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Textural parameters and classification of deposits in the modern glaciomarine environment, Hornsund Fjord, Spitsbergen

ABSTRACT: Two statistical methods (cluster analysis and discriminant function) based on twenty textural and mass physical parameters of the surficial sediments deposited in the modern glaciomarine sedimentary environment of the NW Brepollen Bay, Hornsund Fjord, Spitsbergen, have resulted in the recognition of the three major lithofacies. According to the origin, type of transport, and depositional pattern they were identified as: (*i*) glacial till, (*ii*) ice-rafted sediments, (*iii*) water transported sediments. This classification system enabled the facies identification of older subsurficial deposits from core samples. The areal distribution of analyzed textural and physical properties and their interrelations, against a background of the rapid retreat of the tidewater glaciers (43 to 100 m annually), varied sedimentation rate (4 to 110 mm a year), and presence of dead ice blocks on the bay floor preserved by salt (34°/₀₀) and cold (−1 to + 0.5°C) bottom water, have allowed to gain insight into sedimentary processes of a glaciomarine environment.

INTRODUCTION

This paper is a part of a Ph.D. thesis (FILIPOWICZ 1989) and presents the results of a study of modern glaciomarine environments kept by the Author during four polar expeditions to Spitsbergen. It concerns both the surficial sediment from the grab samples as well as the deeper layers pierced by the cores. Most of sediment samples were collected in 1981 during the VI*th* Oceanographical Expedition of the Gdańsk University, and in 1984 during the oceanographical cruise of m/s "Jantar" organized by the Institute of Geophysics, Polish Academy of Sciences.

For description of glaciomarine sediments very often the term diamicton is used. This term was introduced (FLINT & *al.* 1970) to describe a very poorly sorted sediment without the need to infer its genesis. But the distinction between different facies of glaciomarine sediments is a crucial problem. So far, some authors tried to make distinctions primarily on particle-size distributions (e. g. LẢDIM & FRAKES 1968, BULLER & MCMANUS 1973, FRAKES & CROWELL 1973), while some in addition have applied mass physical properties (EASTERB-

ROOK 1964; BOLTUNOV 1970; KRAVITZ 1982, 1983; ELVERHØI & *al.* 1983; SCHWAB & LEE 1983). Many others have distinguished and described the facies patterns within these complex glaciomarine environments (ANDERSON & *al.* 1980; DOMACK 1982, 1983; POWELL 1981, 1983, 1984; MOLNIA 1983a; ELVERHØI 1984; GÖRLICH 1986).

The main purpose of this study was to establish a reliable set of criteria that can be used in recognition and classification of both modern and ancient glaciomarine sediments, and in distinguishing them from associated glacial tills.

STUDY AREA

The Hornsund Fjord is located in the southernmost part of the Spitsbergen Island in Svalbard Archipelago (Text-fig. 1). It is generally oriented in an east-west direction and penetrates inland for nearly 30 km. Its coast line is irregular and creates five bays. For detailed studies of the glaciomarine sedimentary environment the northwestern part of the Brepollen Bay was chosen (Text-fig. 1). This bay is the biggest in the Hornsund Fjord and well separated from the influence of the open sea. Its shallow nortwestern part is composed of four secondary subbays with the very irregular coast line, which consists of narrow peninsulas and active glacier cliffs.

MATERIALS AND ANALYTICAL PROCEDURES

This study is based on 50 surface sediment grab samples and 6 short cores taken from the ship or small motor boats. Surface sediment samples were recovered with van Veen and Petersen grab samplers. Core samples were collected with use of Goin gravity corer with a barrel 1.3 m long that contained copper liners with an internal diameter (*ID*) of 45 mm. The positions of sampling sites (Text-fig. 1) were determined from the coast using two theodolites for boat stations and by navigation methods for ship positions.

Salinity, temperature and oxygen content were measured for water samples collected with the Nansen bottle at the number of stations using the Laboratory Salinometer Plessey Environmental System for salinity, reverse thermometers for temperature and the Radiometer Autoburette for oxygen titration.

In the laboratory all core sections were split longitudinally in order to receive slices 15 mm thick. Then prior to sampling, slices were X-rayed with use of the medical X-ray unit Televix model 1600. Subsample intervals for scanning electron microscopy (*SEM*), grain-size analysis, and mass physical measurements were selected on the basis of the core radiographs and visual observations. The sediment from grab samples was homogenized and quartered according to standard procedures (*see* KRUMBEIN & PETTIJOHN 1938).

The grain-size analysis of both core and grab samples was carried by conventional sieving methods for the sand and gravel fractions, and using the pipette technique for the silt and clay fractions, according to the methods described elsewhere (FILIPOWICZ 1989).

The data from the sieve and pipette analyses were put trough a computer program providing weight percents of each fraction, plotting the cumulative-frequency curves, and computing statistical grain-size parameters by the moment method (FRIEDMAN 1961, 1967) at the quarter-phi intervals.

The sediment physical properties were determined by standard procedures of American Society for Testing and Materials [ASTM 1982], and by those described by EDEN (1955) and KRAVITZ (1983).

Detailed methodology of field, laboratory and statistical procedures is presented in a separate study (FILIPOWICZ 1989).

BACKGROUND OF SEDIMENTARY ENVIRONMENT

Depositional pattern in the fjord environment is strongly controlled by: bedrock lithology of the source area, position of glaciers and rate of glacial front retreat or surge, iceberg calving, suspended material load supplied by meltwater, bathymetry and bottom configuration, sea water column characteristics, quantity and biological activity of plankton and benthos living in the water column and on the fjord floor.

Keeping this in mind the detailed observations and measurments as well as studies of written materials were carried out in order to recognize and describe the sedimentary environment of the NW Brepollen Bay.

BEDROCK GEOLOGY

Bedrock lithology of the Brepollen coasts, well known and described (BIRKENMAJER 1964a, 1975, 1977; MØRK 1978) is shown in geological sketch-map (Text-fig. 1). The pre-Quaternary rocks ranging in age from the Upper Carboniferous to the Lower Cretaceous occur in this area, but some parts of bedrock are covered with Holocene moraines. All these rocks are the source of dropstones and rock flour delivered to the bay.

The rocks of Treskelodden Formation consist of five major cycles, most of them beginning with quartz conglomerates and coral limestones and ending in clastic deposits (calcareous sandstones, quartzites and shales). The Brachiopod Cherty Limestone (Kapp Starostin Fm) begins with conglomerate of quartz and limestone pebbles contained in a calcareous matrix. Its upper part is built of dark cherty, often bituminous limestones. The Vardebukta Formation consists predominantly of gray to black shale and marly shale with subordinate fine-grained sandstone and siltstone layers. The dominant lithology within the Sticky Keep Formation is a dark calcareous siltstone passing to arenaceous limestone. The Botneheia Formation is represented by varying from gray to blackish, often bituminous shales and dark calcareous siltstone. The Kapp Toskana Formation consists of quartzites and quartzitic sandstones. The dominant sediments of the Janusfjellet Formation are divided into two parts: the lower, quartzitic one, and the upper with interbedded shales and sandstones containing some sideritic concretions.

The southern and eastern parts of the Treskelen Peninsula (Text-fig. 1) are covered by the ground and so-called "shelly" moraines consisting of till with numerous marine mollusk shells dated by radiocarbon method for 8500 to 9000 years BP (Birkenmajer & Olsson 1970). The latter moraines are interpreted (Birkenmajer 1964b) as former marine sediments pushed out by a glacier from the bottom of the Treskelbukta Bay during the last Holocene advance. The northeastern coast of Treskelen, the whole Selodden and unnamed peninsulas are covered predominantly by ablation moraines. The detailed studies in this region (Marks 1983) have shown even more types of Quaternary deposist, not discussed here.

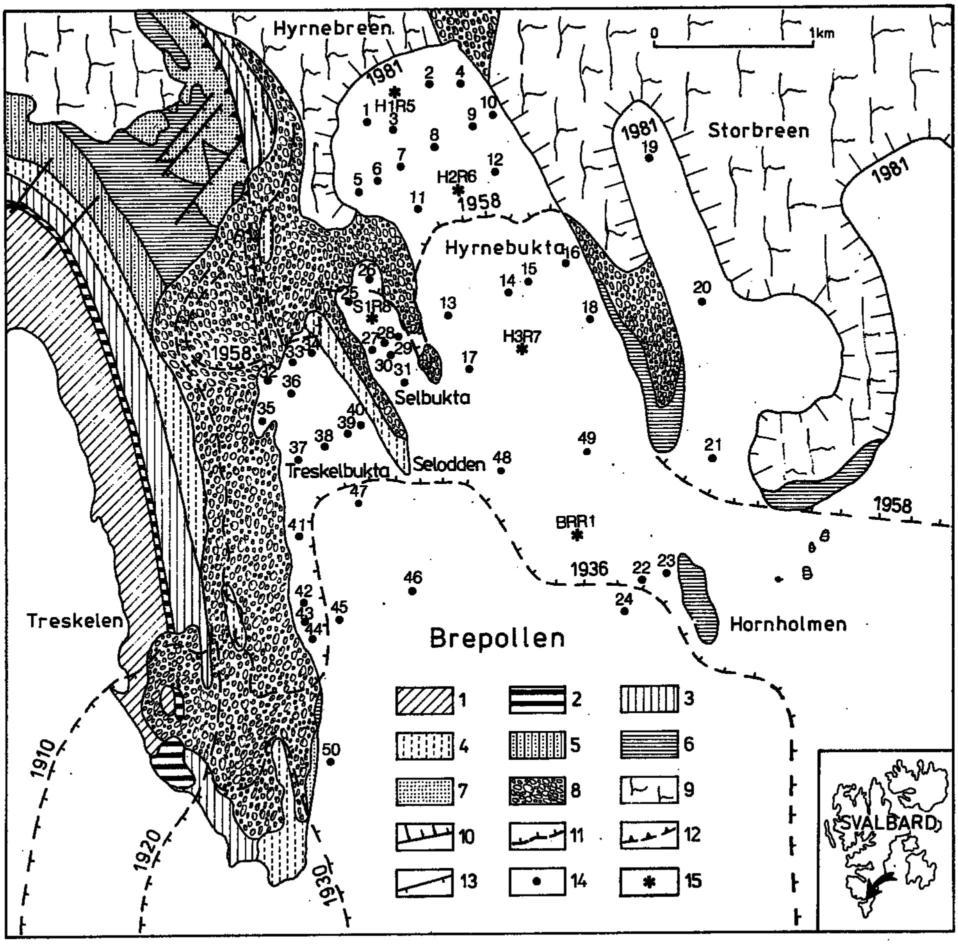


Fig. 1. Location of sampling sites in the NW Brepollen Bay, Spitsbergen

Geological sketch map *after* BIRKENMAJER (1964a) and MØRK (1978); stages of deglaciation *after* BIRKENMAJER (1964b, *modified and supplemented*)

1 — Hyrnefjellet-Treskelodden Fms (Middle Carboniferous — Lower Permian), **2** — Kapp Starostin Fm (Upper Permian), **3** — Vardebukta — Sticky Keep Fms (Lower Triassic), **4** — Botneheia Fm (Middle Triassic), **5** — Kapp Toskana Fm (Middle Triassic — Lower Jurassic), **6** — Janusfjellet Fm (Middle Jurassic — Lower Cretaceous), **7** — Helvetiafjellet Fm (Lower Cretaceous), **8** — moraine cover, **9** — glaciers, **10** — present glacier cliffs, **11** — former glacier margins, **12** — overthrust, **13** — faults, **14** — grab samples, **15** — core samples

GLACIAL HISTORY AND ICE

The Brepollen Bay, as it is typical of the present day environment of the Spitsbergen Island, is surrounded by partly glaciated areas with subpolar tidewater glaciers ending with vertical ice cliffs from which icebergs calve. At the beginning of 20*th* century this bay did not exist yet because its whole area was covered by glaciers.

The oldest positions of the Hyrnebreen Glacier margin were marked by HEINTZ (1953) and BIRKENMAJER (1964b) for the years 1900 and 1910. MARKS (1983), however, on the basis of lateral moraines at the raised marine terraces changes their age to the maximum glacier advance of the Little Ice Age in the 19*th* century. All authors agree about deglaciation stages at the thirties and later. The glacier margin positions in 1936, 1949, 1958, 1977 are confirmed by maps or aerial photographs and in 1981 by own cartographic materials (Text-fig. 1). Nearly the whole investigated area of the NW Brepollen Bay in 1936 was still covered by glaciers. From 1936 to 1958 a glacial front retreat was rapid, more than 100 m annually on the average. The rate of ice face retreat between 1958 and 1981 was slower, but still fast, with an average annual value of 43 m. In result, the Selodden Peninsula as well as the next peninsula located further to the east have been devoid of ice cover. Further eastwards become visible parts of the another peninsulas or rows of islands, exposed in fragments from under the Storbreen Glacier. All these features reflect the structural elements of the bedrock, but in a great part are covered by glacial till.

Since the end of the thirties the outwashes have not been formed in the forefield of the Hyrnebreen Glacier. The ground moraines exposed from under the glacier between 1936 and 1949 are almost dry at present, whereas in 1958 they were still melting (BIRKENMAJER 1964b). Dirt cones, till pyramides and towers occur within the area abandoned by the glacier after 1949. They are mostly developed on the peninsula and on the island eastwards from Selodden. Their coastline is still changing due to the degradation of the ground moraine by slides, solifluction and by wave action.

The Brepollen Bay is the most consistently icebound part of Hornsund Fjord. In waters of the bay three main types of ice are found: fast ice, sea ice and icebergs. Fast ice conditions begin in November and break up about July. The fast ice acts as an extension of the coasts. This ice, particularly the so-called grounded ice developed along the coast and in shoal areas, plays an important geological role by eroding, transporting, and depositing sediments. Grounded ice frozen to the coast and to the sea bottom breaks away modelling the coast and carrying with it large amounts of rock debris, sand and mud.

The Brepollen Bay, at least in the northwestern part, freezes sometimes even in September and is covered with ice till June. Sea ice forms first in shallow water, near the coasts or over shoals particularly in regions protected from wind and with reduced salinity. Sea ice development in the other parts of Hornsund depends on local stability of water and weather conditions, and it varies from year to year.

Vertical active ice cliffs sorrounding Brepollen are 30 km long. Icebergs are delivered by calving of tidewater glaciers during the summer season and drift within the bay in the result of a combined action of winds and currents. Some icebergs, mostly these calved from the Hyrnebreen Glacier, the cliff of which is about 0.9 km long, are initially anchored in mouths of shallow bays in the northwestern part of Brepollen. They play a significant role in an erosion of the bottom and in an ice-rafted debris distribution, spreading considerable amount of dropstones. Some icebergs originated from the glaciers in Brepollen are transported into the main part of the Hornsund Fjord. They are mostly small and only the biggest reach a height up to about 20 m a.s.l.

Due to the isolation by the Treskelen Peninsula, the Brepollen Bay is devoid of Arctic pack ice, carried in masses in June and July into the western part of Hornsund. According to WĘSŁAWSKI & *al.* (1985), this ice is transported from the Barents Sea by Sörkapp Surface Current.

BOTTOM MORPHOLOGY AND BATHYMETRY

The topography of the northwestern Brepollen Bay is characterized by two large and two small, tunnel-valley bays. These are separated by peninsulas or rows of islands developed on the structural elements of the bedrock (Text-fig. 1).

The depths in these bays are not large and only in the Hyrnebukta Bay increase 50 m. In the most shallow bay (Selbukta) on considerable areas the bottom is on the depth less than 10 m. The bottom of the biggest bay (Hyrnebukta) is slightly convex. Near the ice cliff of the Hyrnebreen Glacier the depth oscillates between 30 and 40 m, and increases to the south up to 65 m. The shallower parts are in the area located along the eastern coast with the marginal dead ice of the Storbreen Glacier, where depths range from 10 to 20 m, and in the central part of Hyrnebukta with depths between 25 and 30 m. To the south from that area the depth gradually increases to slightly more than 50 m. The largest depths on the investigated area were measured in the inlet of the NW Brepollen Bay, and were not larger than 130 m.

MASS WATER CHARACTERISTICS

The hydrological conditions in the Hornsund Fjord are not fully recognized yet, and the knowledge of the winter conditions is particularly limited.

According to WĘSŁAWSKI & *al.* (1985), three different water masses dominate within Hornsund and southern Spitsbergen shelf: (*i*) Fjord Coastal and Surface Water, desalted to $28^{\circ}/_{oo}$, with temperature between 0.5 and 3°C, density of 22 to 26, and which forms the upper most 5 to 10 m thick surface layer; (*ii*) Atlantic Coastal Water (Transformed Atlantic Water) with salinity ranging from 33.5 to $35^{\circ}/_{oo}$, temperature 0.5 to 5°C, density of 26 to 28, and which occurs at depths 20 to 100 m; (*iii*) Atlantic Core Water with salinity above $35^{\circ}/_{oo}$, temperature over 5°C, density about 28, and found only in the mouth of the fjord.

The measurements in Brepollen carried out by the Author in 1981 show that the 5—10 m thick summer surface layer has a relatively fresh waters with salinity ranging from 20 to $28^{\circ}/_{oo}$ at the head of the Hyrnebukta Bay, gradually increasing to $32^{\circ}/_{oo}$ down the bay. Both salinity and temperature of the surface water layer increase with the distance from the ice front, when sediment concentration tend to decrease in the same manner. In Brepollen the sediment concentration in points *H1R5* and *H3R7*, located 200 m and 2 km from the Hyrnebreen Glacier front (for location *see* Text-fig. 1), was 920 and 116 mg/l respectively. These data correspond with those received in the Skoddebukta Bay (FILIPOWICZ & GIŻEJEWSKI, *in press*). Vertical profiles of salinity show a well defined halocline near the surface. The surface layer is fresher (less saline), colder (at least near the glaciers), and less dense than the water beneath. Temperature of deeper water close to the ice front decreases slightly. That water is probable a mixture of fjord deep water and meltwater from the glacial ice. However, a maximum sediment concentration measured at mid-depth close to the ice front, coincides with lower salinity and density values which may be caused by interflows from subglacial stream discharges.

The Author's measurements and those reported by URBAŃSKI & *al.* (1980) and GÖRLICH & STEPKO (*in press*) indicate that the sheltered bays or those with an outer sill (*i.e.* Brepollen, Samarinvagen, and Vestre Burgerbukta) commonly bave a cold (−1 to +0.5°C) and saline (about $35^{\circ}/_{oo}$) bottom water mass even during summer season. Waters in the whole vertical profile have a high dissolved oxygen content (6 to 7.5 ml/l) caused by the presence of gas bubbles in melting ice and relatively low biological activity.

In 1984 the hydrological conditions in Hornsund were slightly different (Text-fig. 2). Even in such n isolated basin as Brepollen the influence of relatively warm Atlantic water was moticeable.

The presence of warmer water above boreal benthic fauna suggested that it was only temporary phenomenon (WĘSŁAWSKI & *al.* 1985).

Circulation patterns as indicated by surface plumes and icebergs movements within two or three kilometers of the ice front are extremely chaotic. Different external forces acting together to create this erratic movement include: runoff meltwater streams, subglacial meltwater streams, tidal currents, calving events, and direct melting of glacial ice.

BIOTOPES

Both planktic and benthic fauna play an important role in the sedimentary processes. The former in pelletization of suspended material the latter in bioturbation of soft sediments. Benthic fauna, plankton communities, and biomass distribution in the Hornsund Fjord have been studied in detail by WĘSŁAWSKI & *al.* (1985).

All species found in the investigated area are common in waters of South Spitsbergen. The percentage distribution of dominant planktic species (Text-fig. 3*A*) shows that crustacean decapod larvae and opisthobranch gastropods (*Limacina helicina*) are the most common macroplanktic organisms. The distribution of species in vertical profiles shows that some of them, e.g. pteropod gastropods (*Clione limacina*) and opisthobranch gastropods (*Limacina helicina*) are mainly present in the layer of surface water, whereas tunicates (*Appendicularia*) and crustacean decapoda larvae seem not to be related to any particular water stratum, and are distributed almost equally at all depths.

The zooplankton biomass does not increase 1000 mg of wet weight in 0-50 m water column under 1 m^2 (WĘSŁAWSKI & *al.* 1985). In the Hornsund region, on the most stations the biggest part

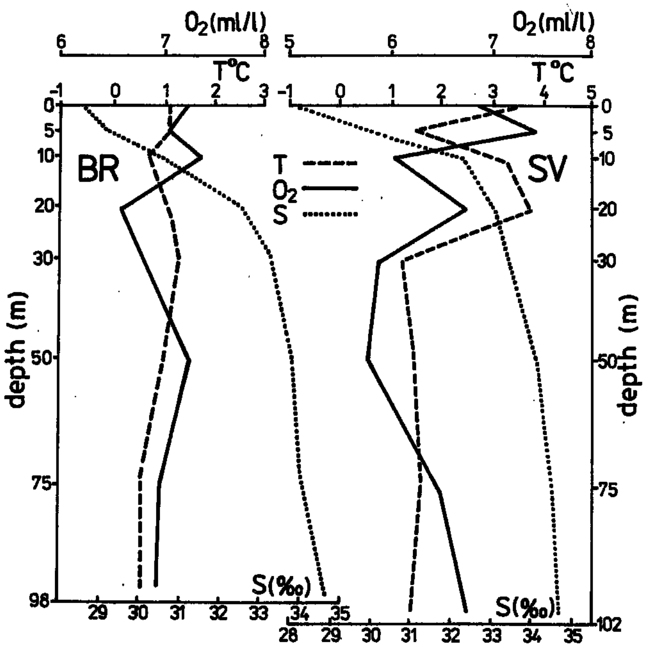


Fig. 2. Temperature, salinity, and dissolved oxygen in waters of Brepollen (*BR*) and Samarinvagen (*SV*) Bays; data from the cruise report of m/s "Jantar"

of biomass occurs in the surface water (0-10 m water startum), as it was the case in the Samarinvagen Bay (Text-fig. 3*B*). The exception was the station located in the NW Brepollen Bay, where the biomass was distributed rather regularly with the biggest amount found within 25-50 m water layer (Text-fig. 3*B*).

Among benthic invertebrate animals in the study area (Text-fig. 3*C*) the polycheates (*Polychaetia*) are the most common, and they dominate on the whole soft bottom. The benthic fauna in Brepollen and Samarinvagen belongs to the community of cold water fauna of the Atlantic origin, which is typical of the whole Hornsund Fjord (WĘSŁAWSKI & *al.* 1985).

RESULTS OF SEDIMENT STUDIES

SURFACE SEDIMENTS

In the Brepollen region during the summer months a glacial erosion together with meltwater rivers eroding subglacially and in periglacial areas supply a high amount of sediment to the bay. The depositional pattern in such

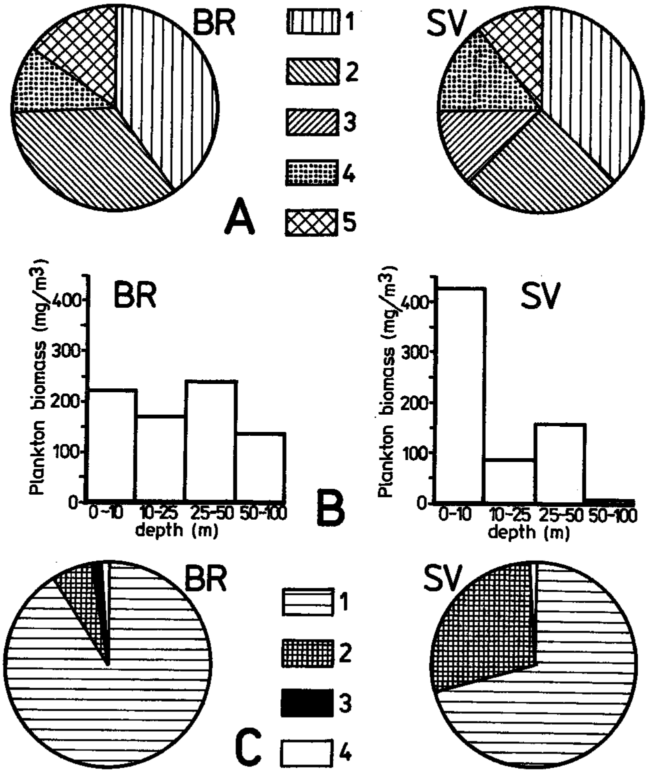


Fig. 3. Plankton and benthos from Brepollen (*BR*) and Samarinvagen (*SV*) Bays
A: Percentage domination of macroplanktic species: 1 — crustacean decapod larvae, 2 — opisthobranch gastropods *Limacina helicina*, 3 — pteropod gastropods *Clione limacina*, 4 — tunicates *Appendicularia*, 5 — malacostracans *Euphasiacea*
B: Plankton biomass distribution in vertical profiles
C: Percentage composition of benthic fauna: 1 — Polychaetia, 2 — Priapulida and Sipunculidae, 3 — Ophiuroidea, 4 — Crustacea

a glaciomarine environment depends on three main sources of sediment: retreating glaciers, icebergs, and meltwater streams.

The retreating glaciers left two main types of sediment: subglacial till released from the base of a glacier, and supraglacial flow till accumulated when the ablation moraine slides down from the ice front.

The dominant ablation process for the main glacier (Hyrnebreen) in the NW Brepollen region is melting rather than calving. But icebergs play the significant role in transport and deposition of coarse-grained englacial material. It is melted out and dropped to the bottom as icebergs float down-fjord. In association with water transported silt and clay supplied by meltwater the resulting sediment is a glacial flour mud with dropstones (so-called ice-rafted sediments).

The main source of sediment delivered to the glaciomarine environment are the meltwater streams. Those from the Hyrnebreen Glacier flow directly to the bay and supply large amounts of silt and clay (glacial flour) rather than coarser-grained sediment. Density contrast between sea water and meltwater helps maintain fine grained sediment in suspension. This suspended material is transported down-fjord by combined action of waves and currents, and settled trough a water column to the floor. Close to a glacial front (*e.g.* the northern part of the Hyrnebukta Bay) where icebergs are rapidly removed, and in shallow bays distant from a glacial front protected from penetration of icebergs (*e.g.* Treskelbukta and Selbukta) periglacial muds are deposited; these are the so-called water transported sediments.

MINERAL COMPOSITION OF THE SURFICIAL SEDIMENTS

The mineral composition of the surficial sediments is tightly related to the bedrock lithology of the source area. Therefore the mineralogy of sediments, especially those deposited in a distance from the land, is very diagnostic in the recognition of the source area, type and direction of transport, and thereby in the classification of sediments into lithofacies according to the origin, type of transport, and depositional pattern.

In the case of the mear-shore glacial and galciomarine sediments in the Hornsund Fjord region, where the bedrock outcrops compose zones of dictinctly different lithology and nearly each bay and galcier is surrounded by the individual source area, the mineral composition of the surficial sediments in the individual bay is nearly the same for all sediments even texturally differentiated, but varies distinctly for different bays.

The northwestern Brepollen Bay is surrounded by clastic and argillaceous rocks (Text-fig. 1), theorfore in the inseparable sediment samples the dominant role is played by quartz with the average content of 35%, and second most plentiful mineral is illite 28%. In a group of minerals with concentration ranging 5 to 10%, there are: feldspar (mostly plagioclase) 9%, kaolinite 7%, muscovite 6%, and siderite 5%. To the group of the lowest frequency belong: chlorite 4%, biotite 3%, and calcite and dolomite all together 3%.

The mineral composlition of analyzed sediments is only slightly size related. Illite is the most ubiquitous and plentiful mineral of the < 0.002 mm sediment fraction. Its average content reaches

37%. The relative increase of the concentration in this fraction is displayd by: kaolinite up to 14%, muscovite to 8%, and chlorite to 5%. The decrease of the concentration was found in quartz, plagioclase, and siderite, and it amounts 23, 4, and 3% respectively. The same content have biotite (3%) and calcite plus dolomite (3%).

TEXTURAL AND PHYSICAL PROPERTIES OF THE SURFICIAL SEDIMENTS

In an attempt to identify and delinite the different types of sediments in the NW Breopollen Bay the detailed examination of the values and areal distribution of the sediment textural characteristics and mass physical properties was performed. Both textural parameters (FRAKES & CROWELL 1973; KRAVITZ 1976, 1982, 1983; ELVERHØI 1984) and mass physical properties (EASTERBROOK 1964; MITCHELL 1976; KRAVITZ 1976, 1982, 1983; ELVERHØI & *al.* 1983; SCHWAB & LEE 1983) were satisfactorily used in the identification and differentiation of the glacial and galciomarine sediments. In this study 20 parameters measured or calculated for 50 sediment samples were analyzed (for location of sampling sites *see* Text-fig. 1).

Gravel content in the surficial layer of the Brepollen sediments is very irregular and oscillates from 0 to 38%. Twenty samples contain no more than 1% of gravel. The greatest gravel content appears in the Treskelubkta Bay in a zone approximately parallel to the moraine covered coast of the Treskelen Peninsula. Sand percentage ranges from 1 to 39%. The greatest concentrations of sand, similarly as it was the case with gravel, are located along the coast of Traskelen. This also happens to the south of the line running between a spit of the Selodden Peninsula and the mouth of the Storbukta Bay, which is due to deposition of coarse-grained material melted out from icebergs. Silt concentration ranges from 14 to 61%, but in 32 samples the silt content is contained in a section 24 to 36%, and is very similar for majority of samples despite the fact if a dominant fraction is gravel or clay. The surface distribution is relatively uniform for the whole study area. In many points clay is the most abundant size fraction, but the range of the clay concentration is wide and oscillates from 9 to 75%.

For the presentation of the regional grain-size distribution, the territorial map with sediment classification proposed by FOLK (1974) was chosen. In the study area (Text-fig. 4) the eight sediment types were defined. The finest one (mud) occurs on the whole area of the Storbukta Bay, in the Hyrnebukta Bay in the wide zone in front of the ice cliff, where it covers the northernmost and central part of the trough. There, sedimentation of suspension dominates, because icebergs are rapidly removed from these areas by relatively stable system of surface currents created by meltwater streams and winds blowing from glaciers. Mud is also present along the both sides of the Selodden Peninsula, in the basal parts of bays Treskelbukta and Selbukta. Both are protected by peninsulas and are too shallow for penetration of icebergs. The exception is the small area located to the west of the straits between Selbukta and Hyrnebukta, where the currents do not allow to settle or even remove by winnowing the already deposited finest fractions. The coarsest fractions cover the zone in Treskelbukta along the coast covered by the ground moraine and in the shallow part of Hyrnebukta on the topographic high along the marginal dead-ice of the Storbreen Glacier. On the remaining vast area of the central part of the NW Brepollen Bay dominate sandy and gravelly muds. Further details are presented on the territorial map (Text-fig.4).

On the basis of size-frequency the seven textural parameters reflecting the shape of the distribution curves and sorting of the sediment samples were calculated. They are sensitive to environment and reflect differences in the transportation and deposition pattern. In general, descriptive statistics requires three parts: location, dispersion, and shape. Every moment system uses mean for location, standard deviation for dispersion, and skewness and kurtosis in combination for distribution shape.

The first moment (mean size) values oscillate in a wide range from 1.31 to 9.14 Φ, but for 23 samples these values are between 7 and 8 Φ. The second moment (standard deviation) ranges from 1.97 Φ (poorly sorted sediments) to 4.93 Φ (extremely poorly sorted sediments) according to the sorting classification (Folk & Ward 1957, Friedman 1962). Over 80% of samples are classified in a very poorly sorted class (2 — 3.99 Φ). The third moment (skewness) for the vast majority (88%) of the samples is negative. The whole range for all samples varies from -0.95 to $+0.25$ Φ. According to Folk & Ward (1957) classification 60% of all samples belongs to the class defined as nearly symmetrical including all samples with a positive skewness value. The fourth moment (kurtosis) measures the peakedness of a given curve and similarly as it was the case with skewness its value is more related to the shape of the grain-size distribution curve, than to the sample fraction. Kurtosis values for all samples oscillate from 1.19 to 6.74 Φ they change gradually in the whole range without any distinct sections. The majority of the samples from the surficial layer in NW Brepollen

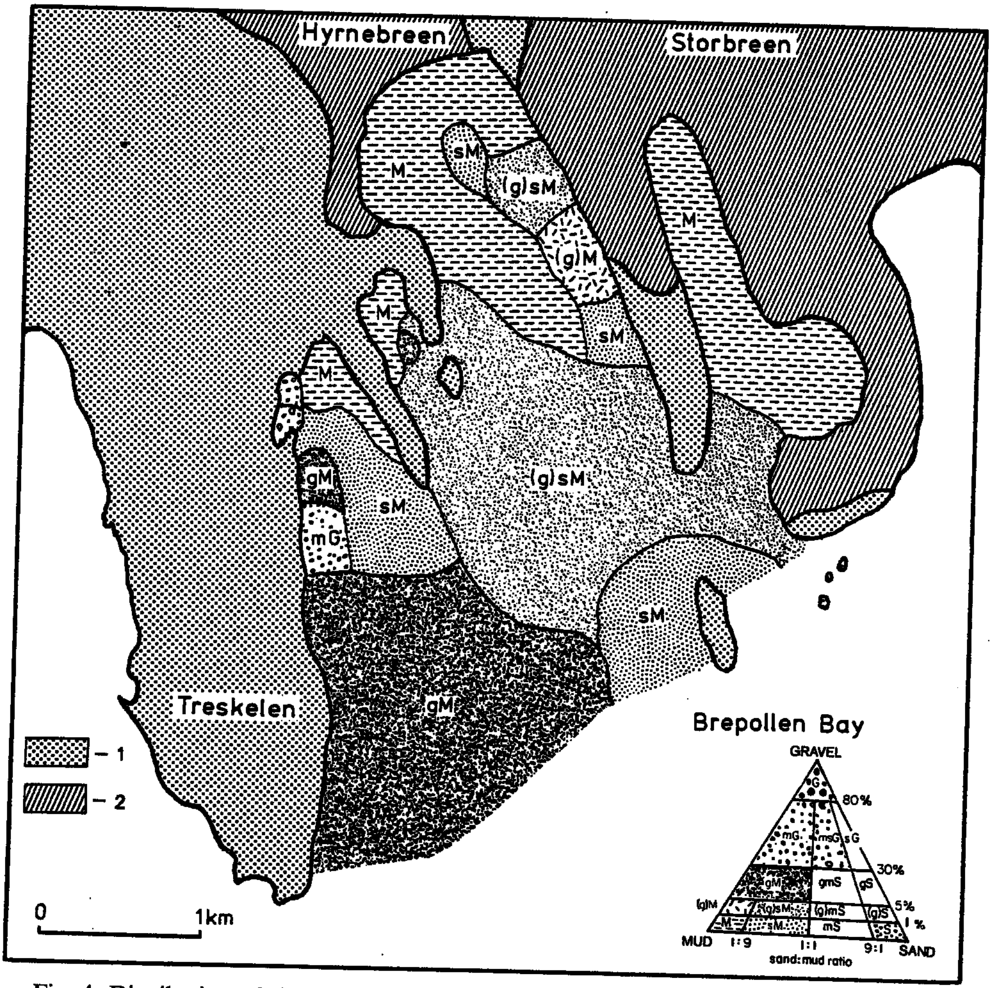


Fig. 4. Distribution of the surface sediments in NW Brepollen: 1 — land, 2 — glaciers. Classification of sediments *after* Folk (1974, *with minor modifications*): G — Gravel, mG — muddy Gravel, msG — muddy sandy Gravel, gM — gravelly Mud, gmS — gravelly muddy Sand, gS — gravelly Sand, (g)M — slightly gravelly Mud, (g)sM — slightly gravelly sandy Mud, (g)mS — slightly gravelly muddy Sand, (g)S — slightly gravelly Sand, M — Mud, sM — sandy Mud, mS — muddy Sand, S — Sand

have platykurtic, board sediment distribution curves and kurtosis values below 3. The minority of samples have leptokurtic curves and their kurtosis exceeds 3. Only three distribution curves can be considered as mesokurtic.

One of rarely computed parameters is mean cubed deviation (*MCD*), proposed by FRIEDMAN (1967). In the surficial sediments of NW Brepollen *MCD* takes values in huge range from −54.26 to +19.26 *Φ*. Up to 88% of samples has a negative values, and 64% is contained in a range between −19 and −1 *Φ*. Deposits with positive values of *MCD* are found close to the coast in the northern part and near the mouth of Treskelbukta Bay. Also in the Hyrnebukta Bay, vis-a-vis the land in not icy parts of the western and eastern coasts. Another parameter rarely computed is delta, which is a derivative of skewness and kurtosis, and for the first time proposed by LEROY (1981). Delta values range from −0.60 to +0.52, however 80% of samples have the negative values. The last prarameter related to the grain-size distribution is grading factor proposed by MARTINI (1971). Its values oscillate betwen −2.08 to +0.77, but up to 94% of analyzed samples has the positive value. In Storbukta and Hyrnebukta the variability is relatively small whereas in Treskelbukta the distinctly higher differentiation of the grading factor values is found.

From among mass physical properties nine were chosen. Four of them are: water content, porosity, unit weight, and void ratio. Natural water content of the surficial sediment layer from NW Brepollen Bay is very differentiated and varies from 18 to 123%. However, the values below 30% and above 85% are found in a few samples only. The regional distribution has an uncomplicated character. The highest water content, over 100% of dry weight, is found in Storbukta and in the narrow zone along the ice cliff in Hyrnebukta. The porosity values oscillate in a range from 33 to 77%, and the regional distribution has a similar pattern to that of water content. The unit weight values determined for the studied sediment samples range from 1.39 to 2.14 g/cm^3, but only six samples have the value over 1.90 g/cm^3. They were collected in three separated areas located close to the coasts in Treskelbukta, Selbukta, and Hyrnebukta. The lowest unit weight values, *i.e.* less than 1.50 g/cm^3, were found in the Storbukta Bay and along the glacier cliff in the Hyrnebukta Bay. The void ratio values oscillate from 0.49 to 3.30. The regional trend of void ratio values is, as expected, similar to that of the water content and porosity, and is inversely proportional to the unit weight distribution pattern.

The next four parameters from the group of mass physical properties are Atterberg limits and indicies. Some intervals within cores were too coarse for Atterberg limits testing, fortunately it was possible to determine them for all 50 grab samples. The liquid limit values range from 20 to 99% and the plastic limit values range from 13 to 47%. Their regional distribution pattern is very similar to each other. The highest values were determined in sediments from Storbukta and from the northern parts of Hyrnebukta. The lowest values have sediments which cover the bottom of Treskelbukta in a zone parallel to the Treskelen coast. On the basis of Atterberg limits and natural water content two indicies were calculated. The first, plasticity index ranges between 7 and 57% with the mean value of 28%. The territorial distribution presents the high variety, particularly in an area of the northern part of Hyrnebukta where in neighboring points the sediment samples have the highest and lowest values. The second computed index is liquidity index the value of which oscillates in a huge range from 69% up to 560%; however, the values higher than 170% were calculated for four samples only.

The last computed parameter characterizing the physical attributes of sediments is activity understood as relationship between plasticity index and clay content. The activity values of the surface sediments range from 0.14 to 1.10. Acording to SKEMPTON's (1953) classification they belong to normal Ac 0.75 to 1.2 and inactive Ac < 0.75, with majority of sediments belonging to the second class. None of the sediments in the study area are classified as active (mean Ac > 1.25).

The detailed analysis of maps presenting the distribution of all 20 measured or computed textural and physical parameters of the surficial sediments in the NW Brepollen Bay (FILIPOWICZ 1989) has shown the existance, for majority of parameters of two regions with a different trend in values changes. In the first, represented by the Treskelen Bay, isolines of values on the maps have a meridional disposition *i.e.* they are parallel to the coast of the covered by ground moraine Treskelen Peninsula. In the second, represented by the Hyrnebukta Bay, isolines are lying evenly with a parallel of latitude, *i.e.* are approximately parallel to the ice cliff of the Hyrnebreen Glacier and perpendicular to not icy coasts of peninsulas in the west and east, showing at the same time the reverse increase of values.

For grading factor, water content, porosity, void ratio. liquid limit, plastic limit the trend is, the closer to the glacier cliff the higher values and reversely the closer to the Treskelen coast the lower values. Distribution of gravel content, standard deviation and unit weight shows the same pattern but with the opposite increase of values. Towards the ice cliff values decrease, whereas towards the Treskelen coast values increase. The different pattern of distribution is displayed by: skewness, kurtosis, mean cubed deviation, and delta. Their isolines of values in the Treskelbukta are lying evenly with a parallel of latitude, *i.e.* are perpendicular to the Treskelen Peninsula, whereas meridionally in the Hyrnebukta, *i.e.* are perpendicular to the Hyrnebreen ice cliff and parallel to bordering peninsulas. Remaining parameters are distributed irregularly, even chaotically, and in the case of liquidity index and plasticity index in the some neighboring points the values show extremely high contrast.

In recapitulation, it should be emphasized that though the analysis of values of the textural and physical properties of the surface sediments from NW Brepollen has allowed to present the detailed territorial distribution and has shown similarities between some samples and differences between the others, but is not sensitive enough to classify unmistakably samples into homogeneous lithofacies. It happens very often that the sediment sample has some features considered to be typical of the glacial environment, whereas the other are typical of marine sediments. Consequently, it is thought that any conclusions with regard to classification of the sediments or any declarations about their origin exclusively from the analysis of values of the individual parameters would have only an approximative character.

CLASSIFICATION

Individually analyzed grain-size distribution, textural measurements, and mass physical properties show a very limited usefulness in recognition and classification of the sediments from the glaciomarine sedimentary environment of the Brepollen Bay. The same results, however, could te the basis for one from the number of statistical analyses. Many of researches have sought new techniques of classification which incorporate the massive data-handling capabilities of the computer. For example, KRAVITZ (1982) satisfactorily uses Q-mode factor analysis, but in DAVIS' (1986) opinion the best method seems to be a cluster analysis. This latter method is used in this study.

CLUSTER ANALYSIS

In cluster analysis, in order to perform classification by assigning observations to groups so that each group is more or less homogeneous and distinct from the others, the data set is arranged as *n* (raws) and *m* (columns) matrix. Columns are created by variables, in this study 20 granulometric, textural, and physical parameters measured for 50 samples which form raws. The mineral composition of sediment samples in consideration of the high uniformity was not included into clustering. Without any preliminary assumptions, treating an each parameter value equally, the measure of similarity between all pairs of samples must be computed. A number of alternative mathematical methods have been developed. The consideration of these clustering techniques and their merits is beyond the scope of this paper, but they were in detail explained by DAVIS (1986) and widely quoted elsewhere (FILIPOWICZ 1989). The last step is the construction of a dendrogram, which is the most common way of presenting the results of clustering. All samples on the dendrogram (Text-fig. 5) are grouped according to their similarity. The picture of them is complex on the level of low distances, but three distinct groups can easily be distinguished.

The first group placed on the right side of the dendrogram (Text-fig. 5) is the smallest one and markedly less homogeneous than two remaining groups. The samples belonging to this group are related to each other at the relatively large similarity distance, but do not compose any distinct subgroups. There are 8 samples (numbered *30, 32, 41, 35, 16, 18,* and *29;* for location see Text-fig. 1). This group as the whole is separated from the others, however at the large distance is related to groups described below. Sediments of these 8 samples belonging to the first group are characterized among the other things by the coarsest-grained fraction (sand and gravel are a major component), very bad sorting, largest skewness values (often positive), distinctly lowest water contents and highest unit weights. These features characterize them as relict sediments. and allow to classify them as galcial tills. Values of all parameters for each of distinguished groups are given below.

The second group (Text-fig. 5) contains 24 samples. This group is not uniform and consists of four subgroups. The first is composed of 8 samples (numbered *13, 24, 8, 14, 21, 15, 11,* and *12*); the second consists of 6 samples (numbered *37, 42, 48, 43, 23,* and *22*); to the third belong 7 samples (numbered *49, 17, 31, 45, 50, 38,* and *47*); and the fourth is the smallest consisting of only 3 samples (numbered *28, 46,* and *39*). This complex group is however very distinct as the whole, and at the medium distance is related to the next. Sediments of these 24 samples are not uniform and their values of particular parameters vary in wide ranges, what sugests that they were deposited by the complex sedimentary processes. The best explantion for supplying such a differentiated material and assemblage of it with typical marine sediments seems to be domination of transport by icebergs. This group was classified as ice-rafted sediments (*IRS*).

The third group, on the left side of the dendrogram (Text-fig. 5), bears 18 samples (numbered *27, 33, 4, 1, 7, 9, 25, 36, 34, 10, 5, 40, 3, 20, 6, 2, 16,* and *26*). This is the most uniform group where

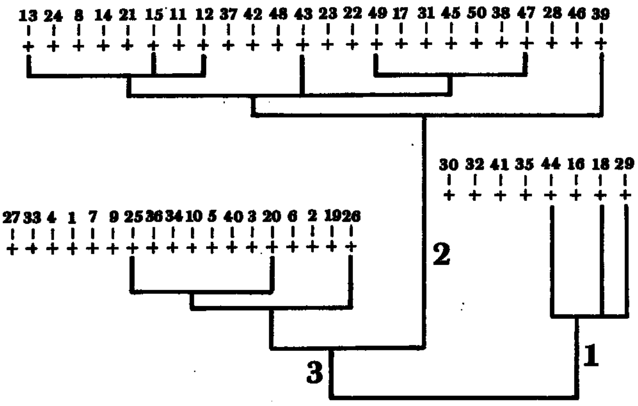


Fig. 5. Dendrogram of hierarchical clauster analysis grouping fifty samples of the surface sediments from NW Brepollen into three sediment types

the samples are related to each other at the relatively low similarity distance. This is a result of relatively narrowest ranges of parameter values. Sediment samples that represent the last group are characterized by the finest-grained texture, best sorting, small skewness values, highest water contents, large void ratios and porosities, and smallest unit weights. Such features are interpreted to characterize recent marine sediments. These sediments were identified with sedimentary envitonment represented by lithofacies deposited from suspension, and were classified as water transported sediments (*WTS*).

DISTRIBUTION OF LITHOFACIES

A composite map of the areal distribution of the three distinguished lithofacies shows the areas of their occurrence in the surface sediment layer of the NW Brepollen Bay (Text-fig. 6). The lithofacies classified as the till occupy

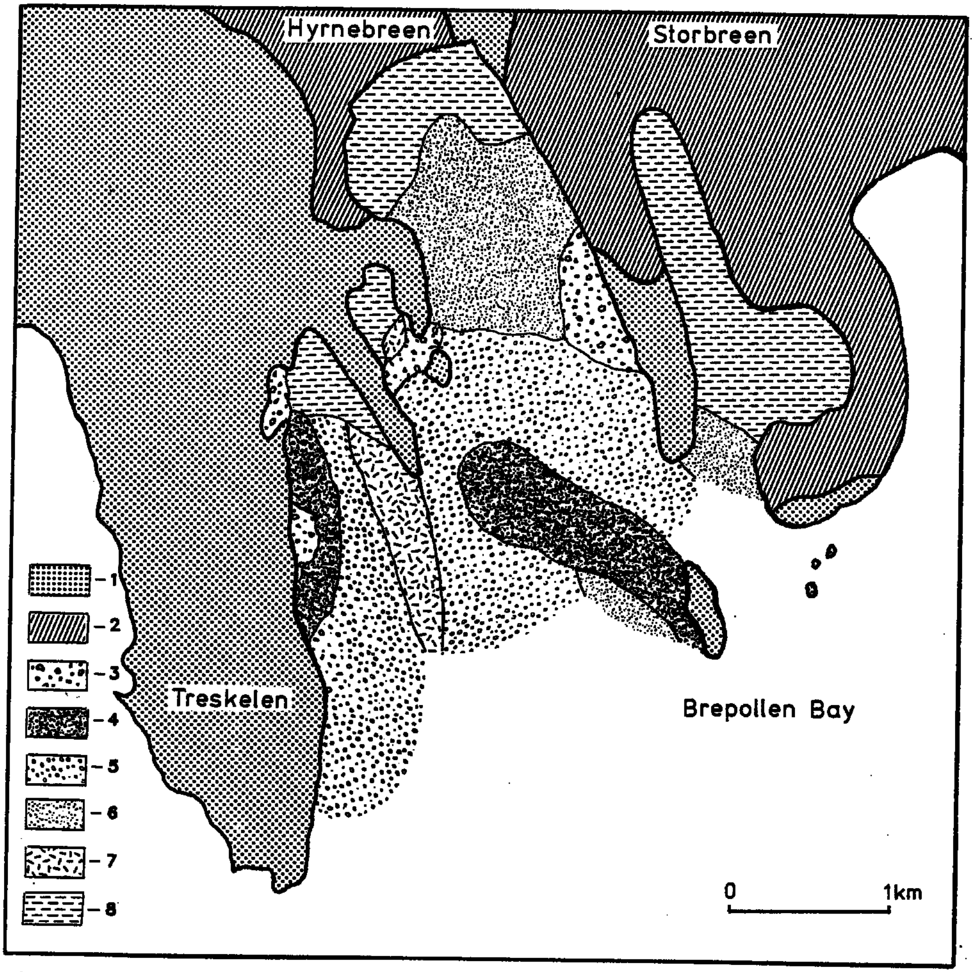


Fig. 6. Territorial distribution of the distinguished lithofacies grouping surficial sediments from NW Brepollen
1 — land, 2 — glaciers, 3 — glacial till, 4-7 — subgroups of ice-refted sediments, 8 — water transported sediments

five small and separated areas. Three of them are located in Treskelbukta close to the Treskelen Peninsula which creates the western coast of the bay. One, which is the biggest is located in the eastern part of Hyrnebukta along the coast of the peninsula covered with moraines and marginal ice of the Storbreen Glacier. The last one occurs in Selbukta vis-a-vis to the straits joining that bay with Hyrnebukta. Water transported sediments occupy four areas representing two types of localization. The first is in Storbukta and in the northernmost part of Hyrnebukta. These two places are surrounded by frontal parts of glaciers with ice-cliffs. The second type is in, well isolated from current activity and iceberg penetration, shallow parts of Treskelbukta and Selbukta. The whole remaining area of the investigated region is covered with not uniform material classified as ice-rafted sediments.

Taking into consideration a fact that sediments representing this group are characterized by varied values of textural and mass physical parameters, and that the dendrogram with results of the cluster analysis of this group consistis of four distinct subgroups, the group of ice-rafted sediments on the territorial map was divided into several fields represented by distinguished subgroups (Text-fig. 6). The strong relation with present bathymetry, distance from the coasts covered with moraines, and distance from the active glaciers ice cliffs is noticeable.

DISCRIMINANT FUNCTION

After distinguishing three homogeneous groups of surficial bottom sediments from the NW Brepollen Bay, the first task is to check if classification is correct and the second to find a function which could define each group. The best method for that seems to be the discriminant function (Davis 1986). This is a statistical technique which is contrary to cluster analysis, because it *a priori* predetermines the number of groups and on each original sample defines as belonging to a specific group. Assuming as such groups those three clusters distinguished on dendrogram the first task is to find a function, based on values of 20 analyzed parameters, expressed as two co-ordinates (so-called canonical discriminant functions) pointing out the position of each sample on the datum plane. Then we must search for linear functions along which the clusters have the greatest separation expressed graphically as straight borders on the territorial map.

Finally, plotting all results extracted during discriminant function one can construct the final diagram (Text-fig. 7) which presents; (*i*) fields occupied by three distinguished lithofacies; (*ii*) borders between them; (*iii*) positions of the group centroids, defined as the mean discriminant scores of the function for each group (the more representative sample for a particular group the closer its position to centroid); (*iv*) the identification of misclassified samples (cases not falling within the outlined boundaries). There are two such samples, number *30* classified in the cluster analysis as till here found itself within the field of ice-rafted sediments and number *11* classified as belonging to *IRS* here is found in the field of water transported sediments. Two of fifty, it means that as much as 96% of semples from Brepollen were correctly classified on the basis of the cluster analysis. This result proves that the cluster analysis is the method that can be used satisfactorily in distinguishing the lithofacies.

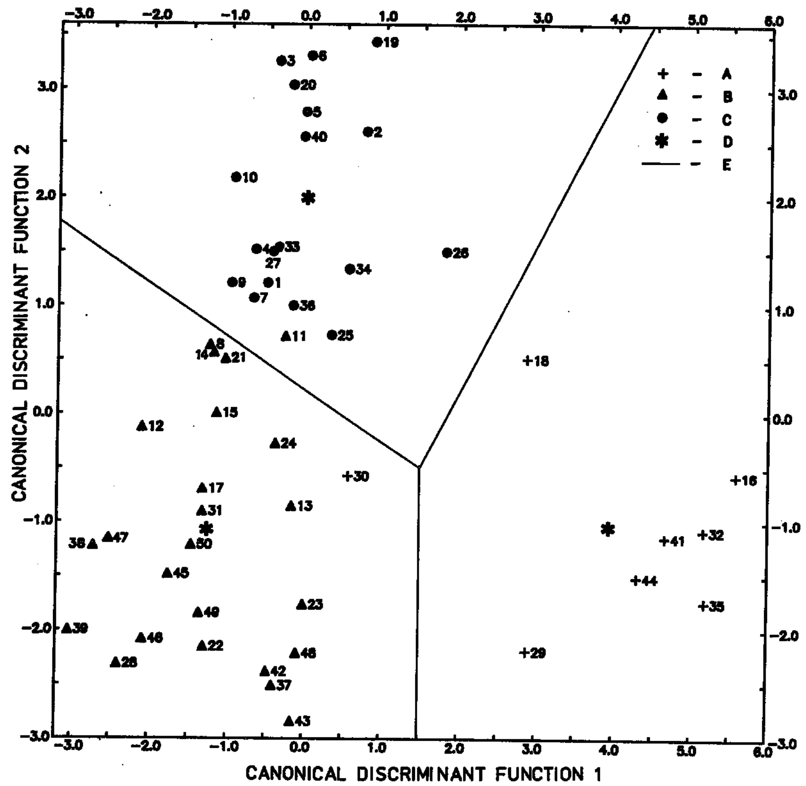


Fig. 7. Scatter plot of two canonical discriminant funtions on the territorial map grouping three types of the surface sediments from NW Brepollen
A — till, **B** — ice-rafted sediments, **C** — water transported sediments, **D** — centroids for each group, **E** — border lines between groups

The discriminant function can be additionally used in classification of samples of unknown origin. For such a sample 20 described above analyses of textural and mass physical properties should be performed and then two canonical functions calculated and their values plotted and marked on the scatter plot of the territorial map (Text-fig. 7). Finally, the position of the mark should be identified with one of three groups (lithofacies).

SUBSURFACE DEPOSITS

Six cores from the Brepollen Bay were availed and analyzed (FILIPOWICZ 1989). Three of them are interesting enough to be described here. The core *BR-R1*, 50 cm long was obtained from the depth of 98 m (for location *see* Text-fig. 1). Even on the surface of the core a regular stratification is well

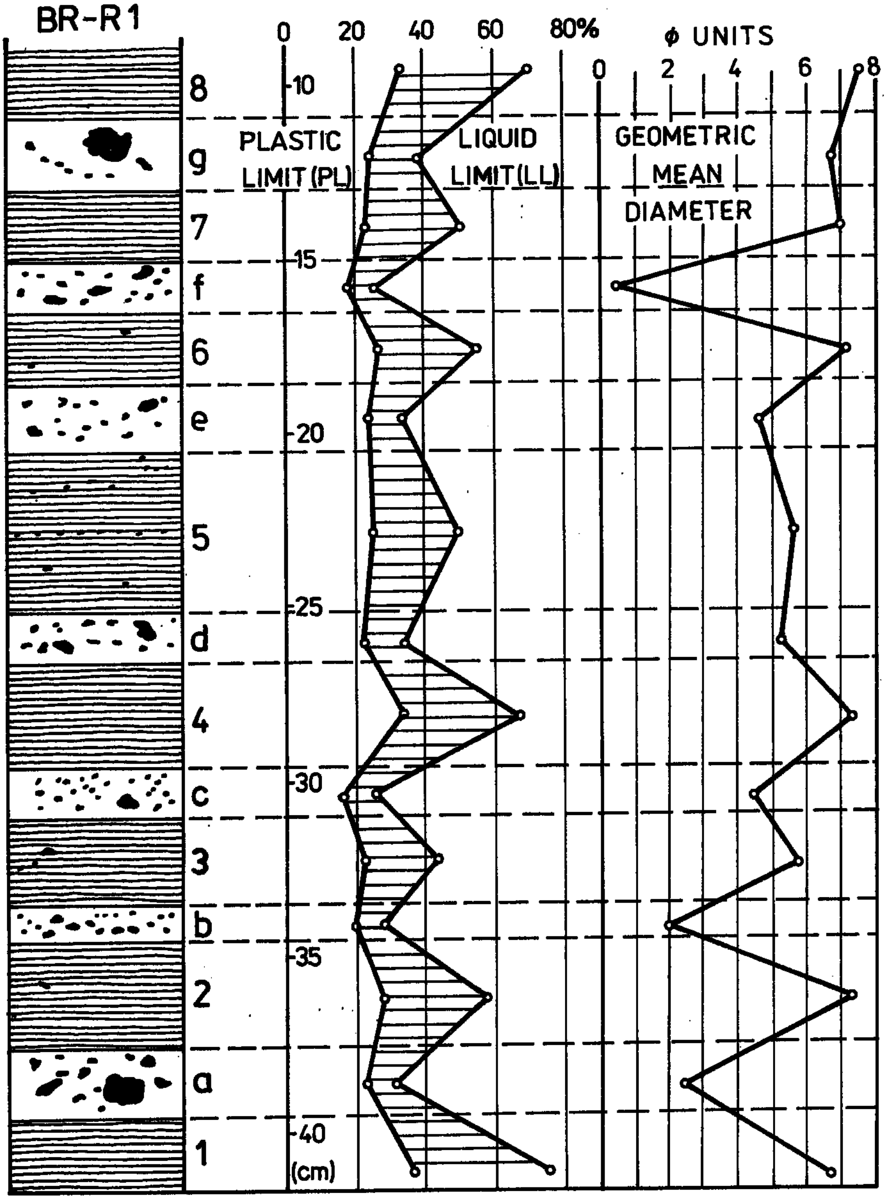


Fig. 8. Vertical section of core *BR-R1* with plasticity (*PI* = *LL*– *PL*) and geometric mean diameter 1, 2,.. 8 — identify beds of argillaceous laminated silts; a, b,.. g — indicate beds of sands with dropstones

visible, but the real thickness of layers and their content on the X-radiography were found. Thicker layers (2 to 5 cm) consist of coherent fine-grained sediment, dark gray in color. These layers (marked with numbers in Text-fig. 8) do not contain any pebbles, however, irregular single laminae of coarse sand are present. Some sporadic current activity may be responsible for the formation of the laminae. The lowest silty layer (bottom of the core) was somewhat mottled in appearance due to the presence of blackish bioturbation patches. The thin layers with the thickness of 2 cm are grayish-brown in color and consist of coarse-grained material with dropstones up to 1.6 cm in diameter. The scattered pebbles, the largest ones including, are mostly sub-angular to sub-rounded. These coarse-grained layers (marked with letters in Text-fig. 8) contain a number of irregular sandy laminae. Those laminae together with the preferred horizontal orientation of the largest pebbles indicate a current activity.

Measurements of size fractions and mass physical properties were carried out separtely for individual layers. The cumulative frequency curves illustrating grain-size distribution of sediment subsamples taken from argillaceous layers and from sandy layers with large content of dropstones were considerably different. The former were monomodal and the mean grain-size for these sediments oscillates from 0.006 to 0,02 mm i.e. 7.4—5.7 Φ (Text-fig. 8). The latter were bimodal with sediment mean grain-size ranging, with one exception, from 0.028 to 0.8 mm, *i.e.* 5.2—0.4 Φ (Text-fig. 8).

Such regular, varve-like layers of silty deposits and coarse-grained ones are very unusual in a glaciomarine sedimentary environment. The core *BR-R1* is the only one, among twelve cores taken in the Hornsund region, which has such distinct layers. In all remaining cores the gravel fraction is scattered without any regularity and does not form any layers. In comparison with cores from other Spitsbergen fjords described by ELVERHØI & *al.* (1983) and those from Canadian Arctic fjords (GILBERT 1982, KRAVITZ 1983) the core *BR-R1* with such a distinct stratification seems to be unique and more similar to typical lacustrine preyglacial sediments. The varve-like stratification of sediments from the fjord environment can be interpreted as a result of density currents. For instance, in the Isbjornhamna Bay located in the western part of the Hornsund Fjord such density currents initiated on the steep slopes of the bottom by an unusually big calvings of the Hansbreen Glacier or by storms from the open ocean. They create irregular, single, coarse-grained interbeddings in homogeneous silty deposits.

The Brepollen Bay, from which the core *BR-R1* was obtained, is nearly completely isolated from the influences of the open ocean, and in addition the point *BR* is placed in a distance from the active glacier cliff. East of that point the elevation of the Hornholmen Island covered with a coarse-grained material is located. Undoubtedly this is the source area supplying sediment for density currents. In spite of Brepollen isolation the only factor which could initiate density currents seems to be a storm. The fact, that for the great part of the year the bay waters are frozen, explains the stratification regularity. The possible storm could happen only in summer season lasting here from July to September.

Another two cores (*H3-R7* and S1-R8) are worthy of notice. The core *H3-R7*, 68 cm in length was obtained in the Hyrnebukta from the depth of 44 m in the point *H3*. The upper 57 cm consists of dark gray fine-grained matrix containing some dropstones (tiny pebbles and granules). This entire layer is only slightly bioturbated but blackish patches are mostly pronounced in the upper 28 cm of the core. There is a sharp contact at the base of this layer. The lower part, 11 cm thick, consisted of sand with a large admixture of gravel. The pebbles are angular to sub-rounded. There were no sedimentary structures in this sediment and no dominant pebbles orientation. This part of the core was incoherent and after being removed from the corer suffered disintegration.

The core *S1-R8* was only 15 cm long and was obtained from the depth of 5 m in the point *S1* in the Selbukta Bay. The upper 9.5 cm of the core is made up of fine-grained sediment without any ice-rafted pebbles or granules. The lower 6.5 cm of the core, below a distinct, sharp contact consists of coarse-grained sand with numerous sharp-edged fragments of rocks up to 2 cm in diameter and angular to sub-rounded pebbles which show no prevailing orientation. Noticeable difference in color between two parts was visible. The upper, silty part was graish-brown and the lower, coarse-grained was dark gray.

The cumulative-frequency curves of samples from a silty part of the core *S1-R8* (Text-fig. 9) are typical of very fine-grained sediments deposited from suspension transported predominantly by water. Their mean grain-size is on the average 0.0055 mm (7.6 *Φ*). Whereas cumulative curves of the silty part from the core *H3-R7* (Text-fig. 9) are bimodal due to an admixture of ice-rafted material and their mean grain-size is on the average 0.045 mm (4.6 *Φ*). The difference resultes from the location of bays from which analyzed cores were obtained. Selbukta is isolated by two peninsulas (for location *see* Text-fig. 1). There is not any glacier on the coast of this bay nor any creek delivering suspension to Selbukta. Thus the only source of the sediment is the finest suspension transported from the Hyrnebukta Bay. This bay is located in the front of the active glacier cliff. There, besides the sedimentation dominated by water transport the important role is played by ice-rafted transport. When the Selbukta Bay is not only well isolated but also too shallow for icebergs. The additional source of the sediment for both bays is the dust blown from the coasts mainly during strong autumn winds. But without detailed measurements it is hard to estimate the scale of this delivering.

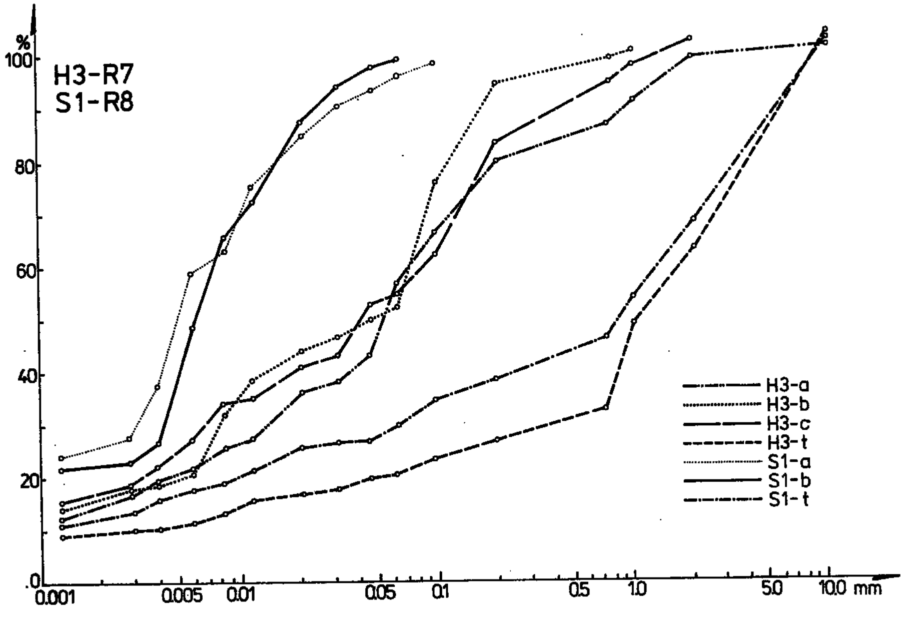


Fig. 9. Cumulative curves of grain-size distribution for various types of glaciomarine and till deposits from cores *H3-R7* and *S1-R8* from Brepollen Bay

Locations of core sampling indicated in Text-fig. 1

H3-a, b, c — unlaminated glaciomarine sediments from core *H3–R7*; H3-t — till from core H3-R7; S1-a, b — unlaminated glaciomarine sediments from core *S1-R8*; S1-t — till from core *S1-R8*

Two remaining cumulative-frequency curves (Text-fig. 9) illustrate size fractions of subsamples taken from described above, distinctly different lower parts of the cores *S1-R8* and *H3-R7*. Their mean grain-size is about 1 mm (0 Φ).

Sediments from the upper silty part of the core *S1-R8* and from argillaceous layers of the core *BR-R1* have an average water content (from 43 to 68%) much higher than the other core sediments. This can be attributed to the finer grained nature of these sediments. The samples containing dropstones as these from the upper part of the core *H3-R7* have the water content values oscillating from 19 to 38%. The coarse-grained sediments from the lower parts of the cores *S1-R8* and *H3-R7* contain on average water content of 16.5%. In some parts of cores the values of water content gradually decreases down the core. This is due primarily to an increase of the coarse fraction, because the water content shows a strong negative covariance with sand and gravel content. However, some parts of cores show the same trend without an accompanying increase of size fraction. It could be due to overburden pressure resulting in the consolidation and dewatering of the deposit.

The plasticity of the sediments was investigated by means of the Atterberg liquid and plastic limits tests and classified according to Casagrande plasticity chart (CASAGRANDE 1948). The highest plasticity (*LL* above 70) is found in some argillaceous laminated silts in the core *BR-R1* (Text-figs 8 and 10). All argillaceous layers from *BR-R1* and silts from the upper part of the core *S1-R8* are plastic with the liquid limit values ranging from 45 to 76 and their plots on the plasticity chart (Text-fig. 10) classifies them as the sediments of medium to high plasticity. The sediments with dropstones are found to have, in most of the samples, low to medium plasticity.

Some parts of coarse-grained sediments from the cores *S1-R8* and H3-R7 were fine enough to undergo Atterberg limits testing and were found to have the liquid limit values from 23 to 28 (low plasticity). The other parts were too coarse for testing and therefore are considered as non-plastic. On the Casagrande plasticity chart (Text-fig. 10) most of plotted sediment samples is located along the straight zone, roughly parallel to the *A*-line, and generally above that empirical boundery. It suggests a similar mineral composition of the clay-sized fraction of the sediments. Similar to the water content, in samples from neighboring layers of the core *BR-R1*, also the plasticity (Text-figs 8 and 10) reveals a great difference, what testifies essential changes in the sedimentation processes.

The activity (*Ac*) values of all fine-grained sediment samples from the cores *BR-R1*, *S1-R8*, and *H3-R7* belong into the normal (*Ac* from 0.75 to 1.25) category (Text-fig. 11). None of the sediments in the cores are clasified as active (mean $Ac > 1.25$). The sediments from the coarse-grained layers of the cores *BR-R1*, *S1-R8*, and *H3-R7* in most cases have activity values lower than 0.75, typical of inactive materials derived in a large part from glacial processes. Because of a very low content of clay size fraction (< 0.002 mm) in these sediments, their positions on the activity chart (Text-fig. 11) are close to the begining of co-ordinates. The relationship between plasticity index and clay fraction content (Text-fig. 11) depends not only on the clay content but also on its mineral composition. Samples with the same content of clay-sized minerals derived largely by mechanical glacial erosion on non-argillaceous rock (*e.g.* sample *g;* Text-fig. 11) have the lower activites than clay fractions composed of clay minerals (*e.g.* samples *b* and *5;* Text-fig. 11).

The comparison by discriminant function of 20 size and mass physical parameters of sediments from cores to surface sediments from NW Brepollen grouped on scatter plot with two canonical discriminant functions, made it possible to classify sediments from cores. Sediments from upper part of *S1-R8* to the group of water transported sediments, from upper part of *H3-R7* to a group of ice-rafted sediments. Both *S1-R8* and *H3-R7* lower parts to a group of till. The last ones are interpreted as glacial till left on the bottom of the bays by the Hyrnebreen Glacier. However, they belong to a group of till but the value of mean grain-size and fine fractions content of these tills is markedly different from the surficial sediments described as tills. On the other hand they

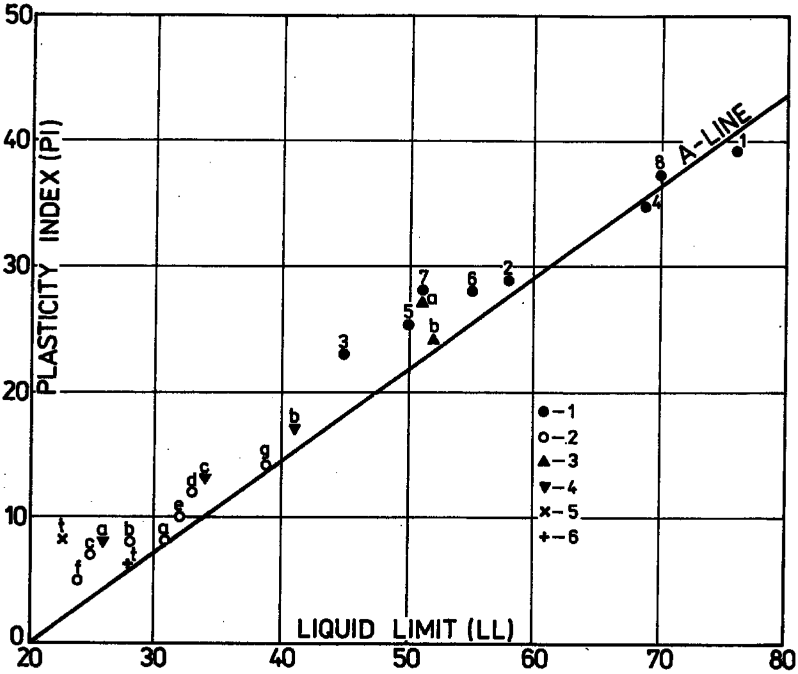


Fig. 10. Casagrande plasticity chart with plots of the Brepollen Bay sediments from core samples 1 — subsamples from beds of argillaceous laminated silts, core *BR-R1* (numbers coincide with bedw indicated in Text-fig. 8); 2 — subsamples from beds of sand with dropstones, core *BR-R1* (symbols coincide with beds indicated in Text-fig. 8); 3 — unlaminated glaciomarine sediment, core *S1-R8*; 4 — unlaminated glaciomarine sediment, core *H3-R7*; 5 — till, core *S1-R8*; 6 — till, core *H3-R7*

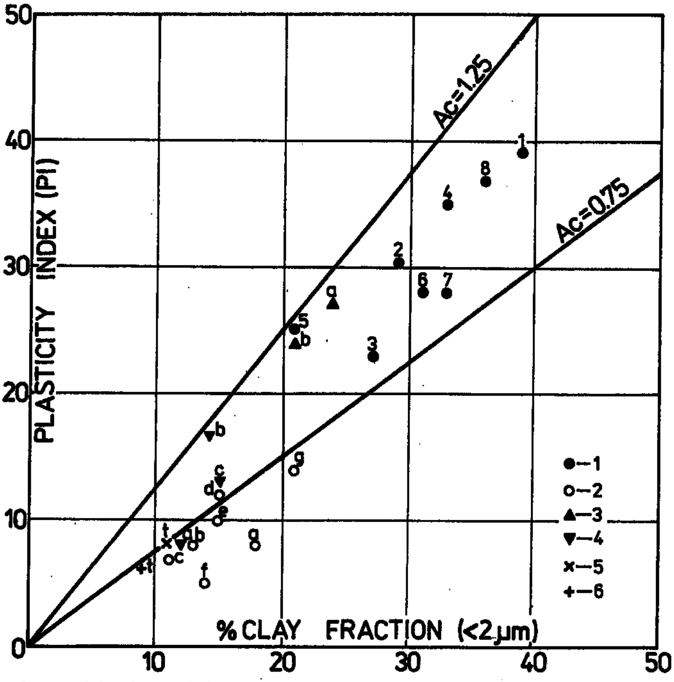


Fig. 11. Activity chart with plots of the Brepollen Bay sediments from core samples (for legend *see* Text-figs 8 and 10)

are very similar to those from Skoddebukta Bay (Filipowicz & Giżejewski, *in press*). There were found zones covered with coarse-grained sediments, sometimes devoid of fine-grained matrix, related to relatively stable currents which remove silt and clay by winnowing.

The identification of sediments with marine and glacial origin allowed to estimate sedimate sedimentation rates in the Brepollen Bay.

SEDIMENTATION RATES

The detailed information on sedimentation rates were obtained from the thickness of the glaciomarine sediments using the till surface as the lower time marker and the time elapsed since the deglatiation of that area. In the core *H3-R7* from the Hyrnebukta Bay, the thickness of the glaciomarine sediments above the till amounts 570 mm. The Hyrnebreen Glacier retreated from that point in 1956, what gives the average sedimentation rate of 20 mm annually. The much smaller rate was calculated for the Selbukta Bay. In the core *S1-R8* from the point *S1R8* the till surface was found under 95 mm ot the water transported sediments. In that point deglaciation also took place in 1956, what gives the average accumulation rate of 4 mm a year. This is due to the fact that after the deglaciation of Selbukta, the only source of the sediment was the suspended matter transported around the peninsula from Hyrnebukta. The highest value of the sedimentation rate is found in the Hyrnebukta Bay close to the Hyrnebreen Glacier cliff (point *H1R5*), where a thickness of glaciomarine sediments amounts 330 mm and the deglaciation took place 3 years before the measurements, what gives a value of 110 mm annually. Similar values of the sedimentation rate were calculated for Kongsfjorden (Elverhøi & *al.* 1983). 50—100 mm a year for the inner basin, and 1—2 mm a year for the central basin.

Such high sedimentation rats of very fine-grained sediments as it was the case of areas close to the Hyrnebreen Glacier cliff prove that the suspended matter is not settled as individual grains but as pelletized by zooplankton and first of all as inorganically flocculated particles. In basins where the suspended sediments remain unflocculated grains settle more slowy. For example, according to Stokes Law, Gilbert (1982) calculates that a particle of fall diameter 14 μm will reach the bottom of a 100 m deep salt water column at 0°C in 12 days; a 4 μm particle requires 146 days, and 1 μm 13 years.

The point *H1R5* is interesting not only because of the highest sedimentation rate, but also because of water content in the surficial sediments. The surficial sediments were so saturated that after several unsuccessful attempts to take the core, the thickness of sediment was calculated from the sility trace left on the corer. Finally, the core *H1-R5* was obtained, and at its bottom the frozen sediment and pure ice were found. This fact proves that after its retreat the glacier leaves the dead ice on the bottom and accumulation takes place on the ice. This fact gives also support for interpretation (Görlich 1986) that depressions in the bottom of the Isbjornhamna Bay were originated by melting of the dead ice blocks. It is known from hydrological measurements that in the Hyrnebukta Bay the salt (34°/₀₀) and cold, near-bottom waters usually stagnate at the temperature about $-1°C$, what can help in preservation of the dead ice for a very long time. On the other hand such a salt water which saturated the accumulated sediment protects it from freezing.

TEXTURAL CHARACTERISTICS OF LITHOFACIES

After distinguishing three lithofacies a thorough study of the parameter values representing the individual lithofacies becomes possible. The comparison of the mean parameters values (Text-fig. 12) of lithofacies from Brepollen as well as of those from the Kane Basin (KRAVITZ 1982) shows that the mean values of individual sediment types are distinctly different. An analysis of the minimum and maximum parameter values calculated for three lithofacies (Text-fig. 12) shows that values of particular parameters are either scattered in the wide range or are concentrated in the very narrow range, and in both cases the ranges of a changeability of parameter values for different lithofacies overlap considerably.

In order to distinguish those parameters which are most sensitive in differentiation and characterization of particular lithofacies the graphs (Text-fig. 13) of all analyzed parameters were drawn. They represent the whole ranges of values, with marked mean values, and amount of samples falling to the same ranges of values.

From among 20 discussed parameters not one is sensitive enough to be the exclusive basis for the complete separation of all three lithofacies. The best separation is given by three parameters: (*i*) grading factor; (*ii*) gravel content; and (*iii*) standard deviation. As a matter of fact the ranges of their values overlap (Text-fig. 13), but majority of samples representing every sediment type found themselves in different ranges, and their mean values are very different. To the group of two parameters, which are less environmental sensitive but at least allow to distinguish unmistakably water transported sediments belong: (*iv*) mean size; and (*v*) mean cubed deviation. The four mass physical parameters: (*vi*) water content; (*vii*) porosity; (*viii*) unit weight; and (*ix*) void ratio, provide a strong evidence for the complete separation between till and water transported sediments (Text-fig. 13) but are less helpful in discrimination of ice-rafted sediments.

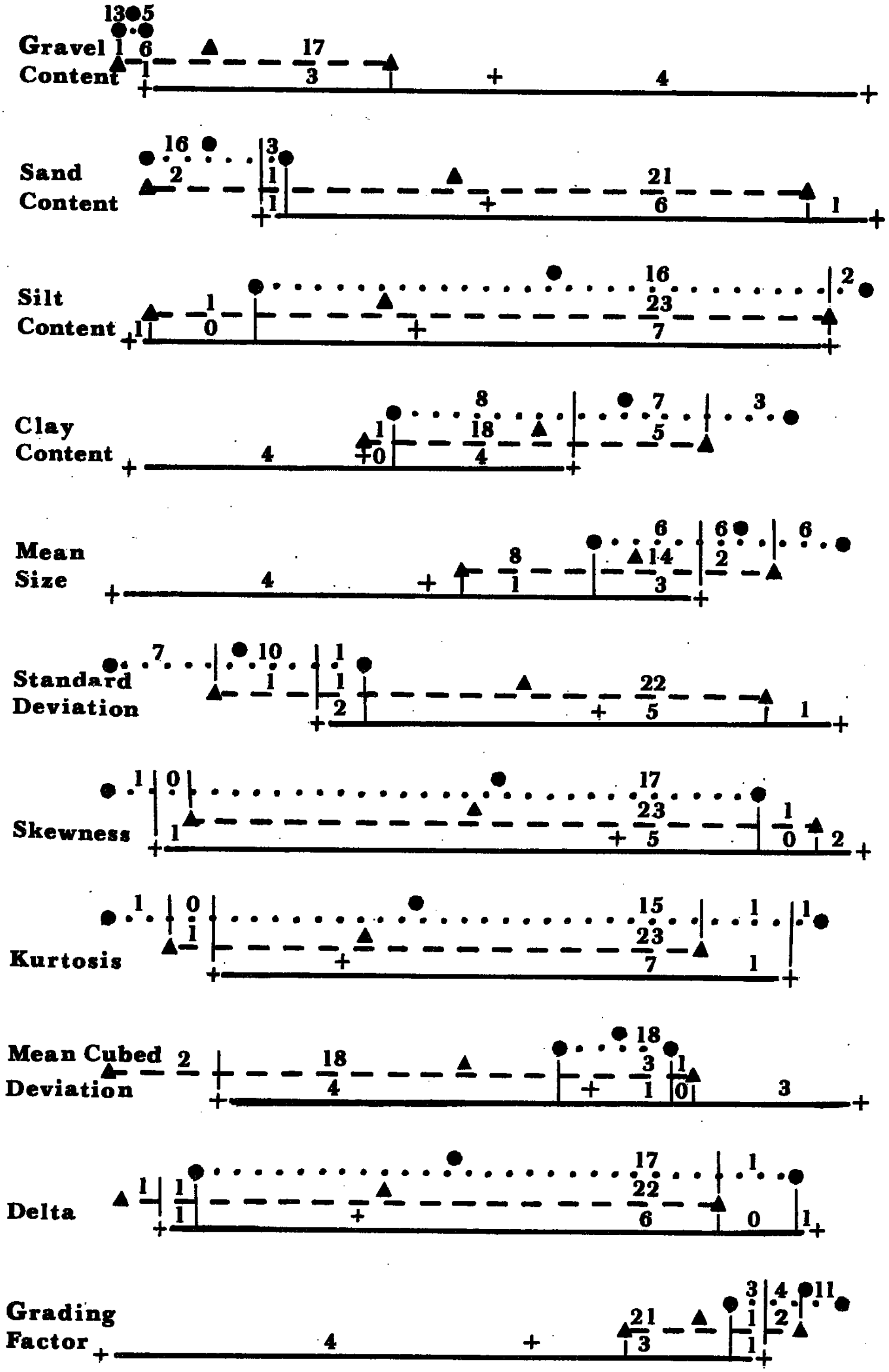
The worst results in differentiation and characterization of three distinguished lithofacies are given by four parameters. Activity in spite of usefulness in other investigations of sediments from glaciomarine environments (KRAVITZ 1982, 1983; SCHWAB & LEE 1983). This parameter is more strongly related to mineral composition of sediments than to other factors including the grain-size frequency. The similar mineral composition of all deposits from Brepollen influences the activity nature even if other parameters are distinctly differentiated. Two parameters computed from the shape of the size frequency curves skewness and kurtosis. Though these parameters are very useful in differentiation of many depositional environments, for example those described by FRIEDMAN (1961, 1962) they are not diagnostic in the case of glaciomarine sediments. The same is with silt content, which for the three sediment types

Parameter	Water Transported Sediments			Ice-rafted Sediments			Glacial Till		
	max	min	mean	max	min	mean	max	min	mean
Gravel Content	1	0	0.3 (1)	13	0	4 (4)	38	1	18 (15/22)
Sand Content	8	1	4 (4)	35	1	16 (20)	39	7	18 (33/42)
Silt Content	61	22	40 (44)	58	16	30 (31)	58	14	32 (29/23)
Clay Content	75	33	56 (52)	67	31	50 (42)	54	9	31 (23/14)
Mean Size	9.1	6.7	8.1 (7.9)	8.5	5.3	7.1 (5.8)	7.8	1.3	4.9 (4.0/2.7)
Standard Deviation	2.9	1.9	2.4 (2.5)	4.8	2.3	3.6 (3.8)	4.9	2.7	3.8 (4.2/4.0)
Skewness	+0.10	-0.95	-0.40 (-0.32)	+0.19	-0.84	-0.42 (-0.21)	+0.25	-0.87	-0.18 (±0)
Kurtosis	6.7	1.2	3.2	5.7	1.6	2.9	6.3	1.8	2.8
Mean Cubed Deviation	+1.7	-10.7	-5.3	+2.4	-54.3	-20.8	+19.3	-43.1	-6.1
Delta	+0.49	-0.49	-0.10	+0.38	-0.60	-0.19	+0.52	-0.53	-0.21
Grading Factor	+0.77	+0.62	+0.70	+0.69	+0.16	+0.48	+0.64	-2.08	-0.28
Water Content	123	52	84 (101)	84	38	61 (50)	47	18	30 (30/20)
Porosity	77	58	68 (72)	69	51	61 (56)	56	33	44 (38/33)
Unit Weight	1.71	1.39	1.54 (1.48)	1.84	1.52	1.66 (1.75)	2.14	1.75	1.95 (2.06/2.15)
Void Ratio	3.30	1.41	2.26 (2.59)	2.27	1.03	1.64 (1.36)	1.27	0.49	0.82 (0.60/0.52)
Liquid Limit	99	33	68	81	33	53	38	20	29
Plastic Limit	47	22	32	41	18	25	23	13	18
Plasticity Index	57	10	36	46	8	28	20	7	11.5
Liquidity Index	560	104	164	350	95	139	146	69	106
Activity	1.10	0.14	0.67	0.88	0.20	0.55	0.92	0.15	0.49

Fig. 12. Maximum, minimum, and mean values of twenty textural and mass physical parameters of surficial sediments from NW Brepollen

WTS — water transported sediments, **IRS** — ice-rafted sediments, **GT** — glacial till

In brackets mean values of *WTS*, *IRS*, and two types of *GT* for samples from the Kane Basin are given (*after* KRAVITZ 1982)


Gravel Content
Sand Content
Silt Content
Clay Content
Mean Size
Standard Deviation
Skewness
Kurtosis
Mean Cubed Deviation
Delta
Grading Factor

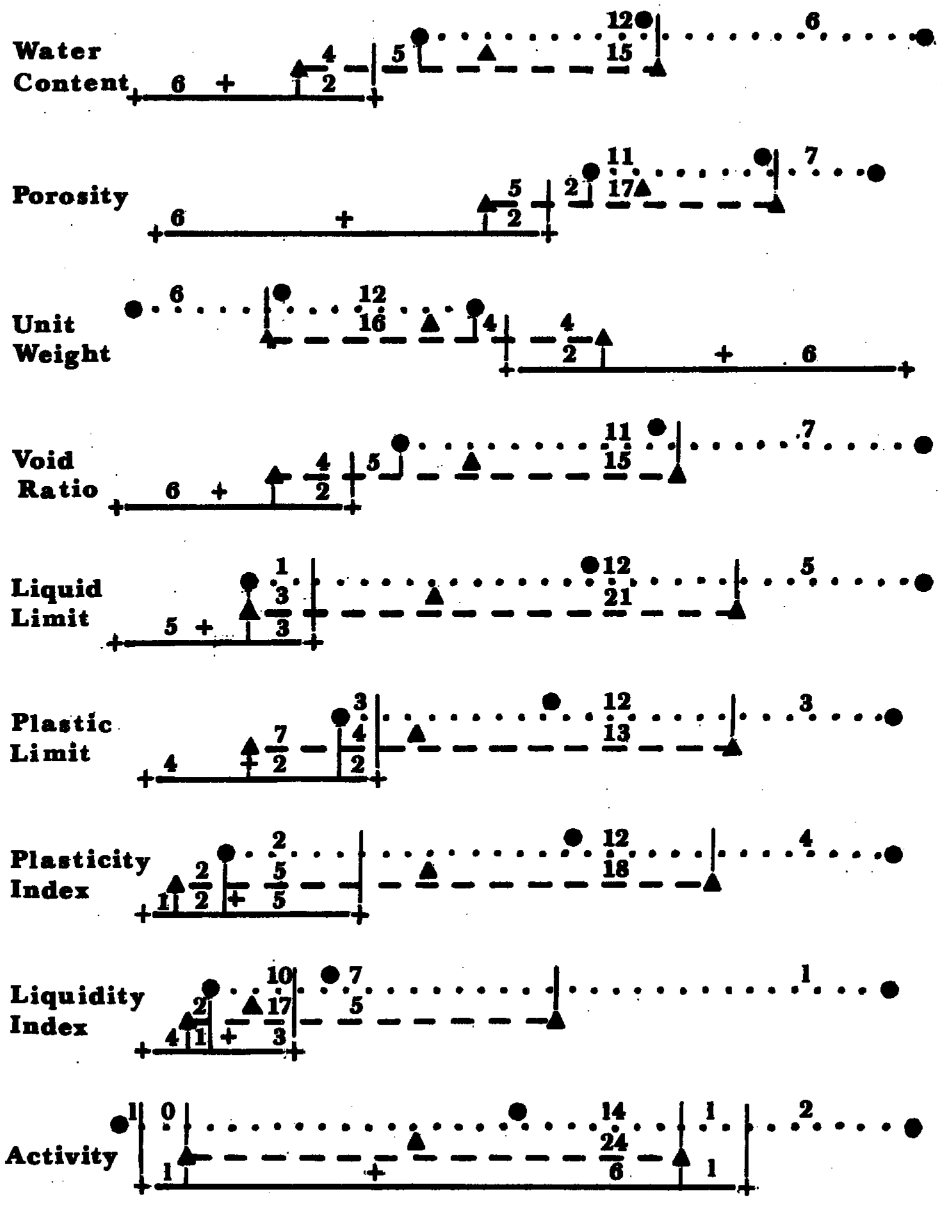


Fig. 13. Graphic comparison of textural and mass physical parameters values
Dotted lines with round spots — water transported sediments; dashed lines with triangles — ice-rafted sediments; permanent lines with crosses — glacial till; round spots, triangles, and crosses — indicate minimum, mean, and maximum values
Number of samples in each section is marked

takes similar ranges of value and its mean content is nearly the same (Text-fig. 13) despite the fact if a dominant fraction is gravel or clay.

In the future testing of the glacial and galciomarine sediments first of all these parameters should be measured which were recognized as most sensitive for such environments and taken into consideration in accordance with numerically marked order.

INTERRELATION OF SIZE AND MASS PHYSICAL PARAMETERS

All textural parameters resulting from grain-size and physical features described above show how difficult is to establish the bounds dividing the particular lithofacies. For the better separation of them several dozen of diagrams with three or two parameters were constructed elsewhere (FILIPOWICZ 1989). The thorough study of these diagrams presenting interrelations of discussed parameters allowed to choose those, which provide the satisfactory separation of distinguished lithofacies.

From the group of diagrams presenting the grain-size distribution of the galciomarine sediments best seems to be the triangular diagram (Text-fig. 14) based on the modified triangle proposed by HOLTEDAHL (*in* MYHRE 1974) and illustrating a content of silt, clay, and a sum of gravel and sand contents. All samples of *WTS* are contained in one category (silty clay), and are nearly completely separated from two remaining environmental fields. From 24 samples classified as *IRS*, twenty two belong to the category of sandy gravelly clay. The remaining two samples of this group belong together with *WTS* to the silty clay category. However one of them, the sample number *11*, according to discriminant analysis should be classified as *WTS*. The sediment samples

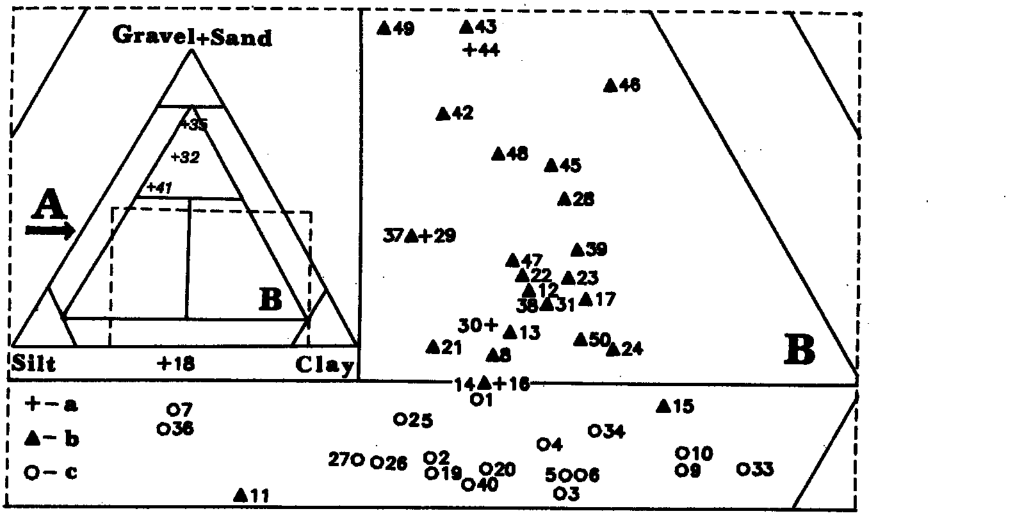


Fig. 14. Triangle illustrating the grain-size distribution
A — An overall picture of triangle
B — Enlargement of the part with majority of sediment samples from NW Brepollen
a — till, **b** — ice-rafted sediment, **c** — water transported sediments; numbers of samples as in Text-fig. 1

classified as till do not occupy any individual field and the area of overlap between till and *IRS* samples exists.

From the group of square diagrams with two-variable scatter plots related to the granulometric parameters in separating glacial and galciomarine sediments four were most effective. The first of these diagrams is the scatter plot of mean size versus standard deviation as a measure of sorting (Text-fig. 15). If a wide range of grain-size (gravel to clay) is present, scatter bands often form a boardered *M*-shaped trend. If the size range is smaller it happen very often that only a *V*-shaped or inverted *V*-shaped trend develops (Folk & Ward 1957). For sediments from NW Brepollen, an inverted *V*-shaped trend occurs, with only one limb of the "*V*" well developed (Text-fig. 15). This diagram points out that nearly all *WTS* can be distinguished from *IRS* and vice versa. This scatter plot presents three fields, the first for fine-grained *WTS*. The second for *IRS*, in which several exceptional till samples are represented, and the third area of till samples located on the downward hook of the second limb of an inverted *V*. Till samples can be distinguished from *WTS* and in part from *IRS*, but in that case the wide area of overlap exists.

In an attempt to differentiate tills from glaciomarine sediments Frakes & Crowell (1973) ploted the mean grain-size versus standard deviation of assorted tills and of glaciomarine sediments from the Ross and Baufort Seas (dotted zones *in* Text-fig. 15). For comparison the zones representing Kane

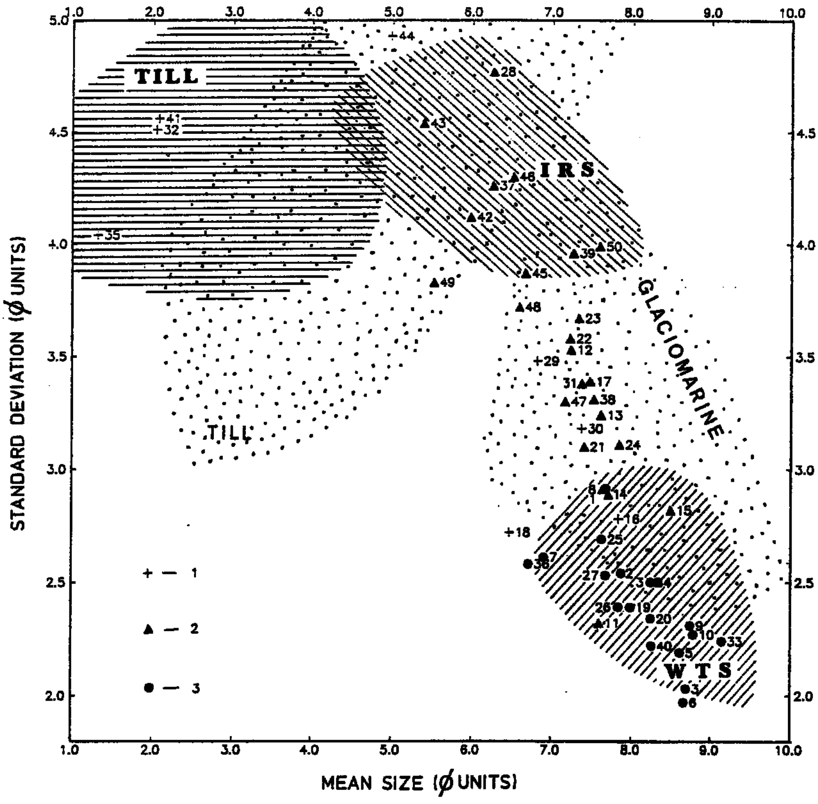


Fig. 15. Scatter plot of mean size *versus* standard deviation of glaciomarine and till deposits from NW Brepollen
1 — till, **2** — ice-rafted sediments, **3** — water transported sediments
Numbers of samples as in Text-fig. 1; other explanations in text

Basin lithofacies after KRAVITZ (1983) have also been drawn on this diagram (lined zones *in* Text-fig. 15). It must be pointed out that the standard deviation values in this study and in the study made by KRAVITZ (1983) are based on moment measures, whereas FRAKES and CROWELL (1973) used FOLK's (1966) inclusive graphic standard deviation. This difference, however, should not have a significant effect on the outcome.

On the second diagram (Text-fig. 16) presenting the scatter plot of mean size versus mean cubed deviation both environment sensitive, a nearly complete separation is found for the two depositional types are found, *WTS* and *IRS* fall into distinct groupings. For *WTS* values of both parameters are contained in the small ranges, therefore the field occupied by them covers a small area. The mean size values of *IRS* are more widely scattered and displaced toward coarser fractions and *MCD* values oscillate in the enormous range with vast majority of negative values. On the diagram (Text-fig. 16) the samples of *IRS* are scattered all over a large area. Some sediment samples classified as till are located in the field predominantly occupied by *IRS*, but 50% of them has a positive *MCD* values which togther with coarse fraction, *i.e.* the small mean size value in phi units, gives an isolated zone.

The third diagram of mean size versus grading factor (Text-fig. 17) taken after MARTINI (1971) shows a significant tendency of the grading factor to increase as the grain-size decreases and the sorting increases. Therefore the samples classified as belonging to the group of *WTS*, as relatively fine-grained and well-sorted, have the highest grading factor values and are located in the distinctly separated field on the diagram. While the samples of *IRS* have the broader scattering on the diagram. The grading factor values of coarse-grained till samples with extremely poor sorting oscillate in the vast range including even the negative values. Thus in the accepted scale some of them are not contained on the diagram (Text-fig. 17).

Both, the sorting index (standard deviation) and mean cubed deviation are environment sensitive textural parameters. That is why a nearly complete separation of *WTS* and *IRS* can be observed on the fourth diagram (Text-fig. 18). In *WTS* most values of *MCD* are negative or near-zero and standard deviation lies in the ranges of poorly and very poorly sorted (using the sorting classification of FRIEDMAN 1962). The *MCD* values of *IRS* are all negative and widely scattered, the standard deviation values fall in the range of exteremely poorly sorted. To the same range of sorting classification belong samples of the last group (till) and their *MCD* values are even more widely scaterred, some of them having high positive values.

Some widely applied diagrams, which present interrelations between moment measurements of the granulometric parameters, for example the scatter plots of mean size and standard deviation versus skewness and kurtosis, and especially skewness versus kurtosis, though are very useful in differentiation of many depositional environments are not sensitive enough to be diagnostic for glaciomarine sediments and therefore they are not reported in this study.

Of the diagrams illustrating combinations of mass physical properties in sediment from the NW Brepollen Bay the scatter plots of water content versus porosity, unit weight versus void ratio, and water content versus unit weight give the complete separation between till and *WTS*, but are much less satisfactory in distinguishing *IRS*. The diagram of void ratio and unit weight values of sediments form the Puget Lowland (EASTERBROOK 1964) presents well defined differences for tills and galciomarine sediments. Even better separation on the same kind of diagram was found for four lithofacies from Kane Basin (KRAVITZ 1982) where three very distinct zones grouping tills, *IRS*, and *WTS* were present. But on the same diagram with sediments from the Brepollen Bay

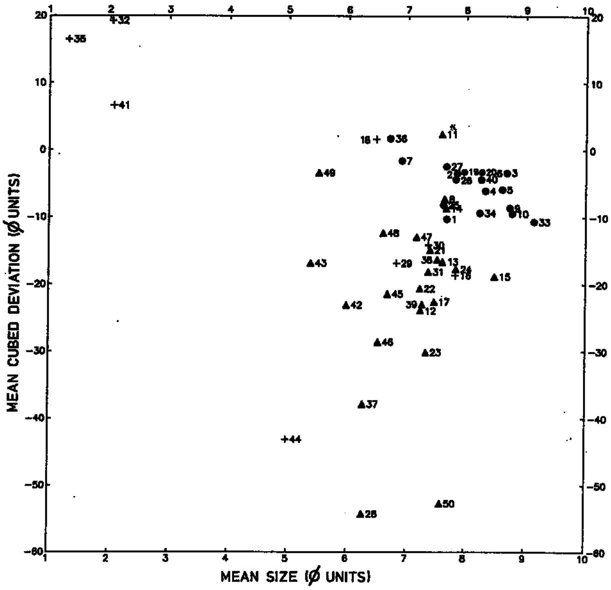


Fig. 16. Scatter plot of mean size *versus* mean cubed deviation; for legend *see* Text-fig. 15

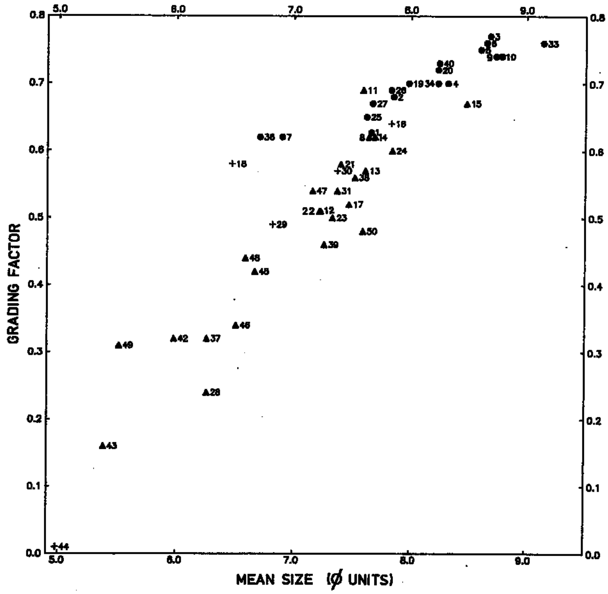


Fig. 17. Scatter plot of mean size *versus* grading factor; for legend *see* Text-fig. 15

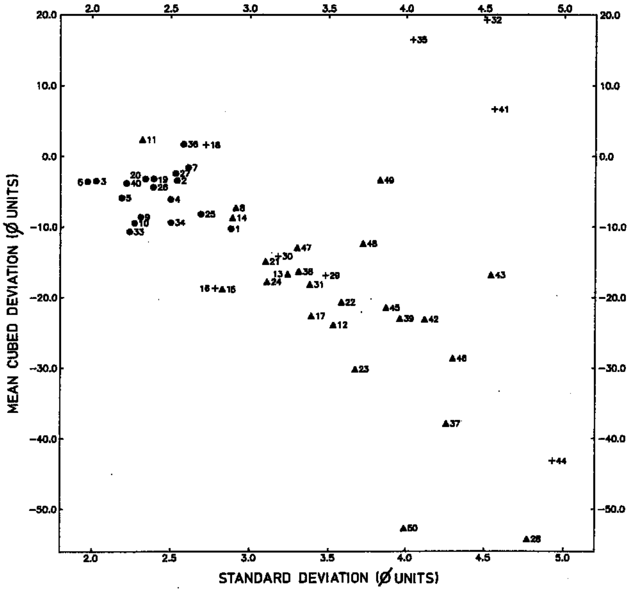


Fig. 18. Scatter plot of standard deviation *versus* mean cubed deviation; for legend *see* Text-fig. 15

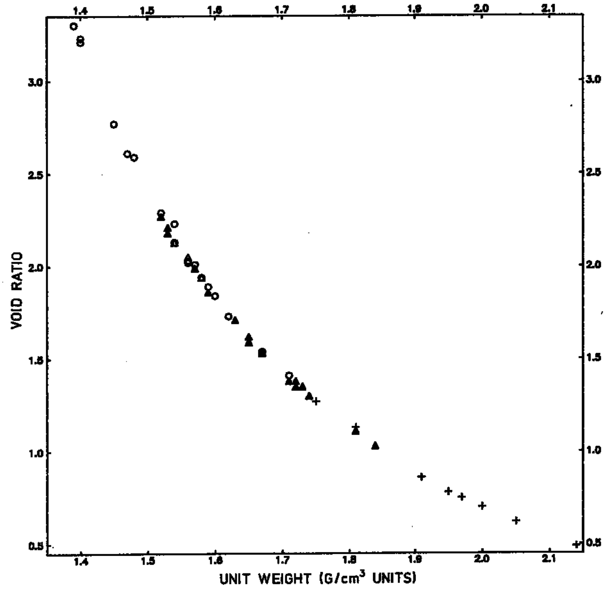


Fig. 19. Scatter plot of unit weight *versus* void ratio; symbols as in Text-fig. 14

(Text-fig. 19) it is difficult to distinguish three zones corresponding to three lithofacies. The zone of *IRS* on one side overlaps the zone of *WTS* and the zone of tills on the other side.

In the group of diagrams with mass physical parameters again the two scatter plots based on plasticity characteristics: Casagrande plasticity chart, and activity chart, widely applied even in classification of sediments from the glaciomarine environment (Schwab & Lee 1983; Kravitz 1982, 1983), for sediments from Brepollen do not provide satisfactory evidence for the separation of any lithofacies. The activity chart (Text-fig. 20) shows the differentiation of activity values of the sediments representing the same lithological type and containing the same clay-size fraction content but coming from different parts of the bay and having slightly different mineral composition. On the other hand sediments of different lithofacies coming from the comparable depths and neighboring areas demonstrate a considerable similarity in activity values. It reduces usefulness of this diagram.

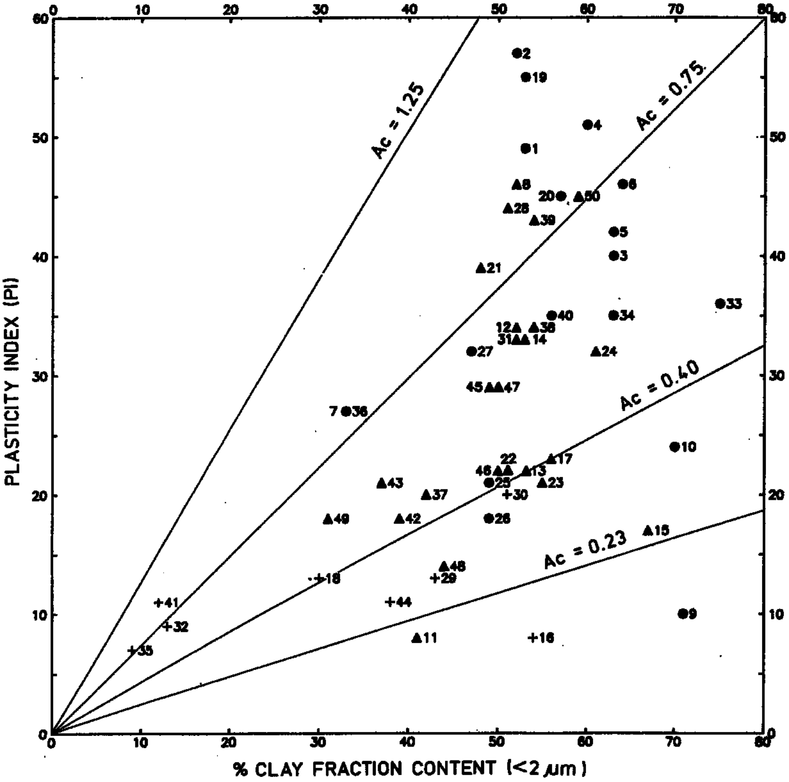


Fig. 20. Activity chart of surface sediments from the study area; symbols and numbers of samples as in Text-fig. 15

MICROSCOPIC (*SEM*) FEATURES

The basic and commonly used criteria for sediments to be considered glaciomarine is the presence of dropstones. But on the other hand the lack of dropstones cannot prejudge a different than glaciomarine origin of a studied deposit. The problem aquires a special importance for fine-grained sediments deposited as *WTS*. The textural and physical features of these sediments allow, as it was proved in this study, to distinguish them from tills and ice-rafted sediments, but they are very similar to other marine deposits of non-glacial origin. In the case of the interpretation of recent sedimentary environment where a presence of glaciers in surroundings of the fjord unmistakably prejudges that the sedimentary environment in such a fjord has a glaciomarine character, the problem resolvs itself into differentiation between sediments of such an environment *i.e.* till, *IRS* and *WTS*.

Studying, however, the profile of the older muddy deposits of unknown origin first of all we are looking for even single dropstones. As it was the case with sediments of North Atlantic described by MOLNIA (1983b), and deposited during the Pleistocene. Core samples were collected from Atlantic bottom in the region to the west of Ireland. By weight and value, the ice-rafted pebble component represented only 1% of the total sediment, but undoubtedly proves an influence of ice rafting in sedimentary processes.

When there is no pebble dropstones at all in studied sediments with help the scanning electron microscopy comes. The *SEM* of quartz grains has anabled several different sedimentary environments to be identified and discriminated on the basis of the grain surface textures (*see* KRINSLEY & DONAHUE 1968, KRINSLEY & DOORNKAMP 1973). Among these environments glacial deposits are included (WHALLEY & LONGWAY 1980). The examination of grains from a number of known, different, glacial environments (WHALLEY & KRINSLEY 1974) or reproduced in laboratory simulations (WHALLEY 1978) allowed to present an attempt to distinguish the differences between subglacial, englacial, and supraglacial deposits.

The microscopic investigations of surface textures on grains from the NW Brepollen Bay have shown that on the surfaces of the grains representing not only tills and ice-rafted sediments but also water transported sediments the characteristic features caused by glacial abrasion are common. Very recently broken quartz grains of glacial origin are characterized by fresh, sharp and angular edges, conchoidal fractures and grooves. Scanning electron micrographs (Pl. 1) present the typical fracture textures on surfaces of quartz grains. The predominant form of surface textures are the different types of steps: sub-parallel steps in the distinct groove (Pl. 1, Fig. 1), well developed and big in size with spacing up to 5.5 μm. Micro-steps (Pl. 1, Fig. 2) as series of fine, nearly parallel lines with spacing about 0.5 μm, developed between bigger arc steps. All these recognized features confirm that grains deposited in Brepollen as water transported sediments have the glacial origin.

A quite different problem arises when we analyze the sediment with easely recognized features of glacial environment, and we are looking for its relation to a marine environment. Besides detailed textural analysis applied in this study, for distinguishing between tills and ice-rafted sediments in the case of older deposits, again with help *SEM* comes. However, in *IRS* very rarely the marine fauna is found what unmistakably indicates the marine environment, but fecal pellest also indicating marine environment and never found in strictly glacial deposits are common. Both, SYVITSKI & MURRAY (1981) and LEWIS & SYVITSKI (1983) report that zooplankton fecal pellets and other biogenic agglomerates are the dominant mechanisms for the sedimentation of glacial flour in fjords, and are significant contributors to the total sedimentation rate, especially to the accumulation of clay particles.

Scanning electron microscopy of *IRS* and *WTS* from NW Brepollen have shown the abundance of fecal pellets (Pl. 2, Fig. 1). The average fecal pellet size is 100 μm in length and 53 μm in width. The pellets contain predominantly plates of clay minerals and chlorite, and minor amounts of quartz. The largest observed constituent particle was 22 μm, although the average particle was only 2.8 μm in diameter. The clays within fecal pellets (Pl. 2, Fig. 2) are packed with randon orientation (*i.e.* face-to-face, edge-to-edge, face-to-edge). When facal pallets are deposited they do not lose the identity and are well preserved in the bottom sediment.

Although the fecal pellets are easily found in Brepollen sediments. What makes them very useful in recognition of a glaciomarine environment, the Brepollen Bay is a basin of largely inorganic deposition in which the rate of sedimentation is in direct response to glacial rivers discharge.

CONCLUSIONS

The glaciomarine sedimentary environment of the Brepollen Bay in Spitsbergen is characterized by the following features observed and measured during the field studies:

(*i*) The rapid retreat of the tidewater glaciers, from 43 to 100 m annualy;

(*ii*) The three main sources of the sediment delivered to the bay: retreating glaciers, icebergs, and meltwater streams;

(*iii*) The sedimentation from suspension as a main type of deposition; the suspension concentration in surface waters 200 m and 2 km from the Hyrnebreen Glacier front, amounts 920 mg/l and 116 mg/l respectively;

(*iv*) The varied sedimentation rate — calculated from the thickness of the galciomarine sediments measured in the cores, knowing the time of deglaciation — from 110 mm annually close to the Hyrnebreen ice cliff, 20 mm a year in the central part of the Hyrnebukta Bay, to less than 4 mm annually in shallow bays located in a distance from the glacial front;

(*v*) The presence of the dead-ice blocks, discovered in core sampling, left on the bay floor by retreating glaciers and preserved by salt (34°/₀₀) and cold (−1 to +0.5°C) bottom water.

Using the textural and mass physical parameters as the basis for cluster analysis the surficial bottom sediments from the NW Brepollen Bay, according to the origin, type of transport, and depositional pattern were classified into three lithofacies: (*i*) glacial till, (*ii*) ice-refted sediments (*IRS*), (*iii*) water transported sediments (*WTS*).

The results of another statistical technique, the discriminant function, have defined mathematically each group and have shown that in cluster analysis as much as 96% of samples from NW Brepollen were correctly classified. Additionally, the usefulness of the discriminant function in classifying samples, for which a group membership is unknown, by comparying them to defined groups (lithofacies), as it was the case with core samples, was confirmed.

After distinguishing three litohofacies a thorough study of the parameters values allowed to distinguish typical values for individual lithofacies and to distinguish those parameters which are most sensitive in differentiation and characeterization of particular lithofacies. From among 20 discussed parameters not one is sensitive enough to be the exclusive basis for the complete separation of all three lithofacies. The best separation is given by following parameters: (*1*) grading factor, (*2*) gravel content, (*3*) standard deviation, (*4*) mean size, (*5*) mean cubed deviation, (*6*) water content, (*7*) porosity, (*8*) unit weight, and (*9*) void ratio. In the future testing of the glacial and glaciomarine sediments first of all these parameters should be measured and taken into consideration in accordance with numerically marked order.

A study of interrelations of the discussed parameters allowed to choose the follownig figures, which provide the satisfactory separation of distinguished lithofacies: (**a**) the triangle illustrating a content of silt, clay, and a sum of gravel and sand contents; the seven (*b* – *h*) square diagrams, viz. (**b**) mean size (*MS*) versus standard deviation (*SD*); (**c**) *MS* versus mean cubed deviation (*MCD*); (**d**) *MS* versus grading factor (*GF*); (**e**) *SD* versus *MCD;* (**f**) water content versus porosity; (**g**) unit weight versus void ratio; (**h**) water content versus unit weight. The diagrams marked in this point with letters are proposed to be constructed and analyzed for interpretation of sediments from glaciomarine environments.

It is hoped that this research will supply additional envidence necessary for the correct identification and interpretation of both present and past glaciomarine sequence in the geologic column.

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C. FILIPOWICZ

PARAMETRY STRUKTURALNE I KLASYFIKACJA OSADÓW WSPÓŁCZESNEGO ŚRODOWISKA GLACJALNO-MORSKIEGO, FIORD HORNSUND, SPITSBERGEN

(Streszczenie)

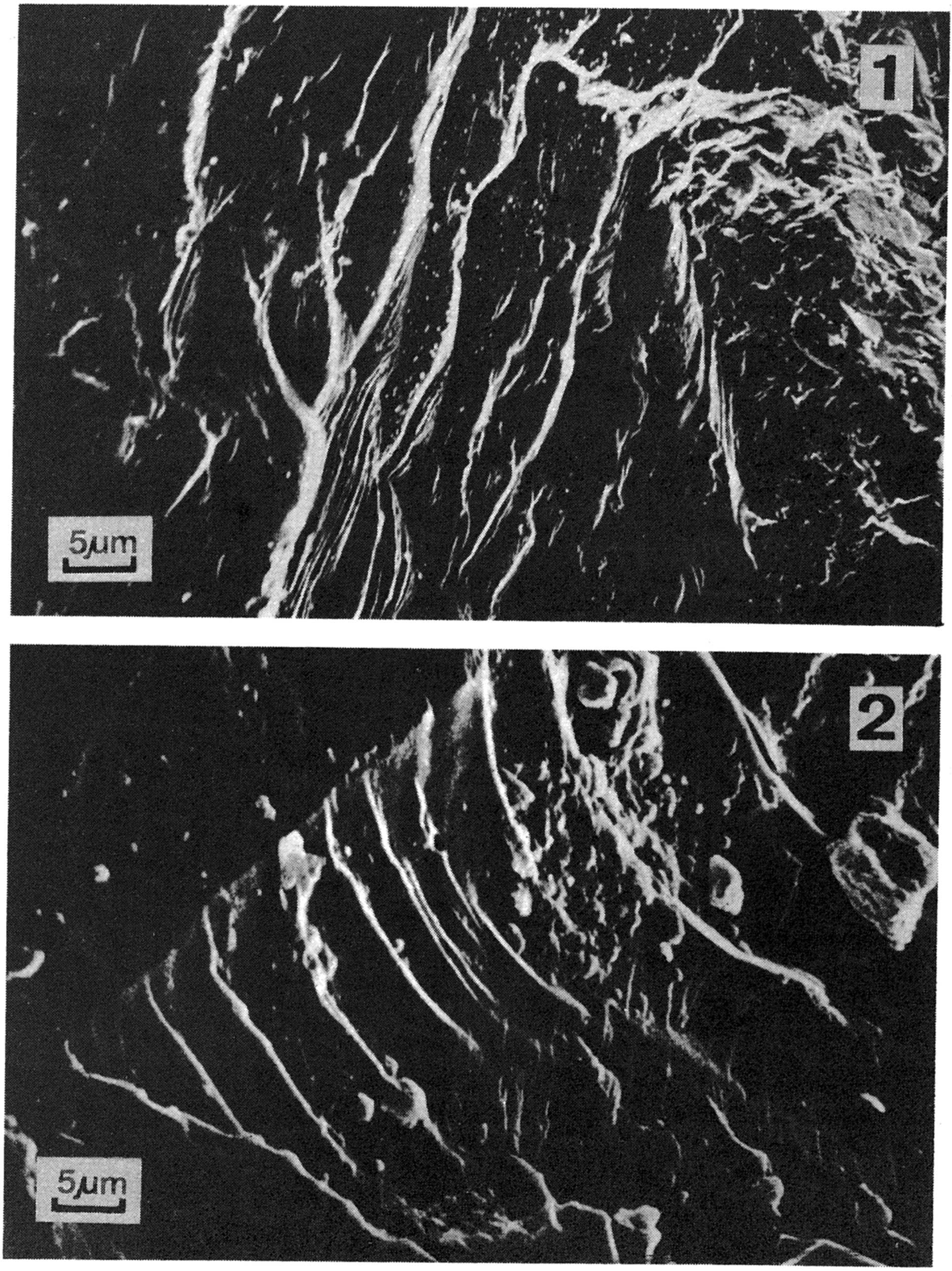
Niniejsza praca jest częścią rozprawy doktorskiej (FILIPOWICZ 1989) powstałej w oparciu o materiały zebrane przez autora podczas czterech ekspedycji na Spitsbergen. Badania prowadzone były w morskich zatokach przylodowych w fiordzie Hornsund zlokalizowanym w południowej części wyspy. Terenem szczegółowych badań (*patrz* fig. 1) była północno-zachodnia część zatoki Brepollen. Zebrane materiały, obserwacje geologiczne, oceanograficzne i biologiczne posłużyły do scharakteryzowania współczesnego glacjalno-morskiego środowiska sedymentacji. Jego główne cechy to: szybka deglacjacja frontalna (ok. 43 m rocznie), zróżnicowane tempo sedymentacji (od 4 mm do 110 mm na rok), powolna deglacjacja arealna w warunkach subakwalnych spowodowana przez zaleganie na dnie słonej (ok. 34°/₀₀) i zimnej (do −1°C) wody (*patrz* fig. 2), niska liczebność i aktywność biologiczna zooplanktonu i bentosu (*patrz* fig. 3), co rzutuje na tempo peletyzacji zawiesiny i przerabianie osadu na dnie, znaczne zróżnicowanie frakcjonalne osadu (*patrz* fig 4), współwystępowanie w osadzie cech środowiska morskiego i lodowcowego stwierdzone w próbach rdzeniowych. W makroskali jest to materiał zrzutowy oraz ślady działalności bentosu w osadzie, a w mikroskali grudki kałowe zooplanktonu morskiego (*patrz* pl. 1) oraz ziarna kwarcu ze znamionami transportu glacjalnego na ich powierzchni (*patrz* pl. 2).

Na podstawie analizy grup (*patrz* fig. 5) wykonanej w oparciu o 20 parametrów uziarnienia i cech fizycznych pomierzonych dla 50 prób osadu wyróżniono trzy typy osadów środowiska glacjalno-morskiego (*patrz* fig. 6), tj. glin lodowcowych (ang. *till*), morskich osadów o przewadze materiału zrzutowego transportowanych przez góry lodowe (*IRS – ice-rafted sediments*) i morskich osadów pochodzenia lodowcowego transportowanych przez wodę (*WTS – water transported sediments*).

Funkcje wyliczone w analizie dyskryminacyjnej (*patrz* fig. 7) definiują każdą z grup i potwierdzają poprawność klasyfikacji uzyskanej w analizie grup (96% prawidłowo sklasyfikowanych prób).

Analiza dyskriminacyjna może być użyta do bezpośredniego klasyfikowania prób osadów ze środowiska glacjalno-morskiego, co z powodzeniem wykorzystano dla podpowierzchniowych prób rdzeniowych (*patrz* fig. 8—11).

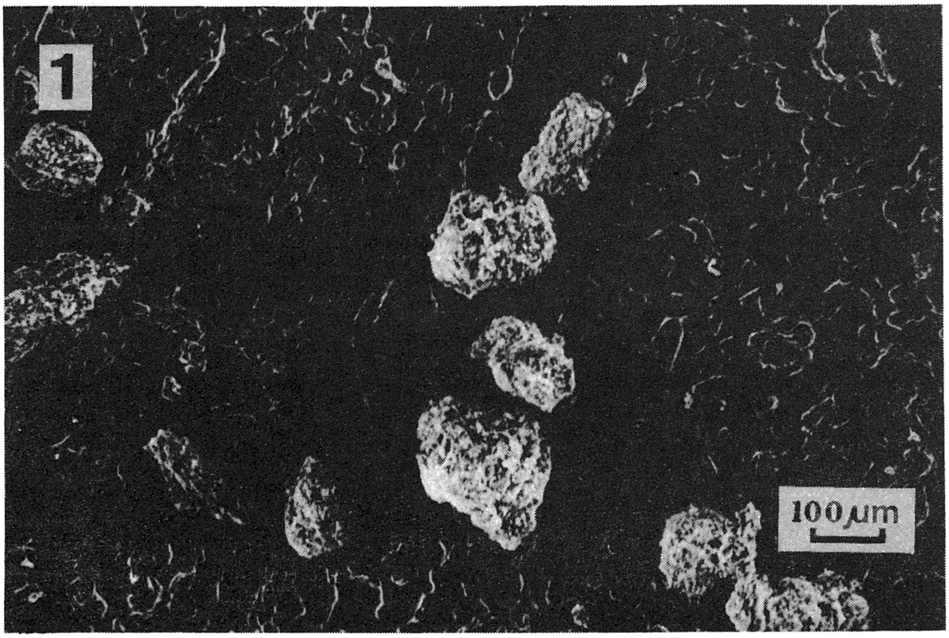
Analiza wartości parametrów posiadanych przez próby zaklasyfikowane do poszczególnych typów osadu oraz wzajemne ich porównanie na diagramach, pozwoliły na wyróżnienie przedziałów wartości parametrów reprezentatywnych dla poszczególnych typów (*patrz* fig. 12). Ponadto pozwoliły na wskazanie parametrów (*patrz* fig. 13) i diagramów (*patrz* fig. 14—20) niediagnostycznych oraz tych szczególnie użytecznych w odróżnianiu typów osadu środowiska glacjalno-morskiego.

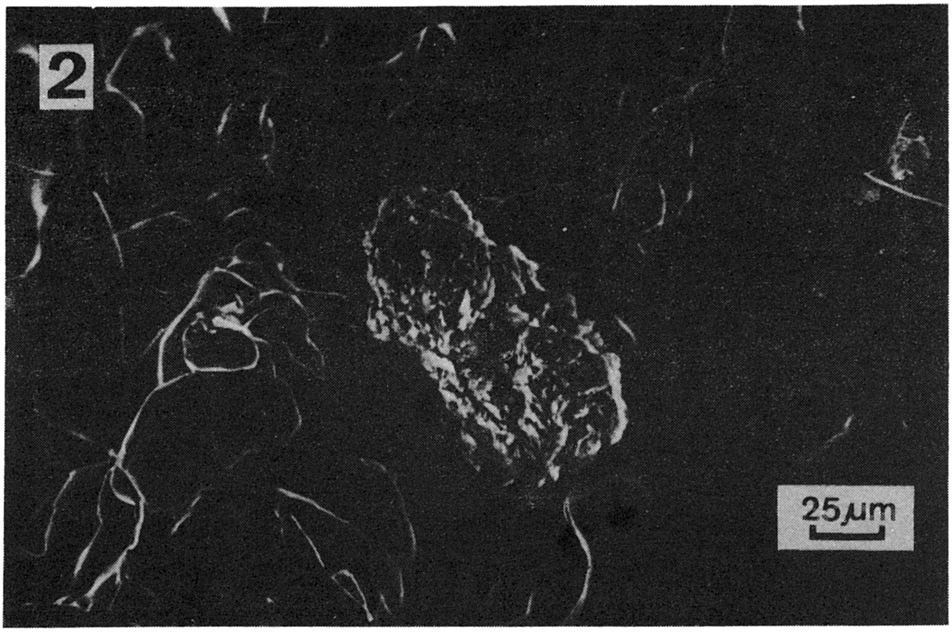


Scanning electron micrographs showing glacial features on surfaces of quartz grains from NW Brepollen

1 — Fractured surface with arc-steps and micro-steps

2 — Sub-parallel steps in distinct groove together with comminution debris





Scanning electron micrographs of fecal pellets collected from Brepollen Bay

1 — Fecal pellets varied in shape and size

2 — Enlargement of a typical pellet showing orientation of particles, with clay minerals in the background