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Sedimentology and Evolution of Subarctic Tidal Flats Along a Rapidly Emerging Coast, Eastern Hudson Bay, Canada

Marie-Hélène Ruz,†* Michel Allard,† Yves Michaud and Arnaud Héquette†

†Centre d'études nordiques
Université Laval
Québec

‡Centre géoscientifique de Québec
Commission géologique du Canada

ABSTRACT

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Detailed investigations were carried out on the sedimentology and evolution of tidal flats located in Manitounuk Sound, along the eastern Hudson Bay coastline. This area is still emerging today at a rate of 1 cm a $^{-1}$ in response to postglacial isostatic uplift. Surface sediments on the Manitounuk tidal flats are distributed in contour parallel fashion, grain-size coarsening seaward from the highest tide level to the shallow subtidal zone. Monitoring of the seasonal evolution showed that sea ice processes are limited in this sheltered micro-tidal environmment, contrary to most tidal flats located in high latitude regions. On a short-term scale, Manitounuk tidal flats are non-depositional. Most sediments derived from eroding bluffs cut into recently emerged fine-grained deposits are exported seaward. Short cores collected across the tidal flats revealed that recent sediments are structureless and are characterized by a compact silty-clay unit overlaid by few centimetres of reworked sediments. This unit is interpreted as fine-grained material originally deposited in deep water and exposed in the intertidal zone due to isostatic uplift. From this study it appears that Manitounuk tidal flats are actually erosion platforms cut into the postglacial Tyrrel sea deep water sediments.

ADDITIONAL INDEX WORDS: *Tidal flats, sedimentology, Hudson Bay, sea ice processes.*

INTRODUCTION

Tidal flats have been intensively studied in the low and mid-latitude regions and a comprehensive review on this topic is given by AMOS (1995). Intertidal flats are often defined as low relief environments where sediments accumulate within the intertidal range (KLEIN, 1977) or where vertical and lateral accretion occur (REINECK, 1978; WEIMER *et al.*, 1982). Tidal flats are best developed in settings of abundant sediment supply and low wave energy (MCCANN, 1980) and they are often associated with sheltered coastal environments and/or fine-grained sedimentation (WELLS *et al.*, 1990). Intertidal flats are usually characterized by a sedimentological and biological zonation (VAN STRAATEN and KUENEN, 1958; EVANS, 1965; REINECK, 1972; AMOS, 1995). Typically, a fining-landwards sedimentological zonation is documented in mid-latitude tidal flats (MCCANN *et al.*, 1981). This zonation is related to the tidal inundation and the effectiveness of tidal currents and waves (VAN STRAATEN, 1961).

In northern regions one of the most important factor affecting tidal flats is ice (DIONNE, 1972, 1988; MARTINI, 1981a; ANDERSON, 1983). Intertidal ice exerts morphological, sedimentological (DIONNE, 1975, 1985, 1988, 1989; KNIGHT and DALRYMPLE, 1976; SASSEVILLE and ANDERSON, 1976; GORDON and DESPLANQUE, 1983) and biological (ELLIS and WILCE, 1969; PETERSON, 1977; GILBERT and AITKEN, 1981; AITKEN *et al.*, 1988) environmental effects on tidal flats.

Few studies have been conducted on modern tidal flats developed along a rapidly emerging coastline. In James Bay and western Hudson Bay, an area still emerging as a result of postglacial isostatic rebound, extensive tidal flats have been studied by DIONNE (1976, 1978, 1980), CHAMPAGNE (1982) and MARTINI (1981b, 1982, 1991). In such context, gradual uplift and exondation of the flats may be as important as sedimentation to change inundation gradients and alter sedimentary processes.

The purpose of this study was to carry out detailed investigations on tidal flat morphology and sedimentology in a sheltered microtidal subarctic environment (Manitounuk Sound, Hudson Bay), in order to determine the respective influence of rapid land emergence and cold-climate processes on the evolution and sedimentology of these tidal flats. A fundamental question was to what extent the "classical" tidal flat morphology (REINECK, 1972) and processes are modified along a coastline were rapid land emergence and cold-climate processes prevail.

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*Present address: Département de Géographie, Université du Littoral-Côte d'Opale, 2 Chaussée des Darses, 59140 Dunkerque, France.

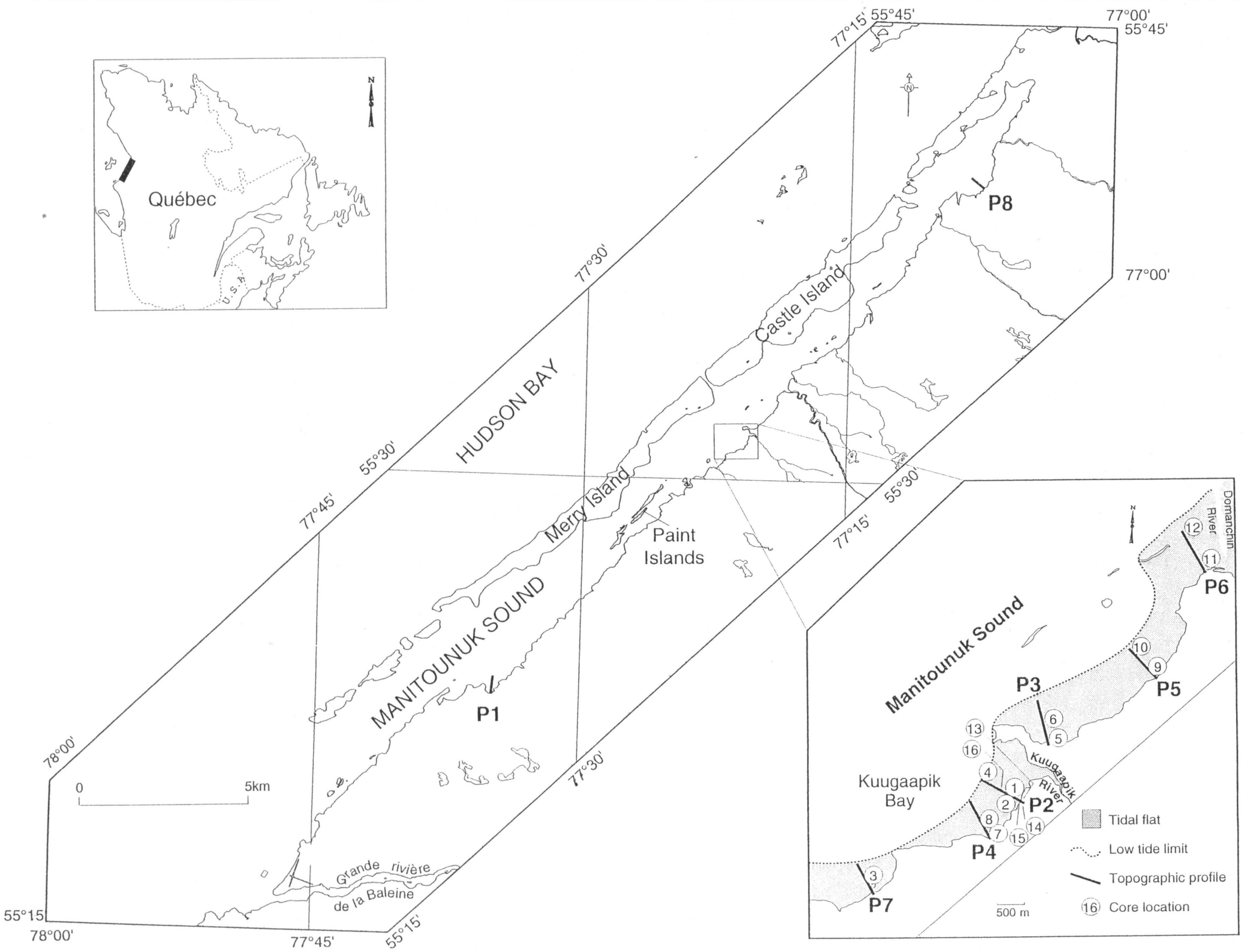

Figure 1. Location map of the study area.

STUDY AREA

Situated 15 km north-eastward of the Great Whale River (grande rivière de la Baleine) estuary, Manitounuk Sound is one of the very few sheltered areas along the eastern coast of Hudson Bay. The Sound is 58 km long, 5.5 km to 1 km wide and is limited seaward by the Manitounuk Islands (Figure 1). These islands are cuestas oriented parallel to the coast, with their dipface sloping gently towards the Hudson Bay. This area was covered by the Laurentide ice sheet during the Wisconsinian. The region was deglaciated at about 8,000 BP (HILLAIRE-MARCEL, 1976) and the Tyrrell Sea postglacial transgression followed ice retreat. This area is an emerging coastline, with present day isostatic uplift of 1 cm a^{-1} (HILLAIRE-MARCEL, 1976; ALLARD and TREMBLAY, 1983; BÉGIN *et al.,* 1993). As the land emerged, the shoreline prograded seaward. Along the eastern shore of the Manitounuk Sound, raised coastal deposits consist of boulder beaches found at elevations ranging from 100 m to 80 m and of sandy beaches developed between 80 m and 15 m. Fine-grained raised coastal deposits are only found below an altitude of 15 m. These emerged intertidal fine-grained deposits are affected by discontinuous permafrost (SÉGUIN and ALLARD, 1984; MICHAUD *et al.*, 1994; ALLARD *et al.,* 1996). Present-day tidal flats, up to 800 m wide, are found in embayments between low and narrow promontories (MOFFET, 1987; RUZ *et al.,* 1994). These intertidal flats are affected by annual freeze and thaw processes (RUZ *et al.,* 1994).

The climate is subarctic. The mean annual temperature is −5.1 °C. Frost is permanent from late-October to mid-May. Manitounuk Sound freezes over in early December and breakup occurs around the end of May. Breakup starts from the mainland and progress seaward. River mouths are free of ice first while the Hudson Bay is usually ice-free 2 to 3 weeks later than the coastal areas (RUZ *et al.,* 1994). Wave action is therefore curtailed for six to seven months each year, beginning in November, by the growth of a icefoot

(BÉGIN and ALLARD, 1982). Published wave data are very sparse for Hudson Bay and no wave record are available for Manitounuk Sound. Limited observations of wave conditions during the summers of 1992 and 1993 allowed to estimate wave heights at 0.1 to 0.5 m, with wave periods of 1 to 4 seconds. The region is microtidal, mean tidal range being 1.45 m with spring tides reaching an amplitude of 1.95 m. Storm surges resulting from low atmospheric pressure and southwesterly winds can occasionnaly induce a rise up to 1 m of the water level (HYDRO-QUEBEC, 1980).

METHODOLOGY

Field work was mainly carried out in the central part of the Sound. In June 1993 and August 1994 the morphology of tidal flats was analysed by topographic profiling using a theodolite along transect lines (Figure 1). Coastal transects representative of the tidal flats were sampled in summer 1992, in June 1993 and in summer 1994. Along these transects, surficial sediments (top 2 cm) were sampled every 50 m. Additional samples were taken from areas showing rapid lateral variations in surficial sedimentary features and grain size. Surficial grab samples were also collected from a zodiac in the shallow subtidal zone. Bathymetric profiles from the very shallow subtidal zone to 10 m depth were carried out in the central Sound using a 200 kHz echosounder and a GPS positioning system.

A total of 155 sediment samples were collected: 17 in the sublittoral zone, 72 on the intertidal flats, 15 in sections at the upper flat limit and 51 in cores. Sediment samples were described (type, size, color) and analyzed for grain-size determination using standard methods of settling tube, laser diffraction and sedigraph. Grain-size parameters were calculated according to the method of statistical moments (MCBRIDE, 1971). In addition, 15 short cores (20 to 50 cm) were collected along transects (Figure 1). Cores were split lengthwise, photographed, described and subsampled for grain-size analyses at 5 cm intervals.

In order to estimate erosion or sedimentation over the intertidal flats, four stations were established in June 1993 along a 500 m long transect across the tidal zone of Kuugaapik Bay (Figure 1). Stations were marked with a stake. Each station comprises two sub-stations located approximately 3.5 m either side of the transect. Two set of two iron stakes 0.7 m high were buried at each sub-station to approximately 0.2 m depth. Each 0.5 m high rod was installed at 1 m apart. A graduate iron bar with a level was then placed above the two stationary rods and bed elevation was measured every two days during ten days in measuring the distance between the graduate bar and the flat surface. Comparison of change in bed elevation using rods and theodolite showed that theodolite measurements have an accuracy of ± 2 cm. Water samples were collected at low tide and at high tide during breakup and summer in order to estimate suspended sediment concentration in the water column.

TIDAL FLAT MORPHOLOGY AND SEDIMENTOLOGY

The Sound is subdivided into three distinct physiographic regions, the inner Sound, the central Sound and the outer Sound (HYDRO-QUEBEC, 1993; AMOS *et al.*, 1996). At the entrance of the Sound (the outer Sound) the coastline is mainly rocky and embayments are not common. Small pocket beaches and narrow tidal flats are present and only one broad tidal flat is found in a sheltered bay located at the entrance of the Sound (Figure 1).

In the central and inner Sound, from Paint Islands to the head of the Sound (Figure 1) transverse narrow promontories consisting of bedrock outcrops, or glacial deposits form sheltered embayments where extensive tidal flats (600 to 800 m wide) have developed. Sandy deltaic deposits are found at the mouth of small rivers entering the Sound. Fine-grained sediment supply to the Sound is very limited because no major river discharge into the Sound and annual sediment load of the small tributaries is minor (HYDRO-QUEBEC, 1993). To the south, 176,000 t of sediment come from the Grande rivière de la Baleine annually (HYDRO-QUEBEC, 1993) of which 45,000 t of sand are deposited on a pro-delta at the river mouth while 131,000 t of suspended fine-grained sediment are delivered to the Hudson Bay and episodically enter the Sound leading fine-grained sedimentation in the deepest basins of the outer Sound (HYDRO-QUEBEC, 1993).

In the central Sound, tidal flats present a morphological and sedimentological zonation. Five major zones have been recognized across typical tidal flats of Manitounuk Sound: a shallow subtidal zone, a lower tidal flat, a mid tidal flat, a channel zone and an upper tidal flat (Figure 2). Each zone is defined by specific morphological and sedimentological characteristics (Figure 3). In the inner Sound a similar zonation was also reported by MOFFET (1987).

Shallow Subtidal Zone

This zone extends from the very low tide level to a break in slope at about −4 m. Surficial sediments consist of fine to very fine well-sorted sand (mean grain-size ranging from 2.11 to 2.7 ø), with no silt. The good sorting of fine sublittoral sands reflects the action of waves and/or currents. On the slope, from 4 m to 8 m depth the mud (silt and clay) content increases seaward very rapidly to reach up to 70% at −8 m. The mean grain-size varies from 3 ø to 6.3 ø at −3.5 m and −7.5 m respectively. Clay content increases significantly with depth too, ranging from 8% to 33%. Fine-grained sedimentation is therefore a function of depth and indicates that waves and currents action is restricted to the very shallow subtidal zone.

Lower Tidal Flat Zone

This zone extends from the very low tide level to the mean low tide level. The morphological transition from the low tide zone to the shallow subtidal zone is progressive. The slope is very gentle (< 0,05%) and no tidal channels nor slope changes do occur in this section of the tidal flat. In sheltered embayments surficial sediments are composed of very fine sand and silty sand (mean grain-size ranging from 2.78 ø to 4.33 ø) moderately to poorly sorted. Mud content varies from 1.30 to 38.8%. Silt is predominant, the amount of clay ranging from 0 to 17%. Near the mouth of small triburaries silt is absent and sand is coarser (Mean: 1.03 ø) than in embay-

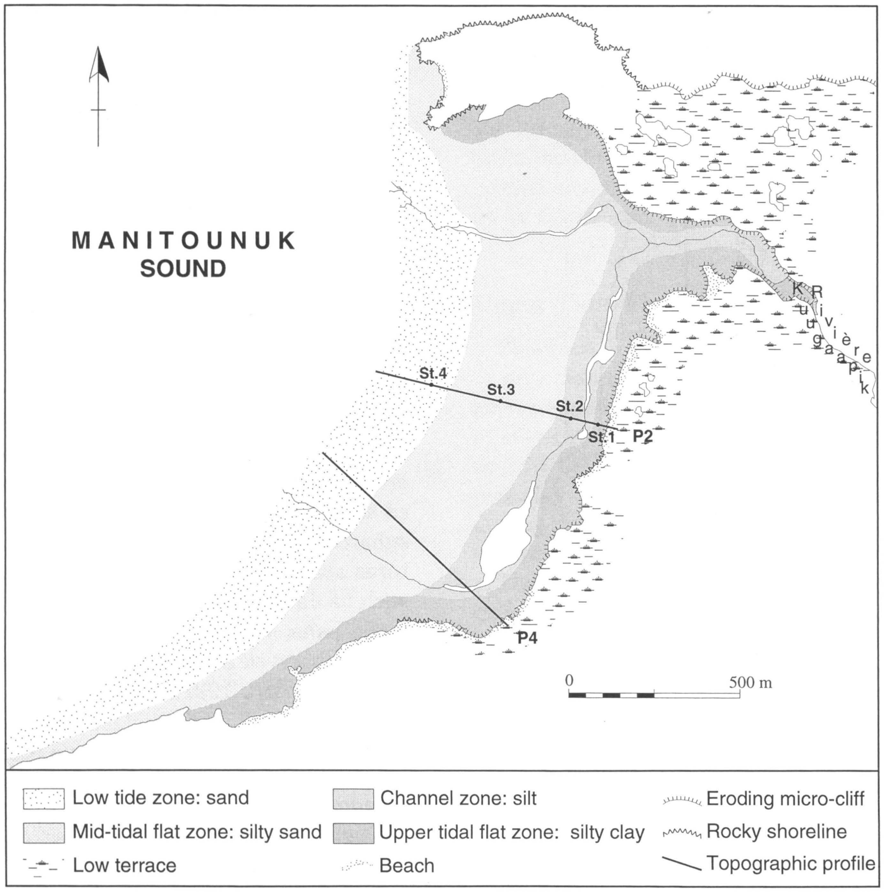

Figure 2. Coastal morphology and zonation of Kuugaapik Bay, central Manitounuk Sound.

ments. The surface of the lower tidal flat is covered by tidal generated ripples of 6 to 10 cm wavelength. Grain size variations (size and sorting) and mud content are the only parameters distinguishing this zone from the shallow subtidal zone.

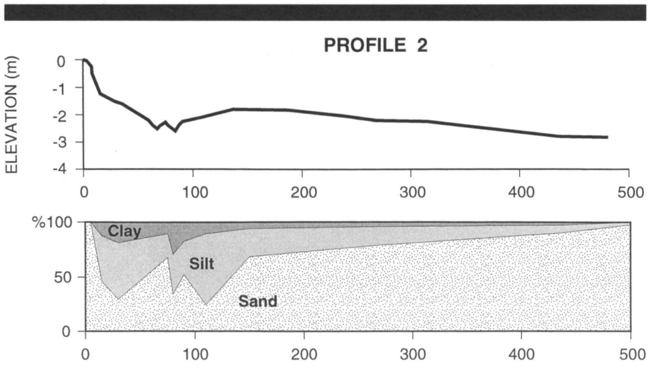

Figure 3. Typical profile and surficial sediment distribution of central Manitounuk tidal flats. See Figure 1 for location.

Three short cores collected at this level (Figure 1) exhibit a thin (< 10 cm) silty sand surficial layer overlying a structureless clayey unit (Figure 4). The transition between these two units is gradational. Typically, black organic-rich horizons are found in the first 10 cm; shell fragments are also common. Depending on location the underlying unit is sandy or clayey. At the mouth of the Domanchin River (Figure 1) where sandy deposition occurs, a core (Core 12, Figure 1) collected at the low tide level on a sandy shoal exhibits a surficial sandy layer overlying stuctureless silty sand (silt content of 16.3%). In embayments where the supply of alluvial sand is low, cores collected at the same level (Cores 10 and 4, Figure 1) show a 2 to 4 cm silty-sand organic rich surficial layer overlying a sandy-silt unit with shell debris. In both cores a basal compacted silty clay unit with clay content up to 37% was found (Figure 4). The surficial silty-sand unit overlying the lower part of the mud flat is therefore a very thin veneer (< 10–15 cm) and is underlain, in sheltered locations, by a semiconsolidated clayey unit (Figure 4).

Mid-Tidal Flat Zone

This unit occupies the centre of the intertidal zone, corresponding approximately to the mean water level. This portion

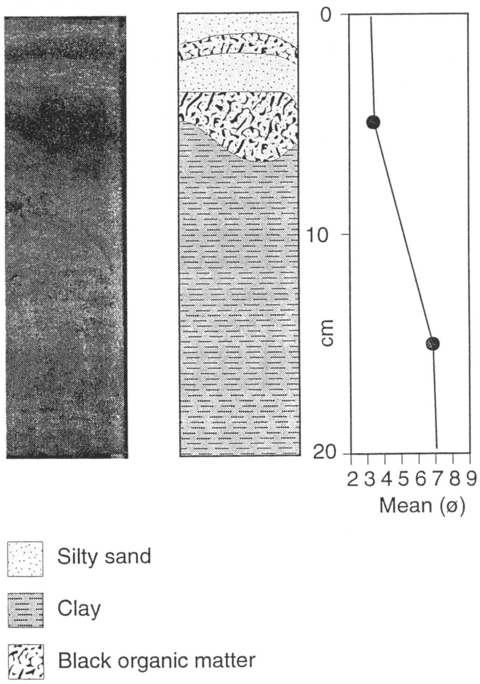

Figure 4. Photograph, textural description, and grain-size of selected samples of core 10 representative of the low-tide zone. See Figure 1 for location.

of the flats is boulder-strewn (Figure 5); boulders rarely exceed 0.75 m in diameter and are essentially of local origin (95% are Archean metamorphic rocks). Boulders and cobbles are widespread and are randomly distributed. No concentration is observed at one particular level as noted for some other localities (DIONNE, 1972; ROSEN, 1979; MCCANN *et al.*, 1981). Cobbles and boulders lay on silty sand (mud content of 17.42 to 30.25%; mean grain-size ranging from 3.31 ø to 3.84 ø). In some areas boulders are concentrated in a narrow zone showing a southwest-northeast orientation which is similar to the orientation of mainland glacial deposits (drumlins). This suggests that such boulder concentrations are in situ lags of eroded glacial till outcrops rather than far distance ice-rafted boulders.

Small pools, 5 to 10 cm deep, occcupy up to 50% of the surface of the mid-tidal flat (Figure 5). These very shallow depressions with a roughly circular shape are interpreted as erosional scars produced locally by the removal of ice-bounded sediments at the base of ice blocks, a common process on subarctic tidal flats (DIONNE, 1981, 1985, 1988). These features are remarkably persistent in low energy environments such as James Bay (MARTINI, 1991). Excepted for these ice-made pans, very few ice scours and furrows, features commonly observed along ice-affected tidal flats (DIONNE, 1975, 1985; MARTINI, 1991), were observed on this portion of the tidal flat.

Two cores collected in this zone (Cores 16 and 6, Figure 1) show a uniform and compact silty clay unit (mud content up to 86%, with clay content up to 50%) with few granules

Figure 5. Photograph of the boulder-strewn mid-flat zone, central Manitounuk Sound.

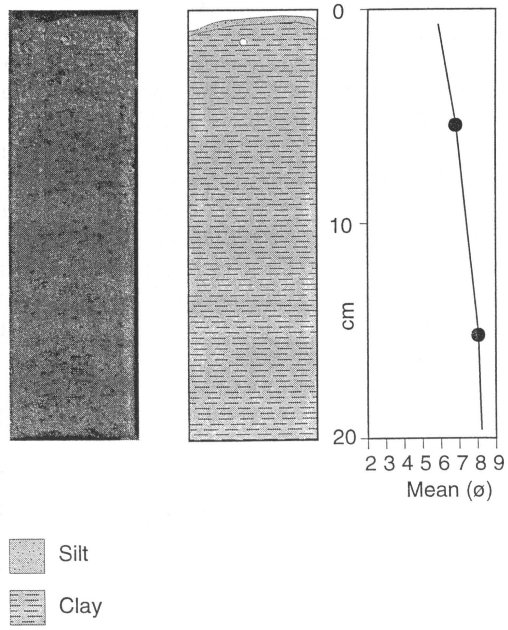

Figure 6. Photograph, textural description, and grain-size of selected samples of core 6 representative of the mid-flat zone. See Figure 1 for location.

throughout overlain by a very thin (2 cm) surficial silty layer. The absence of sedimentary structures as well as organic layers are characteristic of this sub-environment (Figure 6). In core 16 collected in June 1993, voids and cracks were present. This core was collected during spring and voids were probably due to the melting of ice lenses which formed during the winter (RUZ *et al.,* 1994). The surface of the voids was characterized by an irregular shape probably resulting from ice melting.

Channel Zone

On many mud flats studied in the central and inner Sound, the mid-tidal flat and the upper tidal flat are interrupted by a drainage channel running parallel to the shore. These channels, connected to small streams entering the flats, form a unique sub-environment. They are the conduit for flooding and ebbing waters of the intertidal flats. Circular ponds connected the channel are also characteristic features of this zone. On both sides of the channels the surficial sediments are fine-grained, with mean grain size ranging from 3.19 ø to 6.62 ø. Channel bottom is sandy while silt and silty clay (13% to 99.75% of mud content) are dominant along both sides of the channel (Figure 3).

Four cores 37 cm to 53 cm long were collected in this zone (Cores 1, 2, 8, 15, Figure 1). Although collected along different transects, the cores exhibit alternating horizontal layers of sandy silt and black organic-rich horizons (Figure 7). The uppermost unit (from 0 to 1–9 cm) consists of fine sand with silt. This surficial unit is underlain by 10 to 12 cm of structureless fine sand in a silty clay matrix with few granules throughout. The presence of gravel-size sediment in this unit suggests that the sediment is reworked by sea ice or transported by streams. Below, a 10 to 20 cm unit is characterized by alternating dark (organic rich) and light sandy silt layers. This unit reflects conditions of deposition in the channel and the laminated sandy silt may represent seasonal layers. At the base of two cores (Cores 8 and 2, Figure 1) a semiconsolidated structureless silty-clay unit with silt content reaching up to 52.8% and clay content of 20–22% was found (Figure 7).

Upper Tidal Flat Zone

This zone is a narrow fringe extending from mean high tide to very high tide level. The slope is steeper (1:20) than in the previous zones (Figure 3). Surficial sediments are composed of silty-clay with silt content ranging from 11 to 50% and up to 33% of clay. Some deformation structures (frost cracks) probably resulting from annual freezing have been observed during the summer. Locally, the very upper mud flat is partly covered by vegetation, mainly *Carex.* species.

The upper tidal flat is limited landward by a micro-cliff, 20 to 80 cm high. A thin sandy beach is usually found at the base of the micro-cliff. Beach sediment are poorly-sorted coarse to medium sand overlying fine sediments, indicating a low wave energy environment. Scattered turf of marshy vegetation originating from the eroding micro-cliff are often found on the surface of the upper tidal flat.

Six pushcores collected at this level (Figure 1) show similar facies although they were taken in different embayments. The cores show a surficial (0.5 cm thick) yellow organic-rich silty layer underlain by 6 to 14 cm of fine sand in a silty clay matrix. Below this unit, an organic horizon 1 to 4 cm thick or a sandy layer with plant debris was found in three cores. In two cores a pebble was found at 15–18 cm (Figure 8). The basal portion of three of these cores (Cores 7, 13, 14, Figure 1) consists of a structureless sandy silt unit with some clasts (Figure 8). Mud content ranges from 20 to 94% with silt being predominant (11 to 50.6%). The coarse sand layers and pebbles found in these cores may reflect episodic storm events, while the organic layers could originate from the eroding micro-cliff fringing the upper tidal flat.

TIDAL FLATS SHORT TERM EVOLUTION

During winter, the tidal flats of the Manitounuk Sound are covered by shore-ice. Borehole logs and temperature profiles carried out in March 1993 revealed that the ice cover was up to 1.25 m thick and was welded to the frozen silty substrate over the length of the tidal flat, down to the lower zone where tidal cracks developed (RUZ *et al.,* 1994). Because the ice covering the tidal zone is bounded to the underlying sediments during winter months, the surface of the intertidal flats is not affected by waves or tidal currents.

From field observations carried out in June 1993, the icefoot melted *in situ* (RUZ *et al.*, 1994). Since the tide does not penetrate under shore-ice, no erosion related to the sudden departure of the icefoot occurred. Only a very small number of ice scours, furrows or grooves were observed during and after breakup, contrary to observations in other cold regions

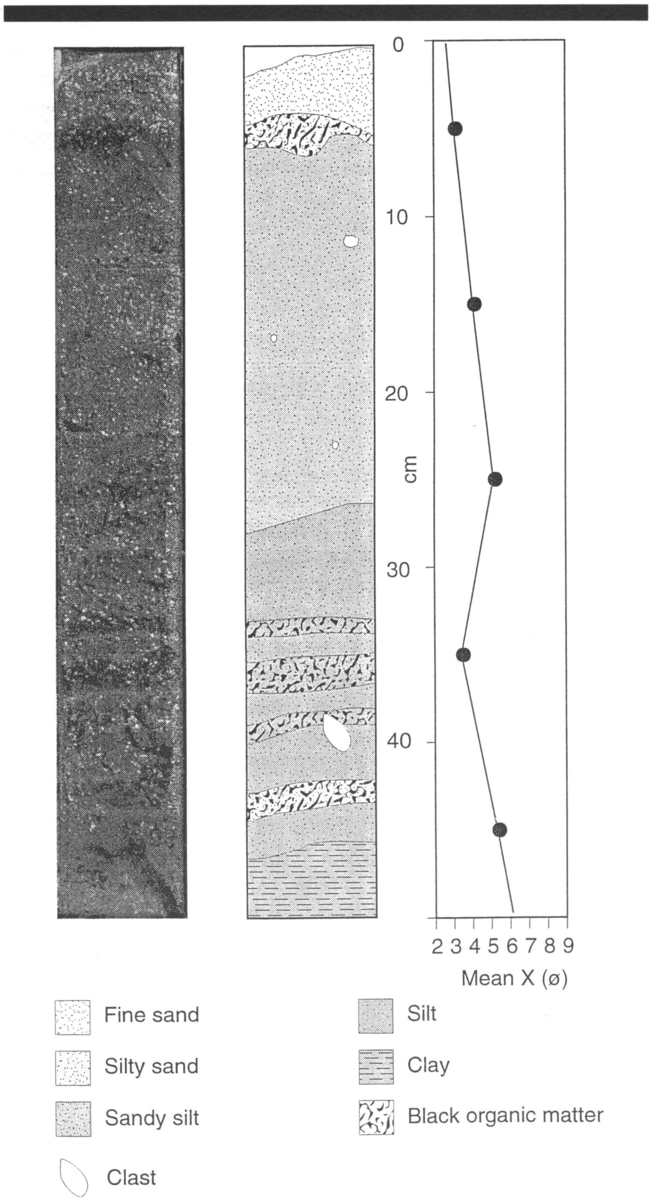

Figure 7. Photograph, textural description, and grain-size of selected samples of core 8 representative of the channel zone. See Figure 1 for location.

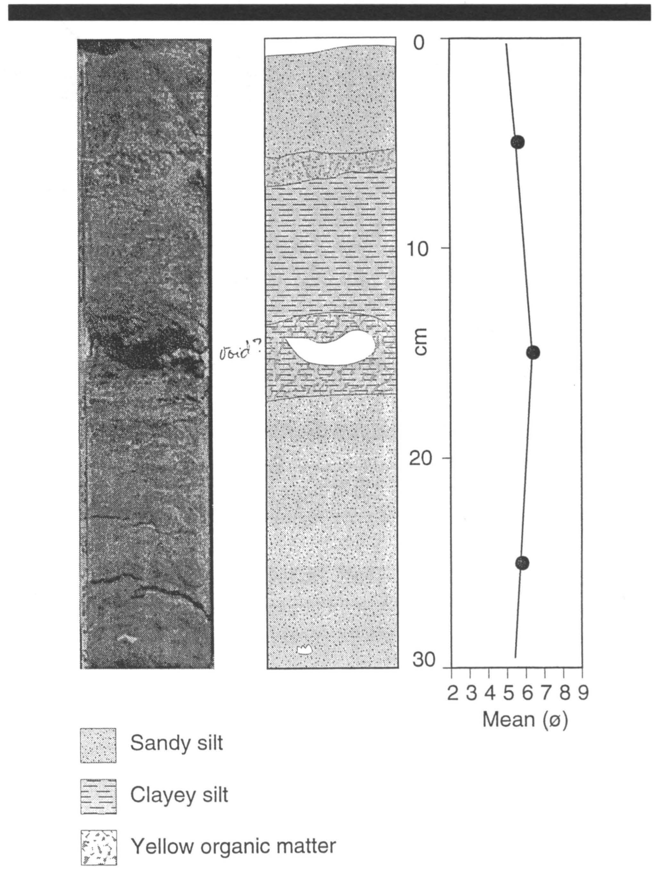

Figure 8. Photograph, textural description, and grain-size of selected samples of core 5 representative of the upper-flat zone. See Figure 1 for location.

where bottom scouring by sea ice is a common process on tidal flats (DIONNE, 1985). The melting of the ice-cover took one week in June 1993. In this process, melting of the ice was not uniform and some ice-blocks were still present on the intertidal zone after a week (Figure 9) producing micro-depressions that could explain the irregular surface of the tidal flat.

The bed elevation measurements at the stations installed during breakup in Kuugaapik Bay showed very little changes over a period of 10 days, from June 10 to June 19 (Figure 10). Station 4 (Figure 1), located at the seaward edge of the transect was disrupted by sea-ice. Rods were folded by onshore moving ice floes from the Sound and the two sub-stations had to be abandoned. Over the survey period net bed change variations were on the order of a few millimetres only. A great variabilty was observed at sub-stations installed only few meter apart. Station 1.1 for example revealed a slight accumulation (< 2 mm), while station 1.2 recorded a net erosion of 5 mm (Figure 10). It is therefore difficult to draw any tendency, excepted for station 2 where an accumulation of 1.8 mm was measured at both sub-stations. During the same period, topographic profiling of two transects in Kuugaapik Bay also showed bed stability over the mid-and upper tidal flat, but revealed an erosion on the order of 5 cm at the seaward margin of the lower flat. This change in bed elevation may be related to erosion by ice floes. Despite the short survey period, bed elevation measurements suggest that during breakup some erosion occurs in the lower tidal flat zone, while slight accumulation prevails in the channel zone.

The stations were re-visited on late August 1993 and in August 1994. No significant morphological changes occurred between June and August 1993. On the upper tidal flat, above the mean high tide level, footprints made in June were still very well defined three months later, indicating that this

Figure 9. Remnants of the icefoot that melted *in situ* on the tidal flat of the Kuugaapik Bay, June 1993.

zone, which is only reached by spring tides is likely a non depositional area.

Comparison of 1993 and 1994 topographic profiles in Kuugaapik Bay (Figure 11) shows net changes in bed elevation in the channel zone. An accumulation of 5 to 20 cm occurred on both sides of the channel as well as on the channel bottom. The shoreward side of the channel particularly showed a positive variation up to 20 cm. This accumulation was restricted to a 85 m long zone. The presence of tension cracks and mud volcanoes, common features on subarctic tidal flats (DIONNE, 1976), suggests that seasonnal frost may also be responsible for some of the changes in bed elevation observed in this zone. On the mid and the lower tidal flat however, no significant changes did occur.

Erosion of the micro-cliff at the upper edge of the tidal zone was observed in June 1993 (RUZ *et al.,* 1994). In the central Sound, tidal marshes are limited in extent and usually a micro-cliff 20 cm to 80 cm high is found at the upper limit of wave action. MOFFET (1987) also described the same morphology in the inner Sound. This micro-cliff is cut into recently emerged intertidal deposits. Sections exposed by cliff recession showed silty clay at the base overlain by silts grading into silty sand at the top of the cliff.

In coastal areas affected by discontinuous permafrost, silt and clay material form permafrost mounds up to 6 metres high. Permafrost aggradation induces rapid uplift of fine-grained material (ALLARD *et al.,* 1996). Some of these mounds are eroded at high tide. Bluff can reach 4 m high as to the south of the mouth of the Domanchin River (Figure 12). Erosion rates obtained by the comparison of 1950, 1979 and 1990 aerial photographs are on the order of 1 m a^{-1}, but rates up to 2.5 m a^{-1} were also measured. Such erosion rates along a coastline affected by a rapid land emergence is unusual. Erosion prevails in fine-grained sediments along coastal areas affected by discontinuous permafrost, while along sandy areas progradation occurs especially at river mouths.

Shoreline erosion is mainly due to thermal erosion in permafrost and in seasonally frozen silty sediments along the shoreline. During the Spring, melting processes induce fusion of the micro-cliff causing a rapid slumping of water-saturated material (RUZ *et al.,* 1994). At high tide, the soft fluid-like mud is easily resuspended by waves and exported seawards. During periods of ice breakup or wave activity sediment resuspension occurred on the tidal flats. Suspended sediment concentrations were on the order of 200 mg/l during these events compared to 50–60 mg/l during fair weather conditions. During breakup, however, very little sedimentation was recorded over the intertidal flats, indicating that suspended sediments were exported seaward and lost for the intertidal zone. Plumes of suspended sediments, extending several hundred meters seaward of the tidal flats, were observed just after breakup (Figure 13).

The erosion of the micro-cliff also reflects wave influence, especially storm waves combined with storm surges that episodically induce a surelevation of 1 m of the mean water level (HYDRO-QUEBEC, 1993). The windy season usually begins in early August and the biggest storms occur in October and November. Therefore, sediments that slumped during

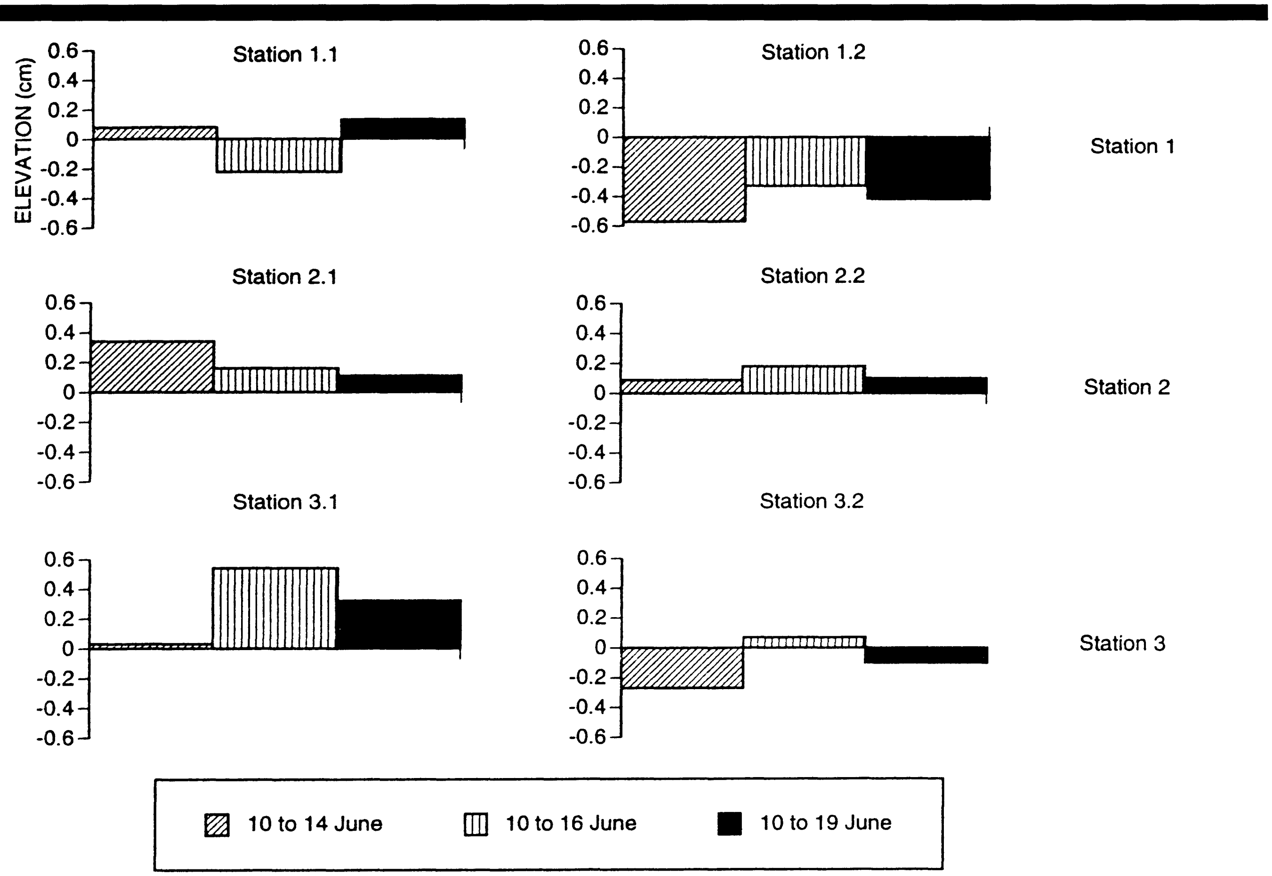

Figure 10. Changes in bed elevation at 3 stations on the Kuugaapik tidal flat during spring 1993. See Figure 2 for location.

the Spring are usually washed away and the micro-cliff is then steepened again to near vertical before the next season. Development of sandy beaches at the uppermost high tide level as well as on top of the low emerged terrace means that even in this sheltered environment, low-frequency storm events represent an important factor influencing short-term dynamics of the landward margin of the tidal flats.

DISCUSSION

The tidal flats of the Manitounuk Sound are boulder strewn, which is a characteristic of northern tidal flats (DIONNE, 1981, 1988). The boulders are scattered throughout the intertidal flats surface and appear to be rarely displaced by ice. Compared with other tidal flats affected by sea-ice (DIONNE, 1969, 1988; KNIGHT and DALRYMPLE, 1976; ROSEN, 1979; MCCANN *et al.*, 1981; MARTINI, 1991), the effect of shore ice seems minor in Manitounuk Sound. In tidal flats affected by ice, bed-scouring occurs primarily during breakup and in some cases intertidal sediments are subject to almost continuous ice scouring throughout the Winter (GORDON and DESPLANQUE, 1983). In Manitounuk Sound ice rafting and scouring is limited during winter because the entire intertidal and offshore zones are locked by sea ice. Furthermore, the ice cover is frozen to the substrate in the intertidal zone. As mentionned earlier, the Manitounuk Sound is a sheltered area and a microtidal environment. Therefore, ice movement is restricted and only minor ice-induced erosion occurs over the intertidal flats. In this area the protective role of ice appears more important that its erosional action. This observation is supported by the shore-parallel zonation of Manitounuk tidal flats.

Surface sediments on the Manitounuk tidal flats are zoned in contour-parallel fashion which is typical for intertidal mud flats (AMOS, 1995). From the very shallow subtidal zone to the highest tide level there is a classical seaward-coarsening of grain size (Figure 2) showing that the intertidal flats are dominated by tidal-induced processes rather than ice-induced processes.

Manitounuk tidal flats, however, lack major morphological features common to intertidal flats. Only few tidal flats in the Manitounuk Sound merge landward into tidal marshes. Furthermore, no tidal creeks or channels normal to the shoreline are present, contrary to many tidal flats where tidal creeks with a dendritic pattern are typical (REINECK, 1972; WEIMER *et al.*, 1982). Although tidal creeks and channels are best developed in meso- to macrotidal environments (VERGER, 1968; REINECK and SINGH, 1980), this typical drainage pattern is also documented in sheltered microtidal environments (DIONNE, 1980, 1981). The absence of such tidal creek pattern on the Manitounuk Sound tidal flats may be ex-

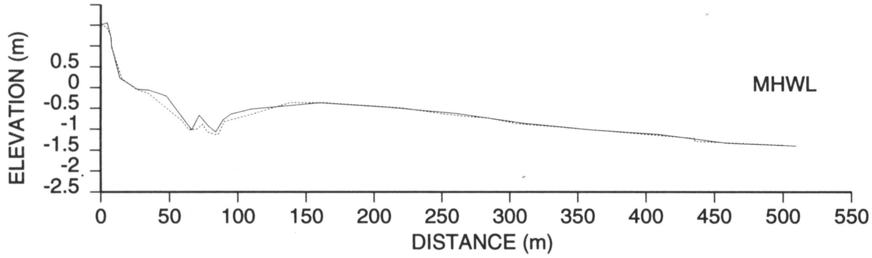

Figure 11. Changes in bed elevation along profile 2, Kuugaapik Bay, between June 1993 and August 1994.

plained by the low sedimentation rates and by the rapid land uplift (1 cm a^{-1}) inducing a seaward sedimentation rather than a vertical one.

From the description of the short cores it appears that recent sediments are structureless, excepted along channel sides. The occurence of laminated silt and clay shows that sedimentation in this zone is dominated by suspension processes. Typical mid-flat ripple cross-lamination (REINECK and SINGH, 1980) were not found in cores, meaning that tidal flat sedimentation is not recorded in the cores. The lack of typical tidal flats sedimentary structures such as lenticular or flaser bedding is either related to the absence of net deposition or to annual freeze and thaw processes, resulting in sediment disturbance. In James Bay tidal flats, flaser bedding as well as ripple crosslaminae alternating with plane beds were reported by MARTINI (1991), although climatic conditions and emergence rate are quite similar to the eastern side of Hudson Bay.

In Manitounuk Sound surficial sediments in cores consist of mixed sand and silt in a clayey matrix with granules

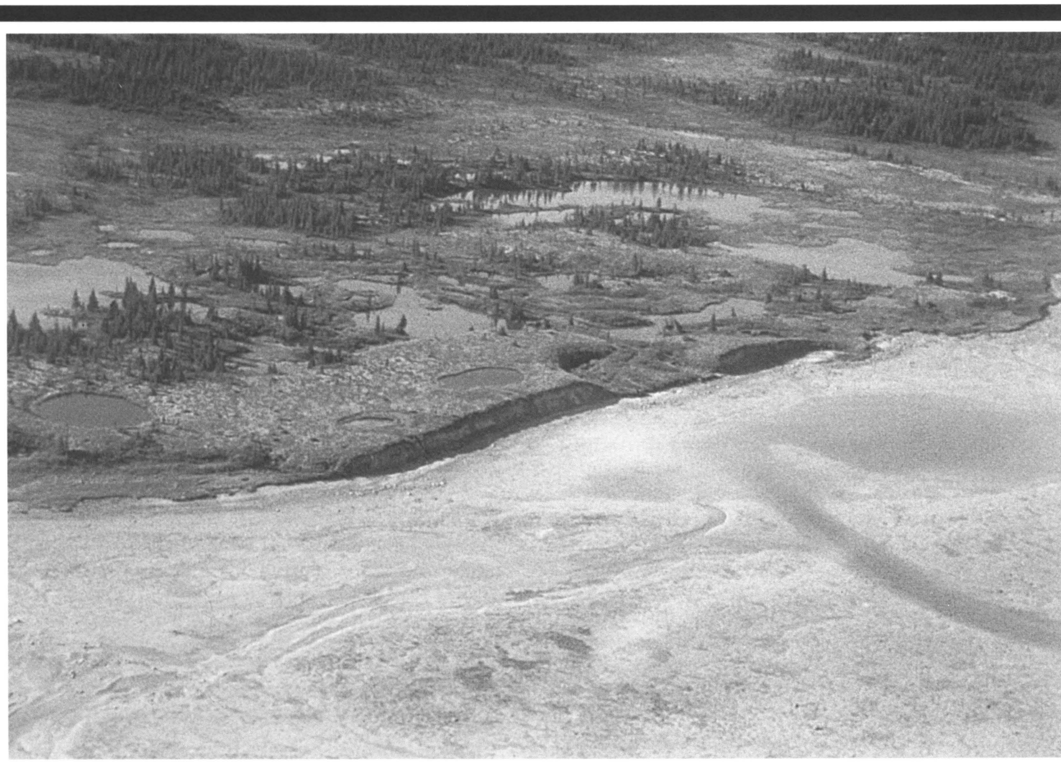

Figure 12. Eroding bluffs, central Manitounuk Sound.

Figure 13. Sediment plume seaward of central Manitounuk Sound tidal flats in June 1993.

throughout. The very poor sorting of these silty sand as well as the absence of sedimentary structures may reflect sediment mixing during the icefoot formation resulting in gravel-size particles incorporation. In many cores collected in the central Sound a compact silty-clay unit was found beneath the uppermost reworked sediments. This basal unit has sedimentological characteristics similar to those of the sediments collected in the subtidal zone at 5–10 m depth (Figure 14). Sand and mud content are comparable; the amount of clay is on the order of 25–30% in the basal unit as well as in the subtidal zone, compared with an average of 8–10% in the surficial unit. This suggests that fine-grained material, originally deposited in deeper water are found immediately below recently reworked sediments. These semiconsolidated sediments found in many cores may be interpreted as marine deposits that are now exposed in the intertidal zone due to isostatic uplift. On the mid-tidal flat surficial mixed sediments are absent and the stiff silty clay is outcropping. These observations also suggest that the mid-tidal flat zone consists of subtidal sediments that are emerging.

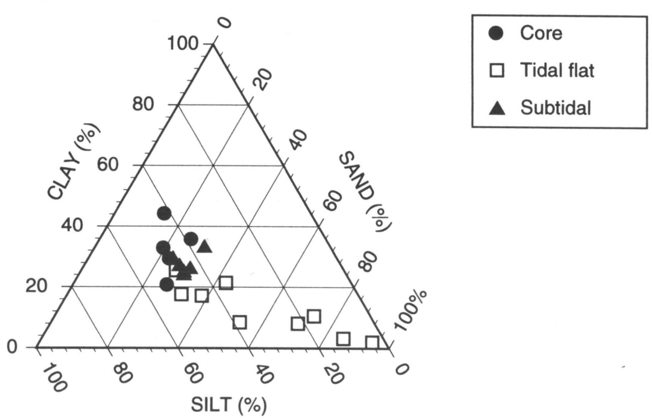

Figure 14. Comparison of sand, silt and clay fractions of samples from core basal units, tidal flat surface sediments, and subtidal zone bottom sediments.

Core interpretation and measurements of change in bed elevation suggest that sediment supply to the flats is limited. At the upper limit of the mud flats, however, the eroding silty-clay bluffs and micro-cliffs represent a potential sediment source for the flats. The surface of the tidal flats, however, appears to be very stable. Manitounuk tidal flats are therefore a non-depositional surface where sediment by-passing does occur. Sediment budget calculations for the Manitounuk Sound also suggest that the tidal flats act as a primary sediment source for the hemipelagic deposits of the Sound (Zevenhuizen *et al.*, 1994; Amos *et al.,* 1996).

These results raise the question of the origin of these tidal flats as well as the question of the preservation potential of intertidal deposits during a marine regression. It appears that in Manitounuk Sound present-day tidal flats are actually erosion platforms cut into clayey silt deposited in deeper water in the postglacial Tyrrel Sea. These deposits were elevated to their present position by glacio-isostatic uplift, a process still active today. In Rupert Bay, located along the south James Bay coastline, CHAMPAGNE (1982) reported that the old marine clay deposited in the Tyrrell sea are being eroded on the lower part of the tidal flats by wave and tidal currents. In Southern Baffin Island, MCCANN *et al.* (1981) also concluded that modern tidal flats are erosional surfaces cut in fine-grained sediments representing marine sedimentation during a period of higher sea level. Along the coastline of central Labrador, ROSEN (1979) also reported that many intertidal zones consist of uplift marine clays planed to a low gradient by contemporary processes. It seems that along emerging coastlines, the preservation potential of tidal flat deposits is very low, especially in sediment-deficit conditions like in Manitounuk Sound.

CONCLUSION

(1) The action of sea ice is minor on the Manitounuk subarctic tidal flats, located in a microtidal and sheltered area.
(2) Although these tidal flats lack typical channel drainage pattern, they present a normal shore-parallel zonation, mainly related to tidal influence.
(3) Coastal erosion is the major supply of fine-grained sediments. Despite this sediment source, the Manitounuk tidal flats are non-depositional, mainly because of sediment by-passing.
(4) In many cores a compact basal clayey unit is interpreted to represent deeper marine sedimentation. This suggests that these modern tidal flats are platforms cut into emerging marine sediments deposited during a period of higher sea level.

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LITERATURE CITED

AITKEN, A.E.; RISK, M.J., and HAWARD, J.D., 1988. Animal-sediment relationship on a subarctic intertidal flat, Pangnirtung Fiord, Baffin Island, Canada. *Journal of Sedimentary Petrology,* 58, 969–978.

ALLARD, M. and TREMBLAY, G., 1983. La dynamique littorale des îles Manitounuk durant l'Holocène. *Zeitschrift fur Geomorphologie,* N. F. Suppl. Bd. 47, 61–95.

ALLARD, M.; CARON, S., and BEGIN, Y., 1996. Climatic and Ecological Controls on Ice segregation and Thermokarst: the Case History of a Permafrost Plateau in Northern Quebec. *Permafrost and Periglacial Processes*, 7.

ANDERSON, F. E., 1983. The Northern Muddy Intertidal: Seasonal Factors controlling Erosion and Deposition-A Review. *Canadian Journal of Fisheries and Aquatic Sciences*, 40, 143–159.

AMOS, C.L., 1995., Siliciclastic tidal flats. In: Perillo, G.M.E. (ed.), *Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology 53.* Amsterdam: Elsevier Science, pp. 273–306.

AMOS, C.L.; SUTHERLAND, T. F., and ZEVENHUIZEN, J., 1996. The stability of sublittoral, fine-grained sediments in a subarctic estuary. *Sedimentology,* 43, 1–19.

BEGIN, Y. and ALLARD, M., 1982. Le glaciel de Kuujjuaraapik (Nouveau-Québec). *Nordicana,* 46, 39–100.

BEGIN, Y.; BERUBE, D., and GREGOIRE, M., 1993. Downward migration of coastal conifers as a response to recent land emergence in Eastern Hudson Bay, Québec. *Quaternary Research,* 40, 81–88.

CHAMPAGNE, P., 1982. Morphologie littorale de la Baie de Rupert. *Naturaliste canadien,* 109, 375–384.

DIONNE, J.-C., 1969. Erosion glacielle littorale, Estuaire du Saint-Laurent. *Revue de Géographie de Montréal,* 25, 5–22.

DIONNE, J.-C., 1972. Caractéristiques des schorres des régions froides, en particulier de l'estuaire du Saint-Laurent. *Zeitschrift für Geomorphologie,* Suppl. Bd., 13, 131–162.

DIONNE, J.-C., 1975. L'action morpho-sédimentologique des glaces dans le Saint-Laurent estuarien. *Cahiers de Géographie de Québec,* 20, 303–326.

DIONNE, J.-C., 1976. Miniature mud volcanoes and other injection features in tidal flats, James Bay, Québec. *Canadian Journal of Earth Sciences,* 13, 422–428.

DIONNE, J.-C., 1978. Le glaciel en Jamésie et Hudsonie, Québec subarctique. *Géographie physique et Quaternaire,* 32, 3–70.

DIONNE, J.-C., 1980. An outline of the Eastern James Bay coastal environment. *In*: MCCANN, S.B. (ed.) *The Coastline of Canada,* Geological Survey paper 80–10, pp. 311–338.

DIONNE, J.-C., 1981. A boulder-strewn tidal flat, North Shore of the Gulf of St. Lawrence, Québec. *Géographie physique et Quaternaire,* 35, 261–267.

DIONNE, J.-C., 1985. Formes, figures et faciès sédimentaires glaciels des estrans vaseux des régions froides. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 51, 415–451.

DIONNE, J-C., 1988. Characteristic features of modern tidal flats in cold regions. *In*: DE BOER, P.L., *et al.*, (eds), *Tide-Influenced Sedimentary Environments and Facies.* Dordrecht: Reidel, pp. 301–332.

DIONNE, J-C., 1989. The role of ice and frost in tidal marsh development. A review with particular reference to Québec, Canada. *Earth-Sciences Reviews,* 26.

ELLIS, D.V. and WILCE, R.T., 1969. Arctic and subarctic examples of intertidal zonation. *Arctic,* 14, 224–235.

EVANS, G., 1965. Intertidal flat sediments and their environnment of deposition in the Wash. *Quaternary Journal Geological Society of London,* 121, 209–245.

GILBERT, R. and AITKEN, A.E., 1981. The role of sea ice in biophysical zonation on intertidal flats at Pangnirtung, Baffin Island, N.W.T. *In*: *Proceedings, Workshop on Ice Action on Shores, Ottawa.* National Research Council of Canada, Publication No. 3, pp 89–103.

GORDON, D.C. and DESPLANQUE, C., 1983. Dynamics and Environmental Effects of Ice in the Cumberland Basin of the Bay of Fundy. *Canadian Journal of Fisheries and Aquatic Sciences,* 40, 1331–1342.

HILLAIRE-MARCEL, C., 1976. La déglaciation et le relèvement isostatique sur la côte est de la Baie d'Hudson. *Cahiers de géographie de Québec,* 20, 185–220.

HYDRO-QUEBEC, 1980. Rapport final des levés en continu des variations des niveauux d'eau aux 4 stations marégraphiques. *Relevés techniques, hydrométrie. Projet: Complexe grande Baleine.*

HYDRO-QUEBEC, 1993. *Complexe Grande-Baleine, rapport d'avant-projet.* Partie 2, tome 5, vol. 2, 100p.

KLEIN, G. DE V., (ed.), 1977. *Clastic Tidal Facies.* Champaign, Illinois: Continuing Education Publication, 148p.

KNIGHT, H.W. and DALRYMPLE, R.W., 1976. Winter conditions in a macrotidal environnment, Cobequid bay, Nova Scotia. *Revue de géographie de Montréal,* 30, 65–85.

MARTINI, I.P., 1981a. Ice effect on erosion and sedimentation on the Ontario shores of James Bay, Canada. *Zeitschrift für Geomorphologie,* N.F.,25, 1–16.

MARTINI, I.P., 1981b. Morphology ans sediments of the emergent Ontario coast of James Bay, Canada. *Geografiska Annaler,* 63A, 81–94.

MARTINI, I.P., 1982. Geomorphological features of the Ontario coast of Hudson Bay. *Naturaliste canadien,* 109, 415–429.

MARTINI, I.P., 1991. Sedimentology of subarctic tidal flats of western James Bay and Hudson Bay, Ontario, Canada. *In*: SMITH, D.G., *et al.* (eds). *Clastic Tidal Sedimentology.* (Canadian Society of Petroleum Geologists) 16, 301–312.

MCBRIDE, E.F., 1971. Mathematical treatment of size distribution data. *In*: CARVER, R.E., (ed.), *Procedures in Sedimentary Petrology.* New York: Wiley, pp. 109–127.

MCCANN, S.B., (ed.), 1980. *Sedimentary Processes and Animal-Sediment Relationships in Tidal Environnments.* Geological Association of Canada, Short Course Notes, 1, 232p.

MCCANN, S.B.; DALE, J.E., and HALE, P.B., 1981. Subarctic tidal flats in areas of large tidal range, southern Baffin Island, Eastern Canada. *Géographie Physique et Quaternaire,* 35(2), 183–204.

MICHAUD, Y.; ALLARD, M.; PARENT, M.; PARADIS, S.; MENARD, E.; FORTIN, M., and BEGIN, C., 1994. *Cartographie préliminaire des zones pergélisolées dans le secteur du détroit de Manitounuk et de la Petite Rivière de la Baleine, Hudsonie.* Geological Survey of Canada, Open File Report 2845.

MOFFET, R., 1987. *La dynamique littorale en milieu de pergélisol discontinu, détroit de Manitounuk, Nouveau-Québec.* Mémoire de maîtrise, Université Laval, 139p.

PETERSON, G.H., 1977. Biological effects of sea-ice and icebergs in Greenland. *In*: DUNBAR, M.J., (ed.), *Polar Oceans.* Calgary: Arctic Institute of North America, 681p.

REINECK, H.-E., 1972. Tidal flats. *In*: RIGBY, J.K. and HAMBLIN, W.K., (eds.), *Recognition of Ancient Sedimentary Environnments.* Tulsa, Oklahoma: SEPM Special publication no. 16, 146–159.

REINECK, H.-E., 1978. Tidal flat geology. *In*: FAIBRIDGE, R.W. and BOURGEOIS, J., (eds.), *The Encyclopedia of Sedimentology.* Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross, pp. 798–800.

REINECK, H.-E. and SINGH, I.B., 1980. *Deposional Sedimentary Environnments.* New York, Springer-Verlag, 550p.

ROSEN, P.S., 1979. Boulder barricades in central Labrador. *Journal of Sedimentary Petrology,* 79, 1113–1123.

RUZ, M.H.; MICHAUD, Y.; ALLARD, M.; SUTHERLAND, T., and ARDILES, B., 1994. *Morpho-sédimentologie et évolution des estrans de la partie centrale du détroit de Manitounuk.* Commission géologique du Canada, Dossier public 2842, 60p.

SASSEVILLE, D.R. and ANDERSON, F.E., 1976. Sedimentological consequences of winter ice cover on tidal flat environnment, Great Bay, New Hampshire. *Revue de Géographie de Montréal,* 30, 87–93.

SEGUIN, M.K. and ALLARD, M., 1984. La répartition du pergélisol dans la région du détroit de Manitounuk, côte est de la mer d'Hudson, Canada. *Canadian Journal of Earth Sciences,* 21, 354–364.

TAYLOR, S.; RACINE, C.H.; COLLINS, C.M., and GORDON, E., 1994. *Ice Formation in an Estuarian Salt Marsh, Alaska.* US Army Corps of Engineers, Cold Regions Research and Enginnering Laboratory (CRREL), Special Report, 20p.

VAN STRAATEN, L.M.J.U., 1961. Sedimentation in tidal flat areas. *Journal Alberta Society of Petrology Geology,* 9, 203–226.

VAN STRAATEN, L.M.J.U. and KUENEN, P.H., 1958. Tidal action as a cause of clay accumulation. *Journal of Sedimentary Petrology,* 28, 406–413.

VERGER, F., 1968. *Marais et wadden du littoral français.* Biscaye, Bordeaux: 541p.

WELLS, J.T.; ADAMS, C.E.; PARK, Y.-A., and FRANKENBERG, E.W., 1990. Morphology, sedimentology and tidal channel processes on a high-tide-range mudflat, west coast of South Korea. *Marine Geology,* 95, 111–130.

WEIMER, R.J., HOWARD, J.D., and LINDSAY, D.R., 1982. Tidal flats and associated tidal channels. *In*: SCHOLLE, P.A. and SPEARING, (eds.), *Sandstone Depositional Environnments.* American Association Petroleum Geologists Memoir 31, pp. 191–245.

ZEVENHUIZEN, J.; AMOS, C.L.; ASPREY, K.; MICHAUD. Y.; RUZ, M.H.; SUTHERLAND, T., and TREMBLAY, C., 1994. *The Sediment Budget of Manitounuk Sound, Southeastern Hudson Bay.* Geological Survey of Canada, Open File Report 2941.