Annales Societatis Geologorum Poloniae (1988), vol. 58: 21 – 52
PL ISSN 0208-9068

MICAS AND TEXTURE OF THE RECENT MUDS IN SPITSBERGEN FJORDS: STUDY OF SUSPENSION SETTLING

Krzysztof Görlich

Institute of Geological Sciences, Polish Academy of Sciences, Senacka 3, 31-002 Kraków, Poland

Görlich, K., 1988. Micas and texture of the Recent muds in Spitsbergen fjords: study of suspension settling. *Ann. Soc. Geol. Polon.*, 58: 21 – 52.

Abstract: XRD, IR and chemical determinations of bulk mineral composition and clay mineralogy have been carried out along with textural analysis in glacial-marine muds of Hornsund and Wijdefjorden on Spitsbergen. Distribution of micas and texture of silt and clay fractions of bottom sediment were found to be sensitive indicators of environmental conditions of supply, dispersal and settling of suspension in the fjord. Quantitative analysis of two dioctahedral mica polytypes ($2M_1$ and 1Md) distinguishes clay-mineral provinces within bottom muds, reveals mineral segregation of clay suspension during transport, and allows one to name differences in suspension settling process among various zones of the tidewater-glacier basins. These zones are: (1) still-water, occasionally turbulent zone in contact with ice-cliff, (2) meltwater jet zone, (3) proximal zone beyond meltwater jet, (4) slow surface-advection zone, (5) bottom-current dominated distal zone, and (6) still-water ice-rafting dominated distal zone.

The results point to geologically important phenomena in the tidewater-glacier sedimentary system: (1) lithology of source substratum rocks on land is inherited by bottom sediment of the fjord, (2) selective settling of clays results in preferential deposition of muscovite in ice-proximal settings, the process being well expressed by a lateral change of $2M_1$-muscovite to 1Md-illite ratios, (3) flocculation strongly coerced by turbulence occurs along shear surface beneath meltwater jet; single grains and immature flocs are captured here within underlying still-water layer producing in the ice-proximal zone mineral sorting and exceptionally high accumulation rates of fine sediment, (4) flocculation of clays mainly due to differences in single-grain velocities takes place in the show-advection surface water layer; this process controls settling of suspension in the distal, slow-advection zone producing relatively low accumulation rates.

Key words: Spitsbergen, glacial-marine muds, illite, muscovite, texture.

Manuscript received May 1987, accepted June 1987

INTRODUCTION

This study aims at elucidating elementary processes occurring in suspension introduced to the fjords within overflow from the tidewater glaciers. The processes of interest are those responsible for (1) mineral fractionation of micas detected in bottom sediment along the meltwater-plume pathway, and (2) distribution of the fine-sediment textures over fjord bottom. In this paper we shall qualitatively discuss:

– dynamics of discharge jet,

– course of flocculation depending on composition of suspension and hydrodynamic conditions in surface water,

– mechanisms of loss of suspension from the advecting surficial water layer to the underlying still-water layer.

Unfortunately, detailed mineralogical study of suspension itself poses numerous problems which have not been overcome here, mainly due to small amounts of suspended material obtained from water samples. Hence, for the purpose of this investigation, the author resorted to analysis of bottom sediments. The bottom sediments are described texturally and their fine components characterized mineralogically and chemically. The mineral features of bottom sediment in turn, are referred to the supposed features of original suspension whose settling produced the bottom muds in question. Thus, the present study employs idea of applying detailed clay-mineralogical analysis of fine bottom sediments to trace processes occurring within suspension.

In fact, only clay fraction of the studied glacial-marine mud may be analysed in this regard, since within its coarse fraction the ice-rafted debris (IRD) contribution obscurs the picture of deposits which have resulted from suspension settling.

Additional limitative factor is geometry of a basin. In case of elongated fjords, with numerous side sources of sediment, no analysis of elementary settling processes can be carried out using bottom-sediment data, because the sediment is mixed (receiving material from different sources) and because no clear proximal/distal relations can be established. However, this study shows that the model elaborated for typical single-source basins proves useful in interpreting sedimentary record also in multiple-source basins. This holds true, e.g., for Wijdefjorden in north Spitsbergen. Hornsund, in turn, has generally single-source basins which are very suitable for studies on elementary processes of dispersal and undisturbed settling of non-blended suspension.

Previous work

In previous papers (Görlich, 1986; Görlich *et al.*, *in print*) it has been postulated that settling of clay suspension in the forefield of tidewater glacier is exceptionally intensive. This conclusion stems from the observation of an exponential seaward decay of fine-sediment accumulation rates, the surface-water turbidity distribution, and the extremely fine texture of proximal sediments. Significant mineral fractionation within clay-mineral assemblage of the proximal bottom muds has been noted. It primarily concerns separation of muscovite from illite. This differentiation was related to the special course of clay suspension settling in tidewater-glacier environment (Görlich, 1986; Görlich *et al.*, *in print*).

The enhanced (coerced) flocculation and selective gravitational settling of coarse clays (due to differences in single-grain velocities) have been invoked to account for these phenomena. The intensification of settling was thought to be correlated with vertical salinity gradients in the ice-proximal zone and broad grain-size spectra within clay fraction of suspension; the latter idea being based on the results of Bogen (1983) for suspension composition in glaciated areas. The interpretation of data obtained both from suspension and bottom--sediment studies was thought to fully comply with the theoretical and experimental findings of Kranck (1975, 1984, 1986).

It has been also suggested in our previous paper (Görlich *et al.*, *in print*) that the process of mineral segregation (preferantial settling) may be best represented by the plot of $2M_1$-muscovite/1Md-illite ratio versus total clay-mineral content in the bottom sediment samples (*cf.* Belzunce *et al.*, *in print*). The texture of source suspension was thought to be well finger-printed by the ratio of the fraction < 0.2 μm to the fraction 0.2–2 μm (called DR/PM, *cf.* Görlich, 1986). The latter indicator was also supposed to reflect the specific texture of

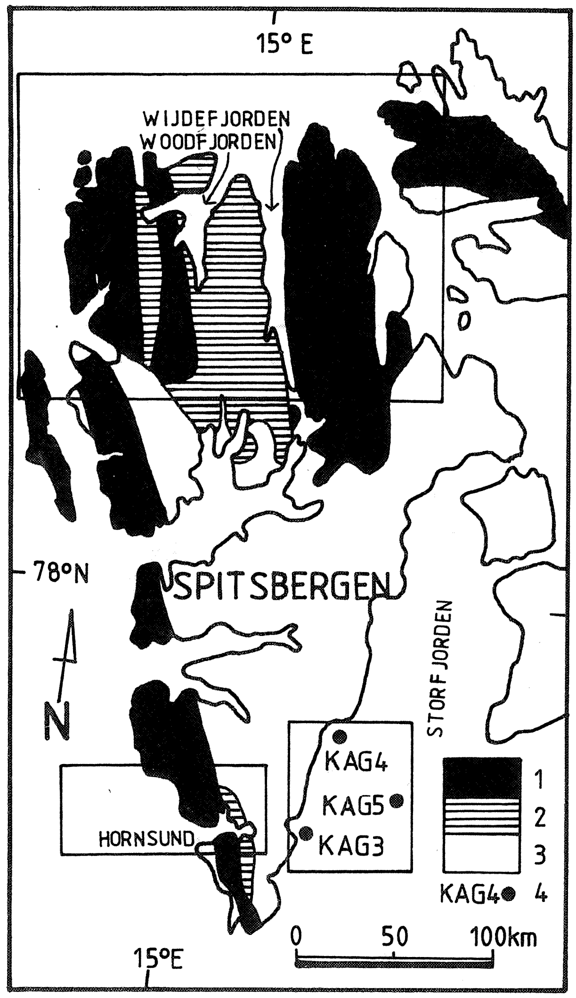

Fig. 1. Sketch map of Spitsbergen showing simplified geology and location of the study areas in Hornsund, Storfjorden and Wijdefjorden-Woodfjorden. The sampling stations in Storfjorden are indicated. *1* – Hecla Hoek Succession; *2* – Devonian strata; *3* – Cainozoic (on land); *4* – numbers and positions of the analysed samples from Storfjorden

the material originally derived from the substratum rocks of the glaciers source areas, i.e. to be a tool for describing direct inheritance of sedimentary material from the bedrock.

Further research, reported in the present paper, was carried out in Hornsund and Wijdefjorden on Spitsbergen (Fig. 1) and it modified both the previously adopted model of suspension settling and the possible use of textural and mineral indicators.

SETTING OF THE STUDY AREAS

The present study has been focused on Wijdefjorden on north Spitsbergen and on two basins of Hornsund fjord on south Spitsbergen, viz. Isbjörnhamna and Brepollen. Reference will also be made to the mineralogical and chemical results obtained for bottom sediment from other areas of south Spitsbergen.

Hornsund

The Hornsund fjord, further referred to as Hornsund, is the southernmost fjord of Spitsbergen (Fig. 2). The geological setting and bottom mud characteristics with some reference to suspension settling processes have been presented in detail in previous papers (Görlich, 1986; Görlich *et al.*, *in print*). Five mineral provinces have been distinguished within the bottom muds of Hornsund, basing on the relative domination of either of the major non-clay

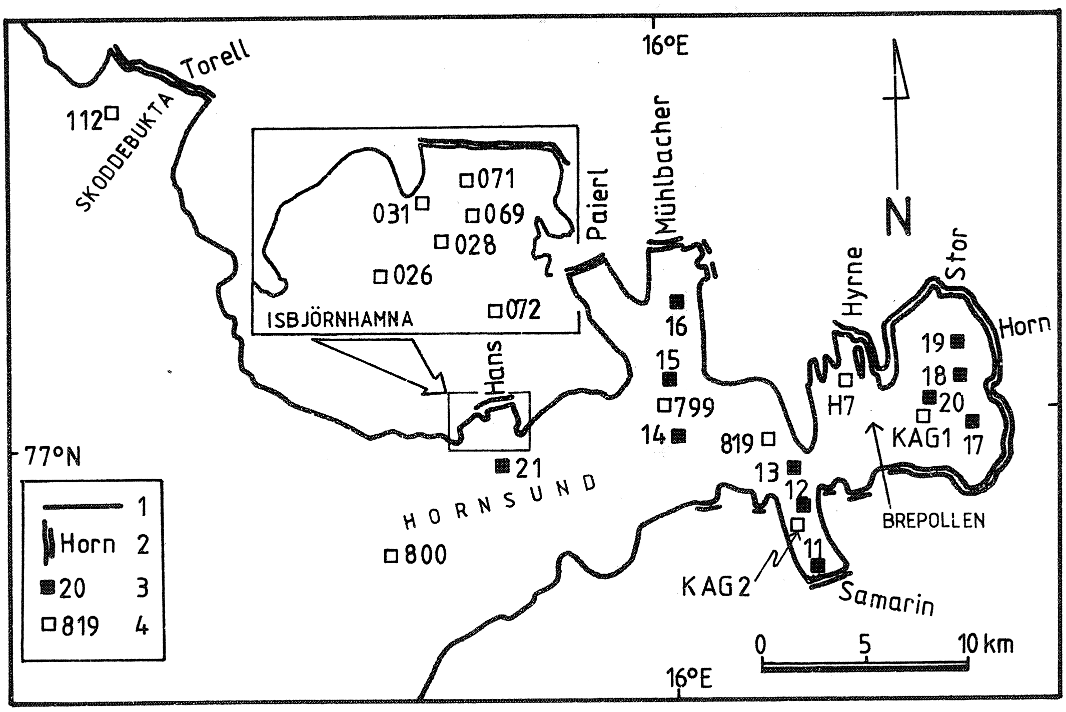

Fig. 2. Sketch map of Hornsund fjord, showing location of sampling stations which are referred to in the text. *1* — shoreline; *2* — tidewater-glacier fronts with abbreviated names for glaciers (the Norwegian ending-*breen* for glacier has been dropped for brevity); *3* — cores; *4* — grab samples; inset map shows enlarged Isbjörnhamna bay

minerals (quartz, feldspars, carbonates). These provinces may be readily matched with the dominant bedrock lithologies exposed in the individual drainage areas on land.

Two distinct clay-mineral provinces have been delineated within the bottom sediment of Hornsund (Görlich, 1986). The biotite-muscovite-rich province is associated with the Precambrian to Lower Palaeozoic source rocks and occurs, e.g., in Isbjörnhamna. The clay-grade illite dominated muds are associated with source areas built up of Upper Palaeozoic through Cainozoic rocks and occur, e.g., in Brepollen. These two basins of Hornsund, viz. Isbjörnhamna and Brepollen, will be treated here in greater detail because of the above differences in composition of mud facies.

The studied surficial muds of Hornsund contain between 70 and 97% of fraction < 60 μm. They represent two basic glaciomarine mud facies, viz. laminated muds and homogeneous to bioturbated muds (Görlich, 1986).

Wijdefjorden

Wijdefjorden in north central Spitsbergen is an inlet about 100 km long and on an average 10 km wide (Fig. 3). Its course is predisposed by major Devonian fault separating Precambrian metamorphic rocks (mainly gneisses,

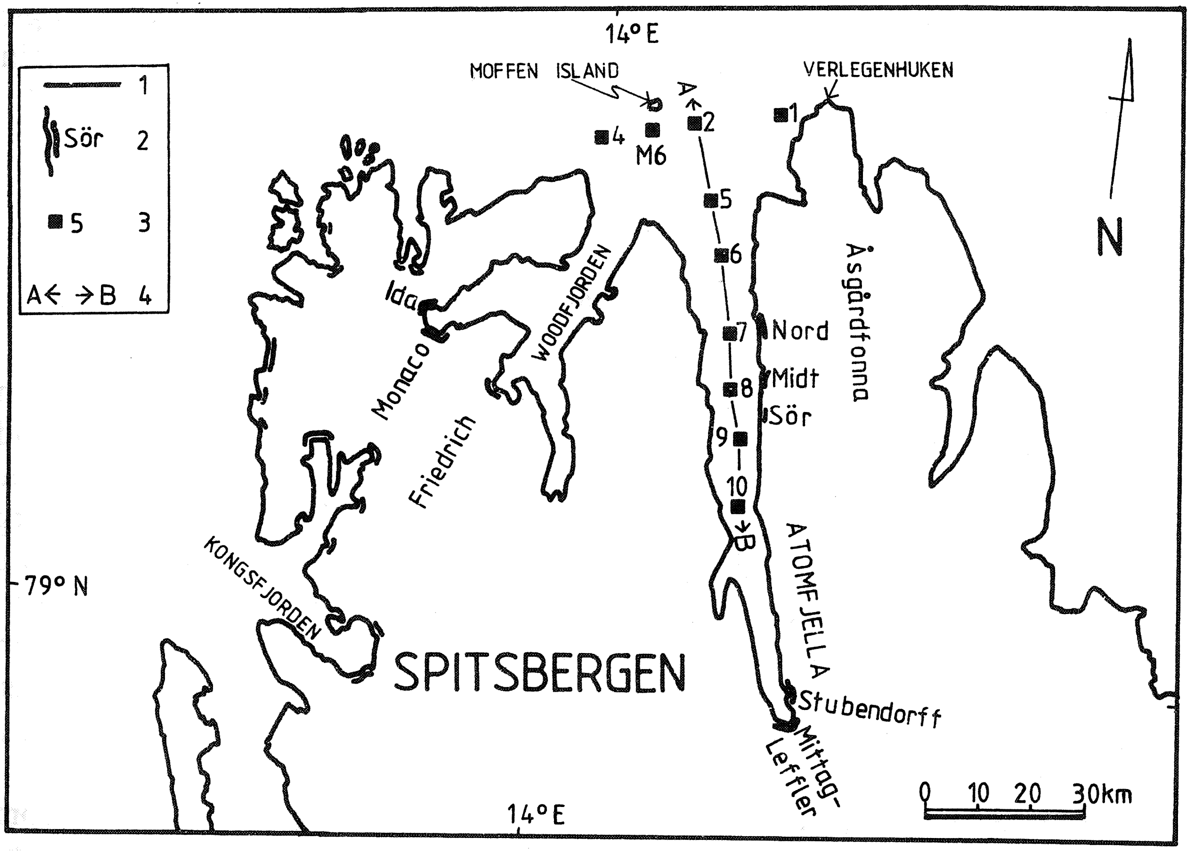

Fig. 3. Sketch map of northern Spitsbergen with sampling sites in the Wijdefjorden-Woodfjorden area. *1* — coastline; *2* — ice cliffs of the tidewater glaciers with their names (the Norwegian endings-*breen* for glacier are dropped for brevity); *3* — station numbers and positions; *4* — the line A—B connecting sampling stations represents a profile illustrated in Figs. 7 and 8

quartzites, and mica schists) of the Hecla Hoek Succession on the eastern coast, from Devonian molasse-type strata on the western coast. The latter deposits consist in the study area of red sandstones and shales of the Wood Bay Formation, mainly of continental origin (Birkenmajer, 1981). In the fjord head and within the catchment area of the main tidewater glacier here (Mittag-Lefflerbreen, Fig. 3) there crop out Carboniferous strata of the Billefjorden Trough. These are mainly red-bed/dolostone/evaporite sequences of the Ebbadalen Formation. Wijdefjorden bounds on five tidewater glaciers located at the fjord-head (Mittag-Lefflerbreen and Stubendorffbreen) and along northeastern coast (Sörbreen, Midtbreen, and Nordbreen). The freshwater contribution from these glaciers to the fjord is at present probably comparable to the fluvial and surface runoff. However, in more glaciated state of the area it must have been considerably greater, especially from the eastern shore, both from Åsgårdfonna and Atomfjella glaciers.

The studied surficial muds of Wijdefjorden are relatively fine, containing on an average 95% of fraction < 60 µm. They are all homogeneous to bioturbated, i.e. they represent more distal of the two basic glacial-marine mud facies distinguished by Görlich (1986). The sediment sampled at the bottoms of the Wijdefjorden cores is coarser.

We may note that Hornsund and Wijdefjorden represent opposite features as regards geometry of the basins and relation to the structural and stratigraphic units (Fig. 1). Hornsund intersects largely variable lithologic zones and major faults, whereas Wijdefjorden follows the course of the main geologic units.

MATERIALS AND METHODS

Sampling

The materials included grab samples collected during the Fifth Expedition to the Hornsund Station and during the cruises of m/s "Jantar" in 1984 and 1985 organized by Institute of Geophysics, Polish Academy of Sciences. The samples from the sediment cores were recovered with the modified Kullenberg piston corer during the II Geodynamic Expedition to Spitsbergen of Institute of Geophysics, Polish Academy of Sciences. The recovered cores were up to 3.5 m long, the corer penetration down to ca. 5 m. The core samples have been offered for this investigation by Dr. S. M. Zalewski, Institute of Geophysics, Polish Academy of Sciences. Positions of sampling sites are shown in Figs. 1, 2 and 3.

The samples selected for this study represent wide range of sediments, from massive diamicts (Dmm facies of Eyles *et al.*, 1983) to laminated and massive (homogeneous) often IRD-bearing muds encoded, respectively, Fl, Fld and Fm, Fmd (*op. cit.*).

Methods

For the purpose of this study fine fractions of sediment were separated using centrifuge after wet-sieving of the samples with the 2, 1, 0.25 mm, and 60 μm, mesh sieves. The following grain-size fractions were obtained: < 0.2 μm, 0.2–2 μm, 2–60 μm, 60 μm–0.25 mm, 0.25–2 mm, and > 2 mm. The dry-fraction weights were used to construct cumulative curves on the phi-probability scale and size frequency distribution (SFD) polygons. The latter are plotted on the log-phi scale and are obtained by approximating abundances of the fractions within the phi intervals: below 2, 2–4, 4–9, 9–12.5, and above 12.5 phi, with trapezoids and then plotting the trapezoid parallel sides on the logarithmic scale.

Prior to separation of clay fractions for preparing XRD mounts, the samples were subjected to chemical purifying using sodium acetate procedure of Jackson (1974).

X-ray powder diffraction of random mounts (Fig. 4) was used for semiquantitative determination of mineral composition of the bulk sediment

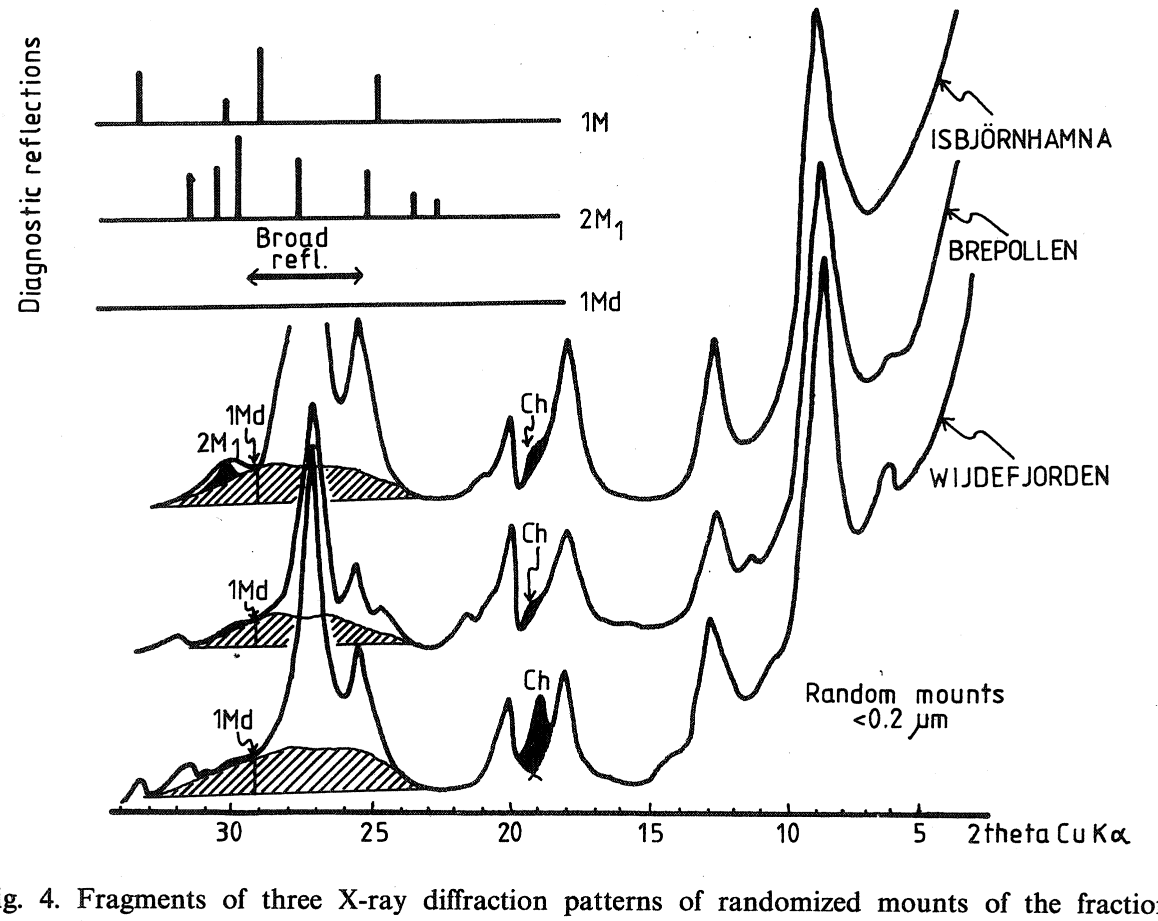

Fig. 4. Fragments of three X-ray diffraction patterns of randomized mounts of the fraction < 0.2 μm to show the clay-mineral composition and define analytical reflections used in the semiquantitative Środoń's method for evaluating percentages of the clay minerals. The symbols are: 1M, $2M_1$ – muscovite; 1Md (hatched reflection) – illite; Ch – chlorite. Other analytical reflections are not present in the pattern for the finest sample fraction. The bars above the X-ray patterns show distribution of reflections in the polytypes 1M, $2M_1$, and 1Md of dioctahedral micas

samples and their fractions according to the method elaborated by Środoń (1984), as well as for the determination of di- and trioctahedral clays (basing on the 060 and associated reflections) and of dioctahedral mica polytypes (basing on the reflections between 29 and 32 degrees 2-theta – Fig. 4). Oriented (sedimented) mounts of the fractions < 0.2 µm of the sediment samples were used for precise identification of clay minerals. In particular, glycolation was used to evaluate expandable clays contribution, 1n HCl treatment and heating at 600°C to distinguish chlorite from kaolinite. Dron-2.0 apparatus with Ni-filtered Cu-Kα radiation was used.

Fourier transform infrared spectroscopy was used to determine iron content in dioctahedral micas and identify their polytypes. The FTS-14 Digilab spectrophotometer with computer processing of spectra and standard Pye Unicam SP1200 spectrophotometer were applied. The measurements were carried out in KBr pellets in the range between 400 and 4000 cm^{-1}.

Chemical analyses included determination of basic elemental composition. The metals were analysed with AAS after heating the samples at 400°C and dissolving them in a mixture of sulphuric and fluoric acids and then in a mixture of nitric and hydrochloric acids. Thus prepared sediment was dissolved in hydrochloric acid. Silica content was determined by melting of 1 g of a sample with Na_2CO_3 and dissolving in hydrochloric acid. The sediment was precipitated with 1:1 hydrochloric acid and after washing and heating at 1000°C, silica was determined by weighing the precipitate. The phosphorus content was determined colorimetrically using the molybdate method. Loss on heating was determined at 550°C. The chemical analyses have been done in Geological Institute, laboratories in Sopot.

RESULTS

XRD data

Table 1 shows the mineralogical results obtained for the bulk samples and averaged over the arbitrarily selected subbasins of Hornsund, Skoddebukta (western coast of Spitsbergen) and Storfjorden (eastern coast of south Spitsbergen) (Fig. 1). These results, discussed in detail elsewhere (Görlich, 1986), reveal existence of mineralogical provinces which may be distinguished within bottom sediment basing on either non-clay or clay-mineral composition.

The XRD analysis was focused on the fine fraction of the bottom sediment. The results gathered in Tables 2 to 4 indicate that the finest clay fraction (< 0.2 µm) is enriched in illite on the expense of muscovite which concentrates in the coarser clay fraction.

These data suggest that the individual clays reveal characteristic modal grain sizes. Basing on the results from Tables 2 and 4 these modal sizes can be ordered as follows:

$$M > K > Ch > B > I,$$

Table 1

Averaged mineral composition of bulk surface-sediment samples for the basins of Hornsund and south Spitsbergen coastal area (in %)

Basin	Q*	M	I	B	Ch	K	S	C	D	Fsp.	di-/tri-micas	M/I
Brepollen	39	8	24	7	3	6	5	1	1	10	4.6	0.33
Adriabukta	39	8	18	5	2	3	3	6	3	13	5.2	0.44
Samarinvågen	28	9	25	8	5	2	3	14	2	4	5.3	0.36
Burgerbukta	26	22	7	13	7	–	2	11	7	5	2.2	3.14
Isbjörnhamna	28	18	8	16	11	2	4	4	2	7	1.6	2.25
Outer Isbjörn.	28	9	18	10	5	–	5	10	5	10	2.7	0.50
Skoddebukta	25	9	11	12	10	9	3	3	14	4	1.7	0.82
Storfjorden	40	7	23	5	4	–	6	1	1	15	6.0	0.30

*Mineral symbols denote as follows: Q – quartz, M – muscovite, I – illite, B – biotite, Ch – chlorite, K – kaolinite, S – siderite, C – calcite, D – dolomite, Fsp. – feldspars. Outer Isbjörn. = outer part of Isbjörnhamna. Numbers of semi-quantitatively analysed samples for individual basins fall between 1 (Skoddebukta) and 6 (Isbjörnhamna). Data according to Środoń's method of quantitative XRD analysis

Table 2

Clays in the fractions of the top (2) and bottom (1) samples from the core 1 near Verlegenhuken, Wijdefjorden area (in %)

Sample fraction	Sample 1(2); fr. < 60 μm = 94%					Sample 1(1); fr. < 60 μm = 62%				
	M*	I	B	Ch	K	M	I	B	Ch	K
2–60 μm	14	11	15	1	6	16	5	15	1	6
0.2–2 μm	23	14	26	2	7	13	33	21	2	?17
< 0.2 μm	14	47	35	2	?	9	50	28	1	?10

* Mineral symbols as in Table 1. Data for katolinite are uncertain

Table 3

Mineral composition of clay fraction (< 2 μm) of surface-sediment samples from Hornsund and Wijdefjorden areas (in %)

Basin	Sample	Q*	Carb.	Fsp.	M	I	B	Ch	K	di-/tri-micas	M/I
Brepollen	KAGI	24	4	6	13	33	6	3	11	7.7	0.39
Adriabukta	819	15	5	5	19	37	7	6	6	8.0	0.51
Outer Hornsund	800	20	13	5	24	32	3	3	–	18.7	0.75
Wijdefjorden	5(7)	10	–	2	10	32	38	5	–	1.1	0.31
Woodfjorden	4(5)	9	–	3	11	24	43	2	3	0.8	0.46
Verlegenhuken	1(2)	9	–	4	23	13	27	2	–	0.8	1.77

* Mineral symbols as in Table 1; Carb. – carbonates, Woodfjorden and Verlegenhuken samples represent inner shelf stations (see Fig. 3). Data from Środoń's XRD method

Table 4

Mineral composition of the fraction < 0.2 μm of the samples from Hornsund and Wijdefjorden areas (in %)

Basin	Sample	Q*	Carb.	Fsp.	*M*	I	*B*	Ch	di-/tri-micas	M/I
Brepollen	19(30)	0	0	0	7	75	1	3	10	0.10
Outer Isbjörn.	21(36)	0	0	0	11	68	15	2	5.1	0.16
Wijdefjorden	5(7)	0	0	0	7	47	27	2	2.0	0.15
Wijdefjorden	9(13)	0	0	0	2	62	18	9	3.5	0.04
Wijdefjorden	9(14)	0	0	0	12	50	26	5	2.4	0.25
Wijdefjorden	10(15)	0	0	0	4	60	29	5	2.2	0.07
Wijdefjorden	10(16)	0	0	0	12	48	23	3	2.6	0.25
Woodfjorden	4(5)	0	0	0	4	72	12	5	6.3	0.05
Verlegenhuken	1(2)	0	0	0	14	47	35	2	1.8	0.31
Verlegenhuken	1(1)	0	0	0	9	50	28	1	2.1	0.18

* Mineral symbols as in Table 1; Carb. – carbonates; *M* and *B* denote here dioctahedral $2M_1$ and trioctahedral varieties of illite, respectively, rather than muscovite and biotite. Data according to Środoń's XRD method. Woodfjorden and Verlegenhuken samples represent inner shelf stations (see Fig. 3)

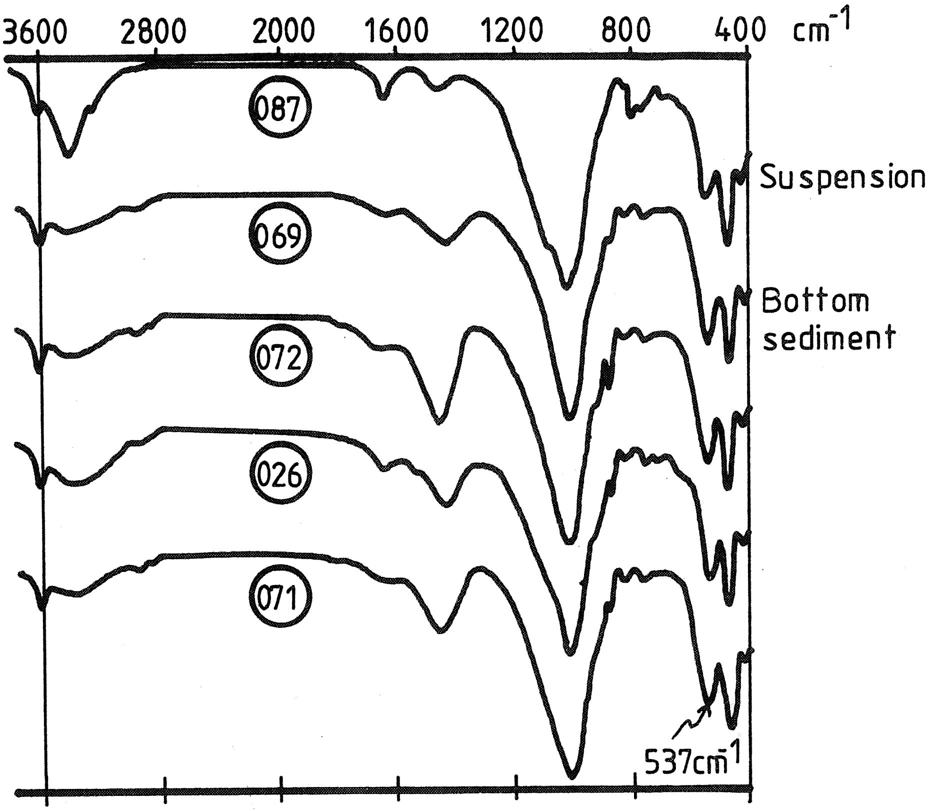

Fig. 5. IR spectra in the range between 400 and 3600 cm^{-1} of the bottom sediment samples (untreated grain fraction < 0.2 μm) and of one suspension sample (top spectrum, sample 087) from Isbjörnhamna area. The band between 530 and 540 cm^{-1} is indicated. This band is used to evaluate (Fe+Mg) content in illite according to the dependence determined by Stubican and Roy (*fide* Görlich, 1986). The position of the band between 535 and 537 cm^{-1} suggests (Fe+Mg) of about 0.10 per $0_{10}OH_2$ in the pictured illites

(symbols as in Table 1). It should be stressed that denotion biotite for the finest fraction be understood according to definition of Środoń & Eberl (1984) as trioctahedral illite rather than mineral biotite.

The XRD patterns of the < 0.2 μm fraction show that its mineral composition is fairly similar for different locations (Fig. 4) and is dominated by illite. From the infrared spectra in Figs. 5 and 6, one may observe that within the individual subbasins (in this case Isbjörnhamna) the mineralogy of the finest fraction is extremely stable. However, in Isbjörnhamna the < 0.2 μm fraction is composed of low-(Fe + Mg) illite and not of iron-rich variety as in Brepollen (Görlich, 1986). This is contraty to what was inferred previously, where it was assumed that the finest fraction (< 0.2 μm) of bottom sediments in Hornsund is uniformly dominated by the high-(Fe + Mg) mica independently of the location with respect to the distinguished mineral provinces (*cf.* Görlich, 1986). The present study revealed that the finest fraction may be also

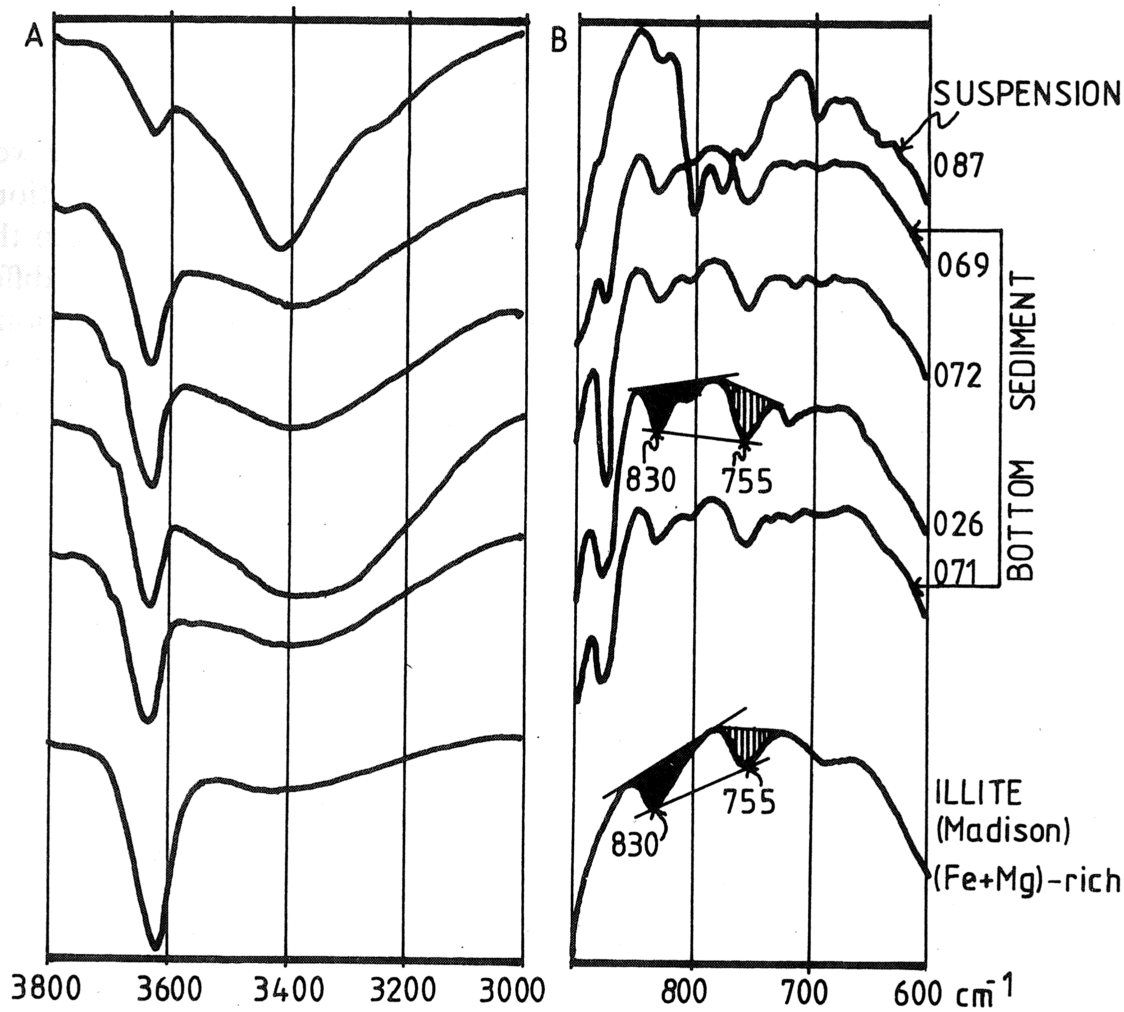

Fig. 6. Enlarged fragments of IR spectra of the fraction < 0.2 μm of the samples in the range 3000 to 3800 cm^{-1} (*A*) and 600 to 900 cm^{-1} (*B*) set against the same fragments of the spectrum obtained for illite standard (bottom spectrum); shaded are bands used to evaluate (Fe + Mg) — the obtained (Fe + Mg) content is the same as obtained using the band about 535 cm^{-1} in Fig. 5.

enriched in the trioctahedral mica (see Wijdefjorden and Verlegenhuken samples in Table 4). The finest fraction may be thus interpreted as illite although its precise crystallochemical nature may vary between more and less dioctahedral as well as between pure 1Md polytype and 1Md admixed with $2M_1$ polytype.

It may thus be seen that both the discussed clay fractions preserve certain compositional integrity within mineral provinces of the fjord's bottom which enables one to draw difference between e.g. samples from Brepollen, Isbjörnhamna and Wijdefjorden, basing solely on the mineral composition of the finest fraction.

The finger-printing compositions of single-source clay-mineral assemblages reveal within single-source basins secondary lateral trends related to the very mechanism of suspension settling. In Isbjörnhamna, for instance, there is a seaward separation of muscovite from illite. This trend has been discussed in Görlich (1986) and Görlich *et al.* (*in print*) and will be interpreted further on in this paper.

Chemical data

The regional differences in mineral composition of fine sediments are well illustrated by the chemical composition of bulk muds and their fractions averaged over the selected subbasins of south Spitsbergen (Table 5). From the table, it may be seen that indeed the sediments of individual subbasins differ chemically (and hence mineralogically) within the same grain-size fractions. For instance, clay minerals of Isbjörnhamna contain on an average more aluminum and potassium but less iron than the Brepollen clays. It complies

Table 5

Average elemental composition of bottom sediment samples in the basins of south Spitsbergen for bulk samples and their fractions < 0.2 μm and 0.2–2 μm (data in wt. %)

Basin	Fraction (μm)	Loss at 550°C	Si	Al	K	Na	Ca	Mg	Fe	Mn	P
Adriabukta	bulk	2.7	28.3	7.9	2.5	1.5	1.2	0.9	4.1	0.027	0.072
Brepollen	bulk	–	–	8.3	2.9	1.7	0.8	1.0	4.0	0.026	–
	0.2–2	–	22.7	11.3	4.0	0.9	0.5	1.2	5.7	0.020	–
	< 0.2	–	–	13.9	5.3	1.9	0.7	1.2	5.4	0.017	–
Isbjörnhamna	bulk	–	26.8	9.3	3.4	1.7	3.3	1.3	4.2	0.026	–
	0.2–2	–	19.8	13.5	5.1	2.1	1.7	1.1	3.9	0.020	–
Outer Isbjörn.	bulk	2.8	26.3	7.7	2.6	1.5	3.1	1.2	3.8	0.026	0.072
	0.2–2	–	22.0	12.2	4.6	1.0	0.7	1.2	5.3	0.018	–
	< 0.2	–	–	11.7	4.7	1.1	0.9	1.4	5.9	0.018	–
Outer Hornsund	bulk	–	26.6	8.5	3.0	1.8	2.8	1.3	4.2	0.033	–
Storfjorden	bulk	–	27.7	6.9	2.4	1.8	1.7	1.1	4.0	0.097	–

Analysed in Geological Institute, Sopot

with the previous finding (Görlich, 1986) that the Isbjörnhamna clays are more muscovitic than the Brepollen ones. The latter are dominated by (Fe + Mg)-rich illites.

Tables 6 and 7 show vertical variability of chemical composition for core 13 from Adriabukta bay and for core 21 recovered from the seaward side of a sill which confines Isbjörnhamna bay (Fig. 2). Chemical composition of sediment cores reveals differences in compositional stability of sediment column in different settings. The core 13 spans *ca.* 400–600 years, whereas the core 21 was deposited at higher accumulation rate (above 1 cm/a) and represents some 200 years of deposition. Clearly, more distal core 13 reveals more stable conditions of sedimentation than core 21. Both cores differ chemically between

Table 6

Chemical composition of the bulk samples from the core Jantar-13 of the Recent muds of Adriabukta bay in Hornsund (in wt. %)

Depth interval (cm)	Loss at 550°C	Si	Al	Ca	Mg	Fe	Mn	K	P
26–30	3.89	28.4	7.9	1.43	1.01	4.1	0.027	2.6	0.073
43–47	2.68	29.2	7.9	1.07	0.95	3.9	0.027	2.4	0.065
63–68	3.26	28.6	7.9	1.20	0.97	4.2	0.027	2.5	0.069
90–95	2.41	28.5	7.9	1.16	0.94	4.1	0.026	2.7	0.080
130–135	3.02	28.3	7.8	1.16	1.02	4.0	0.028	2.6	0.072
165–170	2.36	28.5	8.0	1.17	0.98	4.2	0.029	2.6	0.074
193–198	2.52	28.8	7.5	1.14	0.96	3.9	0.026	2.3	0.066
240–245	1.87	25.3	7.3	1.12	0.94	4.1	0.029	2.4	0.072
268–272	2.92	28.0	8.5	1.23	1.03	4.2	0.026	2.7	0.072
280–284	2.17	29.0	7.8	1.08	0.94	3.9	0.026	2.4	0.076

Analysed in Geological Institute, Sopot

Table 7

Chemical composition of the bulk samples from the core Jantar-21 of the Recent muds from outer Isbjörnhamna in Hornsund (in wt. %)

Depth interval (cm)	Loss at 550°C	Si	Al	Ca	Mg	Fe	Mn	K	P
20–25	1.22	27.6	8.0	2.8	1.3	3.8	0.026	2.4	0.067
46–52	2.79	28.6	7.1	3.0	1.2	3.7	0.026	2.2	0.068
65–70	2.16	26.6	8.5	3.8	1.3	3.6	0.026	2.6	0.074
100–105	2.90	25.0	8.1	2.1	1.2	3.8	0.025	2.7	0.068
125–128	3.12	26.9	7.1	1.5	1.1	4.0	0.025	2.8	0.076
155–160	3.35	24.5	7.5	5.1	1.2	3.7	0.028	2.7	0.079
182–187	4.04	24.9	–	–	–	–	–	–	0.069

Analysed in Geological Institute, Sopot

each other. In general, core 13 is more alumo-silicate, whereas the core 21 more calcareous, which is in accord with the distinguished mineralogical provinces in the bottom of Hornsund.

Textural trends

Textural analyses were carried out in order to obtain an independent check on the dependence between sample position relative the meltwater source and compositional variability of fine sediment.

The bottom sediment along axial profile in Wijdefjorden (Figs. 3, 7, and 8) shows certain textural tendencies, whereas the Hornsund muds show no such general trends (*cf.* Görlich, 1986, table 4).

The axial profiles in Figs. 7 and 8 ilustrate longitudinal distribution of arbitrarily chosen grain-size fractions in Wijdefjorden. The fractions are

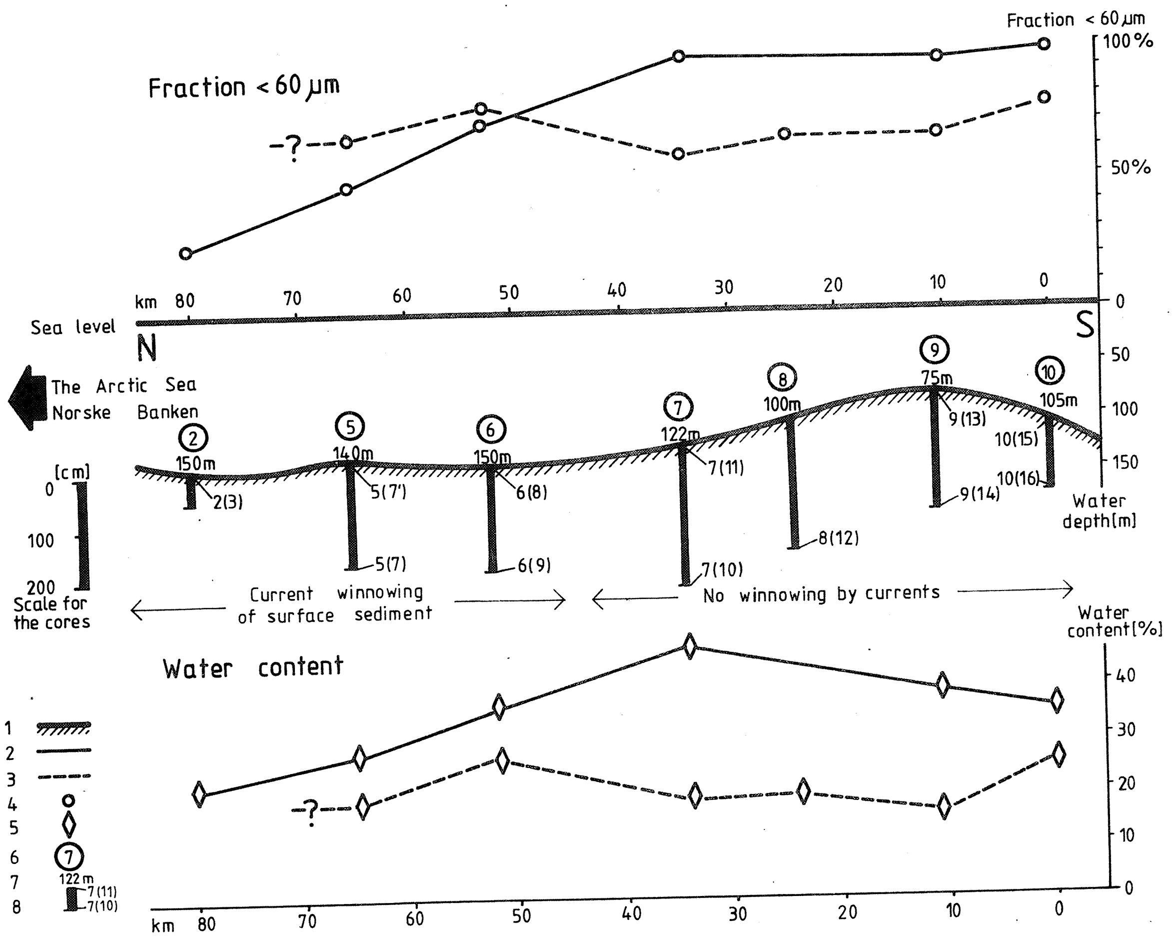

Fig. 7. Schematic cross-section of Wijdefjorden along the profile indicated in Fig. 3 with positions and lengths of the cores as well as sample numbers. Above and beneath the profile plots of the data for the surficial (grab) and core-bottom samples are shown. The upper profile change in the content of the fraction < 60 µm, the bottom one the change in water content. *1* — sea bottom; *2* — plots for the surficial samples; *3* — plots for the core-bottom samples; *4* — fraction < 60 µm; *5* — water content; *6* — core numbers; *7* — water depth in sampling site; *8* — sample numbers located on the core

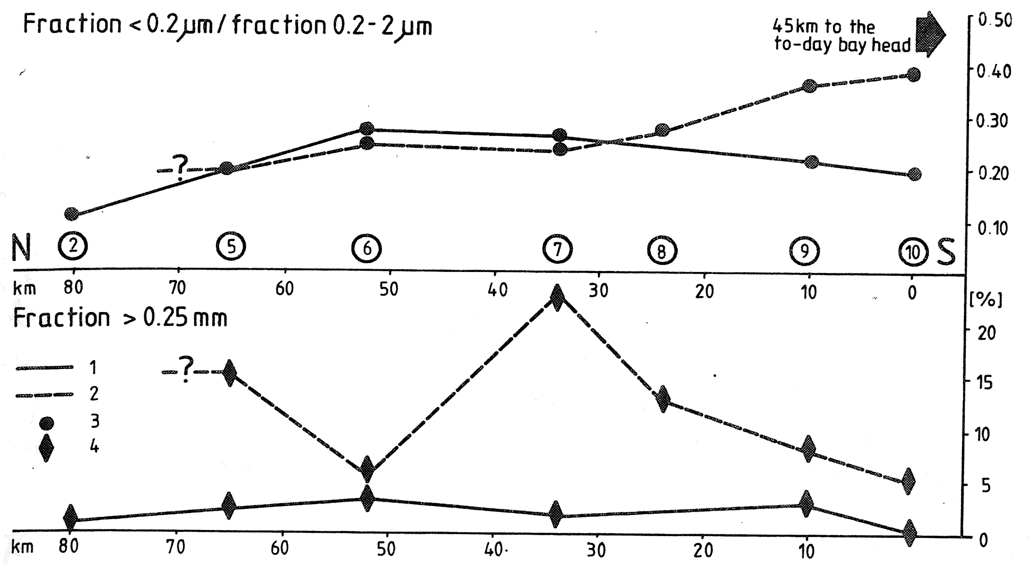

Fig. 8. Textural indices for the surficial (grab) and core-bottom samples at the sampling sites in Wijdefjorden shown in Fig. 7. The upper plot shows lateral changes of the ratio of < 0.2 µm fraction to 0.2 – 2 µm fraction (denoted DR/PM ratio, *cf.* Görlich, 1986), and the bottom plot shows the content of > 0.25 mm fraction interpreted as IRD component in the muds. *1* — plot for surficial samples; *2* — plot for core-bottom samples; *3* — DR/PM ratio; *4* — 0.25 mm fraction

selected to describe pelitic fraction and IRD contribution. The constant and low content of silt fraction in the core-bottom samples, generally low water content, and the conspicuous but variable IRD fraction > 0.25 mm, suggest that the corer reached a diamict facies probably of a meltout type, only in part resulting from settling of the overflow suspension. Cumulative curves in Figure 9A substantiate this opinion. Curves for Hornsund proximal sediments in Figure 9B reveal features close to those of core-bottom samples from Wijdefjorden. However, this similarity reveals some fine differences when presented as size frequency distribution plots, what will be discussed later.

The surficial sediments of Wijdefjorden represent glaciomarine mud of a more distal aspect. The axial change of pelitic fraction (< 60 µm) in the surficial samples suggests winnowing processes occurring in the outer axial part of Wijdefjorden. The seaward sequence of surficial muds from this fjord (Fig. 10A) manifests transition from fine muds (samples: 10(15), 9(13), and 7(11)) to well-sorted fine sands (samples: 6(8), 5(7'), 2(2'), and 6M). The central-fjord Wijdefjorden muds (cores 1, 7, 9, and 10 in Fig. 10A) are close to the finest homogeneous muds of Brepollen in Hornsund (cores 18, 19, and 20 in Fig. 10B).

The fine-fraction ratio (denoted here as DR/PM after Görlich, 1986) is calculated as a ratio of fraction < 0.2 µm to fraction 0.2 – 2 µm, indicated in Figs. 11B with the hatched fields (*a*) and (*b*), respectively. The DR/PM changes for the core-bottom samples of Wijdefjorden from *c.* 0.20 to 0.40 (Fig. 8). DR/PM in Hornsund shows much greater variability from average 0.03 in

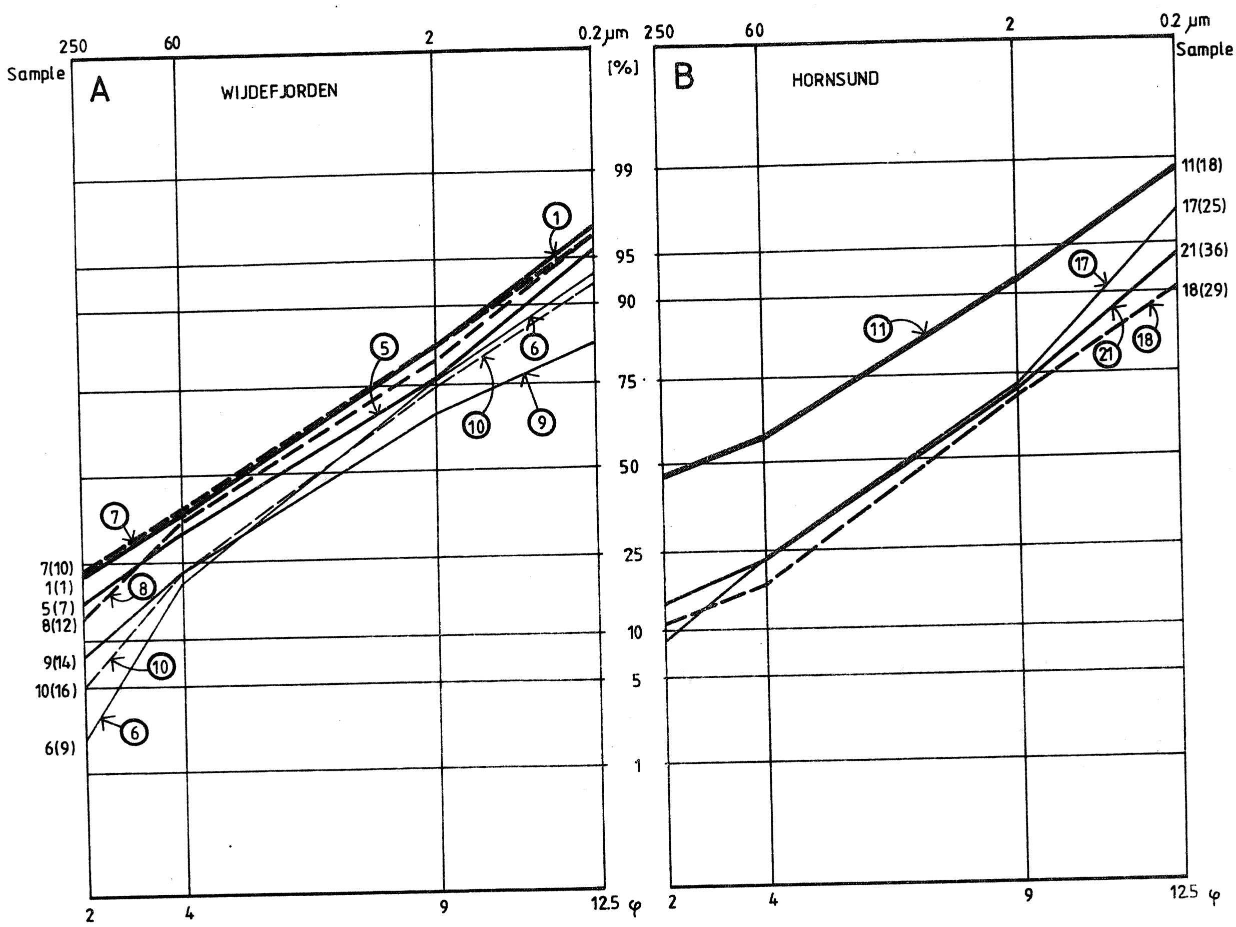

Fig. 9. Cumulative grain-size distributions plotted on probability scale for the pelitic fraction of the core-bottom samples from Wijdefjorden (*A*) and of proximal muds from Hornsund (*B*); the curves for each sample are plotted with different lines and the numbers in circles indicate core numbers (sample numbers are along the sides of the graph)

Isbjörnhamna to average 0.74 in Brepollen (*cf.* Görlich, 1986, table 4), with intermediate values between 0.30 and 0.40 for the central part of the fjord.

The size frequency distribution (SFD) polygons have been constructed for the selected Wijdefjorden and Hornsund samples (Figs. 11 and 12). These distributions are here the basis for distinguishing between textural varieties of bottom sediments and for refinement of previous model (Görlich, 1986) of tidewater-glacier sedimentation.

The following SFD patterns may be distinguished within the illustrated samples:

(1) polymodal distribution with main modes in silt and coarse sand to gravel, found in proximal settings (e.g. 11(18) and 7(10) in Figs. 9A, B, and 12B),

(2) bimodal distribution with modes within clay and silt to fine sand (e.g. 18(27), 17(26), and 12(20) in Figs. 10B, 12A, B, and 5(7) in Figs. 9A, 11B),

(3) broad unimodal distribution, truncated at coarse tail and having a silt mode (e.g. 18(28) and 17(25) in Figs. 10B and 12A),

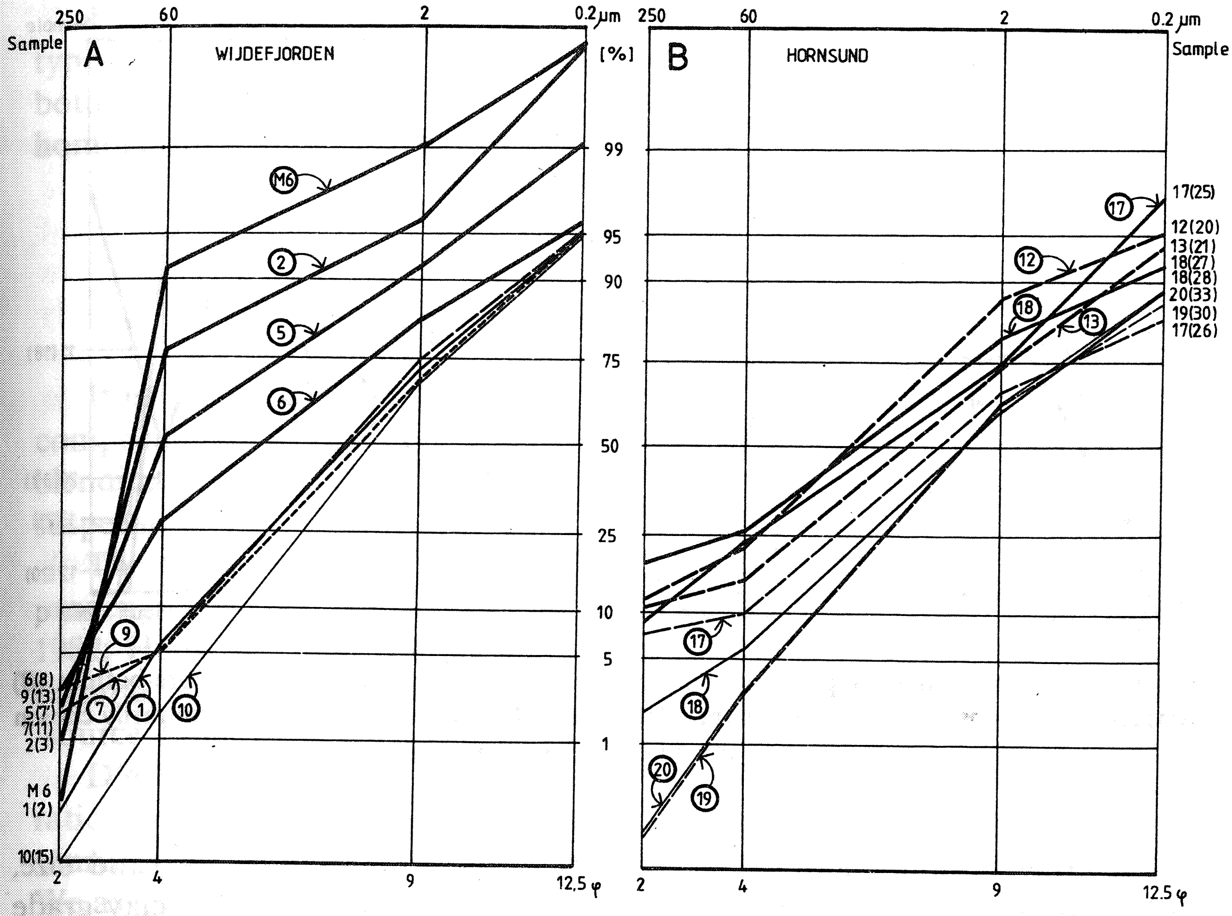

Fig. 10. Cumulative grain-size distributions plotted on probability scale for the surficial samples from Wijdefjorden (*A*) and proximal to distal muds from Hornsund (*B*); other explanations as to Fig. 9

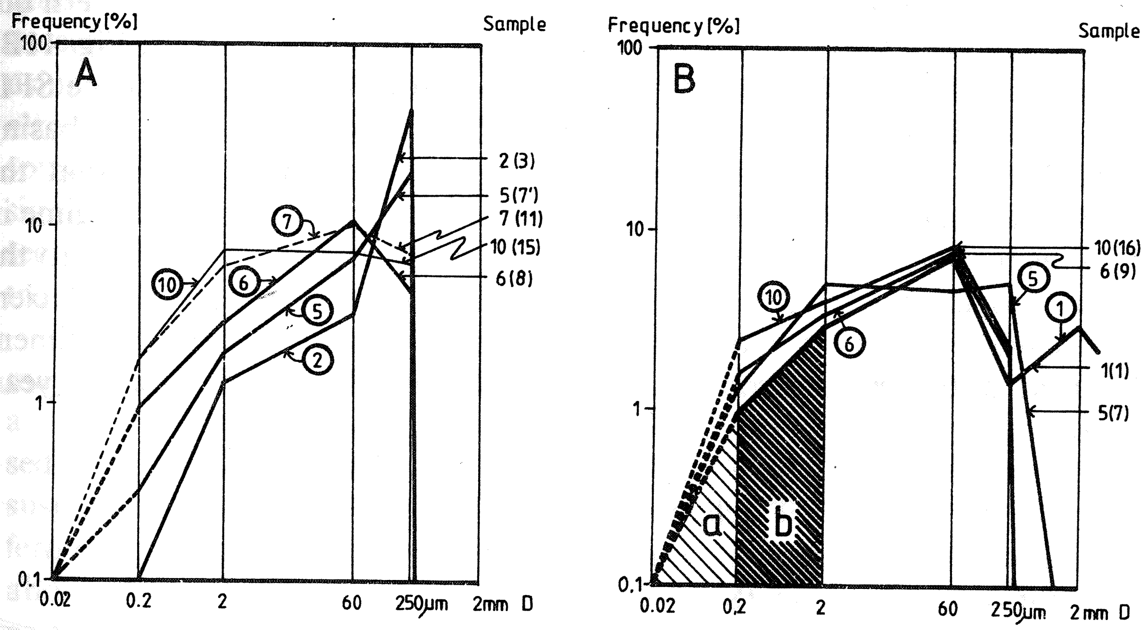

Fig. 11. Grain-size frequency polygons on log-phi scale for the surficial (*A*) and core-bottom (*B*) samples from Wijdefjorden *a* – fraction < 0.2 μm; *b* – fraction 0.2–2 μm; in circles are core numbers; dotted lines are used to extrapolate the plots beyond 0.2 μm to the arbitrarily chosen point 0.02 μm

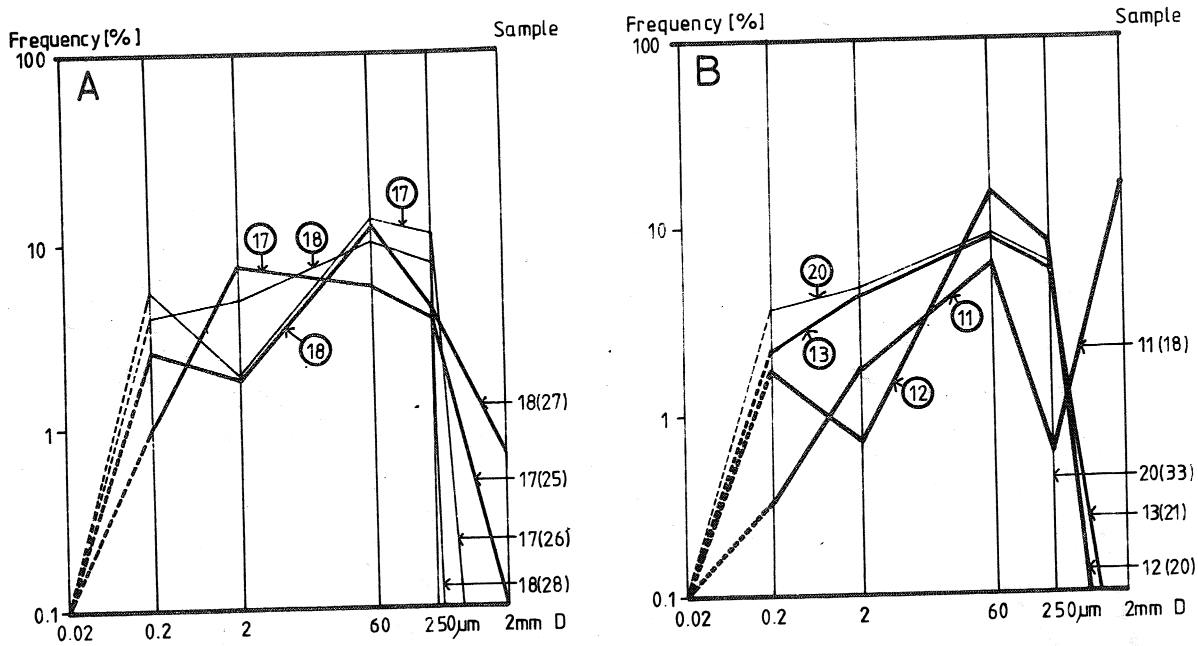

Fig. 12. Grain-size frequency polygons on log-phi scale for the surficial (*A*) and core-bottom (*B*) samples from Hornsund; dotted line extrapolates the SFD beyond 0.2 μm to the arbitrarily chosen point 0.02 μm; in circles are core numbers

(4) broad unimodal to bimodal distribution, truncated at fine-sand size, with mode within silt fraction and possible secondary mode within clay grade (e.g. 20(33) in Figs. 10B, 12B, and 10(16), 6(9) in Figs. 9A, 11B),

(5) well sorted distribution, truncated at fine sand size with conspicuous silt mode (e.g. 5(7'), 2(3) in Figs. 10A, 11A),

(6) bimodal to polymodal distribution resembling the first SFD pattern but found in samples from quite different (ice-distal) settings (e.g. 1(1) in Fig. 11B).

It may be supposed (what was not determined in this study) that the SFD will change rapidly in the sediment column. This may be suggested here basing on the lateral SFD variability in the surficial muds which shows that the fine-sediment texture is very sensible to the dominant active dynamic regime in surface water layer. Since the abrupt changes of this regime are inherent to the system of oscillatory retreating tidewater glaciers (or even to tidewater glaciers as such), one may expect that certain SFD types will alternate within sediment column at distances corresponding to time spans much shorter than a year. This primarily concerns the above SFD types (2) to (4).

In general, we deal here with the following sediment facies:

- ice-cliff meltout till (characterized here by SFD type 1),
- laminated fine sand to mud (SFD types 2 and 3),
- homogeneous mud (SFD type 4),
- sorted mud to sand (SFD type 5),
- IRD-bearing homogeneous mud (SFD type 6).

It must be stressed that the relation between the sediment facies and textural characteristics are only dominant ones and not inversely corresponding.

From the point of view of this study it is noteworthy that there are two types of SFD's (2 and 3) encountered within laminated mud facies and that both these types differ from the SFD (type 4) interpreted as typical of homogeneous mud facies.

DISCUSSION

Provenance and inheritance

It is important for this study to have a clear picture of what part of lateral compositional variability is due to provenance/inheritance and sediment blending factors and what part of it stems from differentiation of single-source suspension.

The use of clay-mineral assemblages to delineate sediments of different provenance (as applied e.g. by Molnia & Hein, 1982; Syvitski & Macdonald, 1982; Hume & Nelson, 1986; and numerous others) is supplemented here by textural and mineral indices. This is done to unequivocally identify single--source basins.

DR/PM ratio proves useful to show the blended nature of sediment. The ratio seems to be more sensitive to different compositions and textures of source suspensions than to gravitational sorting during transport (comp. Fig. 8). We assume here that in the studied Spitsbergen basins, averaged and equalized ratios about 0.30 suggest sediment blending. Blended composition of mud may be seen using this index in the outer axial part of Wijdefjorden and central trough of Hornsund (Fig. 8 and previous section). On the contrary, DR/PM ratios in bottom sediment, distinctly different from the average, may be successfully related to specific lithology of source rocks on land. By this virtue, using DR/PM we may judge not only of the texture of source suspension but also about the extent of fjord-bottom domain receiving material from a given source. The latter procedure is possible only if source-bedrock lithologies differ significantly for individual subbasins as is the case in Hornsund (see Fig. 1 and section Setting). Single-source domains usually include only ice-proximal trough (e.g. Isbjörnhamna and Brepollen).

When applying DR/PM to the sediments of inferred blended character, one may try to interpret this ratio in sediment column (e.g. cores 9 and 10 in Fig. 8) as reflecting the change of dominant sediment source due to change of sedimentation pattern. For the cited Wijdefjorden cores for instance, one may suspect a change from a sediment derived mainly from the Devonian-Carboniferous rocks in the fjord head and along western shore (values of DR/PM about 0.40) to the sediment of mixed prevenance with contribution from eastern-coast Hecla Hoek rocks. Such change implies more ice-proximal settling of the core-bottom sediment, since according to the above reasoning, only such position would have secured that lateral sediment blending was not strong enough to completely override features inherited from bay-head rocks.

The conclusion is that basing on the DR/PM values it is justified to treat Isbjörnhamna and Brepollen basins as single-source ones. Hence, one may interpret all compositional variability there in terms of local processes.

One may arrive at the same conclusion (regarding single-source features of bottom sediment) using mineral indices M/I and di-/trimica measured in the bulk samples. In general, however, these indices reflect both, sediment provenance and selective settling of clays (*cf.* Görlich, 1986; Belzunce *et al.*, *in print*), and hence they should be used in conjunction with the previously discussed DR/PM index.

As regards M/I ratio it may be commented that in the distal sites, the ratio should tend to approach minute values due to pronounced differential settling of muscovite and illite in the proximal settings. However, deviations from this trend will be observed if additional sources of the high-muscovite sediment is present and/or IRD component increases. It is presumably the case with sample 800 from outer Hornsund (Table 3), where both IRD increases and high-muscovite sediment of Isbjörnhamna is introduced.

Redeposition and reworking

The other source of errors in elucidating suspension settling from bottom sediment compositions (besides imprint of provenance) may arise from sediment redeposition. Thus, in order to read the record of different regimes of suspension settling, we must evaluate possible significant effects of redeposition and reworking.

From previous studies (Görlich, 1986; Görlich *et al.*, *in print*) it follows that gravity-flow redeposition resulting in ponded sedimentation within proximal troughs (frequent low-density turbidity currents) involves mainly laminated sand to mud facies. Turbidity currents may produce secondary bimodal texture in homogeneized samples under study by fractionation of bottom sediment of SFD type (3). The redeposition by gravity flows acts in the studied basins at short distances delimited by dimensions of the proximal troughs which are not larger than few kilometres.

Current winnowing may be readily recognised in distal muds as is reflected in the sequence of surficial Wijdefjorden sediments in Figs. 7 and 11A.

It follows that these processes are either clearly distinguishable (current action) or they will not significantly obscure the locus-specific mineral and textural features of bottom sediment.

Dynamic regimes within water mass

According to the present study it seems crucial to divide surficial water mass bounded on tidewater glacier, into most proximal "jet zone" and more distal "slow-advection zone" (Fig. 13). However, more detailed approach to

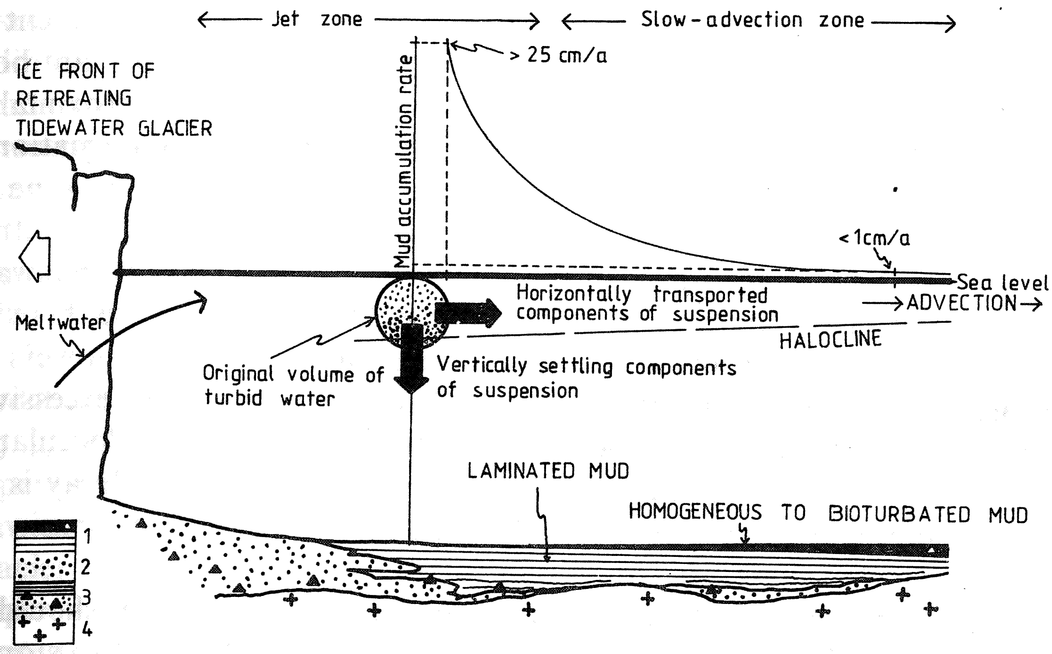

Fig. 13. Principal features of fine-sediment formation from the meltwater overlow with schematic illustration of sediment accumulation rate decay in Hornsund basins. *1* — homogeneous to bioturbated mud (*black*) and laminated mud; *2* — outwash; *3* — diamict and laminated muds with IRD; *4* — bedrock; *dotted circle* — element of turbid water. Approximate horizontal scale for the schematized basin is between 2 and 10 km

textural analysis suggests existence of at least six dynamic environments of diamict to mud deposition from turbid overflow and ice-cliff melting of tidewater glacier. Modifying influence on the bottom sediment of ice-rafting and current winnowing are here included. These dynamic zones are as follows:

(1) a periodically turbulent and dominantly still zone in contact with ice cliff,

(2) meltwater jet zone,

(3) proximal zone beyond meltwater jet and not in direct contact with ice-cliff,

(4) slow-advection zone,

(5) bottom-current dominated distal zone,

(6) still-water distal zone.

Numerous other factors, besides the discussed here mechanisms of suspension settling, affect fine-sediment accumulation rates. These are: melt-water discharge, turbidity of meltwater, and advection velocities in surface water.

The discharge jet leaving the vertical ice-cliff of tidewater glacier will be most effectively retarded compared to other freshwater input modes to marine waters.

The first reason for it is a large sediment load in meltwater which initially gives greater speed of inertial jet, but eventually causes rapid loss of advection energy due to independent (and perpendicular to the jet) movement of suspended particles and water. The latter factor is presumably important both, at the stage of hindered settling of dense susupension in the most proximal jet zone (*cf.* Rao & Carstens, 1971; Kranck, 1986) and at the stage of formation of double-diffusion sediment fingers in the most distal slow-advection zone (*cf.* Green, 1987).

The second flow-retarding agent is an action of a highly saline water beneath the jet. The control on advection velocity takes place here by formation of intensive shearing at sharp halocline what significantly lowers the local Richardson number. The resulting turbulence, in turn, causes excessively strong retardation of surface jet and enhances turbulence-coerced flocculation within shear layer. The other cause of a rapid advection-velocity decay is the lack of solid boundaries (*cf.* Allen, 1969) which in the ice-proximal basin are placed within water mass.

At the farthest reaches of meltwater, where quasi-laminar flow should be expected, the inertial advection of plume may be effectively brought to stop by the formation of sediment/salt fingers (Green, 1987). These latter presumably develop abundantly in the slow-advection zone where Kelvin-Helmholz turbulent instabilities cease.

Bogen (1983) has measured retardation of flow in several fjord-valley lakes and in a low-salinity fjord delta. Power-law change of horizontal jet velocity was found by him, and correspondingly a power-law sedimentation rate decay. On the other hand, it has been found in numerous saline fjords (e.g. Farrow *et al.*, 1983; Gilbert, 1983; Elverhøi *et al.*, 1983) that the decay of sediment accumulation rate is exponential, i.e. much more rapid. The exponential decay coefficients seem to be the highest in the tidewater-glacier systems (Görlich, 1986).

It seems justified then to state that all the named dynamic processes related to sliding of meltwater freshet over strongly saline water in the vicinity of ice cliff, positively influence both, bulk intensity of settling and fine-sediment accumulation rate decay.

INTERPRETATION OF THE SETTLING PROCESSES

General remarks

If there were no lateral changes observed in the mineral composition of bottom mud of a single-source basin, it would mean that no segregation within suspension takes place along the transportation pathway of sediment-laden plume. On the contrary, if any lateral trends in the mineral composition of bottom sediment were observed, this would unequivocally indicate that certain mineral segregation due to selective settling occurred within the source suspension.

Figure 13 illustrates the resulting idea that the composition of original suspension may be obtained as an integrated composition of surficial bottom sediment along the pathway of the package of turbid meltwater. In other words, the bottom mud is formed as a sequence of vertically settled components of suspension, i.e. at a given site the bottom mud consists only of these components of surface-water suspension above this site, which managed to settle out vertically. The bottom mud in this site will neither include components that have left the advection layer in more proximal settings nor will it contain components which have remained within advection layer.

The above trivial statement being the basis of "perforated conveyor-belt" model allows one to evaluate the composition of surface-water suspension at any given location, basing on the knowledge of mineral composition of the uppermost bottom-sediment layer along the profile from this given site seaward. Specifically, due to the rapid sedimentation-rate decay in tidewater--glacier basins one may obtain a picture of the composition of source suspension by approximate integration of bottom-sediment components deposited between a given site and a site where accumulation rate is less than 1 cm/a (Fig. 13).

It means that it is justified to say that the Brepollen source suspension is devoid of coarse muscovite if there is no high-muscovite mud there. On the other hand, we may say that the original suspension of Isbjörnhamna is a nearly 1:1 mixture of muscovite and illite if we compare (Table 1) composition of (inner) Isbjörnhamna and Outer Isbjörnhamna samples.

Evidence of sedimentation zoning in bottom muds

It is argued here that the elementary processes of suspension fall-out are different in each dynamic regime and that these differences may be traced in bottom sediment. What happens in the ice-proximal "jet zone" of turbid meltwater plume, is decisive of total efficiency of sediment removal from the suspended load.

The course of processes in proximal zone is marked in the bottom sediment along the axis of meltwater jet by:

— rapid exponential drop in sediment accumulation rate away from the source (Fig. 13 and Görlich, 1986),

— mineral segregation within clay-mineral assemblage, preferential settling of muscovite (identified as $2M_1$ large-flake dioctahedral mica) with respect to illite (identified as 1Md clay-grade mica), (Fig. 14),

— predominance of clay and sand over silt in bottom sediment manifested by bimodal grain-size distributions.

The strong segregation of micas in the proximal Isbjörnhamna (Fig. 14, and Görlich *et al., in print*) similar but less pronounced than that observed in the micro-tidal mouth of the Vistula River in the Baltic Sea (Belzunce *et al., in print*), is found to be restricted to the jet-zone.

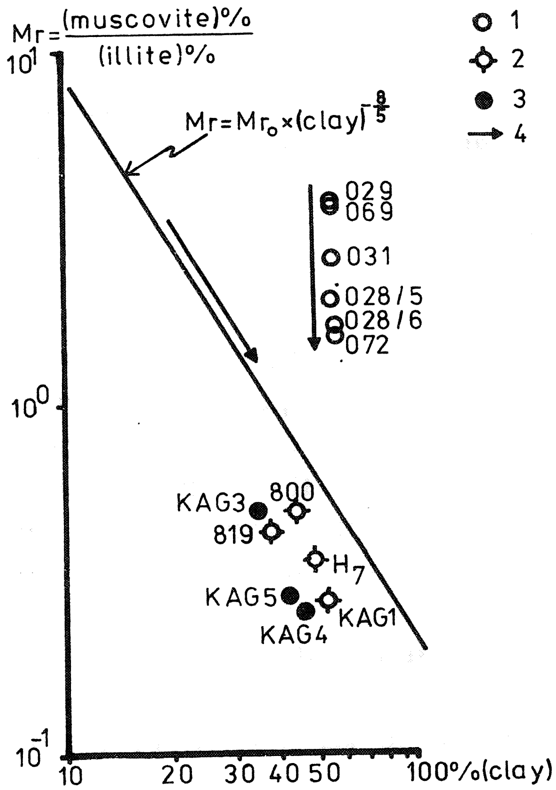

Fig. 14. Plot of $2M_1$ muscovite to 1Md illite ratio against total clay content for the samples from Hornsund and Storfjorden. The straight line shows power-law dependence obtained for the same variables for the samples from the Vistula River mouth in the Baltic Sea. The inclination of the arrows is proportional to rapidity of mineral segregation along the transportation pathway (higher for the Isbjörnhamna sediments than for the Vistula River ones and for Storfjorden; Hornsund samples represent blended sediment and no clear tendency is seen). Samples from: *1* — Isbjörnhamna, *2* — Hornsund, *3* — Storfjorden; *4* — approximate linear regression

Both, proximal and distal mud facies are rich in clays. However, distinct differences may be observed within clay to silt fraction frequency distributions (the above textural types 2—4).

Of the samples identified as proximal, the clays with conspicuous fraction > 0.25 mm reveal distinct clay mode. They are thought to be typical deposits of sedimentation zone 2. Such excessive fall-out of clays in the highly energetic zone 2 is due to turbulent diffusion of sediment and rapid flocculation coerced by turbulence within the shear layer directly beneath the meltwater jet.

There exist, however, proximal samples with SFD truncated about 1 mm, which approach broad unimodal distribution rich both in clay and silt. They are identified as deposits of zone 3. They may be distinguished from often similar SFD of the sediments of zone 4 by more abundant fraction > 0.25 mm.

Instability of meltwater dispersal pattern is typical of the proximal zone. The changes in strength and direction of jet result here in random alteration of dynamic regimes 2 and 3 over a given site. This is manifested by textural lamination in mud (besides the ?annual dark-light lamination) and by variability of mineral and chemical composition in sediment column of core 21 (Table 7).

A more stable dynamic pattern both in surface and bottom water, and hence more uniform sediment composition is revealed by distal sediment column of core 13 (Table 6) remaining within dynamic regimes 4 and 6.

Flocculation and settling

It should be noted that the micas' segregation, found in muds of the distinguished jet zone, follows power-law regularity (Fig. 14), and hence suggests relation to the single-grain stage of suspension settling distinguished by Kranck in her experiments (Kranck, 1986). This would mean that the effect of preferential settling of muscovite observed in the bottom sediments, marks the process in which the fastest settling muscovite reaches the shear boundary and is captured in still-water layer before most of fine clays manage to aggregate and settle down to do the same. The rate of segregation of clays (illustrated by the inclination of lines of the plot in Fig. 14) is thus the difference in the rate at which settling clays attain halocline or rather main shear-surface bound with it.

The thicker and laterally more extensive is the advection-turbulence layer, the more suspension is homogeneously flocculated and suspension segregation during horizontal transport is negligible. Such homogeneous flocculation is enhanced in suspension dominated by very fine clay grains (Brepollen sources). In such case, the fine bottom sediment well repeats (already in fairly proximal settings) the grain-size distribution of the surficial suspension. No clay-mineral segregation is observed in the bottom sediment in such case.

When the turbulent layer is thin, the halocline sharp and the suspension rich in coarse clay (Isbjörnhamna case), abundant single clay grains reach the shear surface and enter still-water layer. The abundant coarse-clay grains manage partly to cross halocline single or as non-equilibrium flocs. In such case, fine bottom sediment does not repeat the grain-size distribution of the source suspension and mineral segregation of gravitational origin takes place within suspended load.

The whole idea is compatible with that of Syvitski & Murray (1981), based on their studies of Howe Sound, British Columbia, that suspension enters marine waters mostly due to diffusion and mixing.

The turbulent diffusion takes place across shear boundary and involves those particles (occasionally, depending on source-suspension composition, abundant single grains) which have managed to reach this surface within the zone of strong jet. It must also be stressed that this process is rapidly overtaken by floc settling through the boundary layer at the halocline (possibly also within sediment fingers of double-diffusion origin) – a settling type which is dominant in the slow-advection zone.

For dynamic zones 3 and 4 (with corresponding SFD types) it can be suggested that the flocculation model of Kranck (1986) holds, i.e. that the bottom sediment repeats broad but already sorted spectrum of suspension carried within the slowly advecting surface water.

In Brepollen and Isbjörnhamna (i.e. in the "end-member" cases as regards suspension composition, thickness of advecting surface water, and sharpness of halocline) the clays are being settled rapidly. The observed sedimentation rate decay is exponential in both the basins (Görlich, 1986). However, the decay takes place at different rate (slower in Brepollen, more rapid in Isbjörnhamna — *op. cit.*). The cause for these differences is thought to be the spatial dominattion of either of two different suspension fall-out regimes: those of jet and slow-advection zones. A given basin may be characterized in this regard by the relation between extent of slow-advection zone and the extent of jet zone. This ratio is much greater in Brepollen than in Isbjörnhamna.

SUSPENSION SETTLING MODEL

The original suspension introduced with meltwater directly from the glacier ice-cliff is dispersed in the fjord due to the energy of the discharge jet. During this seaward transport of meltwater, the jet is intensively retarded and the sediment particles settle out of it. The loss of suspension from surface water follows exponential curve in tidewater environment (Fig. 13). This exponential turbidity decay is reflected in the fjord basins by a seaward exponential decay of the sediment accumulation rate. The conformability of these two processes suggests that suspension settling is the dominant agent controlling formation of bottom sediment in the zone of occurrence of glacial-marine muds. This observation constitutes the base for the reasoning adopted in this study.

The resulting concept of suspension settling may be best illustrated using the scheme in Figure 15. In general, the idea of "perforated conveyor belt" is adopted (Farrow *et al.*, 1983). In the proximal zone, intense flocculation is coerced by turbulent contacts between sediment particles. It takes place in the lowermost layer of meltwater freshet which may be identified with halocline; the latter treated as a layer of abrupt increase of salinity from < 30 to > 34 permill and a major shear surface.

The idealized conveyor-belt model assumes that advection in this layer is dominant to such extent that settling of clays within it is negligible. However, in real system settling of clays occurs already in the proximal zone within meltwater jet, as manifested by vertical distribution of turbidity (e.g. Relling & Nordseth, 1979, in: Bogen, 1983 p. 262). The fast settling of single coarse-clay flakes may be enhanced here by the fact that the fine clays which join initial flocks (in spite of their often fast-growing dimensions) effectively lower their original density due to the fractal type of growth during flocculation. Hence, flocculated fine clays have lower Stokes velocities than single clay grains of equal real dimensions.

At further reaches of the freshet only slow advection takes place. Turbu-

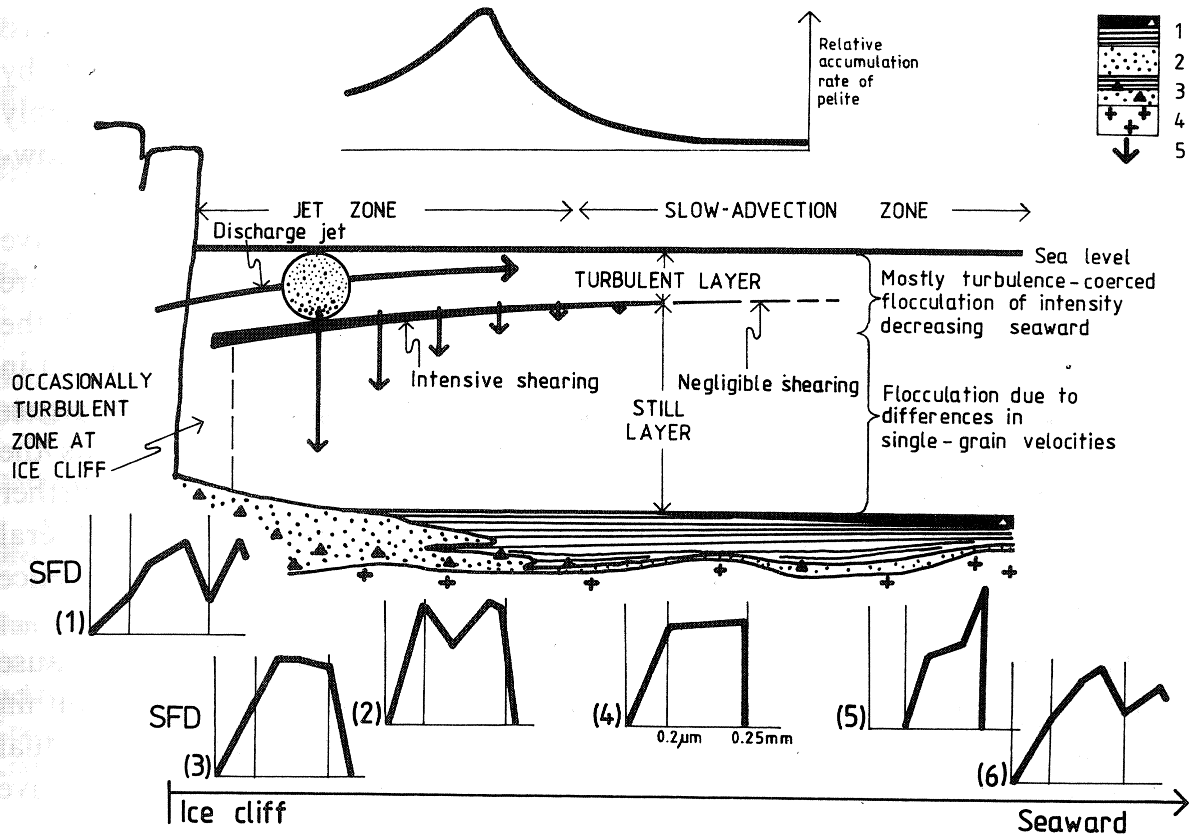

Fig. 15. Hydrological conditions of suspension dispersal and settling in front of the tidewater glacier and schematic SFD's typical of different dynamic zones of the tidewater-glacier forefield. The curve shows evaluated intensity of pelite sedimentation along the profile seaward from the glacier. *1* — homogeneous to bioturbated mud facies and laminated mud facies; *2* — outwash; *3* — diamict and laminated mud with IRD; *4* — bedrock; *5* — approximate intensity of sedimentation of suspended load (relative scale). The SFD plots have all the same scale and thin vertical lines are 0.02 µm, 0.2 µm and 0.25 mm (as indicated for SFD 4). Other explanations as in Fig. 13

lence wanes and halocline becomes diffuse. Thorough but slow flocculation takes place mainly by contacts between particles achieved due to differences in single-grain settling velocities.

Below the turbulent layer, both in the jet and slow-advection zones, vertical settling of particles dominates. This zone of water column is dynamically still. The flocculation occurs here slowly, mainly due to differences in single-grain settling velocities (*cf.* Kranck, 1986). However, this is unimportant for the bottom-sediment patterns, since any grain or aggregate that attains still-water layer (Fig. 15) will, within the period of days or weeks, settle close to the place where it has left the advection layer, whether flocculated or not.

CONCLUSIONS

The bottom sediments of Hornsund and Wijdefjorden on Spitsbergen well reflect the locally changing hydrodynamic regime in the surficial layer of water in the basins bounding on tidewater glaciers.

The fall-out of meltwater-overflow suspension dominates sedimentation in the area of occurrence of glaciomarine muds in the tidewater-glacier basins. The suspension flocculates mainly due to particle contacts coerced by turbulence within shear layer beneath the proximal meltwater jet, and mainly due to differences in single-grain settling velocities in the more distal slow--advection zone and in underlying still-water layer.

In the ice-proximal jet-zone, bottom sediment receives particles which have left the advection layer as single grains and immature flocs, while in the more distal slow-advection zone the sediment is deposited which has crossed the halocline as mature flocs. These differences in settling modes are manifested in bottom sediment. The bottom sediment with conspicuous clay-mineral segregation may occur beneath the jet zone of the meltwater plume, whereas the finest clays and other left-over components of suspension settle further seaward, beneath the slow-advection zone. The intensity of clay-mineral segregation is controlled by texture of source suspension, viz. original presence of abundant coarse clays.

The ice-proximal processes of mineral segregation within suspension cause that the typical source-bedrock inherited features are manifested only within proximal muds. The more distal muds show equalized features of residual suspension which has passed the jet zone of the most intensive and selective sedimentation.

The above results seem to explain well how the synergic action of numerous factors produces the exceptional efficiency of tidewater-glacier basins in trapping suspended load.

Acknowledgements

Thanks are due to Dr Joanna Zachowicz and colleagues, Geological Institute, Sopot, for their chemical-analytical work.

The help of Dr Seweryn M. Zalewski, Dr Stanisław Rudowski, and Eng. Włodzimierz Kowalewski in obtaining the materials from piston cores is gratefully acknowledged. The core-samples have been offered for this study by Institute of Geophysics, Polish Academy of Sciences.

The investigation was carried out within the Polish Academy of Sciences project CPBP 03.03. B6.

REFERENCES

Allen, J. R. L., 1969. *Current Ripples. Their Relation to Patterns of Water and Sediment Motion.* North-Holland, Amsterdam, 433 pp.

Belzunce, M. J., Görlich, K. & Helios-Rybicka, E., *in print*. Heavy metals in surface sediments of the Baltic Sea: Sequential extraction. *Proceedings Conf. Baltic Oceanographers*, Copenhagen, 1986.

Birkenmajer, K., 1981. The geology of Svalbard, the western part of the Barents Sea, and the continental margin of Scandinavia, In: Nairn, A. E. M., Churkin, Jr., M. & Stehli, F. G. (eds.), *The Ocean Basins and Margins*, vol. 5. Plenum Publishing Corporation, New York, pp. 265—329.

Bogen, J., 1983. Morphology and sedimentology of deltas in fjords and fjord valley lakes. *Sedim. Geol.*, 36: 245–267.
Elverhøi, A., Lønne, Ø. & Seland, R., 1983. Glaciomarine sedimentation in a modern fjord environment, Spitsbergen. *Polar Res.*, 1 n.s.: 127–149.
Eyles, N., Eyles, C. H. & Miall, A. D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. *Sedimentology*, 30: 393–410.
Farrow, G. E., Syvitski, J. P. M. & Tunnicliffe, V., 1983. Suspended particulate loading on the macrobenthos in a highly turbid fjord: Knight Inlet, British Columbia. *Can. J. Fish. Aquat. Sci.*, 40: 273–288.
Gilbert, R., 1983. Sedimentary processes of Canadian Arctic fjords. *Sedim. Geol.*, 36: 147–175.
Görlich, K., 1986. Glaciomarine sedimentation of muds in Hornsund fjord, Spitsbergen. *Ann. Soc. Geol. Polon.*, 56: 433–477.
Görlich, K., Węsławski, J. M. & Zajączkowski, M., *in print*. Suspension settling and benthos distribution in Hornsund fjord, Spitsbergen. *Polar Res.*, 5 (2).
Green, T., 1987. The importance of double diffusion to the settling of suspended material. *Sedimentology*, 34: 319–331.
Hume, T. M. & Nelson, C. S., 1986. Distribution of clay minerals in surficial shelf sediments, western North Island, New Zealand, *Mar. Geol.*, 69: 289–308.
Jackson, M. K., 1974. *Soil Chemical Analysis — Advanced Course*. Madison, Wisconsin, 895 pp.
Kranck, K., 1975. Sediment deposition from flocculated suspensions. *Sedimentology*, 22: 111–123.
Kranck, K., 1984. Grain-size characteristics of turbudites. In: Stow, D. A. W. & Piper, D. J. W. (eds.), *Fine-Grained Sediments: Deep Water Processes and Facies*. Blackwell Scientific Publications, Oxford, pp. 83–92.
Kranck, K., 1986. Settling behaviour of cohesive sediment. In: Mehta, A. J. (ed.), *Estuarine Cohesive Sediment Dynamics*. Springer, Berlin, pp. 151–169.
Molnia, B. F. & Hein, J., 1982. Clay mineralogy of a glacially dominated shelf: northwestern Gulf of Alaska. *J. Sedim. Petrol.*, 52: 515–527.
Rao, U. M. & Carstens, T., 1971. Sediment laden submerged horizontal jet. *Proceedings of the 14th Congress of International Association for Hydraulic Research*, pp. 135–143.
Środoń, J., 1984. Mixed-layer illite-smectite in low-temperature diagenesis: data from the Miocene of the Carpathian Foredeep. *Clay Miner.*, 19: 205–216.
Środoń, J., & Eberl, D. D., 1984. Illite. In: Ribbe, P. H. (ed.), *Micas*. Mineralogical Society of America. Book Crafters, Chelsea, Michigan, pp. 494–544.
Syvitski, J. P. M. & Macdonald, R. D., 1982. Sediment character and provenance in a complex fjord: Howe Sound, British Columbia. *Can. J. Earth Sci.*, 19: 1025–1044.
Syvitski, J. P. M. & Murray, J. W., 1981. Particle interaction in fjord suspended sediment. *Mar. Geol.*, 39: 215–242.

Streszczenie

MIKI I SKŁAD ZIARNOWY WSPÓŁCZESNYCH MUŁÓW WE FIORDACH SPITSBERGENU: STUDIUM OSIADANIA ZAWIESINY

Krzysztof Görlich

Abstrakt: Powierzchniowe rozkłady zawartości politypów $2M_1$ i 1Md mik dioktaedrycznych oraz rozkłady uziarnienia w osadach dennych fiordów Hornsund i Wijdefiorden są czułymi wskaźnikami pozwalającymi na opisanie warunków dostawy, rozprowadzania i osiadania zawiesiny. Wyróżniono następujące strefy dynamiczne w basenie przylodowcowym: (1) strefa spokojna, sporadycznie turbulentna, w kontakcie z klifem lodowym, (2) strefa gwałtownego, powierzchniowego strumienia wód lodowcowych, (3) strefa proksymalna poza strumieniem wypływu wód lodowcowych, (4) strefa powolnej, powierzchniowej adwekcji wód lodowcowych, (5) strefa dystalna zdominowana przez prądy przydenne i (6) strefa dystalna zdominowana przez depozycję materiału zrzutowego.

W pracy opisano zjawiska typowe dla układu sedymentacyjnego lodowców uchodzących do morza. (1) Cechy litologiczne skał podłoża na lądzie są dziedziczone przez muły na dnie fiordu. (2) Selektywne osiadanie iłów powoduje wzmożoną depozycję muskowitu w przylodowcowej strefie akwenu, co wyraża się potęgowym spadkiem stosunku muskowitu $2M_1$ do illitu 1Md w kierunku na zewnątrz fiordu. (3) Wzdłuż powierzchni ścinania poniżej strumienia wód roztopowych zachodzi intensywna flokulacja wymuszona przez turbulencję; pojedyncze ziarna minerałów ilastych i niedojrzałe flokule są tutaj wychwytywane przez nieruchomą warstwę niżejległej słonej wody, co daje wysoką stopę akumulacji mułu i efekt sortowania minerałów ilastych w tej strefie. (4) W strefie powolnej, powierzchniowej adwekcji wód lodowcowych zachodzi powolna flokulacja iłów głównie na skutek różnic w prędkościach osiadania poszczególnych cząstek. Proces ten określa wolne tempo akumulacji mułów w tej strefie.

Celem pracy jest opis elementarnych procesów zachodzących w zawiesinie wprowadzanej do wód fiordu wraz z wodami roztopowymi z lodowców uchodzących do morza. Efektem tych procesów są specyficzne rozkłady uziarnienia w basenie na przedpolu lodowca oraz frakcjonacja mik w strefie proksymalnej wzdłuż drogi rozprowadzania wód lodowcowych. W pracy przedyskutuje się jakościowo: (a) dynamikę wypływu wód lodowcowych, (b) przebieg flokulacji zależnie od składu zawiesiny i warunków dynamicznych w wodzie powierzchniowej oraz (c) mechanizmy przechodzenia zawiesiny z powierzchniowej warstwy adwekcyjnej do niżejległej warstwy w spoczynku.

Badania przeprowadzono we fiordach Hornsund i Wijdefjorden na Spitsbergenie (Fig. 1—3). Hornsund przecina różnowiekowe formacje, od prekambryjskich na zachodzie po górnomezozoiczne na wschodzie. Fiord ten przebiega prostopadle do głównych regionalnych uskoków. Wijdefjorden oddziela skały prekambryjsko-kambryjskiej sukcesji Hecla Hoek na wschodzie od dewońskich skał formacji Wood Bay na zachodzie i jest założony na górnopaleozoicznym uskoku Billefjorden. Hornsund i Wijdefjorden reprezentują zatem niemal przeciwstawne cechy z uwagi na ich stosunek do stref litologicznych i jednostek strukturalnych. Z tego powodu wyniki wcześniejszych i obecnych badań we fiordzie Hornsund zostały w tej pracy odniesione do danych z Wijdefjorden.

Analizy wykonano na próbach czerpakowych i rdzeniowych zebranych w czasie wypraw zorganizowanych przez Instytut Geofizyki PAN w latach 1982—1985, a także na materiałach udostępnionych przez wyprawy studentów Uniwersytetu Gdańskiego. Analizowane próbki reprezentują szeroki zakres typów osadów o dużej (ponad 65%) zawartości frakcji poniżej 60 μm — od masywnych diamiktów (facja *Dmm* według kodu Eylesa *et al.*, 1983) do laminowanych i masywnych mułów, często zawierających materiał zrzutowy (facje *Fl*, *Fld*, *Fm* i *Fmd*).

Próbki rozdzielono przez szlamowanie na sitach: 2, 1, 0,25 i 0,06 mm oraz przez odwirowanie na ultrawirówce frakcji 2—60 μm, 2—0,2 μm i poniżej

0,2 µm. Badaniom rentgenowskim poddano próbki nierozdzielone oraz frakcje ilaste (2–0,2 µm i poniżej 0,2 µm). Badano preparaty orientowane sedymentacyjnie i dezorientowane. Te ostatnie – celem oznaczenia politypów mik oraz rozróżnienia tri- i dioktaedrycznych minerałów ilastych (Fig. 4). Widma absorpcyjne w podczerwieni (Fig. 5 i 6) posłużyły do ustalenia zawartości żelaza i magnezu w mikach i chlorytach. Wyniki analiz mineralogicznych dla nierozdzielonych próbek oraz frakcji ilastych przedstawione są w tabelach 1–4.

Dane o zawartości frakcji ziarnowych wykorzystano do wykreślenia profili zawartości wybranych frakcji (Fig. 7 i 8), krzywych kumulacyjnych (Fig. 9 i 10) oraz wieloboków uziarnienia (Fig. 11 i 12).

Tabela 5 przedstawia wyniki analiz chemicznych próbek nierozdzielonych oraz frakcji ilastych, tabele 6 i 7 natomiast zawierają wyniki analiz chemicznych dla dwóch rdzeni osadów z fiordu Hornsund. Rdzeń Jantar-13 z Adriabukta (Fig. 2) reprezentuje osad dystalny o stopie akumulacji osadu znacznie poniżej 1cm/rok, a rdzeń Jantar-21 z przedpola Isbjörnhamna – osad bardziej proksymalny.

Wyniki badań mineralogicznych frakcji wydzielonych z próbek mułów pozwoliły na ustalenie charakterystycznych modalnych rozmiarów blaszek minerałów ilastych, które można pod tym względem uporządkować w następujący sposób: M > K > Ch > B > I (oznaczenia minerałów jak w Tab. 1).

Frakcja poniżej 0,2 µm jest zdominowana przez illit. Ma on różne cechy w zależności od basenu. Illit jest w znacznej mierze trioktaedryczny w Wijdefjorden, żelazisty w Brepollen, glinowy zaś w Isbjörnhamna. Stałość składu mineralnego w obrębie poszczególnych basenów i różnice w składzie pomiędzy basenami sugerują, że:

(1) Poszczególne baseny są zasilane osadem z lądu z wyraźnym zachowaniem źródłowych cech litologicznych, które to cechy przenoszone są do osadu dennego, tak że można określić jednoznacznie zasięg dominacji sedymentacyjnej poszczególnych źródeł.

(2) Fakt, że zależności te odnoszą się także do najdrobniejszej frakcji ilastej osadu oznacza, że na lądzie nie działają regulowane klimatyczne procesy wietrzenia chemicznego i procesy glebowe unifikujące skład mineralny drobnej frakcji ilastej.

Ocena ilościowa zawartości politypów mik dioktaedrycznych $2M_1$ (głównie muskowit) i 1Md (głównie illit) w badanych próbkach oraz charakter zależności stosunku muskowit/illit od całkowitej zawartości minerałów ilastych w próbce (Fig. 14) potwierdzają wydzielenia basenów dokonane na podstawie jednolitych cech zespołu minerałów ilastych (wyraźne zgrupowania punktów na wykresie). Jednocześnie wykres na Figurze 14 ilustruje proces różnicowania składu mineralnego źródłowej zawiesiny w strefie przylodowcowej (próbki z Isbjörnhamna). Różnicowanie to można odnieść do ustalonego w tej pracy ciągu specyficznych modalnych wielkości blaszek minerałów ilastych, w którym muskowit i illit zajmują położenia krańcowe.

Przenosząc stwierdzone cechy osadu drobnoziarnistego na procesy zachodzące w zawiesinie źródłowej zgodnie ze schematem przedstawionym na Figurze 13, stwierdzono, że omawiana dyferencjacja sedymentacyjna minerałów ilastych zachodzi w strefie odpowiadającej występowaniu facji mułów laminowanych i jednocześnie strefie silnego strumienia wypływu wód lodowcowych. Rozprzestrzenianie facji mułów homogenicznych i zbioturbowanych odpowiada natomiast strefie powolnej adwekcji powierzchniowej wód lodowcowych, zdominowanej przez osiadanie rezydualnej zawiesiny (wzbogaconej w illit i inne drobnoziarniste minerały ilaste). Tutaj nie zachodzi już różnicowanie mineralne w zakresie minerałów ilastych.

Na figurze 15 przedstawiono ogólny model sedymentacji ilastej na przedpolu lodowca uchodzącego do morza. Proksymalna strefa silnego wpływu wód lodowcowych wytwarza na dnie fację mułów laminowanych i zaznacza się w osadzie mułowym specyficznymi rozkładami uziarnienia (krzywe 1 i 2) oraz silną segregacją mik (próbki z Isbjörnhamna na Fig. 14). Strefa powolnej adwekcji wód powierzchniowych odpowiada na dnie facji mułów homogenicznych i bioturbowanych, bez wyraźnej segregacji mineralnej i z typowym rozkładem uziarnienia reprezentowanym przez krzywą 4.

Poza głównymi strefami sedymentacji mułów powstają osady proksymalne w strefie kontaktu z klifem lodowym (krzywa 1) oraz dystalne osady mułowe o składzie zmodyfikowanym przez prądy przydenne (krzywa 5) lub dużą dostawę materiału zrzutowego (krzywa 6).

Wynikiem specyficznej dynamiki rozprowadzania wód lodowcowych w basenie przylodowym i silnej stratyfikacji halinowej w tej strefie jest właściwy tylko dla tego układu sedymentacyjnego przebieg flokulacji i wypadanie zawiesiny do osadu. Odznacza się on niezwykle intensywną sedymentacją drobnych ziarn oraz ich segregacją w strefie proksymalnej. Skutkiem takiego przebiegu procesów jest bardzo wysoka stopa akumulacji osadu drobnoziarnistego w strefie przylodowcowej i bardzo gwałtowny, wykładniczy spadek tej stopy wraz z odległością od źródła.