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ICE TECTONICS AND BEDROCK RELIEF CONTROL ON GLACIAL SEDIMENTATION – AN EXAMPLE FROM HANSBREEN, SPITSBERGEN

WPŁYW TEKTONIKI LODOWCOWEJ I RZEŹBY PODŁOŻA NA SEDYMENTACJĘ GLACJALNĄ NA PRZYKŁADZIE LODOWCA HANSA, SPITSBERGEN

ABSTRACT

Hansbreen, a tidewater glacier in southern Spitsbergen, was investigated to reveal the relationship between its tectonic and mode of deposition. In the land terminating zone the bedrock threshold plays major role in sedimentation by creating compression conditions. It causes the most of sediment to be released supraglacially, and redeposited in form of debris flows. The upward debris transport is done mostly by folding deformation of basal ice layer with a minor participation of thrusts. In observed outcrops no subglacial deformed layer of till was found. The debris occurrence was associated only with the debris-rich basal ice layer. However on the foreland exists subglacial till, partly formed in flutings, also with micromorphological evidence of deformations. Various bedrock morphology is supposed to differentiate basal conditions. The flat, but undulated, regelation favouring conditions, leads to the debris-rich basal ice layer formation, however inclined but non undulated relief prefers deformed subglacial sediments development. No structural or sedimentological evidence of surge events were found in the tributary glaciers (Fuglebreen, Tuvbreen), hence this phenomenon is thought to be limited to the main ice stream.

INTRODUCTION

During the last decade, a growing body of literature has focused on the debris structure and structural evolution of surge-type glaciers (e.g. Lawson et al. 1994; Hambrey et al. 1996; Hamilton & Dowdeswell 1996; Hambrey & Dowdeswell 1997; Glasser et al. 1998; Murray et al. 1998; Bennett et al.1999; Bennett et al. 2000). Many investigations have been also made on style of the subglacial material behaviour and its deformation. Some of authors accented the role of subglacially deformed unconsolidated sediments layer (e.g. Boulton 1979; Boulton & Jones 1979; Alley et al. 1986), and another group claimed that basal ice layer (BIL) plays a major role in the sediment transformation and significantly participates in total ice flow velocity (Echelmeyer & Zhongxiang 1987; Knight 1992; Tison et al. 1993; Sharp et al. 1994). Recently Hart (1995, 1998) proposed a deforming bed/debris-rich basal ice continuum model. Factors, which are responsible for the development of one of the mentioned situations are also under discussion. The role of tectonic in sediment transfer was considered by several authors (e.g. Glasser et al. 1998; Hambrey et al. 1999), but there is still a discussion on its real importance, and controlling factors. Among others, subglacial deposition conditions and the way of upward transportation of sediments in ice belong to the most discussed problems. They are strongly accented in relations to glaciers of Svalbard archipelago, where a number of surging glaciers is believed to be the highest in the world – at least 35% (Hamilton & Dowdeswell 1996). The activity of these glaciers has been also used as models for Pleistocene glaciations (e.g. Boulton 1972), so to determine the real mode of their sedimentation is of big importance.

The presented paper aims to: (1) document structural geology and related modes of deposition on the Hansbreen, (2) establish relationship between ice tectonics and style of sediment/landform assemblage, and (3) examine their significance as indicators of subglacial conditions, and former surging events.

STUDY AREA

Hansbreen (fig. 1) is an outlet-valley glacier flowing down for some 10 km from its ice-divide at an altitude of about 500 m a.s.l. and is fed by 7 tributary glaciers. It ends in Hornsund Fjord with an 1.5 km wide ice cliff. Land based marginal zones occur on the western and eastern sides at the foot of scree covered slopes. Earlier investigations and measurements of ice dynamics described detailed ice movement, and conditions of glacier's recession, the volume of glacial transport and glacial geomorphology (e.g. Baranowski 1977; Karczewski et al. 1984; Jania 1988). From the beginning of 20th century the glacier has been receding, but several surge events (Jania 1988; Jania & Głowacki 1996). The dynamics of the ice in the marginal zone is complicated by tributary glaciers (Tuva Glacier and Fugle Glacier on the western side). The flow velocity measurements reveal the existence of short acceleration periods during summer, which are strongly connected with weather conditions (Jania 1998). A huge contrast between the mobility of marginal and centreline parts is easily observed as well. The averaged measured value of velocity in summer months, in the central part, was up to 1m/day (Jania 1998). The Hansbreen is polythermal in type but temperature measurements in the western marginal part of the ice body show it to be warm throughout (Grześ 1980; Jania et al. 1996; Moore et al. 1999).

The bedrock at the western ice margin is composed of rocks of Hecla Hoeck formation represented by various types of schists, gneiss, amphiboles, marbles and quarzi-

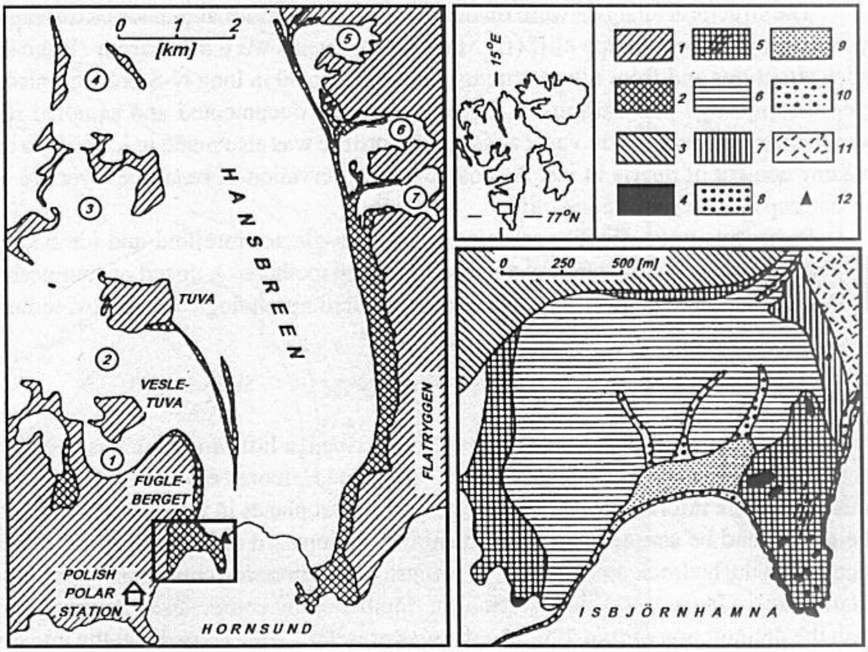

Fig. 1. Location of the study area and distribution of sediments on the western foreland of Hansbreen. The map of Hansbreen basin after Jania et al. (1994). Numbers in circles indicates tributary glaciers: 1 – Fuglebreen, 2 – Tuvbreen, 3 – Deileggbreen, 4 – Staszelisen, 5 – Nördstebreen, 6 – Oleneliusbreen, 7 – Wienerbreen;

Maps legend: 1 – extraglacial features, 2 – glacigenic deposits, 3 – slope deposits, 4 – bedrock outcrops, 5 – subglacial till, 6 – debris covered dead ice area, 7 – unstable water-saturated supraglacial covers, 8 – fluvioglacial deposits, 9 – fluvioglacial stagnant-water deposits, 10 – coastal deposits, 11 – glacier ice.

tes (Birkenmajer 1990; Manecki et al. 1993). Its tectonic history and variable resistance to erosion have produced a complex surface topography over which ice has advanced. The compressional state of glacier ice in this part results from this morphology. The western part of the foreland (fig.1) extends for some 600 m and reaches a 40 m high ice-cored morainic ridge. It is largely covered by supraglacial sediments deposited on dead- or passive-ice patches and only small areas in the vicinity of bedrock outcrops are identified as subglacial till with some fluting features. The central depression of the forefield is filled with lacustrine deposits supplied by proglacial streams.

METHODS OF INVESTIGATIONS

To investigate the way of basal material deformation and its depositional effects observations in the marginal zone of Hans Glacier (Wedel Jarlsberg Land, South Spitsbergen), were made during expeditions in years '96-'98.

Investigations focused on the western terminus and its ice tributaries (i.e. Fuglebreen, Tuvbreen, and western part of the main Hansbreen ice stream).

The structural analysis were made on the glacier surface and in ice cliffs, especially in 200m long passive ice cliff (fig. 1). Measurements were taken from all the debris laden structures and from other structural elements in 50 m long N-S profiles, also with use of oblique air photographs. All structures were documented and sampled if they were debris connected. The vertical sampling profile was also made in ice cliff to reveal volume content of debris in ice. Almost all the observation of basal ice layer are based on outcrops in the passive ice cliff.

Sediments were densely sampled from both glacier forefield and ice itself, and they were analysed with standard sedimentological methods. A dozen of sampleshardened with epidian rosin were prepared to obtain micromorphological image of sediments.

ICE TECTONIC

Although Hans glacier has been well described, a little attention has been paid to its tectonics, except works of Jania (1988, 1998) and Hambrey et al. (1999). Jania (1988) presented some information about existence of thrust planes in western marginal part of the glacier and he assumed their responsibility for upward sediment transport. He also recognised the bedrock morphology as a cause of compression conditions in this part. In a later paper (Jania 1998) the division on dominated by compression or tension zones with the delimitation of transitional zone was presented. He claimed that the transitional zone is responsible for fluted moraine formation. Hambrey et al. (1999) described the relationships between debris occurrence, folding and thrusting. They accented the folding process to be a mechanism of debris uplift and creation of thrusts as a result of shearing off the lower limb of folds.

A large variety of structures can be found in Hansbreen and its tributary glaciers. Fractures, crevasses, foliation, folds, faults, shear zones and probably even ogives (on Wienerbreen – eastside tributary glacier) can be recognised. In the analysis given below, special attention was paid to structures in the western marginal part of Hansbreen, with particular consideration given to the basal ice layer, excellently exposed at the land based ice-cliff.

Sedimentary stratification, the primary structure, is represented by snow layering, superimposed ice stratification, and sediment accumulation layers. Together they provide a complex image of primary stratification on Hansbreen. As a result it is sometimes difficult to distinguish it from some secondary structures. In the western part this primary stratification is strongly deformed. Better examples are visible in the central part where horizontal stratification can be seen in deep crevasses. Layers of white-bubbled ice, blue ice and a few layers of thicker (up to 35 cm) dirt enriched ice are basic components of the sedimentary stratification.

Apart from sedimentary stratification, foliation (cf. Hooke & Hudlestone 1978) is the oldest recognised structural feature in the study area. All other structures cut or deform it. It is best visible in the form of the longitudinal foliation in lateral parts of the glacier and indicate the flow lines, particularly in areas of glacier confluence (fig. 2). In such locations foliation dips 45 to 90 degrees to the ice stream centerline, sometimes with traces of folding; ice crystals are mostly coarse (up to few cm) and foliation bands

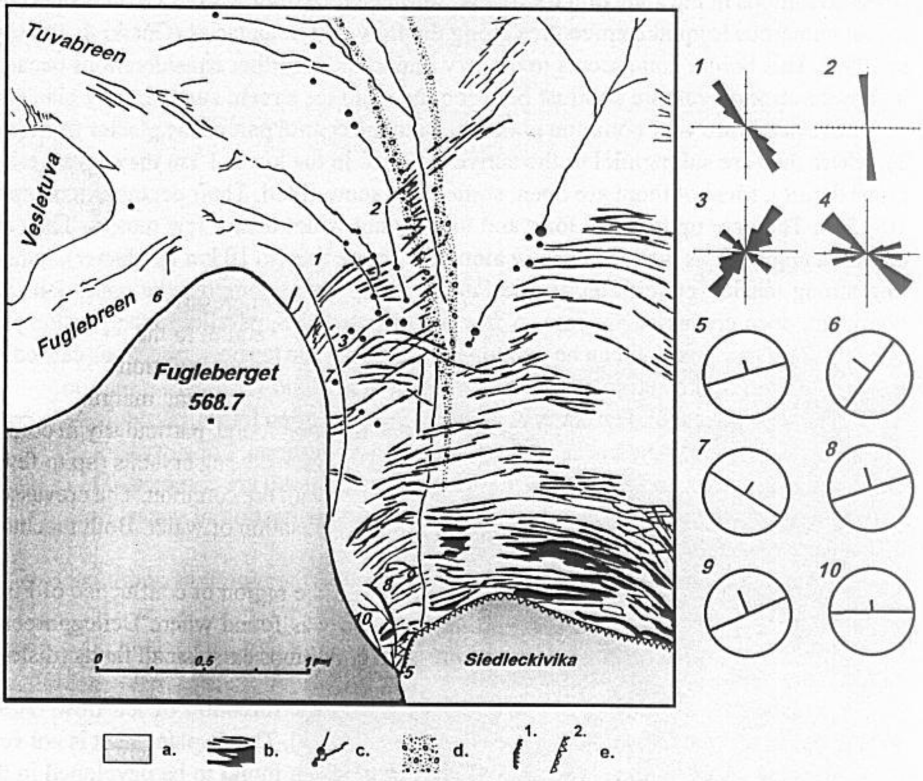

Fig. 2. The distribution of some structural features on Hansbreen. Ice surface features after photogrametric survey (Jania et al. 1994): a – glacier surrounding areas, b – crevasses, c – supraglacial streams and moulins, d – medial moraine, e – ice-cliff (1. passive, 2. active); 1-2 – foliation direction, 3 – strike of fractures, 4 – direction of thrust planes in ice-cliff, 5-10 – direction and dip of structural planes associated with debris bands.

are usually 10 to 20 cm wide. High values of dips in the area of the confluence of tributary glaciers with the main ice stream can be explained by an ice stream width shortening, and resulting strong folding of foliation (Lawson et al. 1994).

Folds are deforming both primary stratification and foliation. Apart from folds observed in the basal ice layer (presented in a later part) they are visible only in a few places and relate to deformed folia. They are mostly small-scale (tens of cm) features with roughly vertical hinges in areas of glacier confluence. Hambrey et al. (1999) mentioned the existence of bigger scale recumbent folds in the western part of Hansbreen in the late 70's.

Fractures are dominant features on the glacier surface in the region of interest and their distribution is very dense. Complementary joint sets can be recognised (fig. 2) allowing interpretation of the main stress direction, which is probably inherited from stress conditions in the zone of ice streams confluencion (fróm NNW). Geophysical data reveal numerous icequake epicentres along the flow unit boundaries (Górski & Teisseyre 1999). This border zone seems to be very important in further considerations because it shows a strong dynamic contrast between the main ice stream and tributary glaciers.

Crevasses are very common phenomena in the central part of the glacier front (fig. 2), where they are subparallel to the active ice cliff. In the lower 1 km they reveal enormous density. Most of them are open, sometimes snow-filled. Their depths extend up to 10-15 m. They are up to 1 km long and usually not wider than a few meters. They are common upglacier as well, especially along the centre line (to 10 km up glacier), indicating strong tension conditions. In the lateral parts, where compressive conditions are dominant, open crevasses are rare. A few are oriented N-S, parallel to the passive cliff line (fig. 2). Their position can be explained in terms of the tension conditions caused by faster recession of the active cliff in comparison to the land-terminating margin.

Crevasse traces (cf. Hambrey & Müller 1978) are often found, particularly in compression zones, clearly indicating changes in stress conditions. Long crystals (up to few cm) arranged in rows and parallel to the former crevasse wall are common. The crevasse closing developed either mechanically and by the crystallisation of water. Both mechanisms were probably acting in parallel.

Several sets of strike-slip faults were observed in the region of confluence of Fuglebreen and the main ice stream. A similar situation was found where Deileggbreen joins Hansbreen. In other places where compression conditions exist, small faults (dislocation range up to few cm) can be found.

Thrust faults are developed striking normal to the direction of ice flow. These structures dip between 30 and 60 degrees upglacier (fig. 2). The displacement is not very large, in some cases up to a few meters. They were often found to be developed in the places of fold limb zone. In the marginal part of the glacier, several ice cored ridges (fig. 3) and dirt cones, which are connected with these structures, are discovered. Several dirt cones composed of organic deposits were also found. Along crevasse walls and moullins in the vicinity of them the connection of organic matter rich thrust plane zones and mentioned forms was proved. Although it was impossible to trace it down to basal zone. In the observed cases of originally subglacial debris transported to the surface, the thrust zones have minor value. The measurements of debris content in ice of this zones were up to 2% and the material was not coarser than sand fraction. As it will be shown in the case of basal ice layer, fold deformation play the main role in upward sediment transport.

Small medial moraine can be observed running from Tuva Nunatak and following the flow lines of the glaciers. It is composed of almost homogenic material (concerning petrography), typical for SE Tuva. The debris cover is up to a few meters wide and 1-2 cm thick. The continuation of this cover can be found on the edge of Baranowski Peninsula providing additional information about former flow lines of Hansbreen. In crevasse cuttings no connection between structures of ice and the existence of medial moraine was found. From the beginning to the end it is supraglacial. On the eastern side of Hansbreen few medial moraines originated from tributary glaciers lateral moraines. In the lower part of the glacier they finally form one wide lateral moraine. According to Eyles & Rogerson (1978) classification they belong to ice-stream interaction type.

Fig. 3. Ice cored ridge on the surface of Hansbreen.

BASAL ICE FACIES AND DEBRIS CONTENT

The debris rich basal ice layer (as observed in the passive ice cliff) is usually 1-1.5 m thick. Only in few places, owing to deformation, the thickness increase to 5m. This layer is separated from glacier ice above by a very distinct décollement (figs. 4, 5, 6). The debris content in ice was determinated as percentage volume of sediment in ice (fig. 4). Above 3m the amount of sediment is less than 0,05% (formed mainly by silt fraction with singular sand grains). Downward the amount of debris is increasing, reaching 2 m above the bed value of 3%. This part is interpreted to represent dispersed facies (Lawson 1979). The „clotted" ice (in the meaning of Knight 1997) was found in this part. Next, the volume of sediment decreases to less than 0,1%, but in comparison with the highest part a much wider grain size distribution was presented. The lowest 95 cm is developed in the form of basal, sediment-rich stratified ice layer. The amount of debris rapidly increases to 36% and next systematically downward to 71%. The debris

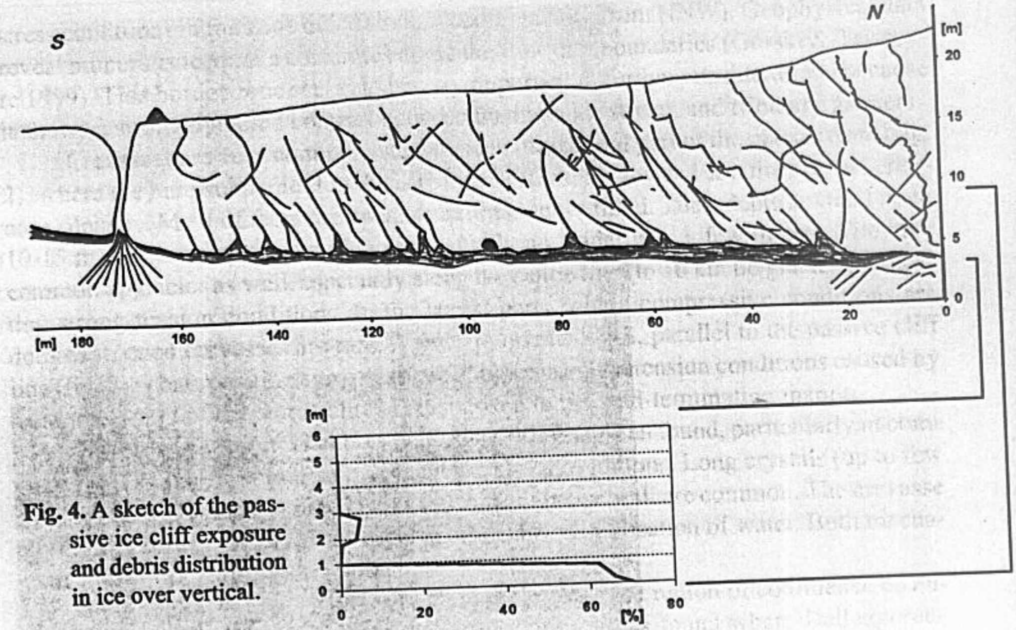

Fig. 4. A sketch of the passive ice cliff exposure and debris distribution in ice over vertical.

represents a very wide size range, with boulders up to several tens of cm in size, and is aligned as parallel to the bedrock strata which are underlined by ice fabric. Grain size distributions show a very high correlation between material, which is found in basal ice layer, in the ice cored ridges on ice surface that are connected with debris lifting structures, in the subglacial till on the foreland, and in supraglacial covers on dead and passive ice (fig. 7). Ice crystals are bubble free and form layers, which can be followed on the distance of several meters. In some places, between bedrock undulations, an additional stratified ice layer, which contained much less debris than the layer above it was found. Clast orientation commonly follows the stratification. On top of the BIL big boulders (up to 0.5 m) with signs of rotation coming out of the surrounding ice structure were found.

BASAL ICE LAYER DEFORMATION

Deformation of the BIL, which were observed in passive ice cliff, are in form of folds and thrusts. Folds can be observed every dozen or so meters (fig. 4). The inclined or overturned folds (figs. 5,6) converge downglacier, often with incipient thrusting evidence (in this case the lower limb is strongly reduced). The typical axial plane dip ranges from 30 to 80 degrees upglacier. Deformation causes finally the upward debris movement in the range of a few meters, which can result in forms of ice cored ridges in the most marginal part of glacier, proving also short vertical debris transportation. In the ice just above basal ice layer shear zones are common. Sometimes they occur independently from the structures below (i.e. in the BIL), sometimes are strongly connected and exist for example as a forward of fold-thrust structures (fig. 6). Shear zones in ice are marked

Fig. 5. An example of folding of basal debris rich ice layer with evidence of incipient thrusting.

by a decrease in crystal sizes. The increase of debris volume percentage (fig. 8) in the shear zone was observed (up to 2% while outside of the shear zone these values were 0.05 and 0.5 %). The material in the shear zone was much better sorted than in the surrounding ice. A cavity was also found as a structure connected with fold. Some large ice crystals the creation of which can be connected with the existence of supercooled stagnant water were found there.

CHARACTER OF SUBGLACIAL DEPOSITION

The basal part of the glacier, which was exposed in the passive ice cliff, has melted lateraly and simultanouesly redeposition of debris by fall, debris flows, creeping and washing occured. Hence the information about subglacial deposition can be gained only from subglacial sediments, which exist in few places on the glacier forefield.

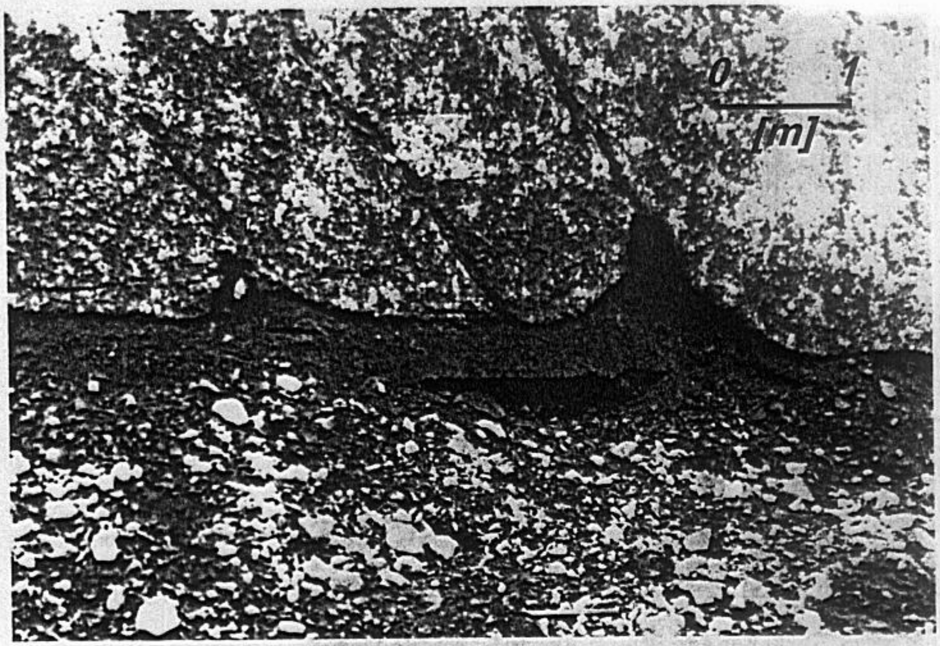

Fig. 6. Dependent and independent structures at the contact between basal layer and overlying ice.

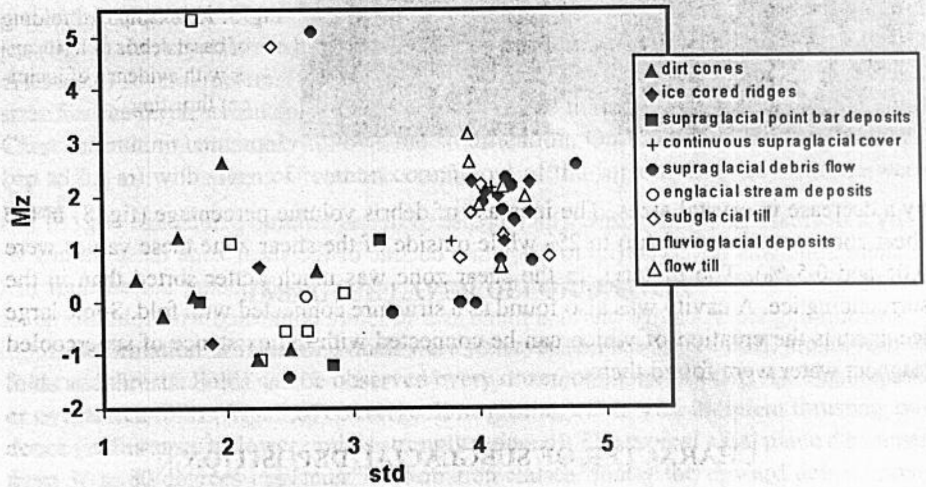

Fig. 7. Diagram showing grain size mean diameter (Mz) vs. standard deviation (Std) for samples taken from different glacial environments on Hansbreen.

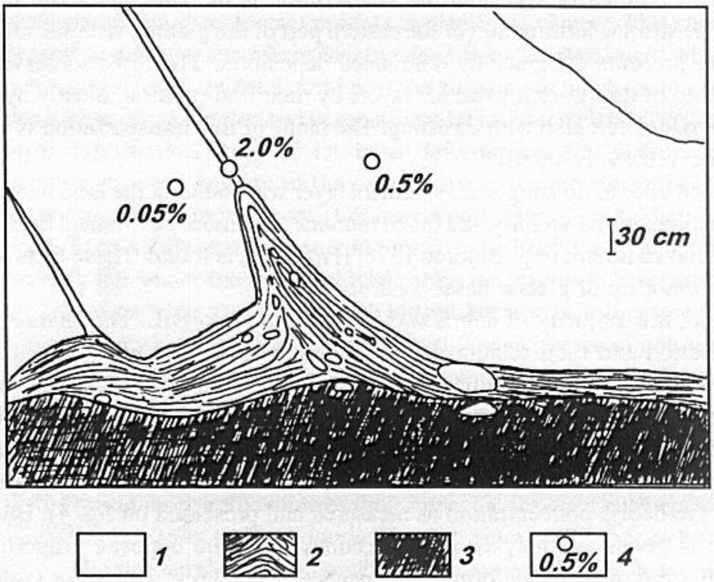

Fig. 8. An example of fold structure with incipient thrusting in the passive ice cliff and related debris content values in volume percentage.

The till surface on the E part of Baranowski Peninsula is inclined on average 10 deg. towards the NE and approaches thickness of 50 cm. It comprises one layer of matrix supported, massive diamicton, deposited directly on bedrock with striae, with 30 cm high fluted ridges on the surface. The flutes are up to 50 m long. Clast orientation is parallel to striae and fluted ridges (fig.9). The predominance of large clasts makes the macroscopic determination of structures almost impossible and gives an impression of a structureless deposit. Thin sections reveal the matrix supported structure with invisible plasmic fabric (it can be caused by high carbonate amount: 10.5-12.3%, and low clay fraction content: 5-8% (van der Meer 1996)). The orientation of grain long axes is mostly horizontal, „galaxy", turbate structures (van der Meer 1997) and crushed grains are common features. Petrographical analysis shows that more than 90% of the sediment is not derived from the local bedrock.

MODEL OF BEDROCK TOPOGRAPHY DEPENDEND SEDIMENTATION

The role of tectonic deformation in sediment transfer in the western land terminating part of the glacier is very important and affects the dominance of supraglacial se-

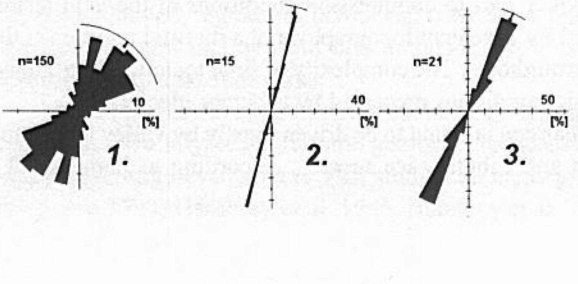

Fig. 9. Clasts orientation in subglacial till (1), flutings orientation (2) and the direction of striations on bedrock outcrops (3) on the Baranowski Peninsula.

dimentation. It can be clearly seen that the key position is the rock threshold in the bedrock relief. The similar termination of the eastern part of the glacier, without such an bedrock obstacle, presents subglacially dominated deposition. The direct observation has shown uplifting of debris-rich basal ice layers by their deformation, mostly by folding, sometimes associated also with thrusting. The range of this transportation is up to several meters (i.e. relatively small).

As was stated above, no subglacial sediment layer was found in the land based ice cliff. At the same time, in the vicinity, the fluted moraine, commonly explained by deformation of subglacial sediment (e.g. Boulton 1976; Hart 1998) is found. These facts reveal a significant variability of glacier basal conditions.

As observed, the majority of debris was incorporated into BIL. The character of basal ice stratification and their relationship to cavities and bedrock obstacles suggest their regelation origin. If the conditions observed in the passive ice cliff are common elsewhere, the subglacial tills on foreland should reveal some features of deposition from basal ice layer melting. The sediment is generally the same, according to granulometry, petrography and even to the volume (if we assume the whole basal ice layer to melt in situ and the debris concentration as measured and presented on fig. 4). But the evidence, which is given by analysis of thin sections show the opposite properties – structures, which are typical for deformed sediments (e.g. „galaxy" structures (van der Meer 1997)). Also the degree of compaction (higher than for supraglacial covers) and morphological image (fluted moraine) suggest subglacial origin. It should be notice as well that the morphological expression in the case of these sediments are different. Instead of generally horizontal but undulated bedrock surfaces, which was observed under the ice cliff, the subglacial till covers inclined upglacier and relatively flat bedrock. These observation suggested to create an bed topography depended model of subglacial debris behaviour. There is the same amount of debris in the general subglacial zone. If there are conditions, promoting regelation processes (like relatively horizontal but undulated bedrock), the debris is incorporated into basal ice layer and then modified, owing to deformation of this layer. Most of the debris can be finally released supraglacially. When the basement topography is gentle, without undulation, discriminating regelation conditions, the same debris is deformed and transported as a subglacial deformed bed layer. Both situations can exist parallel, with the possibility of change from one to another. The melting under pressure could allow the release of the debris, and create the subglacial till again.

CONCLUSIONS AND DISCUSSION

Glacier ice in the area of interest is in the state of transition from a tension dominated condition in the tide water part to compression conditions at the land terminating part. The latter is supported by basement topography, not a thermal regime (in the marginal region ice is warm throughout). The complexity of final tectonic situation is intensified by variety of dynamic conditions presented by tributary glaciers.

The tectonics of Hansbreen is found to be driven mostly by valley topography and interactions between main and tributary ice streams. According to Jania (1988, 1998) sliding is the most important process in glacier movement. This statement deals with the central part of glacier, where tension conditions are dominant, what is expressed in numerous crevasses. In the lateral part the situation is much more complicated. The flow velocity is much slower and is mostly an effect of ice plastic flow and, or subglacial till layer deformation, or basal ice layer deformation. The difference in total velocity is huge. From even 1m/day in the central part to the movement in the range of measurement error (few cm per month) in lateral parts (Jania 1988; Vieli personal communication). Such a difference originated mostly in bedrock topography. In the central part the bedrock lies under the sea level what helps the glacier to keep subglacial water film. In the lateral parts the friction is much bigger, because of valley sides and relief of bedrock (former gullies perpendicular to ice flow). The existence of non-uniform bedrock relief is underlined by alternately present zones with crevasses and thrusted folds – reflecting changing stress conditions. The tributary glaciers differ very much in dynamic in comparison to the main stream. All of them are narrower in places where they join the main stream. It is expressed by foliation deformation. The activity of tributary streams vary as well. During more active phases their impact is stronger, such episodes are coded in sets of strike-slip faults on the boundaries of streams, and in fracture orientations.

The structural development of Hansbreen is intimately associated with debris transfer. As has been also noted on some other glaciers (Boulton 1970; Sharp et al. 1994; Hart 1995; Hambrey et al. 1999), folds of basal debris-rich ice layer, often with incipient thrusting play a significant role in raising basal debris to an englacial position. Debris incorporation only by thrusting (Bennett et al. 1996; Hambrey et al. 1996; Hambrey & Dowdeswell 1997) or into basal crevasses (Sharp 1985) do nat appear to have taken significant place on Hansbreen.

The role of tectonics in sediment transfer in the land terminating part is important and effects in the dominance of supraglacial sedimentation. The rock threshold seems to be the main driving factor. The eastern part of the glacier, without such an obstacle in bedrock, presents subglacially dominated deposition. The direct observation has shown uplifting of debris-rich basal ice layers by their deformation, mostly by folding, sometimes associated also with thrusting. The range of this transportation is up to several meters. In the western land terminating zone the bedrock threshold plays major role in sedimentation by creating the compression condition, it causes the most of sediment to be released supraglacially. The upward debris transport is done mostly by the folding deformation of basal ice layer with a minor participation of thrusts.

In observed outcrops no subglacial deformed layer was found. The bulk of debris is associated with debris-rich basal ice layer. However on the foreland subglacial till with the evidence of deformations, comprising also flutings, was found. The different bedrock morphology is supposed to differenciate conditions of debris behaviour. The flat, but undulated, regelation favouring, conditions, leads to debris-rich basal ice layer development, and inclined but non undulated relief is conducive to the existance of deformed subglacial sediments.

Although Hansbreen is supposed to be surge-type glacier (Jania & Głowacki 1996), it does not show a typical structural geologic characteristic. The structural features connected with surge events were well studied on many glaciers (e.g. Lawson et al. 1994; Sharp et al.1994; Hambrey et al. 1996, Hambrey et al.1999) and a group of typical phenomena was found: looped medial moraines, transverse high-angle thrust across the whole width of glacier, numerous shear zones in the surge front and others. None of them were found on Hansbreen. Similar structures if exist, are limited to relatively small areas, and are resulting from stress fields influenced by topography, or by big dynamic difference between tributary and main ice streams. Medial moraines do not show any sign of disturbance and thrust planes are much more gentle (30 to 60 degrees), typical for bedrock influenced compressional conditions (Hambrey et al.1996).

There exist some indications (Clarke et al. 1984; Hamilton & Dowdeswell 1996) that surge-type glaciers are preferentially developed on softer sedimentary rocks as opposed to more resistant metamorphic rocks. Hence the western part of the Hansbreen basin is composed mostly of metamorphic rocks and central, and eastern (so under the main ice stream) of „softer" sedimentary rocks (Birkenmajer 1990), it can also be one of the controlling factors in the case of this glacier behaviour.

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STRESZCZENIE

Lodowiec Hansa na Spitsbergenie (rejon fiordu Hornsund) należy do politermalnych, szarżujących lodowców uchodzących do morza. Jest on zasilany przez szereg lodowców dopływowych o zróżnicowanej dynamice. Jego strefa brzeżna składa się z szerokiego klifu lodowego w części centralnej oraz lądowych, czołowo-bocznych stref depozycyjnych.

Szczegółowej analizie został poddany zachodni fragment lodowca. Charakteryzuje się on strefą kompresji wywołaną poprzez istniejący w podłożu lodowca garb skalny. Z analizy układu strukturalnego lodu wynika, że przemieszczanie materiału ze strefy bazalnej ku powierzchni odbywa się poprzez fałdowe deformacje bazalnej warstwy lodu oraz strefy ścięciowo-nasunięciowe. Takie warunki powodują, że większość osadu jest uwalniana w pozycji supraglacjalnej i następnie transportowana poprzez różnego typu ruchy masowe na pasywnym lub martwym lodzie. W obserwowanych odsłonięciach strefy bazalnej (w tym około dwustumetrowej długości martwym klifie lodowym) nie znaleziono subglacjalnej warstwy osadów – całość materiału była zawarta w przydennej warstwie lodowca.

Pomimo to na przedpolu lodowca, zdominowanym sedymentacją supraglacjaną, występują także płaty moreny walikowej (fluted moraine), których powstanie powszechnie tłumaczy się przekształcaniem subglacjalnie deformowanej warstwy osadu. Potwierdzają to także struktury widoczne w obrazie mikroskopowym cienkich płytek z tych osadów.

Na charakter procesów depozycyjno-transportowych wpływa też w dużej mierze morfologia podłoża. Horyzontalny relief z nierównościami wychodni skalnych sprzyja inkorporowaniu materiału do bazalnej strefy lodowca, głównie poprzez regelację, zaś nachylony lecz wyrównany teren preferuje rozwój subglacjalnej warstwy deformowanych osadów. Zespół struktur (pęknięcia, foliacja, uskoki, szczeliny, fałdy, nasunięcia, moreny środkowe) podkreśla istotną rolę interakcji pomiędzy strumieniami lodowymi. W obrębie lodowców dopływowych nie znaleziono żadnych wskaźników zjawiska szarży, stąd zapewne jest ono ograniczone jedynie do głównego strumienia.