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Les estrans subarctiques en zones de fort marnage, sud de l'île de Baffin, Canada

Subarktische Wattenmeere in Gebieten von hohem Gezeitenausschlag, südliche Baffininsel, Ost Kanada

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Article abstract

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SUBARCTIC TIDAL FLATS IN AREAS OF LARGE TIDAL RANGE, SOUTHERN BAFFIN ISLAND, EASTERN CANADA

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ABSTRACT Wide, boulder-strewn intertidal flats occur around the head of Frobisher Bay and along parts of the shoreline of Cumberland Sound, in southeast Baffin Island. The coastal environment is characterized by large tidal ranges, severe winter sea ice conditions, and a relative sea level history which involves rapid and then decreasing land emergence during the earlier part of the Holocene, succeeded by slight recent submergence. Summer field investigations were carried out at two sites, Koojesse Inlet on Frobisher Bay, where ice breakup conditions were also monitored, and Pangnirtung Fiord off Cumberland Sound. The results are summarized under three headings: physical and biological zonation across the tidal flats; tidal action and sea ice processes; and geological evolution of the tidal flats. Comparisons are made with similar settings described by others in Labrador and Ungava Bay. The sedimentary shores at both Baffin Island sites exhibit a distinct physical zonation, most evident in the concentration of boulders in the middle tidal flat zone at Koojesse Inlet and in the boulder barricade at the seaward margin of the Pangnirtung flats. Biological observations show a zonation of intertidal flora and fauna across the intertidal zone at Koojesse Inlet. An outstanding problem concerns the mode of transport of very large boulders. Pushing and rolling, by ice floes which are confined to the intertidal zone by the solid ice in the offshore zone during the critical early phase of breakup may be more appropriate processes than ice rafting.

RÉSUMÉ *Les estrans subarctiques en zones de fort marnage, sud de l'île de Baffin, Canada.* De vastes estran couverts de cailloux existent dans le secteur amont de la baie de Frobisher et à plusieurs endroits le long du littoral du détroit de Cumberland, au SE de l'île de Baffin. Le milieu littoral est soumis à des marées de forte amplitude, à des conditions rigoureuses d'englacement et à une variation du niveau marin postglaciaire. Des recherches ont été entreprises, en été, dans deux sites; le rentrant de Koojesse dans la baie de Frobisher où les conditions du déglacement ont été étudiées de près, et dans le fjord de Pangnirtung dans le détroit de Cumberland. Les résultats apparaissent sous trois entêtes: la zonation bio-physique des estrans; les processus glaciels et l'action de la marée; l'évolution géologique des estrans. Des comparaisons sont faites avec des milieux similaires décrits par d'autres chercheurs, notamment au Labrador et dans la baie d'Ungava. Les rivages en matériel meuble des deux sites étudiés à Baffin montrent une zonation distincte en ce qui a trait à la répartition des cailloux, ceux-ci étant concentrés dans la partie médiane de l'estran dans le rentrant de Koojesse, alors qu'à Pangnirtung ils forment des cordons allongés parallèlement à la limite des basses mers. Les levés biologiques ont permis de faire une zonation de la flore et de la faune de l'estran du rentrant de Koojesse. Un des problèmes majeurs soulevés concerne le mode de déplacement des mégablocs. Il semble que les pressions latérales exercées sur les blocs par les radeaux de glace, lors du déglacement, soient plus efficaces que la prise en charge suivie d'une dérive et d'un délestage des blocs, au hasard de la fonte, à divers niveaux de la zone intertidale.

ZUSAMMENFASSUNG *Subarktische Wattenmeere in Gebieten von hohem Gezeitenausschlag, südliche Baffininsel, Ost Kanada.* Grosse, mit Felsblöcken übersäate, Wattenmeere findet man um die Frobischer Bucht und an Teilen der Küstenlinie des Cumberland Sundes im Süd-Osten der Baffininsel. Die Küstenumwelt ist durch hohe Gezeitenausschläge, harte Winter-See -Eis -Verhältnisse, und eine dazu gehörende Wasserstand-Geschichte gekennzeichnet. Im Semmer wurden Beobachtungen an Ort und Stelle gemacht, Koojesse Inlet an der Frobischer Bucht, wo Eisaufbruch Verhältnisse auch studiert wurden, und Pangirtung Fiord am Cumberland Sund. Die Resultate wurden unter drei Überschriften gesammelt: physische und biologische Gebietsaufteilung in den Wattenmeeren, Gezeiten Einfluss und See-Eis -Vorgänge, und die geologische Entwicklung der Wattenmeere. Man macht Vergleiche mit ähnlichen Verhältnissen die von anderen Autoren in Labrador und der Ungava Bucht beschrieben wurden. Die Sediment Küsten in beiden Baffininsel Orten zeigen eine genaue physische Gebietsaufteilung, die sich am besten durch die Ansammlung von Felsblöcken im mittleren Wattenmeergebiet des Koojesse Inlet und in der Blockbarrikade an der seewärtigen Grenze des Pangnirtung Watts kennzeichnet. Biologische Observationen zeigen eine Gebietsaufteilung der Gezeiten Flora und Fauna im Wattenmeer am Koojesse Inlet. Ein besonderes Problem bildet die Frage des Transportes von sehr grossen Felsblöcken. Stossen und Rollen durch Eisschollen die auf den Gezeitensaum durch die feste Eisdecke ausserhalb der Küstenlinie, in der wichtigen frühen Eisaufbruchszeit veschränkt sind, erscheinen als mehr angepasste Vorgänge als Eisflössen.

INTRODUCTION

Tidal effects play a significant role in determining sedimentation patterns and sedimentary sequences in a variety of subtidal and intertidal settings, including open beaches, inlets, deltas, estuaries and across the shallow continental shelf. The interplay of wave processes and river processes with tidal effects has provided a central theme in various attempts to classify and explain the morphology and sedimentology of these coastal sedimentary environments. This paper examines the subarctic tidal flat environment, where the presence of sea-ice adds another variable of considerable importance.

The main objective here is to present a preliminary analysis of the wide bouldery tidal flats developed in the embayments and fiords of southeast Baffin Island, where tidal ranges are large and sea-ice dominates the coastal regime. The data were obtained in 1979, when reconnaissance observations were made at Frobisher Bay and Pangnirtung (Fig. 1), and in 1980 when more intensive surveys were carried out at Frobisher Bay over a ten-week period between mid-June and late-August. The project is continuing this year (1981) with further work at Frobisher Bay. A second objective is to place the discussion of the Baffin Island flats in the context of tidal flat studies in general, and other studies of drift ice action on tidal flats elsewhere on the eastern Canadian seaboard.

TIDAL FLATS

Tidal flats are the most intensively studied of tidal sedimentary environments (GINSBURG, 1975; KLEIN, 1976, 1977; McCANN, 1980; VAN STRAATEN, 1961). They may be defined as broad, low angle, seaward sloping surfaces, often dissected by networks of tidal channels, between high and low tide levels. They are best developed in meso- or macro- tidal settings, characterized by an abundance of sediment and low wave energy, but they also occur in micro-tidal settings with a very low coastal slope and facing the open sea in areas of reduced wave energy. Regular inundation and exposure by tides is the key characteristic, but the intertidal restriction may be relaxed, when there is a continuity of depositional processes and morphology below low water level, to include the shallow subtidal zone. At the opposite end of the intertidal profile salt marsh may be regarded as a well-vegetated intertidal flat (FREY and BASAN, 1978).

Much of the research on tidal flats has been concerned with establishing the zonation across the flat surface, which is related to the length of time a given point on the intertidal profile is inundated (or exposed) by the tide and the relative effectiveness of tidal currents at different stages of the tidal cycle. The zonation may be expressed physically, in variations in sediment size and sedimentary structures across the profile, or biologically, in different associations of plants and animals at the various tidal levels. Chemical and biochemical aspects of tidal sedimentation may also be manifest in this way (HARDIE, 1975). A fining-landwards sedimentological zonation is documented in many mid-latitude clastic tidal flat situations (GROEN, 1967; POSTMA, 1961; VAN STRAATEN and KUENEN, 1958), where muds are transported towards shore and deposited in the upper part of the intertidal profile.

The central question posed at the outset of our research concerned the extent to which 'normal' sedimentary processes due to tides, and the resulting morphological, sedimentological and biological patterns, are modified or suppressed by sea-ice action in subarctic tidal flat environments. ELLIS and WILCE (1961) have documented a biological zonation, indicating that populations on subarctic sedimentary shores generally exist only below mid-tide level because of freezing and ice scour at higher levels, but there are no published studies describing the morphology and sedimentology.

SEA-ICE AND TIDAL FLATS ON THE EASTERN SEABOARD

Sea-ice is present along much of the eastern Canadian seaboard in winter and only the outer coast of Nova Scotia and southern Newfoundland can be considered ice-free coasts, though even there ice may develop in sheltered bays. The effects of sea-ice on tidal flats has been studied in five areas: Minas Basin, Bay of Fundy (KNIGHT and DALRYMPLE, 1976); the St. Lawrence estuary (BROCHU, 1961; DIONNE, 1968, 1969a and b, 1971, 1972a and b, 1973, 1975, 1979 and other papers; GUILCHER, 1981); the Makkovik region, Labrador (ROSEN, 1979); James Bay (DIONNE, 1976a and b, 1978); and Leaf Basin, Ungava Bay (LAURIOL and GRAY, 1980). Ice conditions and tidal range are different in each area and the role of sea-ice in the coastal environment varies accordingly.

Tidal range is greatest (mean range 11.7 m; mean spring range at lunar perigee 15.4 m) in the Minas Basin, where ice, which begins to form in late December and may remain until April, occurs in three main forms: an icefoot, drift ice and an ice crust overlying most of the intertidal sediments. Ice rafted boulders and other coarse debris are deposited across the large intertidal flats, which are predominantly sandy, but KNIGHT and DALRYMPLE (1976) suggest that the most important sedimentological effects are induced by the frozen crust which prevents bedload transport by tidal currents. They indicate that few visible effects of winter ice action remain very long after breakup and that ice action does not outweigh the long term dominating effects of tides.

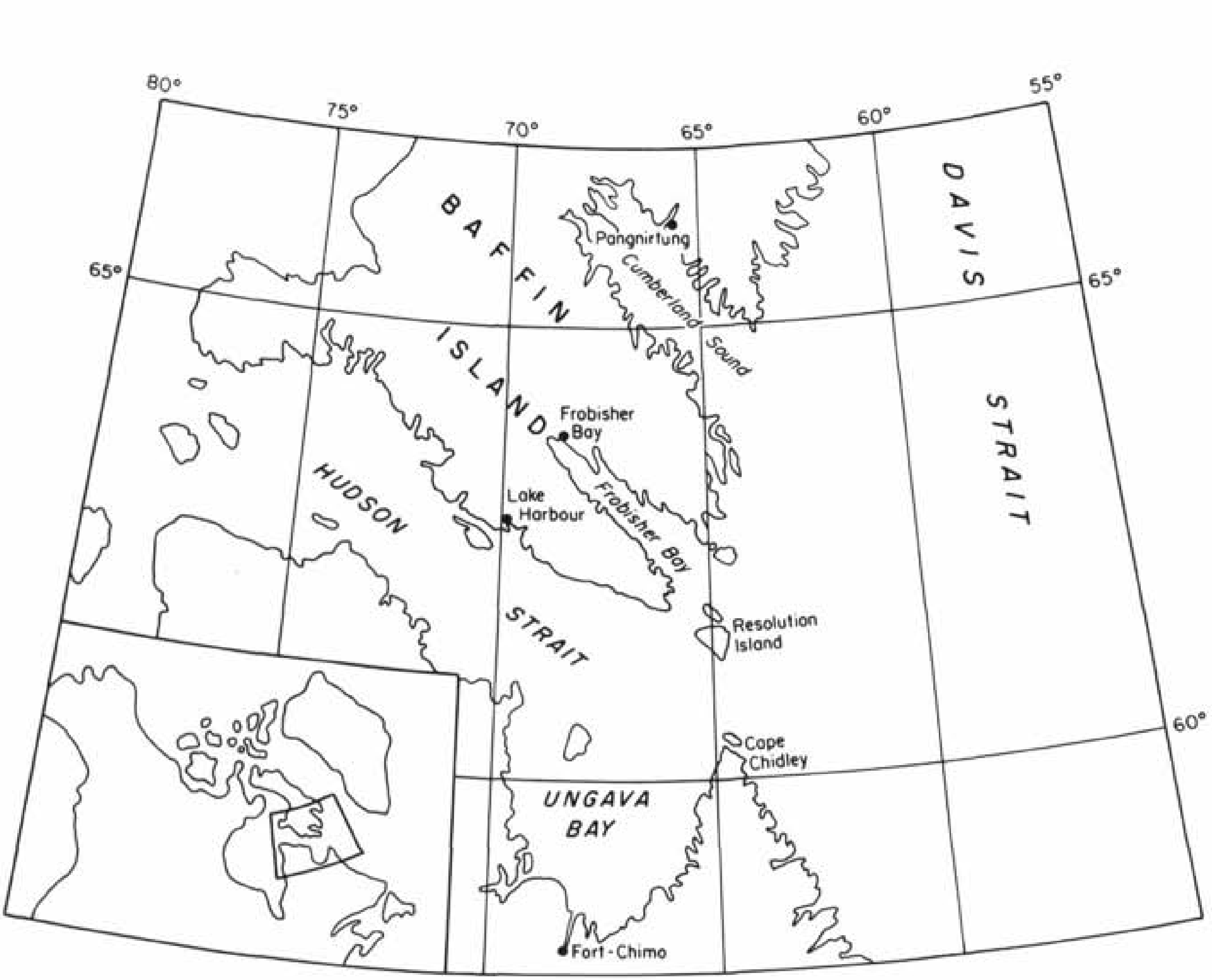

FIGURE 1. Location map of southeast Baffin Island.

Carte de localisation, SE de l'Ile de Baffin.

Dionne's studies, which have subsequently been concerned with river and lake ice action and the coastal environments of Hudson and James Bays, began on the southern side of the St. Lawrence estuary. They document numerous different sea-ice effects on the tidal flats, particularly the salt marshes of the 350 km of shoreline between Grand-Métis and Montmagny. Mean tidal range varies between 3 and 5 m, the icefoot persists for four months, and there is a thick cover of relatively mobile pack ice offshore. The salt marshes (schorre) are characterized by a high proportion of coarse material, the presence of erratic boulders due to ice rafting, and a vegetation cover which is torn up by ice block erosion, and by a relatively slow rate of deposition of fine sediment. The effects are permanent, and DIONNE (1972a) distinguishes between two types of cold region salt marshes: pitted schorre and boulder-strewn schorre. He indicates that most of the boulders have been transported by drifting ice across the estuary from the north shore, and that they are present also in Pleistocene tidal flats. The boulders occur in various arrangements including boulder barricades (DIONNE, 1972b; GUILCHER, 1981).

The studies further north, in central Labrador and Leaf Basin, reflect a different ice environment to that of Minas Basin and the St. Lawrence estuary. The ice season is longer, beginning in early December and extending to late June in central Labrador and early July in Leaf Basin, but more importantly the ice in the offshore zone now forms a more solid and immobile cover. This offshore ice remains in place during the earlier breakup of the ice in the intertidal zone, conditions which are similar to those in southeast Baffin Island. Ice effects dominate the morphology and sedimentology of the tidal flats described by ROSEN (1979) and LAURIOL and GRAY (1980), notably in the development of boulder barricades, elongate rows of boulders usually along the seaward margin of the intertidal zone. In the Makkovik area of central Labrador, where mean tidal range is 1.4 m and mean large tidal range 2.2 m, ROSEN (1979) concludes that, given the rocky setting to provide a source of boulders, there are two requirements for barricade formation. These are sufficient winter ice and water level fluctuations to entrain boulders in ice rafts, which move freely in wide shore leads during breakup, and a marked break in slope near the low water line. He argues that because ice cake thickness is similar to mean tidal range the rafts will tend to ground at the break of slope and deposit the entrained boulders at this location. In Leaf Basin, where mean and large tidal ranges are 9.3 m and 14.8 m, respectively, LAURIOL and GRAY (1980) describe three different intertidal settings: boulder strewn mudflats in Baie Rouge, a wide (up to 300 m) barricade of sand, gravel and boulders across the head of the Leaf River estuary, and a much smaller barricade (3-5 m wide, 2-3 m high), more akin to the features described by ROSEN (1979) across the tidal flats in North Arm. They suggest that the Leaf estuary feature is due to obstruction of meltwater and ice pan discharge from the river by landfast basin ice at the mouth, which prevents the evacuation of the bedload of the river, but are less convinced of this explanation for the North Arm situation. An important contribution of their study is the conclusion that the concentration of large boulders on the intertidal mudflats of the Leaf Basin is a result of slow downslope movement of boulders from the upper marine limit over the last 6000-7000 years, with the progressive displacement of the intertidal zone to its present position.

COASTAL CONDITIONS IN SOUTHEAST BAFFIN ISLAND

Frobisher Bay and Cumberland Sound are large northwest-southeast trending embayments separating the three major peninsulas of southeast Baffin Island (Fig. 1). The overall character of the coastline is steep and rocky, and beach development is generally confined to locally developed steep profile accumulations of coarse material usually derived from a variety of glacial deposits. The physiography of the region reflects Precambrian and Tertiary tilting and block faulting resulted in the formation of the highland and upland peninsulas separated by the large deep re-entrants of Frobisher Bay and Cumberland Sound. Quaternary glacial events and changing sea levels have modified the coast in detail, and most of the glacial and emerged marine sediments of southeast Baffin Island were deposited during the late Foxe (late Wisconsin) stade of the last glaciation (MILLER *et al.*, 1980). True fiords, narrow, glacially scoured, troughs in a mountainous terrain, occur along the northeastern shore of Cumberland Sound. Some of the general physical characteristics of the coastal zone have been described by MILLER *et al.* (1980), but until recently only the biological aspects of the most striking coastal depositional features of the area, the wide tidal flats which occur around parts of Frobisher Bay, Cumberland Sound and Hudson Strait, have received attention.

TIDAL CONDITIONS

Figure 2 shows the regional variation in mean tidal range around the coastline of southeast Baffin Island, as recorded at the tidal reference stations, and the tidal heights at these stations in relation to chart datum. Mean ranges in excess of 4 m occur along the outer coast between Resolution Island and Brevoort Harbour and within Cumberland Sound, with corresponding ranges at large tides greater than 6 m. Mean tidal range increases headwards in Frobisher Bay to more than 7 m and similar values occur in Hudson Strait in the vicinity of Lake Harbour, with ranges at large tides in excess of 11 m. The tides are semi-diurnal in character and thus all of the region described above falls within the macro-tidal coastal class defined by DAVIES (1964, 1972). There is an abrupt decrease in tidal range north of the entrance to Cumberland Sound to 1.9 m at Cape Dyer and less than 1 m at Broughton Harbour and Kivitoo. This reduction in tidal range is reflected in significant differences in shoreline characteristics between the southwest and northeast coasts of the Cumberland Peninsula. Both exhibit steep sea cliffs and are indented by long fiords, but the southwest, macro-tidal, Cumberland Sound side is characterized by a variety of intertidal platforms and flats, often fringing precipitous rock shores.

The tidal flats described in this paper, in Koojesse Inlet at the head of Frobisher Bay and in Pangnirtung Fiord, on Cumberland Sound, are both in macro-tidal settings, but tidal range is larger at the former location. At Frobisher Bay, which is the reference station for southeast Baffin, mean tidal range is 7.3 m and range at large tides is 11.6 m. There are no long term records for Pangnirtung but ranges at the nearest secondary station, Clearwater Fiord, some 150 km away, are 4.8 at mean tides and 7.7 m at large tides. GILBERT (1978) has suggested that the tidal range in Pangnirtung Fiord is up to 6.7 m on the basis of short term observations at Aulatsivik Point. Some of the difference in the tidal flats at the two locations may reflect this difference in tidal range.

ICE CONDITIONS

There are two good sources of long term sea-ice information for Frobisher Bay, the annual *Ice Summary and Analysis* reports (Canada Department of Transport Meteorological Branch, and Environment Canada, Atmospheric Environment Service), which are based on aerial reconnaissance mapping, and the observations

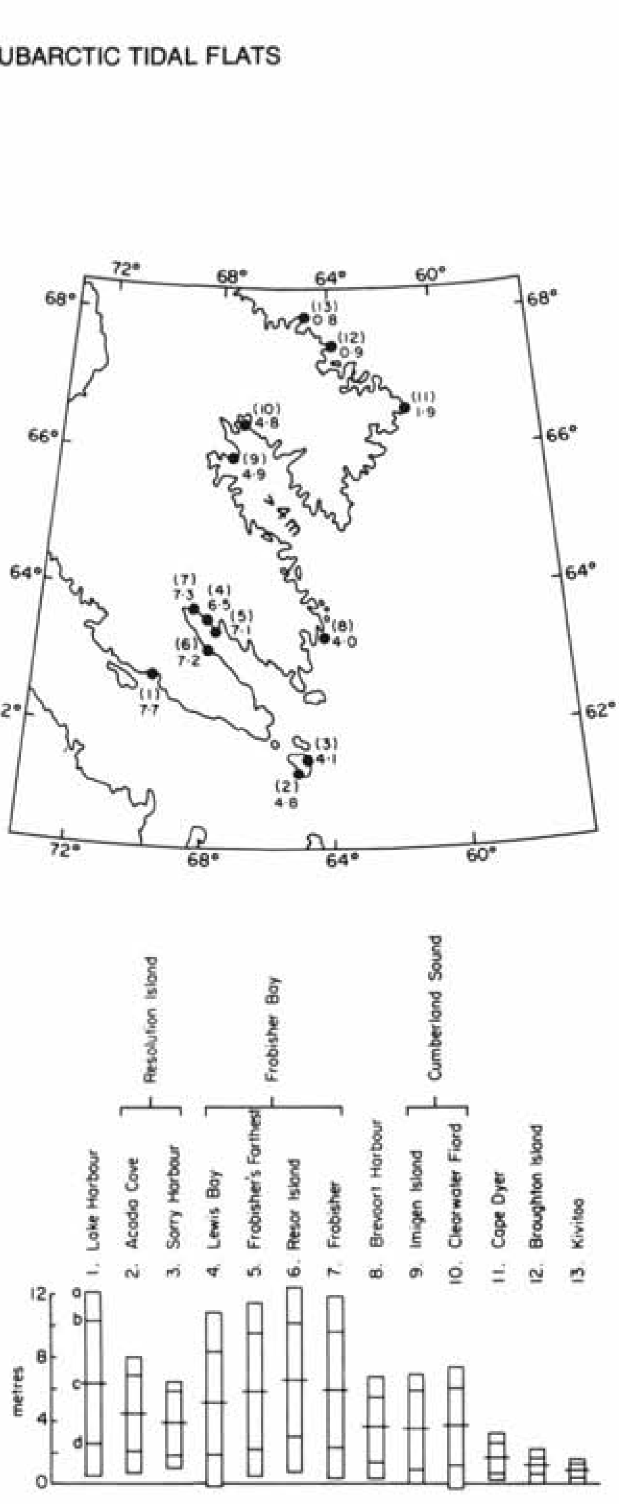

FIGURE 2. Variations in tidal range in southeast Baffin Island. The map shows mean tidal range at thirteen stations; the graph shows tidal heights at each station in relation to chart datum, as follows: a) HHW large tide; b) HHW mean tide; c) mean water level; d) LLW mean tide; e) LLW large tide (source: Canadian Tide and Current Tables, 1979, Vol. 4, Arctic and Hudson Bay).

Variations de l'amplitude des marées dans le secteur SE de l'île de Baffin. La carte indique l'amplitude moyenne à 13 stations, alors que le graphique indique les hauteurs de la marée, à chaque station, dans l'ordre suivant: a) plus haute mer de vive eau; b) plus haute mer ordinaire; c) niveau moyen de la mer; d) plus basse mer ordinaire; e) plus basse mer de vive eau (d'après Canadian Tide and Current Tables, *vol. 4,* Arctic and Hudson Bay, *1979).*

made at the Frobisher Bay airport Weather Station. Because of the importance of Frobisher as the principal settlement and port in Baffin Island, ice conditions in the Bay and the approaches to it have been monitored for navigation purposes on a routine basis for more than twenty years. The series of ice cover maps allow a good assessment to be made, for any year, of the progression of breakup, of the movement and melting of pack ice in the open water season, and to a lesser degree of the progression of freezeup. Though there is considerable variability from year to year, fast ice conditions with only small areas beginning to breakup, generally prevail around the head of the Bay (*i.e.* the area shown in Fig. 4) until June 25. In the succeeding ten days this condition changes very rapidly to one with a close cover of mobile pack ice. Though there is rapid melting thereafter, the final date of clearing from the head of the Bay depends on the pack ice being driven out by westerly winds. Remnant pack ice may remain in, or return to, the head of the Bay into August. Freezeup begins in early November and a thin cover of new ice is usually well developed across the smaller bays by the end of the month. The ice attains a maximum thickness of 1.4 to 2.0 m in the following spring. Not surprisingly, the ice reconnaissance observations, made with shipping interests in mind, do not always provide adequate information about the littoral zone.

The weather station records at Frobisher Bay provide detailed temporal information about ice conditions in Koojesse Inlet (Fig. 3B) and the Sylvia Grinnell River. Again the data reveal considerable variability from year to year, but the fact that actual dates are given for each of five events in the 'ice year' allows average dates to be calculated. The average dates shown in Figure 3C are based on the eleven-year record, 1969-70 to 1979-80, shown in Figure 3B. They suggest that the 'ice year' in Koojesse Inlet can be divided into four periods as follows: 1) freezeup (25 days), from the date of first ice formation (October 20) to the day when ice cover is complete (November 14); 2) complete ice cover (210 days), from the date when ice cover is complete (November 14) to the date when thaw is initiated (June 12); 3) breakup (37 days), from the date when thaw is initiated (June 12) to ice free conditions (July 19); 4) open water (93 days), from the ice free date (July 19) to the date of first ice formation (October 20). The records show that ice rafted back into the inlet in six of the eleven years after the ice free date.

This assessment of ice conditions emphasizes the ice dominated character of the coastal environment. With an open water season of less than a hundred days, the overall effects of wave processes on the tidal flats are likely to be limited but tidal processes operate year round. In winter the ice cover is alternately raised and grounded on the flats seawards of the icefoot. Layers of

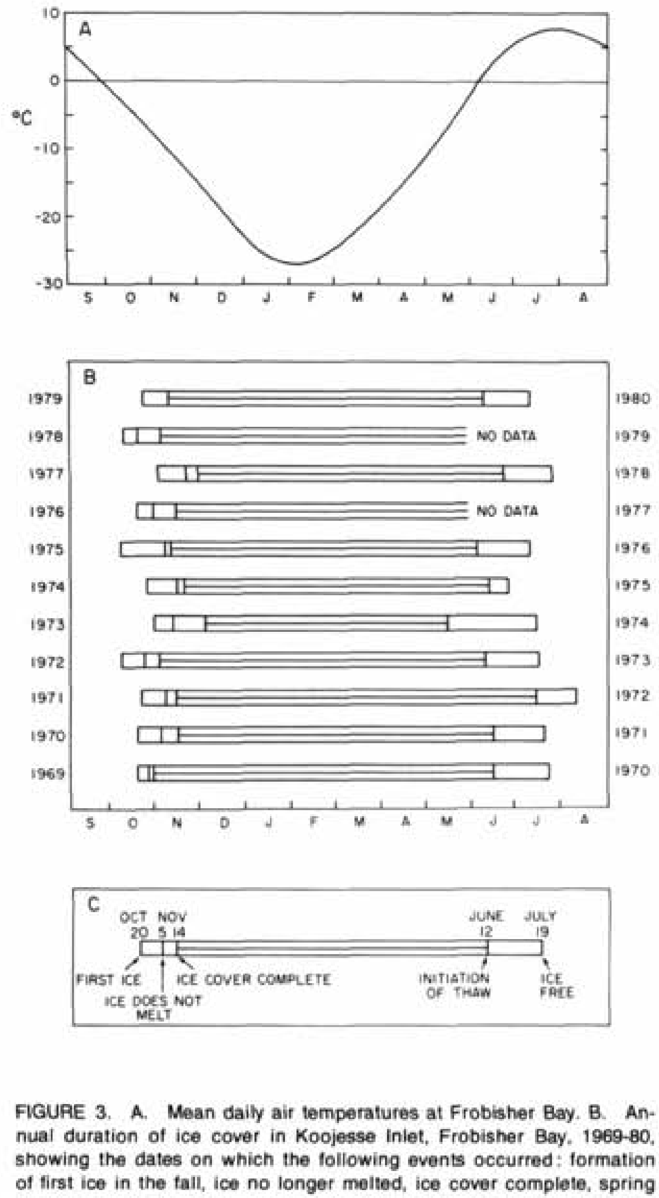

FIGURE 3. A. Mean daily air temperatures at Frobisher Bay. B. Annual duration of ice cover in Koojesse Inlet, Frobisher Bay, 1969-80, showing the dates on which the following events occurred: formation of first ice in the fall, ice no longer melted, ice cover complete, spring thaw initiated, the inlet was ice free. The period from the formation of a complete ice cover to the initiation of spring thaw is indicated by the horizontal line. C. Average ice conditions in Koojesse Inlet in the period, 1969-80. (Sources: Fig. 3A, data from *Climate of the Canadian Arctic, Canadian Hydrographic Service*, 1970: Figs. 3B and 3C, data from station records, Frobisher Bay Weather Station.)

A. Température moyenne journalière de l'air à Frobisher. B. Durée de la couverture glacielle pour la période de 1969 à 1980 dans le rentrant de Koojesse, baie de Frobisher, montrant les dates de l'englacement partiel à l'englacement complet, à l'automne, et du déglacement partiel au déglacement complet, au printemps. La partie médiane de la bande traversée par un trait horizontal indique la période d'englacement total. C. Données moyennes d'englacement-déglacement pour le rentrant de Koojesse, durant la période de 1969 à 1980. (Sources: fig. 3A, données tirées de Climate of the Canadian Arctic, Canadian Hydrographic Service, *1970; fig. 3B et 3C, données extraites des registres de la station météorologique de Frobisher.)*

sediment are incorporated as the ice forms by vertical accretion from the base, and the larger boulders are rocked and overturned. The most dynamic period in terms of ice action is likely to be breakup when the ice, at not much less than maximum thickness, is broken into floes which become free to move across the flats under the influence of tidal currents.

The weather station data does not provide information of the spatial pattern of breakup in Koojesse Inlet, so the first phase of the field work in 1980 was directed to this end. In order to supplement the ground observations in the vicinity of the settlement, and obtain a broader perspective of breakup patterns around the headward reaches of Frobisher Bay, five aerial surveys were conducted, along the route shown on Figure 4, at weekly intervals between the inception of breakup on June 19 and July 13, when essentially ice free conditions occurred. The flights were made at an altitude of 150 to 200 m at a speed of 115 knots, at a distance of about 1 km from shore. A continuous record of shoreline and sea-ice conditions was obtained on each flight using portable colour video equipment. Information from the five, hour-long videotapes, has been reduced to a series of maps, a simplified version of one of which is shown in Figure 5. The flight circuit encompasses a variety of shore environments, which in addition to the wide intertidal flats in Koojesse, Peterhead and Foul Inlets, includes the river dominated estuary of Bay of Two Rivers, the steep rock shores and narrow tidal passages of Bishop and Hill Islands, and the shallow rocky intertidal areas around the Carter Islands. A full analysis of this information will be presented at a later date (DALE, in preparation).

The sea-ice conditions on June 25 (Fig. 5 and 6) have been selected for discussion because they represent a critical phase of breakup. The intertidal zone ice breaks up before the sea-ice in the offshore zone. This is because of its fractured condition, due to repeated grounding, and its decreased albedo, due to the dark incorporated sediments. At the time of the previous flight on June 19 there were small areas of open water at the mouths of the larger streams, such as the Sylvia Grinnell and Bay of Two Rivers, where the nival freshet had accelerated melting, and the ice across the wide tidal flats at the head of Foul Inlet, on the east side of Peterhead Bay and in Koojesse Inlet was beginning to breakup, though it remained in place. In the following six days rapid melting and disintegration of the intertidal zone ice occurred and the tidal flats were characterized by a chaotic assemblage of ice floes increasingly free to move with rising and falling tides. By June 25 more than half of the intertidal zone ice had melted. The mobile pack ice during this early phase of breakup was contained within the intertidal zone by the still solid cover of sea-ice proper. Thus sediment in-

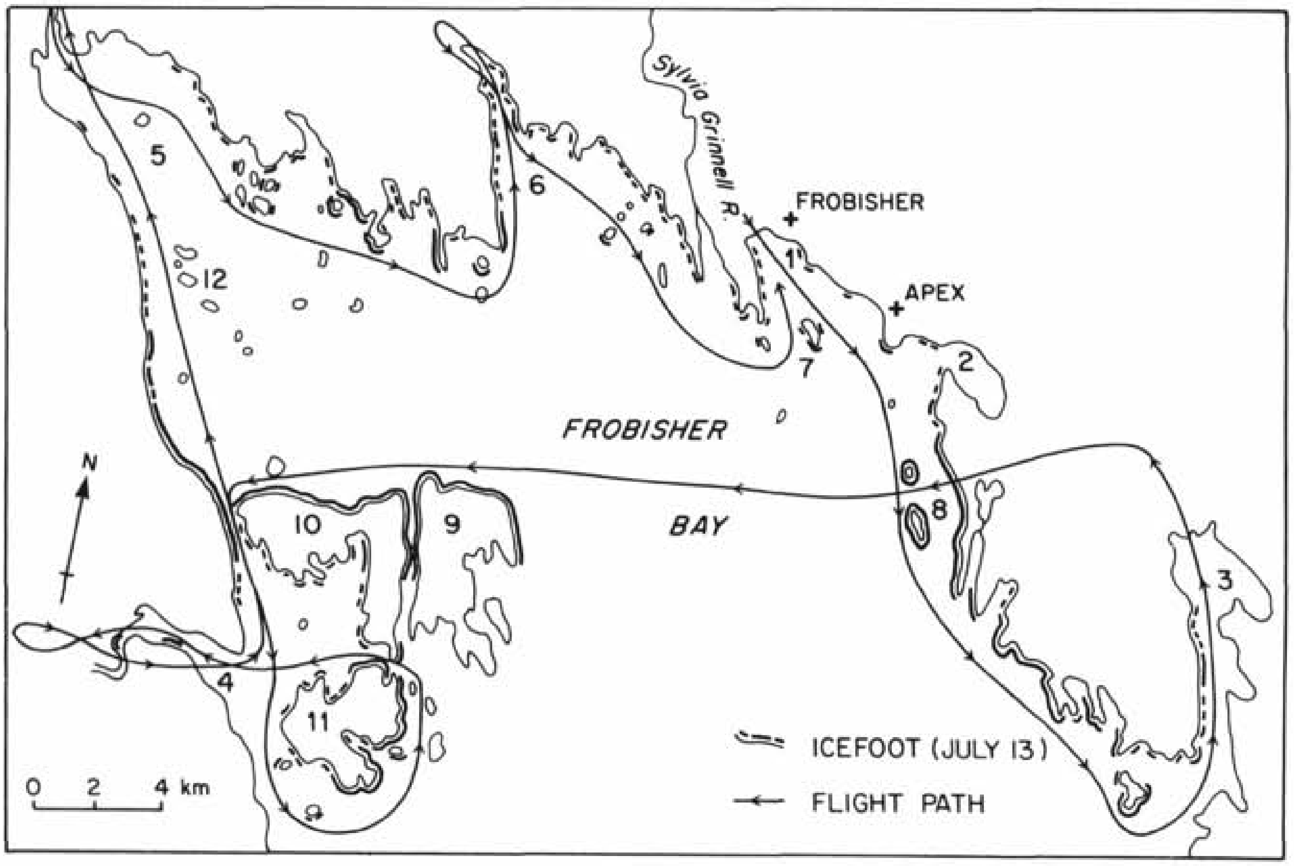

FIGURE 4. Head of Frobisher Bay, showing the flight path of five aerial reconnaissances undertaken during breakup 1980, when a record of shore and sea ice conditions was obtained using portable video-camera equipment. By July 13, the date of the last flight, the only significant ice remaining was the icefoot, the distribution of which is also shown on this map. Major embayments are: 1) Koojesse Inlet; 2) Tarr Inlet; 3) Burton Bay; 4) Bay of Two Rivers; 5) Foul Inlet; 6) Peterhead Inlet. Islands located on the map are: 7) Long Island, 8) Mair Island, 9) Hill Island, 10) Bishop Island, 11) Faris Island, 12) Carter Islands.

Secteur amont de la baie de Frobisher montrant le tracé des levés aériens effectués au cours du déglacement en 1980; les conditions glacielles ont été enregistrées par une caméra-vidéo. Le 13 juillet, date du dernier relevé, il ne restait que des lambeaux du pied de glace indiqués sur la carte par un trait gras plus ou moins continu, suivant le cas. Les principaux rentrants indiqués sont dans l'ordre (1 à 6): Koojesse Inlet, Tarr Inlet, Burton Bay, Two Rivers Bay, Foul Inlet et Peterhead Inlet. Les îles mentionnées sont dans l'ordre (7 à 12): Long, Mair, Hill, Bishop, Faris et Carter.

corporated in the ice was redeposited in this zone, albeit at different locations to where it was entrained.

A more detailed depiction of ice conditions at low tide in Koojesse Inlet on June 25 is given in Figure 6. More than half of the flats on the east side were devoid of ice and the remaining floes of intertidal ice were grounded in a broad zone across the head of the inlet. The map also illustrates the beginning of the subsequent phase of breakup during which the landward margins of the floating sea-ice fractured and broke away. This process of attrition produced ice floes which were rafted across the intertidal zone. However, as these floes were relatively small and thin and contained no sediment they had little effect on the tidal flats.

An almost continuous icefoot was present along both rock and sedimentary shores around the head of Frobisher Bay at the time of the earlier surveys (Fig. 5). In Koojesse Inlet it had a maximum width of 60 m in low gradient beach situations at the back of the tidal flats but was often less than 10 m wide on steep rocky shoreline sections. Very wide areas of fast ice occurred at the head of Foul Inlet and around the intertidal rock islands of the Carter Islands group. By the time of the last survey on July 13 (Fig. 4) the icefoot had largely disappeared in sedimentary shoreline settings but remained along much of the rock shoreline. In particular there had been little change below the north facing, steep cliffs of Hill and Bishop Islands. The presence of an icefoot restricts the distribution of intertidal flora and fauna, and the upper part of the intertidal zone is usually barren.

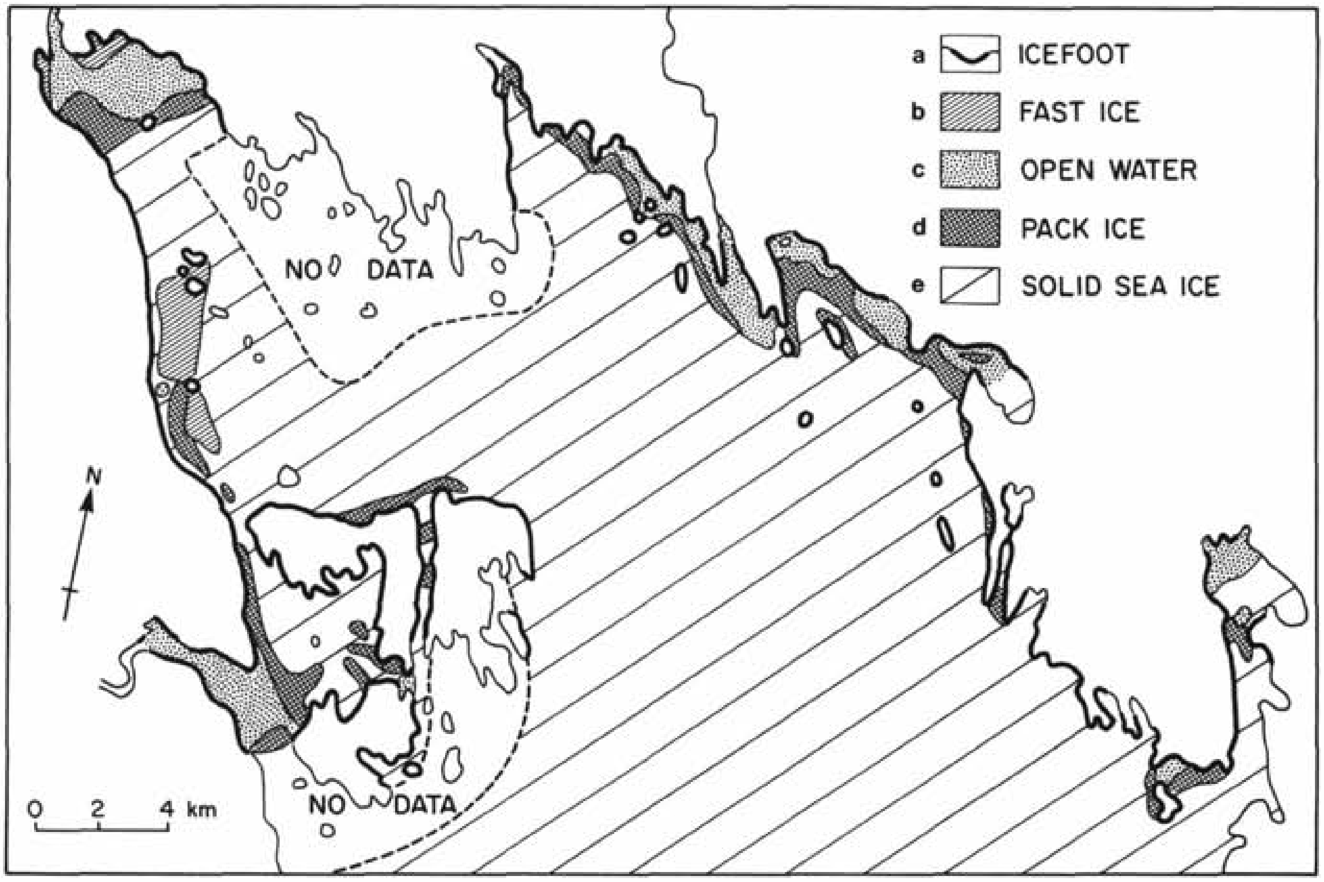

FIGURE 5. Ice conditions at the head of Frobisher Bay on June 25, 1980 (reconnaissance flight #2). Open water occurs at major river mouths (Bay of Two Rivers, head of Foul Inlet, mouth of Sylvia Grinnell River) and along the wide tidal flats on the eastern shores of Koojessee and Peterhead Inlets. (Place names are shown on Fig. 4.)

Conditions glacielles à l'amont de la baie de Frobisher, le 25 juin, 1980 (vol de reconnaissance n° 2). On peut observer des zones d'eau libre à l'embouchure des principaux cours d'eau (Two Rivers, Foul, Sylvia Grinnell) et le long des larges zones intertidales des rentrants de Koojesse et de Peterhead. (Voir fig. 4, pour localisation des noms de lieux.) Légende de la figure: a) pied de glace; b) glace d'estran; c) eau libre; d) glace de dérive; e) banquise.

KOOJESSE INLET

The most striking feature of Koojesse Inlet, at the head of which is the airport and town of Frobisher Bay, are the wide boulder strewn tidal flats exposed at low tide. At high tide the area of the inlet, as defined by a straight line joining Innuit Head, Long Island and Apex Hill, is 7.7 km^2: the area of the intertidal zone at lowest low tides is 5 km^2, of which almost 2 km^2 occurs at the head of the inlet. Away from the head, the intertidal zone is widest (700-1000 m) on the eastern shore, in the lee of Long Island: along the eastern shore, north of Innuit Head, it is only 200 m wide. Three small streams drain into the inlet, but only the one north of Apex Hill appears to have any significant effect on tidal flat characteristics. Except for the 2 km of shoreline backed by low lying ground at the head of the inlet, the backshore consists of rock cliffs surmounted by steep becrock slopes, which are mantled in places by rounded boulders. The rock shoreline is in places glacially smoothed, but for the most part shows evidence of recent and continuing erosion, largely by frost action and plucking of blocks by sea-ice. Natural conditions at the head of the inlet have been disturbed in a number of ways over the last forty years with the building of the airport and the growth of the settlement, most noticeably in the clearing of boulders from parts of the intertidal zone to facilitate the unloading of ships.

The maps in Figure 7 show the general surface character of the intertidal zone around the inlet (see also photographs in Fig. 10-15), and the accompanying surveyed profiles in Figure 8 were selected to typify the different conditions which are obtained along the eastern and western shores. Figure 9 is a generalized profile across the intertidal zone on the eastern side of

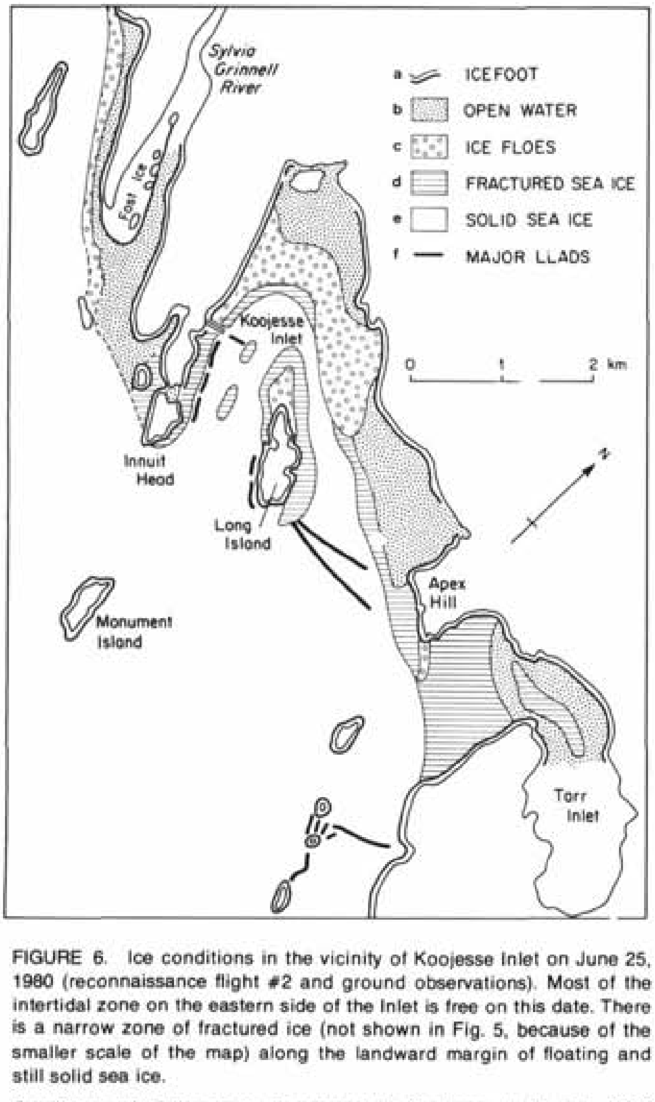

FIGURE 6. Ice conditions in the vicinity of Koojesse Inlet on June 25, 1980 (reconnaissance flight #2 and ground observations). Most of the intertidal zone on the eastern side of the Inlet is free on this date. There is a narrow zone of fractured ice (not shown in Fig. 5, because of the smaller scale of the map) along the landward margin of floating and still solid sea ice.

Conditions glacielles dans le rentrant de Koojesse le 25 juin, 1980 (levé aérien n° 2 et levés au sol). La plus grande partie des zones intertidales du côté est du rentrant est déjà déglacée à cette époque. Il existe une étroite bande de glace fragmentée (non indiquée sur la fig. 5 en raison de l'échelle), en bordure de la banquise. Légende de la figure: a) pied de glace; b) eau libre; c) glace de dérive; d) glace fragmentée; e) banquise; f) polyna.

the inlet showing the morphological, sedimentological and biological zonation which occurs.

Sand beaches occur at the head of the inlet below the town, in two small pocket beaches immediately to the south (profile 1, Fig. 8), and in the embayment north of Apex Hill; mudflats, with salt marsh towards high tide, occupy a small protected area in the extreme northwest corner of the inlet. Elsewhere, the steep upper part of the intertidal profile is developed in bedrock (profiles 2 and 3, Fig. 8). On the east side of the inlet this bedrock section occupies only a small portion of the intertidal profile and the sedimentary section (the tidal flat), which usually commences about 6 m above lowest low water level, is between 600-1000 m wide (Fig. 8, profile 2; Fig. 10). On the west side, in contrast, the bedrock section commonly occupies more than one third of the shorter profile and extends as low as 4 m above lowest low tide level (Fig. 8, profile 3, Fig. 11).

The tidal flats are everywhere littered with cobbles and boulders, resting on, and embedded in, finer sediments, which range in size from clay to gravel but are predominantly coarse sand. On the eastern side of the Inlet these sediments, which constitute the surface of the flats, appear to be only a thin but variable veneer overlying a substrate of bluish-grey clay. The clays outcrop at numerous localities in the vicinity of profiles 1 and 2 (Fig. 9), but the surface of the material is frequently contaminated by admixtures of sand and gravel, which appear to have been ground into it by the overlying weight of sea-ice settling at low tide. The best exposures occur in two settings. On profile 1, a wave and current swept, erosional clay surface can be seen below an intermittent veneer of sand and gravel between 750 and 950 m from the high tide line. On profile 2 the clay outcrops around the margin of boulder mounds in the upper-middle section of the profile between 150 m and 400 m from the high tide line. Here the development of the boulder mounds (see below) appears to have protected the clay substrate from erosion. We interpret the clay as a shallow marine deposit laid down offshore during a phase of high sea level following the retreat of the last ice from the area, but it may represent sedimentation in a glacially dammed lake.

BOULDERS

Three features of the boulder distribution and arrangement across the wide flats on the eastern side of the inlet are noteworthy. Firstly, there is a 250-350 m wide, shore-parallel zone, with a greater concentration of boulders and more frequent occurrence of very large boulders, occupying the centre of the flats (Fig. 7A). The elevation of the zone varies between 3 and 6 m above lowest low tide level, and it is generally the flattest section of the overall profile. Secondly the largest boulders rarely occur in isolation, rather their presence has lead to the localized accumulation of other, usually smaller, boulders and cobbles and the development of boulder mounds in this zone. Thirdly, boulders in the upper parts of the flats tend to be on the surface and free-standing in positions indicating recent movement by ice, whereas boulders on the lower parts are more frequently embedded in finer sediments (Fig. 12 and 13).

Observations at breakup in 1980 indicate that the large boulders are very frequently the site of grounded

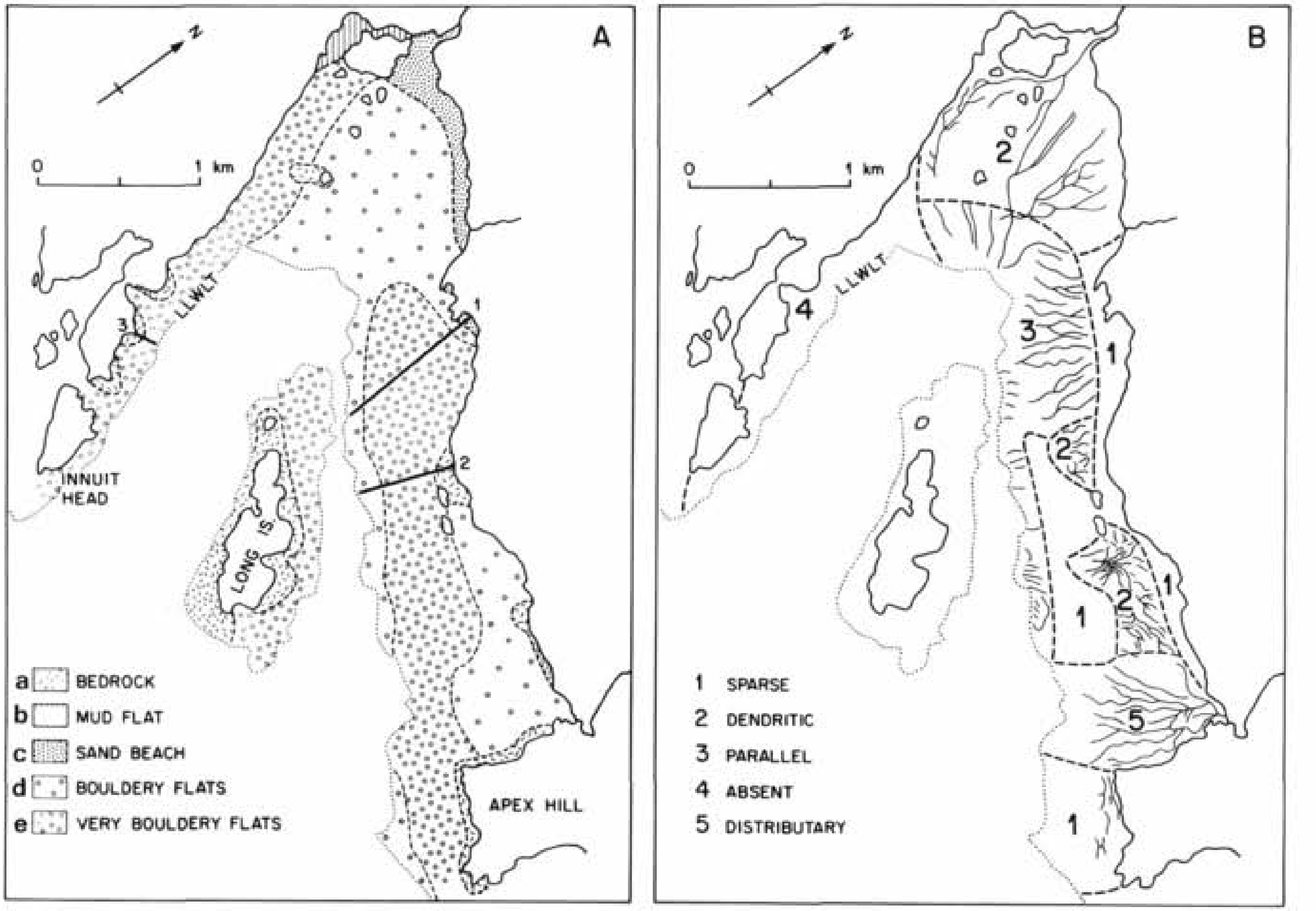

FIGURE 7. Tidal flats in Koojesse Inlet, Frobisher Bay. A) Generalized sediment distribution and location of profiles shown in Figure 8; B) Drainage patterns.

Zones intertidales du rentrant de Koojesse, baie de Frobisher. A) répartition générale des sédiments et localisation des profils de la figure 8; légende de la figure: a) substrat rocheux; b) estran vaseux; c) plage de sable; d) estran caillouteux; e) estran très caillouteux. B) Réseaux de drainage de la zone intertidale: 1) dispersé; 2) dendritique; 3) parallèle 4) non existant; 5) en éventail.

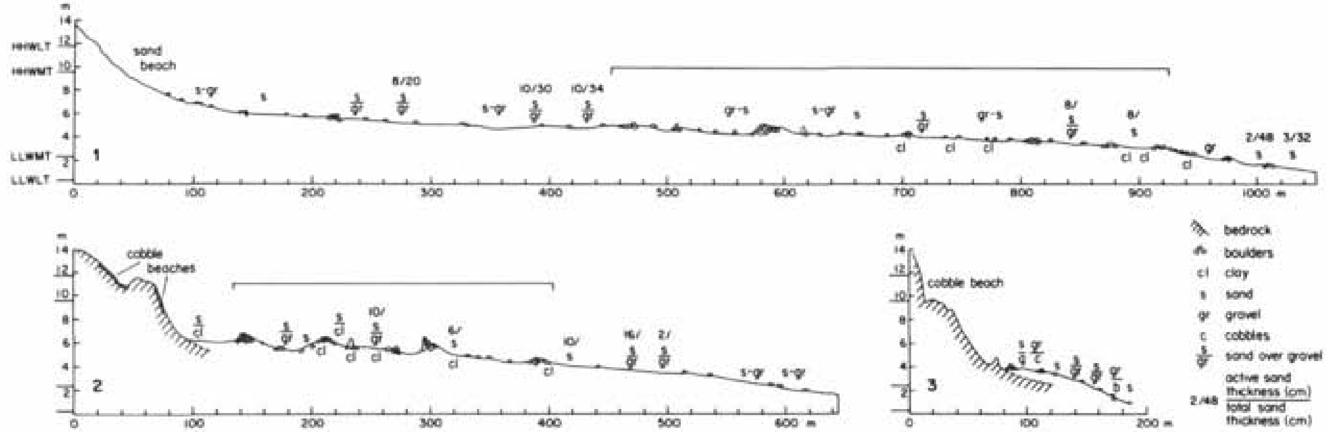

FIGURE 8. Surveyed profiles of the intertidal zone at three sites in Koojesse Inlet (see Fig. 7A for locations), to show variations in tidal flat characteristics and boulder distribution. The position of the middle flat zone, defined in Figure 9, which contains the greatest concentration of boulders and boulder mounds in shown by the horizontal line above the profile. Profiles were surveyed on August 11-13, 1979, using precise level and staff. Tidal heights are referenced to chart datum and taken from *Canadian Tide and Current Tables*, Vol. 4, 1979.

Trois profils transversaux levés sur le rivage du rentrant de Koojesse montrant des différences morpho-sédimentologiques et donnant la répartition des blocs. La partie médiane de la zone intertidale où se rencontre la plus forte concentration de blocs est indiquée par la ligne horizontale au-dessus du profil. Profils levés à l'aide d'un niveau, entre le 11 et le 13 août, 1979. La hauteur de la marée est celle indiquée dans les Canadian Tide and Current Tables *(vol. 4, 1979). La légende de la figure se lit comme suit: substrat rocheux; blocs; argile; sable; gravier; galets; sable et gravier; couche de sable active en centimètres sur épaisseur totale du sable en centimètres.*

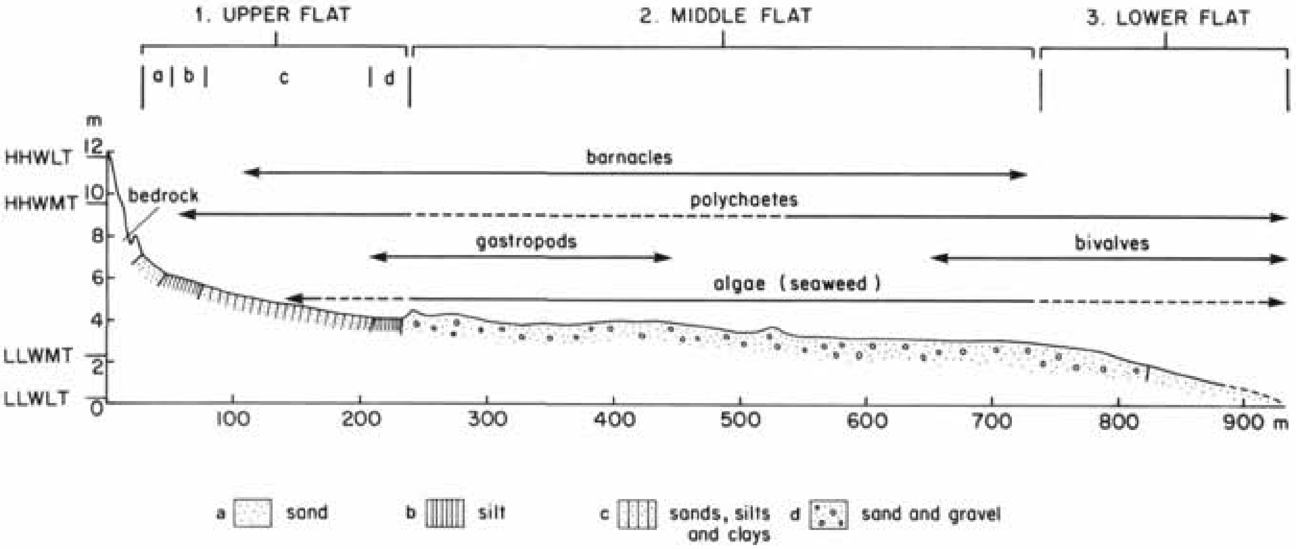

FIGURE 9. Generalized cross-section across the tidal flats on the east side of Koojesse Inlet, showing the three main morphological units, surface sediments and biological zonation. Boulders, which are not shown, occur across the entire profile but are more frequent in the middle flat.

Coupe généralisée de la zone intertidale, du côté est du rentrant de Koojesse, montrant trois zones (haut, moyen et bas estrans), la nature des sédiments meubles et la répartition des organismes vivants. Les blocs, non indiqués ici, se rencontrent partout, mais sont plus abondants dans la zone médiane. Légende de la figure: a) sable; b) limon; c) sable-limon-argile; d) sable et gravier.

floes of intertidal zone ice during the period when this ice is free to move across and along the flats with the tides, but is contained seawards by the sea-ice proper (*i.e.* the conditions of June 25, illustrated in Fig. 6). The intertidal ice floes are melting very rapidly at this time and easily broken as they are lowered by the tide over large boulders. They contain layers of fine sediment and occasional cobbles and small boulders (the largest observed was 30 cm in diameter), and considerable quantities of this material are deposited during each low tide grounding. The fact that the large boulders act as loci for grounding means that much of this material is deposited in their vicinity. Two boulder accumulations are shown in Figures 14 and 15. The first shows some 30 small boulders deposited on the seaward side of a large boulder (310 cm × 230 cm × 160 cm), the second shows what might more accurately be called a boulder mound which consists of four large boulders (the largest is 220 × 180 × 90 cm) surrounded by numerous smaller boulders partly set in a matrix of finer material. Where there are numerous boulder accumulations and mounds (*e.g.* on profile 2, Fig. 8) they produce a local micro-relief, excluding the height of the boulders, of the order of 50-100 cm. The accumulations of boulders not only protect the underlying substrate from erosion by ice scour, they also, by channeling the ebb and flood flows across the flats, increase the potential for erosion by tidal currents, as well as ice scour, in the intervening depressions. The drainage networks on the flats are often difficult to follow on the ground, and the patterns summarized in Figure 7B were interpreted from aerial photographs. For the most part they represent very shallow channels. There are no deep tidal creeks, and lateral erosion and sedimentation associated with the channeling of flood and ebb flows across the flats is unimportant.

In addition to single boulders and boulder accumulations and mounds, centred on single or several large boulders, two other patterns occur. Discontinuous boulder ridges occur on the upper part of the flats below Apex Hill, and circular patterns of partially embedded boulders occur in many places along the lower flats. These last may be due to the repeated lifting and settling of blocks of ice by tidal action during the winter.

The breakup observations did not produce any dramatic instances of boulder movement, such as large boulders in transit by ice floes. This may be due to the fact that observations were limited during the early stages of breakup, when this process may operate most effectively, by the very unstable and dangerous condition of the ice. Access to the flats is difficult at this time, even at low tide. The overall impression, gained from a series of incomplete traverses made before June 24 and more complete observations over the next eight days, was that not more than 10% of the larger boulders (> 1 m) in the upper and middle sections of the flats had moved during the breakup period, and that none had moved very far. Rocking, pushing, dragging and overturning appeared to be the dominant modes of movement of large boulders. The overturning of boulders is facilitated by the scour pits which are produced around their bases by tidal currents. The effectiveness of tidal currents beneath the intertidal ice in winter may be reduced by the freezing of the surface layers were encountered at depths of 15-20 cm below the surface in some places.

FINER SEDIMENTS

It is difficult at first examination to discern any overall size gradation in the veneer of finer sediments across the flats, for the continuity of tidal and wave action is interrupted by the boulders which result in localized

FIGURE 10. Low tide view of the wide intertidal zone on the east side of Koojesse Inlet between profiles 1 and 2, looking south-westwards from high tide level. The upper part of the shore profile is developed in rock and the sedimentary section is 800 m wide.

Vue à marée basse de l'estran, du côté est du rentrant de Koojesse, entre les profils 1 et 2, en direction du SO, vers la limite des basses mers. Le substrat rocheux (bas de la photo) forme la partie supérieure du rivage, alors que la partie inférieure est en matériel meuble et fait 800 m de largeur.

FIGURE 11. Low tide view of the narrow intertidal zone on the west side on Koojesse Inlet in the vicinity of profile 3 (Fig. 9) where the sedimentary section of the shore profile is only 120 m wide. The promontory in the left middle ground is a rubble causeway.

Vue à marée basse de l'étroite zone intertidale, du côté ouest du rentrant de Koojesse, près du profil 3 (fig. 9); l'estran en matériel meuble ne fait que 120 m de largeur; une digue de cailloux pointe vers le large à gauche.

FIGURE 12. View of the middle flat zone in the vicinity of profile 2 (Fig. 9) looking east towards Apex Hill in the background. The flat surface, here at an elevation of 6 m above lowest low tide level, is strewn with boulders, many of which are resting on, rather than embedded, in finer sediments. The large boulder left of centre is 1.5 m long. Thin patches of current-rippled sand, overlying gravels, occur between the boulders. The flat here is relatively barren.

Vue de la partie médiane de l'estran près du profil 2 (fig. 9), vers l'est, en direction de la colline Apex. La surface plane, à une altitude de 6 m au-dessus du niveau des plus basses mers, est couverte de cailloux; plusieurs d'entre eux reposent directement sur le matériel meuble, alors que d'autres sont enfoncés. Le gros bloc, au centre, mesure 150 cm de longueur. Des placages de sable avec rides de courants et des amas de gravier apparaissent ici et là; l'estran est en grande partie dénudé.

FIGURE 13. View of lower flat zone, 400 m seawards of Figure 12. The flat surface, at an elevation of 3 m above lowest low tide level, exhibits fewer boulders and all but the largest are embedded in finer sediments. Sand is more abundant and, though the upper surfaces of the boulders are abraded by ice, attached algae occupy the protected lower faces.

Partie inférieure de l'estran, à 400 m plus bas que sur la figure 12. La surface plane, à 3 m au-dessus du niveau des plus basses mers, est couverte de cailloux, la plupart étant légèrement enfoncés dans le substrat meuble; les espaces occupés pour le sable sont plus vastes et plus nombreux à ce niveau. On peut observer des marques d'abrasion glacielle à la surface des blocs, alors que des algues sont fixées sur les parties des blocs protégées.

channeling and ponding. However, a combination of observations from several profiles suggests the zonation of surface sediments shown on the generalized profile in Figure 9. The profile is divided into three zones on the basis of slope, boulder concentrations (not shown), surface sediments and biology. Sand is thickest (up to 50 cm) in a narrow continuous zone (the lower flat) only exposed at very low tides (see also Fig. 8, profile 1), and also occurs intermittently at the opposite end of the profile as a narrow summer beach. In the middle flat sand is more usually mixed with gravel, or occurs as a thin veneer over gravel. Mud occurs mainly in the upper flat where it settles from suspension at high tide; it may occur as a silt veneer, subject to removal during periods of wave activity, or mixed with sands and gravels.

FIGURE 14. Single large boulder (310 × 230 × 160 cm) in the middle flat zone, northwest of profile 1, with an accumulation of smaller ice rafted boulders on the seaward side. Commonly, barnacles occupy the protected lower faces of the larger boulders, as illustrated here.

Méga-bloc (310 × 230 × 160 cm) dans la zone médiane de l'estran au nord-ouest du profil 1 et accumulation associée de petits blocs glaciels du côté de la mer. Habituellement, les balanes se fixent dans les parties protégées de la base des blocs comme ici.

FIGURE 15. Boulder mound in the middle flat zone, northwest of profile 1, consisting of four large boulders, surrounded by many smaller boulders.

Monticule de cailloux glaciels dans la zone médiane de l'estran, au nord-ouest du profil 1, constitué de 4 gros cailloux entourés de plusieurs blocs beaucoup plus petits.

FIGURE 16. Low tide view of the intertidal zone at Pangnirtung in the vicinity of profile 2 (Figs. 18 and 19), looking towards shore. Most of the boulders are partially embedded in sand or sandy-gravel. The uppermost part of the intertidal zone is developed in bedrock and there is a discontinuous low rock cliff. There is an abundance of attached algae along this profile.

L'estran à Pangnirtung, à marée basse, au voisinage du profil 2 (fig. 18 et 19); vue prise en direction de la côte. La plupart des blocs sont partiellement enfoncés dans le sable ou le sable-gravier; la partie supérieure du rivage est taillée dans le substrat rocheux et correspond, par endroits, à une petite falaise. Les algues fixées aux blocs glaciels abondent dans ce secteur.

FIGURE 17. Low tide view of the tidal flats at Pangnirtung in the vicinity of profile 2, looking seawards towards the boulder barricade from the same position as the previous photograph.

Batture à marée basse, à Pangnirtung, près du profil 2; photo prise en direction du large mais du même endroit que la précédente.

Measurements of the depth of the recently active surface layer of sand were obtained during the profiling exercises in August 1979 (Fig. 8, profiles 1 and 2) when tidal ranges approached maximum values. They indicated that, in general, not more than a 10 cm thickness of sand was reworked during the ten-day period of calm weather conditions. In July and August, 1980, there were only ten days when waves greater than 10 cm in height affected the Koojesse flats, and we were again unable to evaluate the contribution by wave processes to sediment transport. However, the profile of the sand beach in the embayment north of Apex Hill, and the presence of cobble beaches (Fig. 8, profile 2) above normal high tide levels, indicates that wave action must, intermittently, at least, be an important factor, a suggestion which is given further support by the fact, that, on average, there is a high frequency of winds from the southeast, the direction of maximum fetch, during the open water season (*Climate of the Canadian Arctic*, 1970).

BIOLOGY

There are several good reconnaissance type studies of the intertidal fauna and flora of the eastern arctic and sub-arctic area, encompassing eastern Baffin Island, western Greenland and northern Labrador, and the results from the Canadian Arctic Expedition, 1913-1918 (DALL, 1924) have provided a sound basis for subsequent Canadian studies (DUNBAR, 1951; ELLIS, 1955). Of the more recent studies in the vicinity of Frobisher Bay, ELLIS and WILCE (1961; see also ELLIS, 1955 and 1960), DEN BESTE and McCART (1978) and Wacasey (pers. comm., 1980) have utilized a comprehensive zonation approach, which links the spatial, and ideally, the numerical aspects of floral and faunal distributions with the physical characteristics of the habitats. ELLIS and WILCE (1961) indicate that, in spite of faunal differences due to different sediment sizes, the vertical distribution of animals and plants was essentially similar along all the sedimentary shores examined in southeast Baffin Island: "generally barren above MTL, sparsely populated in the lower part of the middle area, but gradually acquiring a flora and fauna as shallow water forms become abundant, particularly below LWN" (1961, p. 231-232). They developed a comprehensive species list, but provided no indications of population densities. DEN BESTE and McCART (1978) studied biological zonation at the Frobisher Bay headlands along Davis Strait, sampling both subtidal and intertidal locations to determine sedimentary characteristics and animal and plant densities. There is no published account of species densities on the tidal flats of Koojesse Inlet, but research is being undertaken by personnel from the Arctic Biological Station at Sainte-Anne-de-Bellevue (Wacasey, pers. comm., 1980). The species list presented in Table I compiles results of our collections in 1980 and earlier studies. It should be noted that some subtidal species are included, that the list contributed by Wacasey contains only principal species, and that the small number of species recorded by DEN BESTE and McCART (1978) is a reflection of the Davis Strait location of their study and the fact their sampling sites were narrow beaches and not wide intertidal flats.

TABLE I

Intertidal species list (bivalvia, Gastropoda and Polychaeta), Frobisher Bay vicinity, Baffin Island

	ELLIS (1955, 1960, 1961)	DENBESTE and McCART (1978)	Wacasey (pers. comm., 1980)	Dale (collected 1980)
Bivalvia (Pelecypoda):				
Astarte borealis	X		X	XD[1]
Astarte montagui	X			
Astarte striata				XD
Axinopsis orbiculata	X		X	
Crenella faba	X	X		X
Cyrtodaria kurriana	X			X
Hiatella arctica	X			X
Macoma balthica	X			
Macoma calcarea	X			
Musculus discors	X	X		X
Musculus discors laevigatus				XD
Musculus niger	X			XD
Mya truncata	X		X	X
Mytilus edulis	X			
Serripes groenlandicus	X		X	XD
Thracia cf. *myopsis*				XD
Thyasira flexuosa			X	

	ELLIS (1955, 1960, 1961)	DENBESTE and McCART (1978)	Wacasey (Pers. comm., 1980)	Dale (collected 1980)
Gastropoda:				
Acmaea testudinalis	X			XD
Boreotrophon clathratus		X		
Buccinum sp.	X			
Buccinum bayani		X		
Buccinum finmarkianum verknizen				XD
Buccinum scalariforme				XD
Colus pubescens				XD
Coryphella salmonacea	X			
Cylichna alba				XD
Cylichna occulata	X	X		
Lacuna cf. *vincta*				XD
Lepeta caeca		X		
Littorina littorea		X		
Littorina sp.			X	
Littorina saxatilis	X			X
Lora scalaris		X		
Margarites sp.		X		
Margarites groenlandicus	XD			
Margarites helicinus	X			XD
Margarites oblivaceous				XD
Margarites umbilicalis		X		XD
Polychaeta:				
Ampharete acutifrons				X
Ampharete grubei	X			
Capitella capitata	X	X		X
Cistenides granulata	X			
Eteone flava	X			X
Eteone longa	X			X
Eulalia sp.		X		
Flabelligera affinis				XD
Harmothoe imbricata	X			X
Harmothoe truncata		X		
Laonice cirrata				X
Nephtys caeca				X
Nephtys ciliata				X
Pareurythoe borealis		X		
Phyllodoce groenlandica				X
Polydora caeca	X			X
Polydora quadrilobata			X	
Praxillella praetermissa			X	X
Pygospio elegans			X	
Sabella crassicornis				X
Scolelepis (Nerinides) sp. *sensu*				X
Scoloptos armiger	X			
Spio filicornis	X			
Spiophanes wigleyi		X		
Spirorbis sp.		X		
Spirorbis spirillum	X			
Syllis cornuta		X		

Note 1: D indicates that shells only, not live animals were collected.

Taken overall, the list is probably representative of a number of intertidal habitats, characterized by variations in water temperature and salinity, tidal and wave processes, and sediment size.

Our observations and collections were made on three different transects in Koojesse Inlet selected to include a range of conditions. Sequential sampling of the transects between late-June and late-August yielded fifteen species of Polychaetes, eleven Bivalves and ten Gastropods (Table I), and provided the spatial and temporal information discussed below. Field work in 1981 will be directed to obtaining data on population densities in Koojesse Inlet and an examination of the flats on the west side of Peterhead Inlet.

The generalized profile in Figure 9 illustrates the distribution across the Koojesse Inlet flats of the three major classes of fauna — Polychaetes, Gastropods and Bivalves, as well as the sedentary Crustacea, barnacles, and the attached algae. Polychaetes are found across most of the intertidal zone except in areas of mobile coarse gravels in channels and of dense boulder accumulation. Most prefer the silts and better sorted sands of the upper and lower flats. Each year after the sea-ice melts, species such as *Praxillella praetermissa* and *Pygospio elegans* recolonize the surface sediments of the upper flat zone. The herbivorous Gastropod, *Littorina saxtilis*, prefers the middle zone of the flats where the high densities of algae and boulders occur (Fig. 17). Bivalves are limited, with few exceptions, to the lower flats. Some attach themselves by byssus threads to algae fronds (*Crenella faba*) or boulders (*Musculus discors*), other burrow into the sorted sediments (*Mya truncata, Hiatella arctica*, and *Cyrtodaria kurriana*). The Mya, which had an average burrow depth of 21 cm, require strong sediments which will not collapse during exposure or periods of more dynamic wave and tidal current action (PURCHON, 1968). A common infaunal species not found in Koojesse Inlet in 1980 was *Macoma balthica*. NEWELL (1965) found that the abundance of Macoma is correlated with an abundance of fine sediment in the substrate. The general absence of muds in the inlet, especially in the lower flat zone, may account for their absence.

PANGNIRTUNG FIORD

Pangnirtung Fiord extends 43 km from the northeast coast of Cumberland Sound into the montainous terrain of the Cumberland Peninsula, terminating just south of the Arctic Circle at the Weasel River. The fiord has an average width of 2.5 km and a maximum water depth of only 160 m (GILBERT, 1978). The walls of the fiord rise steeply to more than 500 m asl, so that only a small proportion of this glacial through is presently occupied by the sea. Tides in the fiord are of semi-diural type but the absence of long term records precludes detailed statements about tidal range and mean water level. The nearest secondary port is Clearwater Fiord some 150 km away. Field observations showed a general agreement between the times of high and low water at the two places, and the Clearwater tide levels have been tentatively accepted as being representative of conditions near Pangnirtung hamlet. They are indicated on the profiles shown in Figure 19: large tidal range is 7.7 m, mean tidal range is 4.8 m, and mean water level is 3.5 m (CANADIAN HYDROGRAPHIC SERVICE, 1979). The times of breakup and freezeup are similar to conditions in Koojesse Inlet, and the tidal flat ice again breaks up before the offshore ice.

Tidal flats are present along much of the fiord shoreline, and are particularly well developed in the vicinity of the hamlet (Fig. 18). The most striking feature almost everywhere is the nearly continuous boulder barricade which fringes the outer margin of the flats, and provides a marked contrast with the conditions in Koojesse Inlet where this feature does not occur. Our investigations covered 18 km of shoreline between Aulatsivik Bay and a point some 4 km southwest of Pangnirtung. Shore normal transects were surveyed across the intertidal zone to record the morphological and sedimentological conditions prevailing (Fig. 19). These, together with reconnaissance observations of the intervening areas provide the basis for the following discussion. Profiles 1 to 4 show conditions near the hamlet, profiles 5 and 6 somewhat different conditions in Aulatsivik Bay.

The intertidal zone close to the settlement varies from less than 100 m to over 600 m in width and the outer margin is defined by a boulder barricade, 12-25 m wide and 0.5-1.7 m in height, which consists of boulders ranging in size from less than 0.5 m to more than 3.5 m, though most fall between 0.8 and 1.5 m in long axis (Fig. 22 and 23). The boulders are well rounded but

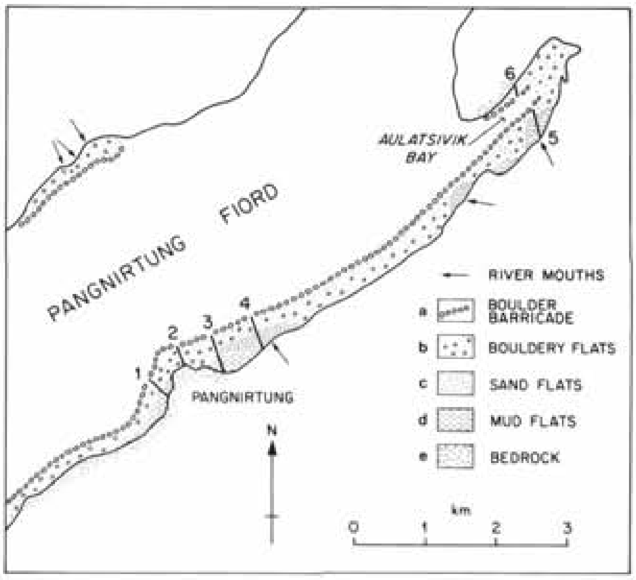

FIGURE 18. Tidal flats and boulder barricades in the vicinity of Pangnirtung, showing generalized sediment distribution and the location of the profiles shown in Figure 19.

Zones intertidales et cordons de blocs frangeants près de Pangnirtung; répartition des sédiments et localisation des profils de la figure 19. Légende de la figure: a) cordon de blocs frangeant; b) estran caillouteux; c) estran sableux; d) estran vaseux; e) substrat rocheux.

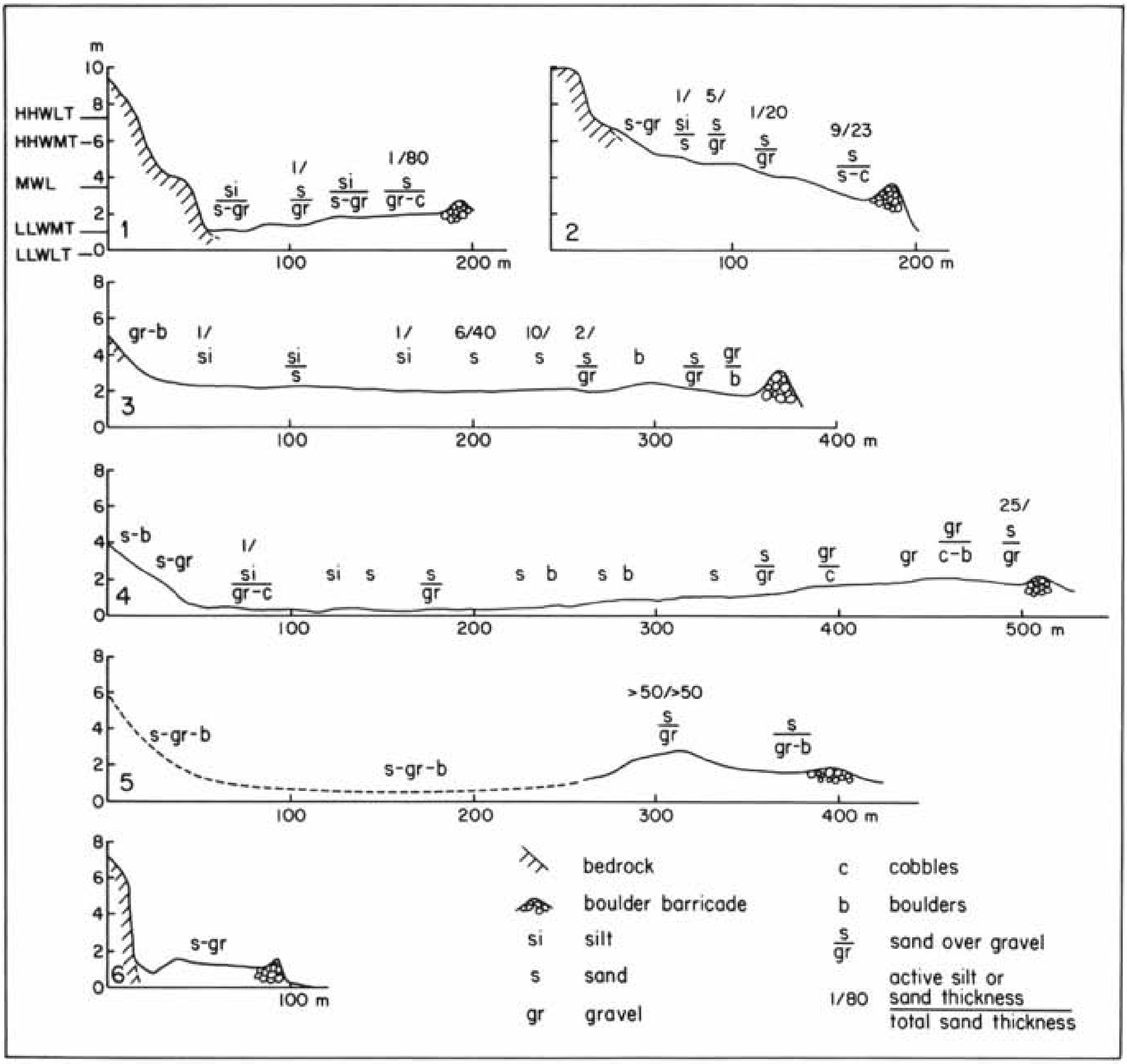

FIGURE 19. Surveyed profiles across the intertidal zone along the south shore of Pangnirtung Fiord in the vicinity of Pangnirtung. Profiles were surveyed using the simple method described by EMERY (1961). They were standardized to a common datum by reference to water levels at the time of the surveys and to the tidal predictions for Clearwater Fiord (*Canadian Tide and Current Tables*, Vol. 4, 1979). The tidal levels, shown on profile 1, are those given for Clearwater Fiord in the tables.

*Coupes transversales levées dans la zone intertidale, au voisinage de Pangnirtung; profils réalisés suivant la technique simple décrite par EMERY (1961). Niveau de base commun à l'ensemble des levés raccordé aux niveaux de la marée pour le fjord de Clearwater (*Canadian Tide and Current Tables*, vol. 4, 1979). Les niveaux de la marée indiqués en 1 correspondent à ceux du fjord de Clearwater fournis dans les tables de la marée. La légende se lit comme suit: substrat rocheux; cordon de blocs; limon; sable; gravier; galets; blocs; sable et gravier; couche de sable ou limon active en centimètres sur épaisseur totale de sable en centimètres.*

exhibit scours and scratches suggestive of erosion by sediment-laden ice floes. In cross section the barricade is generally asymetric landwards and the largest boulders occur on the steeper landward slope. In places along the barricade the boulders are arranged in roughly circular patterns. The crest of the barricade varies in height along shore: thus it is about mean sea level (if the tidal heights are correct) in the vicinity of profile 3

(Fig. 19) and declines in height towards both the northwest and southeast. Two artificial breaches have been created in the barricade to facilitate boating activities under conditions other than high tide: one in front of the Hudson's Bay Post and the other on the north side of the hamlet. According to local information these were created about 15 and 7 years ago, respectively: there appears to have been little change since they were made.

The intertidal zone shorewards of the barricade is strewn with boulders, which are generally smaller than those in the barricade, but are again well rounded. They appear to be randomly distributed but decline in number shorewards. Some rest on the surface but others are partially buried in finer sediments. Many are colonized by *Fucus* and appear to be relatively stable (Fig. 16 and 17). The finer sediments range in size from muds to gravels, which may locally be well sorted. Discrete patches of sand overlying cobbly-gravels may occasionally reach a thickness of 80 cm, though the sand veneer is usually thinner than this. The depth of recent activation, as shown by the contact between clean washed sand and the underlying mottled sands was rarely more than 10 cm in August, 1979. The thickest

FIGURE 20. Low tide view from about mid-tide level towards the head of Aulatsivik Bay, showing the field of large boulders resting on the surface of flats.

Champ de blocs épars à la surface de l'estran, dans la baie d'Aulatsivik; vue prise vers la rive.

FIGURE 21. Large upright boulder in Aulatsivik Bay (the staff is 1.6 m long). The horizontal lines on the boulder are water lines. The flat surface shows evidence of ice gouging and irregular deposits of finer material due to the melting of ice floes.

Méga-bloc glaciel sur l'estran, baie d'Aulatsivik (la règle à mesurer fait 160 cm). Des marques d'affouillement glaciel et des débris grossiers sont visibles dans la zone plane entre les blocs. Les lignes horizontales sur le méga-bloc correspondent à divers niveaux de la marée à cet endroit.

FIGURE 22. Boulder barricade in the vicinity of profile 2. The barricade appears relatively stable and the boulders are wedged tightly in position. The upper surfaces of the boulders are much abraded by sea ice action.

Cordon de blocs frangeant près du profil 2, à Pangnirtung, limite des basses mers. La mobilité des blocs composant le cordon est relativement faible, car les blocs sont serrés les uns contre les autres, mais ils subissent l'action abrasive des glaces.

FIGURE 23. Boulder barricade northeast of Pangnirtung hamlet, showing, left of the figure, a patch of sandy-gravel contained by boulders.

Cordon de blocs frangeant près de Pangnirtung montrant un placage de gravier sableux emprisonné par les blocs.

sands were encountered towards the outer part of the intertidal zone, immediately shorewards of the barricade on profiles 1, 2 and 4 (Fig. 19), and at these locations the boulders were generally well embedded in the sand. On profile 3 the thickest sands occur in the centre of the intertidal zone but this is probably due to the artificial channel which crosses the lower part of the profile. Silt drapes occur at some places in the inner part of the intertidal zone, but the fining shorewards sequence, often associated with tidal flat sedimentation, is ill-defined. In part, this may be due to local topographic variations across the flats. Profiles 2 and 3 (Fig. 19) show a seaward slope, but profile 1 has a reverse slope and the lowest part of the intertidal zone inside the barricade is close to shore; this low area is not exposed at all low tides.

The surficial distribution of gravel, sand and mud is also related to fluvial inputs of new sediment during high nival runoff in the spring. The largest river in the study area is the Duval River near the hamlet, and the absence of a flood tide delta, seawards of the barrier breach through which most of the discharge in funnelled at low tide, suggests that most of its load is deposited shorewards of the barricade. The low elevation of the inner part of profile 4 reflects the erosive nature of the fluvial outflow: deposition occurs lateral to the main outflow and on the outer part of the flats following flow dispersion. Fan shaped areas of sandy flats characterize the intertidal zone opposite the mouths of two other streams to the northwest.

Aulatsivik Bay is noteworthy because it contains the largest boulders in the study area and the largest bedform, a large asymetric sand wave. Boulder barricades extend into the mouth of the bay but are not present towards the head. Small boulders, generally less than 1 m, occur towards high tide level, and exceptionally large, rounded boulders, for the most part not embedded in finer sediments but resting on top of them, predominate at about mean water level. Most of these boulders are flat lying, but some, including the largest, are upright. In this section of the bay the surface of the very poorly sorted, finer sediments showed clear evidence of ice block grounding and ice scour. This contrasts with most other locations across the flats in the study area, where the superficial effects due to ice action during the previous breakup had been obliterated by tidal action. The sand wave occurs in an area of abundant sand, inside the barricade on the southern side of the entrance to the bay. It is 2 m high (profile 5, Fig. 19), and trenches dug across it to a depth of 50 cm indicate that the sand is subject to frequent reworking by strong tidal currents: the predominance of landward dipping cross-stratification suggests flood dominance.

Because of the findings at Koojesse Inlet, where the boulders and other surface sediments of the modern flats appear to be underlain in places by a bluish-grey silty clay, a search was made for similar material at Pangnirtung. There is a greater abundance of mobile finer sediments at Pangnirtung, due to the continued addition of new material by streams, consequently any substrate is less likely to be exposed at the surface. However, silty-clay, similar to that in Koojesse Inlet was found at three places: 60 m from shore on line 1, 30-50 m offshore on line 3, and 160 m offshore on line 4.

DISCUSSION AND CONCLUSIONS

The above observations of boulder-strewn tidal flats at Koojesse Inlet and Pangnirtung, and the descriptions of similar features in Labrador (ROSEN, 1979) and Ungava Bay (LAURIOL and GRAY, 1980), suggest that the problems associated with their formation and present surface expression can be discussed under three headings: *physical and biological zonation on the present flats*; tidal action and sea-ice processes, now and in the past; and the geological evolution of the flats since deglaciation.

PHYSICAL AND BIOLOGICAL ZONATION

The most obvious zonation at Koojesse Inlet and Pangnirtung is manifest in the arrangement of the boulders, which at the former location are more concentrated in a broad zone across the middle of the flats, and at the latter in a narrow zone at the lower edge of the flats to form the distinctive boulder barricade. The difference in tidal range between the two places (mean tidal range, M.T.R., at Koojesse Inlet is 7.3 m, at Pangnirtung 4.8 m) may account in part for the different arrangement of boulders, but this cannot be the only factor. Barricades occur in Labrador (M.T.R. 1.4 m) and in Leaf Basin (M.T.R. 9.3 m) in quite different tidal settings, where tidal ranges bracket the values at the Baffin Island sites.

An across-flat zonation is also apparent at Koojesse Inlet and Pangnirtung in the distribution of the finer sediments, which range from clays to gravels, though this is ill-defined in some locations and not manifest as a simple, fining-landwards trend. Mud, either as a temporary, silt veneer or mixed with sands and gravels, occurs most frequently in the upper part of the intertidal zone at Koojesse Inlet and there are distinct areas of mud deposition near to shore at Pangnirtung. Sand beaches may occur in the upper part of the intertidal zone, where this is not developed in rock, but the thickest sands occur in a narrow zone towards and below low tide levels at Koojesse Inlet, and in a variable zone inside the barricade at Pangnirtung.

The biological observations made at Koojesse Inlet substantiate the conclusions of ELLIS and WILCE (1961), concerning the barren nature of the upper part of the intertidal zone due to the icefoot and exposure to freezing. They also indicate the relationships between habitat (substrate conditions, boulder distribution and tidal exposure) and species distributions lower down the flats, which are summarized in Figure 9. The bio-physical zonation of the Pangnirtung tidal flats is presently being investigated by GILBERT and AITKEN (1981).

TIDAL ACTION AND SEA-ICE PROCESSES

Tidal control on sea ice processes is manifest in two ways, the alternate raising and lowering of the ice cover during the tidal cycle and the lateral movement of ice floes due to tidal currents. Grounding of the ice in the intertidal zone results in the entrainment of sediments which may be rafted away and deposited in a different location during melting at breakup. In the subarctic tidal flat environments under discussion (*i.e.* in Labrador, Leaf Basin, and S.E. Baffin Island) sea-ice effects dominate sedimentation. In particular, ice-related processes, not necessarily restricted to ice rafting, play a key role in the movement and arrangement of boulders. These environments may be distinguished from tidal flats further south in the St. Lawrence estuary and Minas Basin, by the fact that the sea-ice offshore forms a solid cover, containing the ice in the intertidal zone. This is particularly important at breakup when the scouring, transporting and depositing effects of the intertidal zone ice, which breaks up first, are most effective. Intertidal sediments are redistributed within the intertidal zone.

Our observations in Koojesse Inlet did not provide any instances of large boulders being rafted by ice floes, but indicated that rocking, overturning, and pushing were important processes of boulder movement. It is not appropriate here to discuss the large and varied literature which deals with rafting of sediments by sea-ice, but it should be noted that some aspects of the process have not been fully evaluated, in particular the entrainment of large boulders. Entrainment can be achieved by the deposition of material on the ice surface (by landslides, debris flows and rockfall below steep slopes, and by fluvial processes during flood conditions at river mouths), by frost riving and plucking at the shore, especially in the icefoot zone, and by material freezing to the base of the ice during grounding at low tides. This last process is well documented for finer sediments, which become incorporated as layers within the ice, as it grows downwards by vertical accretion during intervening high tides. However, it is not clear if any of the larger boulders across the flats at Frobisher and Pangnirtung are incorporated in the ice in this manner. The rising and falling of the intertidal ice over large boulders produces circular, cone-shaped, ice-deformation structures (termed *pustules de pied de glace* by DIONNE, 1973; *ballycatters* by ROSEN, 1979; and *cratered pustules* by LAURIOL and GRAY, 1980) through which the boulders may protrude at low tide. Some temporary lifting and entrainment of boulders may occur in association with these features. It seems likely, however, that the lifted boulders would be deposited *in situ* during the early stages of breakup, for the deformation structures are focus points for the initial melting of the ice and the centre of a series of radiating fractures rather than the centre of potential ice floes.

Considerations of ice strength and flotation potential (DRAKE and McCANN, in press) indicate that during the early stages of breakup the intertidal ice floes are large enough and thick enough to float the largest boulders on the flats. The constraints on the ice rafting process for large boulders relate to entrainment.

LAURIOL and GRAY's (1980) hypothesis, that the progressive downslope movement of boulders during land emergence over the past several thousand years has resulted in the present concentrations in the tidal flats of the Leaf Basin, is probably appropriate for both Baffin Island sites. If this is the case then the existence of the boulder barricade at Pangnirtung implies net transport of boulders seawards across the tidal flats by some combination of pushing, rolling and rafting processes at breakup. The effective limit of these processes is presumably the landward edge of the solid cover of sea-ice proper, which remains in place during the breakup and melting of the ice in the intertidal zone.

Other explanations have been offered for barricade formation in different settings. In Labrador ROSEN (1979) invoked rafting of boulders by ice floes which, because their thickness approximates mean tidal range tend to ground and deposit their load more frequently at the nearshore break of slope which occurs near low water level. LAURIOL and GRAY (1980) suggested that river ice action is important at one location in Leaf Basin: they use the term "bulldozing" rather than rafting to describe ice transport processes for very large boulders. GUILCHER (1981) indicates that barricades near Rimouski in the St. Lawrence estuary have formed by deposition of boulders from ice rafts which become stranded on the lower foreshore at the seaward margin of the icefoot. The most informative of the older accounts is by TANNER (1939), who described their fine development in the fiords of the Barents Sea and in Labrador and commented on their poor development along micro-tidal Baltic coasts. He noted their association with tidal ranges between 2 and 4 m in areas of severe winter ice conditions, and proposed that they were formed at breakup from material gouged and pushed shorewards from the sub-littoral zone by large floes of fiord (*i.e.* offshore) ice.

GEOLOGICAL EVOLUTION OF THE TIDAL FLATS

The discussion thus far has been largely concerned with contemporary processes and responses across the intertidal zone, but a further question arising concerns the origin of the shelf of material underlying the modern flat surface, which is related to the history of sea level changes over the past several thousand years. Isostatic uplift of southeast Baffin Island commenced by 11,000 years BP and initially land emerged rapidly so that by 6000 years BP 75-90% had been recovered. By 3000 years BP uplift on the outer coast had probably ceased and the recent trend is one of submergence (MILLER *et al.*, 1980). There are no relative sea level curves for the head of Frobisher Bay, but, in a series of tentative curves for southwestern Cumberland Peninsula, DYKE (1979, Fig. 10) suggests that sea level at Pangnirtung had fallen from a marine limit of 50 m to its present level by *ca* 6000 BP, that it may have been 8-10 m lower by 3000 BP, and that the ensuing rise of sea level is continuing today.

The evidence at Koojesse Inlet indicates that the modern flat surface is an erosional surface cut in silty-clays, which probably represent deeper water marine sedimentation during the initial period of higher sea levels, elevated to their present position by emergence. The boulders have been derived by progressive downslope movement in the manner proposed by LAURIOL and GRAY (1980). The present supply of new boulders and finer sediments appears to be negligible and there is continuing erosion of the silty-clay substrate, which may also be enhanced by slow submergence. There is some evidence of a silty-clay substrate at Pangnirtung also, but the greater abundance of new surface sediments from fluvial sources make relationships difficult to ascertain. The existence of the boulder barricade, indicating net movement of boulders seawards, suggests that the tidal flats may have been extended seawards by a combination of tidal and sea-ice processes over the period since 6000 years BP, and that buried barricades may exist beneath the modern flat surface.

The Koojesse Inlet and Pangnirtung tidal flats are probably both undergoing slow recent submergence, but the former represents sediment-deficit conditions, with erosion of the surface of the flat platform, and the latter relatively sediment-abundant conditions with upward and outward accretion of the flat platform. For comparison, ROSEN (1979) reports that many of the sedimentary intertidal zones in central Labrador consist of uplifted marine clays planed to a low gradient by contemporary ice processes. Two of the tidal flat settings described by LAURIOL and GRAY (1980) appear to receive abundant fluvial sediment.

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