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Texture of recent morainic deposits of a terminal zone of the Werenskiöld Glacier (Spitsbergen)

ABSTRACT: A structure of recent morainic sediments, mainly of gravel — boulder fraction (15—60 mm) was studied in the extremely marginal part of the Werenskiöld Glacier. The data were collected within three environments of glacial deposition i.e. supraglacial of dead glacial ice and layer of relegation ice adhering to the glacier bottom and subglacial ones.
A distinct textural individuality is typical for supraglacial deposits. Arrangement and orientation of boulders coming from the basal part of a glacier as well as from the morainic subglacial sediment deposited under the active ice show many similarities. But in both latter zones as well as certain differentiation was found to be caused by morphology of the older bedrock, changes during a subglacial deposition and preliminary epigenetic changes that occur in the conditions of a subglacial regelation before a stabilization of a passive zone of subglacial permafrost.

Key words: Arctic, Spitsbergen, geomorphology, sedimentology

1. Introduction

In July 1972, during a successive Polish Spitsbergen Expedition, the morainic deposits of a marginal zone of the Werenskiöld Glacier have been studied. The glacier is situated in the southern part of Wedel Jarlsberg Land (Fig. 1). Nowadays it keeps retreating and its tongue ends on the land. The trough valley of the Werenskiöld Glacier is surrounded in the north by mountain massifs of Jens Erikfjellet (576 m a.s.l.) and Wernerknatten (634 m a.s.l.), and in the south — by a mountain slope of Angellfjellet (591 m a.s.l.).

Texture, structure, principal physical characteristics and lithofacial features of morainic deposits were analysed. The studies dealt with deposits that actually melted out at the surface of the glacier and also the rock debris that was not melted out but still occurred within the glacial or regelation ice. The morainic covers of already stabilized, subglacial deposit were analysed too. Therefore, an insight into three principal glacial environments was done, the environments closely connected with evolution and decline of glacier i.e. — supraglacial, -englacial, of bottom ice-morainic part of gently front of the Werenskiöld Glacier and — subglacial, represented mainly by a lithofacial complex of basal till.

The paper deals entirely with a problem of a texture of morainic boulders (fraction 15—60 mm: length of a longer axis of the boulders i.e. of the axis *L* or *a*).

2. Present knowledge of texture of Spitsbergen morainic deposits

In the territory of Spitsbergen the areal deglaciation is the prevailing one (Szupryczyński 1963a, 1963b, 1965a, 1968). A deglaciation of this type leads to a formation of supraglacial covers of an ablation moraine. They create a type of postglacial topography — *plains of ablation moraine* (Olszewski 1969). Such morainic sediment is displaced on the ice surface, mainly by flowing. Most frequently, the proglacial area of just exposed subglacial basal deposits is the accumulation basis for flowing ablation moraines. Klimaszewski (1960, 1963) found in the area situated between Kongsfjorden and Eidembukta (northwestern Spitsbergen), a diagenetic ablation moraine with a fluidal or chaotic structure, what depended on distance of its displacement.

Secondary structural transformations within the supraglacial deposits were found by Boulton (1967) in the foreland of the Sør Glacier (Ny Friesland). These transformations were expressed by pebbles and stones orientation in the surface part of ablation sediments (about 0.9 m thick), flowed down along an ice slope. In the section of supraglacial deposits of the Sør Glacier, the lowermost sediment bed only (0.9—1.05 m), the deepest one and underlain by ice, presented a debris orientation parallel to the ice movement. A similar structural duality was also typical for a *flow till* of the Dunner Glacier (Boulton 1968). Frequently, the supraglacial sediment formed chaotically arranged cobbles, occurring on ice or on ground moraine surfaces (Szupryczyński 1966, 1968).

The general textural problems dealing with morainic material in the inner part of Spitsbergen glaciers have been mainly described by Drygalski (1911), Gripp and Todtmann (1926), Szupryczyński (1963a, 1968) and Lavrušin (1969). According to Boulton (1970a, 1970b) most rock debris was incorporated by an englacial morainic drift of the glaciers by means of basal freezing and was generally deposited as — *supraglacial flow* or as — *basal till*.

He pointed out a particular importance of bedrock undulations for a development of tensions within the basal part of a glacier and creation of its dynamics. At the same time he emphasized their principal influence on a local formation of a rock debris texture within an active glacial

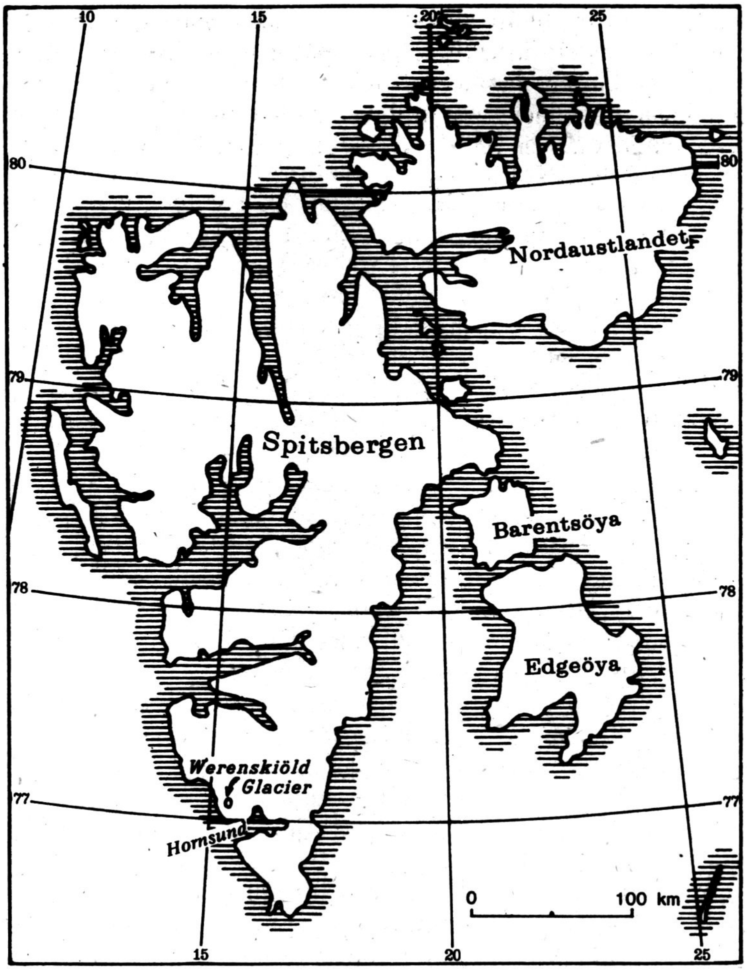

Fig. 1. Position of the studied area at the background of a Spitsbergen map

ice. In a zone of passing a bedrock obstacle by a bottom, heavily morainic-rich zone of Makarov Glacier, the rock debris tended to a bilateral and perpendicularly crossing orientation of azimuths of their long axes. A direction perpendicular to a glacier movement prevailed. It was described by Boulton (1970a) as an orientation of a normal maximum. In places where such an obstacle was absent and open upwards crevasses pointed out a state of tension, the long axes of boulders proved a full predominance of the orientation parallel to the ice flow. Besides, maximum side surfaces (*L-l* or *a-b*) of many boulders, especially laminar and tabular ones, were agreeable with a plane of inner foliation of glacial ice. Lavrušin (1969) as well found a full conformity of boulder orientation in debris-rich (basal) ice and direction of movement of axial parts of Spitsbergen glaciers. In the marginal parts only where the glacier speed is decreasing, the mentioned regularity was less distinct. There, the boulders were frequently arranged at small acute angles or even perpendicularly to the main direction of glacier flow.

In a polar environment the subglacial sediments seem to be most easily accessible to studies in unfrozen forefields of glaciers. But in fact they are frequently destroyed there, partly or entirely transformed or covered by a thick cap of sediments of supraglacial or solifluction deposition. The latter readically make more difficult their finding as well as their interpretation. At the same Klimaszewski (1960) emphasized that it was just the gneissic structure of a ground moraine till the typical feature of a long-time glacial basal transport at glacier foot.

In the nearest proglacial forefield where the subglacial sediments have not been transformed, they create a so-called *fluted moraine* type. Such topography and sediments were described in front of the Werenskiöld Glacier by Szupryczyński (1963a, 1965a, 1965b, 1968) and Baranowski (1970). „Segregation of boulders is typical for a ground moraine of this type. The long boulder axes are parallel to morphological axes of ridges" (Szupryczyński 1965a). Instead, in popular loamy walls the smaller boulders are distinctly arranged vertically, in agreement with a vertical position af a scaly structure of that till matrix. Such structure is a result of a long-distance glacial basal transport. Only the larger „boulders have a varying orientation" (Szupryczyński 1968).

Lavrušin (1969) proved a close textural connection of exclusively rocky morainic sediments of a subglacial facies and of foot parts of glaciers, enriched in morainic material. The texture of subglacial tills is created during their basal transport, under the influence of a plastic glacier flow (with which stratification or banding of till matrix is connected) as well as a vertical pressure (taht causes a formation of a schistic texture).

The most detailed data connected with till texture of basal transport are included in a paper of Boulton (1970b). He found a considerable similarity of orientation of long boulder axes of the analyzed fraction 5—20 cm (4 localities, 50 measurements each) in a glacial ice of a frontal part of the Erik Glacier (Oscar II Land) and in a type of a basal till, called by him a *melt-out till*. There were some texture differences in:

— a scope of dispersion of directions (greater in morainic sediments than in ice),

— a distribution of inclinations of long boulder axis along their azimuth (of distinct tendency to a bilateral — distal and proximal, distribution in the sediment and generally unidirectional in ice), and

— a value of an inclination angle (more horizontal postion in a morainic sediment than in ice).

Boulton (1970b) was the first one who has done a detailed textural analysis of a morainic sediment or of a probable morainic rock that he found in a contact zone of ice and its bedrock. Under the active sole of the Nordenskiöld Glacier a till of a basal complex included abundant subhorizontal joints that separated it into elongated lenticles of varying thickness (from 5 to 30 cm). In this subglacial sediment the large boulders usually had „strong orientations transverse to glacier flows" although there was in one of the diagrams „a minor parallel peak" (Boulton 1970b).

Unfrozen subglacial sediment exposed in an edge of a meltter stream in the forefield of the same glacier (Nordenskiöld Glacier), without any ice at all due to melting out, possessed in its elongated and almost horizontal lenses a fine-lumpy texture of the matrix, created by three systems of joints of varying course and inclination. There „the orientation maximum of long axes of small stones within this appears to lie parallel to the inferred direction of glacier movement rather than transverse, suggesting that an original transverse orientation has been converted to a parallel one due to the reorientation of stones which are intersected by shear planes" (Boulton 1970b) In that situation there was a change from a transversal orientation (Glen Donner and West 1957), reflecting a previous movement phase of a series of debris bands in an actively flowing glacial ice, into a parallel one — in places where later on, in a younger phase of a sliding movement, the boulders got into the shear planes.

3. General features of a terminal zone of the Werenskiöld Glacier

A gentle front of the Werenskiöld Glacier (Fig. 2) is not active at all nowadays. Already the glaciological studies of the Kosiba (1958, 1960) group proved that a dead zone in the frontal part of that glacier has occuppied in 1957—1959 a strip 200—500 m wide. It occurred then at altitudes from 30 m a.s.l. up to about 60 m a.s.l. such zone of increased marginal ablation has been existing until now but its altitude and area were not constant.

The marginal cover of a flat margin of the Werenskiöld Glacier is very thin. Its thickness in a vertical section, parallel to a direction of a previous glacier movement, gradually decreases towards the peripheries of the glacier. In the following distance from the glacier edge: about 20 m, 15 m, 12—10 m, 8—5 m, 3—2 m and 1 m, the ice thickness is respectively about: 1.10 m, 1.00 m, 0.90—0.80 m, 0.75—0.50 m, 0.40—0.25 m, 0.15 m, 0.10 m and 0.05 m.

The glacier retreat was quite quick. It was found e.g. that from 17th to 27th July 1972 a retreat of a frontal part of the glacier equalled 10—12 m i.e. almost 1 m every summer twentyfour hours of a polar day. In the same time the measurements at a locality situated almost 15 m far from a thin glacier edge, proved the glacier thickness decreased for a half a metre, from 0.7 to 0.2 m. Already at about 31st July 1972 the glacier ice completely disappeared in a zone of about 15 m wide. At the turn of July and August of the same year 1 m lowering of the frontal part of the Werenskiöld Glacier occurred during 20—25 days.

In results of the glacier retreat, abundant and quite large undulations of the bedrock are exposed. Among them there are roche moutonnêe of schist or quartizite outcrops as well as destroyed fragments of marine

Fig. 2. General view on a marginal zone of the Werenskiöld Glacier. The arrow marks the studied locality. The photograph was done on 12th July 1972 from Gulliksenfjellet, (552 m a.s.l.)

Photo A. Olszewski

terraces. In summer 1972, an exposition of such an elliptic bedrock lump has almost completely finished in the middle part of the glacier tongue. The lump is built of beigebrown fine-stratified schists of the Hecla Hoek Formation (pre-Cambrian). The described roche moutonnêe is parallel to the axis of the glacial trough; it is about 150—200 m long and 0 m wide at its base. A development of the areal deglaciation is just connected with a quicker melting out the ice at the mentioned schist lump, dominating 6—8 m over its surroundings. The whole roche moutonnêe is covered by subglacial deposits with rare boulders of a surface ablation moraine. At the top and in the upper parts of slopes there is mainly a morainic cover, 0.2 m thick. Down the slopes of the elevation this cover is more thick — up to 0.3—0.4 m and at the foot of the lump it passes into subglacial deposits 0.5—0.8 m thick (Fig. 3).

A locality for studies of present morainic sediments was chosen at the northen part of the mentioned elevation. It was localized in the area still covered by the glacial ice, close to a supraglacial meltwater stream (Fig. 3 and 4). The principal research area was chosen in such a place where no fine, several centimetre wide, linear depressions of supra-glacial water draining occurred and so, a deposition amidst the sediments of

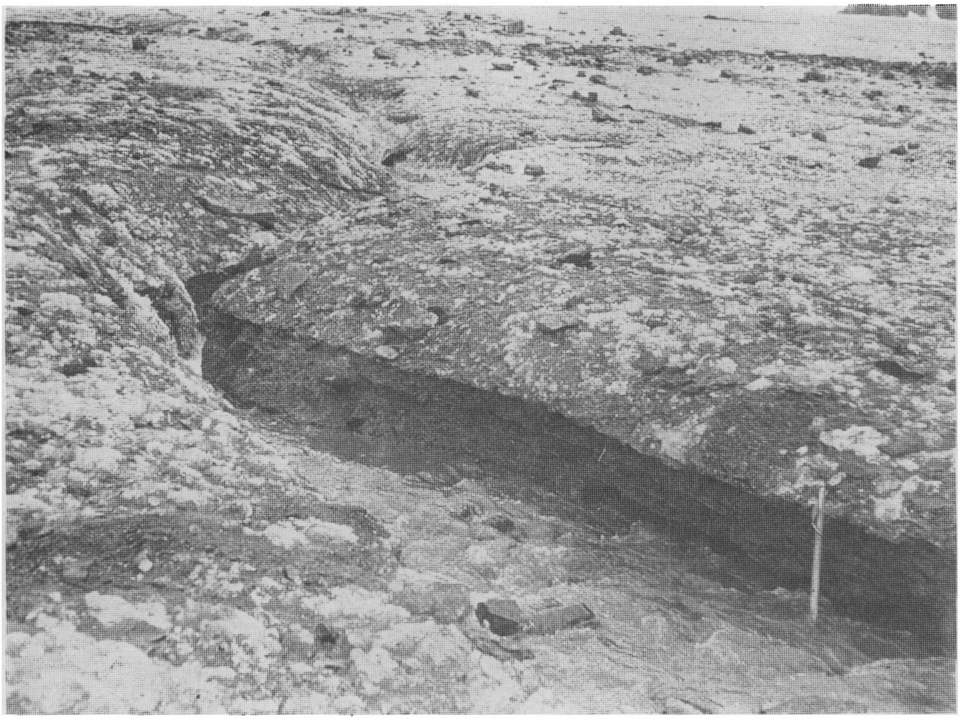

Fig. 3. Surface of intensive ablation of the glacier covered in a marginal part by a morainic supraglacial sediment. Beneath the ice (about 0.70—0.90 m thick) there is a subglacial sediment with thin interbeds of regelation ice exposed in walls of a meltwater stream channel

Photo A. Olszewski

fluvial transport material was not possible; besides, a thickness of subglacial morainic sediments accessible for studies, was the greatest there. About 15—20 m far from the ice edge the stream, incised in ice and in a subglacial deposit, was 1 m wide.

In the studied place the stream was incised into an ice cover of already mentioned thickness (0.7—0.8 m). Besides, it was also cut into about 0.5—0.6 m thick underlying, frozen and very compact subglacial deposit (Fig. 3). At the channel slope, between the glacier foot and the stream water level, a considerable part of the basal subglacial sediment (about 0.45—0.50 m thick) was visible and could be studied (Fig. 4).

The channel, upstream the locality, was more and more narrow and delimited by steeper and steeper and then, ice slopes. The channel bottom, eroded in a frozen sediment of a subglacial moraine (coverred by a deposited and very changeable channel facies of fluvioglacial sediments created in a result of transformation of all the other glacial facies), passed into a smooth ice bed in the same direction. There, it was already rarely covered by fluvioglacial gravels and pebbles.

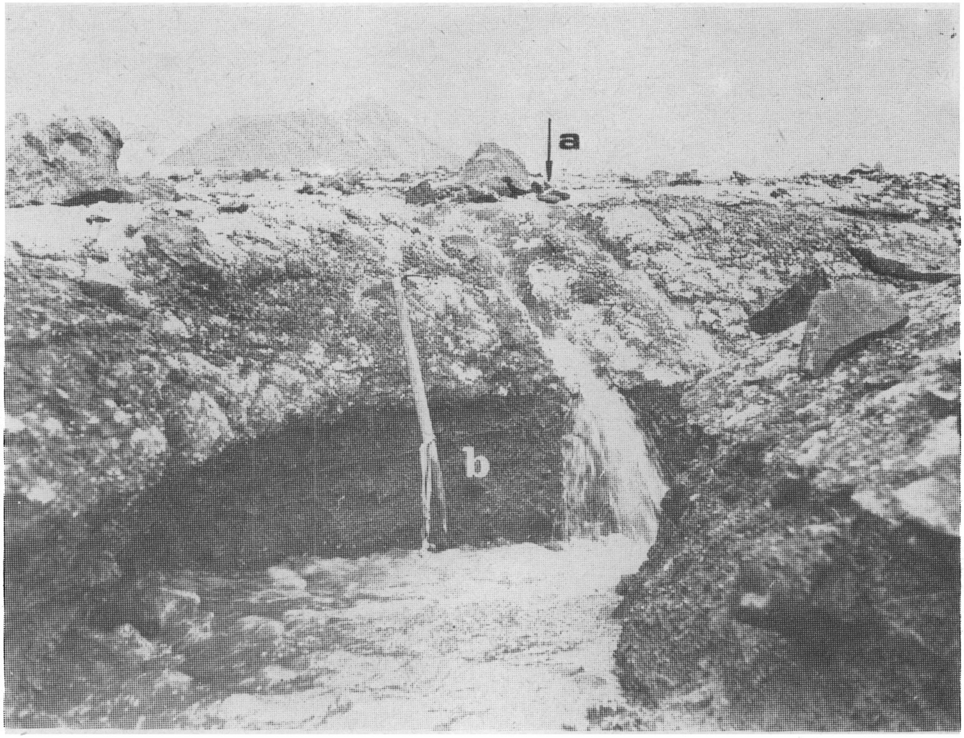

Fig. 4. Supraglacial zone *(a)* dead cover of glacial ice *(b)* and subglacial sediment in a locality of extremely marginal part of the Werenskiöld Glacier
Photo A. Olszewski

4. Recent supraglacial sediments of intensive surface ablation in an extremely marginal zone of the tonque glacier

A distribution of the surface debris in the marginal part of the Werenskiöld Glacier is quite differentiated. Some fragments of the area were completely covered by autochtonous ablation sediment whereas aside, there were completely clear zones of the glacier in contact with an exposed ground moraine (Fig. 3). Ablation supraglacial sediments composed of vari--grained fraction, starting from large boulders (over 0.6 m in diameter) to fine clayey deposit. Also, their external development and distribution were changeable.

The ablation sediment may form:

a) compact and quite vast boulder-gravel-clayey covers of distinct triangular shape e.g. in the southern part of the lowered marginal zone of the glacier front;
b) elongated ice-morainic ridges with an orientation generally agreeable with a direction of ice movement. At the base the ridges are 0.5—1.3 m

wide and 0.3—0.6 m high. The ridges are ice cored; they are covered by an angular debris and a thin discontinuous cap of clayey matrix;
c) loose and chaotically distributed angular boulders and gravels, of schists mainly. Some of them are badly treated.

The last (of the mentioned) variety of supraglacial sediments can be usually found in the lowermost part of the marginal zone where there is a pronounced minus glacial balance. Just the area of this kind was cut by the described meltwater stream in its lower course.

Above the ice slope, at the northern bank of the stream a position of a measurement area of a square metre surface was fixed. This test surface contained a single boulder (over 0.4 m diameter) and a few rock pieces with their longer axes over 6 cm. In the tested fraction (15—50 mm) all boulders at the surface (i.e. 71 boulders) were measured. Among them there were mostly angular schist plates. Their chaotic spatial arrangement was also typical for this group of ablation sediments. Besides, an orientation of most of these pieces, approximate to a transversal one referring to a local azimuth of glacier flow (80°N), facilitated much a distinction between the supraglacial sediments and the ones of extremely ice-morainic part and subglacial deposit.

Therefore, in a sector of the highest frequency of the boulder azimuth: 110°—140°/290°—320°N, there were 33.9% of the measured boulders. Among them already 62.2% were inclined in agreement with a general slope of the ice i.e. in a distal direction. At the same time three other, less abundant directions of orientation were distinguished: a direction agreeable with the ice movement 80°N (5.7%) and 50°N (7.1%), 210°N (8.5%).

A slight inclination of their longer and middle axes was a typical structural feature of these boulders. It caused the plane of the main gravel section (*L*-1) to be frequently approximate to an almost horizontal one. A mean inclination angle of the longer axis equals 10.3° and of the middle axis — 10.8° (Fig. 5 — diagram I).

Many boulders of the supraglacial cover were distinctly „melted into" the ice. But a part of them, a previously melted material as well, occurred „loosely" on its surface. Both these kinds of boulder position on the glacier surface recorded a continuous changeability to which an ablation sediment was subjected in the supraglacial environment. This changeability was also revealed by a definite reorientation of the longer axis direction. It should be emphasized that among three analyzed environments it was just the supraglacial one that represented the most changeable zone.

5. Structure of a dead glacial cap in the terminal part of the glacier

Features of the inner and outer glacier structure are varying so they connect with and frequently condition one another. Therefore the evolution on the one hand and stability on the other, of inner structure of glaciers, of their ice, are possible to be studied along as well as deep inside the glacial mass. As described by Kamb and La Chapelle (1964), the important features of inner glacial ice structure, typical for the basal part, can develop already in zone of ice accumulation and in the primary phase of glacial transport. They change or disappear in the terminal part of the glacier where the basal part stops to represent its lower part only in a vertical section. Also on the periphery of the Wernskiöld Glacier its basal part is distinctly bipartite (Fig. 5):

a) The main part of ice extends from the top surface almost to the glacier foot. It forms about 95—97% of its entire thickness (0.70—0.85 m). Such old coarse-grained glacial ice possesses quite a monolithic macrotexture re. Only in the bottom part of the ice there are ice layers, about 10—15 cm thick. Indistinct or lack of stratification in the overlying part of ice can be possibly explained by the above mentioned changes. In the marginal part where the ice is completely passive due to development of downward ablation of the glacier surface, the fundamental pressure changes have occurred. A horizontal cryokinetic pressure has disappeared there. Gradually but consequently a cryostatic vertical pressure has decreased. Thermodynamic changes of the active (up to recently) basal zone do influence the structure of that part of the glacier. Anyway, this main part of the ice composes of ice crystals of great dimensions; sometimes they are up to 10 cm. In comparison with other parts of the section the glacial ice formed (in the studied locality) a bed situated between the thickest layers of shear-plane type (close to the section such intraglacial layers were from 0.5 m to over 1.5 m thick).

The changes of the whole inner glacial structure (in the zone of its marginal stabilization and decrease) are supposed to be quicker and more distinct than the changes of the inner texture of the glacial ice itself. Among others while the basal part of the glacier has been passing from active to dead ice phases so, when the ice-morainic rock was already deposited, the changes of crystal magnitude were more and more hardly perceptible. At last the process was stopped in result of gradually diminished ablation on crystal walls. They did not change their horizontal position in a dead ice cover thus, no changes in the texture of the morainic material occured — the texture was the same as in the movement phase. That is why dead, marginal inner part of the Werenskiöld Glacier (unlike the supraglacial zone) was interpreted by the authors as the stable environment for purposes of finding the textural properties of the rock debris. It was then unchangeable and preserved, for a certain period of time, the state from a flowing phase of the bottom glacier zone. Inner structure of the ice as well as arrangement and composition of the morainic material presents the end of the movement phase, just before its stoppage.

b) Extremely bottom part of the glacier is composed of a thin layer, about 2—3 cm thick, of hard and much more compact, fresh regelation ice. Shumskij (1955) calls this kind of ice, connected with cryostatic pressure cannot be removed, a compressive — regelation ice. Due to greater content of the rock debris such ice is generally more stiff than the coarse-grained or fine-grained glacial ice.

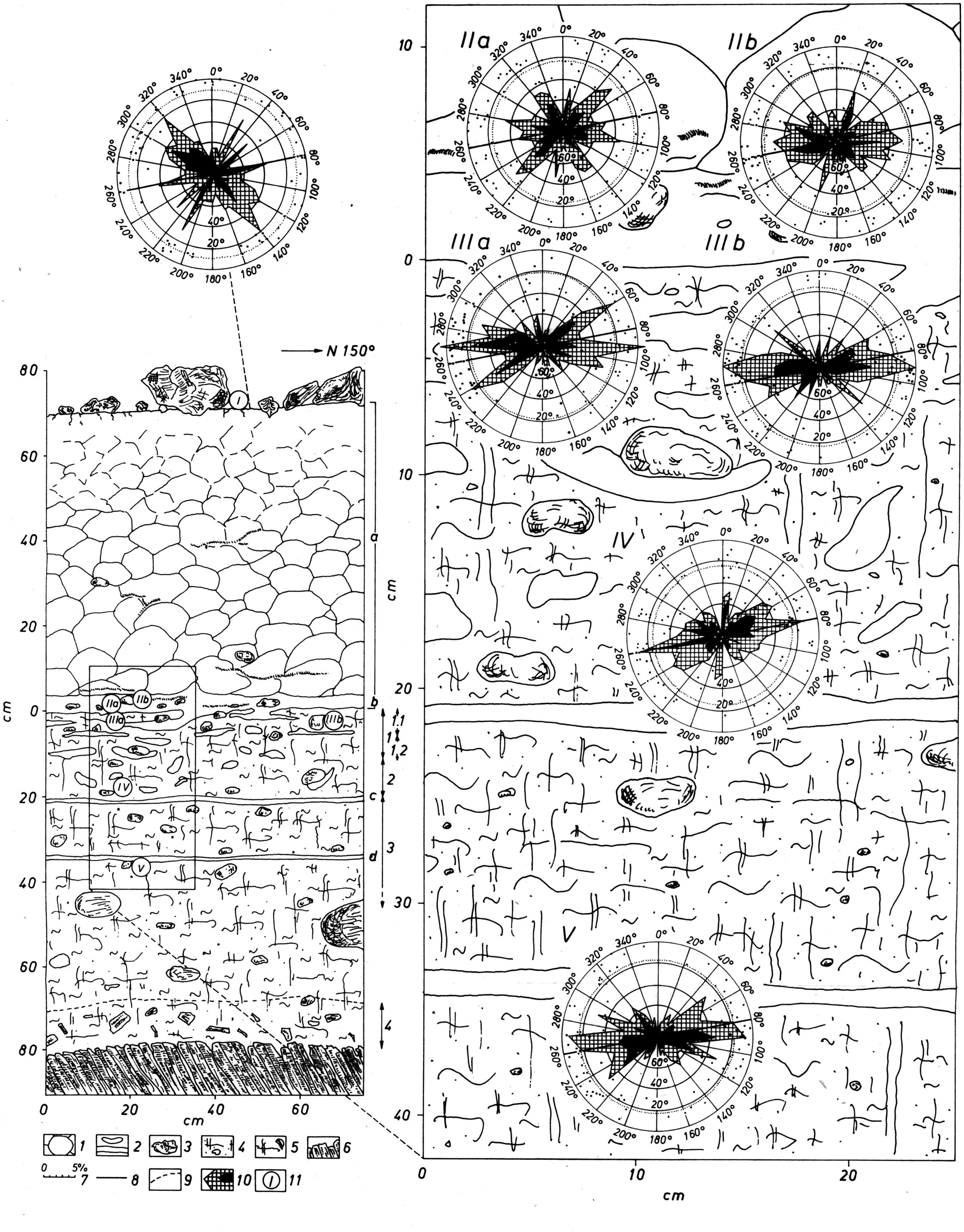

Fig. 5. Structure of the marginal of the Werenskiöld Glacier and of its supraglacial and subglacial sediments

Notations *a — d* and 1—4 at the right side of the exposure drawing mark the units of ice and of subglacial sediment described in the paper, 1 — coarse-grained glacial ice, 2 — lenticles and beds of regelation ice, 3 — sharp-angular stones and boulders of supraglacial sediment, 4 — dark-gray subglacial sediment (of lithofacial basal complex), 5 — till of bottom part of the section enriched in pieces of local schists (lithofacial subbasal complex), 6 — schists of Hecla Hoek Formation, 7 — scale of percentage boulder content of diagrams (I—V), 8 — azimuth of ridges of fluted moraine, 9 — probable top of bottom part of morainic sediments enriched in local boulders, 10 — outline of symmetrical (checkerwise) and asymmetrical (black colour) diagrams of boulder orientation, 11 — places of measurements of boulder texture

The regelation bed has guite constant thickness in the analyzed distance of about 2.5 m. Due to a compact structure it can be easily distinguished from the overlying glacial ice.

These two types of ice contact each other in the basal part of the Werenskiöld Glacier in a sharp and locally, rectilinear surface. Instead, the lower part of the regelation layer is really differentiated. Small, several milimetres high elevations or elongated banded lensed are frequent. By means of them the regelation ice tightly interfingers with a frozen (to its bottom part) subglacial sediment. Schytt (1959) emphasized that fine layers and lenses of ice that were popular in the top part of subglacial deposits of the Isfall Glacier and accompanied the elongated ridges of a ground moraine (of *flued-moraine* type), were not the glacial ice but „frozen meltwater with long columnar crystals".

6. Texture of boulders and morainic matrix in a glacial ice and in a bottom regelation bed of a glacier

The boulders of the studied fraction were very rare in a coarse-grained glacial ice. They represented only 18.5% (of 200 boulders) of measured rock fragments in ice. Also few thin inserts of fine clayey material occurred mainly in the bottom part of the stratified coarse-grained ice. These fine inserts of the morainic material, 10—20 cm long and up to 1 cm thick, were generally horizontal. At short, several centimetres distances, their vertical inclination reached 2—8 cm but most frequently 2—5 cm. A quantity of the morainic debris in these interbeds was irregular. In one of them only a single boulder was found. This type of spatial arrangement of the material that frequently took advantage of contact borders of crystals, originated during a phase of glacier movement. At that time the inner englacial melting on the outer crystal walls occurred. Thus, that was the place of accumulation of a fine debris. So, these inserts, frequently of discontinous course, were rather the small concentrations of an intraglacial regelation contact. They originated in a period of activity of the bottom part of the basal glacier bed.

The regelation layer contained several times more gravel and boulders (15—60 mm) than the overlying ice. But even rough analyses proved that their volume was changeable here and there. Generally it was not greater than 10—20% by volume of the analyzed fragment of the regelation ice.

During studies a vertical thickness was measured of the ice situated between the lowermost part of 200 boulders and the top of a subglacial sediment matrix. It made the data of a vertical arrangement of boulders more detailed. As long as the thickness of ice between the boulders and the sediment top was not greater than 3 cm they occurred either completely inside the regelation layer or at the contact with its top (Fig. 5). These boulders were fixed to compose as much as 81.5% of all the boulders (163 among 200 boulders measured in the ice 0.70—85 m thick).

The extremely bottom part of the glacier was saturated with boulders what depended prinicipally on depth of their occurrence. The results are presented in the Table I.

Table I.

Dependence of boulder content of the fraction15—60 mm on ice thickness that overlies them in an extremely bottom (regelation) part of the glacier.

Thickness of ice beneath a boulder (in cm)		Number of boulders (in cm)	
3.0—2.5	3.0—2.0	5.5	12.0
2.5—2.0		6.5	
2.0—1.5	2.0—1.0	11.0	24.0
1.5—1.0		13.0	
1.0—0.5	1.0—0.0	24.5	45.5
0.5—0.0		21.0	
3.0—0.0	3.0—0.0	81.5	81.5

The layer of the regelation ice that was transported along a shorter distance, contained not only more loose boulders and gravels. More frequently there ware there also narrow, lenticular layers of silty-clayey matrix. These layers were more horizontal than in the overlying coarse--grained ice. They were usually more narrow and shorter than the ones, described previously.

Diagrams of azimuth and inclination of the longer axis (Fig. 5 — diagram IIa, and IIb) point out a great or even a principal participation of orientation parallel to a direction of a local glacier movement. But at the same time they also show a considerable differentiation.

The diagram IIa presents a three-directional orientation. Two directions cross at an acute angle (20°—30°). They include the ranges of directions 40°—60°/220°—240°N (19%) and 80°—120°/260°—300°N (28%). The latter one represents disctinct bilateral inclinations. The third direction: 140°—160°/320°—340°N is perpendicular to the azimuth of movement direction; its inclinations predominate in the north-west sector and it represents 14% of all the boulders. A mean inclination angle of L axis is 22.1°.

At the same time as many as 20% of boulders are inclined at an angle over 35°. Among them, most of the sector 35°—60° possess distal (south-west) or transversal positions in relation to a movement direction. Instead, in the sector of maximum inclinations 60°—90°, a proximal direction predominates.

The orientation texture of the boulders in the ice, several dozen centimetres (about 1 metre) northwards, is presented in the diagram IIb. It points out a decided predominance of the direction parallel to the glacier movement. In the sector 70°—110°/250°—290°N there are as many as 38% of boulders. Two-third of them are inclined in a distal direction. A mean inclination angle of the L axis is 21.0° and of the l axis — 18.3°.

7. Structural-textural features of a subglacial sediment

Description of the sediment and circumstances of its deposition.

Beneath the ice of the terminal zone of the Werenskiöld Glacier there is an ice-morainic sediment of highly differentiated structure. It is completely frozen in the passive subglacial environment. A cover of dead-ice armor has conserved it and protected against melting (Figs. 3 and 4).

A textural differentiation is well visible in the top and middle part of the section i.e. to a depth of about 0.50—0.55 m (the whole morainic sediment is there about 0.80 m thick). The sediment can be called a till of steel-gray colour, intensively dark one. It is highly saturated with water (what is thermicaly consolidated).

When frozen the sediment is macrostructally differentiated due to various and abundant agglomerations of regelation ice. They are differently preserved and possess a changeable occurrence density. At the same time the structure of the sediment is quite homogenous what is best proved by small changes of the granulometric composition of the sediment in a vertical section.

The contact zone of a subglacial sediment and of the underlying *regelation layer* of the glacier forms generally a horizontal border. Not quite linear arrangement of it does not mark anyway a sure shear plane. It is generally a narrow border zone of mutual regelation interfingering of a glacier and its moraine (Fig. 5).

Beneath the presented contact of the glacier and the morainic sediment there are two long (50 5—7 m) layers of the *regelation ice* (Fig. 5 — c and d). They are localized within the subglacial sediment at a depth of about 20 and 30—35 cm from the till top. They have quite a constant thickness; about 1—1.5 cm on the average. Only seldom their thickness is slightly over 1.5 cm. They have a levelled course, approximate to a horizontal one. They are almost parallel to the local shape of the glacier foot. Such spatial arrangement probably accentuate a relatively uniform upward development of a passive zone of subglacial permafrost. In a vertical zone of the exposure a process of selective melting of a the dark surface of the morainic sediment brings out these *regelation layers*. They form a "ribbed" relief, about 1 cm over the compact morainic sediment.

The analyzed longitudinal section has passed across the area without ridges and throughs of a *fluted moraine*. Any relief of that kind was noticed in the neighbouring glaciar forefield, several metres wide, exposed at that time from under the ice. Such a small fragment of a ground moraine represents a topography of a flat, levelled surface.

It was found already under the ice during sample collection that a distribution of these relatively continuous *regelation layers* was quite small. It could be particularly well seen in northsouth direction, transversally to the glacier movement where the layers were much shorter. About 30—70 cm northward displacement of the exposure wall already proved a lack of main *regelation lyers* of the subglacial sediment. In the small areas of gentle subglacial topography, without regular ups and downs of a *fluted moraine*, the *regelation layers* of this kind formed elongated strips.

The authors' observations suggested that they were parallel to the glacier movement.

7.1. Texture of a frozen ice-morainic sediment

But these two *regelation interbeds* (Fig. 5) are not the ones that enable to find three main parts of the sediment; it can be done on the ground of the way of development of other ice fragments as well as on the changeability of saturation by them of the morainic sediment. In the locality (in 0.50—0.55 m section) the following layers are distinguished:

1. uppermost one or top contact layer,
2. lower upper layer, and
3. middle layer.

The last one was not analyzed in full.

Layer 1. A tight connection of the uppermost part of the sediment with a bottom *regelation layer* of the glacier enables to call it the top contact layer. Its thickness is up to 10—12 cm. Physical properties of the deposited and frozen top part of the sediment can be characterized by a considerable saturation of the *regelation ice* in a form of layers, lenticles and small elongated blocks. Irregularities of ice distribution in the top contact layer makes it possible to distinguish two units of a lower order.

Layer 1.1. The uppermost one, about 2—5 cm thick. It contains the greatest quantity of *regelation ice* in the whole section. This ice is of a linear distribution. Generally its longest and at the same time the uppermost layers are the several dozen centimetres long branches of the foot regelation layer of the glacier. The unit enables a tight contact of the basal part of the glacier ice with a morainic, frozen subglacial sediment.

A thickness of the ice layers that penetrate the top of the ground moraine are small (up to 2 cm). Between them and the glacier foot there are many gravels and boulders. A considerable amount of boulders can be found at the contact of the neighbouring masses. Thus they are partly "submerged" in the morainic sediment and in the regelation foot of the glacier. They remain outside the lowermost surface of the glacier ice i.e. outside the previous basal environment of glacial transport.

Among the boulders deposited at the top of a previous active layer of subglacial permafrost, in a contact zone of ice and morainic sediment (Fig. 5 — IIIa and IIIb) one may found, in comparison with a texture of debris in ice, the changes that have originated entirely during deposition. Of course, these changes were caused by transformations during passing of a mobile ice-morainic mass into a morainic sediment (already deposited).

Layer 1.2. A part of the uppermost layer that occurs directly beneath its top, is already more morainic one and is about 8—10 cm thick. It is less overcharged by discontinuous layers or shorter lenses of regelation ice. They are usually of "banded" type and are from 10 to 30—40 cm long. Their thickness is generally small, usually less than 1.5 cm. Most frequently the longer layers are thinner and the shorter create more "bulgy" lenses.

Independently on the shape all these elements are generally still horizontal ones what is quite typical. Besides, many single boulders are envelopped at the bottom by a coast of hard *regelation ice*.

Layer 2. A transition to the next, lower part of the sediment, completely localized over the upper one of two continuous intramorainic *regelation layers* (Fig. 5 — c), is almost entirely indictinct. Particularly, it is quite difficult to be found if taking only the changes of the frozen sediment matrix into account. But this unit — called by the authors the lower upper layer — can be distinguished from the overlying and the underlying sediment by a completely other general physiognomy of the permafrost. The point of the matter is that the layer presents a specific development of fine fragments of the *regelation ice*.

First of all, the layer (over 8 cm thick) possesses a smaller quantity of ice agglomerations in comparison with the overlying top contact layer 1 of the sediment. They contain already single, usually isolated short lenses and blocks. A variety of irregular forms is typical for them. Usually their thickness is varying and their outline is "bended". They are greatly inclined in relation to the generally horizontal ice layers of the uppermost part of the sediment (layer 1). Ice agglomerations coming from a frozen water can be distinguished in this layer on the ground of element structure and their spatial arrangement. A quantity of ice keeps decreasing towards the bottom of the layer.

Ice agglomerations occur quite frequently under gravels and boulders where they create small "cup-shaped" framing of the outlines of lower walls of rock pieces. Also, a certain differentiation of the principal dimensions of ice can be seen, depending on the surface of boulder walls, enveloped by an ice "cup" at the bottom. These relations are presented in the Table II.

Table II.

Dependence of dimensions of regelation ice forms that "coat" boulders and stones, on their fraction

Longer axis (*L*) of gravels and boulders (in cm)	Approximate length of ice coat (in cm)	Maximum thickness of ice coat (in cm)
12—8	16—10	2—1
6—5	8— 6	1—0.5
3—1	4— 2	⩽0.5

Therefore a more distinct differentiation of a quantity and way of development of the ice enables to divide the top part of the sediment, occuring between the floor and the upper inner regelation layers, into two described layers (1,2).

The lower upper layer 2 of the sediment (2) may be just the one that has possessed for a pretty long time a plastic, almost muddy consistency as it was the bottom part of the active layer of subglacial permafrost. While freezing the layer was under influence of increasing and the greatest cryogenic pressure coming from two opposite sides. The pressure developed vertically: on the one hand, from the bottom upwards in agreement with an increase of thickness of the passive permafrost layer, on the other hand it was coming from the top, from the glacier floor downwards i.e. from the top and contact part of the active permafrost layer that started to freeze firstly. These processes resulted in breaks and maximum isolation of the elements of regelation ice as weel as in a considerable differentiation of their spatial distribution and orientation. Just in this layer the measurements of till fabric type of the fraction 15—60 mm have been done (Fig. 5 — diagram IV).

Layer 3. The other, visible in the first phase of studies — the middle series directly underlies the higher one of two inner, continuous *regelation layers*. Therefore, it can be found at a depth beneath 20 cm. It is then entirely a morainic part of the sediment. Lack of small (but easy to be seen) lenses and blocks of isolated ice is typical fot it. A thickness of the studied part of the sediment was about 30—35 cm (it contains both continuous layers of the regelation ice that were described before).

7.2. Texture of the morainic matrix of distinguished ice-morainic sediment layers

Inner arrangement of the matrix of distinguished morainic layers is similar to a thin-layered texture. By its spatial arrangement, approximate to a horizontal one, it reflects the texture of a basic *shear plane* system of the active glacier.

A similar structure has been described earlier from Spitsbergen by Boulton (1970b) beneath the foot of the Nordenskiöld Glacier. Thickness of the same layers in the sediments of the Werenskiöld Glacier is small and close to 1.5—2.5 cm. These layers can be locally seen in the permanently insolated and melting vertical exposure walls; but they are to be seen best in the middle layer.

The texture of the frozen sediment undoubtedly reflects a texture of the basal ice-morainic part of the Werenskiöld Glacier. It is to be related to a schistic texture described by Olszewski (1974) in sediments of a lithofacial basal complex of Pleistocene subglacial tills along the Lower Vistula area. But no detailed analysis has been carried over the texture (microtexture) of the matrix inside the mentioned thin layers. Therefore, it is not fixed if there is the successive (and of the lower order) arrangement of parting, related to the inner foliation of the glacier ice.

8. Granulation of recent subglacial deposits of the Werenskiöld Glacier

A described granulometric analysis of the sediments in the marginal zone of the Werenskiöld Glacier was described by Karczewski and Wiśniewski (1979) in an analytical study. They have also collected two samples in the frontal part of the glacier for granulometric and roundness analyses of quartz grains.

Fraction of a subglacial sediment analyzed in two sequences (5 samples each) in the same exposure wall, at a distance of 1.5—2.0 m from each other, is presented in Table III and Fig. 6.

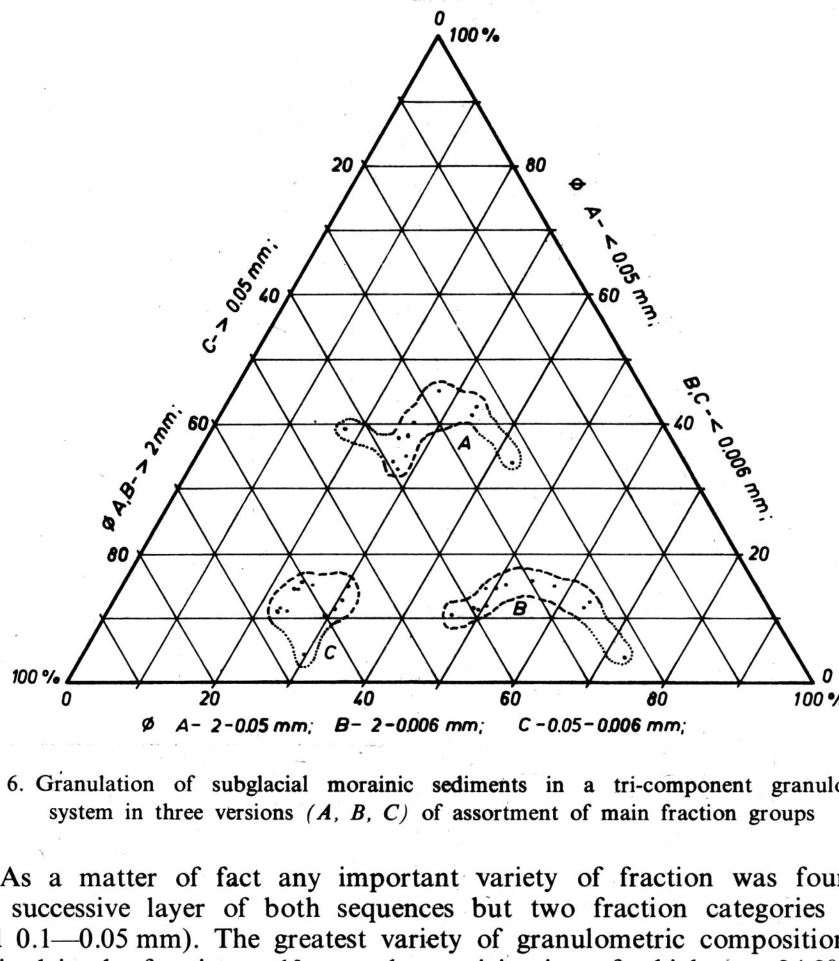

Fig. 6. Granulation of subglacial morainic sediments in a tri-component granulometric system in three versions *(A, B, C)* of assortment of main fraction groups

As a matter of fact any important variety of fraction was found in the successive layer of both sequences but two fraction categories (> 10 and 0.1—0.05 mm). The greatest variety of granulometric composition was noticed in the fraction > 10 mm, the participation of which was 24.8% and 14.85% respectively in both sequences. An important fact was that the greatest participation of the fraction (in both sequences) occurred at the top and also in the lowermost sample of the middle layer. But a vertical arrangement of both successive layers of the maximum participation of the fraction was reverse in both sequences (Table III). As it could be noticed in a confrontation of the table data it reflected a certain more general trend. A reverse in a vertical arrangement of maximum and minimum percentage content could be observed as well in many successive fractions of both sequences. In the sequence I many fraction e.g. 10—5, —2, 1—0.5, —0.25, —0.1 and —0.05 mm had the smallest participation in the

Table III.

The granulometric composition of modern subglacial sediments (bottom moraine) from Werenskiöld glacier

Number of sample	Depth (cm)	Percentage amount of fraction (mm) >10	10—5	5—2	2—1	1—0.5	0.5—0.25	0.25—0.1	0.1—0.05	0.05—0.02	0.02—0.006	0.006—0.002	<0.002	Summa
I—5	0—5	20.92	9.26	8.81	3.98	5.02	3.24	5.27	9.00	11.50	11.00	5.00	6.00	99.00
—4	10—15	5.97	8.12	9.10	5.35	5.99	3.94	6.76	20.52	15.72	14.04	2.77	1.62	99.90
—3	20—25	14.12	6.62	12.29	4.27	5.49	3.82	5.34	7.60	13.42	11.81	7.60	7.62	100.00
—2	30—35	18.13	7.62	13.36	3.88	5.69	3.50	6.07	8.03	11.34	11.34	4.60	6.44	100.00
—1	40—45	30.45	5.26	7.28	3.94	4.88	3.21	5.05	—	15.91	13.12	4.16	6.74	100.00
Difference between maximal and minimal amount in each cathegory		24.48	4.00	6.08	1.47	1.11	0.73	1.71	20.72	4.57	3.04	4.83	6.00	—
Ia—5	0—6	19.96	8.80	7.98	3.85	5.66	0.77	5.07	10.00	13.00	10.00	8.00	7.00	100.09
—4	10—15	8.81	9.77	11.01	4.84	5.77	4.05	5.64	10.27	11.74	11.74	5.36	11.00	100.00
—3	20—25	5.11	10.01	9.88	5.40	5.71	4.34	7.60	10.00	15.00	15.00	6.00	6.00	100.05
—2	30—35	6.14	7.60	10.07	5.26	6.29	4.16	6.42	10.80	15.12	15.18	5.40	7.56	100.10
—1	40—47	12.50	6.10	9.20	4.99	5.74	3.79	5.65	7.00	14.00	16.00	7.00	8.00	99.97
Difference between maximal and minimal amount in each cathegory		14.85	3.91	3.03	1.55	0.63	3.57	2.53	3.80	3.38	6.00	2.64	5.00	—
Mean difference of amounts		19.66	3.95	4.55	1.51	0.87	2.15	2.12	12.16	3.98	4.52	3.73	5.50	—

lower part of the sequence (middle layer). At the same time the percentage minimum values in the sequence Ia corresponded to top samples of the sediment.

A result value of particular maximum and minimum percentage contents of successive fractions from > 10 to < 0.002 mm had a specific distribution. The fractions: 1.0—0.5 mm (0.63% — Ia) and 0.5—0.25 mm (0.73% — I) were the less variable classes of grain diameter. Also the distribution analysis of successive fraction groups and particular layers (horizontal system of granulometric analysis) emphasized that only in the mentioned (sequence I) or in the neighbouring (sequence Ia) sections there were general minima of material distribution of the sample. Therefore, even these modest statistical data from Spitsbergen proved a principle of a bimodal distribution of granulation fixed by Dreimanis (1969) for morainic sediments of the central Ontario.

Thus, a distribution of the lowermost average differences of maximum and minimum participation of the fraction in a general granulometric composition of medium fraction 2.0—0.1 mm (Table III) supported the known statements. A bimodal granulation distribution, proved by analyses of many older morainic tills of various areas and emphasized among others by Dreimanis (1969) and Olszewski (1974), was also a specific feature of recent subglacial sediments of the Werenskiöld Glacier. Thus, it could be taken for a specific feature of this genetic type of sediments, the basal facies of which was to be connected with a glacial basal transport and with subglacial transport and deposition.

9. Texture of debris of subglacial deposits in a marginal zone of the dead Werenskiöld Glacier front

9.1. Texture of debris at the contact of ice and top layer of a subglacial sediment

Two diagrams (Fig. 5 — IIIa and IIIb) of gravel and boulder orientation in the uppermost contact layer (1.1.) prove a general similarity of debris texture in subglacial sediments with the azimuth of a local direction of the glacier movement. Azimuth 90°—270°N is the most popular and it is deviated for only 10° from the azimuth of *fluted moraine* ridges in the neighbourhood. But both diagrams represent another kind of the texture with a predominance of the direction parallel to the glacier flow.

Diagram IIIa (Fig. 5) is an example of two oblique predominant directions (60° and 90°N), arranged at both sides of the azimuth 80°N. A certain prevailing value of distal inclinations of longer boulder axes (33° in a sector of 240°—290°N) can be noticed over a more dispersed and less abundant proximal inclinations (20% in a sector of 50°—90°N). The data presented in the diagram have been collected in a distance of less than 1 metre from the mentioned elevation of schist outcrop than the ones that

enabled to draw the diagram IIIb (Fig. 5). Therefore, they were collected beneath the ice current overpassing the bedrock elevation. The stronger movement aside the obstacle is proved:
— by the mentioned synthetical diagram,
— by greater mean inclination of the longer axis ($L = 20.7°$) than in the diagram IIIb (Fig. 5) and
— by a small but already distinguishable participation of orientation transversal to the ice movement (340°—10°N).

On the other hand the diagram IIIb (Fig. 5) is an unimodal type of a closed diagram. It possesses a more bimodal proximal-distal distribution of inclinations of the L axis (60°—100°N: 25% and 250°—290°N: 23%). The boulders from the diagram IIIb (Fig. 5) occurring a little farther from a schist elevation, present also the smallest value of mean inclination angle of the longer axis among all the samples of a subglacial sediment ($L = 15.9°$).

A confrontation of the diagrams of the contact zone "sediment-ice" have been done with a texture of debris occuring completely inside the ice. The analysis emphasizes a greater coincidence of dispersion of main directions, relatively in the diagrams IIIa and IIa as well as in IIIb and IIb (Fig. 5). The first two diagrams present the debris deposited closer to the mentioned bedrock obstacle. The latter is supposed to cause the predominance of two (contact of morainic sediment and ice) or three (ice) directions and greater mean inclination of the axis L than in the diagrams IIIb and IIb (Fig. 5). They just illustrate orientation and inclination of debris a bit farther from the bedrock obstacle. The diagrams IIIb and IIb (Fig. 5) are similar to each other due to greater closement of dispersion in main azimuth sector and smaller inclination of a longer axis. Definite and slightly varying bedrock relief (varying inclination of schist surface and of upward accreting surface of a passive layer of subglacial permafrost) caused a stabilization or even an increase of differences (e.g. inclination of *l* axis in diagrams IIIa and IIIb (Fig. 5) during deposition of the top, still plastic part of a subglacial sediment.

One should also emphasize a certain, slightly greater general closement of azimuth and smaller values of inclination angles of *L* axes of the boulders from a contact environment of ice and floor regelation ice in relation to debris coming entirely from the overlying ice. Such an undoubtedly slight but distinct difference that can be found by means of some comparable aspects as palaeomorphological criterion of deposition phase, their orientation and inclination of *L* and *l* axis, are the signs of secondary changes. First of all, during passing from a glacial environment into a subglacial sediment there is a small re-orientation of azimuth directions (with a trend of their closement). But generally a vertical range of inclination angles of *L* axis decreases. Therefore, these are small but still preliminary effects of consolidation of a glacial sediment, visible already during "recorded" deposition (a subglacial permafrost). The latter change — decrease of an inclination angle of the longer axis in a morainic environment of a subglacial sediment (in comparison with feature in ice) was already mentioned by Boulton (1970b) as well as Olszewski and Szupryczyński (1975).

9.2. Orientation and inclination of debris of the lower upper layer

At greater depth as well (over 15—20 cm) the orientation of longer axes of boulders is the same as the azimuth of ice movement. In a close unimodal diagram (Fig. 5, diagram IV) that presents a texture of gravels and boulders of the lower upper layer 2, the inclinations are generally evenly distributed in a proximal-distal direction. It is the only diagram in which the azimuth of ice movement (80°N) and the direction of the most abundant boulder participation in a ten-degree angular subdivision (75°—85°N) are the same.

These three specific features: — general shape of a diagram rose, — predominance of boulder texture agreeable with a direction of elongated elements of microrelief at the top of subglacial sediments and — bimodal uniformity of occurrence of longer axis inclination prove that this diagram presents a very close connection of boulders with a texture of debris in active basal environment of the Werenskiöld Glacier.

But there is a feature that allows to dinstinguish the diagram among the others: a maximum mean inclination of both, the longer axis ($L = 23.3°$) and the mean axis ($l = 28.1°$). The boulders of the higher category of inclination angle of L axis participate, as it is most common, in azimuth transversal to glacier movement. One should also emphasize that they are also represented in a wider angular range of the main direction i.e. parallel to glacier route. This texture feature of the boulders that can be studied only in the sediment of the layer with thin, vari-shaped and differently arranged "chips" of *regelation ice*, seems to support as well the most delayed freezing of that part of the sediment. Besides, the fact that it was subjected at that time to the greatest and most deformating cryogenic pressure. It disturbed the texture of the created regelation ice and also intriduced distinct deviations in some of the elements of syn-transported texture of the boulders (Fig. 7).

9.3. Texture of boulders in a middle layer

The diagram (Fig. 5 — diagram V) is a classic diagram for a slightly metamorphozed sediment of a subglacial deposition due to its azimuth direction, generally close and unimodal shape, bimodal participation of opposite directions of axis inclination along the main direction. It reflects well the texture of the basal environment of the glacier. Small mean angles of inclination of both axes (Fig. 7) seem to support the opinion that it is just the sediment of this part of the section that was subjected to a greatest cryostatic pressure. At the same time it was situated as much above the bedrock, in a zone of more gentle cryokinetic pressure that during the final phase of the sediment transport no texture disturbances were possible to occur that would be connected with a local deriving and upward transport of debris from a schist bedrock.

Measurements of the boulder texture in the lowermost part of the sediment, accessible to studies i.e. of debris in the lower upper (2) and

Denotation of the: Measurements	Denotation of the: Morainic layer	Average angle of inclination of the axis L (•) and l (∘)	Depth of the measurements in the morainic deposit (cm)	Thickness of the layer (cm)	Horizon in which the orientation of pebbles was measured
I					surface of the melting glacier
IIa,b				a: 70 – 85 b: 3	a: normal glacier ice (18.5 % of pebbles) b: bottom regelation layer of glacier (81.5 % of pebbles)
IIIa,b	(1) 1.1.		0 – 5	(10 – 20) 2 – 5	(top contact layer) upper part, extremely in the top
IV	2		10 – 20	> 8	downstairs upper
V	3		30 – 40	30 – 35	middle

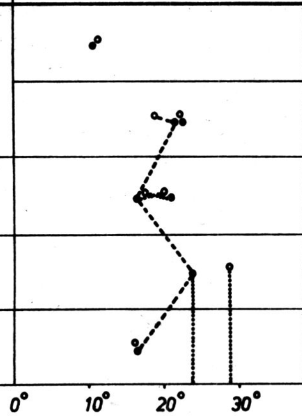

Fig. 7. Mean inclination angles of longer *(L)* and mean *(l)* axes of boulders in supraglacial, englacial and subglacial environments of a marginal zone of the Werenskiöld Glacier

middle (3) layers were done in a final phase of the first study period (July 1972). At that time the exposure wall was already withdrawn about 1 m referring to the starting position. Therefore, it is more correct to confront these diagrams (IV and V) with the diagrams IIIb and IIb (than — IIIa and IIa) that represent the data of a contact zone and of ice in a section localized farther from the mentioned schist elevation (Fig. 5).

10. Features of a bottom part of a ground morainic sediment in a recently exposed forefield of the Werenskiöld Glacier

The ground moraine beneath the ice as well as in the forefield of the Werenskiöld Glacier consists of a morainic clayey-clastic sediment. It has originated in result of a typical basal and subglacial transport. Its morphology in also created under the glacier. Getting into the glacier forefield the sediments enter a zone of very different environmental type in comparison with the features of active or dead subglacial environment. First of all the previously existing, overlying thin cover of the glacier front disappears what results in a stoppage of its direct static charge on the local bedrock (of formed ground moraine). Together with the end of previous isolation the thermic conditions usually change, especially at the top of the sediment.

But occassionally vast areas of ground moraine may be preserved where the possibilities of sediments and subglacial relief changes are small. In places where for example the surface part of a *fluted moraine* has not changed much the texture of boulders reflects probably still the orientation of movement and subglacial modelling phases. The results of Kozarski and Szupryczyński (1973) studies over a texture of boulders at the ridges of *fluted moraine,* in the forefield of the Sidu Glacier in Iceland may be taken as example. Along the ridge axes, at the surface and at a depth of 0.18—0.22 m as 0.22—0.68 m, the orientation of the longer axis is quite similar and concordant with the azimuth of the ridge. A small inclination of the longer axis is also typical. Price (1970) has found too in glacial sediments of the basal and subglacial transport occurring in the morainic ridges connected with squeering of semi-liquid deposits from beneath the Fjakksjökull Glacier in Iceland, a conformity of boulder texture and direction of ice flow — he found that in ridges occurring already in the forefield of the glacier.

At the same time seems to be quite obvious that certain texture changes undoubtedly occur at repeated long-term processes of extramarginal regelation. They are particularly typical for inclined surfaces of a ground moraine e.g. on the slopes of a *fluted moraine.* Intensity of processes of

Fig. 8. Structure of a clayey subglacial sediment about 0.80 m thick, localized in the close forefield of the Werenskiöld Glacier and exposed from under the ice cover in result of summer ablation during 1972
The sediment covers a roche moutonnêe of schists of Hecla Hoek Formation. A thickness of the ground-morainic sediment decreases southwards (i.e. in the distance of a photograph) where it reaches at the slope of schist elevation a thickness of 0.20 cm
Photo A. Olszewski

epigenetic reorientation increases as the summer season keeps longer and warmer what results in an advancing deglaciation of the area.

During the second studying period (September 1972) a macroscopic analysis of entirely exposed section of subglacial sediments (Fig. 8) was done in the freshly exposed forefield o the Werenskiöld Glacier, along the same stream channel. This area was completely unfrozen to a depth of 0.50—0.80 m; therefore, the sediment could lose its all regelation ice already during the first summer season if it occurred outside the dead subglacial envirnoment.

Postdepositonal epigenetic transformations are suggested to play an important part in origin and present outlook of ancient. Pleistocene ground morainic sediments of various lithofacial complexes. Observations in present areas of polar glaciation prove that the epigenetic changes result from interference of various processes that transform more or less these sediments.

The lowermost, bottom part of the sediment (marked as the layer 4) was the most interesting in the section (Fig. 5). It was directly overlying the schists of Hecla Hoek Formation. The bottom part of the sediment (coming from a longer transport) was found to be higly saturated with sharp-angular schist pieces of the nearest bedrock.

The local material at the bottom of a ground moraine of the Werenskiöld Glacier can be distinguished not only on the ground of a petrographic analysis. As a morainic debris is has quite a specific textural feature. Local bulders, gravels and coarser sands are characteristic for their lower treatment, roundness and other textural indices.

Thus, this bottom part distinctly connected by its lithological features with a local bedrock can be for certain considered for a *lithofacial subbasal complex,* the same one as has been earlier distinguished in till sections of the Polish Lowlands — Olszewski (1974).

11. Conclusions

The studies were carried through in an extremely marginal, completely dead and subjected to an intensive surface ablation part of the Werenskiöld Glacier. The analysis of a texture of debris (fraction 15—60 mm) was done in three environments. The supraglacial environment was the most changeable one but two others — englacial and subglacial ones — were found to form a stable object for textural analyses of a morainic material. Results of studies allowed also for conclusions concerning the basal part of the active glacier. Besides they describe well the thermic conditions of a subglacial environment in a final phase of the movement and during its stoppage.

Therefore, the most important conclusions are as the following:

1. A supraglacial environment in a marginal part of morainic sediments during its formation is quite a distinctive type of sediment texture in relation to debris in ice and under the overlying glacial ice. Distribution and orientation of debris are easily adapted to a local inclination of ice surface and so, result in a great dispersion of orientation directions. One can distinguish then a direction transversal to the ice movement

that is at the same time a reflection of short-time arrangement of debris, moving at the ice surface. Small mean inclinations of both boulder axes (*L* and *l*) are typical.

2. Contens of boulders and matrix of a morainic sediment in glacial ice depends much on depth of its occurrence. Forh horizontal layers in main beds of the ice — in between the more significant *shear planes* — a principal has been proved: the deeper and closer to the glacier foot the more debris can be found.
3. Most boulders of the analyzed fraction occur just directly in a bottom *regelation layer* of the glacier, 2—3 cm thick (81.5%; Table I).
4. No ablation on the outer crystal walls in the bottom part of glacial ice no subglacial melting of regelation ice suggest that a compact dead glacier possesses the textural elements of a final phase of basal glacier foot movement.
5. Predominance of boulders with an orientation parallel to glacier movement suggest that at relatively constant thermodynamic conditions it is the principal debris orientation inside a glacial ice and a related regelation ice. Small mean angles of inclination of a longer axis (*L*) define a trend to relatively parallel position of boulders inside a stratified glacial ice or a horizontal contact zone of regelation ice.
6. An influence of bedrock elevations on glacier dynamics in noted in a greater content of boulder orientation transverse or oblique to a glacier movement. This fact has been noted in ice (Fig. 5 — diagram IIa) as well as in in a top contact zone of the sediment (diagram IIIa).
7. During a passing of debris and matrix an active basal part of a glacier into a subglacial environment (active firstly, then — dead) there is a trend of greater concentration of azimuths and of smaller inclination of boulders. It is favoured by an increase of cryogenic pressure resulting from regelation processes.
8. Detalied structural studies enabled also to fix the phases of evolution of a marginal subglacial permafrost and to find that at the top of subglacial sediments a series can be distinguished that has represented for the longest time an active layer of a permafrost in a subglacial environment (Fig. 5 — layer 2). It is described by mostly deformed spatial structures of a regelation ice and by a greatest mean inclination of a longer (*L*) and a mean (*l*) axes of boulders.
9. In deep parts — in a lithofacial basal complex of a ground moraine — in a middle layer (Fig. 5 — layer 3), there is in a greater distance from a bedrock obstacle, a trend of a considerable concentration of the azimuth of boulder longer axis (diagram V). There, the mean inclination angles of *L* and *l* axes are also smaller (Fig. 7) what results from an integrated effect of cryogenic and cryostatic pressure. At the same time, at this depth there is already no influence of upward moving of debris eroded by a glacier from a local bedrock.
10. Content of local debris i.e. of angular schist pieces, in the lowermost, bottom part of the sediment (layer 4) allows to conclude that at a small general thickness of a subglacial facies there is its (subglacial) movement along the whole vertical sequence of the sediments.

11. A subglacial environment, at least in its top part under the active ice, is highly saturated by melwaters what is proved by abundant interbeddings of regelation ice (in the studied section found at least down to about 35 cm).
12. During a thermic evolution of a subglacial environment, in a marginal part of a glacier, a fluted moraine as well as a flat landscape can be formed to each other. They are strictly associated and their sediments under the glacier are saturated by abundant pieces of *regelation ice* The ice forms frequently the ice strips parallel to a direction of the glacier movement.
13. In a subglacial environment there are in phases of transported as well as deposited sediment, during regelation, the definite changes of debris texture that already belong to a group of secondary transformations in relation to the active basal environment of a glacial ice.
14. Only a very detailed analysis of glacial morainic sediment, simultaneously from its surface, inner part and from under the ice, suggests a possibility of fixing the secondary textural changes of a deposition phase or successive phases of sediment diagenesis from the main textural features that have originated in the active basal environment of the glacier.

An application of structural-textural methods results in a precise description of recent morainic sediments. Besides, by the quantitative formulat ons the poligenetic qualitative changes can be motivated; the latter are really active in an environment of present development of a glacial landscape. These changes are in turn recorded in a differentiated system of present glacial sediments. These remarks concern as well the subglacial morphology and sediments that are considered by many scientists to be slightly differentiated and slightly changeable.

In a marginal part of Spitsbergen glaciers the morainic landscape and sediments are nowadys created, pass a conservation phase and are also subjected to preliminary epigenetic changes. Thus, particulary there a use of statistic structural-textural methods can be tested for studies of ancient moraines and Pleistocene morainic sediments. With an application of actualism principle the current opinions on formation of sediments of Pleistocene vast continental glaciations.

Carrying through of such and of similar studies in the areas of present glacial cover is an important or even a necessary phase in obtaining a full lithofacial description of formation the sediments of direct glacial deposition in general.

12. Summary

In July 1972 an analysis of morainic sediments of a frontal zone of the Werenskiöld Glacier was done. The glacier is localized in a southern part of Wedel-Jarlsberg Land (Fig. 1). Texture, structure, general physical properties and lithofacial features of morainic sediments were studied. The analysis dealt with sediments that melted out on the glacier surface at that time (Fig. 5 — a) and the ones still occurring in the ice (Fig. 5 — b). The morainic covers of already solidified subglacial sediment were also analyzed (Fig. 5 — c).

The studies were carried over the sediments of three main glacial environments: supraglacial, intraglacial and subglacial ones. The problem of texture of till boulders of a fraction 15—60 mm is described exclusively in the paper.

The supraglacial environment in a marginal zone of the glacier keeps creating now and represents quite an individual textural type of the sediments in comparison with the matter in the ice and under the overlying glacial ice. Orientation and position of boulders is in agreement with a local inclination of the surface and therefore a considerable dispersion of their azimuths is noted (Fig. 5). Small inclinations of boulder axes are typical.

The englacial environment is diversified. Most debris and granular matter of the morainic sediment is localized close to the glacier foot. Most boulders are oriented parallelly to the azimuth of the glacier movement. Small mean inclination angles of their longer axes (Fig. 5) define a trend to a relatively horizontal position of boulders in a stratified glacial ice.

In the sublgacial environment a trend to greater concentrations of azimuths and to smaller inclinations of boulders is noted (Fig. 5 — diagram V).

An application of textural-structural methods makes a description of present morainic sediments more detailed. In frontal zones of Spitsbergen glaciers a relief and the morainic sediments nowadays deposited, are conserved or are subjected to preliminary epigenetic changes. So, particularly there a usefulness of statistic textural-structural methods for studies over ancient moraines and Pleistocene morainic sediments can be tested. With a use of the actualism princple the previous opinions can be controlled, the ones dealing with formation of Pleistocene sediments of vast Pleistocene glaciations.

13. Резюме

В июле 1972 года, во время очередной Польской Экспедиции на Шпицберген проведено исследование моренных отложений конечной зоны Ледника Веренскиольда. Этот ледник расположен в южном районе Земли Ведель Ярльсберг (рис. 1). Исследовано структуру, текстуру, общие физические свойства и литофациальный характер моренных осадков. Изыскания охватили осадки актуально вытапливающиеся на поверхности ледника (рис. 5-а), а также горный материял ещё не вытопленный (рис. 5-б). Проанализировано также моренный покров уже установленного, субгляциального осадка (рис. 5). Проведено также исследования трёх основных ледниковых сред: супрагляциальной, интергляциальной, субгляциальной. В статье проанализировано исключительно вопрос текстуры моренных валунов фракции 15—60 мм.

Супрагляциольная среда в конечной зоне ледника находится в фазисе in statu nascendi и представляет отдельный тип текстуры осадков по отношению к материалу во льду и под наложенным ледниковым льдом. Расположение и ориентация скальных обломков легко приспособливается к локальному наклонению поверхности льда и отсюда происходит значительная д дисперсия направлений ориентации (рис. 5). Характерны небольшие наклонения оси валунов.

Ингляциальная среда разнообразна. Больше всего рассыпного материала и зернистой массы моренного осадка находится в близи основания ледника. Большинство валунов проявляет направление паралельное к движению ледника. Небольше средне углы наклонения более длинной оси (рис. 5) определяют тенденцию к относительно горизонтальному расположению валунов в слоевом ледниковом льду.

В субгляциальной среде констатировано тенденцию к большей плотности азимутов, а также меньших наклонений валунов (рис. 5 — диаграмм V).

Применение структурально — текстуральных методов утогняет характеристику современных моренных осадков. В конечной зоне шпицбергенских ледников релеф и моренные осадки создаются, переходят этап консервиеования, а также находятся в состоянию вступительных эпигенетических изменений. Здесь особенно можно проверить

пригодность статистических структурально-текстуральных методов к исследованиям старых морен и плейстоценских моренных осадков. При использованию принципа актуализма можно проверить существующие до сих пор взгляды на тему формирования плейстоценских осадков, обширный плейстоценских оледений.

14. Streszczenie

W lipcu 1972 roku w czasie kolejnej Polskiej Wyprawy na Spitsbergen przeprowadzono badanie osadów morenowych strefy czołowej lodowca Werenskiölda. Lodowiec ten leży w południowej części Ziemi Wadel Jarlsberga (rys. 1). Przebadano strukturę, teksturę, ogólne właściwości fizyczne i charakter litofacjalny osadów morenowych. Badaniami objęto osady aktualnie wytapiające się na powierzchni lodowca (rys. 5a) oraz materiał skalny jeszcze nie wytopiony (rys. 5b). Przeanalizowano także pokrywy morenowe już ustalonego, subglacjalnego osadu (rys. 5c). Badaniami objęto osady trzech zasadniczych środowisk glacjalnych: supraglacjalnego, intreglacjalnego, subglacjalnego. W artykule przeanalizowano wyłącznie zagadnienia tekstury głazików morenowych frakcji 15—60 mm.

Środowisko supraglacjalne w strefie marginalnej lodowca znajduje się w fazie in statu nascendi i reprezentuje bardzo odrębny typ tekstury osadów, w stosunku do materiału w lodzie i pod nadległym lodem lodowcowym. Ułożenie i orientacja okruchów skalnych łatwo dostosowuje się do lokalnego nachylenia powierzchni lodu i stąd pochodzi znaczniejsze rozproszenie kierunków orientacji (rys. 5). Charakterystyczne są małe nachylenia osi głazików.

Środowisko inglacjalne jest zróżnicowane. Najwięcej materiału okruchowego i masy ziarnistej osadu morenowego znajduje się blisko spągu lodowca. Większość głazików wskazuje kierunek równoległy do ruchu lodowca. Niewielkie średnie kąty nachylenia osi dłuższej (2) określają tendencję do względnie poziomego usytuowania głazików w warstwowym lodzie lodowcowym.

W środowisku subglacjalnym stwierdzono tendencje do większej zwartości kierunków azymutów oraz mniejszych nachyleń głazików (rys. 5 — diagram V).

Zastosowanie metod strukturalno-teksturalnych uściśla charakterystykę współczesnych osadów morenowych. W czołowej strefie lodowców spitsbergeńskich rzeźba i osady morenowe są w trakcie powstawania, przechodzą etap zakonserwowania oraz znajdują się w stanie wstępnych zmian epigenetycznych. Tu szczególnie więc można sprawdzić przydatność statystycznych metod strukturalno-teksturalnych do badań starych moren i plejstoceńskich osadów morenowych. Przy wykorzystaniu zasady aktualizmu można skontrolować dotychczasowe poglądy na temat formowania się osadów pleistoceńskich, rozległych zlodowaceń plejstoceńskich.

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