Estonian Journal of Earth Sciences, 2008, **57**, 4, 241–255 doi:10.3176/earth.2008.4.04

Two-dimensional apparent microfabric of the basal Late Weichselian till and associated shear zone: case study from western Latvia

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Received 23 May 2008, accepted 26 September 2008

Abstract. The examination of glacial sediments in thin sections has become a common procedure in recent years. Apparent sand grain orientation (microfabric) in thin sections is one of the key elements marking certain microstructures. In an attempt to make till micromorphology studies less subjective and investigate the orientation of sand-sized particles in tills, we have developed an image analysis procedure to measure and analyse the spatial distribution of the till microfabric. We studied 13 thin sections of the Weichselian subglacial till and basal shear zone outcropping in the Baltic Sea bluffs at the Ziemupe site in western Latvia. The results were visualized as a two-dimensional grid of rose diagrams covering the area of the thin section and were compared to macrofabric. We found that in larger areas microfabric, although much weaker than macrofabric, coincides with macrofabric orientation. In the sub-centimetre scale till microfabric in short distances appears to be highly variable both in strength and preferred orientation, and a domain-like pattern appears.

Key words: shear zone, till, microfabric, micromorphology, thin sections, subglacial deformation, image analysis.

INTRODUCTION

Till fabric, especially orientation of principal axes of single clasts, has been routinely used in examining glacial till (e.g. Raukas et al. 1978; Dreimanis 1989), with the study focus shifting towards the process of till formation (Boulton & Hindmarsh 1987; Benn 1994; Larsen & Piotrowski 2003). In recent decades studies of till micromorphology have also been used to understand till genesis (van der Meer et al. 1992, 2003; van der Meer 1993, 1996, 1997; Hiemstra & van der Meer 1997; Menzies 2000; Lachniet et al. 2001; Menzies & Zaniewski 2003; Hart et al. 2004; Piotrowski et al. 2006; Thomason & Iverson 2006; Larsen et al. 2007). In these studies orientation of sand grains in tills is often used as one of the key elements to identify certain microstructures. However, only few attempts have been made to describe till microfabric using quantitative approaches (Chaolu & Zhijiu 2001; Carr & Rose 2003; Roberts & Hart 2005; Stroeven et al. 2005; Zaniewski & van der Meer 2005; Thomason & Iverson 2006).

In many studies certain microstructures, such as galaxy or rotation structures (van der Meer 1997; Menzies 2000) and grain stacks (Larsen et al. 2007), have been identified from visual assessment of spatial arrangement of few skeletal grains. This approach can easily lead to overestimation of the abundance of these structures as random sand grain arrangements can produce similar structures (Fig. 1). Therefore a statistically based approach is needed to study the till microstructure.

The regular till macrofabric analysis applies a point-like approach – all measurements are reduced to a single point and, unless a large number of observations are performed, it does not describe the spatial distribution of macrofabric. There have been attempts to evaluate spatial patterns of till fabric in mezzo(outcrop)-scale (Larsen & Piotrowski 2003). However, collection of till fabric data is labour-consuming and spatial evolution patterns are difficult to pick. Computerized image analysis of thin sections at least offers a possibility of studying the spatial distribution of apparent microfabric in short distances, but the linking of the micro- and macroscale still remains a problem.

The work of Thomason & Iverson (2006) is a fine example of statistical evaluation of microfabric data. Their work uses a point-like approach, analogous to regular till fabric analysis (e.g. Larsen & Piotrowski 2003). Additionally, Thomason & Iverson (2006) suggested that any large clast will affect the orientation of the surrounding smaller clasts in certain way, depending on the mode of the deformation of till. Identification of the spatial pattern of microfabric can help to reconstruct the mode of till formation and hence contribute to our understanding of subglacial processes.

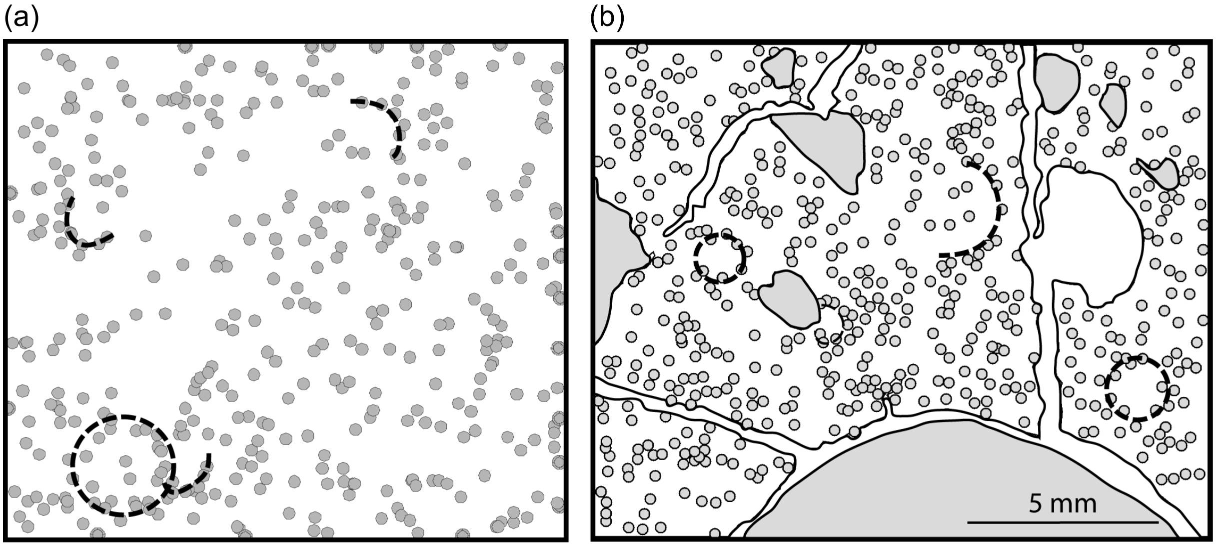

Fig. 1. Demonstration of apparent turbate (rotation) microstructures: (a) artificially generated random distribution of dots; (b) distribution of sand grains (marked by dots) in thin section of basal till. Dashed lines denote probable turbate structures, as interpreted by an inexperienced observer.

General data about till microfabric – orientation of elongated sand grains – are sparse in geological literature. Sometimes till microfabric is referred to as being roughly coincident with macrofabric (Dreimanis 1973, 1989), however, it has rarely been demonstrated with actual results. Additionally, it is understood that large clasts will significantly affect the orientation of elongated sand-sized particles (Thomason & Iverson 2006) and the depositional process for different-size till particles will be different (Benn 1994). Khatwa & Tulaczyk (2001) conclude that the same till-forming process, i.e. subglacial deformation, may result in distinctly different till micromorphology as microstructural characteristics are strongly influenced by factors other than shear deformation.

The aim of this paper is to contribute to understanding of till microfabric. Using thin sections we are examining apparent (as pointed by Chaolu & Zhijiu 2001) microfabric distribution in the Late Weichselian basal till and associated shear zone exposed in western Latvia. We are interested in whether the till microfabric is similar to its macrofabric and whether there is any genetic signature in till microfabric distribution. We have developed a tool (Kalvāns et al. 2007) to study the spatial distribution of till microfabric and compare it with observed till structures and macrofabric. Simple image analysis is used to acquire microfabric data and the microfabric distribution over the selected area of the thin section is visualized to compare it directly with till microstructure.

STUDY AREA: LOCATION AND GEOLOGICAL SETTING

The study area is a part of the Baltic Sea coastal lowland that has been repeatedly overridden by the Scandinavian ice sheets, at least from the Elsterian glaciation onwards (Dreimanis 1936; Danilāns 1973; Meirons & Straume 1979; Segliņš 1987; Juškevičs et al. 1998; Kalnina 2001). The recent landscape of the adjacent mainland area is a gently undulating sandy abrasion-accumulation plain of the Baltic Ice Lake, altered to some extent by postglacial aeolian activity (Veinbergs 1964).

The outcrop at Ziemupe is situated at the Baltic Sea cliff, approximately 30 km north of the Liepāja Town, in western Latvia; the geographical coordinates are x = 003-20-261E, y = 062-93-812N in the LKS92 reference system. The nearly 600 m long cliff section exposes the complex sequence of Pleistocene marine and glacigenic sediments characteristic of this region (Segliņš 1987; Kalniņa et al. 2000; Saks et al. 2007). It is the southernmost portion of several 10–18 m high coastal bluffs providing insight into Pleistocene glacial and non-glacial deposits in the coastal area of western Latvia (Fig. 2).

So far stratigraphy, glacial sedimentology, and structures of the Ziemupe section have not been explored in detail. Glacial stratigraphy in the area is based only on formal principles such as the correlation of till units between boreholes, difference in till colour and petrographical and mineral composition (Ulsts & Majore 1964;

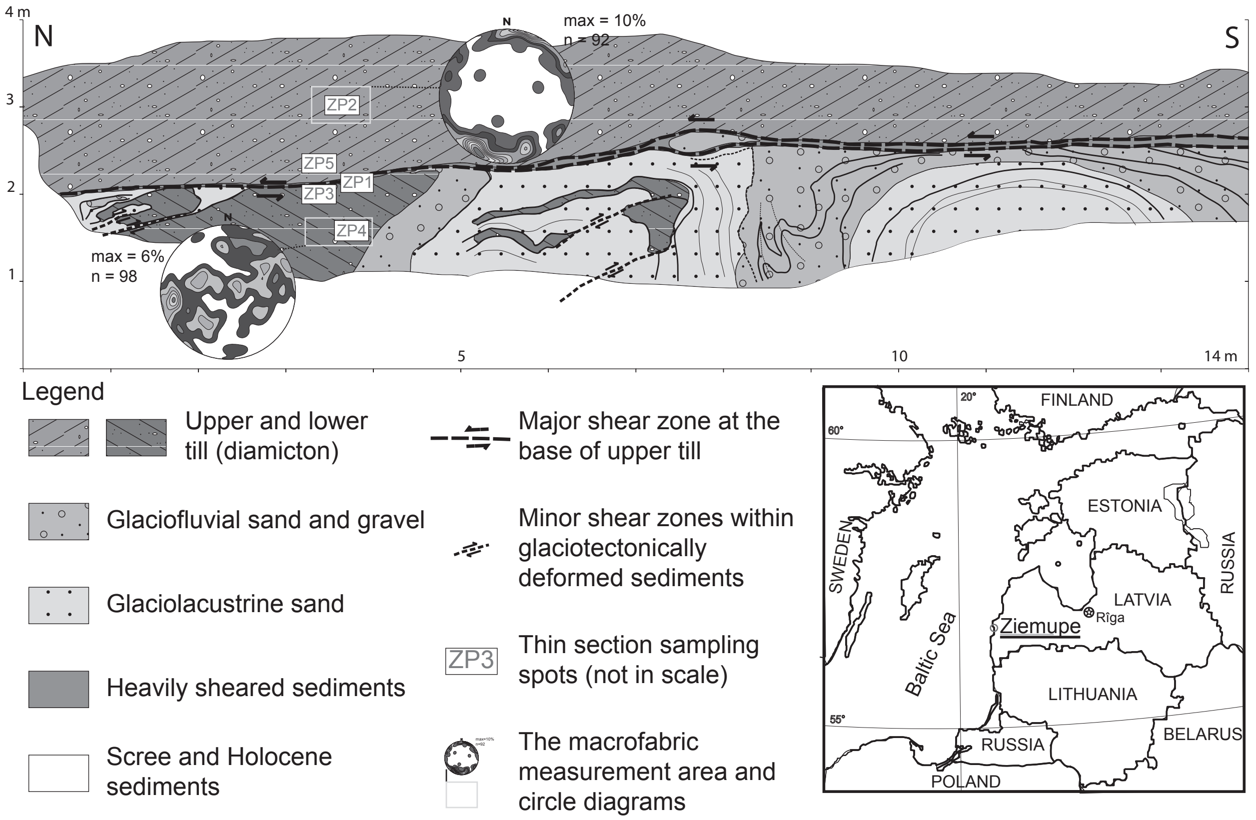

Fig. 2. Location, geological structure, and thin section sampling sites of the study area at Ziemupe, the southernmost strip of the Baltic Sea bluffs in western Latvia. The lower hemisphere Schmidt projection circle diagrams demonstrate the respective macrofabric distribution at the thin section sampling places, with the number of measured particles and maximum orientation concentration (in %) indicated.

Konshin et al. 1970; Danilāns 1973; Meirons & Straume 1979; Segliņš 1987; Kalnina 2001). The till unit (upper till), which outcrops widely alongside the Baltic Sea coast and covers the Pleistocene marine and glaciolacustrine sediment sequence, has been originally referred to as of Saalian age (Dreimanis 1936; Konshin et al. 1970; Danilāns 1973). However, recently obtained OSL dates of sandy sediments beneath upper till indicate the Middle Weichselian age and subsequently the Late Weichselian age of the upper till (Zelčs et al. 2007). A second till unit is sometimes observed in boreholes several tens of metres below the earth's surface in the middle part of the Pleistocene sediment sequence. In the light of new OSL dates it is suspected to be of Middle Weichselian age (*ibid*).

Gaigalas et al. (1967) attempted to establish a regional glacial movement direction pattern for the eastern Baltic coastal area. They emphasized that during the last glacial maximum the glacier advanced from the NNW direction, from the area outside the Baltic depression. This is supported by the palaeoglaciological reconstruction of the Scandinavian ice sheet dynamics through the Weichselian glacial cycle (Punkari 1997; Boulton et al. 2001; Zelčs & Markots 2004).

At the investigation site glaciotectonically deformed fine sand and silt sediments, as well as glaciofluvial coarse sand and gravel topped by the basal till unit (referred to as the upper till) of late Weichselian age, are exposed (Fig. 2). Additionally, a second diamicton unit (referred to as the lower till) crops out below the upper till.

The deformation style of sedimentary strata can be described as a result of two factors: (1) density inversion that led to the formation of fine sand diapir structures and sinking of denser glaciofluvial sand and gravel and (2) glaciotectonic compression and dragging of material at the glacier bed approximately in the NNW to SSE direction. The formation of gravity-driven structures was likely triggered by dramatic loss of sediment strength at some point when pore water pressure reached the flotation point. Probably, the lower till unit at this site formed as basal till, detached and sank in loose sediments at the glacier bed simultaneously with the formation of other gravity-driven structures.

The top of the structural complex associated with diapirs is cut by the shear zone at the base of the upper till. This suggests decoupling of the glacier from its bed.

The upper till macrofabric has a well-developed NNW to SSE orientation (Fig. 2; eigenvalues $S_1 = 0.675$ and $S_2 = 0.256$). This is in good agreement with studies on the regional ice movement direction (Gaigalas et al. 1967; Punkari 1997; Boulton et al. 2001; Zelčs & Markots 2004).

The interpreted shear direction in the shear zone beneath the upper till is from S to N, hence in contrast with the inferred regional ice movement direction. We assume that it is due to a short-lived local glaciological event.

The macrofabric of the lower diamicton is not as well developed (Fig. 2; eigenvalues $S_1 = 0.443$ and $S_2 = 0.370$). The large S_2 value suggests more grid-like distribution that can be interpreted as a result of initial fabric re-orientation due to penetrative deformation. The mean macrofabric orientation is in NEE–SWW direction.

METHODOLOGY

Thin section preparation

Samples for thin section preparation were collected using a 5 cm × 6 cm × 7 cm metal container. The container was cut in the face of the outcrop in a manner similar to that described by van der Meer (1996). The upper face and northern direction were marked on each sample. In the laboratory the samples were air-dried and pre-impregnated with epoxy resin dissolved in acetone (in proportion approximately 1 : 4) and, after evaporation of acetone and hardening of resin, cut into sections. As after the first impregnation stage most of the pores in the sample were left open, the second impregnation stage was necessary: the samples were impregnated with epoxy resin diluted with acetone in proportion 3 : 1. A dye was added to the epoxy to facilitate the image analysis at a later stage. After hardening, thin sections were prepared in a manner similar to the procedure described by Camuti & McGuire (1999) and Carr & Lee (1998). The samples were cut and ground with silicon carbide grinding powder (Grit P600), mounted on glass slides, and finished to the slide thickness of 30 to 20 µm. Three mutually perpendicular thin sections were prepared from each sample.

Thin sections were examined and photographed using *Leica DMLA* polarization microscope. Overlapping photographs covering a 3 mm × 4 mm large area of the thin section were mounted in mosaic image using Adobe® Photoshop®.

Microlineation data acquisition

The microfabric was measured for light-coloured transparent grains, predominantly quartz. Sand grains were identified using the colour threshold technique, and their size, orientation, and position parameters were recorded using the image analysis software ImageProPlus®.

The acquired data set was filtered by size and elongation ratio criteria. Only particles with the apparent axial ratio between 1.5 and 3 were selected. The lower limit was chosen as overall agreed standard in till fabric studies (e.g. Krüger & Kjær 1999). The upper limit was selected as only few particles have the elongation ratio above 3, and it is likely that many such objects are imperfections, such as cracks and linear voids, which were accidentally recognized as quartz grains. Grains with the section area between 0.0005 and 0.05 mm^2, which approximately fall in the range of fine sand, were considered.

Data processing and visualization

The data processing was done using free statistical software R. A rectangular grid was created matching the size of the thin section, with a given distance between grid points R (Fig. 3). All measurements that fall into the distance R from any grid point were counted in the statistics of the particular grid point. In this way optimal representation of lineation in the immediate surroundings of a grid point is achieved. However, each measurement is added to the charts of two to four adjacent grid points. The resolution of the grid can be adjusted: the increased generalization level (large distance between grid points) would lead to more measurements in a single diagram and hence represent the average microfabric; increased resolution (smaller distance between grid points) would show fine patterns of apparent microfabric in the same area.

The processing of the microfabric data set was simplified by splitting it into classes of 10°. This is justifiable as the accuracy of the input data is considered to be no better than 10°. Additionally, 10° is the most often used resolution in rose-diagrams in case of till macrofabric studies (Ehlers et al. 1987).

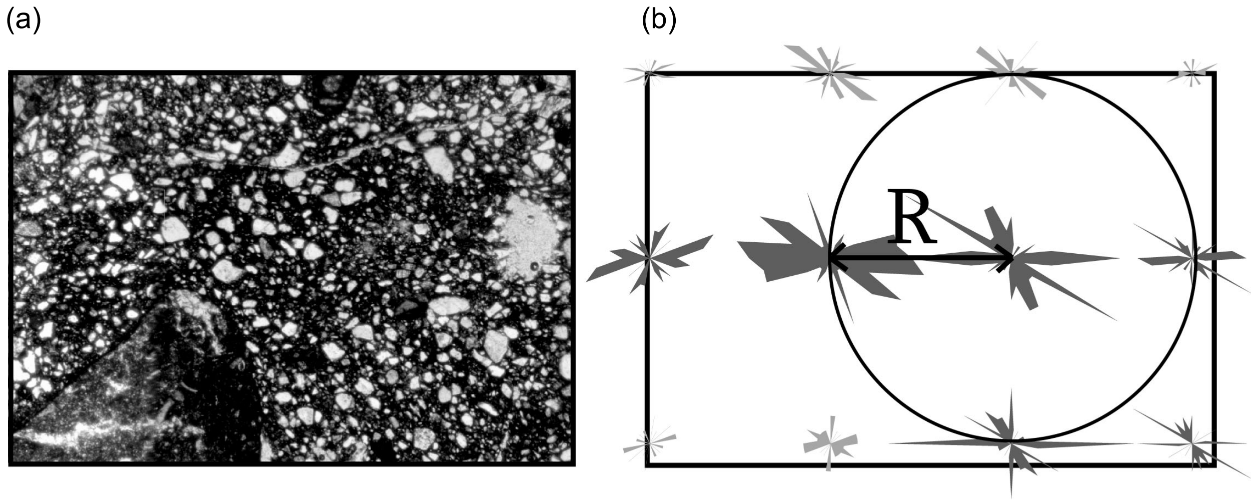

Fig. 3. An example of visualization of the apparent microfabric: (a) original thin section image; (b) microfabric image. Dark grey diagrams have statistically significant lineation assuming von Mises (normal) distribution, light grey ones denote cases with unreliable values; the circle indicates the area from which data are plotted on a single diagram; R is the distance between the centres of adjacent diagrams.

To test the microfabric strength, a simple statistical evaluation of monomodal (von Mises) distribution is used: the length of the normalized resultant vector (Rn) is calculated from orientation data (Davis 2002, pp. 322–330) and compared to critical values for the 0.9 confidence level given by Davis (2002, p. 619):

$$\mathrm{Rn} = \frac{\sqrt{\left(\sum \sin 2\alpha\right)^2 + \left(\sum \cos 2\alpha\right)^2}}{n},$$

where n is the number of measurements around the grid point and 2α is the doubled orientation value of measurement.

The measured tilt angle α of a long axis before the statistical interpretation is doubled due to bi-directional nature of orientation data: a measured tilt of 0° is identical to tilt of 180°. By doubling both measurements we get 0° and 360° or 0°, that is the same values (Davis 2002, pp. 316–322).

Resultant bi-directional diagrams for each grid point are plotted using dark grey colour for data points of statistically significant preferred orientation and light grey – for statistically insignificant preferred orientation (Fig. 3). To avoid the exaggerated representation of data classes with the largest measurement numbers, instead of the real number of measurements square root is used to calculate the relative height of any data class in the diagram (Davis 2002). This allows considering both the statistical significance and detailed distribution of lineation. The advantage of the method is its simple and understandable use, however, it has considerable backslash as only monomodal distribution is identified as statistically significant.

The data were visualized in five different grids ($R = 0.7$; 1.4; 2.8; 5.7; 11.3 mm). Data grids with the resolutions $R = 0.7$ mm and $R = 2.8$ mm proved to be most informative, therefore they are presented in illustrations.

Comparison of microfabric and macrofabric

The macrofabric data are three-dimensional (3D); the microfabric data are two-dimensional (2D), but represented in three perpendicular sections. It is hard to reconstruct a true 3D pattern of microfabric from thin sections, therefore, for comparison of micro- and macrofabric, we project macrofabric 3D data to three mutually perpendicular plains that correspond to orientation of thin sections (Fig. 4). In this way it is possible to compare microfabric and macrofabric orientation in the same form of data visualization.

Calculating the projections of macrofabric to the plain it is assumed that macrofabric is formed by perfect rod-like particles, with no flattening. Unfortunately flattening of the pebbles has not been recorded in the field. This introduces some level of uncertainty in projected data.

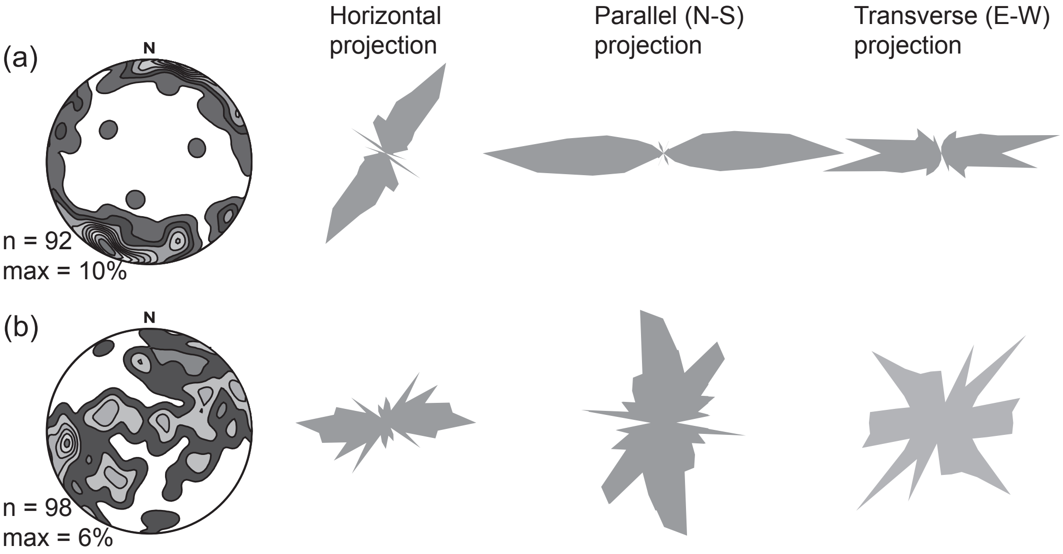

Fig. 4. Macrofabric lineation of the upper (a) and lower (b) till units and its projections to single planes.

TILL MICROMORPHOLOGY

Five samples were collected for micromorphological examination: two above, one within, and two below the shear zone separating upper and lower tills (Figs 2 and 5). Sample ZP1 was taken directly from the shear zone. Samples ZP2 and ZP5 were taken from the upper till, respectively 1 m and 10 cm above the shear zone. Sample ZP3 was collected directly below the shear zone and sample ZP4 0.5 m below the shear zone.

Initially statistical micromorphological analysis following the methodology introduced by Carr (1999) was done. A simplified set of four microstructure categories was adopted from Larsen et al. (2007): (1) turbate structures, also known as galaxy or rotation structures, are circular grain alignments that occur both with and without a core stone; (2) lineations comprising three or more aligned elongated grains; (3) grain stacks are microscale equivalents of grain bridges consisting of stacks of at least five equal-sized sand grains; (4) intraclasts and domains are inclusions or zones of sediment with unique textural characteristics that can be distinguished from the surrounding sediment. Probably due to low clay contents of the studied tills, no plasmic fabric structures (i.e. clay-sized particle arrangement observable in cross-polarized light) were observed.

The microstructures were counted in the thin section area of 23 mm × 16 mm. The results of microstructure counts are presented in Fig. 6. For each sample the number of counted microstructures in each thin section is standardized to the proportion of glacial diamicton to other material (like sand lamina, gravel grains of significant size or technical defects) in the analysed area of the thin section and summed together. To standardize the number of microstructures for sample ZP4, from where only one thin section is available, the total number of the microstructures was multiplied by three.

Fig. 5. The shear zone at the base of the upper till; the image is half a metre wide. The sampling spot of sample ZP1 is at the end of the sand stringer, indicated by smooth dark colour at the extreme left-hand side of the image, in the contact between the upper and lower tills.

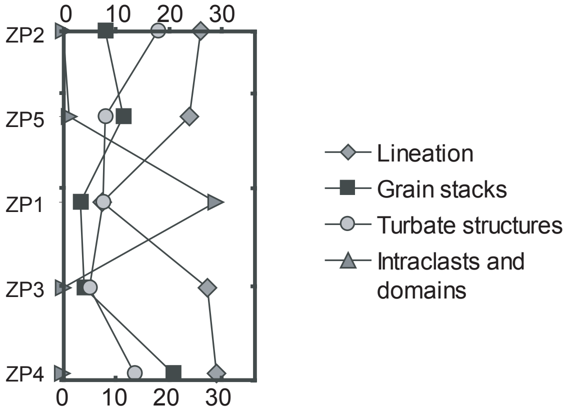

Fig. 6. Synoptic results of microstructure calculation. Sample ZP1 from the shear zone is distinctly different from other samples, especially as regards the number of intraclasts and lineations of grains. A decrease in the number of identified turbate structures can be observed in the immediate vicinity of the basal shear zone (samples ZP5, ZP1, and ZP3). The large number of structures observed in sample ZP4 from the lower till unit is probably due to a finer granular composition of the lower till, resulting in a greater number of observed microstructures.

Upper till: sample ZP2

Both in macroscale and microscale the upper till has uniform composition with dominantly sand and silt matrix and occasional gravel grains. Sample ZP2 taken well above (1 m) the basal shear zone has microfabric orientation close to that of macrofabric orientation in both vertical and horizontal sections (Figs 4 and 7). However, in the horizontal plane (Fig. 7a) multiple domains of different orientation can be observed and in large generalization levels (greater than $R = 1.4$ mm) the statistically significant lineation has not been detected. The overall shape of the diagrams indicate a N–S trend. Effects of gravel grains on microlineation are almost negligible and cannot be traced much farther than 1 mm from it.

In the vertical section parallel to macrofabric (Fig. 7b) microlineation is well developed and in all resolutions statistically significant lineation domains are observed, coinciding with macrofabric. Several curved microlineation structures associated with gravel grains are present and discontinuous microfabric can be observed. Transverse section to macrofabric (Fig. 7c) shows several domains with statistically significant lineation. However, in large generalization the microlineation is not as strong as in the section parallel to macrofabric. As demonstrated in Fig. 4a, macrofabric in the upper till is distributed in the subhorizontal plane, and this corresponds to microfabric distribution in the horizontal plane (Fig. 7) as well. Even the strength of macrofabric and microfabric is similar in both projections – larger in the N–S projection (Fig. 4a, N–S projection, and Fig. 7b) and weaker in the E–W projection (Fig. 4a, E–W projection, and Fig. 7c).

Upper till: sample ZP5

The sample was taken a few centimetres above the extrapolated basal shear zone (Figs 2, 5). In general, microfabric in this sample is in agreement with the macrofabric orientation of the upper till, especially in the horizontal plane. However, the vertical sections show preferred sand grain orientation dipping 30° to 45° from the horizontal plane. A similar, steeply dipping microlineation in basal tills with several orientation domains has also been reported by other researches (Carr 2001; Carr & Rose 2003), deemed as an indicator of the large strain. The summary of the apparent microfabric in vertical sections has only weak subhorizontal maximum.

There is a zone of well-developed microfabric in the horizontal section, which coincides with the orientation of the macrofabric of the upper till. However, it is situated near large gravel grains and the trend of microfabric coincides with the observed trend of the gravel grain surface. Elsewhere in the horizontal section the domain pattern of microfabric is observed.

Shear zone: sample ZP1

The sample was taken so that it included the termination of the sand stringer that can be followed from the basal shear zone of the upper till (Figs 2 and 5). The horizontal thin section and one vertical thin section are cutting this stringer. In contrast to other samples, this sample has plenty of silt intraclasts, and a smaller number of lineations and grain stacks as illustrated in Fig. 6. A sand lamina or stringer and silt nodules are signs of assimilation of subglacial material in deforming till due to shearing along the basal shear zone of the upper till. No “armour” of sand grains is observed on the surface of glacial diamicton and sand lamina. This indicates that the contact is not of sedimentological character and has been formed or renewed during deformation.

The margin between the sand stringer and diamicton is sharp and undulating, perturbed by secondary shear structures such as echeloned joints and Riedel shears (Fig. 8c). Similar to the structure described by Larsen et al. (2007), it has undulating boundaries and shows little mixing between contrasting lithologies. Only slight statistically insignificant lineation of NWW–SEE direction

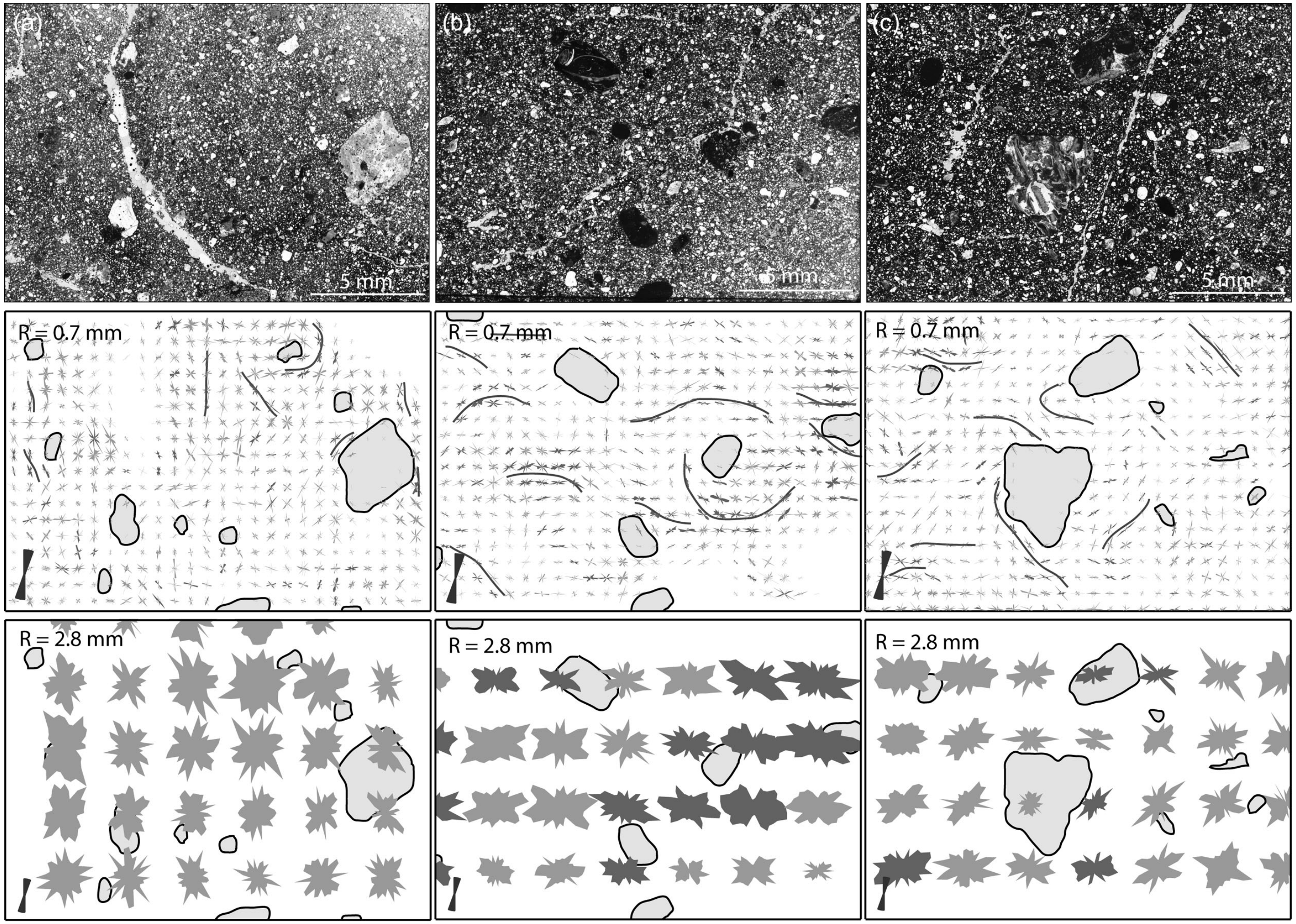

Fig. 7. Photographs and apparent 2D microfabric of thin sections from the upper till unit (sample ZP2), in columns: (a) horizontal section; (b) vertical section subparallel to the upper till macrofabric (N–S projection); (c) vertical section subperpendicular to the upper till macrofabric (E–W projection). The sand grains in thin section photographs predominately appear as light spots, and matrix consisting of silt and clay is in dark colours; black "triangular" diagrams in the left corner of the two lower rows are the scale corresponding to 300 measurements evenly spread across the sector of 30°; dark grey diagrams have statistically significant preferred orientation, the light grey ones indicate cases with unreliable values; the gravel grains and silt pebbles in sketched images are in grey colour. In general ($R = 2.8$ mm) microfabric is in agreement with macrofabric (Fig. 4a), however, it is not always statistically significant. In the image of column (b) with the grid resolution $R = 0.7$ mm, discontinuous microfabric indicated by lines can be observed around a gravel grain, however, it is not recognizable in the image with the resolution $R = 2.8$ mm. Similarly in the image of column (c) with grid resolution $R = 0.7$ mm, the alignment of the microfabric can be identified along gravel grains, while in grid resolution $R = 2.8$ mm, the image is blurred.

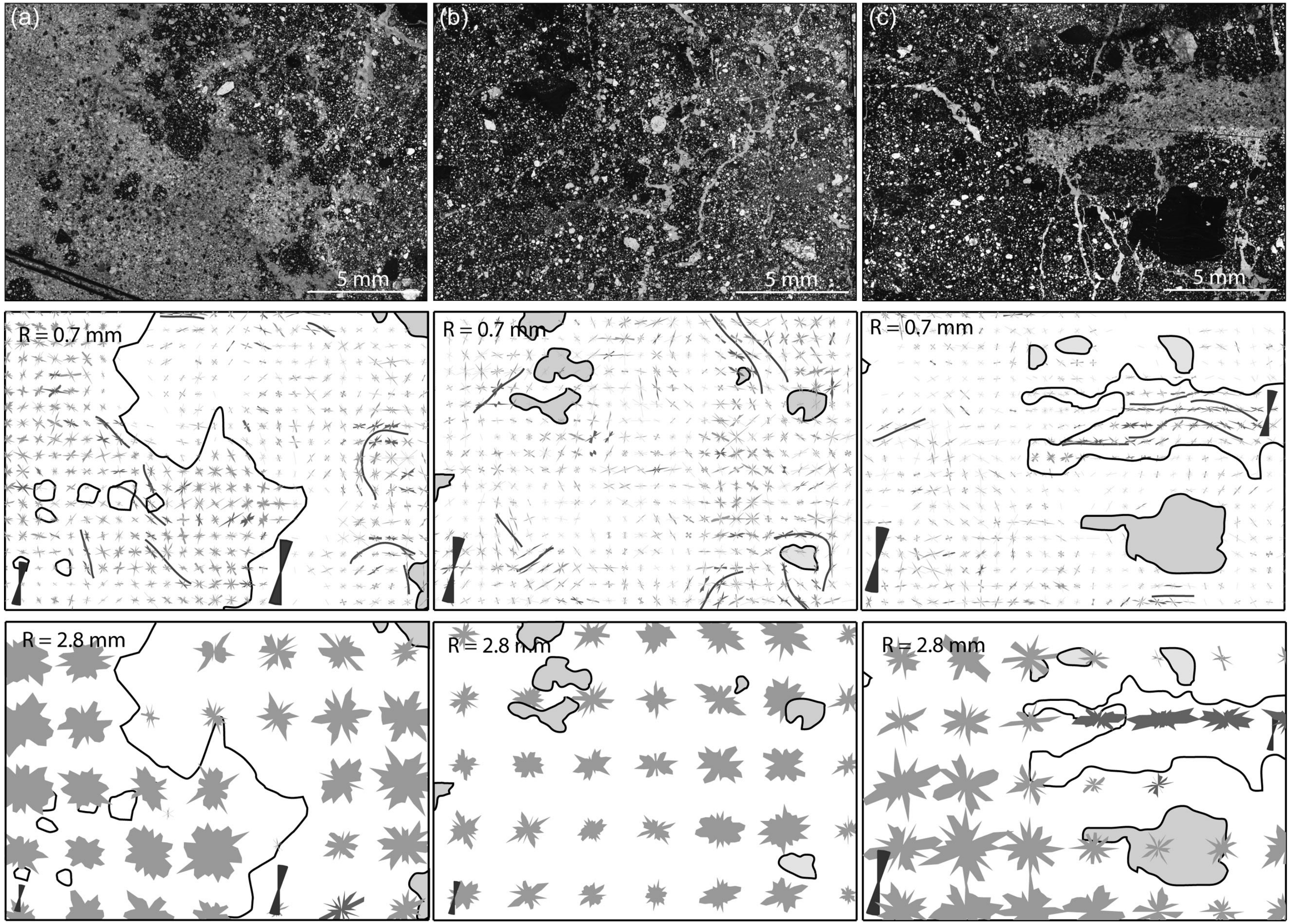

Fig. 8. Thin sections from sample ZP1, taken directly from the shear zone, in columns: (a) horizontal section; (b) vertical section subparallel to the upper till macrofabric (N–S projections); (c) vertical section subperpendicular to the upper till macrofabric (E–W projection). For explanation of the symbols in sketched images see Fig. 7. Microfabric with the resolution $R = 0.7$ mm shows some domains with statistically significant lineation (e.g. lower left corner of the image of column (b) with $R = 0.7$ mm), which are not represented in the grid resolution $R = 2.8$ mm. Note the contrasting lineation patterns in the sand stringer and surrounding diamicton (images in column (c)), indicating either different modes of deformation or different sand grain response to shear in contrasting lithological environments. Neither diamicton nor sand part in the horizontal section, column (a), revealed any significant preferred orientation of sand grains.

in large generalization levels can be observed in the horizontal section of the sand lamina (Fig. 8a), however, strong subhorizontal sand grain lineation occurs in the vertical section (Fig. 8c).

The microfabric of diamicton in the horizontal plane has no significant orientation, but in large resolution some circular structures can be traced (Fig. 7a). The domain-like microfabric pattern in large resolution is presented in the vertical section as well, but no preferred orientation can be traced in low resolution – large generalization levels. The microfabric of the till of sample ZP1 is not similar to the macrofabric of either till unit.

Lower till: sample ZP3

The sample was taken just below the position of the basal shear band of the upper till, which can be interpreted by continuing the basal contact from the parts of the section where sand is exposed below the upper till and the base of the upper till is identifiable.

The horizontal section has strongly developed apparent sand grain microfabric in E–W direction, which is consistent with the macrofabric of the lower till. In large resolution several well-developed lineation domains with discontinuous contacts can be identified.

Several domains of well-developed, often steeply dipping, lineation can be observed in vertical sections as well. In some cases lineation in domains is bending but it is difficult to identify any clear circular structure. In other cases contrasting (cross-cutting) lineation is observed in neighbouring lineation domains, which probably is an indication of brittle deformation. In large generalization the irregular shape of diagrams suggests the non-random orientation of elongated grains and the presence of several distinctly oriented grain populations.

Lower till: sample ZP4

The sample was taken from the lower till unit. Only preparation of the horizontal thin section was successful. The microlineation in it is rather well developed with several distinct domains (Fig. 9). In low resolution – large sample area – microlineation is parallel to the macrofabric orientation (Fig. 4). However, in larger resolution several domains of the microfabric can be identified. Like in ZP3 and ZP5, the lineation is preserved in higher generalization levels. The observed microfabric is in good agreement with the calculated horizontal projection of the macrofabric of the lower till.

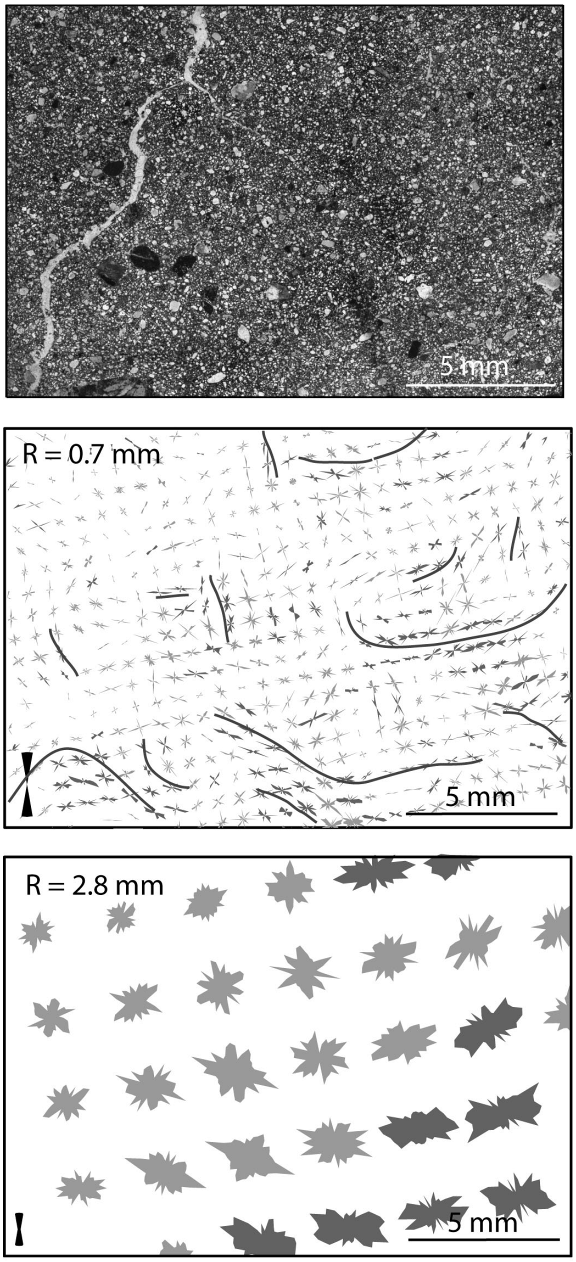

Fig. 9. Microfabric distributions in the horizontal section of the lower till (sample ZP4); see Fig. 7 for legend. N is to the top of the image. A mixed, domain-like microfabric picture is observed in the grid resolution level $R = 0.7$ mm, however, the lower resolution ($R = 2.8$ mm) leads to more general microfabric distribution that is similar to the approximately E–W trending macrofabric orientation.

DISCUSSION

Here we have demonstrated that microfabric exhibits great variations in short distances and distinct orientation domains can be identified in tills. However, when moving from the sub-centimetre scale to the scale of several centimetres, local variations are usually levelled out and one general direction that seems to be consistent with macrofabric can be identified. The generalized apparent microfabric seems to be much weaker, although still compatible with macrofabric at the same spot.

Usually only one broad maximum of microfabric can be identified in large generalization levels where the sample size reaches several thousands of individual measurements, however, in some cases (vertical sections of samples ZP5 and ZP3) several distinct modes of the apparent orientation of the sand grain can be identified. This indicates that lineation in certain domains is not random and probably several networks of domains with similar microfabric exist through the larger till volumes.

In large resolution (small distance between grid points) microfabric tends to have statistically more significant values than in large domains. In contrast to large domains, the orientation of average microfabric in small neighbouring domains is highly variable. This indicates that lineation has some systematic origin acting in the scale of a few millimetres. We suggest that during the deposition till is undergoing internal deformation that is heterogeneous in small scale but uniform in large scale. The scale at which average microfabric becomes uniform can be termed the scale of homogeneity. Probably it is determined by the largest skeletal grains present in the till.

Sometimes circular structures (Fig. 7b) of sub-centimetre size can be identified in microfabric diagram sets. This supports the particle and aggregate mobility (“marble bed”) model proposed by van der Meer (1997). He argues that the rotating of semi-permanent structures or particle aggregates is responsible for well-mixed basal tills that show no significant vertical compositional differences.

Thomason & Iverson (2006) published the results of the experiments with ring-shear apparatus of emulated shearing in subglacial tills. They used subglacial till with rather large clay contents and removed all large clasts. Their results gave good correlation between the microfabric strength and accommodated shear rate. We have demonstrated that in real tills microfabric orientation and strength are highly variable despite the significant shear rate, which must have been accumulated in a till at the basal shear zone. Experimental results are not directly applicable to real tills, where large clasts are the most obvious actor that chaotically contributes to microfabric development. Combining the observation of van der Meer (1997), results of Thomason & Iverson (2006), and our observations, we conclude that till microfabric development in pervasively deformed tills is complicated by the presence of large clasts and aggregates that can give rise to rotational structures. In addition, the localized, possibly short-lived shear planes as outlined by Larsen et al. (2007) will further complicate the microfabric.

Using discrete element mathematical modelling with the object size in the range of 0.45 to 1.4 times of a median value D_{50}, Kuhn (2005) found that the thickness of the mature shear zone will be around 8 units of the median value D_{50}. We admit that the morphological and mechanical characteristics of individual grains will strongly influence the mechanical properties of sediments (Lebourg et al. 2004) and therefore will influence the thickness of shear zones. Nevertheless, we suggest that grain size distribution is one of the key factors determining the shear zone thickness in the given stress conditions. For well-sorted sediments this relation is relatively simple and straightforward and will be comparable to values calculated by Kuhn (2005). The strong microfabric in the sand stringer (Fig. 8) is contrasting with the poorly developed domain like microfabric of the diamicton, although both sediment types must have undergone shearing under the same conditions as they are located in the same shear zone. The median grain size for the studied tills is silt to fine sand fraction and shall lead to the development of less than 1 mm thick shear bands. Till is a heterogeneous sediment: obstacles of size from sand grains to large boulders will stand in a pass of the propagating microscale shear zone and lead to branching and bending of it, and preclude the development of strong microfabric as seen in sands (Fig. 8c). The shear zone in diamicton will “get lost”; it will diverge and only the largest particles such as gravel grains and pebbles will be oriented in shear direction. Smaller particles will be affected by a swarm of micro-shear zones, oriented in directions diverging from the overall shear direction and a rather chaotic microfabric pattern will develop (Fig. 10). Nevertheless, in large scales the general orientation of small particles will be similar to that of large ones.

Piotrowski et al. (2006) concluded that the deforming till below the marginal zone of active ice could be only a few centimetres thick and formed under conditions of combination of lodgement and deformation. According to our observations, pervasive shearing of a thicker till unit will probably result in a much smoother than the observed distribution of microfabric, as gravel and pebble contents of the studied tills are relatively low and effects of rotation of individual clasts would introduce only minor and local disturbances in overall microfabric.

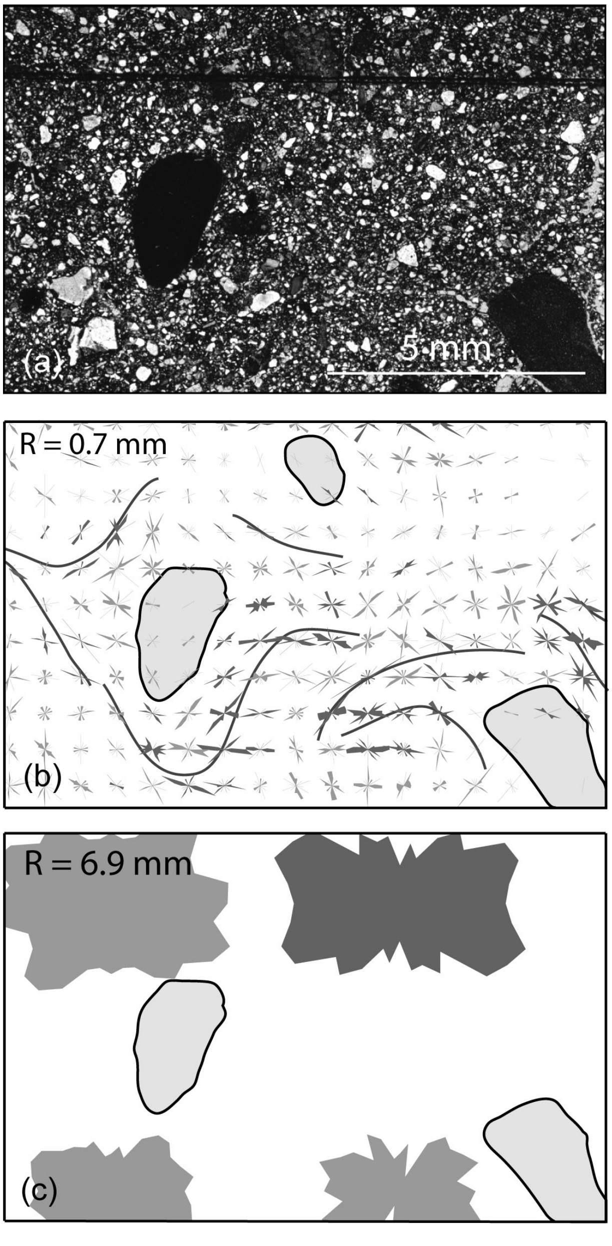

Fig. 10. Distribution of microfabric around gravel grains in the N–S plane oriented vertical thin section form sample ZP2 (Fig. 7b): (a) thin section photograph; (b) in the resolution $R = 0.7$ mm zones of distinct lineation that probably formed due to gravel grain rotation can be identified; (c) the sum of different small domains in the resolution $R = 6.9$ mm forms subhorizontal, occasionally statistically significant microfabric. The field of deformation in tills in small scale is highly heterogeneous but appears smoother in larger scale.

Thomason & Iverson (2006) suggested that the pattern of microfabric around the rotating clast in pervasively sheared till would be different from that of the lodged clast in lodgement till or, using the terms proposed by Ruszczynska-Szenajch (2001) “soft lodgement till” opposite to “hard lodgement till”. Proving this statement is the most obvious application of the described methodology. We observed several structures where microfabric is bending around small gravel grains (Figs 7b and 8b) and the microfabric pattern could be used to reconstruct the mode of till formation. However, the earlier discussed chaotic nature of till deformation in microscale will preclude the development of easily identifiable microfabric patterns, and the approach suggested by Thomason & Iverson (2006) to identify the till formation mechanisms may not be as simple as initially seen.

CONCLUSIONS

We developed a novel tool for sediment microfabric studies and used it to examine the Weichselian subglacial till of western Latvia. We demonstrated that till microfabric can form complicated spatial patterns that cannot be used straightforward for interpreting the local glacial stress direction or till formation processes. A distinct characteristic of till microfabric seems to be domain-like structure, with statistically significant lineation in neighbouring domains often having contrasting orientations. As a result of this study we draw the following conclusions:

1. a characteristic feature of till microfabric is domain-like distribution;
2. large grain-size variations in tills preclude the development of well-expressed shear zones as propagation of displacement is randomly diverged by larger obstacles like gravel grains;
3. analysis of apparent microfabric in thin sections can be used to reconstruct glacial stress orientation only if a significantly large thin section area is used.

ACKNOWLEDGEMENTS

This study is co-financed by EU funded project No. 2004/0001/VPD1/ESF/PIAA/04/NP/3.2.3.1/0001/0001/0063. The authors are grateful to the assistant Jānis Klimovičs, the Rock Research Laboratory at the University of Latvia, for helping with preparation of thin sections. Special thanks go to the Norwegian government for funding the University Centre in Svalbard where the authors had space and opportunity to nourish the most crucial ideas lying in base of this paper. The laboratory equipment that allowed this study was purchased within EU funded project No. VPD1/ERAF/CFLA/04/NP/2.5.2./00008/016.

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Hilis-Weichseli moreeni ja selle basaalse nihketsooni kahedimensiooniline nähtav mikrotekstuur Lääne-Läti (Ziemupe) läbilõikes

Andis Kalvāns ja Tomas Saks

Glatsiaalsete setete uuringutes on saanud oluliseks meetodiks piklike liivaterade orienteerituse e mikrotekstuuri uurimine õhikutes, mis võimaldab lisaks makrouuringutele paljandis seletada täpsemalt moreenitekke protsessi ja sellest tulenevalt liustikualuseid protsesse. Uurimisobjektiks on Hilis-Weichseli moreen ja selle basaalne nihketsoon Balti mere rannajärsaku Ziemupe läbilõikes Lääne-Lätis. Moreeni liivaterade ruumilise jaotuse mõõtmiseks ja analüüsiks on kasutatud nn pildianalüüsi, kus orienteeritus on esitatud roosdiagrammide kahedimensioonilise võrgustikuna kogu õhikupinna ulatuses (23 × 16 mm). Saadud tulemusi on võrreldud makrotekstuuri e veeriste orienteeritusega, mida mõõdeti paljandis. Tulemusena on leitud, et suurema, mõnesentimeetrise skaala puhul esineb valdavalt üks eelistatud orientatsioon, mis langeb kokku makroorientatsiooniga. Samas väiksemas (<1 cm) skaalas ilmneb terade orienteerituses suurem muutlikkus. Eristuvad väiksemad kindla orientatsiooniga piirkonnad, kusjuures kõrvuti seisvatel aladel võib esineda täiesti vastandlik orientatsioon. Seega tuleks antud uurimismetoodika puhul siiski kasutada suuremat settepinda, et võimalikud orientatsioonid selgemalt esile tuleksid.