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Résumé de l'article

Pangnirtung Fiord is a glacial trough draining the southwest portion of Penny Icecap, Baffin Island. Sills associated with riegels divide the fiord into four basins. Despite a large inflow of sediment from streams draining the glaciers and Penny Icecap, glacio-marine sediments have been deposited in sufficient thickness to mask glacial features only in the central portion of the fiord. A major trench in the fiord floor is believed to result from erosion by turbidity currents. A shallow sill (12 to 22 m below mean tide level) at the mouth of the fiord, a large tidal range (up to 6.7 m), and moderate fresh water inflow strongly influence circulation and stability of fiord water. Replacement of bottom water occurs frequently or continuously during the year and helps to determine the distribution of sediment. The oxygen~rich bottom water supports a large benthia fauna which severley bioturbates the sediments making them useless for the interpretation of Holocene events in the region.

Reports

OBSERVATIONS ON OCEANOGRAPHY AND SEDIMENTATION

AT PANGNIRTUNG FIORD, BAFFIN ISLAND

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Pangnirtung Fiord is a glacial trough draining the southwest portion of Penny Icecap, Baffin Island. Sills associated with riegels divide the fiord into four basins. Despite a large inflow of sediment from streams draining the glaciers and Penny Icecap, glacio-marine sediments have been deposited in sufficient thickness to mask glacial features only in the central portion of the fiord. A major trench in the fiord floor is believed to result from erosion by turbidity currents. A shallow sill (12 to 22 m below mean tide level) at the mouth of the fiord, a large tidal range (up to 6.7 m), and moderate fresh water inflow strongly influence circulation and stability of fiord water. Replacement of bottom water occurs frequently or continuously during the year and helps to determine the distribution of sediment. The oxygen-rich bottom water supports a large benthic fauna which severley bioturbates the sediments making them useless for the interpretation of Holocene events in the region.

INTRODUCTION

Understanding of the oceanography of fiords in Arctic and West Coast regions is steadily increasing (see review by Lake and Walker 1976), but much less is known of sedimentary processes, especially of fiords in northern latitudes. With the exception of studies by early explorers (for example , Kiaer 1909), offshore studies (Kranck 1966, Jackson *et al* 1977), and reconnaissance results (Knight 1970, Piper Iuliucci 1978) little is known of the relationship between physical oceanography and the sedimentary processes of arctic fiords.

The study at Pangnirtung Fiord provides preliminary information to compare with the fiords of western North America and Europe, to assist in the study of Pleistocene and Holocene history in a region where interpretation based on subaerial evidence is difficult (Dyke 1977), and to provide understanding of the impact of human activity, especially the exploitation of mineral and petroleum resources on the natural environment.

FIORD MERPHOLOGY

Pangnirtung is one of several glacial troughs leading from the Penny Highlands of eastern Baffin Island to Cumberland Sound. The fiord is 43 km long, averages 2.5 km wide and reaches a maximum depth of 160 m (Fig. 1). The area tributary to the fiord is 1700 km^2, 25% of which is glacier-covered. Two major streams, Weasel River which enters at the head of the fiord ((40% glacierized) and Kolik River, drain 67% of the basin.

Studies of the Pleistocene glacial geology of the region (especially Dyke 1977) indicate a complex history of advances from the nearby Penny Icecap. Landscapes tributary to the fiord vary from ancient (at least pre-Wisconsin) to areas now glacier-covered. Incomplete evidence suggests that a mid-Wisconsin ice advance reached the mouth of the fiord, and that prominent lateral moraines especially north of Kunguk Peninsula and near the head of the fiord represent later re-advances or stillstands. The fiord was probably ice-free by the end of the Wisconsin, although nearbly glacial advances and retreats, and at least 50 m of isostatic rebound during the Holocene have altered the sedimentary environments of the fiord.

Raised marine beaches and deltas are everywhere evident around the shore, but the exact height of the marine limit is uncertain since ice-dammed lakes probably occurred in side valleys, especially at Kolik River, and the deltas and shorelines of these lakes confuse interpretation (J. Shaw, personal communication). Around most of the shore of the fiord are broad tidal flats reaching maximum width of 0.5 km near the settlement of Pangnirtung. Large boulders scattered over the surface and a prominent boulder rampart at the outer edge indicate the importance of seasonal ice in creating these features. No features of comparable size are preserved as raised marine forms, indicating a relatively stable sea level for some considerable period of time. Dyke (1977) indicates that during the period 6000 years B.P. to the present sea level may have been lower than at present by as much as 10 m, although no submerged forms were observed in our echograms.

As evidenced by the relatively shallow water of the fiord, the sea occupies only the bottom of the deep glacial trough; mountains around the head of the fiord stand 1500 m above sea level, and the plateau through which glaciers cut the lower reaches of the fiord is 600 m above sea level.

The results of echo-sounding carried out in 1977 reveal a number of characteristics of fiord morphology. A prominent sill extends completely across the mouth of the fiord at a depth of 12 to 14 m below mean tide level, except in one place on its southern margin where depth exceeds 22 m below mean tide. The sill consists of a single, narrow transverse ridge (Fig. 2a) the shape of which indicates a major terminal moraine. As shown below, the sill plays a large role in the circulation pattern which develops in the fiord.

Behind the sill, the fiord is divided into four basins by smaller sills (Fig. 3) probably consisting largely of bedrock associated with the riegels.

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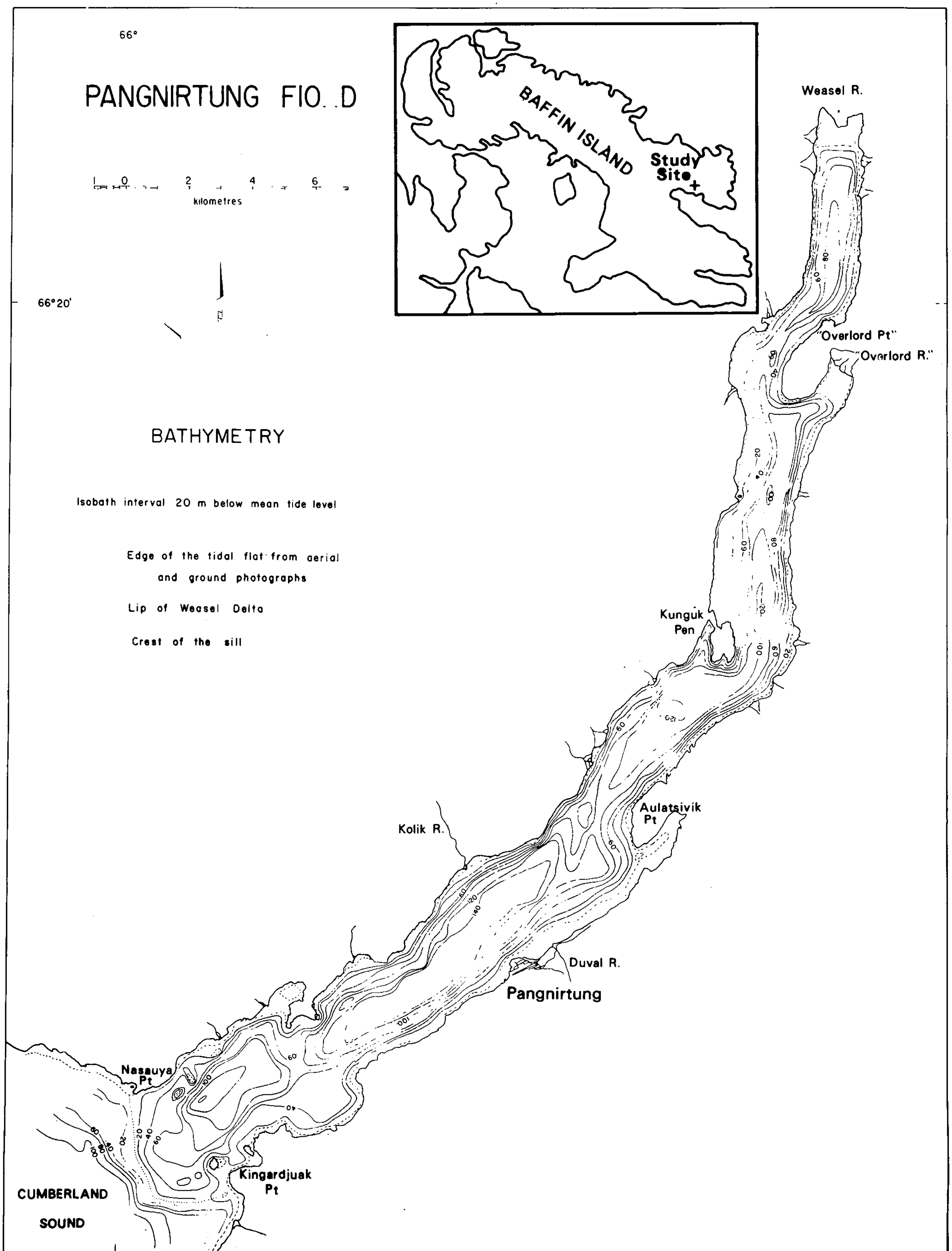
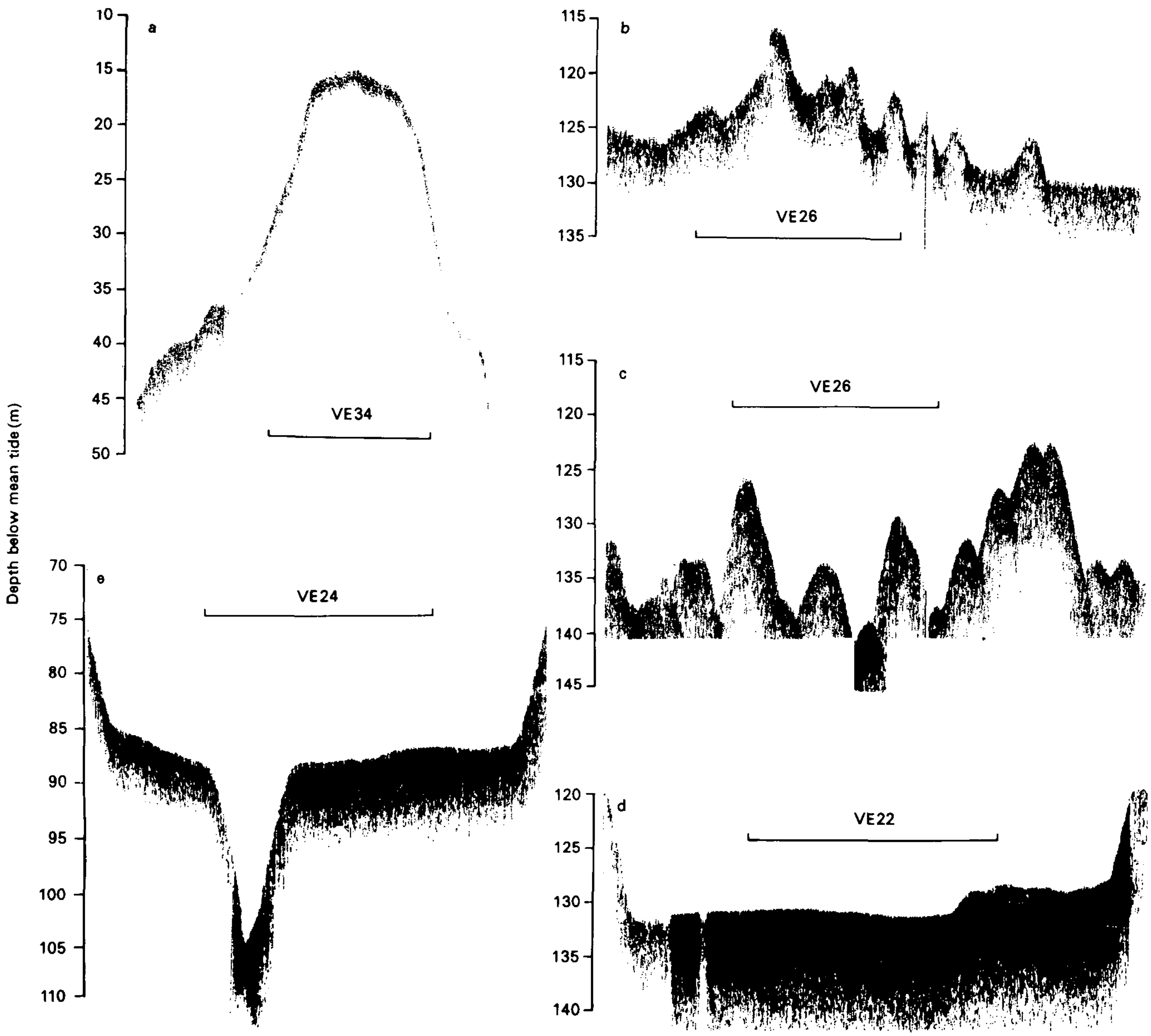

66°
PANGNIRTUNG FIO..D
0 2 4 6
kilometres
66°20'
BAFFIN ISLAND
Study Site
BATHYMETRY
Isobath interval 20 m below mean tide level
Edge of the tidal flat from aerial and ground photographs
Lip of Weasel Delta
Crest of the sill
Weasel R.
"Overlord Pt"
"Overlord R."
Kunguk Pen
Aulatsivik Pt
Kolik R.
Duval R.
Pangnirtung
Nasauya Pt
Kingardjuak Pt
CUMBERLAND SOUND
outline from NTS 26 I/4, 5 and 6

FIG. 1 Bathymetry of Pangnirtung Fiord. A conventional echo sounder was operated on transects across the fiord at 0.5- to 1-km intervals, and down the length of the fiord. Positions were determined by line-of-sight to points recognisable on aerial photographs. Depths are below mean tide level based on water levels recorded at Aulatsivik Point. Names in quotation marks are not officially recognised.

FIG. 2 Selected echograms from Pangnirtung Fiord. Horizontal bar scale is 500m. Bearings in degrees from true north are left to right on echograms. (a) down-fiord over the mid portion of the distal sill (240°), (b) down-fiord over moraine associated with a major lateral moraine at Kunguk Point (240°), (c) down fiord over irragular (bedrock?) topography southeast of Aulatsivik Point (235°), (d) across the fiord between Aulatsivik and Kunguk Points (140°) and (e) across the fiord south of "Overlord Point" (100°).



Glacial and bedrock features are still prominent on many parts of the floor of the fiord as they are not masked by accumulation of marine sediment (Fig. 2b, c). In other areas sediments have accumulated to considerable thickness as a flat featureless plain on the fiord floor except where evidence of redistribution by currents and slumping was noted (Fig. 2d).

Cutting through the sediments at several locations is a single deep trench. Its width averages approximately 200 m, depth 15 m and the side slopes approximately 8° (Fig. 2e). The trench begins northwest of Overlord Point and descends to the floor of the basin south of the riegel with a maximum slope of 0.032. In the central portion of the basin it disappears, perhaps filled by sediments from Weasel and Overlord Rivers, only to reappear passing around Kunguk Peninsula where its slope varies from 0.027 north of the peninsula to -0.014 south of the peninsula. The shallow sill at the mouth of the fiord precludes a fluvial origin of the trench. It has been proposed that turbidity currents are capable of carving these channels in lakes (Houbolt and Jonker 1957) and open oceans (Buffington 1952). Trenches also have been reported in an Alaskian fiord (Hoskin and Burrell 1972).

Powerful turbidity currents perhaps associated with infrequent slumps may account for the trenches observed in Pangnirtung Fiord. Consideration of the equation for the velocity of flow of turbidity currents (Harleman 1961) and the Hjulstrom relation (1935) between stream velocity and the erosion of sediments, indicates that to drive a current just filling the trench at sufficient velocity to erode the fine sediment on the fiord floor (0.5 m/s), its density would need to be 1.146 g/ml. This represents a concentration of suspended sediment (of density 2.65 g/ml) of 120 g/l in salt water or 230 g/l if the turbidity current were composed of fresh water. These loads are in excess by 1 to 2 orders of magnitude values observed in inflowing streams during summer (A. Plamondon, personal communication), leaving the mechanism of slump-generated turbidity currents (Morgenstern 1967) as a viable alternative (see also Macdonald and Murray 1973). Turbidites of similar origin have been described from a Norwegian fiord (Holtedahl 1965), and from fiords on northern Baffin Island and Devon Island (Lewis *et al* 1977). The foreset beds of Weasel Delta rest at 20°, and mounds of slumped material like those observed in fresh-water proglacial environments (Gilbert 1975) are seen in the echograms, especially at the base of the foreset beds.

DISTRIBUTION OF WATER AND SEDIMENT

In an attempt to assess sedimentary processes and the distribution of sediments in the fiord, measurements were made of the characteristics of the fiord water. Temperature, transmissivity and salinity were measured in situ to 30 m depth. Salinity at depths greater than 30 m, and dissolved oxygen were determined from water samples recovered with a van Dorn bottle.

The principal source of water and sediment is Weasel River entering at the head of the Fiord. The flow regime is arctic proglacial (Church 1974), increasing from a few cubic metres per second in mid-June to more than 70 m^3/s by late July 1977, before decreasing slowly through August (A. Plamondon, personal communication). Glaciers in the basin provide a large load of suspended sediment: concentrations exceed 2 g/l during flood. Overlord River which drains one third as much area as Weasel River probably has similar water and sediment discharge characteristics. The only other large stream entering the fiord is Kolik River. Although the drainage area is approximately the same as Weasel River and this inflow is probably similar, the sediment input is much less since most is trapped in a series of lakes on the river system. Duval River, which enters the fiord opposite at Pangnirtung, is monitored by the Water Survey of Canada and has a typical arctic nival regime, with peak flow due to snowmelt occurring in late June and early July (25 m^3/s in 1977) and steadily decreasing flow thereafter except for lesser events caused by precipitation. Suspended sediment concentrations in the nival streams are less than 10 mg/l even during floods.

Although the characteristic thermohalocline develops between salt and fresh water (Fig. 3), and sediment is deposited by flocculation from suspension in the surface water as it moves down-fiord (Fig. 4), there is evidence of significant and repeated circulation of the entire mass of fiord water. Concentration of dissolved oxygen remains high throughout the depth of the fiord during summer (Fig. 5), and there is evidence that concentration increases at depth due to replenishment of bottom water. It is unlikely that photosynthesis occurs at a sufficient rate to replace the oxygen at depth as has been proposed elsewhere (Apollonio 1973), and the release of air by icebergs (Lake and Walker 1976, Berthois 1966) is not significant except at the surface. Further evidence of movement of near-surface water from Cumberland Sound over the sill and into the bottom of the fiord is seen in the temperature and salinity data of Fig. 3. The water at depth between Pangnirtung and the sill is 1° to 2° C warmer than further up-fiord and the isohaline surfaces converge near the sill.

Many authors have proposed that salt water moving into the fiord under the influence of tides may plunge beneath and mix with benthic water of the fiord - for example, Pickard (1975) from data on fiords of the west coast of Canada. Nebert and Matthews (1972) following the model of Ippen (1966) showed that the relationship between the volume of fresh-water inflow and the tidal prism is a diagnostic measure of this circulation as long as a density difference exists between the water inside and outside the sill, and also that the control of circulation is less due to entrainment of salt water in outflowing fresh water. Measurements of inflow at Weasel and Duval Rivers extrapolated to the other tributary basins, and the observed tidal range at Aulatsivik Point of between 2.70 m and 6.68 m during the summer yield an approximation to the inflow/tidal prims ratio for Pangnirtung Fiord. The ratio varied between 4.6×10^{-3} and 7.5×10^{-3} in summer 1977. The values are 1 to 2 orders of magnitude less than values required for stability

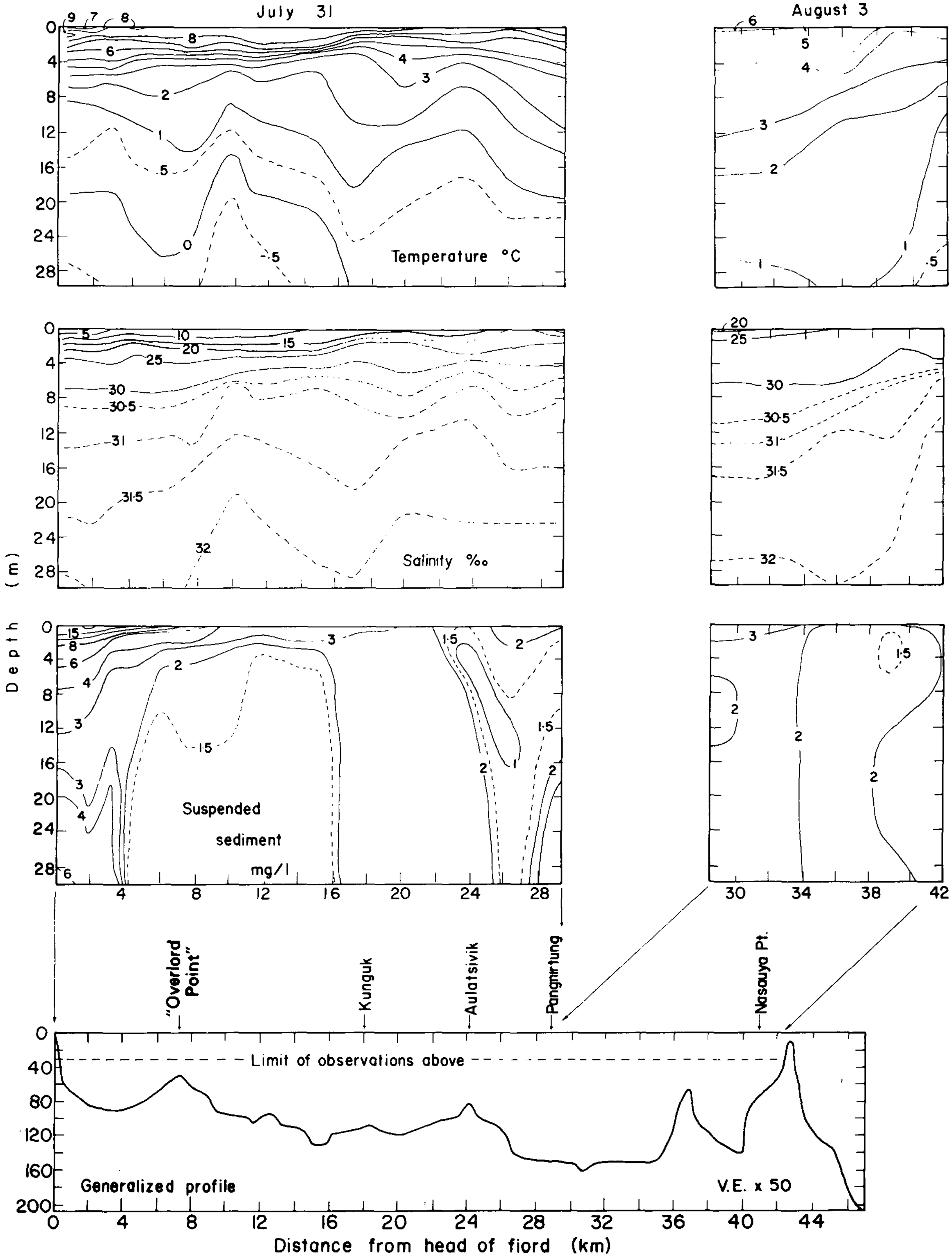


FIG. 3 Temperature, salinity and suspended sediment in the upper 30 m of Pangnirtung Fiord. Transmissivity of incandescent light was calibrated against dried residue retained on 0.22 μm filters from samples taken beside the probe near the surface. Measurement stations were located at 1- to 2-km intervals along the fiord.

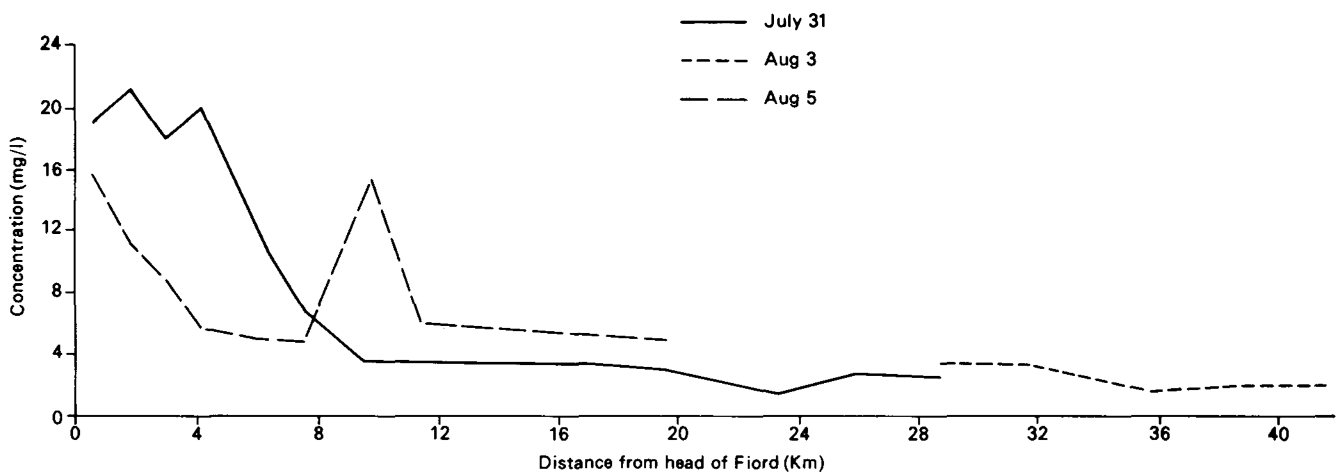


FIG. 4 Concentration of suspended sediment at the surface of the fiord.

(Nebert and Matthews 1972, Ippen 1966) and, although the ratio is an oversimplification of stability criteria, it indicates the role of the large tides in causing instability in Pangnirtung Fiord. During winter when inflow is near zero, the ratio becomes even smaller. However, the density gradient between the water inside and outside the sill will be much less because of the reduced inflow and because of salt expelled from the surface ice on the fiord as it freezes, so that the water moving into the fiord over the sill may not plunge to the bottom of the fiord as readily. In fact, this increase in salinity may of itself be sufficient to cause instability (Gade *et al* 1974).

Sedimentation in Pangnirtung Fiord is greatly influenced by the circulation pattern. High oxygen concentration in bottom water supports a rich benthic fauna which severely bioturbates the sediment. Macroorganisms recovered from the fiord floor include: brittle stars — *Ophiocten sericeum, Amphiophiura* (sp.); marine worms — *Onuphis (Nothria) concylega*; molluscs — *Chlamys islandica, Portlandia arctica, Neptunea despecta, Colus* (sp.), arthropods — *Pagurus pubescens;* bryozoans — *Parasmittina jeffreysi;* urochordates — *Boltenia echinata* and porifera — *Tetilla sibirica* (cf. Ellis 1960). The brittle stars and marine worms were particularly common; at least several of each were recovered in all but a few of the Ekman dredge samples taken. The short undisturbed sediment cores showed no remaining structure on visual examination or on x-radiographs of 1-cm thick sections, except a bioturbated band of sand about 1 to 2 cm beneath the sediment surface in cores near the head of the fiord. We propose (Shaw *et al*, in press) that this sand is blown onto the ice from the delta of Weasel River during winter to be released at breakup. Subaerial deposits of wind-blown sand are common in the vicinity of the fiord-head and a number of boulders have been etched and faceted by blowing sand. Local residents report intense sand storms especially in winter, and the fine sediment on top of the sand probably represents inflowing flacial sediment deposited during the time the sand was released by melting ice, about July 1 and July 19 when the cores were taken.

To assess sedimentary processes qualitatively, grain size determinations were carried out from small mixed samples of each core; the fraction finer than 2 mm by wet sieving, and the fraction finer than 62 μm by analysis of settling velocity in a Sedigraph Particle Size Analyser. In order to investigate the degree of flocculation, each sample was split; half was analyzed in distilled

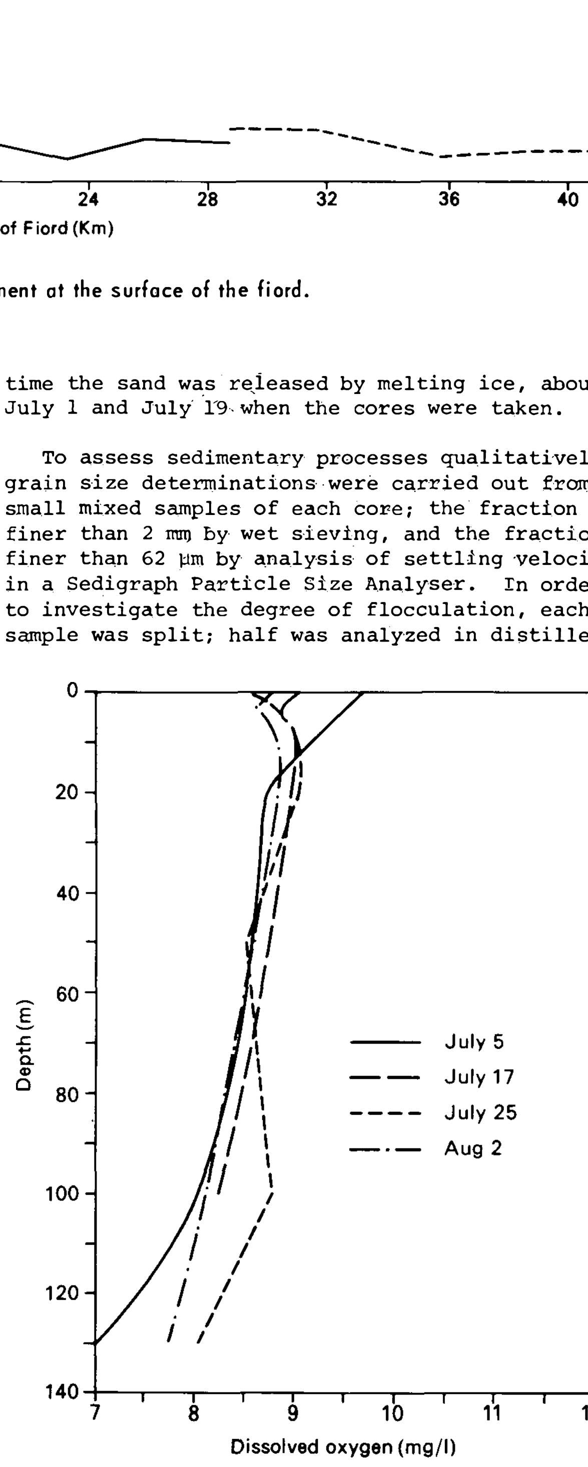


FIG. 5 Concentration of dissolved oxygen in the centre of the fiord opposite Pangnirtung.

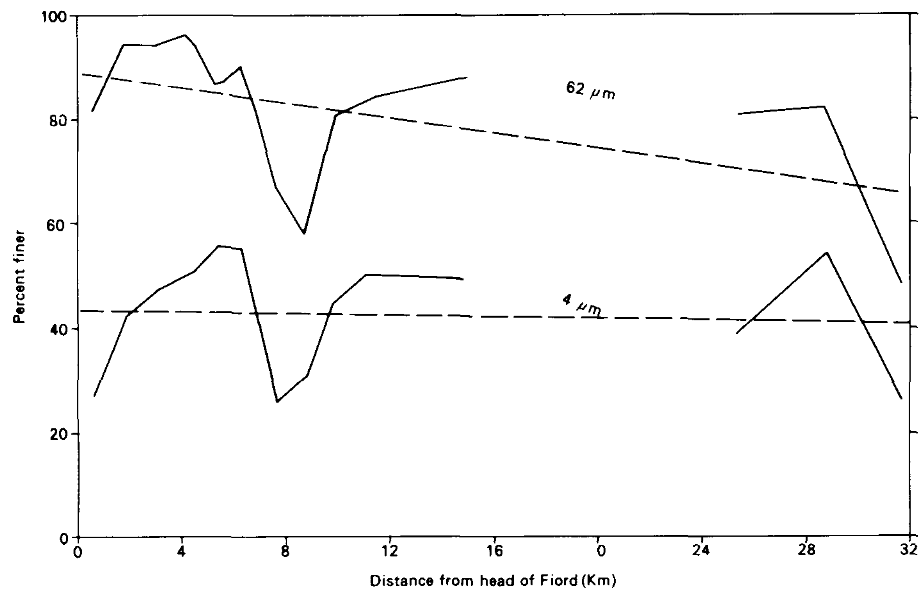


FIG. 6 Texture of flocculated sediments less than 2 mm diameter deposited in Pangnirtung Fiord. Dashed trend lines divide sand, silt and clay size.

water and half in dispersing agent according to recommended procedure (Day 1965). Some of the results of these analyses are presented in Figures 6 and 7. Figure 6 shows the percentages of sand, silt and clay in the undispersed sediment as a function of distance from the head of the fiord. The clay-size fraction is large, averaging 41%, and does not exhibit a significant trend along the fiord to a distance of 32 km from the head. Sand content on the other hand, increases significantly (at statistical confidence of 95%) down-fiord. This is unlike most delta environments where the coarse fraction decreases distally. In this case, the sedimentation rate of fine material decreases as the overflow plume becomes more dispersed down-fiord (Fig. 4), and more medium-sized silt is deposited from suspension closer to the fiord-head because of its higher settling velocity. The coarse fraction (sand and gravel) is brought from the valley sides by small streams, or is picked up on the beaches and tidal flats by grounded ice to be carried out and released by melting, more or less at random along the fiord. Therefore, in distal areas where deposition of fines is slower, the sand represents a larger portion of the sediment.

That the sediment is flocculated can be clearly seen in Figure 7. In a number of the samples the sediment when dispersed shows a decrease in silt size and an increase in clay size, representing the breakup of flocculants. In all samples the clay size content increases significantly upon dispersion. The degree of flocculation is qualitatively assessed in Figure 7, where the median diameters of the fraction less than 62 µm are plotted. The difference between the medians of the dispersed and undispersed samples as a fraction of the undispersed median is also plotted. This ratio varies from approximately 0.4 to 0.7 and appears to decrease at least in the upper

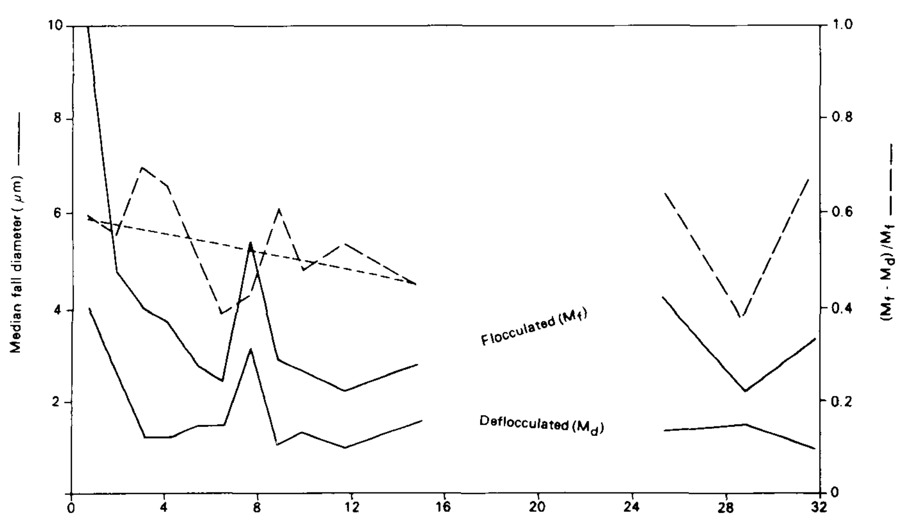


FIG. 7 Qualitative representation of the degree of flocculation of sediments in Pangnirtung Fiord. Median diameter is of sediment less than 62 µm diameter. $R = (M_f - M_d)/M_f$ where M is the median diameter of the sample before treatment to deflocculate ($_f$), and after ($_d$).

portion of the fiord, although the trend is not statistically significant. In other words, the maximum amount of flocculation has occurred near the head of the fiord.

Ice-rafted gravel (greater than 2 mm diameter) is common everywhere in the fiord sediments, and in the most distal 10 km of the fiord the fine sediment is almost totally absent from the floor, being replaced by gravel, cobbles, boulders, and bedrock. Apparently all fine sediment is retained in suspension or the small amounts which are deposited are subsequently eroded by currents associated with circulation discussed above.

CONCLUSION

The large tidal range of up to 6.7 m is believed to drive complete circulation of fiord water frequently or continuously through the year. The turbidity currents generated by dense, sediment-laden inflowing waters which are dominant in proglacial lacustrine environments (Gilbert, 1975) cannot occur in the fiord because of the greater density of the sea water. Sedimentation is largely by settling from suspension in overflows, although icerafting of coarse sediment is also important. However, the large trench observed in the floor of the upper to mid-regions of the fiord may be evidence of powerful, slump-generated turbidity currents. Although no turbidites were observed in the very short cores recovered from Pangnirtung Fiord, they have been observed in fiord sediments from Norway and northern Baffin Island.

One of the major objectives of the work, the determination of Holocene glacial and geomorphic events from the sediments, could not be achieved because of severe bioturbation. On the other hand, because the glacial sediments in many places are poorly masked by marine sediments, careful examination of subaqueous morphology may be very useful especially when related to terrestrial studies as for example those of Dyke (1977).

The rapid circulation of the water of the fiord indicates that much more information is required to assess adequately the environmental impact of polluting substances, since effects would probably be rapid and wide-spread. This is especially important considering the rich marine biota of the area and its importance in the economy of the Inuit people. The work also points out the need to assess the distribution of sediments by seismic methods and to recover long cores (both of which were beyond the logistics of this project) as part of a useful study of subaqueous sedimentary processes.

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