditions of the eastern Arctic are relatively well documented. Recent studies have been reviewed and summarized by Fraser (1983, climate), Fissel *et al.* (1981, oceanography) and Marko (1982, ice conditions). Specific descriptions of the climate, oceanography and sea ice of Cape Hatt are presented in Meeres, 1987; Buckley *et al.*, 1987; and Dickins, 1987.

Cyclonic storms, frequent in Baffin Bay throughout the year and most intense during winter, control the climate of the area. At Cape Hatt, intertidal zones are exposed to essentially undamped wave action only during August and September. During August, winds are often calm (22% of the time) or gentle (3.8 $km \cdot h^{-1}$) from the east or southwest. Wind speed increases during the open water season, and during September winds are calm only 14% of the time. When blowing, they have an average speed of 10 $km \cdot h^{-1}$ from the northeast or west. The maximum hourly speeds observed at Pond Inlet between 1975 and 1980 were 57 $km \cdot h^{-1}$ (August) and 74 $km \cdot h^{-1}$ (September), both from the northeast. During the remaining 10 months of the year, mean speed is generally higher than during August and the predominant direction is from the south (Atmospheric Environment Service, 1982a). Temperatures vary between a mean daily maximum of 7.9°C during July and a mean daily minimum of –37.1°C during February. At Pond Inlet, the mean daily temperatures are above 0°C only during June, July and August (Atmospheric Environment Service, 1982b), and the mean yearly rainfall and snowfall are 58 mm and 88 cm respectively (Canadian Hydrographic Service, 1978).

Few long-term or year-round tide data are available for the Cape Hatt area. In general, the tidal wave progresses in a northwesterly direction in Baffin Bay and westerly in Lancaster Sound (Fissel *et al.*, 1981). The tides have two complete oscillations daily, and as a result of the combination of both diurnal and semi-diurnal components, successive highs and lows are of unequal magnitude. At Cape Hatt, the average tidal amplitude is 1.9 m, the neap tides 0.9 m and the spring tides 2.1 m. At Pond Inlet, the tidal stream is reported to run west at about 103 $cm \cdot sec^{-1}$ (Canadian Hydrographic Service, 1978).

SHORELINE MORPHOLOGY AND SEDIMENTOLOGY

For the following sections, the terms backshore, foreshore, and nearshore are defined as follows: The backshore is the upper zone of the shore lying between the mean high-water line and the landward limit of marine processes. The backshore is affected by waves or covered by water only during storms or exceptionally high tides. It often includes at least one nearly horizontal shelf or terrace of wave-deposited sediments called berm. The foreshore, or beach face, is the part of the shoreline subject to wave uprush. It corresponds roughly to the zone lying between mean high and mean low water. When exceptionally wide and of gentle slope, the foreshore is called an intertidal flat. Nearshore is an ambiguous term. It has been used by different authors to denote the zone extending from the lower water line to well beyond the breaker zone, to the breaker zone or to the first (landward) change in slope of the sea floor. It is used here to describe all subtidal areas profiled and sampled, irrespective of distance to land, water depth or bottom morphology.

Summaries of shoreline morphology and sedimentology are listed in Tables 1 and 2 respectively. For more data, see Mclaren *et al.* (1981) and Barrie *et al.* (1981).

Bays Facing Eclipse Sound

Bays 101 and 102 (Fig. 1) have wide backshores (28 and 21 m) and well-developed berms (7 and 12 m), a reflection of the relatively high wave energy that can be generated in Eclipse Sound. Backshore sediments are very coarse, relatively well-sorted sand with little gravel and little or no mud.

Bays 101 and 102 also have the widest foreshores present at Cape Hatt. They are about 30 m wide, with slopes of about 6-7°, and are made up almost entirely of sand and gravel. The sand fraction is very coarse or coarse and well sorted compared to those of other bays.

A nearshore profile in Bay 102 indicates a slope of about 5°. Bottom samples along this profile show a relatively high proportion of sand and gravel compared with those of other bays. Bottom photography of Bay 102 shows a surface composed mainly of cobbles, pebbles and granules.

The width of the backshore, berm and foreshore, the relatively well-sorted nature of the sand and the absence of fines in the backshore, foreshore and at the surface of the nearshore sediments indicate that, of all bays, 101 and 102 are exposed to the highest level of wave activity.

Bays of Z-Lagoon

Most bays of Z-Lagoon have a gently sloping shore zone, with little or no morphological differentiation of backshore and foreshore. Where present, backshores reach widths of about 16 m. Bays 108 and 109 have steeper slopes and small berms, 3-6 m wide. These have developed probably as a result of waves generated by southwesterly winds funnelled by the valley leading to Ragged Channel. Backshore samples from Bays 103, 104 and 105 show a fairly consistent gravel content (about 15%) and variable proportions of sand and mud. The mean grain size, excluding gravel, is in the range of medium to fine sand and all samples are poorly sorted.

The gentle slopes and low wave activity have prevented the differentiation of foreshores in Bays 103, 104, 105 and 106. In Bays 107, 108 and 109, slopes are steeper (5-8°), and foreshores 23-28 m wide have developed. Foreshore sediments from these bays show a narrow range in sand content (51-67%) and variable amounts of gravel and mud. The range of sand sizes is variable and sorting is always poor. Intertidal flats present in Bays 103, 104, 105 and 106 range in width from 42 to 75 m and consist mainly of poorly sorted fine to coarse sand.

Nearshore profiles in Z-Lagoon show consistent gentle slopes of less than 4°. Nearshore sediments generally contain more than 80% mud, mainly poorly sorted medium and fine silt, with gravel and sand making up less than 3 and 20% respectively.

Bays Facing Ragged Channel

Small berms (up to 7 m wide) make up the entire backshore of Bays 9, 10 and 11, except where eroding bluffs adjoin the foreshore. The backshore width is least in Bay 9 and greatest in Bay 11. Bay 13, the most exposed bay on Ragged Channel, has a 15 m wide backshore that includes a 4 m berm. Backshore samples from this bay show a general similarity with those of bays facing Eclipse Sound.

Of all bays facing Ragged Channel, Bay 9 has the most narrow (17 m) and steep (11°) foreshore. Bay 11 has the widest (31 m) and most gently sloping (4°) foreshore. The slope appears to be controlled by the mean grain size of the sediments; it is

TABLE 1. Summary of shoreline morphology

Morphologic unit	Parameter and units	Eclipse Sound		Z-Lagoon							Ragged Channel			
		101	102	103	104	105	106	107	108	109	9	10	11	13
Backshore	Mean width (m)	28	21	10	16	5	0	0	3	6	1	2	4	10
Berm	Mean width (m)	7	12	np	np	np	np	np	3	6	1	2	4	2
Beach face	Mean width (m)	32	29	np	np	np	np	23	28	28	17	18	31	18
	Mean slope (°)	6.8	6.1	np	np	np	np	7.7	5.1	5.3	10.7	8.6	3.9	7.2
Intertidal flat	Mean width (m)	np	np	50	64	42	75	np	np	np	np	np	np	np
Nearshore	Mean slope (°)	nd	4.7	2.2	3.5	2.5	2.2	nd	3.6	2.9	10.5	8.3	4.0	7.1

nd — No data.
np — Not present.

TABLE 2. Summary of shoreline sedimentology

Bay no.	Morphologic unit	Texture (%)			Moment measures (ϕ)[1]			Number of samples	Water depth (m)
		Gravel	Sand	Mud	Mean size	Sorting	Skewness		
Eclipse Sound									
101	Beach face	25±12	75±12	<1	0.17±0.22	1.04±0.15	0.24±0.22	5	na
102	Backshore	6±9	92±8	2±1	0.68±0.50	0.95±0.23	1.95±1.33	5	na
	Beach face	40±18	60±17	1±0	−0.41±0.43	0.67±0.33	1.26±1.04	8	na
	Nearshore surface	26	59	15	1.77	2.82	2.22	2	12
Z-Lagoon									
103	Backshore	19	74	7	1.30	2.12	1.49	2	na
	Intertidal flat	16±7	82±7	2±1	0.46±0.20	1.48±0.28	2.01±0.68	4	na
	Nearshore surface	1±0	15±13	85±13	6.11±0.56	2.26±0.84	0.88±0.26	10	9±2
104	Backshore	12	45	43	3.72	3.65	0.72	2	na
	Intertidal flat	20	70	10	1.40	2.51	1.79	2	na
	Nearshore surface	3±3	20±9	78±10	6.36±1.15	3.31±0.22	0.15±0.37	9	11±4
105	Backshore	15	55	30	2.58	3.30	0.99	1	na
	Intertidal flat	14±5	51±8	36±12	3.08±1.01	3.67±0.19	0.87±0.33	4	na
	Nearshore surface	<1	5±1	95±1	6.60±1.73	2.56±0.31	0.65±0.72	7	7±2
106	Intertidal flat	12±3	59±2	29±4	2.81±0.37	3.28±0.10	1.06±0.11	3	na
	Nearshore	<1	5±3	95±3	7.71±0.56	2.79±0.13	0.00±0.22	8	5±1
107	Beach face	13	51	36	3.32	3.46	0.99	2	na
108	Beach face	15	67	18	2.14	2.94	1.28	2	na
	Nearshore	<1	8±4	92±4	6.76±0.61	2.59±0.28	0.77±0.46	9	9±2
109	Beach face	40±22	51±29	9±7	0.30±0.12	2.42±0.78	2.77±0.80	3	na
	Nearshore	2±1	16±11	82±12	6.86±0.87	3.33±0.46	0.08±0.39	9	4±2
Ragged Channel									
9	Beach face	19±5	80±6	1±0	0.36±0.19	1.16±0.15	0.53±0.56	9	na
	Nearshore surface	3±3	57±14	40±14	4.24±0.73	3.00±0.49	1.11±0.50	16	11±5
10	Beach face	17±9	80±10	4±3	0.70±0.49	1.57±0.59	1.74±1.50	8	na
	Nearshore surface	3±2	57±20	41±20	4.09±0.85	2.54±0.53	1.40±0.80	20	10±6
11	Beach face	24±12	72±11	4±2	0.84±0.68	1.76±0.28	1.48±1.02	13	na
	Nearshore surface	8±7	59±19	33±22	3.39±1.58	2.88±0.75	0.86±0.60	15	6±5
13	Backshore	9±10	87±13	4±3	1.25±0.18	1.53±0.45	2.76±1.04	3	na
	Beach face	14±11	86±11	1±0	0.64±0.47	0.97±0.25	0.08±0.62	6	na
	Nearshore surface	4±2	66±16	30±16	3.80±1.03	2.97±0.62	1.26±0.62	19	10±5

na: not applicable.
[1] Moment measures are in ϕ units and refer to sand size and smaller fractions only.

coarsest in Bay 9 (0.36 ϕ) and finest in Bay 11 (0.84 ϕ). In general, foreshore sediments of bays facing Ragged Channel contain more sand and their texture is more consistent than those of bays of Z-Lagoon or Eclipse Sound. The proportions of mud and gravel are mostly less than 4% and between 14% to 24% respectively. The mean grain size corresponds to coarse sand and sediments are generally poorly sorted.

Bays 9, 10 and 13 have similar nearshore slopes (8 and 10°). Bay 11 has a much more gently sloping nearshore (4°). In general, the nearshore sediments have a gravel content similar to that of Z-Lagoon (less than 8%), but their sand content is much greater (50-70%). On average, they consist mainly of poorly sorted very fine sand or coarse silt. All nearshore samples show a good correlation between grain size measures and water depth. As water depth increases, the mean grain size becomes finer, the sorting poorer and the skewness less positive. These relationships are thought to reflect the relative importance or the energy level of the processes operating in each bay. The best correlation is found in Bay 10, followed by Bays 9 and 11. Thus Bays 10 and 11 appear to be the most and least energetic of the three.

FIG. 2. Sampling of the nearshore zones using the sea-ice cover as working platform.

FIG. 4. Overturned ice cake with adfrozen gravel on the upper intertidal zone of Bay 102.

FIG. 3. Kettles or ice-melt depressions in the intertidal zone of Bay 102.

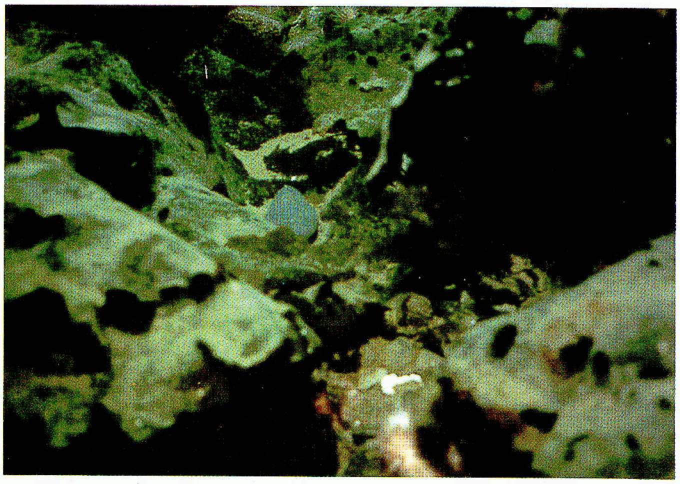

FIG. 5. Pebble resting on algae at a depth of 22 m, an indication of ice rafting.

SEDIMENT TRENDS

A method of interpreting trends in grain size measures developed by McLaren (1980, 1983, 1984; Mclaren and Bowles, 1985) has been applied to the sediments of Cape Hatt (McLaren *et al.*, 1981). According to this method, the mean grain size, sorting and skewness of a sedimentary deposit are dependent on the grain size distribution of the source sediment and on the processes that led to its erosion, transport and deposition. If a sediment undergoes erosion, the lag remaining must be coarser, better sorted and more positively skewed. Sediments in a down-current direction may become progressively finer or coarser than the source, but the sorting will become better and the skew either more negative or positive respectively (McLaren and Bowles, 1985). These trends can be used to infer the net sediment transport paths among sedimentary deposits.

Application of this model to the shorelines of Cape Hatt suggests the following: In Z-Lagoon the shoreline sediments are lags of the lagoon deposits as a result of the winnowing of fines by tides, ice and low levels of wave energy. In Bay 103, the most exposed bay in Z-Lagoon, the nearshore sediments are also lags derived from the original deposits deeper in the lagoon. The winnowed fines appear to be lost through the channel leading to Eclipse Sound. Fines winnowed from Bays 104 and 109 appear to be undergoing complete deposition in Bay 106. This last bay, the most sheltered in Z-Lagoon, may be receiving sediments from both the land and other bays.

In the bays facing Eclipse Sound, all nearshore and foreshore sediments appear to be lags derived from a subsurface glacial sandy silt deposit observed in a core from Bay 102. As a result of waves, tides and ice action, fines are increasingly lost with decreasing water depth, and the coarsest, best sorted and most positively skewed sediments are found on the foreshore. In addition, the foreshore sediments of Bay 101 appear to be a source for those of Bay 102. A similar east-to-west net movement of sediments is also present within Bay 102.

In Ragged Channel, as in Eclipse Sound and Z-Lagoon, the shoreline sediments are winnowed lags derived from nearshore subsurface deposits. The source sediment is also present in the eroding backshore bluffs of Bays 9 and 10. Within Bay 9, foreshore sediments show a weak northward trend and within Bay 10 both nearshore and foreshore sediments have dominant southward trends. The delta that divides Bays 9 and 10 appears to provide sediments to the two bays: however, Bay 10 seems to receive a much greater input. In Bay 11, both the nearshore and foreshore sediment trends indicate a weak northeast movement, and in Bay 13 the beach face sediments show a strong southward transport direction.

ICE AND SHORELINE SEDIMENTS

With the approach of winter, new sea ice begins to form nearshore and often includes old grounded floes, growlers and cakes in its growth. Although new ice forms in late September, a stable ice cover may not develop before late October. Throughout winter, Cape Hatt is surrounded by a continuous shorefast ice cover. New growth normally stops by mid-May, and the first deterioration takes place by mid-June (Dickins, 1987). Melting occurs first along the shoreline, particularly at river mouths and in bays and inlets; and by the end of July, melting floes move according to prevailing wind conditions. The proximity of Navy Board Inlet enables old ice to drift in from Lancaster Sound at any time during summer.

As a result of the climate and the presence of sea ice, the shorelines of Cape Hatt show many features characteristic of arctic and cold regions. These include ice-push and ice-melt features; ice-rafted sediments; nearshore ice scouring; and the presence of an icefoot, ice-cored ridges and nearshore anchor ice.

Ice-push and ice-melt features are all of small dimensions and are all ephemeral. A few ice-push mounds less than 50 cm high were observed on the upper intertidal in bays facing Eclipse Sound; these were obliterated by wave action during the next tidal cycle. This is consistent with observations made by Taylor and McCann (1976) in Eclipse Sound and reflects the limited fetch conditions of Cape Hatt. Ice-melt depressions or kettles (Fig. 3) occur frequently in almost all bays, including those of Z-Lagoon. They are usually less than 1 m in diameter and 30 cm in depth. The formation of kettles has often been attributed to the melting of ice cakes or boulders buried in beach sediments during freeze-up in both arctic (Owens and McCann, 1970; Greene, 1970; Short and Wiseman, 1974; Nichols, 1961) and non-arctic cold environments (Davis, 1973; Dionne and Laverdiere, 1972). However, kettles are not necessarily spring thaw phenomena; they can also be produced during the summer open water season by the grounding and rocking motion of floes, growlers and cakes followed by melting *in situ* or refloating (Taylor, 1981; Short, 1976; Dionne, 1969, 1971). Like ice-push mounds, all kettles observed were located in the intertidal zone and were reworked rapidly by wave action.

Ice rafting of beach sediments and their subsequent deposition occurs in all bays. Sediments observed on and in grounded floes and cakes are of all sizes and are generally similar to those present nearby on the beach, indicating little transport (McLaren *et al.*, 1981). Several overturned ice cakes with adfrozen gravel were observed after they became stranded on the upper intertidal zone of bays facing Eclipse Sound (Fig. 4), and in the sheltered waters of Z-Lagoon thin veneers of mud left by melting cakes blanket surface sediments in distinct patches. During dives in Ragged Channel, gravel, pebbles and cobbles were observed resting on algae (Fig. 5) or, more frequently, in small craters in the fine bottom sediments. These observations indicate that sediments are transported by ice both alongshore and offshore, but it is difficult to estimate the absolute quantities of material involved in these processes.

Nearshore scours ranging up to 5 m wide and 1 m deep were observed within 20 m of water depth during dives in Ragged Channel. These scours mark the grounding of wind and current-driven bergy bits and growlers.

During spring thaw, all shorelines of Cape Hatt show a well-developed icefoot (fringe of ice attached to the shore, unmoved by tides and remaining after fast ice has broken away). Although the term icefoot has been used in the literature on coasts of the Arctic, Antarctic and cold regions since 1856 (Kane, 1856), there is little consensus with respect to definition, description, classification, origin, effects on a beach or even spelling of the term (Dionne, 1973; McCann and Carlisle, 1972).

Observations made before the beginning of the 1981 spring thaw indicate that the ice on the beaches and in the nearshore zones of Cape Hatt has profiles generally similar to the one measured in Bay 11. There the ice is generally less than 1 m thick over the backshore areas; it thickens progressively seaward over the intertidal zone, and immediately nearshore it reaches a thickness of up to 3 m. Farther offshore, the ice thickness is normally less than 1.8 m. Repeated surveying of the ice surface at low and high tides indicated that the offshore vertical displacement of the ice becomes progressively attenuated toward the land, not by vertical slipping along the fractures invariably present parallel to the shore (Fig. 6), but by the rotation of successive zones of ice between adjacent fractures. The maximum vertical offset observed at any fracture during successive tidal cycles was only 30 cm. This process has been observed elsewhere (Owens and McCann, 1970; Frederking, 1980) and has been attributed to the irregular nature of the fracture planes and to sufficient pressure and friction across fracture planes to prevent individual zones of ice from moving

FIG. 6. Ice fractures over the intertidal zone at Cape Hatt.

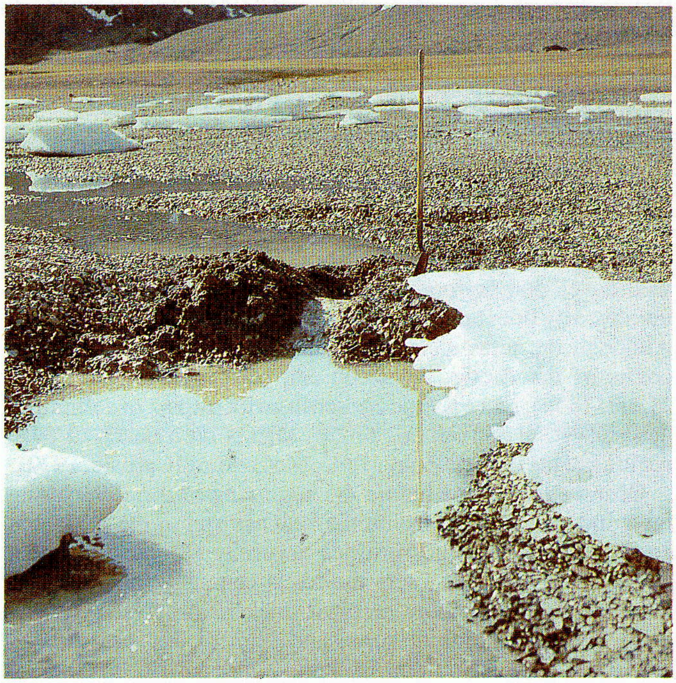

FIG. 7. An example of an ice-cored ridge, a feature found on all beaches at Cape Hatt after the melting of the icefoot.

vertically to a condition of hydrostatic equilibrium (Sadler and Serson, 1981a). The process also accounts for the repeated flooding of strips of ice during high tides.

Salinity profiles and crystallographic observations indicated that in 1981 the ice overlying the backshore, the icefoot and the fast ice all formed by different processes. Over the backshore, salinity is generally low but very variable and the ice is made up entirely of thin, irregular horizontal transparent and translucent layers. Crystals are invariably small (less than 1 mm), equigranular and randomly oriented. Ice overlying the upper intertidal zone is generally similar, although the average crystal size is larger (1-5 mm) and more brine channels are present. Ice overlying the lower intertidal and nearshore zones is very different. Salinity is more consistent, and crystals are very coarse (up to 5 cm long), platy, and show a well-defined preferred orientation with their c axes horizontal (elongation vertical). Brine channels are invariably present and oriented vertically. These observations suggest that the ice overlying the backshore and the upper intertidal zone consists mainly of frozen spray, slush and recrystallized snow. The lower intertidal and nearshore ice results from the freezing of calm sea water, although bodies of frozen slush and old ice cakes are also present.

FIG. 8. Nearshore anchor ice in Bay 107.

Thin horizontal, discontinuous layers and lenses of sediment of all sizes were encountered in the bottom 50 cm of ice over the intertidal zones. Wave action has been observed in the past to cause the incorporation of sediment and the growth of the icefoot (Wright and Priestley, 1922; Rex, 1964; Davis, 1973; Short and Wiseman, 1973, 1974; Bourget, 1977). This may have taken place at Cape Hatt, especially in the fall of 1979, as the melting of the icefoot in the spring of 1980 showed large amounts of sediment present in distinct, discontinuous layers (Dickins and Brown, 1981). However, observations made during the early spring of 1981 suggested that (1) relatively little sediment was incorporated into the icefoot (later verified during the following spring thaw) and (2) most of the sediment became incorporated during the downward growth of ice when in contact with bottom material at low tide. This process of growth of ice and incorporation of sediment has been discussed by Dionne (1973), Rosen (1979) and Sadler and Serson (1981a) and is further substantiated by the presence of sediment in a zone where the ice is, or was at some time during its growth, in repeated contact with bottom material at low tides. Detailed observation of the sediment layers and lenses also shows that they are often thin (2-5 mm), interbedded with ice layers 5 mm to

5 cm thick and often limited by a sharp upper boundary and a gradational lower one.

Ice-cored ridges (Fig. 7) form a pronounced topographic feature on all beaches of Cape Hatt after the melting of the icefoot. The ridges are up to 30 cm in height and invariably parallel the length of the beach close to the mean low water level. They are usually overlain by 20-40 cm of sediment, and consequently their ice cores persist for weeks after all surface ice has disappeared from the beach. The ice cores contain no sediment, are made up of coarse crystals and have a steeply seaward-sloping upper surface. Their thickness is not known. Ice-cored ridges are not restricted to Cape Hatt; they were observed at different times by the author on Devon and Baffin islands and in Labrador.

Nearshore anchor ice was observed in Bay 107 in Z-Lagoon (Fig. 8). It resembles ice-cored ridges in terms of morphology, position on the beach, salinity and coarse ice crystals, but it differs in that it lacks the sediment cover present on ridges.

Both ice-cored ridges and nearshore anchor ice were thought at first to be the last part of the icefoot to melt. Sediments present within the icefoot and derived from land run-off during spring melt could account for the cover present on ice-cored ridges, as proposed by Taylor and McCann (1976). However, a number of features observed at Cape Hatt do not support this. First, both anchor ice and ice-cored ridges have a very low salinity, usually between 0.1 and 1 ppt, much less than that of sea ice or the icefoot (2-8 ppt). Second, coring and excavation of the ice overlying the middle and lower intertidal zone showed that although the ice cover remains unaffected by tides until spring thaw, it is not attached or frozen in place by the bottom. This was demonstrated by the rapid seepage of sea water along the icefoot-sediment interface, in and out of excavations in response to the tides.

Although little is known about the formation of the ice-cored ridges and nearshore anchor ice, they seem to result from the movement and freezing of fresh ground water, as proposed by Sadler and Serson (1981b) and discussed by Mackay (1972). This is further supported by the beach temperature observations made in Bay 106. Readings taken during the fall of 1980 show that as temperature declines, beach face sediments freeze both by the downward movement of a newly created frost table and by the simultaneous upward movement of the persisting permafrost. At some time during beach freeze-up this process forms an unfrozen seaward-dipping channel through which fresh ground water could move or be squeezed out as freezing progresses.

COASTLINES OF CAPE HATT AND THE EASTERN ARCTIC

In the eastern Arctic, between southeastern Devon Island (75° N) and Clyde Inlet (70°N), more than half of all coastlines consist of steeply sloping rock coasts without beach deposits (McLaren and Barrie, 1985). This type of coast occurs on the northwestern part of Cape Hatt Peninsula, on the eastern coast of Ragged Island and in many fiords of Baffin Island, especially south of 70°N (Sempels, 1982). The shorelines of eastern Z-Lagoon and those facing Eclipse Sound include pocket beaches of coarse sediments, which are generally uncommon in the eastern Arctic (<3% of all shorelines). They are generally limited to southeast Devon Island and eastern Eclipse Sound in sediment-poor environments. When present, they are usually narrow and made of coarse sediments (gravel, boulders and cobbles, in decreasing order of abundance). The bays facing Ragged Channel include continuous beaches of sand and gravel, a much more common type that makes up approximately 20% of all coastlines of the eastern Arctic. Continuous beaches occur frequently along Lancaster Sound, Eclipse Sound and on the outer coast of Bylot and Baffin islands. Sediments found in continuous beaches are, in order of decreasing abundance, gravel, cobbles, sand and boulders. The intertidal flats present on the western part of Z-Lagoon occur in less than 9% of the coastlines of the eastern Arctic, mainly in western Eclipse Sound, southern Navy Board Inlet and Milne Inlet.

The bays facing Eclipse Sound have a fetch associated with about 12% of all coastlines of the eastern Arctic. The fetch associated with the bays of Ragged Channel and Z-Lagoon are much more representative of the numerous fiords, inlets and bays present on Baffin Island; approximately 72% of all coastlines of the eastern Arctic have a similar fetch environment (Sempels, 1982).

IMPLICATIONS FOR THE BIOS PROJECT

The main objectives of this study were to obtain and evaluate geomorphic and sedimentologic data in order to contribute to the selection of (1) the three most suitable bays for the experimental spill component of the BIOS Project and (2) of these three bays, the one best suited for control, the one best suited for the oil-alone spill and the one best suited for the oil-dispersant-mix spill.

It was recognized early that geomorphic and sedimentologic selection criteria may not warrant as high a priority as meteorological and oceanographic ones, as the geological parameters reflect an integration of processes over a period of time much longer than the one involved in the BIOS Project. Nevertheless, a selection rationale based on geological parameters only was developed to contribute, along with the meteorological (Meeres, 1987) and oceanographic (Buckley *et al.*, 1987) studies, to the final selection of bays.

It was assumed that, within the limits imposed by the experimental design and allowable realistic concentrations of oil, the experiments would yield the most useful results if the persistence and interaction of the oil and oil-dispersant mix with the biota and sediments were maximized. Thus the bay that, because of its geomorphic and sedimentologic characteristics, would retain oil longest on and in its foreshore and backshore sediments should be selected for the oil-alone spill. Similarly, the bay that would ensure the longest persistence of oil-dispersant mix in its nearshore and foreshore sediments and in its nearshore water column should be selected for the oil-dispersant-mix spill. Finally, the bay with the least possibility for cross-contamination should be selected as control.

Initial consideration of oceanographic, geomorphic and especially biological data indicated that of the 13 bays screened as candidate sites, Bays 9, 10 and 11 were best suited for the experimental spill component of the BIOS Project. The significance and relative importance of the geological features of the these bays were then assessed qualitatively to arrive at a final recommendation with respect to the selection of bays. The features considered include the presence of a berm, the slope and width of the beach face, the nature of beach and nearshore sediments, the degree of relationship of grain size parameters with water depth, the results of the sediment trend analysis and the role of ice.

The presence of a berm is a reflection of wave activity, and there is a greater probability for oil to be cast up and retained on the backshore of shorelines that include well-developed berms. To maximize the longevity and interaction of oil with biota and sediments, the bay with the widest berm (Bay 11) should receive the oil alone (best probability for long-term retention of oil on the shoreline), and the bay with the smallest berm (Bay 9) should receive the oil-dispersant mix (best probability for long-term retention of mix in the nearshore water column and bottom sediments). Bay 10 should, by default, be used as control. This backshore criterion was thought to be of low importance as, in any case, it would not be practical to have the experimental spill take place duirng a period of wave energy sufficiently intense to throw oil on the backshore.

The slope and width of the beach face affect the fate and behaviour of spilled oil. According to this criterion, oil alone should be spilled in Bay 11 because it has a greater area for contamination and a better chance for retention due to wave attenuation over its gently sloping foreshore. The bay with the steepest beach face (Bay 9) should be selected to maximize the retention of the oil-dispersant mix in the nearshore zone. Studies of oil spills showed that beach face width and slope have a significant effect on the fate and behaviour of oil; consequently, a relatively high importance rating was assigned to this factor.

Coarse and well-sorted beach sediments can absorb and retain oil best because of their large porosity and permeability. Accordingly, Bay 9 (coarsest and best-sorted beach face sediments) should receive oil only and Bay 11 (next coarsest and next best-sorted beach face sediments) the oil-dispersant mix. However, as the grain size distributions of the three bays are relatively similar, this factor was given a low importance rating.

Sorting will also affect the fate of oil in the nearshore zone. Consequently, Bay 10, with the best-sorted nearshore sediments, should be selected for the oil-dispersant mix and Bay 11, with the next best-sorted nearshore sediments, should be selected for the oil-alone experiment. As for beach face material, the variation in the degree of sorting of the nearshore sediments was considered to be too small to assign a high importance rating to this factor.

The relationship of the grain size parameters to water depth is thought to reflect the energy level of the processes operating in each bay. The best correlations of mean grain size, sorting and skewness with water depth were found in Bay 10 and the worst in Bay 11. Bay 11 thus appears to be the least energetic and should receive the oil-dispersant mix to maximize interaction time with the biota. Oil alone should be spilled in Bay 9, and the most energetic bay (Bay 10) should be kept for control. The relationship of the grain size parameters with water depth was considered to be important and was assigned a high rating.

The sediment trend analysis provides a means of assessing the potential for long-term cross-contamination between bays, the single most important factor in the selection of bays. Bay 11 shows weak trends away from the other bays and should be selected for the oil-dispersant mix, the most difficult spill to control. Bay 9, with the next weakest trends, can be considered as the next least possible source for cross-contamination and should receive the oil alone. Bay 10, with its strong trends, can be considered the most energetic of the three and should be used as control.

Persistence of oil and oil-dispersant mix in both the foreshore and nearshore zone is undoubtedly affected by ice, the single most important coastal process in the Cape Hatt environment. Moving ice causes considerable scouring, gouging and scraping of nearshore sediments, and these impacts increase with decreasing water depth. Ice-push and, in some cases, ice-melt features found on foreshores are similar to nearshore scouring in many respects. Although oil deposited on the substrate can be subjected to burial, mixing or even resuspension, in general it was felt that persistence will be longer where scouring is least. Diving observations showed that along Ragged Channel all bays are affected by ice scouring. However, the bay with the steepest nearshore has the smallest area subjected to this process. According to this criterion, Bay 9, with its steepest nearshore, is best suited for the oil-dispersant-mix experiment; Bay 10, with its next steepest slope, for the oil-alone spill; and Bay 11 for control. The importance rating assigned to this criterion was kept low because the effects of ice scouring on oil contained in or on bottom sediments have not yet been well documented. Even less is known about the effects of the accumulation and growth of the winter ice cover and about the processes that lead to the formation of ice-cored ridges and nearshore anchor ice. These factors were left out of the selection of bays, as they are ubiquitous at Cape Hatt.

Consideration of these geological factors and their relative importance in terms of the overall project led to the final recommendation that Bay 10 be used for control, Bay 9 for oil alone and Bay 11 for the oil-dispersant-mix experiments. The final selection of bays, after taking into account meteorological and oceanographic parameters, was different because of the overriding concern about the immediate control and longer term fate of the oil slick.

CONCLUSIONS

Shoreline sediments of Cape Hatt are reworked glacial and glacial-marine deposits occurring in the subsurface of nearshore zones and in backshore zones. Ice and wave processes cause the sediments to become increasingly coarser, better sorted and more positively skewed as water depth decreases.

Bays facing Eclipse Sound are the most exposed to wave and ice action. Bays facing Ragged Channel are intermediate in terms of exposure, and those of Z-Lagoon are the most sheltered.

Sediment trend analysis indicates a westerly transport in the bays of Eclipse Sound, a winnowing of fines from the most exposed bays of Z-Lagoon and in Ragged Channel a strong southerly transport in Bays 13 and 10, a weak northerly transport in Bays 9 and 11 and a clockwise gyre in Bay 10.

Ice action is the single most important process at Cape Hatt. Ice-push and ice-melt features are negligible; nearshore ice scouring, ice rafting and the buildup and breakup of the winter beach ice cover have the greatest effect on shoreline sediments.

During the winter of 1980-81, sediments became incorporated into the icefoot by freezing during low tide to the downward growing intertidal ice rather than as a result of wave action. Ice-cored ridges and nearshore anchor ice appear to have a ground-water rather than marine origin.

Qualitative assessment of geomorphic and sedimentologic criteria alone led to the recommendation that Bay 10 be used as control, Bay 9 for the oil alone and Bay 11 for the oil-dispersant-mix experiments. The final selection of bays, however, had to take into account the more important meteorological and oceanographic parameters and the existing potential for cross-contamination. Ultimately, the BIOS Project management chose Bay 11 for the oil-alone experiment, Bay 9 for the oil-dispersant experiment and a bay located south of the study area in Ragged Channel as control.

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