# Suspension settling effect on macrobenthos biomass distribution in the Hornsund fjord, Spitsbergen

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Seasonal variations and spatial distribution of suspension composition and concentration were determined in the Hornsund fjord on south Spitsbergen along with bottom sediment mineralogy and glacial-marine mud accumulation rates. These data were related to macrobenthos biomass distribution, as well as geochemical and hydrographic data. The axial distribution of sediment accumulation rates follows exponential decay. Slopes of the seaward decay are different for individual meltwater sources in Hornsund and, in general, they are higher than in river-fed fjords. Intensity of suspension settling is enhanced by strong retardation of meltwater flow and turbulence within the shear layer of meltwater jet sliding over strongly saline water. The most intensive settling, controlling the overall efficiency of mud deposition (up to 35 cm/a) occurs in the ice-proximal jet zone of meltwater plume. It results from turbulent diffusion of dense suspension (>1,000 mg/l) to the underlying still-water layer. Within the more distal, slow-advection zone the sediment accumulation rate falls below 1 cm/a. Suspension is deposited here mostly due to slow settling of mature flocs across the halocline. This bipartite lateral zonation results in (1) clay-mineral segregation observed in bottom mud in the ice-proximal jet zone ($2M_1$ large-flake muscovite is separated from 1Md clay-grade illite), and (2) high accumulation rate and extremely rapid decay away from the source. High concentration of surface-active clays in the rapidly accumulating sediment renders the proximal mud a closed system and a physical trap for nutrients.

The seasonal rhythm of changes in suspension composition reveals a time lag between maximum of organic suspension concentration and onset of clastic sedimentation. This lag along with the absolute dominance of clastic flux during summer-autumn, result in sulphidic (dark-light) lamination of ice-proximal mud. High clastic input and high surface water turbidity result in formation of a benthos-poor zone in the ice-proximal settings. There, formation and preservation of original monosulphidic lamination and scarcity of benthic life are mutually dependent. Control over these follows by damping of primary production in the photic zone and trapping of nutrients in the bottom sediment by clastic dilution and fast burial of organic material.

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Settling of suspension in the forefield of tidewater glaciers is by no means fully understood and its peculiarities not well defined. Also, in the resulting glacial-marine mud the mutual relations between the extreme sediment loading, geochemical environment in the sediment, and abundance of benthic life need clarifying. The present paper aims at contributing data on the above problems and, specifically, we put forward the following questions:

(1) Peculiarities of mechanism of fine sediment settling in the forefield of tidewater glaciers:
—seasonal rhythmicity of suspension settling,
—mechanisms controlling lateral distribution of sediment accumulation rates in ice-proximal settings.

(2) Main agents causing strong lateral biomass changes and the related problem of primary control over formation and preservation of original sedimentary structures (e.g. varve-like lamination).

The sediment deposited in the proximity of an ice cliff seems to be exceptionally fine, with silt and clay fraction constituting up to 90% of the bulk sample. The transition from mud to outwash and diamict facies (or inverse) in vertical sections and laterally, is rapid. This is observed both in the Spitsbergen fjords of today (Elverhøi et al. 1983; Görlich in print) and in the Pleistocene sequences (e.g. McCabe et al. 1987). It suggests that in a tidewater-glacier environment intensive settling of fines from the meltwater overflow starts nearly at the ice cliff, producing fine intercalations within the coarse-grained bottom sediment and,

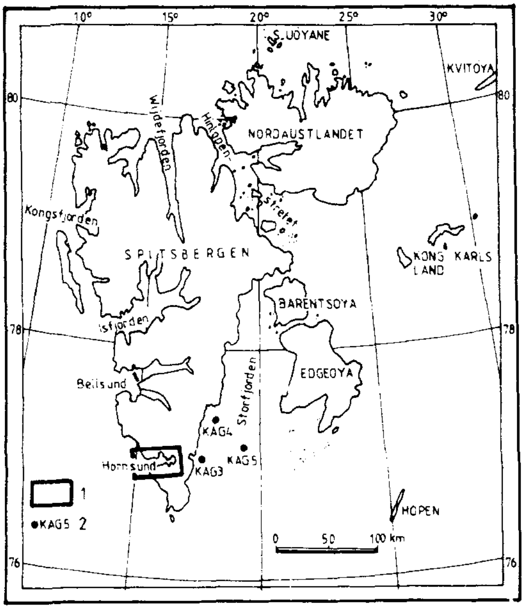


*Fig. 1.* Sketch map of Spitsbergen. 1. location of the study area, 2. sampling sites (grab samples) in Storfjorden and their identification.

already hundred metres or so from the source glacier, continuous mud sequences.

We noted that suspension settling intensities differ for individual tidewater-glacier subbasins of Hornsund and, even more significantly, they differ with respect to suspension behaviour observed in river-fed fjords, or, as an example of the temperate zone micro-tidal estuary at the Vistula River mouth in the Baltic Sea. Hence, we assumed that to explain near-source suspension settling patterns one must invoke, besides horizontal salinity gradients and discharge, other controlling mechanisms too, in particular, vertical salinity gradients, mineral and textural composition of original suspension, as well as dynamics of the discharge jet.

Our approach in the present study was to collect such sets of field data which could be used to test the applicability of the existing experiment-based models of suspension settling and formation of fine sediment. In order to do so, we sampled suspension and bottom mud. The present report also includes data on the distribution pattern of

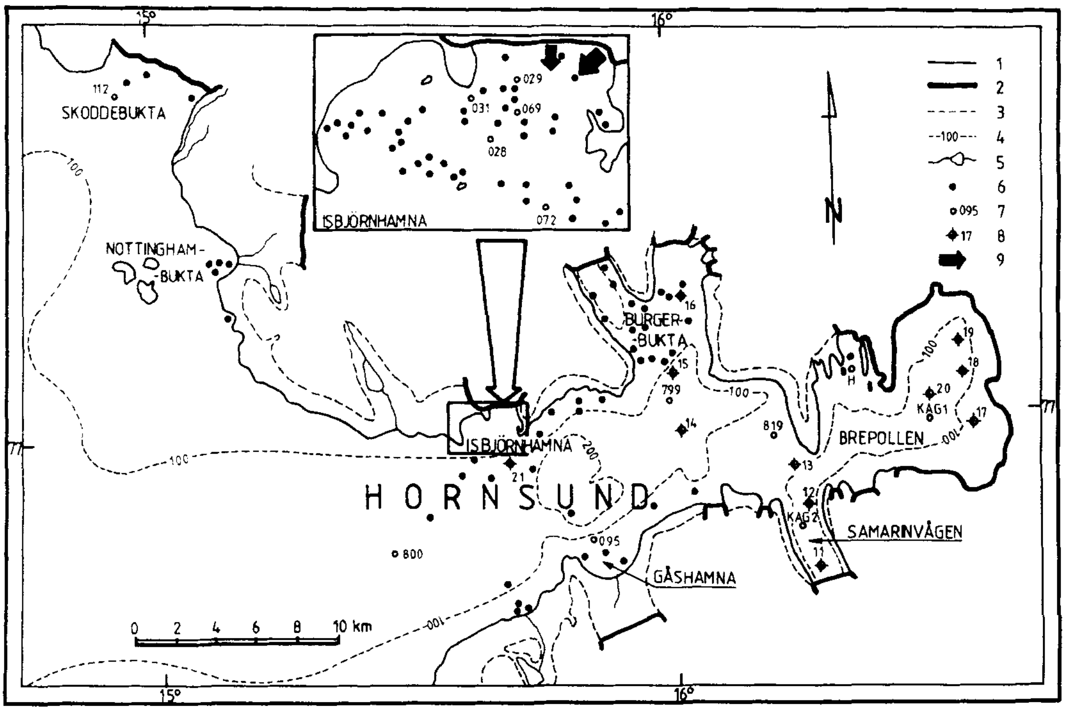


*Fig. 2.* Sampling stations in Hornsund. Inset map shows enlarged Isbjörnhamna. 1. shoreline, 2. ice cliffs of tidewater glaciers, 3. 100-m isohypse (on land), 4. isobaths with depths in metres, 5. major streams and lakes, 6. bottom sediment sampling stations (grab), 7. samples (with their identification) discussed in this paper, 8. sediment cores recovered with Kullenberg corer, 9. meltwater outflows in Isbjörnhamna.

bottom macrofauna in Hornsund, and some hydrological and geochemical results.

The paper focuses on two subbasins of Hornsund on south Spitsbergen (Figs. 1 and 2), Isbjörnhamna and Brepollen, and the discussion is concentrated on the phenomena occurring in the ice-proximal settings.

## Previous work

Much effort has been devoted to study suspension flocculation and settling in natural and experimental systems. The experiments in simplified systems (e.g. Kranck 1975, 1980, 1986; Gibbs 1985; Green 1987) and theoretical considerations (e.g. Hahn & Stumm 1970) offered insight into elementary processes during flocculation and settling, but they still failed to produce a coherent comprehensive model for natural estuaries (sensu lato). This is due to the fact that some crucial agents are disregarded in the experiments. These omitted or underestimated factors are (1) different crystallochemical quality of particles in the far ends of the size spectra (from surface-active: sheet silicates, organic matter, iron and manganese hydroxides, to inert: quartz, feldspars, and carbonates), (2) turbulence, and (3) localized advection and convection within the water mass—to name only the most significant.

Observations on the sediment loading controls over the bottom fauna communities in fjords are abundant in the literature (see Farrow et al. 1983 with references). Few papers, however, deal with very proximal settings in fjord environments dominated by active tidewater glaciers. Pearson (1980) gave a comprehensive review of current understanding of the fjord macrobenthos, concluding that the ecology of the Arctic fjords dominated by tidewater glaciers differs from that of the boreal to temperate fjords. The most characteristic factors affecting benthic fauna distribution in the Arctic tidewater-glacier dominated fjords are (1) the presence of strongly seasonal freshwater discharge, (2) high sedimentation rates, and (3) high oxygen and nutrient concentration in near bottom waters (Appolonio 1973; Pearson 1980; Gulliksen et al. 1984).

The field research on suspension settling in the most proximal settings is scarce, although numerous conceptual models for tidewater-glacier sedimentation have been elaborated (Domack 1983; Gilbert 1983; Molnia 1983; Powell 1984). This study will also refer to the papers dealing sedimentologically with glacial-marine sediments of Spitsbergen fjords (Elverhøi et al. 1980, 1983; Elverhøi 1984).

## Setting

### *Hydrography*

Hornsund fjord (Fig. 2), henceforward denoted as Hornsund, is situated on southern Spitsbergen, opening to the Greenland Sea. Morphologically it is divided into several troughs separated by sills (there is no sill at the fjord's mouth). The central trough is 200 m deep. The ice-proximal troughs are 55 m (Isbjörnhamna), 150 m (Brepollen), and 180 m (Vestre Burgerbukta and Samarinvågen) deep.

Hydrologically, Hornsund is under mixed influence from Atlantic Coastal Water and Atlantic Core Water (Swerpel 1985; Węsławski et al. 1985). Bottom water salinities range from 33.5 to 35 per thousand, whereas surface water salinities reveal horizontal gradients resulting from mixing of meltwater with underlying saline water (op cit.). Salinities of surface water rarely fall beneath 20 per thousand.

Water stratification is strong and sedimentologically significant only within the proximal forefield subbasins of the debouching tidewater glaciers (Urbański et al. 1980; Swerpel 1985; Görlich & Stepko in print). Freshwater discharge is unknown and, so far, impossible to evaluate due to scarcity of pertinent hydrographic data from ice-proximal zones.

The current system of Hornsund as a whole is unknown. A photogrammetric record of sea-ice drift (Madejski 1985) suggests that the surface water movements in the fjord are dominated by slow tidal currents (spring-tide amplitude is about 1.5 m) and drift currents strongly depending on the instantaneous wind directions. The geometry and wind-dependent fluctuation of meltwater plume dispersal in the proximities of the tidewater-glacier are shown in Fig. 3, using the example of Isbjörnhamna.

### *Sediment sources*

Bedrock in the source areas covers a wide range of ages and lithologies (Fig. 4), from metamorphic rocks of the Precambrian Hecla Hoek complex in

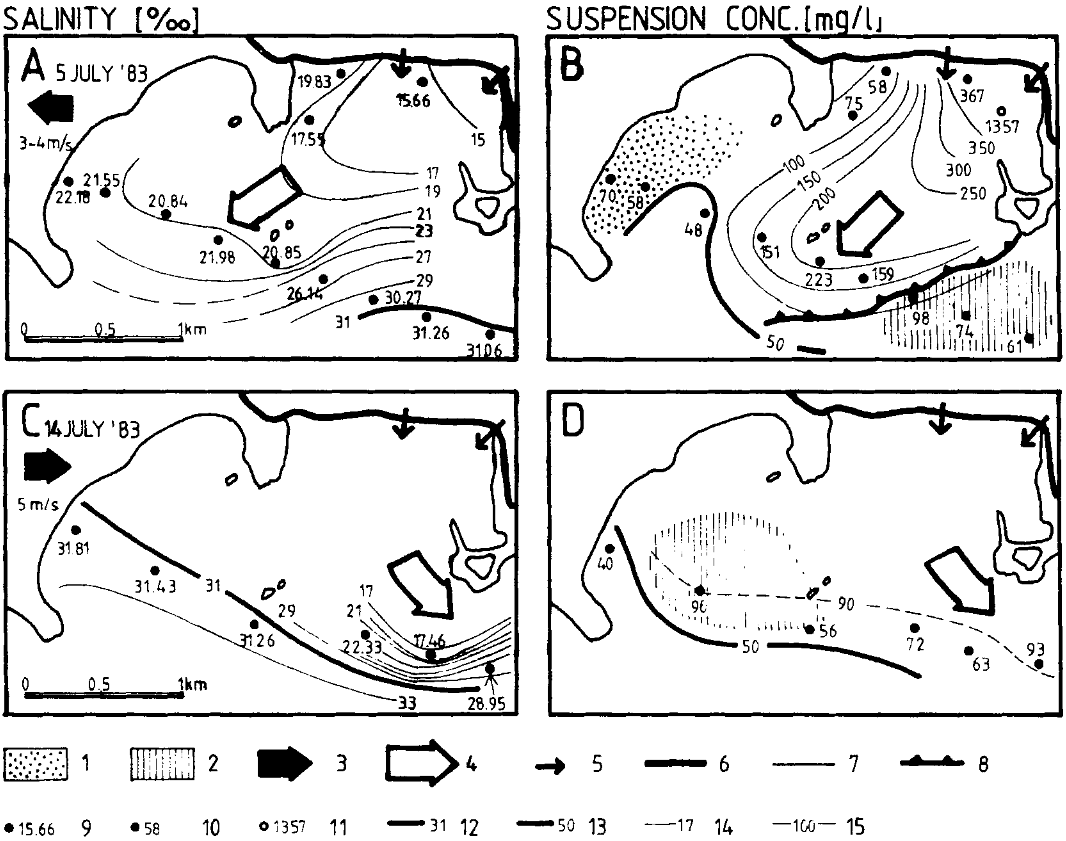


*Fig. 3.* Dynamic patterns of meltwater plume dispersal in Isbjörnhamna, depending on the wind direction. A & B. salinity and suspension concentration data collected on 5 July 1983, by wind direction 100° and force 3–4 m/s, C & D. analogous data collected on 14 July 1983, by wind direction 270° and force 5 m/s. 1. resuspension of bottom sediment, 2. remnant suspension left-over after the change of plume direction, 3. wind direction, 4. direction of the plume motion, 5. location of meltwater input, 6. tidewater-glacier front, 7. shoreline, 8. recorded course of the visible boundary of the sediment-laden water, 9. measured salinity values (A & C), 10. measured suspension concentrations (B & D), 11. suspension concentration measured on 3 July 1983, 12. isohaline 31 per thousand, 13. isoline of suspension concentration 50 mg/l, 14. isohalines (A & C), 15. isolines of suspension concentration (B & D).

the outer (northwestern) part, through the lower Palaeozoic carbonate rocks in the central part of the fjord, to the predominantly siliciclastic upper Palaeozoic and Mesozoic rocks in the bay head area (for more detailed description see Görlich (1986), and references in caption to Fig. 4).

Sediment input follows through meltwater discharge from eight major tidewater glaciers. Other sediment and freshwater sources seem negligible. The meltwater input is strongly seasonal. With freshwater discharge unknown, we cannot attempt at determining the sediment budget within the fjord.

### *Bottom sediment*

The variety of substrata on land is reflected by conspicuous differences in lithologies of bottom sediment. Five mineralogical provinces were distinguished in the bottom sediments using the relative abundance of carbonates, quartz, and feldspars (Görlich 1986). In the siliciclastic province of Brepollen and Storfjorden there are on an average 40% quartz, 12 to 22% feldspars, and 3% carbonates. In calcareous provinces (e.g. Samarinvågen) the carbonates reach 20%, the feldspars dropping to 4%. Clay-mineral composition suggests existence of two distinct mineral provinces: the biotite-muscovite dominated sediment (up to 35% of these minerals against 10% of illite) and the illite dominated sediment (up to 25% of illite against 10% of muscovite and biotite). See Fig. 4 and Görlich (1986).

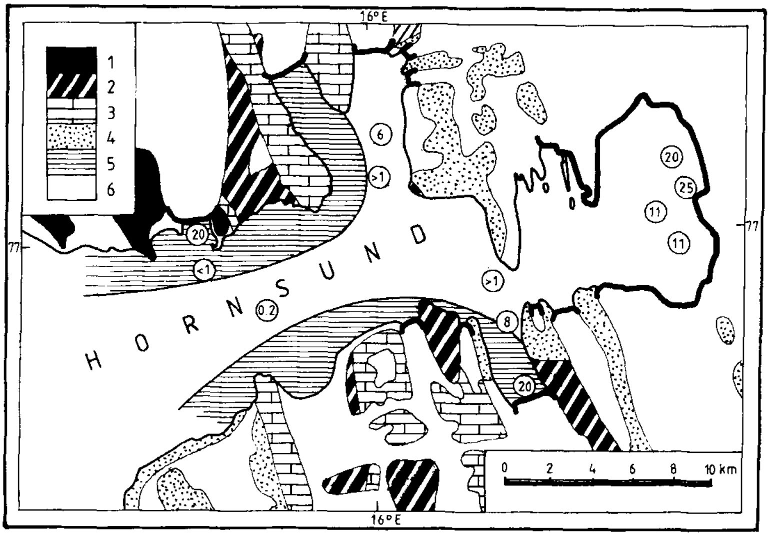


*Fig. 4.* Schematized dominant lithologies of the exposed bedrock on land as well as clay-mineral provinces within the bottom sediment of Hornsund. Land lithological data compiled from Birkenmajer (1960, 1964, 1975, 1977, 1978a, b), Radwański & Birkenmajer (1977), Siedlecka (1968), and Smulikowski (1965). 1. amphibolites and mica-garnet schists, 2. phyllites, 3. marbles, limestones and dolomites, 4. siliciclastic rocks. Bottom sediment provinces: 5. muscovite-biotite province, 6. illite province; in circles are sediment accumulation rates of mud types from Görlich (1986).

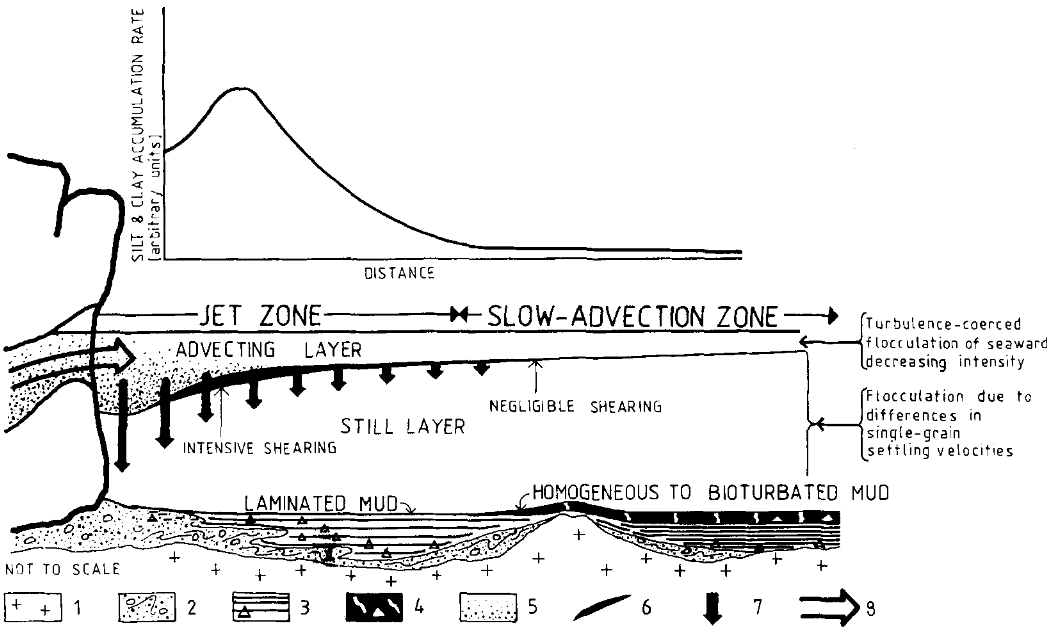


*Fig. 5.* Model of development and sequence of sedimentary facies in front of an oscillatory retreating (micro-surging) grounded tidewater glacier (based on the case study of the Hansbreen basin in Isbjörnhamna, Hornsund). The plot in the upper part of the figure shows inferred change of silt and clay accumulation rate with distance from the source glacier. Hydrodynamic features and flocculation modes of fine suspension are according to Görlich (in print). 1. substratum rocks, 2. till, outwash and surge deposits, 3. laminated mud facies, 4. homogeneous to bioturbated mud facies, 5. sediment-laden meltwater, 6. zone of intensive shearing on the boundary between advecting surficial freshet and underlying saline water (identified with halocline), 7. approximate intensity of suspended load settling, 8. discharge of meltwater from englacial channel.

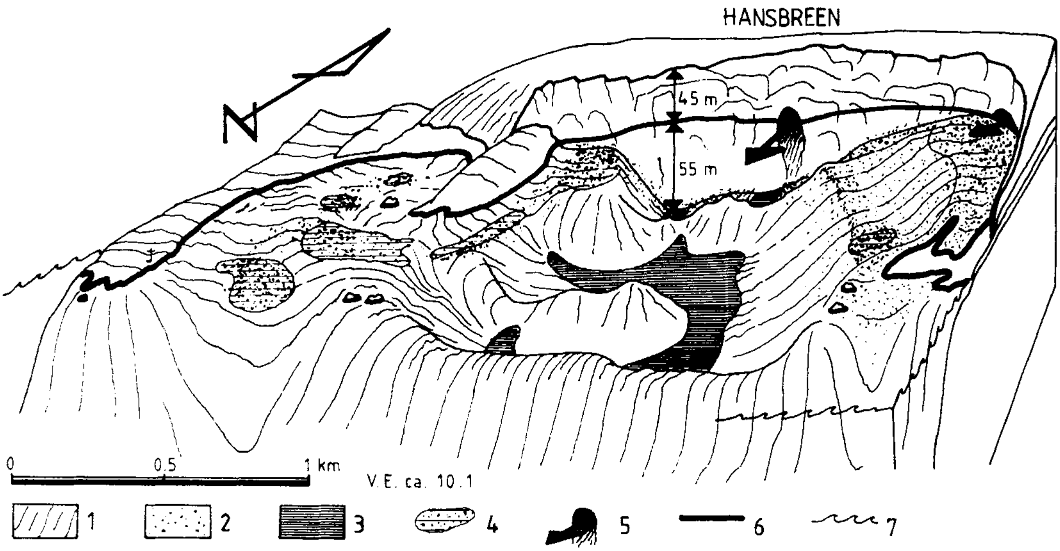


*Fig. 6.* Block sketch of bottom relief of Isbjörnhamna with features of sediment fill (based on 28 echo-sounding profiles made in 1979 by Swerpel pers. comm.). 1. schematic slope lines, 2. fine sand to gravel, 3. ponded deposits of laminated mud facies, 4. ponded deposits of fine sand, 5. outflows of glacial meltwater from englacial and subglacial channels, 6. shoreline, 7. sea level.

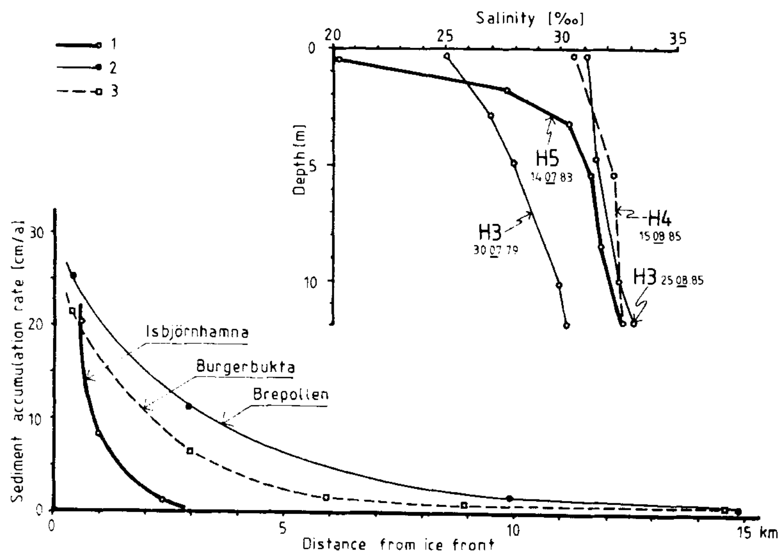


*Fig. 7.* Sediment accumulation rates for selected subbasins of Hornsund and vertical salinity profiles in the uppermost water layer for these subbasins (inserted). Hydrographic stations and water-sampling dates are indicated. The sediment-accumulation curves are based on the data from the following cores (see Fig. 2): 17, 18, 19, 20, 13 (Brepollen), 14, 15, 16 (Burgerbukta), and 23, 22, 21 (Isbjörnhamna), as well as on the seismo-acoustic (boomer) data from the central fjord (the latter provided by Zalewski & Kowalewski pers. comm.). July salinity profile for H3 from Urbański et al. (1980). For location of hydrographic stations see Fig. 9. Lines indicate: 1. plots for Isbjörnhamna, 2. plots for Brepollen, 3. plots for Burgerbukta.

Based on the presence of lamination or bioturbation, two main mud facies were distinguished in the bottom sediments of Hornsund (Görlich 1986): laminated mud and homogeneous-bioturbated mud (see Fig. 5 for schematic presentation). The respective mud facies are deposited at widely different rates ranging from 35 cm/a (for the proximal laminated mud) to less than 0.1 cm/a (for the distal homogeneous-bioturbated mud). See Figs. 5 and 7.

Besides the most proximal settings where ice-rafted detritus (IRD) is abundant, the ponded laminated mud facies which fills proximal basins (Figs. 5 and 6), is poor in drop stones and originates primarily from suspension settling. Coarse sand intercalations in this latter facies are rare, which excludes significant contribution from underflow sedimentation or large scale turbidity currents. Small scale turbidites produced by low-density currents occur in the central parts of the proximal troughs. The IRD contribution increases with diminishing sediment accumulation rate, producing inverse lateral grading of sediment texture within the discussed mud facies.

## Materials and methods

### *Sampling*

The samples for this study have been collected in Hornsund and selected locations on the south Spitsbergen shelf. Location of sampling sites and hydrographic stations are shown in Figs. 1, 2, and 9.

Water samples for salinity and suspension-concentration determinations were collected with 1-l Nansen bottles (for vertical hydrographic profiles) and with glass 1-l bottles (for surface water samples). A total of 85 water samples was collected between September 1982 and July 1983, and 272 water samples between September 1984 and August 1985. Water sampling has been carried out during the expeditions to the Hornsund Station of the Institute of Geophysics, Polish Academy of Sciences. Additional hydrographic data from Urbański et al. (1980) are included.

The sediment samples were recovered with the Petersen 0.16-m$^2$ grab, 1-m gravity corer and dredge (on hard bottom). The preliminary results of coring with Kullenberg piston corer, done by the 'Jantar' expedition of the Institute of Geophysics, Polish Academy of Sciences, in 1985, are also included (cores up to 3.5 m long).

### *Methods*

The results from Hornsund, presented in this paper, include (1) hydrographic data, (2) suspension concentration in vertical profiles, (3) surface water suspension concentration in time series, (4) quantitative data on organic and inorganic components of suspension, (5) concentration of phytoplankton chlorophyll and zooplankton in suspension, (6) mineral composition of bottom sediment, (7) Eh, pH and phosphorus concentration in bottom sediment cores, (8) sediment accumulation rates, and (9) lateral distribution of benthic biomass.

Water-temperature data were obtained in situ with reversible and electronic thermometers. The salinity of the water samples was determined with salinometer.

Weight suspension concentration was obtained by filtering of water samples through Milipore 0.45 μm filters. The filters had been dried to constant weight prior to filtration. After filtration they were dried again at 110°C for 24 hrs. and weighed. Organic matter in suspension was measured as weight loss by oxidizing the filters with suspension using hydrogen peroxide.

The chlorophyll concentration was measured using a spectrophotometric routine of Koblentz–Mishke & Semenova (1977).

Prior to mineralogical and chemical analyses, the bottom sediment samples were grain-size fractionated by wet sieving the fraction >63 μm and centrifuging the fractions 0.2–2 μm and <0.2 μm. The separation of clay fractions was preceded by chemical purifying with acetate buffer and sodium dithionite (Jackson 1974).

The mineralogical methods included (1) XRD mineralogical analyses carried out on oriented (for phase determination) and random (for polytypes determination and quantitative assessment) mounts, (2) determination of organic matter plus monosulphide content in the bottom sediment by heating the samples in the muffle furnace at 550°C for 24 hrs.

X-ray powder diffraction of random mounts was used for quantitative determination of mineral composition of the bulk sediment samples using a method elaborated by Środoń (1984) and described by Görlich (1986). The method enables distinguishing between the dioctahedral mica 1Md and $2M_1$ polytypes.

The preliminary study of cored sediments included macroscopic description and chemical analyses of cores 13 and 21 (Fig. 2). Eh and pH have been measured in the laboratory by inserting an electrode into the freshly cut sediment, immediately after the opening of a core. The unpublished pH and Eh data have been offered by S.M. Zalewski (pers. comm.). The phosphorus content in sediment samples was determined colorimetrically using the molybdate

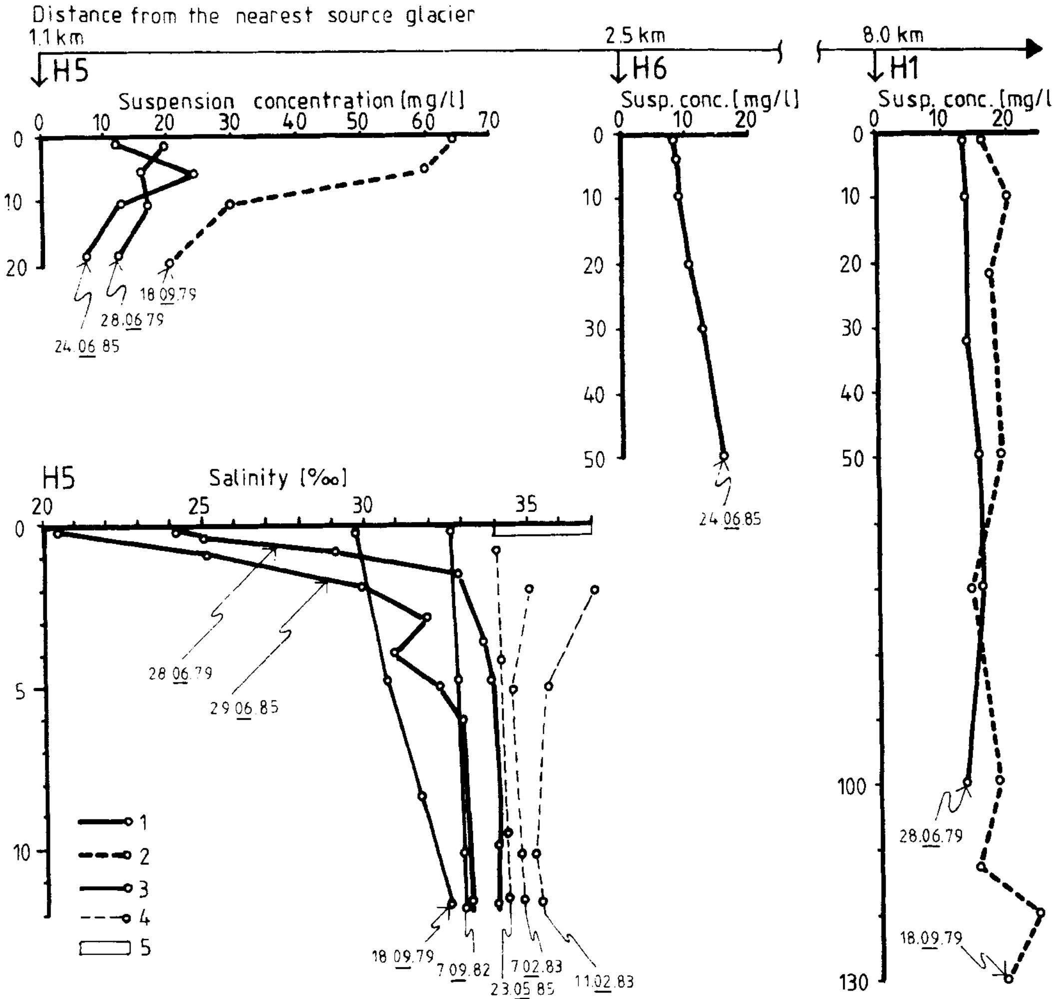


*Fig. 8.* Vertical distribution of suspension concentration at stations in Isbjörnhamna (H5), Isbjörnhamna sill (H6), and central trough of Hornsund (H1). In the lower left corner are salinity profiles for station H5 in Isbjörnhamna for different dates. Positions of the stations are shown in Fig. 9. Symbols denote: 1. plots for the samples collected in June, 2. plots for the samples collected in September (suspension), 3. plots for the samples collected in September (salinity), 4. salinity plot for the samples collected under sea ice, 5. bar marking salinity range for samples collected under sea ice.

method. The other chemical determinations are not discussed in this paper.

A Petersen 0.16-$m^2$ grab was used to obtain quantitative data on benthos. Usually three samples were taken from each station. The sediment was sieved with 2 mm mesh size and the macrofauna was hand-sorted and preserved in 4% Formalin water solution. Samples were taken in August 1984 and July 1985.

The unpublished results (microseismic activity of Hansbreen done by J. Dąbrowski, air temperatures, ground temperatures, and snow-cover thickness done by P. Adamski and J. Książek) have been kindly provided by the authors and are used here in the discussion.

## Results

### *Suspension dispersal*

Sediment accumulation rates obtained in a previous study (Görlich 1986) for three subbasins of Hornsund (Isbjörnhamna, Burgerbukta, and Brepollen—Fig. 7), suggest significant differences in sediment accumulation rates. These differences

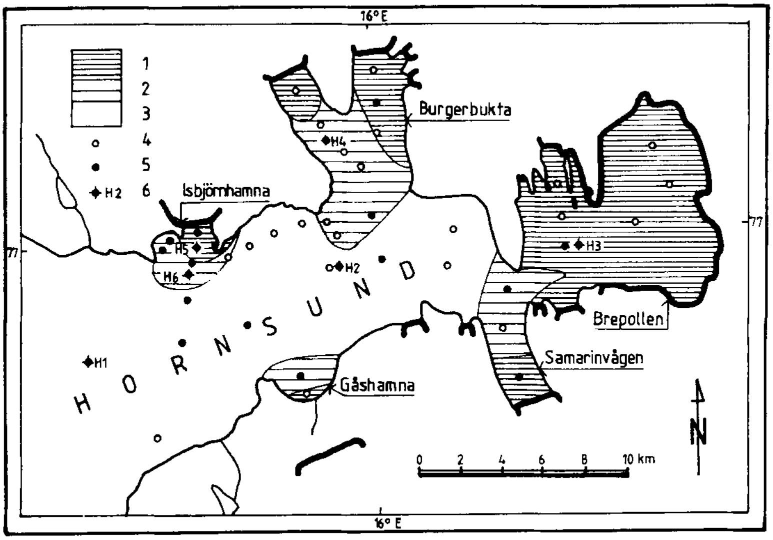


*Fig. 9.* Mean monthly (July) suspension distribution in surface waters of Hornsund. Symbols: 1. above 50 mg/l, 2. 20 to 50 mg/l, 3. below 20 mg/l, 4. suspension sampling stations (irregular sampling), 5. fixed sampling stations (suspension sampled five times in July 1985), 6. hydrographic profiles with identification, illustrated in Figs. 7 and 8.

were related in the above-cited paper either to different vertical salinity gradients (inset in Fig. 7) or to the position and intensity of meltwater sources.

In order to approximate the relative significance of these agents and to identify new possible controlling factors, the time and space variability of suspension concentration and composition within the water mass were studied. The results of the investigation are shown in Figs. 3, 8, 9, and 10.

The development of sediment-laden freshet in the water column of the proximal bay in June may be observed at station H5 in Isbjörnhamna (Fig. 8). The effect of the discharge plume is hardly noticeable already some 2.5 km away from the source (profile H6 in Fig. 8). Both the June profiles of suspension concentration at station H5 show maxima at 5 to 10 m water depth. The maxima may indicate that the load of suspension settles within the advecting surface water layer. At the salinity profile for this date (station H5, lower-left corner of Fig. 8) there is a secondary salinity minimum at that level, suggesting that the vertical stability of the water column is here indeed maintained by an increased suspended load.

The September profiles (stations H5 and H1) show distribution of suspension during the decline of meltwater discharge. Both from these profiles and from the surface water patterns in Fig. 3 we may note that the suspension concentrated up to 90 mg/l reveals a certain stability. The hatched fields in Fig. 3 suggest that suspension remained there after a change of the main direction of plume dispersal. The September profile H5 in Fig. 8 shows no indication of strong settling either. We infer that within the slowly advecting water in distal settings (or, during the decline of discharge, also in more proximal positions) the fall-out of suspension is not extremely rapid.

The slowly settling 'remnant' suspension is deposited within the fjord during the summer months, decreasing its concentration to the level of 'residual' values in the range between 10 and 15 mg/l. At the central fjord station H1, suspension concentration only slightly increases during summer above the 'residual' value. There are strong indications that a bulk of suspended load is deposited within the first few kilometres from the input where the surface water suspension concentration locally exceeds 1,000 mg/l.

The averaged lateral pattern of suspension dispersal is presented in Fig. 9. The map is based on the interpolated mean July values of suspension concentration measured five times at the fixed stations and irregularly at the other indicated stations. It may be seen from this figure that the reaches of individual sources suspension depend on the geometry of the basin and the position of

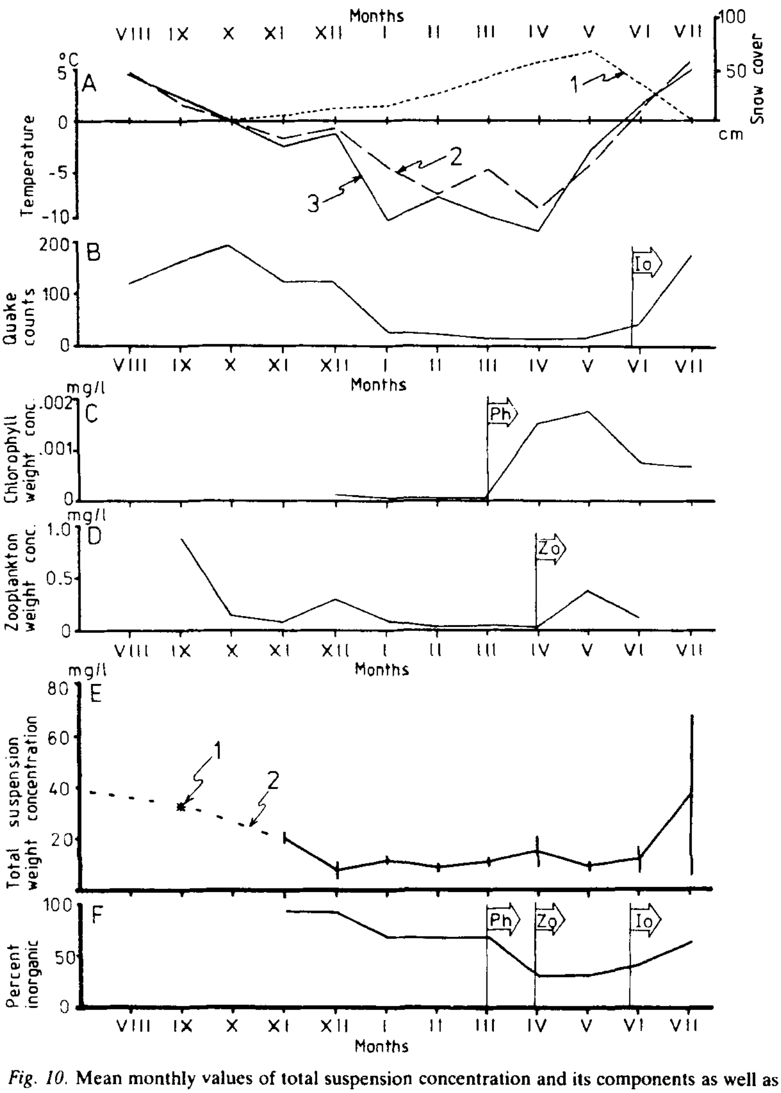


*Fig. 10.* Mean monthly values of total suspension concentration and its components as well as the controlling factors. A. meteorological data measured at the Hornsund Sation in 1985 (Adamski & Książek, pers. comm.): 1. snow-cover thickness, 2. mean monthly ground temperature at 5 cm, 3. mean monthly air temperature; B. monthly counts of microquakes recorded at the Hornsund Station in 1985 (Dąbrowski, pers. comm.) related to the calving activity of the nearby Hansbreen glacier (Io-flag marks the onset of the thawing process and thus the beginning of calving and meltwater input to Isbjörnhamna); C. chlorophyll weight concentration (Ph-flag marks the onset of primary production); D. zooplankton weight concentration (Zo-flag marks the first spring zooplankton bloom); E. total suspension weight concentration; data from the fixed stations in Fig. 9 (vertical bars indicate standard deviation): 1. datum for September 1983, 2. inferred course of distribution; F. percentage of inorganic part of suspension – the appropriate flags are those from plots B, C, and D.

the sources within it (e.g. Brepollen, encircled by tidewater glaciers, is filled up with dense suspension). The lateral extent of suspension coming from individual glaciers also depends on the discharge of meltwater sources. Thus, in order to describe the elementary mechanisms of settling, we shall later discuss the lateral variability of sediment accumulation rate rather than its absolute values (cf. Fig. 7).

One should note that a part of the residual

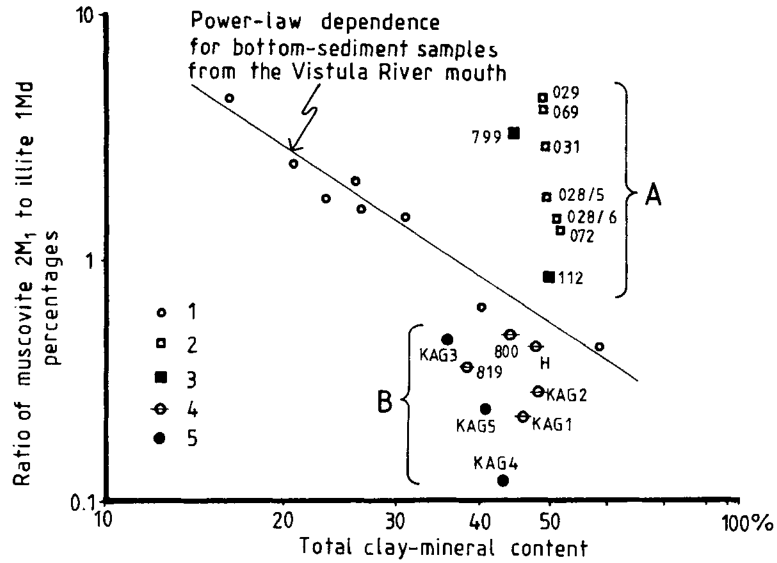


*Fig. 11.* Plot of percentage ratio (Mr) of $2M_1$ muscovite to 1Md illite against the total clay mineral content in surface sediment samples from the Vistula River mouth (in the Baltic Sea) and south Spitsbergen subbasins. The Hornsund samples are plotted against the power-law dependence of bottom sediments from the forefield of the Vistula River mouth (straight solid line, cf. Belzunce et al. in print). Data for samples from: 1. the Vistula River mouth, 2. Isbjörnhamna, 3. muscovite-biotite province in Hornsund and Skoddebukta (see Figs. 2 and 3), 4. illite province in Hornsund, 5. illite province in Storfjorden (see Fig. 2). A delineates samples within muscovite-biotite province, B delineates samples within illite province of the south Spitsbergen bottom mud.

suspension in the fjord (Fig. 10c, d, f) is made of organic components. The changes of phytoplankton and zooplankton concentrations presented in Fig. 10c and d, reveal strong maxima distinctly preceding the onset of clastic input with meltwater. The latter may be well dated using continuous microseismic data recorded at the Polish Station in Hornsund (Dąbrowski unpublished data). The record allows one to count quakes resulting from calving of the neighbouring Hansbreen glacier (Fig. 10b). The calving activity is correlated with the melting of englacial waters and the beginning of meltwater discharge to Isbjörnhamna. Comparison of the calving frequency curve with the meteorological data (Fig. 10a, b) shows that the meltwater discharge rather than the surface runoff is responsible for the bulk of clastic material delivered to the fjord. This is seen from the intensity of supply of clastic suspension to the fjord, which continues until December in spite of the presence of snow cover and mean air temperatures below freezing point since October–November.

*Bottom sediment features*

The observed intensity of suspension settling is supposed to be controlled, i.a. by textural composition of suspended material. This was noted by Görlich (1986) when comparing ratios of fraction <0.2 μm to fraction 0.2–2 μm in bottom sediment samples from different basins of Hornsund. A correlation between this ratio and local intensity of fine sediment settling was found; the latter feature measured as the sediment accumulation rate decay along the profile seawards from the glacier. For instance, in Isbjörnhamna the above fine fraction ratio (fraction <0.2 μm to fraction 0.2–2 μm) is on an average 0.03, and the suspension settling is exceptionally effective, whereas for the Brepollen province, the average ratio is 0.74 and the falling out by the suspension is less effective. These values of clay-fraction ratio indicate that the Isbjörnhamna sediment is coarser within the clay fraction than the Brepollen one.

Unfortunately, we have no Coulter-counter

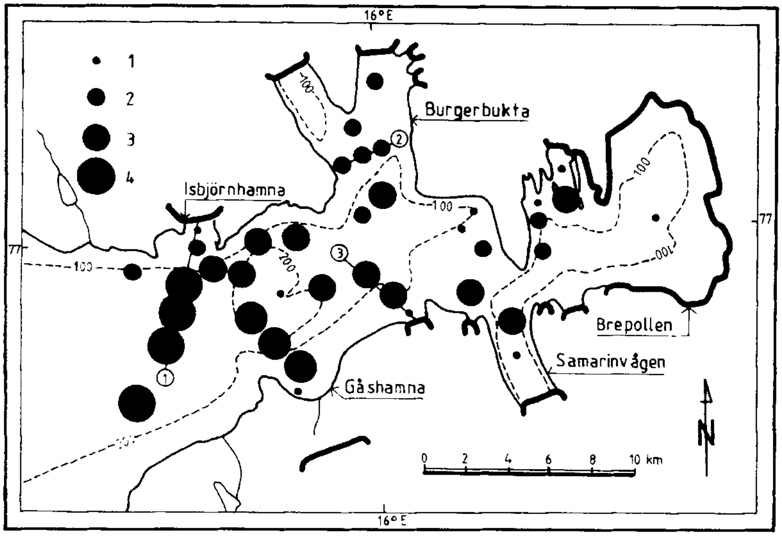


*Fig. 12.* Macrobenthos biomass distribution in the surface sediments of Hornsund, measured in August 1984 and July 1985. Numbers in circles indicate profiles illustrated as bar diagrams in Fig. 13. 1. >100 g/m², 2. 10–100 g/m², 3. 1–10 g/m², 4. <1 g/m².

grain-size spectra for suspension to show directly the dependence between the texture of primary suspension, its settling efficiency, and the resulting texture of the bottom sediment. However, we may use an indirect evidence. In order to do that we shall refer to the mineralogical method elaborated for the Vistula River sediments (cf. Belzunce et al. in print). This method traces gravitational segregation within fine suspension by measuring in the bottom sediment the relative changes of abundance of two mica polytypes: $2M_1$ muscovite and 1Md illite. Both polytypes, besides crystallochemical differences, reveal different specific modal grain-sizes. Muscovite is a large-flake mica concentrating in the upper limits of clay fraction, whereas illite is a clay-grade mica variety. The abundance of these mica polytypes may be measured in bottom sediment samples using XRD patterns of random powder mounts. The method of quantitative analysis applied here is that of Środoń (1984).

Thus, obtained data are plotted as abundance ratio muscovite/illite against the total clay-mineral content in the samples (Fig. 11), the total clay-mineral content being selected as a parameter well representing the sedimentary maturity of bottom mud (or the effective length of the transportation path from the source to the site of deposition). From the figure, we can see that the data for the sediments belonging to the Vistula River sedimentary province are plotted on the power-law curve. We may conclude that suspension from the Vistula source undergoes such differentiation during transportation that coarse-grained muscovite is separated from the clay-grade illite.

The data for Hornsund and Storfjorden plotted on this graph show that (1) there are two lithologic types of fine bottom sediment in the area: the Isbjörnhamna and Brepollen–Storfjorden ones, (2) the Isbjörnhamna mud, although rich in clay minerals (about 50%), contains much more coarse muscovite flakes and reveals extremely rapid differentiation, (3) the Brepollen–Storfjorden mud types are compositionally very close to each other (in spite of their being separated by the Spitsbergen mainland), contain predominantly illite, and segregation of muscovite from illite is only slightly more intensive here than in the Vistula River sediment.

### *Benthos distribution*

As regards benthic macrofauna, our data from Hornsund (Figs. 12 and 13) show tendencies similar to those observed in other fjords (e.g. Gage 1972; Feder & Matheke 1980).

The taxonomic composition of benthos in the samples collected for this study will be published elsewhere (Węsławski et al. unpublished). In gen-

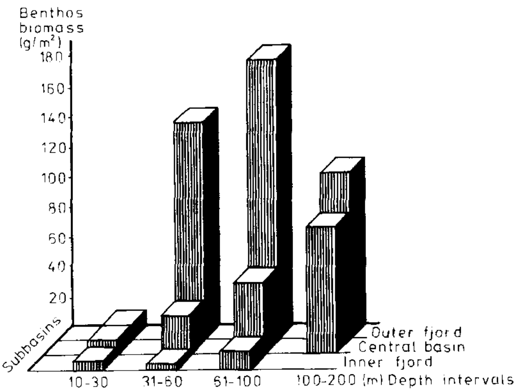


*Fig. 13.* Dependence of macrobenthos biomass on water depth and position within the fjord.

eral, 30 species of Polychaeta, 22 species of Mollusca, and 28 species of Crustacea have been determined. Polychaeta constitute some 80% of the benthic biomass. Crustaceans are abundant only above the 30 m isobath. In the outer fjord, in its deepest part, up to 90% of the biomass with 98% frequency is composed of Foraminifera of the genera *Rhabdammina* and *Hyperammina*. The bottom sediment of the inner fjord is practically devoid of microfauna.

The sketch map in Fig. 12 shows macrobenthos biomass distribution measured at different locations in Hornsund. There is some rough similarity between these results and the picture of suspension dispersal in Fig. 9. Comparison of Figs. 4 and 12 suggests, in its turn, that there is no relation whatsoever between the bottom sediment lithology and abundance (mass) of benthic life.

The forefields of the glaciers (inner fjord) always reveal low values of biomass, not depending on the depth. The sites with biomass lower than 1 g/m$^2$ in Brepollen and Samarinvågen occur at depths of about 150 m, whereas at the entrance to Burgerbukta the biomass approaches 100 g/m$^2$ at a depth of 50 m.

These relations are more easily visible in the synthetic graph of Fig. 13. One may see that the depth-related change is less pronounced than the change related to the position within the fjord. For fine sediments occurring below the wave base and the reach of frequent iceberg plowing (i.e. beneath the depth interval 10–30 m), there is a continuous seaward increase in benthos biomass for all the depth intervals. For the central and outer fjord locations the benthic biomass also increases with depth. However, this dependence is monotonic only for the inner fjord area.

# Discussion

## *Effects of source suspension composition on bottom sediment*

The clay-mineralogical procedure of analysing the muscovite/illite ratio, introduced in the preceding section, deals with bottom sediment. However, if we adopt a modified 'perforated conveyor belt' model of suspension settling in a fjord (cf. Farrow et al. 1983; Görlich in print), the data for the sediment will become applicable to source suspension. Hence, we may characterize source suspensions in the two subbasins of extreme conditions in Hornsund, viz. Isbjörnhamna and Brepollen: (1) Isbjörnhamna suspension is abundant in coarse clays, and its segregation is very intensive, (2) Brepollen–Storfjorden source suspensions are compositionally similar to each other, much more illitic and finer than the Isbjörnhamna one, and segregated at a rate only slightly higher than that encountered in the Vistula River mouth.

Suspensions from different sources settle rapidly in the proximal subbasins. The rapidity is different for individual basins (Fig. 7). It was shown in a previous study (Görlich 1986) that the fine sediment accumulation rate data for the Hornsund basins may be fitted with an exponential curve according to the formula proposed by Syvitski and collaborators (see Farrow et al. 1983). The exponent $m$ of this formula, determining the slope of the decay curve, falls for the Hornsund basins in a range between 0.1 (Brepollen and axial profile in the fjord) and 0.4 (Isbjörnhamna). This is on an average more (the slope being steeper) than for British Columbia fjords which are fed by rivers originating from the glaciers on land. For these latter fjords the exponent $m$ was estimated at 0.1 (Farrow et al. 1983). The value of this exponent for the Vistula River estuary is estimated by the present authors to be lower than in Hornsund.

The discussed slope of sedimentation rate decay is influenced by the dynamics of the discharge jet and the morphology of the basin. However, in the Hornsund basins it is most probably controlled by vertical salinity gradients and by the primary texture of suspension. The former follows by lowering of the local Richardson number at the shear surface between the advecting and still-water layers, and thus enhancement of turbulence, in case of a large vertical salinity gradient (Figs. 5 and 7—Isbjörnhamna). This, in turn, promotes excessive settling of suspension (Görlich in print).

The concept of grain-size distribution in clay suspension playing a role in promoting flocculation and settling, is based on the above distinction of two types of suspension in Hornsund, using the graph of muscovite/illite concentration ratio vs. total clay concentration (Fig. 11) as well as comparing the ratios of the grain fractions <0.2 μm to 0.2–2 μm for the different basins of Hornsund (Görlich 1986, see preceding section). The different sediment accumulation rates seem to be coupled with these different textural types of suspensions.

Besides stronger segregation of mica polytypes in Hornsund subbasins than in the Vistula River estuary, there is an additional specific feature of the studied bottom sediments (and hence, as we infer, source suspensions). Namely, the range of total clay content for each selected group of samples (Isbjörnhamna, Brepollen, Storfjorden) is very narrow. If we consider that the distance between the far end samples is up to 15 km for the Brepollen samples (or even 50 km for the Storfjorden ones) we must conclude that we deal here with a sort of process where the general textural spectrum of the settling suspension is kept constant. The effect of inverse lateral grading of texture (cf. Görlich 1986), resulting from relatively increasing IRD contribution, must be allowed for in this case (especially for the Storfjorden samples).

Anyway, we may state that the constancy of clay content in mud, nearly independent of the distance to the source glacier, points to an excessively intensive deposition of fines in the ice-proximal setting. The reasons for such behaviour of meltwater suspension in the tidewater-glacier system are discussed elsewhere (Görlich in print). Fig. 5 summarizes the main concept of the cited paper, that the excessive intensity of suspension settling in the ice-proximal zone is caused by turbulence-coerced flocculation and simultaneous turbulent diffusion of suspended load to the still-water layer in the jet-zone of the meltwater plume.

The annual contribution from organic components in the surface water suspension is quantitatively negligible. However, qualitatively it is of great importance. The time lag between the organic blooms and maximum of clastic supply, invoked by Elverhøi et al. (1980) to explain formation of dark lamination in proximal mud, is well visible in Fig. 10b, c, d, f, and seems to be a source of ?annual sulphidic laminae. However, in the cores recovered in Hornsund within the laminated mud facies, the distribution of dark and light laminae is in some core segments very irregular (although in general complying with the estimated yearly accumulation rates). Some laminae are double, separated by cm-thick bright layers. Sedimentary features (erosional surfaces, textural grading) suggest occasional presence of intervening turbidites (Görlich 1986). The dark lamination is thus far from the varve-type regularity.

### *Applicability of suspension settling models*

According to the results of Kranck (1980), flocculated suspension would attain uniform concentration in a short interval of time independently of the initial concentration. If we adopted Kranck's (op. cit.) interpretation, we snould have expected different settling magnitudes in proximal zones, which would then be equalized in more distal settings. This seems to be the case in Hornsund.

If we further assumed validity of Kranck's empirical results (op. cit.), the ice-proximal situation would reflect the stage where the single-grain and floc settling co-occur. The power-law dependence (Fig. 11) and the very presence of micas' segregation also suggest that the elementary processes of suspension aggregation are at the stage of single-grain and immature floc settling in the proximal zone.

However, there are some meaningful discrepancies between the model and reality. Firstly, there is the fact that fine suspension apparently settles out of meltwater overflow near the glacier much more rapidly than at a distance (see Figs. 3, 5, and 8). The exponential curves of the sediment accumulation rate (Fig. 7) speak unequivocally for such an interpretation. Experiments (Kranck 1980) predict that during induction time of flocculation, i.e. at the single-grain settling stage, the sedimentation is slower than at the later floc-stage, and occurs at power-law rate. The exponential decay of sediment accumulation rate is in clear conflict with it. Moreover, if we consider the ?exponential retardation of the meltwater jet ('perforated conveyor belt'), the discrepancy with the experiment becomes still greater.

The presence of remnant suspension in slowly advecting surface water, persisting at concentrations above 50 mg/l for hours or days (Figs. 3 and 8) also contradicts the theory that this may be the stage of exponential (i.e. the fastest) loss of sediment from suspension. The actual rates of flocculation due to differences in single-grain settling velocities, and rates of subsequent settling through halocline, are much slower than predicted by the experiment. That is why we favour dynamic controls over suspension fall-out from the surface plume (turbulent diffusion to the still-water layer from the meltwater jet, cf. Görlich in print).

### *Conditions for benthic life*

Depletion of the innermost fjord basins of both biomass and number of species has been commonly reported (Gage 1972; Gulliksen et al. 1984). This is also clearly seen in our data.

Specific conditions prevail in the proximal pools bounded on tidewater glaciers. High rate of clastic sediment accumulation results in dilution of organic material in the bottom sediment. High surface water turbidity and long periods of fast ice cover within the proximal basins suppress primary production and result in low flux of organic matter to the bottom. Intense freshwater discharge results in water stratification with a strong stability maximum at 5–20 m water depth, restricting vertical exchange of energy and matter. It was shown by Sargent et al. (1983) that a very short pelagic food web is typical of Sub-Arctic fjords, hardly involving bottom sediment in energy and mass cycle.

The bottom sediment is oxic in its bulk (Eh between 75 and 200 mV), but locally with slightly anoxic conditions within the dark laminae (about 0 mV), and it contains on an average less than 2 wt.% of organic matter. Simultaneously, the proximal sediment is typified by a relatively high phosphorus content (about 0.07 wt.%) when related to the low organic matter content. For comparison, the sediments of the Baltic Sea with about 10% of organic matter contain 0.07–0.09 wt.% of P.

The release of phosphorus from the sediment in pools seems limited. It is marked by generally low content of phosphate ion in water (below 1 μmole/l). This concentration is slightly increased in spring. In June 1979, Urbański et al. (1980) recorded 4 μmole/l of phosphate ion in near bottom water in Isbjörnhamna, probably due to enhanced phosphorus recycling from the organic-rich lamina deposited during winter/spring and not yet buried by clastic material.

However, since the increased content of phosphate ion in near bottom water is accompanied by its equally high content in the surface water layer (Fig. 6 in Urbański et al. 1980), one may suspect that the discussed spring maxima of phosphate concentration are bound rather with surface runoff of thaw-water bringing abundant phosphates from the nearby bird rocks (*Plautus alle* colonies). If this were true, the bottom water maximum would suggest that the thaw water is included in the glacial meltwater, and that the latter forms both an overflow and an underflow in the bay. The lack of the phosphate maxima in summer suggests, in turn, that the summer/autumn meltwaters dilute the tundra phosphates to such an extent that their presence in the water mass of the bay becomes negligible.

Fast disappearance of the phosphate maxima in July suggests that the water mass of Isbjörnhamna (55 m deep) is mixed or exchanged. Such exchange in pools deeper than Isbjörnhamna is restricted. In Brepollen (up to 150 m deep), the T/S diagrams show throughout a year stagnant water with a temperature of −1.55°C, separated by sharp thermocline at a 100 m water depth from the overlying mixed (?exchanged) water (fide Urbański et al. 1980; Swerpel 1985).

The above values of phosphate concentration may be better understood when we look at the average values for the world ocean (below the photic zone) which range between 5 and 8 μmole $PO_4$/l (Horne 1969), or the values for the restricted basins of the temperate zone, e.g. the Bay of Finland in the Baltic Sea where the phosphate ion concentration reaches 45 μmole/l in spring, showing a minimum value of 3 μmole/l in June (Hällfors et al. 1981). The values for Antarctic Bottom Water are above 100 μmole/l (Horne 1969).

It is suggested here that the residence times of macronutrients are longer in the ice-proximal pools than in the central and outer fjord basins. The low concentrations of nutrients in water mass result from low input rather than high efficiency of biological sinks.

It was empirically found by Hallberg et al.

(1972) that phosphorus release requires anoxic bottom water, anoxic sediment, and high concentration of organic matter. Neither of these conditions are fulfilled in the Hornsund proximal subbasins. The process of phosphorus release is, however, not that of inorganic solution, but is microbially mediated (McConnell 1979; Suess 1981). The observed low level of phosphorus release allows us to infer that the conditions in the sediment (oxic to locally anoxic, pH between 7.5 and 6.7, low organic matter content) are apparently unfavourable for microbial activity. In their study of northern Norwegian Balsfjorden, Sargent et al. (1983) have found that molecular composition of most of the bottom sediment organic matter points to microorganisms as the main constituents. Hence, the absence of effects of microbial activity (low phosphorus release) would indirectly suggest very low overall content of digestible organic matter in the bottom sediment.

In general, the ice-proximal sediments provide poor conditions for supporting benthic life, by containing low levels of organic matter biologically available to sediment-ingesting organisms. The weak links in this food chain are: low level of primary production, dilution of scarce organic matter in the bottom sediment, and (possibly) low activity of bacteria.

We suggest that physical controls interrupt the food chain at the level of primary production in water and bacterial activity in surface bottom sediment. Hence, they are the main agents causing lack of higher organisms (micro- and macrobenthos) at the bottom of the proximal subbasins. Thus, we suggest that even by the lack of direct physical effect of sediment loading on bottom fauna, the benthic life would not develop abundantly here.

Considering the sediment itself, the observed low activity of benthic organisms in the ice-proximal sediment results, due to poor mixing of sediment by bioturbation, in (1) higher preservation potential of locally concentrated organic matter in the laminated mud facies, and (2) much better preservation of original sedimentary structures in this facies.

## Conclusions

We suggest that primary control over biological processes and over the sedimentary facies distribution is exerted by high surface water turbidity and extremely high fine clastic flux in the most proximal settings. Hence, the bipartite zonation of meltwater overflow (jet zone and slow-advection zone – Fig. 5) is reflected in the bottom sediment by occurrence of benthos-poor laminated mud deposited at a high rate, and benthos-rich homogeneous to bioturbated mud deposited at a much lower rate.

In the first instance, in proximal settings the physical agents result in scarcity of biologically useful energy and digestible organic matter in the sediment by lowering the flux of organic material to the bottom and by dilution of this scarce food supply by high inorganic accumulation. Fine texture of the rapidly accumulating bottom sediment is an additional factor impeding the matter exchange at sediment-water interface by screening the buried organic-rich layers.

The situation in the ice-proximal subbasins is of the negative feedback type, since the poor benthic life and, consequently, low bioturbation considerably diminish the recycled fraction of organic matter, and vice versa, the lack of food suppresses the development of benthic life.

The proximal laminated mud is laterally delimited from homogeneous to bioturbated mud facies by a zone where the above negative feedback mechanism ceases and is replaced by positive synergic action of a low sediment loading and low clastic dilution of organics, accompanied by enhanced turnover of organic matter due to abundant benthic life (see Table 1).

The picture presented of glacial-marine sedimentation of muds in Hornsund points to differences between suspension settling in the temperate to Sub-Arctic riverine estuaries and the tidewater-glacier environments. The vertical gradients of water salinity are unusually high in the ice-proximal settings, positively influencing the retardation of meltwater jet flow, suspension flocculation, and settling rates. The effect is the exceptionally intensive trapping of fine sediment near the ice cliff. This property of the tidewater-glacier sedimentary system affects not only local phenomena in fjords but also the sediment budget of the Arctic and Antarctic marine basins and should be considered when interpreting present day sediment patterns and paleorecord, e.g. of the North Atlantic cores, regarding controls over glacial/interglacial alternation of calcareous and siliceous (terrigenous) layers.

*Table 1.* Environmental factors affecting benthic biomass distribution in Hornsund. Data for 60–100 m water depth interval on soft bottom. Compiled from Görlich (1986), Swerpel (1985), Zalewski & Kowalewski (unpublished data), and this study. *Summer.

| Factor | Outer fjord | Central basin | Proximal subbasins |
|---|---|---|---|
| *Oxygen in bottom water | 70% | 80% | Up to 98% |
| *$PO_4$ concentration | 0.98 μmol/l | 0.68 μmol/l | 0.55 μmol/l |
| *$SiO_4$ concentration | 15.1 μmol/l | 15.4 μmol/l | 16.9 μmol/l |
| *$NO_2$ concentration | 0.15 μmol/l | 0.22 μmol/l | 0.13 μmol/l |
| Water salinity | 34.9–35‰ | 34.7–34.9‰ | 34.5–34.9‰ |
| Water temperature | −1.88 to +4°C | −1.88 to +3°C | −1.88 to −0.5°C |
| *Suspended matter in surface water | <15 mg/l | 15 to 20 mg/l | Tens to above 1500 mg/l |
| *Near bottom suspended matter | <15 mg/l | Occasionally high due to low-density turbidity currents | Occasionally high due to meltwater underflows |
| Average sediment accumulation rate | <0.1 cm/a | C. 1 cm/a | Up to 35 cm/a |
| pH distribution in the bottom sediment | | 7.2 at the surface decreasing to 6.7 at 3 m below surface | 7.1 at the surface increasing to 7.5 at 1 m below surface |
| Eh distribution in the bottom sediment | | C. 130 mV at the surface, then up to 200 mV | C. 190 mV at the surface, locally down to 0 mV. |
| Organic matter content | | Fluctuating between 2.5 and 4 wt.% | Less than 2 wt.% |
| Sediment type | IRD-rich homogeneous bioturbated | IRD-poor homogeneous bioturbated | Laminated mud with coarse intercalations |
| Sediment mass redeposition | Negligible | Low-density turbidity currents | Meltwater underflows, turbidity currents |
| Bioturbation | Strong | Strong | Negligible |

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