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Baffin Island Fjord Macrobenthos: Bottom Communities and Environmental Significance[1]

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ABSTRACT. Cluster analysis of the benthos from ten Baffin Island fjords defines six faunal associations. The macrotidal Sunneshine Fiord has a shallow kelp-related Isopod Association. Cambridge Fiord supports a shallow Onuphid Association controlled by gravel from dropstones. A widespread *Portlandia* Association typified the shallow zones of more recently glaciated fjords where sedimentation rates are high. An Ophiuroid-Anemone Association was defined from current-affected submarine channel environments. A Maldanid Association covered the greatest area in all fjords and passed into an Elasipod Association in the deepest water in Cambridge Fiord.

Fjord-head faunas are used to model ecological changes accompanying glacier retreat, from monospecific *Portlandia*, through mature *Portlandia* Association to Onuphid Association accompanied by diverse filter feeders and herbivores. *Chlamys islandica* was found living in Cambridge Fiord, which substantially increases its northern limit.

Key words: macrobenthos, Arctic, cluster analysis, bivalve, Quaternary, sediment

RÉSUMÉ. L'analyse d'ensemble du benthos de dix fjords de la terre de Baffin, laisse apparaître six associations fauniques. Le fjord macrotidal Sunneshine a une association isopode peu profonde reliée aux algues. Le fjord Cambridge possède une association d'onuphidées contrôlée par du gravier venant de blocs isolés. Une association largement répandue de *Portlandia* caractérisait les zones peu profondes de fjords ayant subi une glaciation plus récente, où les taux de sédimentation sont élevés. Une association d'ophiures-anémones s'est manifestée dans un environnement de chenaux sous-marins affectés par les courants. L'association la plus prolifique dans tous les fjords était une association de maldanes, qui passait à une association d'élasipodes dans les eaux les plus profondes du fjord Cambridge.

La faune à l'amont des fjords sert à construire le modèle des changements écologiques accompagnant le recul des glaciers, qui vont des *Portlandia* monospécifiques, à l'association des onuphidées accompagnée de plusieurs espèces filtreuses et herbivores, en passant par l'association des *Portlandia* évoluées. On a trouvé que les *Chlamys islandica* étaient présentes dans le fjord Cambridge, ce qui étend considérablement leur limite nordique.

Mots clés: macrobenthos, Arctique, analyse d'ensemble, bivalve, quaternaire, sédiments

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INTRODUCTION

Fjords are ideal natural laboratories, with their obvious gradients in many key environmental parameters — salinity, suspended loads, sedimentation rates, to name but a few (Syvitski and Skei, 1983). For instance, Farrow *et al.* (1983) noted the deleterious effect of sediment loading on the distribution of epifauna.

Farrow *et al.* (1983) also drew attention to the Palaeozoic aspect of the most tolerant epifauna groups, the sponges, solitary corals and articulate brachiopods. Similarly, the infauna also includes primitive elements, such as priapulid worms, that are common to shales of Cambrian age (Conway-Morris, 1977). Bivalves are dominated by protobranchs, which originated in the Ordovician and attain their highest percentage among today's shallow water fauna in arctic Canada (Nicol, 1972). Furthermore, the present-day arctic fauna has "an astoundingly high percentage of species (52%) belonging to Palaeozoic families" (Nicol, 1970).

Coupled with this undoubted geological and palaeontological relevance comes the opportunity to evaluate environmental factors that might limit the distribution of organisms. Benthic ecologists are still debating the value of the community concept. Many fjord workers have tended to abandon the concepts originally propounded by Petersen (1913, 1915), Gislen (1930) and Thorson (1933, 1957), for example, in favour of gradient analysis (e.g., Curtis, 1970; Pearson and Rosenberg, 1978; Pearson, 1980), which examines the association between taxa and particular environmental variables. This latter approach is particularly suited to the kind of multidisciplinary study being undertaken by the Sedimentology of Arctic Fjords Experiment (SAFE) project (Syvitski and Schafer, 1985). The gradient approach is of interest not only to ecologists but also to Quaternary ecostratigraphers (e.g., Andrews, 1978; Spjeldnaes, 1978; Thomsen and Vorren, 1986a,b).

There has been little work on Baffin Island marine communities, though impetus was given by the Eastern Arctic Marine Environmental Studies (EAMES) program (Sutterlin and Snow, 1982). Ellis (1960) has described molluscan assemblages collected by grab sampling. Andrews (1972) and Andrews *et al.* (1981) have described Quaternary fossil localities from raised marine sequences on Baffin Island. A major zoogeographic boundary extends from Cumberland Peninsula northeast to near Thule, Greenland (Fig. 1). South of the boundary subarctic molluscs are found (e.g., *Mytilus edulis*), although outliers possibly introduced by whaling ships exist at Pond Inlet, north Baffin Island.

Our purpose is to evaluate the macrobenthos in the SAFE fjords in an attempt to understand the ecological changes accompanying glacier retreat. Ten Baffin Island fjords were studied during the reconnaissance phase in 1982, with three being selected for more detailed study in 1983 (Fig. 1). Cambridge, Itirbilung and McBeth were chosen because of clearly

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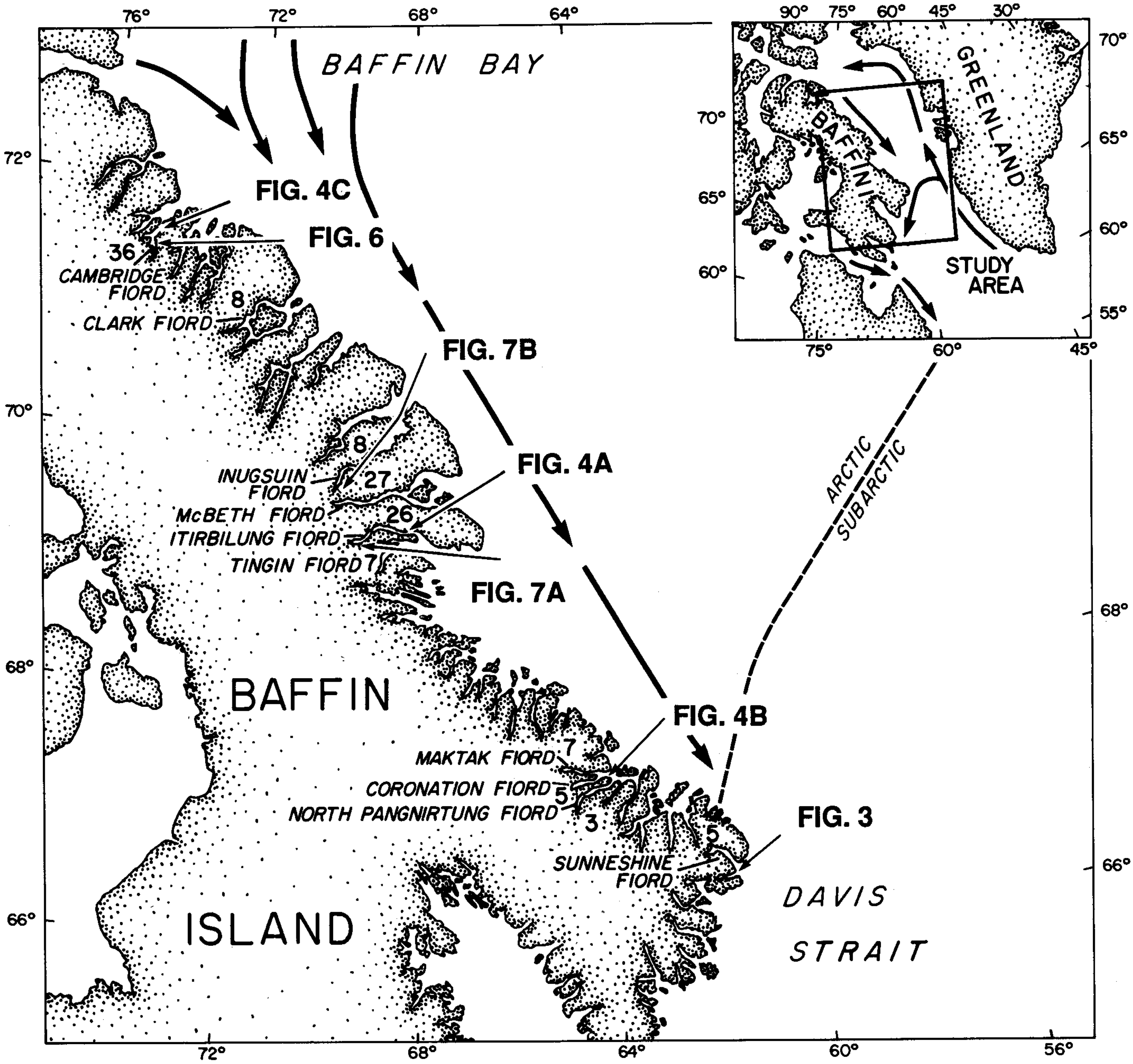

FIG. 1. Location map of Baffin fjords from which grab samples and bottom photographs were obtained. Fjords in bold type are illustrated or discussed in some detail in this paper. The combined total number of stations for each fjord is indicated.

marked differences in fjord geometry, glacier cover in the hinterland, suspended sediment levels and complexity of side-entry systems.

Baffin fjords are generally colder than those of West Greenland and Spitsbergen, the open water season lasting from 60 to 30 days. All fjords visited are microtidal except for Sunneshine (Table 1). Sills do not occur in some southern fjords, but they may be multiple in the north, where they vary from 64 to 439 m in depth. Maximum depths of the fjord floors are commonly in the range 500-700 m. In the Baffin fjords, there is little down-fjord variation in nutrients or dissolved oxygen for a given depth; these parameters are strongly vertically stratified and thus water-depth dependent. Fjord waters are everywhere oxygenated (>3 ml·L^{-1}), and thus depth-dependent differences in the dissolved oxygen content are thought not to be a limiting factor. The nutrients (silicate, phosphate, nitrate) have a large depth-dependent range (Trites *et al.*, 1983; Petrie and Trites, 1984) and may be limiting to some of the water-depth dependent macrofauna (e.g., Pearson, 1980).

METHODS

Field Method

In 1982, 36 grab sample stations and 36 bottom camera stations were occupied in ten fjords between 9 and 24 September and during *Hudson* Cruise 82-031 (details in Syvitski and Blakeney, 1983). In 1983, 45 grab sample stations and

TABLE 1. Physical parameters of fjords studied

	Fjord length (km)	Maximum depth (m)	Maximum station depth (m)	Sill depth (m)	Minimum station depth (m)	No. of stations 1982/83	September Fjord-head surface[1]		Large tidal range (m)	Glacial ice in fjord-head basin (%)	Glacial ice in all drainage basins (%)
							T°C	S.ppt			
Cambridge	61	708	681	439/225	15	6/30	0.2	29.7	1.8	3	12
Itirbilung	55	435	416	249	55	4/22	0.9	29.8	1.2	28	32
McBeth	93	563	572*	249	5	10/17	0.9	29.0	1.2	4	26
Clark	67	720	755*	108/185	192	8	1.5	30.7	1.3	26	40
Inugsuin	98	563	585*	121	160	8	−0.4	32.3	1.3	5	24
Tingin	47	523	800*	≈180	98	7	2.7	26.4	1.1	20	37
Maktak	26	320	658*	no sill	90	7	3.6	24.0	1.4	53	47
Coronation	41	606	497	no sill	98	5	3.1	26.4	1.4	76	70
N. Pangnirtung	48	479	347	no sill	80	3	?	?	1.4	57	35
Sunneshine	36	215	215	64	67	5	−0.8	30.0	4	19	16

[1] From Trites *et al.*, 1983.
*Seaward of sill.

26 bottom camera stations were occupied in three fjords between 19 September and 4 October during *Hudson* Cruise 83-028 (Asprey and Johnston, 1984). Sample station locations for our three principal fjords are shown in Figure 2.

On neither cruise was it possible to devote sufficient time for a dedicated five-replicate grab benthic sample program, as recommended by Holme and McIntyre (1984). Our numerical data must therefore be viewed with caution, the more so because about 5% of the total volume had been removed from the 37 x 37 cm Van Veen grab samples (Schafer *et al.*, 1984) before the remainder was sieved through a 2 mm screen. The macrobenthos, once removed, were sorted and photographed aboard ship. Samples were taken from the shallow prodelta by a 24 x 24 cm Ekman grab, operated by hand from a launch. The numbers of animals recovered have been converted to individuals·m^{-2} in Appendix Table 1.

Underwater photographs were taken by a stereo Benthos camera system triggered by a compass-bearing weight. The area photographed was 1.68 x 1.22 m. Organisms were counted from enlarged photographs and numbers divided by 2 to obtain individuals·m^{-2}. An average of 17 frames per station was obtained. Densities in Appendix Table 2 are mean counts per station. Dropstone occurrence was recorded as the percentage number of frames in which dropstones were visible.

Laboratory Methods

Animals were preserved in buffered formalin and identified at Millport Marine Biological Station. Grain size analysis was carried out at Bedford Institute of Oceanography. Gravel was separated on a standard 2 mm sieve, mud by a 53 μm wet sieve. The sand fraction was analyzed by a computerized settling tube; the mud fraction by a computerized Sedigraph® 5000D. Organic carbon was determined from one of the nine 1-2 g subsamples by a Leco model WR-12 Carbon Determinator® equipped with a Leco induction furnace (Clattenburg *et al.*, 1983). Total nitrogen determinations were performed by the "Kjeldahl" method. The determination of bacterial numbers and biomasses is described by Albright and Stroh (1983).

Statistical Techniques

The matrix presented in the Appendix was evaluated by cluster analysis using Jaccard's coefficient, which is based on presence/absence, and Czekanowski's coefficient, which deals with quantitative data (Boesch, 1977). All sorting was by average cluster linkage. The Jaccard method gives less weight to the poorly fossilizable maldanids than does Czekanowski's. The results given below are therefore of relevance to the interpretation of raised marine sequences.

RESULTS

General Aspects of the Macrobenthos

The macrofauna ranges in size from 2 mm to more than 20 cm and is dominated by bivalves and polychaetes, the former characterizing shallower water (Fig. 3A). Epifaunal amphipods and isopods were associated with drifting kelp (Fig. 3B,C). Ophiuroids had a wide distribution, as did buccinid gastropods, common in deeper water (Fig. 4C).

The underwater photographs showed a much greater variety of both infauna and epifauna than the grabs, particularly the widespread pycnogonids and the characteristically deep-water elasipod holothurians (Fig. 4B). This is partly to be expected from the contrast in area covered, the Van Veen sampling only 15% of the area seen in a bottom photograph. Dropstones of ice-rafted origin commonly result in an increased epifauna, dominated by sponges, ascidians, bryozoans and crinoids (Fig. 4A). Burrowing anemones were seen at >80% of the camera stations, though none was recovered in grab samples; neither were pennatulaceans (sea pens) — a possible result of the bow wave generated by the grab sampler. Cumaceans were found by both methods, but *Mesidotea sabini* was photographed only in Sunneshine Fjord (Fig. 3B).

Tubicolous polychaetes were common. The mud- and mucus-walled long tubes often seen on underwater photographs were sampled in CA1 (photograph 82 0446) and are confirmed as sabellids. The coarse gravel tubes previously attributed to *Pectinaria* sp. by Farrow (1983:9-8, 9-22) are now known to be onuphid polychaetes (*Nothria* sp.). The parchment-like tubes referred to in Appendix Table 2 were probably produced by terebellid polychaetes (possibly *Thelepus cincinnatus*; Dale *et al.*, 1989). All were empty except at IN6 (82 04428), where a large specimen contained a carnivorous phyllodocid polychaete. Several maldanid species are present in the samples, but these are taxonomically difficult and no identifications are yet available. Other

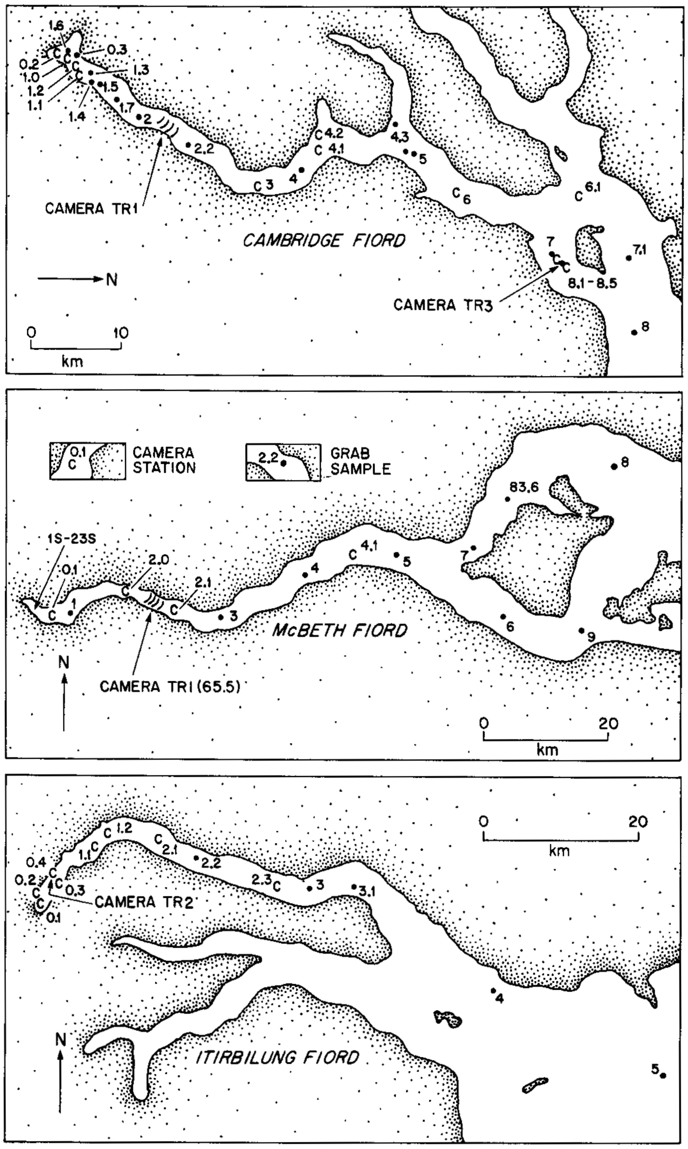

FIG. 2. Maps of Cambridge, McBeth and Itirbilung fjords showing stations from which data were obtained for the cluster analyses.

polychaetes include a scalibregmid from CA Sill3 (18220) and possible nephtyds. There are also other tubicolous polychaetes, probably capitellids, in several samples. Polynoidae also occur (e.g., CL1); characteristically they lose their elytrae after transportation in formalin.

Macrofaunal Associations Defined by Cluster Analysis

Grab Samples: Both Jaccard's and Czekanowski's coefficients seem to have produced meaningful clusters of the grab data (Fig. 5A,B). Both produce a *Portlandia* Association (mean depth = 55 m), a Maldanid (mud-tube) Association (mean depth = 418 m), an Onuphid (gravel-tube) Association (mean depth = 272 m), and a miscellaneous assemblage, which included *Astarte* sp. from 19 m along with ophiuroids from 520 m.

The Onuphid Association was associated with gravel, dropstones invariably being present (Fig. 5C). The polychaetes are errant and produce distinctive traces (Fig. 6). The Onuphid Association occurs over a wide range of sand/clay

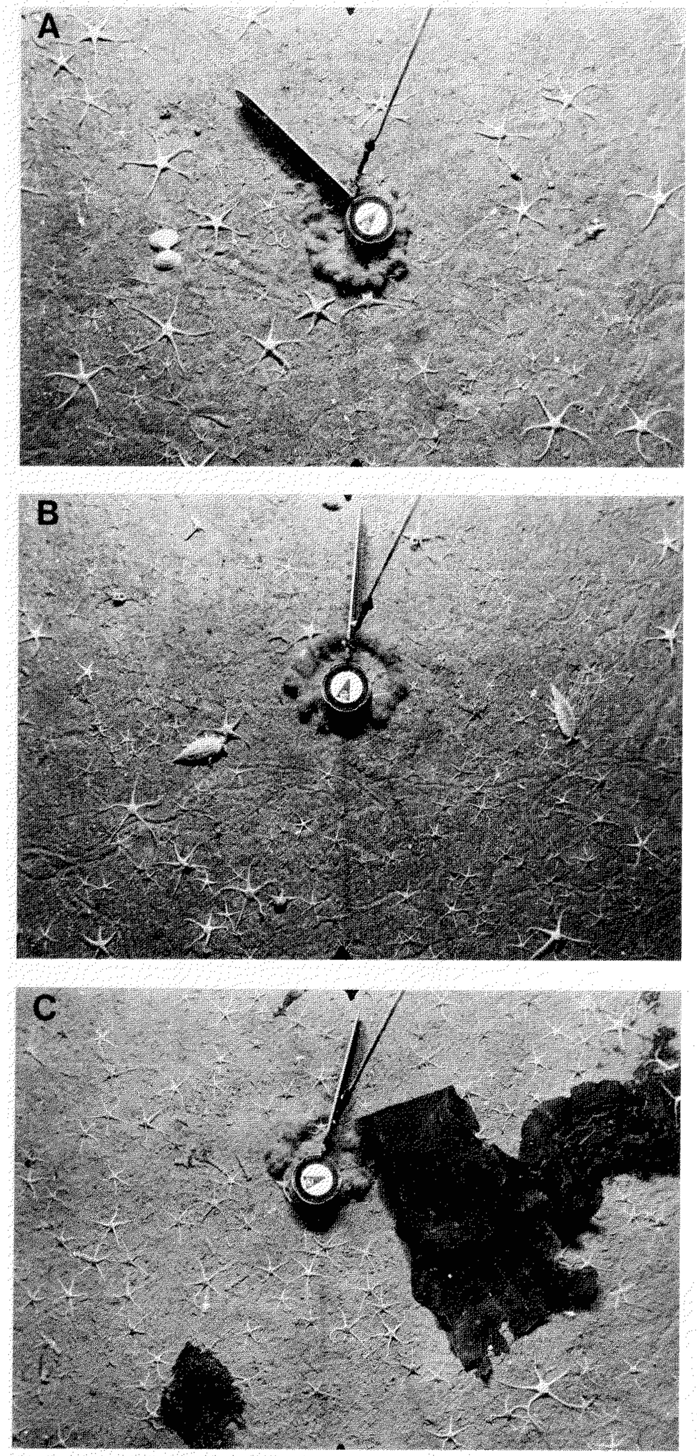

FIG. 3. Underwater photographs taken with Benthos camera: **3A**. Sunneshine Fiord, SU7, 67 m. Diverse fauna on bottom rich in comminuted shell debris. Large and small ophiuroids, asteroid, buccinid gastropod, isopod and small fish (gobiid?) in depression. Fused siphons of infaunal bivalve and united valves of dead bivalve *Serripes groenlandicus* also visible. **3B**. Sunneshine Fiord, SU7, 67 m. Two large *Mesidotea sabini*, abundant ophiuroids, asteroid (in hunched feeding position), large and small fused bivalve siphons, burrowing anemone, fusiform gastropod and pycnogonid are visible. The sediment is shelly. **3C**. Sunneshine Fiord. SU6, 117 m. Drifting kelp debris covering ophiuroids carries two isopods. Several onuphid tubes are present but are not producing trails (cf. Cambridge Fiord, Fig. 6). Compass weight has a diameter of 7.5 cm.

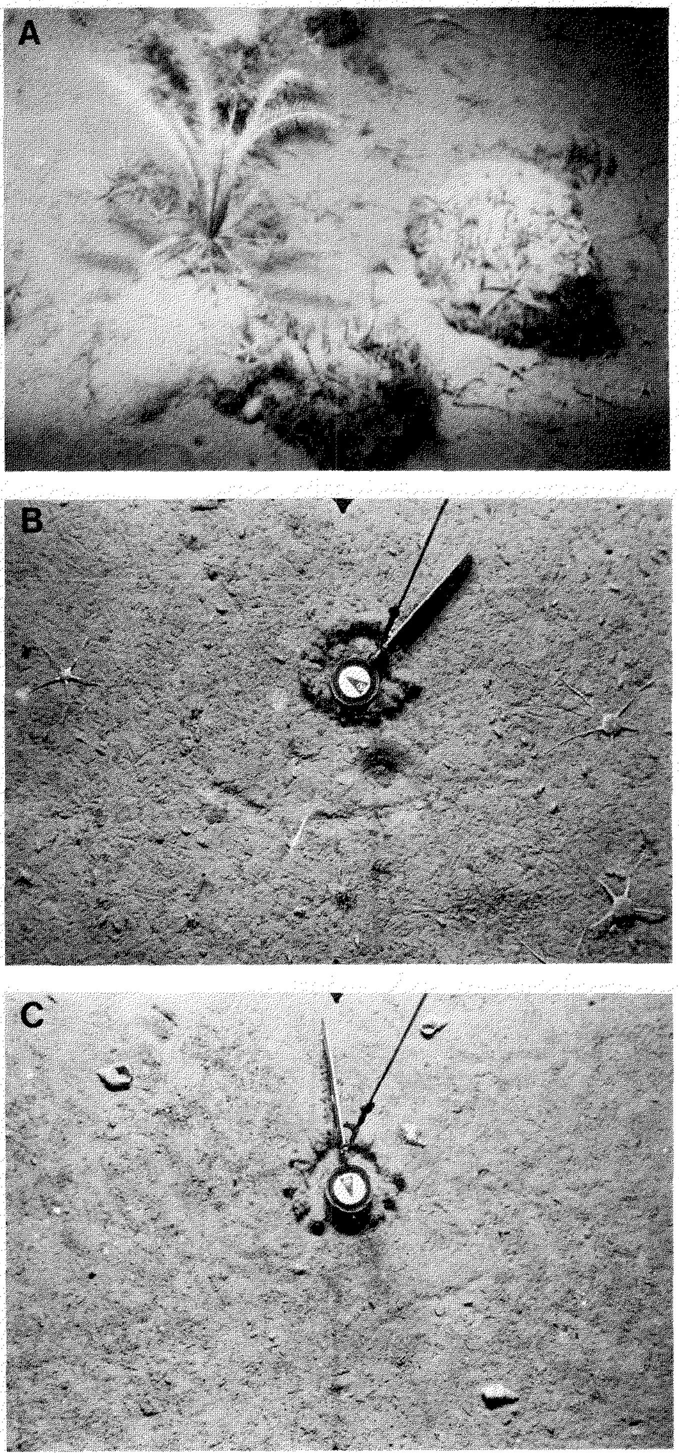

FIG. 4. Underwater photographs taken with Benthos camera: **4A.** Itirbilung Fiord, IT2.1, 288 m. Crinoid on dropstone. **4B.** Maktak Fiord, MA5, 585 m. Three thin-armed ophiuroids, abundant elasipod holothurians, mysid shrimp, pycnogonid, burrowing anemone and unidentified burrow opening. **4C.** Cambridge Fiord, CA6, 640 m. Four dead *Buccinum* sp. and one elasipod holothurian on a bottom covered with faecal strings but otherwise devoid of trails (cf. B): scattered shell debris is evident. Compass weight has a diameter of 7.5 cm.

values, from 18.6 to 0.4. The Maldanid Association is rarely associated with gravel and tends to be associated with clay, except where side-entry inputs or along-shelf transport have introduced sand (Table 2, cluster A′).

More stations fall into the *Portlandia* Association with Jaccard than with Czekanowski (10 vs. 6) (Table 2, cluster D′). Neither cluster includes all the stations yielding *Portlandia*. A wide tolerance of sand:clay ratios is indicated, but greatest abundance is reached in finer-grained lithologies (Table 3B). A fuller treatment of gradients within the *Portlandia* Association is given later in this paper.

The final grab sample cluster consists of a miscellany of odd samples that will not cluster elsewhere. This commonly happens with this technique, and it is not thought to represent a natural grouping. Only three real benthic associations are thus revealed by clustering the grab data — i.e., the Onuphid, Maldanid and *Portlandia* associations.

Bottom Photographs: Epifaunal or semi-infaunal ophiuroids were seen far more readily on the photographs than in grab samples; in fact, they occurred at all but two of the camera stations. Station MC 0.1 at 150 m showed the greatest density of ophiuroids (63 m^{-2}) together with other indications of a varied fauna (Appendix Table 2); yet the grab sample was barren — a reflection more perhaps on the representativeness of grab samples than on patchiness, to judge from the photographs.

Onuphid sites contrast with ophiuroid-anemone sites (Table 2). The former are consistently associated with dropstone material (Fig. 5C), occur in slightly deeper water and are almost confined to Cambridge Fiord, which has a far higher percentage of dropstones (42.1%) than either McBeth or Itirbilung (8.0%, 3.3%). The ophiuroids and anemones are often seen to be living in stronger current areas (Fig. 7) with little dropstone material and are associated with submarine channel areas that have been mapped by depth profiling and side-scan sonar surveys (Syvitski *et al.*, 1984b). Cluster analysis of the bottom photographs enables a deep-water Elasipod Association (Fig. 4B) to be further identified — essentially part of the Maldanid Association defined from grab data (Fig. 5B).

Gradient Analysis

Gradients in sediment parameters were more consistent in the organic than in the inorganic fraction (Fig. 8). In Cambridge Fiord, for instance, an antipathetic relationship between the sand/clay ratio and the % organic carbon is clear (Fig. 8A). There is an initial seaward increase in organic carbon in the inner basin, reflecting the decrease in sedimentation rate away from the fjord-head river mouth. The pattern of organic carbon in the main basin decreases slightly seaward and may reflect the seaward increase in side-entry glaciers with associated higher rates of sedimentation.

The pattern is similar in McBeth Fiord (Fig. 8B): 1) an inner basin that increases in organic carbon with distance away from the main fluvial source; 2) a more or less constant organic carbon content along the main basin sea floor (indicative of more constant sedimentation rates from side-entry systems (Syvitski *et al.*, 1984a); and 3) a rapid increase in organic carbon in the outer fjord/shelf complex reflecting the contribution of shelf water productivity.

In Itirbilung and Coronation fjords, organic carbon increases rapidly with increasing distance from the dominant fjord-head sediment source (Fig. 8B). The use of organic carbon content as a proxy indicator of sedimentation rates is supported by Figure 8C, which shows the relationship as

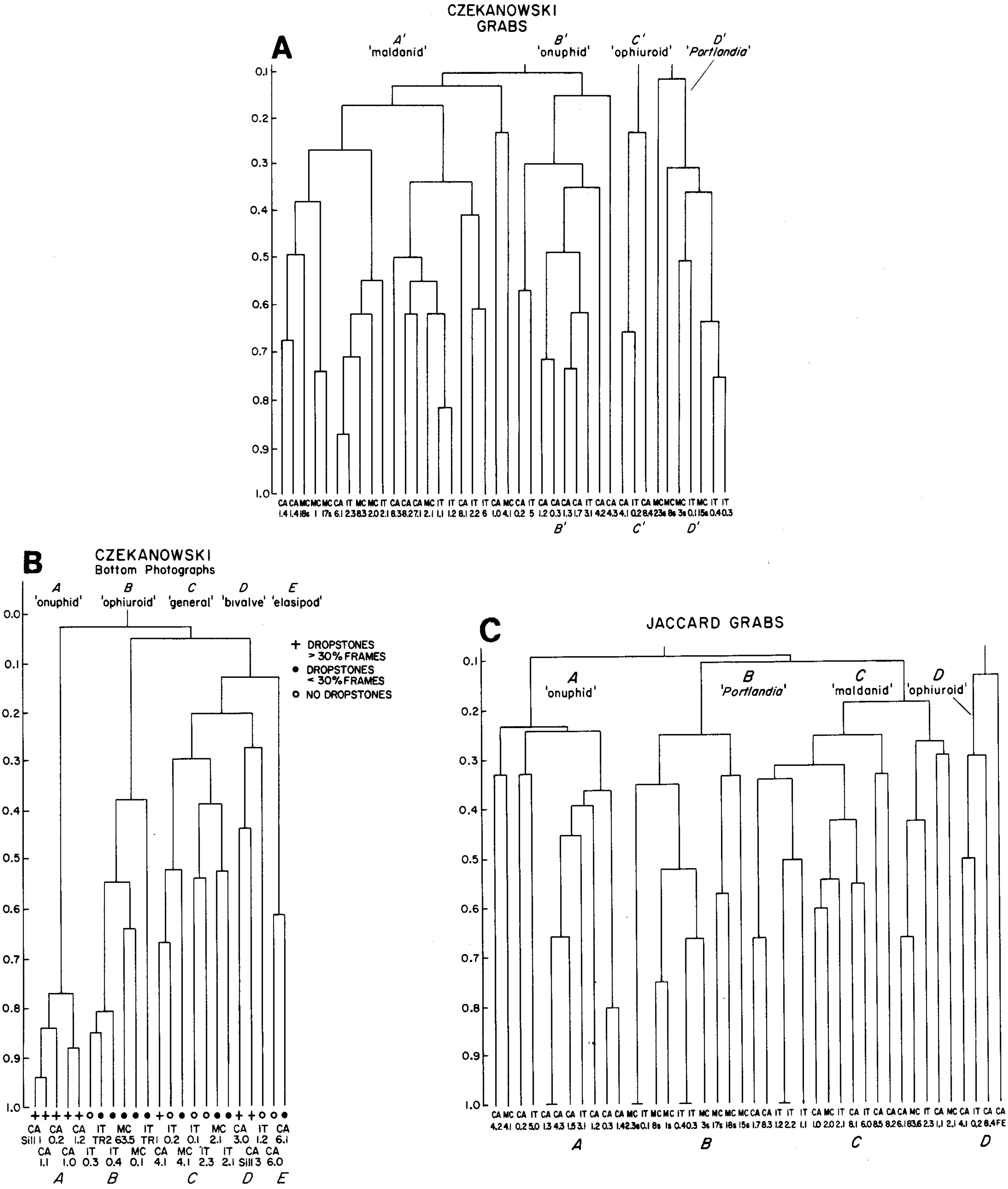

FIG. 5. Results of cluster analysis of station faunal data using: **A.** Czekanowski's coefficient applied to grab samples. **B.** Jaccard's coefficient applied to grab samples. **C.** Czekanowski's coefficient applied to bottom photographs.

being exponential, not linear. Cambridge and Inugsuin fjords are, however, not well predicted, and oceanographic evidence suggests that these basins exchange at a slower rate with the shelf waters (A.E. Hay, pers. comm. 1983). With longer

FIG. 6. Bottom photograph, Cambridge Fiord, CA1, 196 m. Interfering horizontal trails made by onuphid gravel-tubed worms. Whip-like arms are of buried ophiuroids. Width of view = 25 cm.

residence times for the basin waters of these two fjords, carbon utilization could be greater and could account for their uniqueness. (Care should be used when comparing the relationship given in Figure 8C to individual samples and stations, as the model is based on basin-averaged values.)

From an ecological viewpoint it is of interest to examine the fjord-head prodelta regions, where the *Portlandia* Association occurs. The deposit-feeding bivalve *Portlandia arctica* may be remarkably abundant close to active tidewater glaciers. It colonizes rapidly deposited sediments very soon after ice retreat. Gilbert (1982) sampled a flourishing young *Portlandia* conmunity from a station in Coronation Fiord that was covered by a tidewater glacier 25 years ago. (*Portlandia* is, surprisingly, relatively rare in raised proglacial marine muds of early Holocene age, especially as equivalent facies to those sampled by us are well exposed in many sections.)

Although absolute levels of organic carbon may be low, lower than temperate fjords, bacterial biomass in the surface sediment is high (Table 3), being twice as high close to the glacier than 6 km down-fjord. Over this distance the density of *Portlandia* decreases from its maximum of over 1000 m^{-2} at 70 m depth to 142 m^{-2} at 230 m, near which there is only 0.06% organic carbon in the sediment. Proximal to the glacier ($\approx$1 km), the sedimentation rate is predicted to be 400 $mm \cdot a^{-1}$, decreasing exponentially to 2 $mm \cdot a^{-1}$ some 30 km down-fjord (Syvitski, 1989). Farrow *et al.* (1983) have noted a similar dilution factor in British Columbia fjords where high inorganic input dilutes the organic carbon.

In McBeth Fiord densities of *Portlandia* are lower and the association is confined to depths shallower than 40 m (Fig. 9). Where numbers are low it is observed that other bivalves, such as *Macoma calcarea*, *Mya truncata* and particularly the byssate *Hiatella arctica*, and maldanid tubes occur (Fig. 9). *Hiatella* shows a definite association with clay bottoms, where sand/clay ratios are in the range 0.06-0.16. It does not, however, extend into water shallower than 20 m, even though an appropriate clay bottom exists.

The shallower Itirbilung stations are sandier than those observed in McBeth Fiord, and *Portlandia* is accompanied by ophiuroids rather than maldanid tubes. The numbers of Portlandia increase toward the lower limit of its depth range (Fig. 9), where the sand/clay ratio is lower (Table 3).

Variation in Faunal Association among Fjords

McBeth, Coronation and Itirbilung have a similar pattern, with a fjord-head *Portlandia* Association passing down into a Maldanid Association, (Fig. 10B,C). Cambridge, in contrast, has an Onuphid Association in place of *Portlandia*, and this extends further down-fjord (Fig. 10A). It also occurs where large side-entry drainage basins join the fjord. Somewhat surprisingly, the Cambridge sill environment supports a Maldanid Association (minimum depth =225 m), whereas the outer Itirbilung sill (356 m) and a shelf bank (175 m) fall into the Onuphid Association.

Depth Distribution of Macrobenthos

Knowledge of the depth range of particular living taxa is essential for palaeoenvironmental reconstructions (e.g., Norton, 1975) and is presently somewhat limited for certain groups. Data tabulated in Table 4 are collated from Appendix

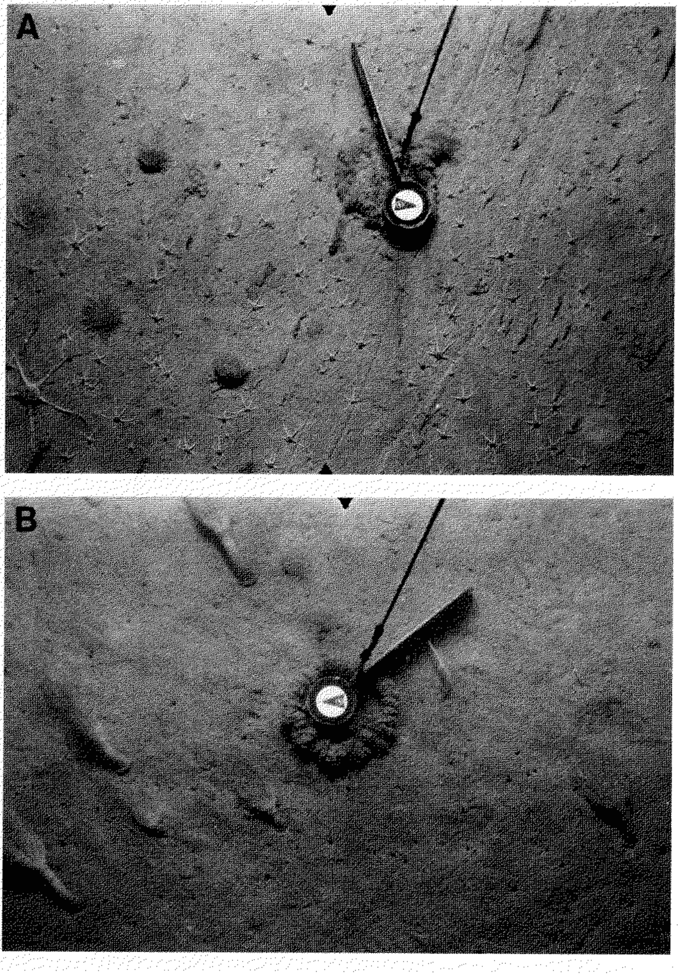

FIG. 7. Bottom photographs. **7A.** Itirbilung Fiord. IT1, 167 m. Bottom current from northeast is strong enough to orientate vane but is not parallel to the grooves. Stubby anemones occur with abundant ophiuroids of several different sizes. **7B.** Inugsuin Fiord. IN1, 160 m. Elongate anemones leaning into current from northeast. Small stellate traces resembling those of *Macoma* are associated with some small burrow openings. Compass weight has a diameter of 7.5 cm.

TABLE 2. Faunal associations defined by cluster analysis of station macrobenthos

Grab sample CLUSTER B′: Onuphid Association (n=14) using Jaccard's coefficient

Station	Depth (m)	Gravel (%)	Sand/clay ratio	Organic carbon (%)	Environment	Clustered* by Czekanowski
CA0.2	125	0.50	2.16	ND	prodelta	*
IT5.0	175	0.20	18.57	0.20	shelf bank	*
CA1.0	182	0.80	0.90	0.54	prodelta	maldanid
CA1.1	183	—	—	—	prodelta	*
CA1.2	190	1.62	0.80	0.51	prodelta	*
CA0.3	200	2.83	0.56	0.54	prodelta	*
CA1.4	218	3.70	0.41	0.56	prodelta	maldanid
CA1.3	240	1.30	0.46	0.55	prodelta	*
CA1.5	262	0.60	0.46	0.58	prodelta	maldanid
CA2.2	292	0.71	0.69	—	sill slope	*
CA1.7	310	7.66	0.49	0.62	prodelta	*
IT3.1	356	0.80	5.30	0.30	outer sill	*
CA4.2	512	—	—	0.22	side entry	*
CA4.3	560	—	—	0.36	side entry	*
mean	272	1.88	1.22	0.45		
±SD	±28 m	±2.19	±.52#	±0.15		

Grab sample CLUSTER A′: Maldanid Association (n=15) using Czekanowski's coefficient

Station	Depth (m)	Gravel (%)	Sand/clay ratio	Organic carbon (%)	Environment	Clustered* by Jaccard
IT1.1	256	0.40	0.40	0.47	prodelta	*
IT1.2	293	0.30	0.15	0.57	prodelta	*
IT2.1	310	0	4.83	0.26	side entry	*
MC2.0	320	0.30	0.09	0.66	sill slope	*
MC2.1	320	0	0.14	0.66	sill slope	*
CA8.3	322	9.65	0.48	0.38	sill	*
CA8.2	327	2.60	0.52	0.30	sill	*
CA8.1	397	10.10	0.24	0.37	sill	*
IT2.2	402	0	0.65	0.56	basin	*
IT2.3	424	0	0.28	0.89	basin	*
MC8.3	439	0	0.13	1.06	basin	*
IT6.0	502	0	2.35	0.49	shelf basin	*
MC4.1	549	0	5.65	c. 0.20	side entry	onuphid
CA7.1	660			0.57	basin	*
CA6.1	750			0.43	basin	*
	418	1.80±	0.31	0.52		
	±143 m	±3.65	±0.14#	±0.23	# excludes side-entry and shelf samples	

Grab sample CLUSTER D′: *Portlandia* Association (n=11) using Jaccard's coefficient

Station	Depth (m)	Gravel (%)	Sand/clay ratio	Organic carbon (%)	Environment	Clustered* by Czekanowski
MC8S	5	0.1	2.67	0.36	delta slope	*
MC1S	10				delta slope	maldanid
MC3S	20	0.1	0.11	0.48	delta slope	*
MC17S	20				delta slope	maldanid
MC23S	30				delta slope	*
MC18S	32				delta slope	maldanid
MC15S	40	0.	0.16	0.48	delta slope	*
IT0.1	55	0.	1.37	0.36	prodelta	*
IT0.2	88				prodelta	ophiuroid
IT0.4	148	0.	0.26	0.41	prodelta	*
IT0.3	155	0.	0.13	0.52	prodelta	*
	55	trace	0.78	0.43		
	±53		±1.04	±0.07		

Photograph CLUSTER B: Ophuiroid — Anemone Association (n=6) using the Jaccard coefficient

Station	Depth (m)		Environment	Clustered* by Czekanowski
ITTR2	126		prodelta	*
IT0.4	140	(grab = *Portlandia* Association)	prodelta	*
IT0.3	155	(grab = *Portlandia* Association)	prodelta	*
MC0.1	150	(grab barren)	prodelta	*
MC65.5	168		prodelta	*
ITTR0	196		prodelta	*
	156±24 m			

Photograph CLUSTER E: Elasipod Association (n=4) using the Jaccard coefficient

TI3	487	(from 1982 photographs)	basin	*
MA5	585	(from 1982 photographs)	basin	*
CA6.0	665		basin	*
CA6.1	750		basin	*
	622±112m			

TABLE 3. Environmental gradients within the *Portlandia* Association

A. Coronation Fiord (from Gilbert, 1982; Albright and Stroh, 1983; Clattenburg *et al.*, 1983)

Distance from glacier (km)	Water depth (m)	*Portlandia* (no. m^{-2})	Organic carbon (%)	Sediment bacterial biomass (mgC m^{-3})
0.6	70	1285		
1.3	98	ND	0.06	45.5
2.6	155	642		
4.4	190	284		
5.8	215	355		
6.0	248	ND	0.10	21.8
8.8	230	142		
11.4	250	0		
15.7	266	0		

B. McBeth Fiord (from Farrow, 1984; Schafer *et al.*, 1984)

Distance from delta (km)	Depth (m)	*Portlandia*	*Maldanids*	*Dacrydium* (no. m^{-2})	*Hiatella*	*Axinopsida*	*Macoma*	Sand/clay
0.2	40	452	0	40*	122	17*	0	0.16
0.3	30	17	0	0	0	0	0	0.37
0.5	5	174	470#	52	0	0	0	2.67
0.7	10	244	870	104	0	0	0	0.07
0.7	20	104	70	0	35	0	0	0.11
1.0	32	17	348	0	244	52	17*	0.06
1.2	20	17	877	0	0	139	70	0.14

C. Itirbilung Fiord (from Farrow, 1984; Schafer *et al.*, 1984)

Distance from delta (km)	Depth (m)	*Portlandia* (no. m^{-2})	*Maldanids*	*Ophiuroids*	Sand/clay	Organic carbon (%)
0.8	55	197	0	No	1.37	0.36
1.6	88	7	0	Yes	2.51	0.32
4.1	148	584	15	abundant**	0.26	0.41
4.8	155	956	15	abundant**	0.13	0.52
6.0	167	ND	ND	ND	0.30	0.37

#Coiled sand tubes.
*Dead shells.
**Abundant on photos.

Tables 1 and 2, supplemented by additional data on species not used in the cluster analysis.

Lumping the data together for statistical purposes averages out a great deal of variation, particularly among the grab samples. Some of this may be meaningful, though there is unequal representation of shallow samples. *Axinopsida orbiculata*, for instance, certainly has a bimodal depth distribution in McBeth. *Macoma calcarea*, however, lives at shallow depth in McBeth, moderately deep in Cambridge and extends into deep water in Itirbilung.

The deposit-feeding bivalves appear to have a much more ubiquitous depth distribution than the suspension feeders, many of which were found in only one fjord. *Bathyarca glacialis*, *Chlamys islandica*, *Astarte montagui* and *A. borealis* are confined to Cambridge samples. *A. striata* was found only in Itirbilung, while *Mya truncata* and *Hiatella arctica* occurred only in McBeth (Table 4B). Most epifaunal organisms seen on the bottom photographs, however, were widely distributed (Table 4A).

CANADIAN ARCTIC FJORD MACROBENTHOS

Most of the common faunal elements of the Baffin fjords occur elsewhere in the region, though the occurrence of *Chlamys islandica* living at the head of Cambridge Fiord is a newly established northern limit for the species. The remainder of the shallow Cambridge biota compares well with that described by Fallis (1982) from Strathcona Sound, where *Strongylocentrotus* is associated with the alga *Agarum* and where *Mya truncata* occurs.

In a detailed transect off Brevoort Harbour, south of our area, Wacasey and Bedard (1980) noted many of the bivalves also found in the Baffin fjords, but as Thomson (1982) also documents in his study of the Lancaster Sound region, *Portlandia arctica* is not among them. This bivalve seems peculiarly adapted to active fjord heads (Fig. 10), as noted by Sparck (1933), Thorson (1933, 1934, 1957) and Bertelsen (1937). Although Quaternary palaeoecologists use *Portlandia arctica* as an "arctic" indicator, its occurrence appears to be controlled more by substrate and other factors.

The shallow fauna photographed in Sunneshine Fiord (Fig. 3) shows a strong similarity to that recorded from Upper Frobisher Bay by Wacasey *et al.* (1979), with the kelp-associated isopod *Arcturus baffini* and the large isopod *Mesidotea sabini*.

Spjeldnaes (1978:197) has offered an ingenious explanation for variations in patchiness in mixed *Portlandia-Macoma* communities, observing that the former always suffers more from naticid predation than the more deeply buried *Macoma*. *Portlandia* therefore may outcompete *Macoma* in sediments from which naticids are excluded.

The shallow bivalve association and a deeper polychaete association that we document has been observed by other arctic workers (cf. Hoskin, 1977; Thomson, 1982:Fig. 2). Also our density data support the notion that biomass is greatest between 30 and 80 m (Wacasey *et al.*, 1979).

There are some striking similarities to the fauna of Alaskan fjords, such as those described from Prince William Sound by Hoskin (1977). The fauna is dominated by deposit feeders, with suspension feeders more abundant in glacier-free fjords.

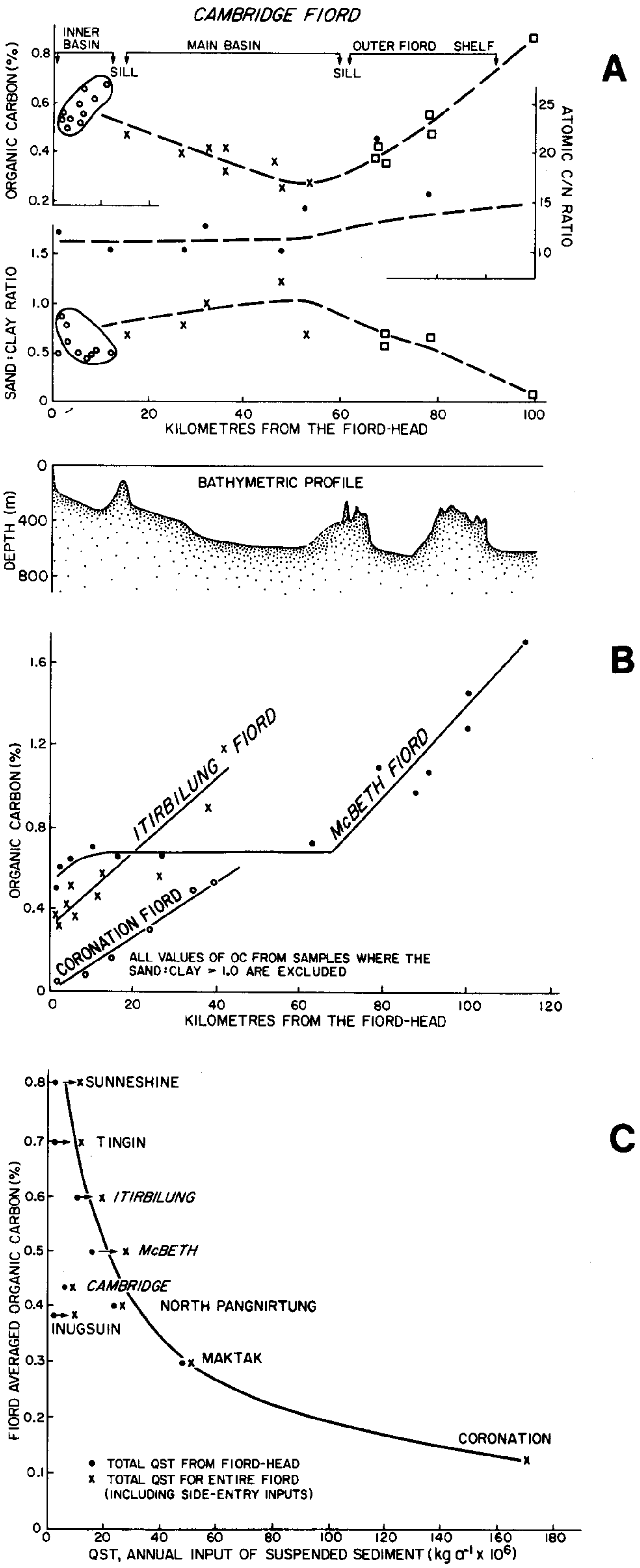

FIG. 8. **A.** Gradients in sediment parameters (sand:clay ratio, percent organic carbon, atomic C/N ratio) for Cambridge Fiord. **B.** Gradients in organic carbon for Itirbilung, McBeth and Coronation fjords. **C.** Organic carbon as a function of estimated annual input of suspended sediment (data from Syvitski *et al.*, 1984a).

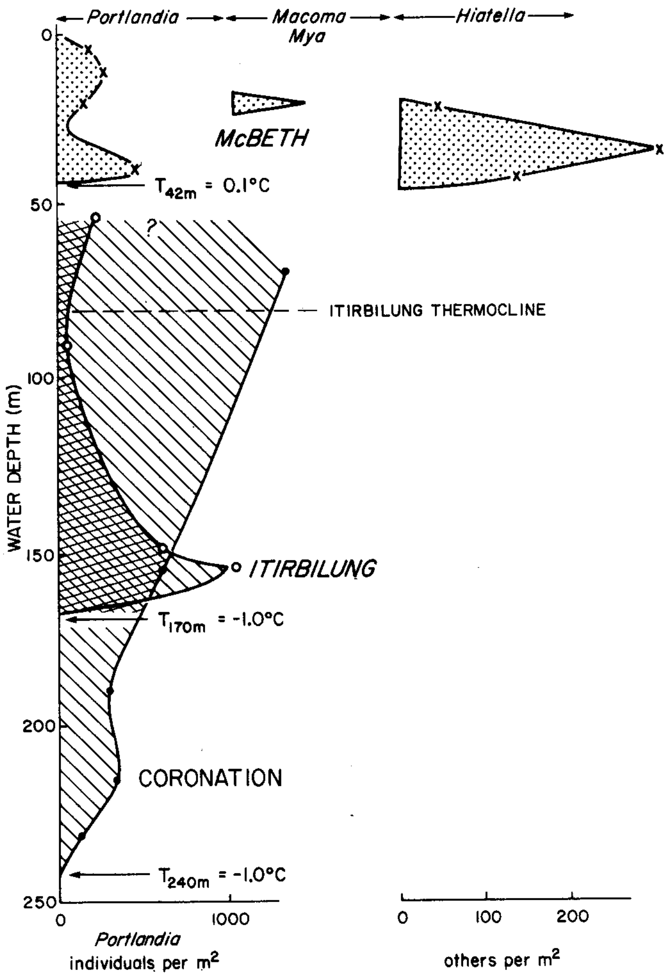

FIG. 9. Environmental gradients and density of bivalves as a function of depth within the *Portlandia* Association.

Axinopsida extends over a wide depth range. *Nuculana pernula* is much more abundant than in Baffin, but *Portlandia arctica* is absent from shallower water. An equivalent of our Onuphid Association may have replaced it, as in Cambridge Fiord. Hoskin (1977) records abundant *Onuphis iridescens* from 67 m in Alaskan fjords. *Hiatella arctica* occurs much deeper in Prince William Sound than in McBeth Fiord (111 vs. 30 m).

PRESERVATION POTENTIAL AND APPLICATION TO THE QUATERNARY

The association between high bivalve population and rapid sedimentation close to a retreating tidewater ice front (Fig. 8C; Table 3) should lead to fossils occurring in life position, close to a boundary with underlying till. In addition, the sediments in which they occur may show evidence of slope deposition, such as large-scale cross bedding and slumping, again related to loading instabilities associated with high sedimentation rates.

This has indeed been observed in many well-preserved raised marine deposits. These deposits have been used for 20 years as a source of radiocarbon dates for developing postglacial relative sea-level curves (e.g., Andrews *et al.*, 1970; Andrews, 1980). During our SAFE fieldwork we sampled them behind the Keel River delta in Cambridge Fiord, where

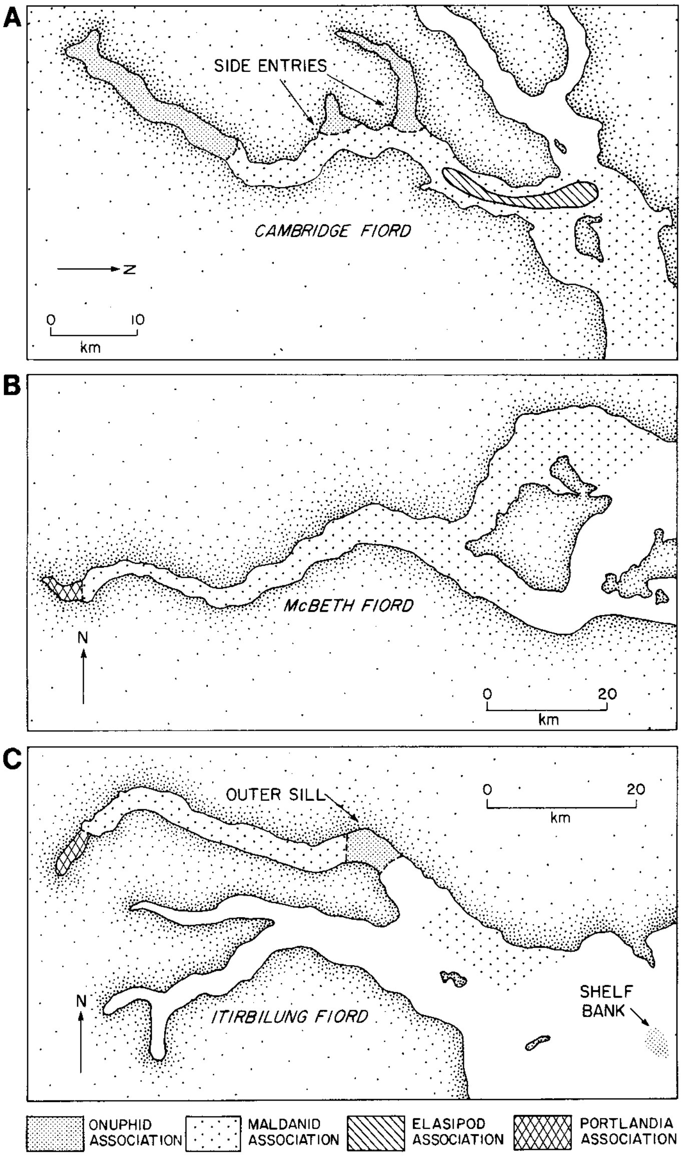

FIG. 10. Occurrence of the three dominant faunal associations in Cambridge, Itirbilung and McBeth fjords.

Mya truncata, *M. psuedoarenaria* (with periostracum) and *Hiatella arctica* occur in prodelta stratified muds that, from the evidence of coeval raised tidal flat sediments, must have been deposited at a depth of about 39 m at a moderate rate of sedimentation (Syvitski *et al.*, 1984a). Similar deposits now raised above and behind the McBeth delta reveal giant *Macoma calcarea*, *Mya truncata* and *Portlandia arctica* in life position in a folded slump that consists of very finely micaceous, bioturbated sandy clay deposited at about 30 m palaeo-depth.

There is, however, a notable increase in faunal diversity in many other raised marine sequences (cf. Fig. 11). *Mytilus edulis*, for example, is commonly found in foreset beds of late glacial prodeltas throughout northeastern Baffin Island (Andrews, 1972).

Between 12 500 and 9500 years B.P., the Champlain Sea spread westward through Quebec into Ontario. Its fossil fauna has many similarities to that now living in the Baffin Island fjords; not only the molluscs but also ophiuroids (impressions and ossicles) and the isopod *Mesidotea sabini*, beautifully preserved in a concretion (Wagner, 1984:Fig. 19, p. 34). The infauna are dominated by bivalves, commonly preserved in life position. *Portlandia arctica* is ubiquitous in marine clays and is often also found in silty sands (cf. Table 2, cluster D′). The subtidal *Macoma calcarea* is less common than the intertidal *M. balthica*, which contrasts with present Baffin fjord fauna. *Mya arenaria* reaching 150 mm in length occurs in sand. *Hiatella arctica* is recorded from the widest range of lithologies, nestling among pebbles and even boulders or boring into soft rocks. Even the tiny *Axinopsida orbiculata* has been found.

Thomsen and Vorren (1986a,b) proposed a palaeoecology reconstruction of a northern Norway shelf environment using autochthonous faunal assemblages. They note two major environmental events: 1) onset of deglaciation of the troughs, and 2) intrusion into the troughs of warm saline Atlantic water at around 10 kyr B.P. There the Pleistocene arctic fauna demonstrate a succession that is very similar to that of a modern faunal development in a fjord following an anoxic event. Although the level of the dissolved oxygen is suggested by Thomsen and Vorren to have influenced their shelf succession, our work suggests the effect of sediment loading (fouling) is of particular importance for the interpretation of a deglacial sequence. Thomsen and Vorren (1986a,b) also note a major faunal change at 10 kyr B.P., where arctic fauna is replaced by a Boreal faunal succession as aided by a rise in temperature, salinity and nutrient supply. The fjords of northeast Baffin Island have yet to experience this later transition, although the equalivalent effect of sediment loading has been greatly reduced both generally through the Late Foxe deglacial period (since 6 kyr B.P.) and specifically since the retreat of the Little Ice Age (c. 1890).

Spjeldnaes (1978) records laminae in the Oslo Fjord raised sediments, with *Portlandia* alternating with *Macoma*, which are again slumped. There is one level of *Hiatella*, with minor associated *Mya truncata* and *Nuculana pernula* — a remarkable similarity to the present-day McBeth Fiord situation. In view of the temperature deductions that Spjeldnaes makes from this fossil fauna, it is of interest to note the temperatures recorded in Baffin fjords at the lower limit of our *Portlandia* Association. In McBeth, the sharp lower limit of *Portlandia* at 42 m coincided with the summer thermocline (Fig. 9). In Itirbilung, however, the base of the thermocline was at 80 m, yet *Portlandia* extended to 170 m at −1.0°C. The maximum depth in Coronation was 240 m, again at −1.0°C.

Hiatella arctica is the common bivalve in Quaternary fossil locations. In Holocene samples, shell characteristics compare favourably with those collected in our surveys. We have not seen the thick and massive individuals that typify material 30 000 yr B.P.

FAUNAL SUCCESSION FOLLOWING GLACIER RETREAT — A MODEL

We propose that it is possible to use the contrasted environments among the SAFE-investigated Baffin Island fjords to model the predicted macrobenthic associations that should follow one another sequentially during glacier retreat. In our proposed scenario, a pioneer (monospecific) *Portlandia* Association is the first to develop within the sediments

TABLE 4. Depth distribution of macrobenthos in three Baffin Island fjords

Taxon	Trophic group	Stations (n)	Mean depth[1] x±σ (m)	Cambridge Fiord	McBeth Fiord (depth range, m)	Itirbilung Fiord
a) Grab samples						
Strongylocentrotus	H	1	19	19		
Chlamys islandica	S	1	19	19		
Mya truncata	S	1	20		20	
Hiatella arctica	S	3	31 ± 10		20- 40	
Portlandia arctica	D	12	61 ± 54	125	5- 40	55-155
Astarte montagui	S	8	211 ± 90	19-322		
A. striata	S	7	197 ± 133			155-310
A. borealis	S	7	190 ± 82	19-327		
Nuculana pernula	D	3	208 ± 94	125-190		310
Thracia sp.	S	4	208 ± 129	240-262	20	310
Macoma calcarea	D	9	223 ± 152	190-218	20- 32	175-502
Nucula? *belloti*	D	5	234 ± 193	181-218	20-549	
Yoldiella sp.	D	12	324 ± 113	181-397	320-549	310-502
Axinopsida orbiculata	SD	13	325 ± 227	181-750	20-549	
Bathyarca glacialis	S	6	385 ± 140	292-660		
Cuspidaria glacialis	C	3	385 ± 249	660	320	175
b) From underwater photographs						
Epifaunal & Ophiuroids >0.4 m^{-2}	SD	9	135 ± 38	102-108	150-168	72-196
Sea pens	S	6	174 ± 66	102-182	150	126-288
Anemones >0.4 m^{-2}	S	7	206 ± 68	182	168-320	140-288
Buccinid gastropods	ScC	17	221 ± 128	102-300	168-549	72-424
Pycnogonids	D	9	289 ± 135	182-365	150-549	196-424
Axius burrows?	D	10	296 ± 146	182-665	168-320	196-288
Irregular echinoid furrows	D	11	337 ± 202	182-750	320	140-424
Sabellids	S	10	361 ± 177	365-665	320-549	140-424

[1] Mean depth (±one standard deviation) of stations that contained the indicated animal.
H = herbivore; S = suspension feeder; D = deposit feeder; Sc = scavenger; C = carnivore.

proximal to a retreating tidewater glacier (Fig. 11), which experience exceptionally high rates of sedimentation. Our type example is Coronation Fiord. The association would begin colonization some hundreds of metres out from the ice front due to the completely inhospitable environment directly at the front. Gorlich *et al.* (1987; Gorlich, 1986) similarly found for Hornsund Fjord, Spitsbergen, that too close to the ice front — i.e., under the influence of a submarine jet — there is: 1) a scarcity of biologically useful energy and digestible organic matter in the sediment, and 2) a rapid burial of any organic rich layers representative of the spring plankton bloom. (For details on the sediment dynamics near an arctic tidewater margin see Syvitski, 1989.)

The second stage in the faunal succession would see a mature *Portlandia* Association develop at a period where the glacier front has retreated on land and a large sandur has formed (Fig. 11). The rates of sedimentation associated with this benthic association would be moderate. The mature association would include *Hiatella*, *Mya*, *Macoma* and *Axinopsida*, in addition to *Portlandia*. Our type example is McBeth Fiord. Interestingly, Dale *et al.* (1989) noted *Axinopsida* to be common to the active delta front in Pangnirtung Fiord, and thus its inclusion in this association remains questionable.

The final stage in the deglacial faunal succession is within an environment where the proglacial discharge is filtered by an extensive valley floor sandur (>20 km in length) and/or kettle lakes, the discharge of sediment is greatly reduced, and thus the prodelta rates of sedimentation are low (Fig. 11). The Onuphid Association typical of this environment would include algae, echinoids and filter-feeding bivalves (*Chlamys*, *Astarte* spp., *Musculus* sp.). A critical factor in the development of this stage is the introduction of sea ice (and allocthonous icebergs) and the deposition of dropstones into an environment experiencing low rates of sedimentation.

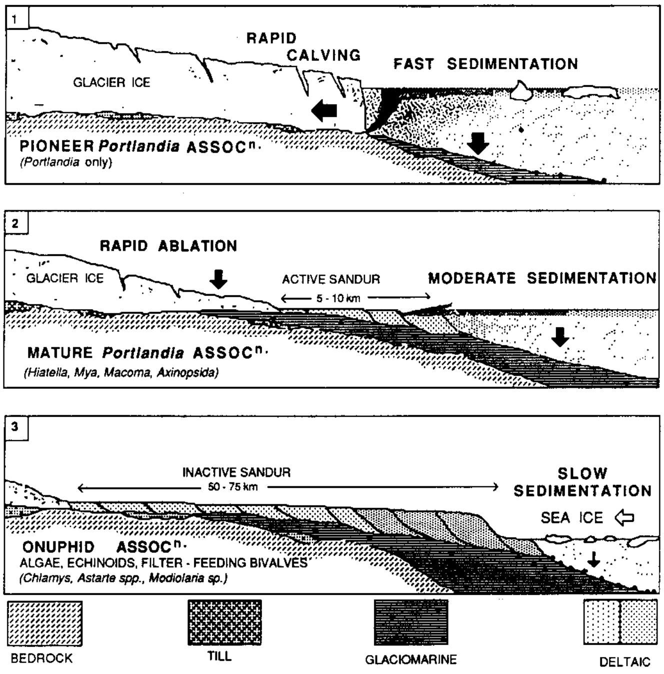

FIG. 11. Schematic diagram relating faunal associations to glacial retreat, modelled on stages developed in Coronation, McBeth and Cambridge fjords: (data from Figs. 5, 8c, 9, Tables 2, 3).

The high fossilization potential of the diagnostic bivalve species should enable the model to be used as a powerful tool for studies of Quaternary palaeoclimate. The palaeoceanographic regime, however, will also affect the model profoundly (Andrews *et al.*, 1981). Tidewater glaciers were in active retreat in Baffin Island fjords 8000 years ago, but the *Portlandia* community was not as dominant as it is today. Instead the prodelta sand facies was dominated by *Mya truncata* and *M. pseudoarenaria* (with subordinate *Serripes groenlandicum* and *Clinocardium ciliatum*).

CONCLUSIONS

The macrobenthos of Baffin Island fjords is dominated by widespread deposit feeders. Suspension feeding bivalves are localized and more common in glacier-free fjords, for example, Cambridge Fiord.

Portlandia colonizes rapidly deposited sandy muds within 25 years and within 500 m of a retreating tidewater glacier (e.g., Coronation Fiord). Despite very low organic carbon associated with areas of high sedimentation rates, bacterial biomass is twice that found at 6 km down-fjord, and densities of *Portlandia* may exceed 1000 m^{-2} (Table 3A).

In McBeth Fiord, which no longer has an active tidewater glacier, but which has an active sandur, suspension feeders make their appearance, with the byssate *Hiatella arctica* and *Mya truncata* recorded.

In Cambridge Fiord, where overall sedimentation rates are lowest and influence from fjord-head glaciers is presently minimal, a relatively prolific flora and fauna occurs, dominated by suspension feeders such as *Astarte* spp. and omnivores such as *Strongylocentrotus*.

A conceptual model is postulated that describes these contrasted situations and predicts the macrobenthic associations that should follow one another during glacier retreat. This succession begins with a monospecific *Portlandia*, followed next by a mature *Portlandia* Association and finally developing into an Onuphid Association by diverse filter feeders and herbivores.

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APPENDIXES: pages 246 and 247.

APPENDIX — TABLE 1. The number of individuals per m^2 recovered from grab samples taken in September-October 1983 from three Baffin Island fjords (CA = Cambridge; MC = McBeth; IT = Itirbilung)

Station	Depth (m)	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
CA F.E.	19					104	17														
CA 0.2	125		73		15				7							200					
CA 1.0	181	7			15			22		15			7								
CA 1.2	190		110					7			22										
CA 0.3	200		88		22					22	15										
CA 1.4	218	292	44		15					7	7										
CA 8.5	225			44			7	44							1000						
CA 1.3	240	73	73																		
CA 1.5	262	219	37					139													
CA 2.2	292		44										7				14				
CA 8.4	292					7						22									22
CA 1.7	310	58	44	7				15				7									
CA 8.3	322	29		15		7		7				22									
CA 8.2	327	29					7					7			7						
CA 8.1	397	15		29				15				15	15		73	15					(1)
CA 4.2	513		50	50									44								
CA 4.1	520																				7
CA 4.3	560	7	15																		
CA 7.1	660	37										7		15						7	
CA 6.1	750	100											7	7							
MC 8S	5	35			470				174								52				
MC 1S	10	870							244								104				
MC 3S	20	70							104									35			
MC 17S	20	887							17	17	70		139						35		
MC 23S	30								17												
MC 18S	32	348							(17)		(17)		52					244			
MC 15S	40								452				(17)				(40)	122			17
MC 19S	42																				
MC 0.1	152																				
MC 2.0	320	95						15					73								
MC 2.1	320	44						15									(7)			7	7
MC 83.6	439	183											15								
MC 4.1	549		7					51		29			219			17					
IT 0.1	55								197												
IT 0.2	88								7												7
IT 0.4	148	15							584												
IT 0.3	155	15							956												
IT 5.0	175		73		7	7*					(7)		(7)			73				7	60
IT 1.1	256	44		7											7	15					
IT 1.2	293	44		7																	
IT 2.1	310	88			7			(7)			29		29			73					
IT 3.1	356	117	117	22							15										
IT 2.2	402	44		73																	
IT 2.3	424	117																			
IT 6.0	502	37		132				(7)			(7)		15		44						

Polychaetes

A. Maldanid: mud tube
B. Onuphid: gravel tube
C. parchment-tube worms
D. Maldanid: coiled sand tube
M. Infaunal holothurians
N. Branched agglutinated foraminifera
O. Beaded agglutinated foraminifera
T. Ophiuroids

Bivalves

E. *Astarte montagui* (**A. striata*)
F. *Astarte borealis*
G. *Yoldiella* sp.
H. *Portlandia arctica*
I. *Nucula ?bellottii*
J. *Macoma calcarea*
K. *Bathyarca glacialis*
L. *Axinopsida orbiculata*
P. *Musculus* sp.
Q. *Hiatella arctica*
R. *Mya truncata*
S. *Cuspidaria glacialis*
( ) Dead shells

APPENDIX — TABLE 2. The number of individuals per m^2 observed on bottom photographs taken in September-October 1983 from three Baffin Island fjords (CA = Cambridge; MC = McBeth; IT = Itirbilung)

Station	Number of frames	Depth (m)	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
CA SILL1	51-73	102		79	0.02	0.14	4.09	0.02				0.10			0.19		0.02		0.07	0.02	0.43	95
CA 0.2	22-34	108		109			5.00	0.04								1.00						61
CA 1.0	74-83	182		163		0.55	0.30	0.10	0.05				0.05	0.10						0.05	0.05	30
CA 1.1	109-128	183		83	0.05	0.07										0.80	0.03				0.13	30
CA 1.2	84-97	194		131		0.12	0.58							0.08	1.54					0.12		50
CA 3.0	99-108	365	0.80			0.25	0.45		0.05					0.05	3.00							50
CA Sill3	149-164	225-397		5		0.07	0.70	0.07		0.03		0.13	0.03	0.23	2.67		0.10				1.10	63
CA 4.1	35-50	515	0.10			0.19	0.66			0.03					0.06							37
CA 6.0	129-148	665	0.60			0.10	0.20	0.17			2.27	0.05	0.03	0.03								0
CA 6.1	1-17	750				0.07	0.29				1.39		0.25					0.04				5
MC 65.5	407-432	168				0.56	23.92	0.03	0.08			0.06		0.11		24.44					0.06	17
MC 0.1	367-387	150			0.05	0.05	62.85		0.13						0.20	36.00		0.05			2.50	5
MC 2.1	347-366	320	1.10			0.57	2.33	0.07					0.03	1.17		3.00						5
MC 4.1	387-406	549	1.05			0.23	1.05	0.03	0.05	0.03		0.05										
IT 0.1	258-276	72					4.32	0.03														0
IT 0.2	183-200	88					0.80	0.14														0
IT 0.4	200-211	140	1.83			0.40	34.75	0.05				0.03	0.05									5
IT 0.3	285-304	155	1.03			0.50	53.80	0.15					0.05									0
IT TR2	238-256	126			3.29	0.12	43.38															6
IT 1.2	277-284	283	0.60	0.25		1.00	0.85	0.10	0.10				0.05	0.05	16.25	4.30						0
IT 2.1	305-325	288		0.75	0.10	0.10	3.55	0.07	0.15				0.07	0.43	1.90	7.23						10
IT TR 1	222-237	196-234	0.78	0.47	0.13	0.66	13.50	0.06	0.03				0.03	0.88		72.97						6
IT 2.3	327-346	424	0.37			0.03	2.13	0.13	0.17		0.03	0.03	0.07		0.75							0

EPIFAUNA (soft substratum)

Sessile

A. Sabellid tubes
B. Onuphid tubes
C. Sea pens
D. Anemones

Mobile

E. Ophiuroids (+ *Asteriacites*)
F. Buccinid gastropods (+ trails)
G. Pycnogonids
H. Caridean shrimp
I. Elasipod holothurians
J. Fish

INFAUNA

K. irregular echinoid furrows
L. *Axius* burrows and volcanoes
M. Bivalve siphon openings
N. burrow pits

EPIFAUNA (rock)

Sessile

O. Sponges
P. Ascidians
Q. Alcyonaceans
R. Bryozoans

Mobile

S. "Bristly" ophiuroids
T. DROPSTONES (% of frames)