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Sedimentation in Expedition Fiord, Axel Heiberg Island, Northwest Territories
La sédimentation dans le fjord Expedition, île d'Axel-Heiberg, Territoires du Nord-Ouest.
Содержание Дедьта реки Зкспедишен

Robert Gilbert

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Article abstract

Expedition River which drains 1079 km2 of glaciated landscape on eastern Axel Heiberg Island is advancing 8.7 m/a (averaged since 1959) into Expedition Fiord. This rate is the highest reported in the Canadian Arctic. Bed material is deposited in the fiord by sediment gravity flows down the foreset beds of the delta. Fresh water forms a well-defined overflow on the sea which is not significantly mixed at least 15 km from the river. However, fine-grained suspended sediment (maximum measured concentration 2.24 g/L) flocculates and settles from suspension soon after entering the fiord. As a result, the sea floor near the delta is thickly mantled with rapidly accumulating deposits of very underconsolidated. fine-grained sediment. Beyond 3 km from the delta modern sediment is restricted to a thin cover with isolated pockets of thicker accumulation in depressions.

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SEDIMENTATION IN EXPEDITION FIORD, AXEL HEIBERG ISLAND, NORTHWEST TERRITORIES

Robert GILBERT, Department of Geography, Queen's University, Kingston, Ontario K7L 3N6.

ABSTRACT Expedition River which drains 1079 km² of glaciated landscape on eastern Axel Heiberg Island is advancing 8.7 m/a (averaged since 1959) into Expedition Fiord. This rate is the highest reported in the Canadian Arctic. Bed material is deposited in the fiord by sediment gravity flows down the foreset beds of the delta. Fresh water forms a well-defined overflow on the sea which is not significantly mixed at least 15 km from the river. However, fine-grained suspended sediment (maximum measured concentration 2.24 g/L) flocculates and settles from suspension soon after entering the fiord. As a result, the sea floor near the delta is thickly mantled with rapidly accumulating deposits of very underconsolidated, fine-grained sediment. Beyond 3 km from the delta modern sediment is restricted to a thin cover with isolated pockets of thicker accumulation in depressions.

RÉSUMÉ *La sédimentation dans le fjord Expedition, île d'Axel-Heiberg, Territoires du Nord-Ouest.* La rivière Expedition qui draine 1079 km² du territoire en grande partie englacé de l'île d'Axel-Heiberg progresse de 8,7 m/a (moyenne depuis 1959) dans le fjord Expedition. Ce taux est le plus élevé de tout l'Arctique. Le matériel du lit est déposé dans le fjord par écoulement de sédiments vers les lits deltaïques frontaux. L'eau douce apparaît dans la mer comme un courant de surface nettement visible et ne se mélange vraiment qu'à partir de 15 km de la rivière. Toutefois, les sédiments fins en suspension (concentration maximale mesurée de 2,24 g/l) sont floculés et se déposent peu après être entrés dans le fjord. Conséquemment, le fond marin près du delta est couvert d'un épais manteau de dépôts rapidement accumulés de sédiments fins très peu consolidés. Au-delà de 3 km du delta les sédiments récents se limitent à une mince couverture comprenant, dans les dépressions, des poches isolés de plus fortes accumulations.

Содержание Дельта реки Экспедишен, которой воды стекают из площади 1079 км² ледникового ландшафта на востоке острова Аксель-Хейберг, нарастает в фъиорд Экспедишен максимально 8.7 м/г (усредненная от 1959). Эта скорость является самой большой из измеренных в канадской Арктике. Донные наносы откладаются в фъиопд гравитационным стоком вдоль диагональных пластей дельты. Пресная вода создает на морской воде хорошо определимый слой который только незначительно мешается и простирается, по меньшей мере, до 15 км от реки. Однако, мелкие взвешенные наносы (макс. измеренная концентрация — 2.24 г/л) флокулируют и оседают немедленно после входа в фъиорд. В резултате, дно моря по близости дельты покрыто толстым слоем быстро нагромождающихся очень рыхлых осадков. В расстоянии 3 км от дельты современные осадки ограничены до тонкого крова, которого толщина повышается только в изолированных впадинах.

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INTRODUCTION

During the past decade some attention has been focused on the sedimentary environments of Canadian arctic fiords (Gilbert, 1983; Syvitski and Schafer, 1985). However, with the exception of work by Lemmen (1988) at Disraeli Fiord on Ellesmere Island, present-day fiord sediments in the High Arctic are uninvestigated. This paper reports a reconnaissance of Expedition Fiord on Axel Heiberg Island (Fig. 1) obtained during an 8 day visit in August 1988 as part of the Trent University field program in glaciology. Working from an inflatable boat, bathymetry of the inner part of the fiord was determined by echo sounding on lines at intervals of between 0.6 and 1.5 km; temperature, salinity and dissolved oxygen profiles were measured with YSI instruments; 0.22 μm filters were used to recover suspended sediment from 0.5 L water samples, and short cores were taken in an Ekman sampler and preserved in 0.1 m diameter tubes. In the laboratory cores were split, logged and x-rayed. Grain size was determined by sieving and Sedigraph analysis.

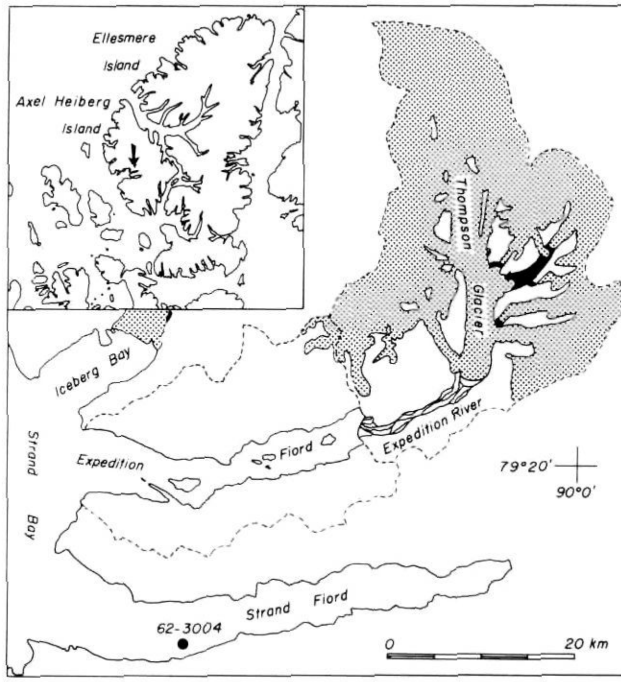

FIGURE 1. Map showing the drainage basin of Expedition Fiord with glaciers (stippled) and lakes (in black), the oceanographic station in Strand Fiord, and the location on Axel Heiberg Island (at arrow on inset).

Carte de localisation montrant le bassin versant du fjord Expedition, les glaciers (en gris), les lacs (en noir) et la station océanographique dans le fjord Strand. Le carton montre l'emplacement dans l'île d'Axel-Heiberg.

PHYSICAL SETTING

The major source of water and sediment to Expedition Fiord is Expedition River which drains an area of 1079 km^2, 72% of which is glacier covered (Fig. 1). Small streams reach the fiord from 495 km^2 along the sides, although only 2.4% of this area is covered by glaciers. The sandur of Expedition River extends 14 km from the terminus of Thompson Glacier to the fiord. The river braids across a flood plain that covers most of the valley floor and in the lower reaches is composed mainly of muddy sand. Input of coarse-grained sediment to the fiord is unknown, but may be estimated from progradation of Expedition River delta into the fiord. Comparison of air photographs taken in 1959 and a line-of-sight survey from the hillside above the delta in 1988 shows that the delta advanced a maximum of 2.5×10^2 m (or 1.3×10^2 m averaged over the entire delta front) (8.7 m/a and 4.5 m/a respectively).

From a sharp break in slope at the outer edge of the delta, echo soundings (Fig. 2) show foreset beds sloping downward at 8-12° to about 13 m depth. Beyond a second distinct break in slope at this depth, the surface slopes downward at 1.5° to about 55 m depth. This zone is covered with small mounds of sediment less than 2 m high. Depressions among them are partially filled with horizontally layered, acoustically transparent sediment. East of Erratics Island the nearly flat fiord floor is thickly mantled with soft sediment. West of Erratics Island the fiord consists of shallow basins (maximum depth

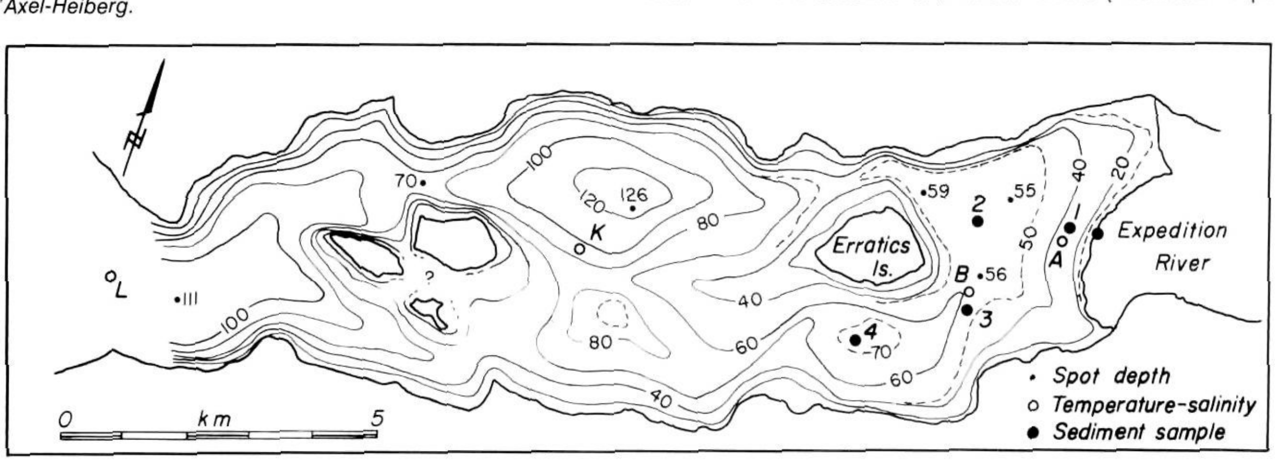

FIGURE 2. Bathymetry of Expedition Fiord (determined in 1988 from echo sounding profiles at 0.6 to 1.5 km intervals) and the location of sampling stations. Isobath interval, 20 and 10 (dashed lines) m.

La bathymétrie du fjord Expedition (établie en 1988 à partir des échogrammes réalisés à intervalles de 0,6 à 1,5 km) et l'emplacement des stations d'échantillonnage. Intervalle de l'isobathe: 20 et 10 (lignes brisées) m.

126 m) with a sill at 70 m depth located north of a group of three islands and a minor longitudinal sill between these islands and Erratics Island (Fig. 2). Soft, acoustically transparent sediment occurs only in small pockets or as a thin veneer on the irregular surface beneath. There is no evidence of erosion in the form of trenches anywhere on the fiord floor or on the foreset slopes of the delta.

OCEANOGRAPHIC CONDITIONS

Even in a 'good year' Massey Sound to the west of Axel Heiberg Island maintains 70 to 90% sea ice cover through the summer (Maxwell, 1982). However, in 1988 the mean July temperature in the central Arctic was 2°C or more above average (Anon, 1988) and Expedition Fiord and Strand Bay to the west were completely free of sea ice by mid-August.

Measurements of temperature and salinity in Expedition Fiord (for example those in Fig. 3) show the presence of a well-defined overflowing cap. A sharp pycnocline at 6 to 8 m depth separates overflow with temperature from 2 to 7.8°C (the latter at station A on 15 August following mean air temperature of 11°C the day previously) and salinity from 0.8 to 14‰, from the sea water below where temperature decreased downward to −1.7° and salinity to 30-32‰. Although the overflow became thinner and the salinity gradient less sharp at the distal sites in the fiord (Fig. 3), the overflow formed a strong cap everywhere at least in the inner 15 km of the fiord. Tides and tidal currents probably contribute little energy to drive the mixing processes. In the period from 14 to 22 August 1988, staff gauge readings at the northeast corner of the fiord showed a semi-diurnal tide with a mean range of 0.38 m.

The only other measurement of temperature and salinity in the region was taken in Strand Fiord (Hunter and Leach, 1983) and is similar to those in Expedition Fiord (Fig. 3). A zone of heating below the pycnocline attributed to trapping of solar heat (Ford and Hattersley-Smith, 1965) is absent in the water of Expedition Fiord near the fiord head, but may be weakly developed at the distal site (Fig. 3). It is probable that the presence of suspended sediment in the overflow blocks penetration of solar radiation, especially where concentrations are highest near the fiord head (see below).

Dissolved oxygen values were high everywhere in the upper 50 m of Expedition Fiord in mid-August 1988. They ranged from 9.4 to 11.8 mL/L with the higher values at depth. Hunter and Leach (1983) report values of 8.23 to 10.06 mL/L at the Strand Fiord station.

SEDIMENTARY ENVIRONMENT

Measurements of suspended sediment in inflow from Expedition River and in the fiord are shown in Figure 4. Concentrations in the river reached a maximum of 2.24 g/L on August 15. There are few other measurements of sediment concentration in the river, but values of 3.2-6.4 g/L in the middle reach of the river reported by Maag (1969) suggest that the 1988 values are not exceptional.

In the overflow within 0.5 km of the river mouth values dropped to less than about 100 mg/L. Values continued to decrease rapidly down-fiord to less than 10 mg/L (Fig. 4). Similar exponential decreases in concentration have been reported in other fiords by Syvitski *et al.* (1985) and Görlich (1988). This pattern suggests that about 93% of the sediment in suspension in Expedition River is deposited within 0.5 km of the river mouth, about 2.6% is deposited in the inner basin from there to Erratics Island, and less than 0.5% escapes beyond 15 km. Thus, although the temperature and salinity of the plume of overflowing water maintain themselves throughout the inner fiord, the sediment is quickly lost.

One set of measurements on August 15 from sea water below the pycnocline shows concentrations there 2 to 4 times those in the overflow above (Fig. 4). This may relate to settling through the water column of mud from previous overflow (*cf.* Cowan and Powell, in press).

Five short cores (Fig. 5) were obtained, one from topset beds in the mouth of the largest distributary and four from the floor of the fiord near the delta (Fig. 2). Except for a silty layer between 5 and 6 cm depth, bed material in the river mouth sample consisted of plane-bedded sands with a small fraction of silt and no particles larger than 2 mm (Fig. 6a).

Sample 1 from 32 m depth near the delta consisted of interlayered sand and silt (Fig. 6b). The sand layers are massive

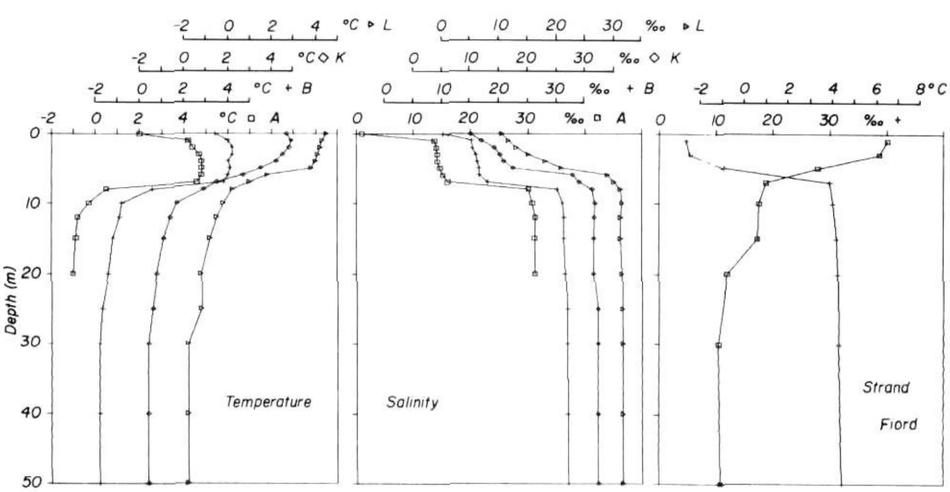

FIGURE 3. Temperature and salinity at four stations in Expedition Fiord on 18 August 1988 between 0730 and 0830, and in Strand Fiord on 18 July 1962 (Station 62-3004: Hunter and Leach, 1983). Station locations are shown on Figures 1 and 2.

Mesure de la température et de la salinité à trois stations du fjord Expedition, le 18 août 1988, entre 7 h 30 et 8 h 30, et au fjord Strand le 18 juillet 1962 (station 62-3004; Hunter et Leach, 1983). Localisation des stations aux figures 1 et 2.

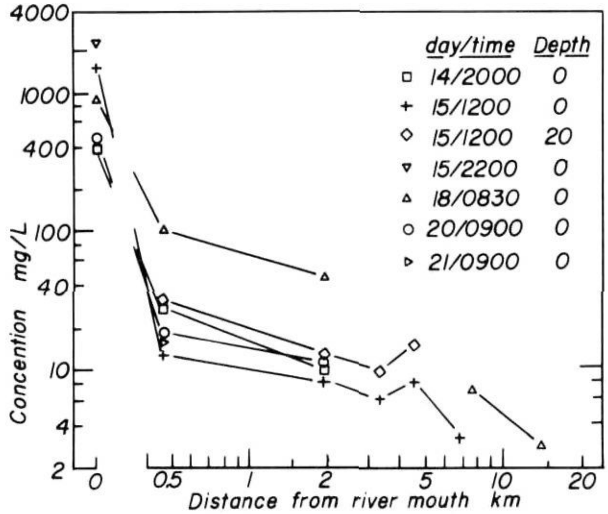

FIGURE 4. Concentration of suspended sediment in Expedition Fiord in August 1988.

Concentration des sédiments en suspension au fjord Expedition, en août 1988.

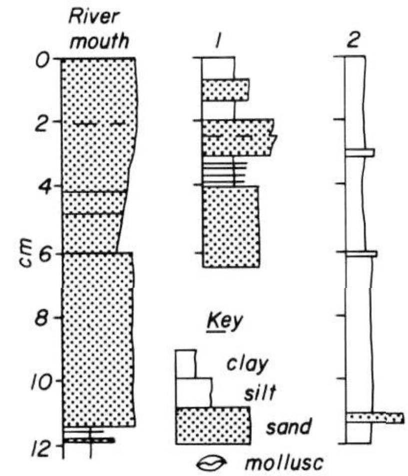

FIGURE 5. Logs of sediment samples from the mouth of Expedition River and Expedition Fiord assessed from split samples, x-radiograph images, and grain size analysis.

Diagramme des échantillons de sédiments de l'embouchure de la rivière Expedition et du fjord Expedition déterminé à partir des échantillons, des radiographies et des analyses granulométriques.

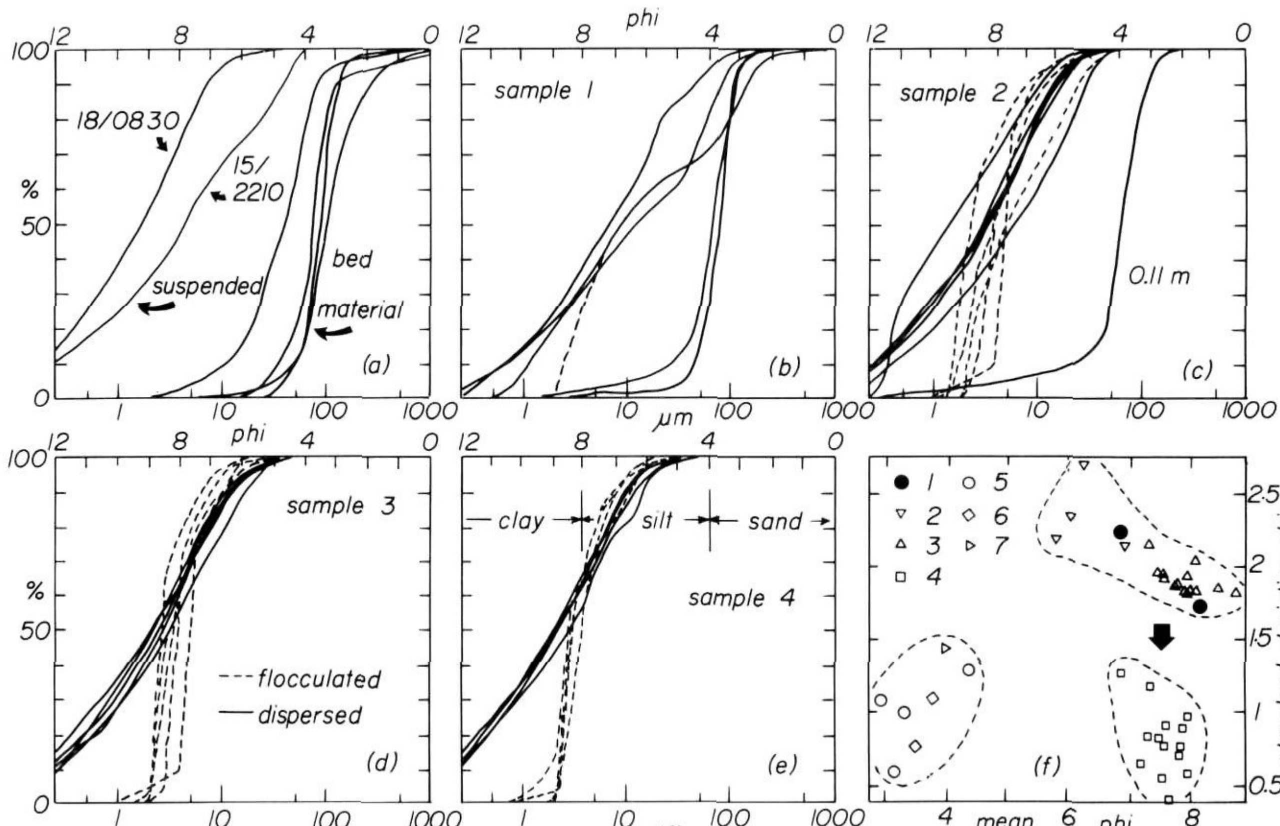

FIGURE 6. Grain size of sediments (a) from the mouth of Expedition River, (b-e) in samples 1-4, and (f) mean against standard deviation for all sediments: (1) suspended sediment from the mouth of Expedition River, (2) fine-grained, dispersed sediments from sample 1, (3) dispersed sediments from samples 2-4, (4) flocculated sediments from samples 1-4, (5) bed material from the mouth of Expedition River, (6) coarse-grained sediment from sample 1, and (7) sample 2.

Granulométrie des sédiments (a) de l'embouchure de la rivière Expedition, (b-e) des échantillons nos 1-4, et (f) moyenne sur l'écart type pour tous les sédiments: (1) sédiments en suspension de l'embouchure de la rivière Expedition, (2) sédiments fins dispersés de l'échantillon no 1, (3) sédiments dispersés des échantillons nos 2-4, (4) sédiments floculés des échantillons nos 1-4, (5) matériel du lit en provenance de l'embouchure de la rivière Expedition, (6) sédiments grossiers de l'échantillon no 1 et (7) de l'échantillon no 2.

with little evidence of grading. Grain size is similar to that in the bed material of the river (symbols 5 and 6, Fig. 6f), suggesting that slope failures from the upper part of the delta have moved sediment down the foreset beds. The fine sediments between the sand layers are only slightly coarser than the sediments on the fiord floor beyond the delta (symbols 2 and 3, Fig. 6f).

Samples 2 and 3 are from the flat floor of the fiord east of Erratics Island. They consist of silt and clay-sized particles with no sand. Analysis of this material before and after dispersion shows that the sediment is flocculated with most of the flocs in the range 3 to 5 μm equivalent fall diameter (Fig. 6c, d and e). Fig. 6f indicates that this sediment (symbols 2 and 3) is derived from the suspended load of the river (symbol 1). Flocculation creates a mud of more uniform grain size (symbol 4).

Rapid deposition is indicated by extreme underconsolidation of the sediment in this region. Water content (as ratio of weight of water to weight of sediment) varies of 0.95 to 1.1 in samples 2 and 3. Grain-size data and x-radiograph images show little structure, although two faint silty layers occur in sample 2 and slight variations occur in sample 3 (Fig. 5).

Coarse sediment in samples from this region is found only in a 3 mm thick layer at 0.11 m in sample 2 (Fig. 6c). Its grain size characteristics (symbol 7, Fig. 6f) are similar to the sands of the river mouth and on the foreset slope, suggesting that a gravity flow travelled at least this far from the delta. The fine tail (Fig. 6c) which creates the higher standard deviation indicates that some of the silts and clays over which the flow rode were incorporated during transport. Frequency of these events cannot be determined, although echo sounding resolved 8 to 10 strong reflecting horizons in the upper 5 m of sediment, each nearly horizontal and traceable over several hundred metres. Some may be associated with annual draining of ice-dammed lakes (Maag, 1969) and the slugs of water and sediment delivered to the fiord from these events.

Sample 4 is from the floor of the basin south of Erratics Island, an area transitional from the region toward the delta where soft sediment forms a thick blanket everywhere, and the region to the west where sediment accumulation is restricted to depressions. This sample is similar to samples 2 and 3 in grain size (Fig. 2), although no coarser layers could be distinguished. Two specimens of the mollusc, *Portlandia arctica* var. *portlandica* were recovered from 0.075 m depth in sample 4. These were the only macroorganisms in any of the samples.

No coarse particles that might be interpreted as ice-rafted debris were recovered in any of the samples. Although a number of large, sediment-laden icebergs from the calving glacier in Iceberg Bay (Fig. 1) drift into Expedition Fiord, most are trapped on the sill at the group of three islands in mid fiord. The few small bergs that are able to enter the inner fiord probably deposit some ice-rafted debris, but the rate of deposition of sediment from suspension is sufficiently high that it is a minor component of the record. Passive loading (Gilbert, in press) of coarse sediment onto sea ice by inflowing streams in the spring also occurs at Expedition Fiord (Adams, personal communication, 1989), but this is also probably of minor importance.

DISCUSSION AND CONCLUSIONS

The sedimentary environment of Expedition Fiord is similar in many respects to fiords in more southern regions. Fine-grained, flocculated sediment is rapidly deposited from suspension in the overflowing plume. The modal grain size of about 5 μm is lower than the values of about 10 μm reported by Gilbert (1982) and Syvitski *et al.* (1985) from fiords elsewhere. The smaller floc size in Expedition Fiord may be related to the low degree of turbulence and mixing inferred from the sharp pycnocline and low salinity of the overflow. Circulation and thus sediment dispersion is probably of minor importance because the tidal range is small and the sea is normally ice-covered and protected from wind (Lake and Walker, 1976). Flocs may settle from the water column before they have the opportunity to collide with and gather as many individual particles as in a more turbulent environment (Görlich, 1988).

However, it is remarkable that the sedimentary environment of Expedition Fiord is more active than many locations farther south. Progradation of the Expedition River delta has been nearly 9 m/a since 1959. Syvitski's (1987) measured rates of progradation of 5 deltas in fiords of Baffin Island vary from less than 0.5 to 6 m/a (mean 1.6 m/a). Measured concentrations of fine-grained sediment of up to 2.24 g/L in inflow to Expedition Fiord are also high compared with values elsewhere in the Arctic (for example, Syvitski *et al.*, 1987). Rapid deposition of this fluvial sand and mud in the fiord near the delta produces a sedimentary environment different from present conditions elsewhere in the High Arctic (Lemmen, 1988).

Rapid sedimentation and the resulting soupy nature of recent deposits prevents establishment of benthic organisms that are abundant elsewhere. It is probable that further out in the fiord away from the soupgrounds at the head, the benthos is much more extensive (*cf.* Dale *et al.* 1988). Benthic hauls from the station in Strand Fiord contained "a good deal of benthonic invertebrates" (Leach, personal communication, 1988).

Echo soundings west of Erratics Island indicated that here too modern sediment occurs as a thin cover on an irregular surface and that thicker deposits are restricted to depressions. In this respect, the sedimentary environment appears more like conditions in the open sea among the high Arctic islands away from glacial sources (Sonnichsen and Vilks, 1987; MacLean *et al.*, 1989). The thin sediment cover can be explained if these conditions prevailed through the Pleistocene in the absence of glaciers occupying Expedition Fiord as England (1987) has demonstrated elsewhere in the High Arctic. This condition is very different from the fiords of Baffin Island where large outlet glaciers deposited and overrode thick glacimarine sedimentary sequences (Andrews, 1990). Thus, conventional coring techniques might produce a long sedimentary record from this area.

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