



Progressive ductile shearing during till accretion within the deforming bed of a palaeo-ice stream

Emrys Phillips^{a,*}, Matteo Spagnolo^b, Alasdair C.J. Pilmer^b, Brice R. Rea^b, Jan A. Piotrowski^c, Jeremy C. Ely^d, Simon Carr^e

^a British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP, UK

^b Department of Geography and the Environment, School of Geosciences, University of Aberdeen, Aberdeen, AB24 3UF, UK

^c Department of Geoscience, Aarhus University, Denmark

^d Department of Geography, University of Sheffield, Sheffield, S10 2TN, UK

^e School of Geography, Queen Mary, University of London, Mile End Road, London, E1 4NS, UK

ARTICLE INFO

Article history:

Received 18 April 2018

Received in revised form

1 June 2018

Accepted 4 June 2018

Available online 2 July 2018

Keywords:

Micromorphology

Glacier bed deformation

Ductile shearing

Foliation development

Palaeo-ice stream

ABSTRACT

This paper presents the results of a detailed microstructural study of a thick till formed beneath the Weichselian (Devensian) Odra palaeo-ice stream, west of Środa Wielkopolska, Poland. This SE-flowing ice stream was one of a number of corridors of faster flowing ice which drained the Scandinavian Ice Sheet in the Baltic region. Macroscopically, the massive, laterally extensive till which formed the bed of this ice stream lacks any obvious evidence of glaciotectionism (thrusting, folding). However, microscale analysis reveals that bed deformation was dominated by foliation development, recording progressive ductile shearing within a subhorizontal subglacial shear zone. Five successive generations of clast microfabric (S1 to S5) have been identified defining a set of up-ice and down-ice dipping Riedel shears, as well as a subhorizontal shear foliation coplanar to the ice-bed interface. Cross-cutting relationships between the shear fabrics record temporal changes in the style of deformation during this progressive shear event. Kinematic indicators (S-C and ECC-type fabrics) within the till indicate a consistent SE-directed shear sense, in agreement with the regional ice flow pattern. A model of bed deformation involving incremental progressive simple shear during till accretion is proposed. The relative age of this deformation was diachronous becoming progressively younger upwards, compatible with subglacial shearing having accompanied till accretion at the top of the deforming bed. Variation in the relative intensity of the microfibrils records changes in the magnitude of the cumulative strain imposed on the till and the degree of coupling between the ice and underlying bed during fast ice flow.

© 2018 Published by Elsevier Ltd.

1. Introduction

Ice streams play an important role in regulating the behaviour of modern ice sheets (e.g. Antarctica, Bamber et al., 2000) and take the form of corridors of fast flowing ice bounded by ice flowing up to an order of magnitude slower (Stokes and Clark, 2001; Bennett, 2003). However the factors controlling fast ice flow are incompletely understood. Published studies of modern and ancient ice stream beds have led to two possible explanations governing ice stream flow: (i) basal sliding facilitated by elevated water pressures at the ice-bed interface with the ice stream effectively becoming decoupled

from the underlying sediments (e.g. Alley, 1989; Piotrowski and Tulaczyk, 1999) or hard bedrock substrate (Margold et al., 2015); and (ii) basal motion accommodated by deformation of either a thick (several metres) or thin (centimetres to decimetres) layer of 'soft' sediments (till) (e.g. Alley et al., 1986, 1987a; b; Boulton and Hindmarsh, 1987; Clarke, 1987; Humphrey et al., 1993; Boulton et al., 2001). However, in reality these two processes are not mutually exclusive and may periodically "switch" to form the dominant movement mechanism of ice stream movement depending upon the water content and/or pressure within the bed. Understanding these processes has fundamental implications for our understanding of subglacial sediment erosion, transport and deposition. Furthermore a greater understanding of the subglacial environment of ice streams may also elucidate controls on ice streaming such as basal thermal regime (Hindmarsh, 2009) and/or

* Corresponding author.

E-mail address: erp@bgs.ac.uk (E. Phillips).

subglacial hydrology (Kyrke-Smith et al., 2015), leading to the development of more sophisticated and robust models of ice stream flow dynamics and, ultimately, ice sheet mass balance and sea-level change.

The recognition of a characteristic suite of subglacial landforms (including megascale glacial lineations) formed beneath palaeo-ice streams (e.g. Dyke and Morris, 1988; Hodgson, 1994; Patterson, 1997, 1998; Stokes and Clark, 2001, 2002, 2003) has enabled the establishment of a set of criteria for identifying the presence and areal extent of these ancient ice streams (Stokes and Clark, 1999). These criteria have been, at least partially, validated by observations of the subglacial landscape beneath contemporary Antarctic ice-streams (King et al., 2009; Bingham et al., 2017). The exposed beds of palaeo-ice streams provide an ideal laboratory to investigate the sedimentary and structural processes occurring beneath fast flowing ice. However, on a macroscale the sediments (tills) deposited beneath many palaeo-ice streams are massive, lacking any visible signs of stratification and/or glaciectonic deformation (see Evans, 2018 and references therein). As a consequence micromorphology is increasingly being used as a primary tool for the analysis of these and other subglacial sediments (tills) (see Menzies and Maltman, 1992; van der Meer, 1997, 1987; Menzies et al., 1997; Khatwa and Tulaczyk, 2001; van der Meer et al., 2003; Hiemstra et al., 2005; Baroni and Fasano, 2006; Larsen et al., 2006, 2007; Phillips et al., 2007, 2011; 2013, 2018; Narloch et al., 2012; Neudorf et al., 2013; Gehrman et al., 2017; Evans, 2018). This technique can provide far greater detail on the depositional and deformation histories recorded by these sediments than can be obtained from macroscale studies alone; for example, unravelling the often complex deformation histories recorded by glaciogenic sequences (van der Meer, 1993; Phillips and Auton, 2000; van der Wateren et al., 2000; Menzies, 2000; Phillips et al., 2007; Lee and Phillips, 2008; Vaughan-Hirsch et al., 2013; Narloch et al., 2012, 2013) and the role played by pressurised meltwater during their deformation (Hiemstra and van der Meer, 1997; Phillips and Merritt, 2008; van der Meer et al., 2009; Denis et al., 2010; Phillips et al., 2013, 2018; Narloch et al., 2012, 2013).

This paper presents the results of a detailed micromorphological study of the thick till sequence laid down by the Weichselian (Devensian) Odra palaeo-ice stream as it flowed SE across

Wielkopolska Lowlands of Poland (Fig. 1). The study area is located near Poznań, in a region dominated by NW-SE-trending subglacial landforms (megascale lineations) interpreted as having been formed during fast ice flow (Przybylski, 2008; Spagnolo et al., 2016). Thin sections are used to investigate the strain signature imparted by this palaeo-ice stream on the laterally extensive till formed within its bed. The results of this detailed microstructural study have been used to investigate the nature of deformation and in particular foliation development during progressive ductile simple shear within an evolving subhorizontal subglacial shear zone. Spatial variations in the relative intensity of the microfibrils are interpreted as recording changes in the magnitude of the cumulative strain imposed on the till, potentially reflecting the degree of ice-bed coupling during fast ice flow.

2. Location of study area and geological setting

During the Weichselian (Devensian) glaciation much of the Baltic region was covered by the Scandinavian Ice Sheet. This ice sheet was drained by a series of ice streams, including the Odra palaeo-ice stream (OPIS) which flowed SE across the Wielkopolska Lowland region of western Poland (Przybylski, 2008; Spagnolo et al., 2016). In this region, the bed of the Odra palaeo-ice stream (over 1000 km²) is characterised by a suite of well-preserved NW-SE-trending megascale glacial lineations (MSGSL) underlain by a thick (c. 30 m) sequence of Quaternary sediments. This study is focused on the bed of the OPIS to the west of the town of Środa Wielkopolska, approximately 30 km southeast of Poznań (Fig. 1a and b), close to the c. 21 ka Leszno phase ice margin (Kozarski, 1988; Przybylski, 2008; Marks, 2012). The geomorphology of the study area (c. 180 km²) is dominated by a suite of elongate (>16 km long), low-relief (2–4 m high) MSGSL with a crest-to-crest spacing of 600–800 m (Fig. 1c). It is possible that these landforms were originally much longer (Przybylski, 2008) as they have been locally truncated by glaciifluvial erosion, as well as the extensive urbanisation of the region which has locally overprinted/strongly modified this subglacial landscape. Although locally modified the morphology of these subglacial landforms are comparable to MSGSL described from other palaeo-ice stream settings worldwide (Spagnolo et al., 2014).

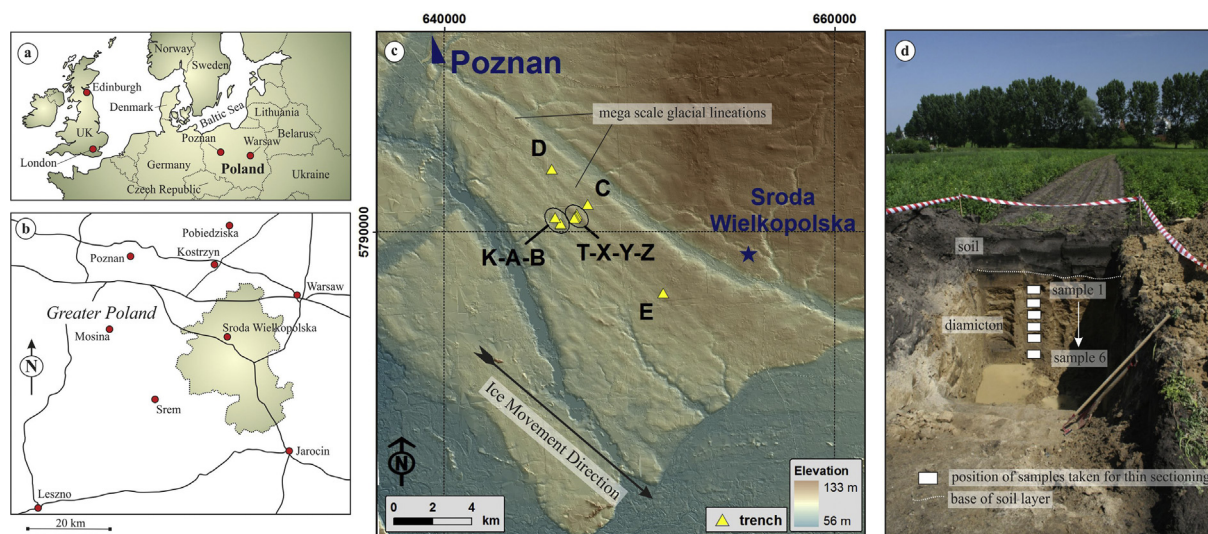


Fig. 1. (a) and (b) Maps showing the location of the study area in western Poland; (c) Digital Elevation Model (DEM) of the Środa Wielkopolska area showing the well-developed NW-SE-trending megascale glacial lineations and locations of the trenches excavated into these subglacial landforms. Also shown is the SE-directed regional ice flow across the area; and (d) An example of a trench dug into the Quaternary sediments forming the landforms showing the position of the samples collected for thin sectioning. Note that the samples were collected from below the base of the soil layer.

The sediments making up the bed of the OPIS are in general poorly exposed and detailed sedimentological analysis of these deposits has relied upon trenches excavated at key positions across the MSGL's (Fig. 1c; see below). The trenches reveal that these subglacial landforms are composed of a homogeneous, matrix-supported, yellow coloured silty-sandy diamicton (Fig. 1d) containing rare gravel (2–64 mm) and extremely rare cobble (>64 mm) sized clasts (Spagnolo et al., 2016). The massive, laterally extensive diamicton (interpreted as a subglacial traction till; sensu Evans et al., 2006) lacks any obvious macroscale evidence of glaci-tectonism (e.g. thrusting, folding ... etc.) and no other sedimentary units have been recognised. Fine gravel clasts (2–4 mm) contained within the diamicton are composed of a range of sedimentary and crystalline rock fragments, including Palaeozoic limestones derived from the Baltic Basin as well as metamorphic and igneous rocks from Scandinavia, indicating that this deposit contains a significant far-travelled component (Spagnolo et al., 2016). The diamicton is relatively unaltered, exhibiting only very minor to rare macroscopic evidence of calcification, typically occurring in patches of <200 cm². Clast a-axis macrofabric data published by Spagnolo et al. (2016) are remarkably uniform (vertically and laterally) across the bed of the OPIS within the study area. These shallow dipping macrofabrics are orientated NW-SE, concordant with the long axes of the MSGL and parallel to the regional ice flow direction.

3. Methods

Detailed analysis of the till forming the bed of the OPIS has focussed on 10 sites located on the crests (A, B, C, D, E, K, T; Fig. 1c) and flanks (X, Y, Z; Fig. 1c) of three of the mega-scale lineations. A trench (6–10 m long, 2–3 m wide and 3–5 m deep) was excavated at each site (Fig. 1d) and the samples for thin section preparation collected using standard Kubiena tins. Prior to sampling, the temporarily exposed sections were logged, photographed and described in detail with particular emphasis being placed on recording the macroscale variation in lithology and structure of the till. The samples were collected in a vertical profile (e.g. C1M highest to C6M lowest) below the base of the modern soil and with a 20 cm spacing between each Kubiena tin (Fig. 1d). This approach was adopted to provide detailed information on the range of microstructures developed at different stratigraphical/structural levels within the till. The Kubiena tins were either cut or pushed into the face in order to limit sample disturbance. The position of the sample within the sequence, its orientation relative to magnetic north, depth and way-up were marked on the outside of the tin during collection.

Sample preparation was carried out at Royal Holloway, University of London, using the methods outlined by Palmer (2005). Large format (10 × 8 cm), orientated (parallel to the long axis of the MSGL and former ice flow direction) thin sections were taken from the centre of each of the resin impregnated samples, avoiding artefacts associated with sample collection. The thin sections were described using a Zeiss petrological microscope revealing that the composition, texture and structure of the diamicton are uniform across the study area. The detailed microscale study focused upon site C, located on the crest of a prominent NW-SE-trending MSGL, as well as three samples from sites X, Y and Z, which provide a traverse across the flank of one of these landforms (Fig. 1c). The location of site C on the crest of the MSGL means that the thin sections represent a vertical section through the landform and therefore provide a valuable insight into the processes which may have occurred during the formation of this landform. The terminology used to describe the various microtextures developed within these sediments follows that proposed by van der Meer (1987, 1993) and

Menzies (2000) with modifications. Microstructural maps and quantitative data for the clast microfabrics (Figs. 2–7) developed within the till were obtained using the methodology of Phillips et al. (2011) (also see Vaughan-Hirsh et al., 2013; Neudorf et al., 2013; Gehrmann et al., 2017; Phillips et al., 2013, 2018; Brumme, 2015). During this process the relationships between successive generations of clast microfabrics (S1 oldest to Sn youngest) and other microstructures (e.g. plasmic fabrics, turbate structures, folds, faults, shears ... etc) present within the diamicton are determined, allowing a detailed relative chronology of fabric development to be established, enabling the investigation of the complex polyphase deformation histories recorded in these deposits (see Phillips et al., 2011 for details of this process). Each thin section was divided into 16 rectangular areas (A to P on Figs. 2–7) and the orientation of the long axes of the clasts (skeleton grains) plotted on a series of rose diagrams and the eigenvalues (E1, E2) calculated for each area using the commercial software package StereoStat by RockWare™ (see Figs. 2–7). In order to assess the effects of grain size on clast microfabric development within tills, the long axis data were divided into three sets: (i) grains < 0.25 mm in length (fine-sand and below); (ii) grains between 0.25 and 0.5 mm in size (medium-sand); and (iii) grains over > 0.5 mm in length (coarse-sand and above). The resultant data sets were plotted on a series of histograms and rose diagrams to highlight any variation in clast size versus long axis orientation.

In conjunction with the manual microstructural mapping methodology (Phillips et al., 2011) an automated approach using ArcGIS line density tools was conducted on selected thin sections (X1M, Y1M, Z1M) to provide a robust, objective interpretation of the clast microfabrics. These automated tools allow the calculation of the magnitude of long axes per unit area within a thin section and was applied to each of the clast microfabrics. The variation in density (mm²) of the clasts defining each microfabric was calculated with the resulting output raster files providing a map of relative intensity of clast microfabric for each thin-section (Fig. 8).

4. Results of the micromorphological and microstructural analysis

4.1. Composition and provenance of the till

In thin section (C1M, C2M, C3M, C4M, C5M, C6M) the till is massive, lacking any obvious stratification (e.g. bedding) or other primary structure. It is composed of fine- to medium-grained, open-packed, matrix-supported, silty sand (Figs. 2–7) containing scattered, angular to well-rounded granule, to small pebble-sized rock fragments composed of sedimentary rocks (siltstone, sandstone, mudstone, indurated quartz-arenite, bioclastic limestone, micritic limestone), igneous (biotite-granite, muscovite-granite, alkali granite, micrographic intergrowth, altered volcanic rocks) and metamorphic rocks (amphibolite, biotite-schist) (Table 1). Angular to subangular, coarse-silt to sand-sized grains within the till matrix are composed of monocrystalline quartz and feldspar (plagioclase, K-feldspar). The compositional data support the conclusion of Spagnolo et al. (2016) that the till was laid down by ice advancing from the NW and contains far-travelled material derived from Palaeozoic sedimentary sequences within the Baltic Basin and crystalline basement rocks from Scandinavia; similar till compositions have also been reported from Germany and Denmark (Piotrowski, 1994a; b; Kjær et al., 2003).

The thin sections reveal that the till is compositionally, essentially homogenous with only a slight increase in the proportion of limestone and fine carbonate grains downwards through the sequence (Table 1). This increase in detrital carbonate is accompanied by the appearance of small, irregular patches of a micritic

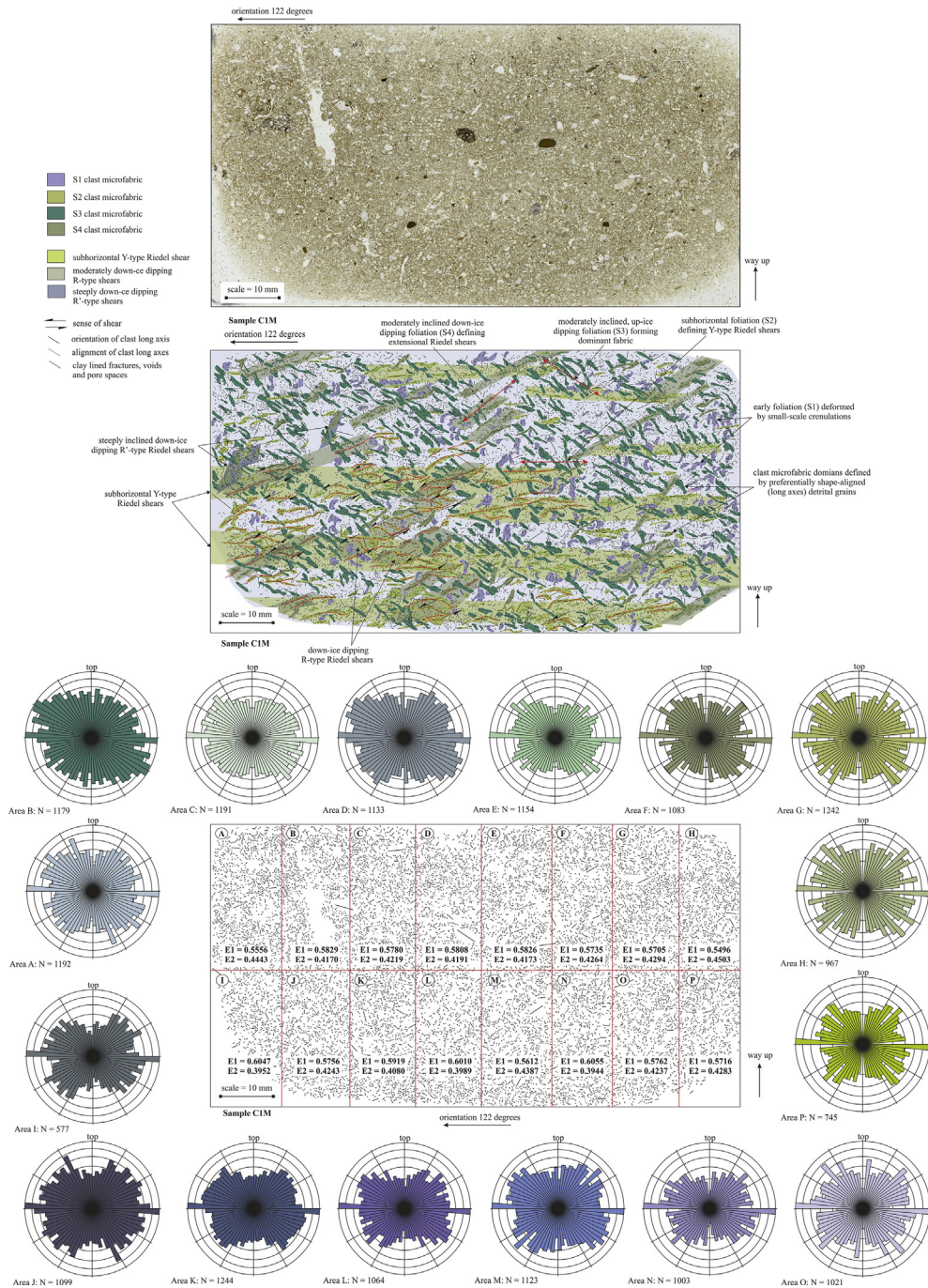


Fig. 2. Microstructural map and high resolution scan of thin section C1M. The orientation of the long axes of sand to granule sized clasts included within the diamicton are shown on a series of rose diagrams. The thin section has been subdivided into 16 subareas and the E1 and E2 eigenvalues calculated for each area (see text for details).

carbonate cement which appears to replace the clay within the matrix (Fig. 9a, b, c; red areas on Figs. 4–7). Small, rounded to irregular voids and fractures within the till are lined or filled by massive to very finely laminated, highly birefringent clay (Fig. 9d, e, f). These clay-filled features form between 5 and 15% (visual estimate) of the matrix, and locally (e.g. C1M) define a weakly developed subhorizontal “foliation”. The dark orange-brown clay is petrographically similar to clay cutan within soils, suggesting that it was deposited by water flowing through the till matrix, with the laminated nature of these fines recording several phases of fluid flow.

4.2. Microstructures developed in response to subglacial deformation

Microstructural analysis of the thin sections (C1M to C6M; Figs. 2–7, respectively) has revealed that the tills possess five successive generations of clast microfabric (S1 to S5) defined by the preferred shape alignment of elongate coarse silt to sand-grade clasts. The relative intensity of these microfabrics varies across the thin section, reflecting the heterogeneous nature of shearing within the glacier bed. The spacing of the microfabric domains is controlled by the overall grain size of the diamicton and occurrence

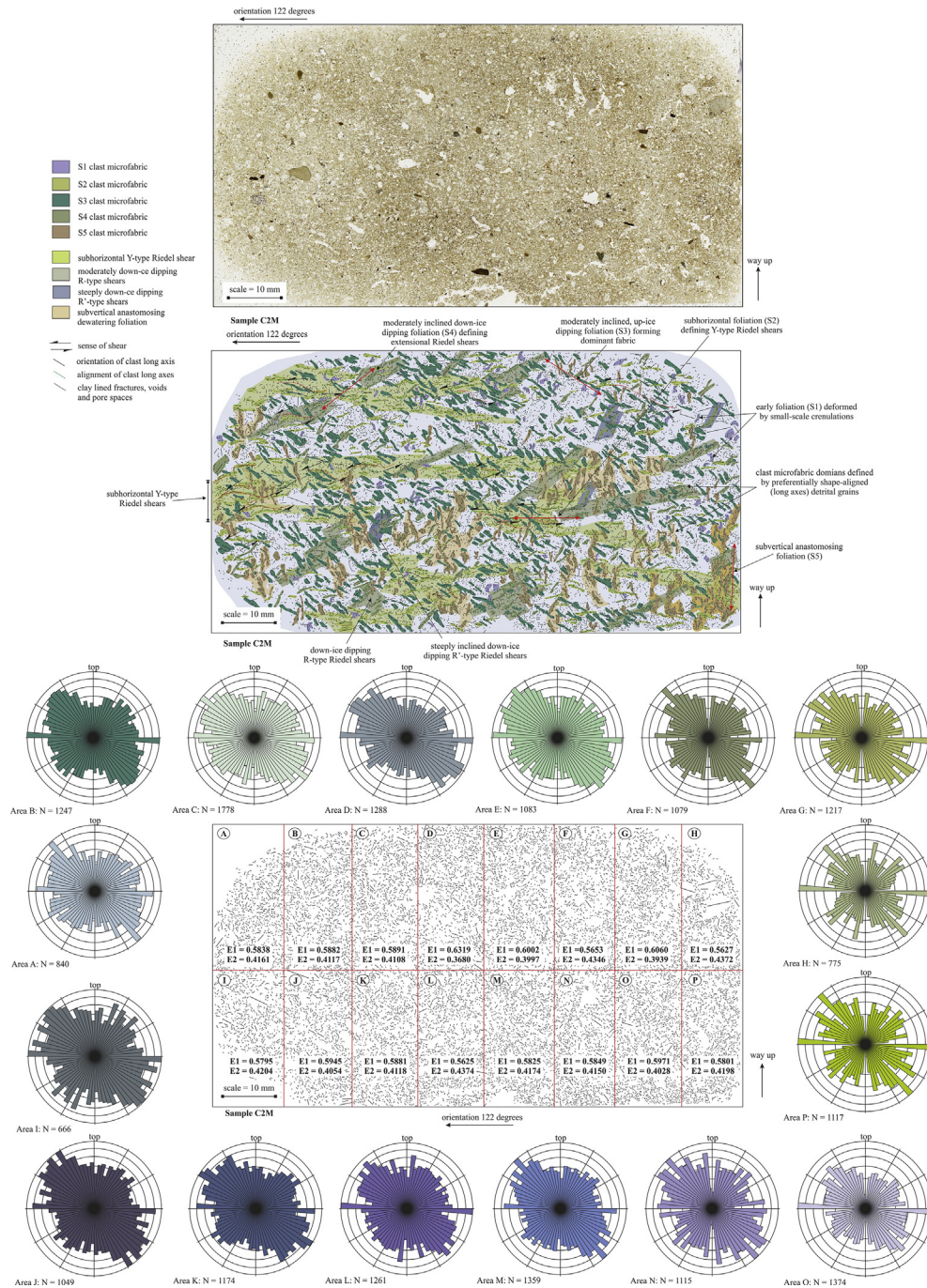


Fig. 3. Microstructural map and high resolution scan of thin section C2M. The orientation of the long axes of sand to granule sized clasts included within the diamicton are shown on a series of rose diagrams. The thin section has been subdivided into 16 subareas and the E1 and E2 eigenvalues calculated for each area (see text for details).

of coarse-sand to small pebble-sized clasts which acted as rigid bodies during deformation. Although the results of detailed microfabric analysis described below focus upon site C, comparable fabric geometries have been observed in the thin sections from sites X, Y and Z (Fig. 8).

The earliest microfabric is a very poorly developed/preserved, typically down-ice dipping S1 fabric (purple on Figs. 2–7). This fabric, where present, is cross-cut by a highly heterogeneous, subhorizontal to very gently inclined S2 fabric (pale green on Figs. 2–7). In the upper part of the till (C1M to C3M) S2 occurs within weakly to moderately well-defined, lenticular bands (Figs. 2

and 3) and is interpreted as having formed coplanar to the bed of the overriding ice. A weakly developed asymmetrical to S-shaped fabric geometry (S-C-type fabric) within the bands of S2 records a sinistral (in this plane of section) SE-directed (down-ice) sense of shear (Figs. 3–5 and 7). Lower within the till sequence (C4M to C6M), however, the banded appearance of S2 is less apparent as this fabric has been variably overprinted by a later foliation (see below).

Poorly to rarely developed, arcuate grain alignments and turbate structures (van der Meer, 1993; Menzies, 2000) occur within the microlithons between S1 and S2, and are locally truncated against these foliations. Turbate structures are interpreted to have formed

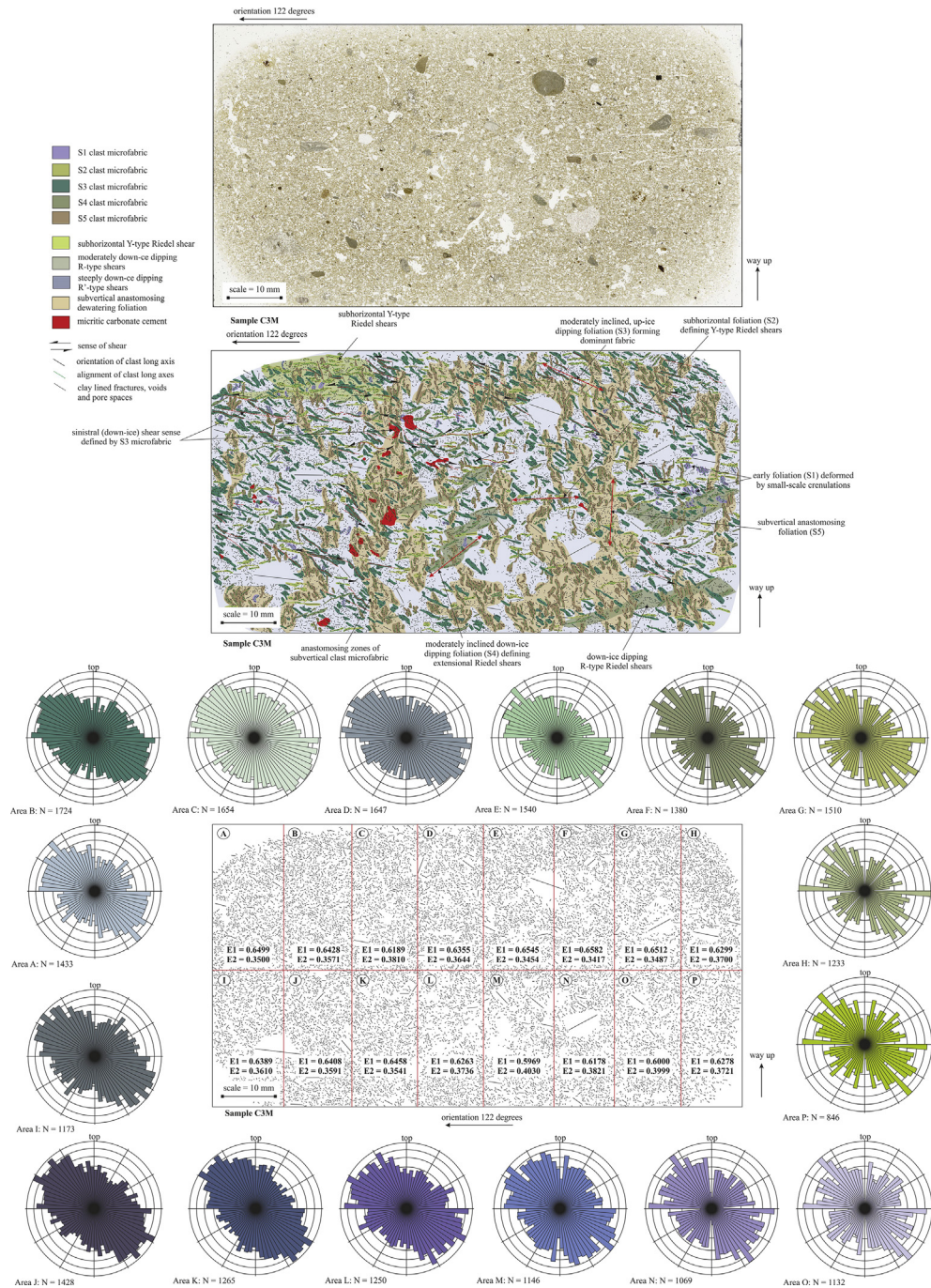


Fig. 4. Microstructural map and high resolution scan of thin section C3M. The orientation of the long axes of sand to granule sized clasts included within the diamicton are shown on a series of rose diagrams. The thin section has been subdivided into 16 subareas and the E1 and E2 eigenvalues calculated for each area (see text for details).

where larger clasts rotate through angles up to, and greater than 360° entraining the adjacent finer grained matrix (van der Meer, 1993, 1997; Menzies, 2000; Hiemstra and Rijsdijk, 2003; Lea and Palmer, 2014). Their variable preservation within the S1 and S2 microlithons suggests that this rotational deformation occurred prior to the imposition of the clast microfabrics.

The dominant fabric is an up-ice dipping S3 microfabric (dark green on Figs. 2–7). This fabric cross-cuts S2, with the earlier S1 being preserved within the microlithons separating the S3 domains. In detail S3 is composed of two components: (i) a moderately to steeply (40°–50°) up-ice dipping foliation; and (ii) a more

gently inclined (20°–40°) foliation (Figs. 2–4). The later, down-ice dipping (20°–40°) S4, microfabric is heterogeneous, potentially reflecting the partitioning of deformation into increasingly narrower zones of shear during the later stages of bed deformation. S2 and S3 are deformed by S4 resulting in a distinctive S-shape to sigmoidal fabric geometry comparable to an extensional crenulation cleavage (ECC fabric) associated with extensional shears formed in brittle-ductile shear zones (Passchier and Trouw, 1996). This fabric geometry once again records a sinistral, SE-directed sense of shear (Figs. 2, 3, 5 and 6) consistent with the ice movement direction in the study area (see Fig. 1c).

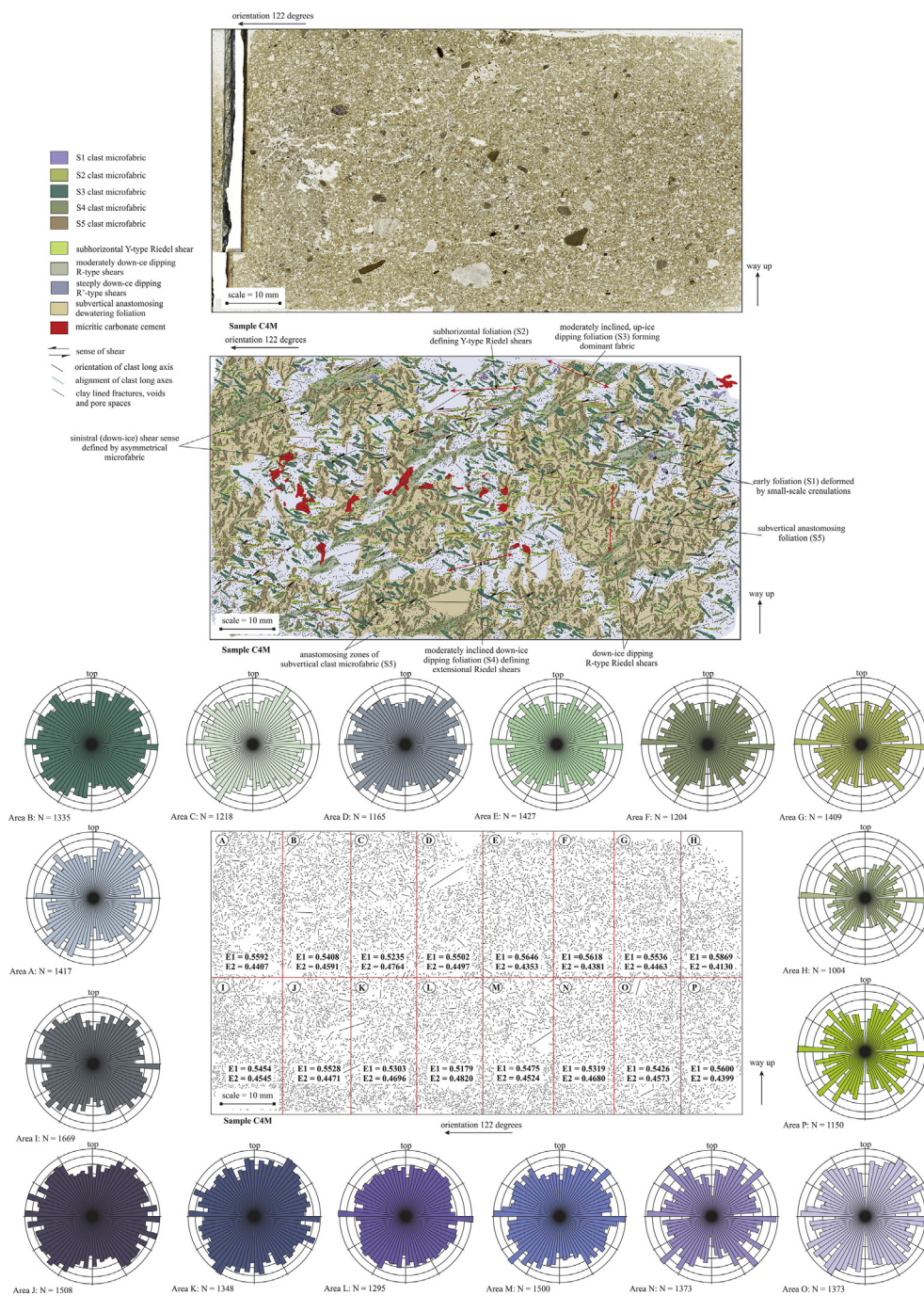


Fig. 5. Microstructural map and high resolution scan of thin section C4M. The orientation of the long axes of sand to granule sized clasts included within the diamicton are shown on a series of rose diagrams. The thin section has been subdivided into 16 subareas and the E1 and E2 eigenvalues calculated for each area (see text for details).

The same microfabric relationships (S2 to S4) were recorded in all thin sections (see Figs. 2–7) indicating that not only were these fabrics developed in response to the same overall stress regime, but that this regime (dominated by SE-directed shear) was maintained throughout the deposition of the entire till sequence. This conclusion is supported by the rose diagrams shown on Figs. 2–7 which indicate that the orientation of S2, S3 and S4 remains essentially constant throughout the till with very little modification due to compaction. The geometry of these fabrics is consistent with their development in response to the formation of Y (S2), R (S3) and P-type (S4) Riedel shears (c.f. Spagnolo et al., 2016) within a

subhorizontal subglacial shear zone formed beneath the overriding OPIS (Fig. 10).

S1 to S4 shear related fabrics are cross-cut by a subvertical, anastomosing S5 fabric which locally wraps around the larger granule to pebble sized clasts (Figs. 3–7). The overall intensity of this fabric increases down-wards through the till (C2M to C6M) where it locally overprints the earlier developed foliations. The patches of micritic carbonate within the matrix of the till occur within, or close to the areas possessing a well-developed S5 fabric (Figs. 4–7), indicating that development of this fabric may have accompanied the passage of CaCO₃-bearing fluids through the

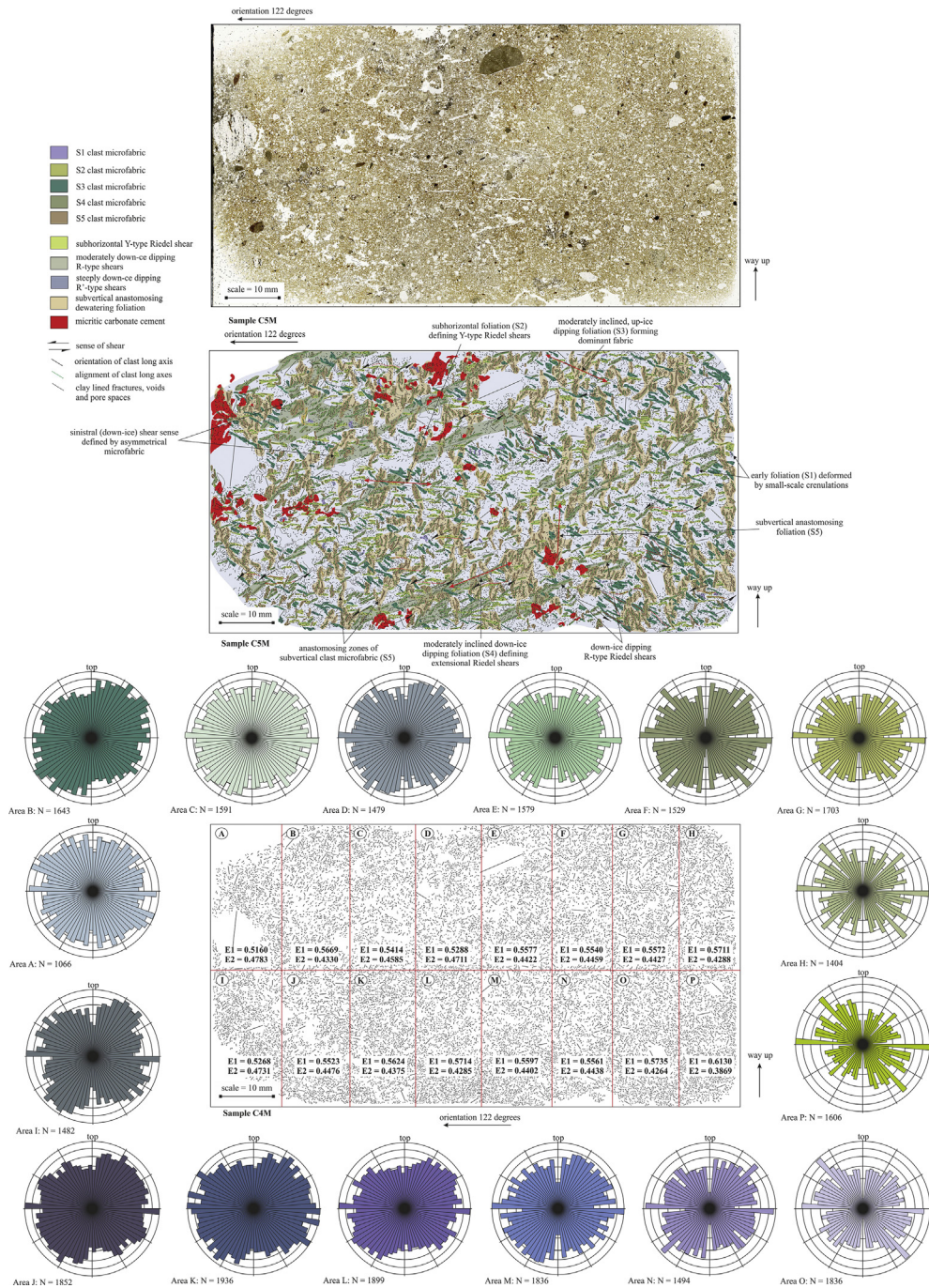


Fig. 6. Microstructural map and high resolution scan of thin section C5M. The orientation of the long axes of sand to granule sized clasts included within the diamicton are shown on a series of rose diagrams. The thin section has been subdivided into 16 subareas and the E1 and E2 eigenvalues calculated for each area (see text for details).

sediment (see section 5).

4.3. Effect of grain size on microfabric development

To assess the effects of grain size on clast microfabric development the long axis data were divided into three sets: (i) < 0.25 mm (fine-sand and below); (ii) 0.25–0.5 mm (medium-sand); and (iii) > 0.5 mm in size (coarse-sand and above). The orientation data derived for these sets are shown on Figs. 11 and 12. Although the same clast microfabrics are present within all three clast sizes (Fig. 12), they are most pronounced within the finer grained components with the data highlighting a change in the orientation of

the dominant fabric downwards through the till (Fig. 11). In the “upper” part of the till (C1M, C2M, C3M), the up-ice dipping S3 is dominant and its relative intensity appears to increase downwards (Figs. 11 and 12). This variation in the intensity of fabric development may record a progressive change in the relative intensity of deformation/magnitude cumulative strain imposed at the ice/bed interface during till accretion (Boulton, 1996; Boulton and Hindmarsh, 1987; Evans et al., 2006 and references therein). In the “lower” part of the till (C4M, C5M, C6M) the relative intensity of the shear fabrics decreases with S3 being replaced by the down-ice dipping S4 as the dominant foliation (Figs. 11 and 12). However, the fabrics (S2, S3, S4) in the “lower” part of the till have been strongly

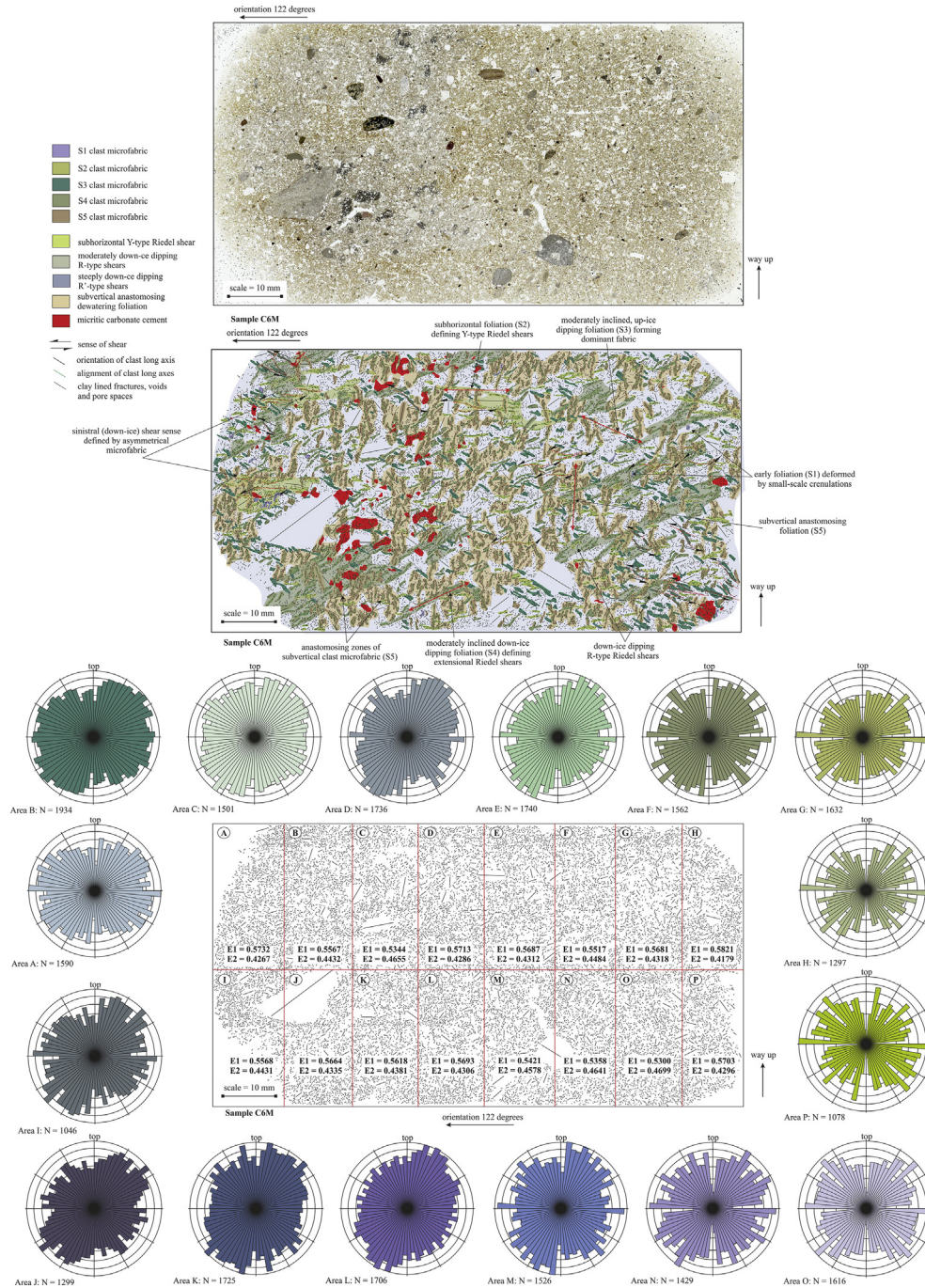


Fig. 7. Microstructural map and high resolution scan of thin section C6M. The orientation of the long axes of sand to granule sized clasts included within the diamicton are shown on a series of rose diagrams. The thin section has been subdivided into 16 subareas and the E1 and E2 eigenvalues calculated for each area (see text for details).

modified by the imposition of S5 (see Figs. 5–7). The boundary between these “upper” and “lower” till units appears to be relatively sharp and located between samples C3M and C4M. However, no obvious boundary was observed at this level within the trench (see Fig. 1c).

5. Variation in microfabric intensity within the OPIS till

The results of the micromorphological study indicate that there is a significant variation in the relative intensity of microfabric development within the till.

5.1. Automated clast microfabric analysis

The results of the automated approach to quantify the variation in clast microfabric strength are shown in Fig. 8. The thin sections used (X1M, Y1M, Z1M) represent a traverse down the flank of an MSGL (Fig. 1c) designed to investigate any potential lateral changes in the style and relative intensity of fabric development across this subglacial landform. Importantly this method has revealed a similar pattern of microfabric development within each of the thin sections as those analysed using manual methodology of Phillips et al. (2011) (compare Figs. 2, 3 and 8). It is clear from Fig. 8 that all of the microfabrics (S2, S3, S4, S5) are heterogeneously

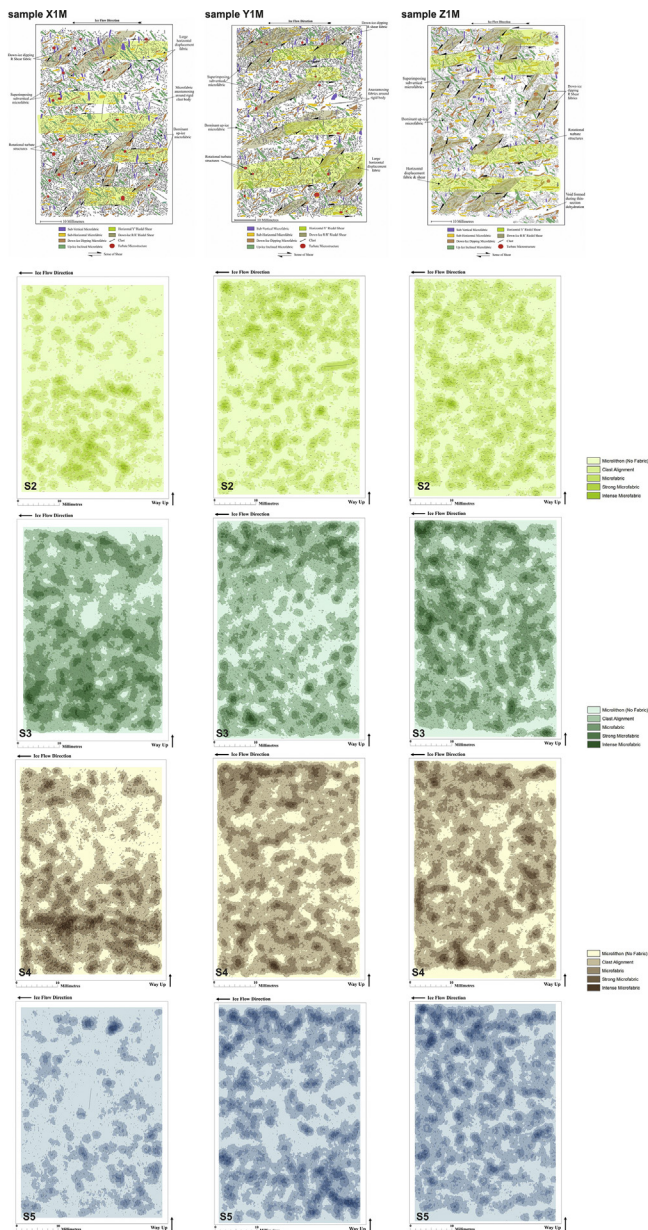


Fig. 8. Microstructural maps and automated clast density maps of the main clast microfabrics (S2, S3, S4, S5) identified within samples X1M, Y1M and Z1M.

developed, even within a single thin section, reflecting the partitioning of deformation on a microscale within the bed of the OPIS. S3 is the dominant fabric and is most intensely developed within the samples located close to the crest of the MSGL (X1M) and within the adjacent trough (Z1M) (Fig. 8). In contrast, both S2 and S4 are more weakly developed on top of the landform (X1M) in comparison to its flanks (Y1M, Z1M) the strength of S5 increases down the flank of the MSGL towards the adjacent trough.

5.2. Statistical clast microfabric analysis

The variation in E1 eigenvalues calculated for the samples from site C (C1M to C6M) are illustrated on Fig. 13. The red colours represent areas of the thin sections with higher E1 values (0.65–0.68), corresponding to relatively stronger fabric development, and purple lower values (0.53–0.51), highlighting areas

where the clast microfabrics are less well-developed. This approach reveals that fabric strength not only varies within an individual thin section, but also vertically through the till (Figs. 13 and 14a), supporting the results of the grain size fabric analysis (Figs. 11 and 12). The eigenvalues are typically higher within the upper part of the till (C1M, C2M, C3M; Table 2), recording an overall relative increase in fabric strength upwards through the till (Fig. 13); although sample C3M has the highest E1 values compared to the other two samples. In contrast, the lower three samples all possess low eigenvalues (Figs. 13 and 14a; Table 2) corresponding to much weaker fabric strengths. Although it is tempting to suggest that the lower part of the till is more weakly deformed, this may simply reflect the overprinting of the earlier shear related fabrics (S2 to S4) by the later S5 microfabric (see Figs. 5–7).

The eigenvalues (<0.6; Fig. 13 and Table 2) can be used to suggest that the amount of shear being transmitted into the bed of the OPIS was relatively low. In the absence of any obvious strain markers (e.g. deformed clasts known to have been originally circular in shape) estimating the magnitude of the shear strains imparted by the overriding ice remains problematic. Several workers have used the relative abundance of selected microstructures (e.g. micros shears, grain stacks) as a proxy for estimating strain in subglacial traction tills (Larsen et al., 2006, 2007; Narloch et al., 2012). However, the development of such features can be strongly lithologically controlled; e.g. micros shears defined by a unistrial plasmic fabrics will only form in clay-rich sediments. Furthermore, their identification is qualitative and potentially subjective (Leighton et al., 2012; Neudorf et al., 2013). Phillips et al. (2013) suggested that shear strain curves established from experimental deformation studies (e.g. Thomason and Iverson, 2006) can be used to provide a minimum estimate of the shear strains experienced by subglacial traction tills. In the absence of strain curves for a range of naturally occurring tills, the potential closest “match” to the sand-rich OPIS till is the Douglas till strain curve of Thomason and Iverson (2006) (Fig. 14b). When projected onto this curve the range of average E1 values for the OPIS till suggests that microfabric development occurred in response to shear strains of <15 (Fig. 14b). If this approach is valid then it supports the suggestion that the amount of shear being transmitted into the bed of the OPIS by the overriding ice was relatively low (cf. Larsen et al., 2007; Narloch et al., 2012; Phillips et al., 2013).

6. Implications for bed deformation beneath the OPIS

6.1. Foliation development in response to progressive simple shear

Results of this detailed microscale study reveal that deformation within the bed of the OPIS was dominated by foliation development which lacked any concomitant folding and/or faulting (c.f. Spagnolo et al., 2016). The microfabrics define a set of up-ice and down-ice dipping Riedel shears (S3 – P-type and S4 – R-type shears; Fig. 10), as well as a subhorizontal shear foliation (S2 – Y-type shears; Fig. 10) with S2 having formed parallel to the ice-bed interface (Figs. 10 and 15). The consistency of the geometry and orientation (Figs. 2–7, and 15) of these microfabrics indicate that not only did subglacial deformation occur in response to the same overall stress regime, but also that they have undergone very little modification due to compaction/loading subsequent to formation which would have led to the “flattening” (decrease in dip) of the fabrics at depth within the till (see rose diagrams on Fig. 15). The consistency of the data also indicates that ductile shearing beneath the OPIS was spatially uniform and occurred within an essentially subhorizontal subglacial shear zone (see Fig. 10). Furthermore kinematic indicators (S-C and ECC-type microfabrics) record a consistent SE-directed (sinistral) sense of shear, coincident with the

Table 1
Detrital clast assemblage identified within the silty sand subglacial traction till exposed at Site C.

Sample Number	Detrital Components	
	major	minor to accessory
C1M	monocrystalline quartz, feldspar (plagioclase, K-feldspar)	polycrystalline quartz, opaque minerals, altered volcanic rocks, clinopyroxene, microcline, mudstone, sericitised granitic rock, amphibole, glauconitic material, micrographic intergrowth, ?alkali granite, garnet
C2M	monocrystalline quartz, feldspar (plagioclase, K-feldspar)	cryptocrystalline quartz (chert), opaque minerals, pyroxene, siltstone, mudstone, microcline, altered igneous rock, glauconitic material, micrographic intergrowth, amphibole, feldspar-chlorite rock, biotite-schistose metamorphic rock, fine sandstone (hematitic cement)
C3M	monocrystalline quartz	polycrystalline quartz, biotite, metamorphic rock, indurated quartz-arenite, echinoderm fragments, plagioclase, carbonate mineral(s), micritic limestone, brachiopod fragments, K-feldspar, glauconitic material, amphibole, opaque minerals, cryptocrystalline quartz (chert), very fine-grained micaceous material, epidote, siltstone/very fine-grained sandstone, foraminifera, garnet, ?zircon, muscovite
C4M	monocrystalline quartz, feldspar (plagioclase, K-feldspar)	micrographic intergrowth, carbonate minerals, mudstone, microcline, glauconitic material, amphibole, indurated siltstone, bioclastic limestone, glauconite-bearing micritic limestone, biotite, ?alkali granitic rock, micritic limestone, hematised siltstone, opaque minerals, altered granitic rock, ?garnet, brachiopod fragments, echinoderm fragments, quartz-epidote-rock, amphibolite
C5M	monocrystalline quartz	polycrystalline quartz, siltstone, amphibole, opaque minerals, carbonate minerals, micritic limestone, glauconitic material, microcline, plagioclase, altered granitic rock, devitrified igneous rock/felsite, zircon, muscovite, garnet, bioclastic limestone, glauconitic sandstone, biotite metamorphic rock
C6M	monocrystalline quartz	plagioclase, K-feldspar, carbonate minerals, bioclastic limestone, glauconitic material, micritic bioclastic limestone, muscovite-granite, amphibole, opaque minerals, biotite-granite, laminated siltstone, amphibolite, altered igneous rock, microcline, garnet, calcareous siltstone, very fine-grained sandstone/siltstone, zircon, epidote, tourmaline

long axes of the MSGL and regional pattern of ice flow across the Wielkopolska Lowland (Przybylski, 2008; Spagnolo et al., 2016).

The cross-cutting relationships displayed by S2, S3 and S4 can be interpreted as reflecting temporal changes in the style of deformation being accommodated within the till. However, the consistent SE-directed sense of shear recorded by these fabrics clearly indicates that they formed in response to the same overall stress regime imposed during a single progressive shear event rather than completely separate phases of deformation. S2 defines a series of subhorizontal Y-type shear planes indicating that the earlier stages of ductile deformation were dominated by shear occurring coplanar to the base of the overriding ice. S2 is cross-cut by the up-ice dipping S3 foliation which defines a number of P-type shears indicating that initial layer-parallel shear was superseded by compressional deformation. S3 is then cross-cut by the later down-ice dipping S4 which records the nucleation and growth of apparently late-stage extensional R-type shears within the bed of the OPIS. The same relationships were observed in all the thin sections and are interpreted as recording temporal changes in the style of deformation imposed on the till during its evolution.

6.2. Clast microfabric development in tills

The individual clast microfabrics within the OPIS till formed as a result of the passive rotation of coarse-silt to sand-grade particles into the plane of the developing foliation(s) (Fig. 16) reflecting the stress field imposed by the overriding ice (c.f. Hiemstra and Rijdsdijk, 2003; Phillips et al., 2011). Once aligned, further rotation will cease and the clasts will maintain their preferred alignment unless there is a change in the orientation of this stress field within the evolving Reidel shears. As deformation continues, the microfabric domains defining the shear fabrics will propagate laterally as more grains become aligned. Further deformation within the microscales will be accommodated by either sliding of the grains past one another (Fig. 16a) and/or the partitioning of shear into the intervening finer grained matrix. If the matrix contains a significant modal proportion of clay minerals then this may lead to the formation of a unistrial plasmic fabric (van der Meer, 1993; Menzies, 2000, 2012; Hiemstra and Rijdsdijk, 2003) coplanar to the evolving clast microfabric.

The grain size of the sediment also influenced microfabric development with preferred clast alignments being most apparent

within the finer grained (<0.25 μm ; 0.25–0.5 μm) components (matrix) of the till (Figs. 11 and 12). During deformation, it is suggested that the larger grains (cobbles, pebbles) were the first to stop rotating, becoming “locked” into position with subsequent increments of deformation being partitioned into the still “active” matrix (c.f. Evans et al., 2016; Evans, 2018). Consequently the matrix of the till continued to respond to shear long after the larger clasts have become immobile and therefore provide the most complete record of subglacial deformation. Results from several micromorphological studies (Phillips et al., 2011, 2013, 2018) suggest that larger sand, granule to pebble sized clasts (where present) control the spacing of the developing microfabric domains, influencing the pattern of deformation partitioning within the till (Fig. 16). By the way of analogy, in metamorphic rocks the mica domains, defining the schistosity in amphibolite facies pelitic rocks (metamorphosed mudstones), are thought to nucleate upon the margins of ridged porphyroblasts (e.g. garnet), propagating laterally away from these relatively higher strain areas as deformation/fabric development continues (Bell, 1985; Bell and Rubenach, 1983; Bell et al., 1986; Vernon, 1989; Johnson, 1990). It is possible that a similar process also occurs in tills with the microfabrics nucleating upon the larger clasts due to the concentration of strain along the margins of these rigid grains. The evolving foliation then propagates away from this nucleation point into the adjacent matrix. The presence of larger rigid clasts will affect/distort (on a microscale) the stress and strain field imposed upon the till matrix (Fig. 16b) leading to the development of anastomosing microfabric, wrapping around these coarse sand to pebble-sized grains (Fig. 16c).

Evans et al. (2006) suggested that deformation (fabric development, folding, faulting) within the bed will only occur when the intergranular pore water pressure falls and a coherent “till-matrix framework” develops (also see Evans, 2018). Consequently, the nucleation and subsequent evolution of the clast microfabrics is likely to be controlled by the water content and packing of the till. However, increasing the packing of the constituent grains within the sediment will lead directly to an increase in its peak frictional strength and its resistance to deformation, which may be overcome by an increase in the magnitude of the imposed shear stress. Consequently, there is likely to be a critical range in intergranular porewater content/pressure and sediment packing for foliation development to occur within tills. For example, foliation development within a “dry” till comprising dense, closely packed grains

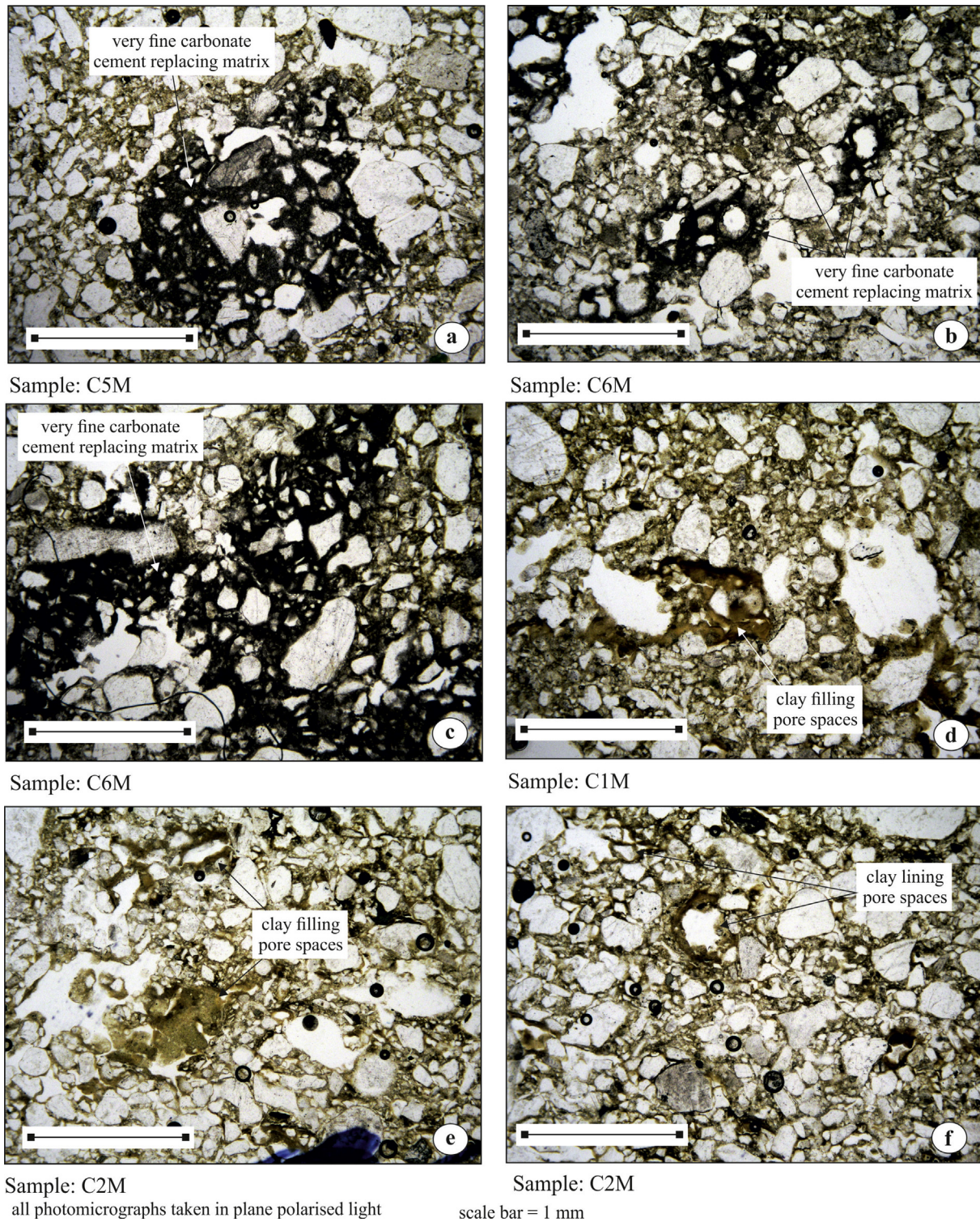


Fig. 9. Photomicrographs showing the fine-grained, dusty looking carbonate which locally replaces the matrix to the diamicton (a to c) and clay lined and filled pore spaces (d to f).

will be limited due to the high percentage of inter granular contacts restricting grain rotation. In contrast, a shear stress applied to a water-saturated till is likely to induce dilation or even localised liquefaction which will not only inhibit fabric development, but also lead to the overprinting of earlier developed microstructures (Evans et al., 2006; Phillips et al., 2011, 2013; 2018). The inherent spatial variation in the water content and packing of the till will lead to the small-scale partitioning of deformation and

heterogeneous fabric development within the bed of the OPIS (Figs. 2–8).

6.3. Evidence of intergranular fluid flow and dewatering of the bed

The matrix of the till forming the bed of the OPIS contains clay-lined or filled voids, intergranular pore spaces and fractures (Fig. 9). The clay is petrographically similar to clay cutan within soils,

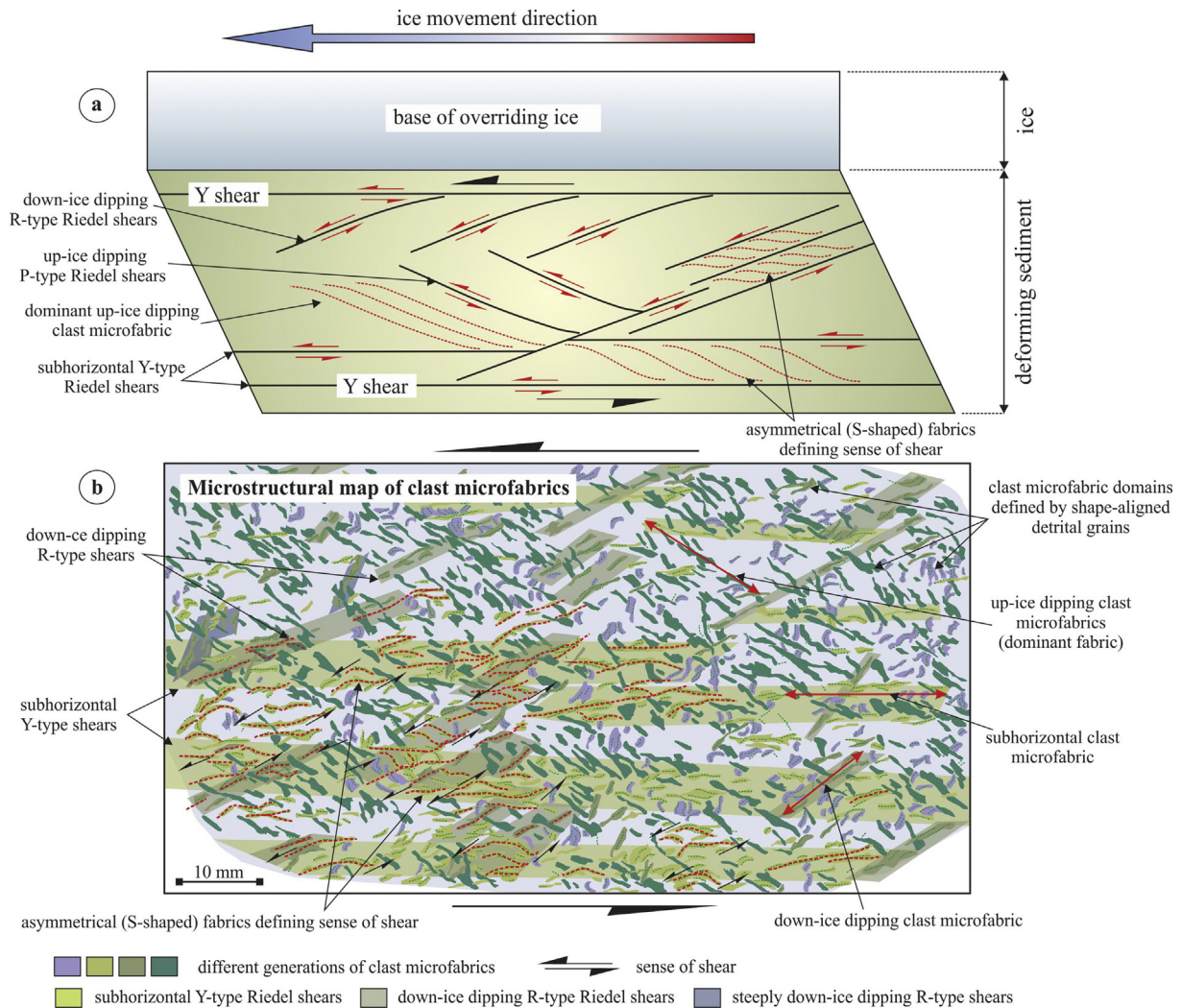


Fig. 10. (a) Diagram showing the relationships between the different sets of Riedel shears developed within the diamicton in response to deformation imposed by the overriding ice stream; and (b) Example of a detailed microstructural map of sample C1M. The coloured polygons represent the different generations of clast microfabrics, which define the Riedel shears, subhorizontal shear fabric and up-ice dipping foliation.

suggesting that it was deposited by water flowing through the till so that the laminated nature of these fines records several phases of fluid flow. Although clay infiltration can occur during pedogenic processes, these features occur well below the base of the modern soil (see Fig. 1d) indicating that it was unrelated to recent pedogenic processes. Observations from contemporary (Alley et al., 1986; Tulaczyk et al., 1998) and palaeo (Cofaigh et al., 2007) ice stream beds indicate that the tills are typically highly porous and weak, with a water content close to the liquid limit. The clay within the OPIS till forms between 5 and 15% of the matrix and is observed variably infilling intergranular pore spaces, consistent with the nature of tills described from modern ice stream beds (Alley et al., 1986; Tulaczyk et al., 1998; Cofaigh et al., 2007). Significant compaction of the OPIS till would have led to an increase in its packing, reducing in its porosity and permeability. Consequently the preferred interpretation is that fluid flow and clay infiltration probably occurred shortly after till deposition; a conclusion supported by the dark coloration of the clay resulting from its replacement by Fe/Mn during 'maturation' (Phillips and Auton, 2008).

In the lower part of the OPIS till the earlier shear fabrics (S2 to S4) are variably overprinted by S5 (Fig. 15). The intergranular clays

show very little, if any, evidence of disruption/fragmentation suggesting that they post-date any significant deformation and/or reorganisation of the structure and packing of the till during the imposition of S5. Consequently, it is suggested that S5 pre-dated the intergranular fluid flow and clay infiltration, with the imposition of this late stage foliation probably accompanying the dewatering of the till driven by the ice overburden pressure; a conclusion supported by the relative increase in the intensity of this fabric downward through the till (Fig. 15). The micritic carbonate within the matrix of the till (red areas on Fig. 15) exhibits a close spatial relationship to S5, indicating that diagenesis may have accompanied the imposition of this fabric and recording the passage of a CaCO_3 -bearing fluid phase through the sediment. If the carbonate was pedogenic then it should increase upwards towards the base of the modern soil, possibly forming a calcified crust at the base of the soil profile. Several studies have examined the dissolution of carbonate in glacial environments (e.g. Fairchild et al., 1993, 1994; Menzies and Brand, 2007) with McGillen and Fairchild (2005) suggesting that this process may be facilitated by the crushing and comminution of carbonate grains within subglacial traction tills. Menzies and Brand (2007) argued that carbonate cementation of ice-contact sands and gravels exposed within core

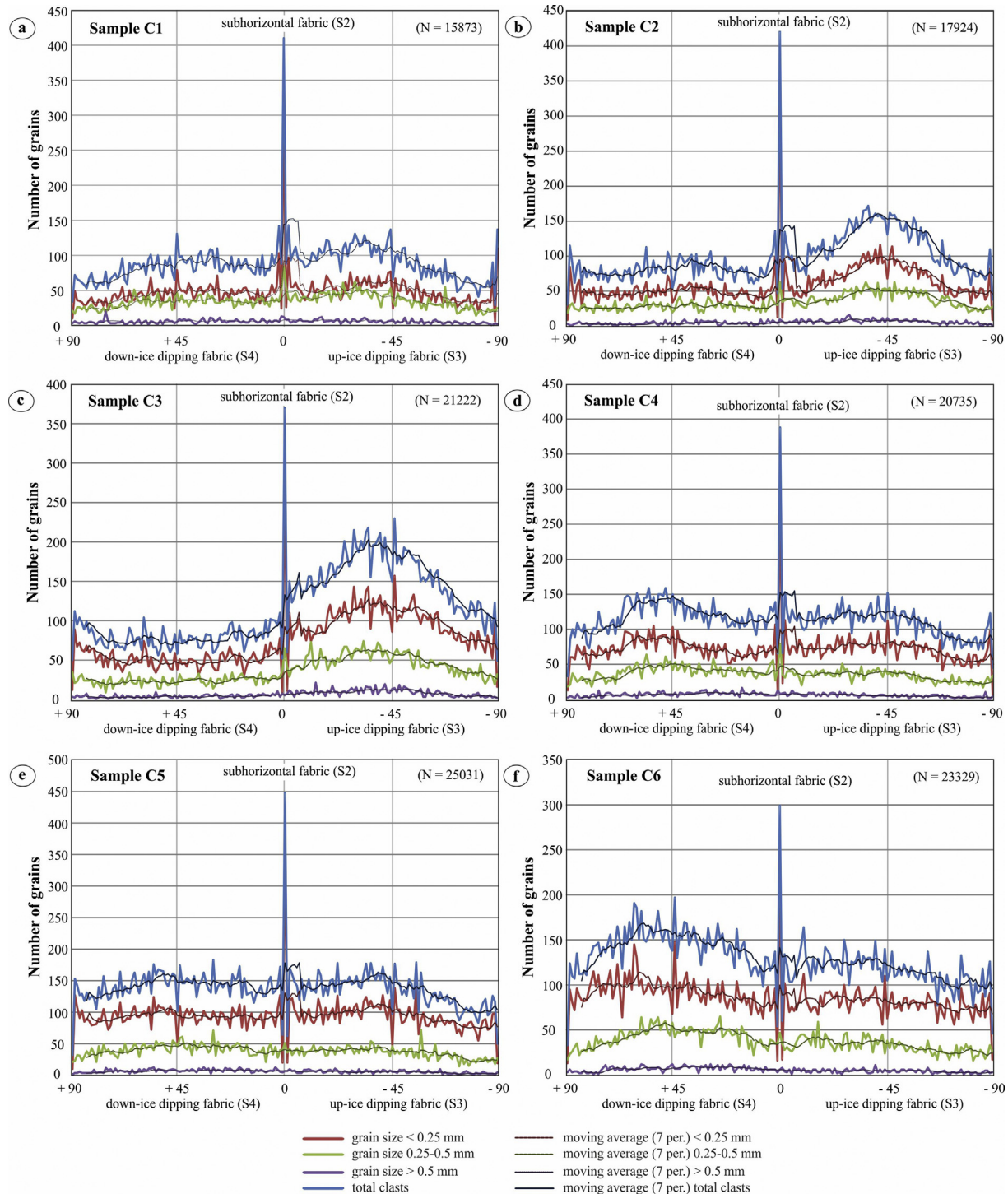


Fig. 11. Graphs showing the effects of grain size on clast microfabric development within the diamicton at site C. The long axis data for each thin section (C1M to C6M) are divided into three sets: (i) grains < 0.25 mm in length; (ii) grains between 0.25 and 0.5 mm in size; and (iii) grains over > 0.5 mm in length. The number of grains in each of the three classes is plotted against the orientation of their long axis (0° represents horizontal). The large “spike” in the data set for the finest grains and total clasts at 0° results from the unavoidable “snapping” to the horizontal of short long axes dipping at very low angles (-2° to $+2^\circ$) during digitisation using CorelDraw. On Fig. 12 the data are plotted on a series of rose diagrams showing the dip of the long axes within the 2D plane of the thin section.

of a large drumlin in New York State occurred in response to a reduction in hydrostatic pressure and release of CO_2 from the meltwater escaping from beneath the Laurentide Ice Sheet. Consequently, it is possible that carbonate diagenesis within the OPIS till may have occurred penecontemporaneous with subglacial deformation. As noted above, S5 clearly overprints the shear related

fabrics within the till and therefore post-dated subglacial shearing. However, due to the potentially diachronous nature of deformation within the OPIS till, dewatering and imposition of S5 within the structural lower parts of the sequence is thought to have been initiated whilst subglacial shearing was continuing at a higher level within the bed (Fig. 15) (see below).

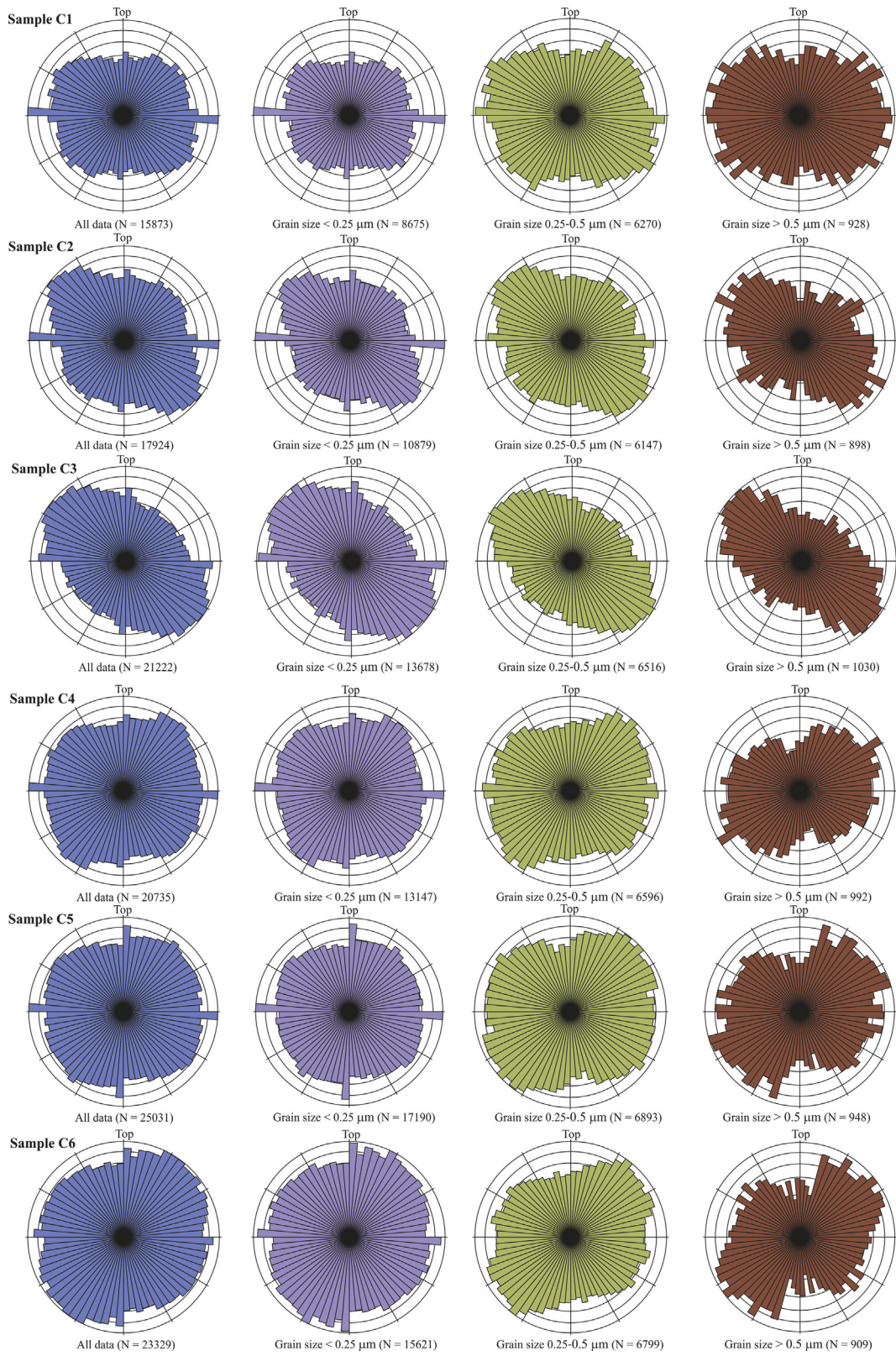


Fig. 12. Rose diagrams showing the variation in dip of the long axes of coarse silt to sand sized clasts within the 2D plane of the thin sections C1M to C6M. The data are divided into three sets: (i) grains < 0.25 mm in length; (ii) grains between 0.25 and 0.5 mm in size; and (iii) grains over > 0.5 mm in length.

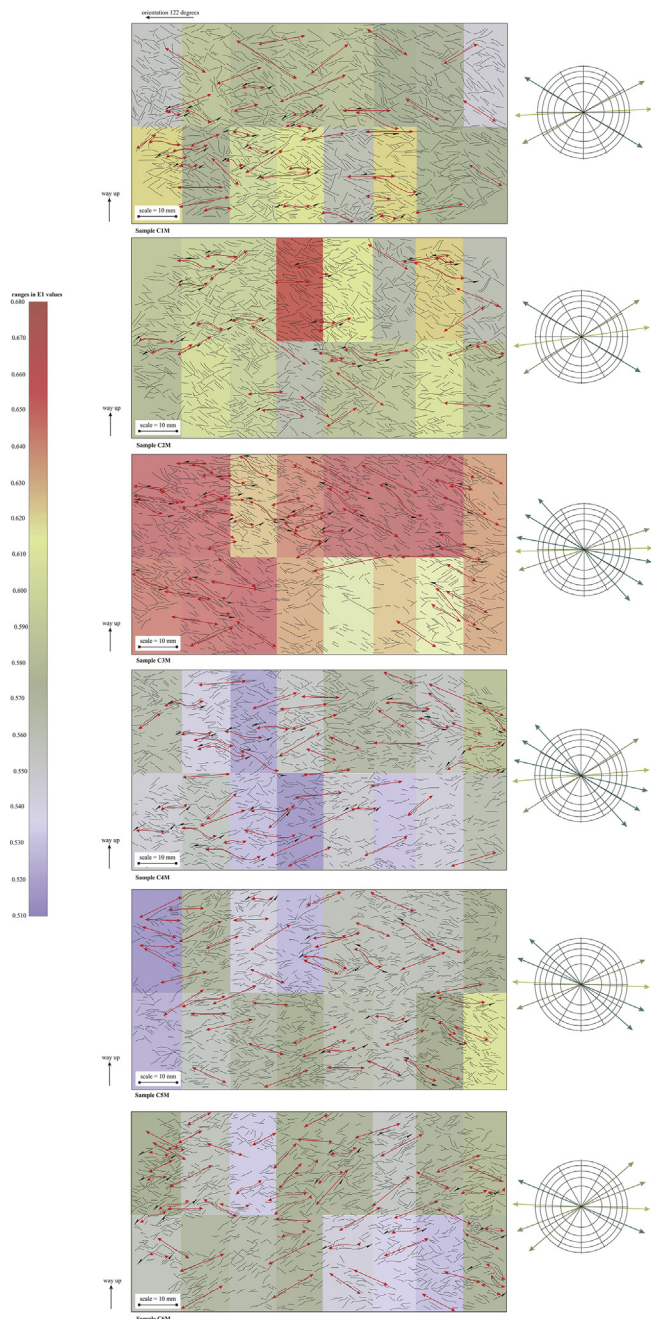


Fig. 13. Variation in E1 eigenvalues calculated for the thin sections (C1M to C6M) showing the variation in relative fabric strength both with an individual thin section and vertically through the diamicton at site C. Red colours represents areas of the thin sections with higher E1 values (0.65–0.68) and purple low E1 values (0.53–0.51). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

6.4. The nature of bed deformation beneath the OPIS: deformation partitioning or incremental progressive simple shear during till accretion

Spagnolo et al. (2016) argued that the till beneath the OPIS was being continuously accreted at the top of a shallow-deforming bed (cf. Tulaczyk, 1999; Iverson et al., 1998; Fuller and Murray, 2002; Piotrowski et al., 2001, 2004; Evans et al., 2006; Cuffey and Paterson, 2010; Iverson, 2011; Evans, 2018). However, the possibility that pervasive bed deformation may have occurred to greater

depths beneath this ice stream needs to be considered. Quantitative data presented here provides evidence that fabric (S2, S3, S4, S5) strength varies (on a microscale) both laterally and vertically within the bed of the OPIS (Figs. 13 and 15). If this variation in fabric strength can be used as a proxy for the relative intensity of shear imposed on the till it may reflect either: (i) the partitioning of deformation within the subglacial shear zone formed beneath this ice stream, within the deforming bed and potentially encompassing the entire thickness of the till; or (ii) the variation in the magnitude of the shear being transmitted into the deforming bed during the progressive accretion of the OPIS till.

A number of studies have suggested that subglacial shear zones migrate through the bed due to spatial and temporal fluctuations in water content/pressure (Tulaczyk, 1999; Truffer et al., 2000; Evans et al., 2006; Kjær et al., 2006; Lee and Phillips, 2008) and/or the ability of these sediments to drain intergranular porewater (Piotrowski et al., 2004). Deformation within the shear zone can either be ‘pervasive’ (homogeneous) and transmitted throughout the entire bed (van der Meer et al., 2003; Menzies et al., 2006), or heterogeneous where the bed comprises a ‘mosaic’ of actively deforming and stable (non-deforming) zones (Piotrowski and Kraus, 1997; Piotrowski et al., 2004; Lee and Phillips, 2008). Tills within the beds of ice streams are thought to be water-saturated and weak (Alley et al., 1986; Tulaczyk et al., 1998; Ó Cofaigh et al., 2007), and therefore able to accommodate a significant proportion of the forward motion of the overriding ice. The consistency of the orientation and geometry of the shear fabrics (S2 to S4; Fig. 15) throughout the OPIS till, coupled with the very low preliminary estimates of shear strain (Fig. 14) may be used to support the presence of weak, water-saturated sediments beneath this palaeo-ice stream, facilitating the transmission of shear throughout its entire bed (Menzies et al., 2006; Hart and Boulton, 1991; van der Wateren et al., 2000; van der Meer et al., 2003; Menzies et al., 2006). In detail, the relative intensity of the shear fabrics vary both laterally and vertically (Figs. 8 and 13). However, there is no obvious macroscale evidence for the presence of a significant décollement surface (thrust) within the bed of the OPIS till (see Fig. 1d). So as a result, it cannot be argued that forward motion of the OPIS was accommodated by deformation at a deeper level within the sediment pile (Fig. 17a). Consequently, variations in the relative intensity of foliation development within the OPIS till is more likely to record the small-scale partitioning of deformation during subglacial shear.

The deforming bed model for glacier motion predicts an increase in cumulative strain upwards toward the ice-bed interface (Boulton, 1996; Boulton and Hindmarsh, 1987; Evans et al., 2006) with deformation being accommodated by a weak, water-saturated layer located immediately adjacent to, or at the ice-bed interface (Fig. 17b). The continuous deposition of a soft (weak), compositionally homogenous (well-mixed; see section 4.1) till layer at the top of the bed of the OPIS (Spagnolo et al., 2016) means that over time deformation will have progressively shifted upwards as till accreted (Fig. 17b). The trenches in the study area reveal that the till sequence beneath the OPIS is at least 1.2–1.4 m thick, with Ground Penetrating Radar data indicating that the diamicton may be in the order of 2–3 m thick (Spagnolo et al., 2016). The soft deforming layer responsible for till accretion at the top of this sequence is likely to have only been a few tens of centimetres thick (Menzies, 1982; Alley et al., 1986, 1987; Boulton, 1996; Hindmarsh, 1998; Larsen et al., 2004, 2007; Evans et al., 2006; Stokes et al., 2013) and localised in nature reflecting the spatial and temporal changes in bed conditions. Phillips et al. (2018) suggested that the term ‘transient mobile zone’ for this actively deforming layer in order to emphasize the spatial and temporal variations in subglacial deforming bed processes proposed by a number of researchers (e.g.

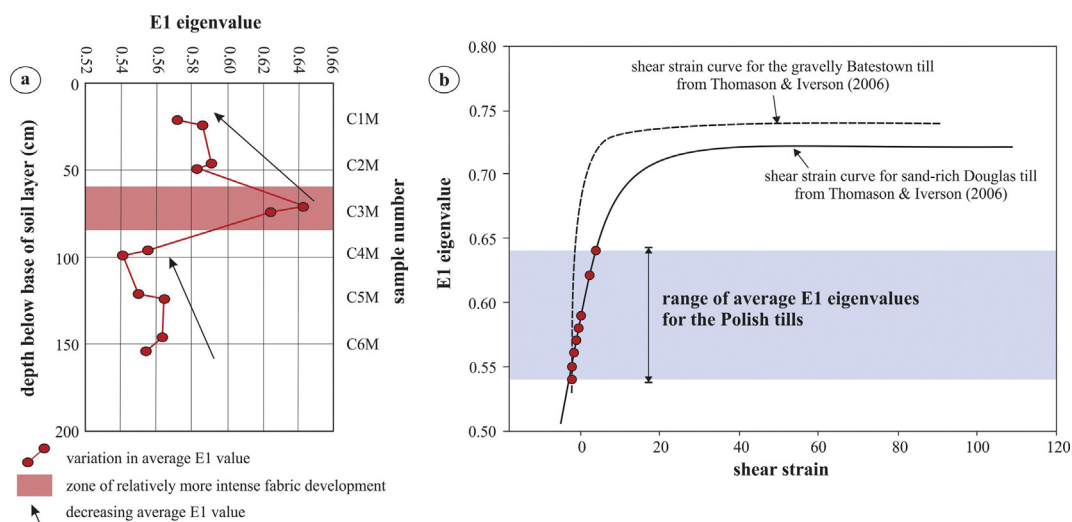


Fig. 14. (a) Plot showing the variation in average E1 eigenvalue calculated for each thin section (C1M to C6M) with respect to depth within the diamicton sequence; and (b) Plot of E1 eigenvalue against shear strain. The shear strain curves for the Batestown (gravelly) and Douglas (sand-rich) tills are taken from Thomason and Iverson (2006) and are used to obtain an estimate of the range of shear strains encountered by the diamicton exposed at site C.

Table 2

Average E1 and E2 eigenvalues calculated for clast microfabrics developed within subglacial traction till samples C1M to C6M.

Depth below surface (cm)	Sample	Eigenvalues								Median	Average
		E1	E1	E1	E1	E1	E1	E1	E1		
21	C1M a-h	0.555	0.582	0.578	0.580	0.582	0.573	0.570	0.549	0.575	0.571
24	C1M i-p	0.604	0.575	0.591	0.601	0.561	0.605	0.576	0.571	0.584	0.586
46	C2M a-h	0.583	0.588	0.589	0.631	0.600	0.565	0.606	0.562	0.588	0.590
49	C2M i-p	0.579	0.594	0.588	0.562	0.582	0.584	0.597	0.580	0.583	0.583
71	C3M a-h	0.649	0.642	0.618	0.635	0.654	0.658	0.651	0.629	0.646	0.642
74	C3M i-p	0.638	0.640	0.645	0.626	0.596	0.617	0.600	0.627	0.627	0.624
96	C4M a-h	0.559	0.540	0.523	0.550	0.564	0.561	0.553	0.586	0.556	0.555
99	C4M i-p	0.545	0.552	0.530	0.517	0.547	0.531	0.542	0.560	0.544	0.541
121	C5M a-h	0.521	0.566	0.541	0.528	0.557	0.554	0.557	0.571	0.555	0.549
124	C5M i-p	0.526	0.552	0.562	0.571	0.559	0.556	0.573	0.613	0.561	0.564
146	C6M a-h	0.573	0.556	0.534	0.571	0.568	0.551	0.568	0.582	0.568	0.563
154	C6M i-p	0.556	0.566	0.561	0.569	0.542	0.535	0.530	0.570	0.559	0.554
		E2	E2	E2	E2	E2	E2	E2	E2	Median	Average
21	C1M a-h	0.444	0.417	0.421	0.419	0.417	0.426	0.429	0.450	0.424	0.428
24	C1M i-p	0.395	0.424	0.408	0.398	0.438	0.394	0.423	0.428	0.415	0.413
46	C2M a-h	0.416	0.411	0.410	0.368	0.399	0.434	0.393	0.437	0.411	0.409
49	C2M i-p	0.420	0.405	0.411	0.437	0.417	0.415	0.402	0.419	0.416	0.416
71	C3M a-h	0.350	0.357	0.381	0.364	0.345	0.341	0.348	0.370	0.353	0.357
74	C3M i-p	0.361	0.359	0.354	0.373	0.403	0.382	0.399	0.372	0.372	0.375
96	C4M a-h	0.440	0.459	0.476	0.449	0.435	0.438	0.446	0.413	0.443	0.444
99	C4M i-p	0.454	0.447	0.469	0.482	0.452	0.468	0.457	0.439	0.455	0.458
121	C5M a-h	0.478	0.43	0.458	0.471	0.442	0.445	0.442	0.428	0.444	0.450
124	C5M i-p	0.473	0.447	0.437	0.428	0.440	0.443	0.426	0.386	0.438	0.435
146	C6M a-h	0.426	0.443	0.465	0.428	0.431	0.448	0.431	0.417	0.431	0.436
154	C6M a-p	0.443	0.433	0.438	0.430	0.457	0.464	0.469	0.429	0.440	0.445

Piotrowski and Kraus, 1997; Boyce and Eyles, 2000; van der Meer et al., 2003; Larsen et al., 2004, 2007; Piotrowski et al., 2004, 2006; Evans et al., 2006; Meriano and Eyles, 2009; Evans, 2018). The focusing of deformation into this water-saturated mobile layer would have effectively switched off deformation at a deeper level within the bed. As a consequence of this progressive till accretion-deformation, the relative age of subglacial shearing beneath the OPIS would be diachronous, becoming progressively younger toward the top of the bed. The observed vertical variation in the relative intensity of the shear fabrics (S2 to S4; Figs. 13 and 15) may therefore be interpreted as recording changes in the magnitude of the cumulative strain being recorded by the till during this accretion-deformation process (Fig. 17c) (cf. Larsen et al., 2004). The

variation in fabric strength may reflect the degree of coupling between the ice and the underlying bed; the greater the fabric intensity the higher the degree of ice-bed coupling and transmission of shear into the bed.

Preliminary estimates of the shear strains involved are low (<15; Fig. 14b) indicating that the amount of shear being transmitted into the bed of the OPIS was relatively small (cf. Larsen et al., 2006; Narloch et al., 2012; Phillips et al., 2013). Consequently, fast flow of this ice stream would have been largely accommodated by either basal sliding and/or flow deformation within a weak, water-saturated layer located at the top of the accreting till sequence (Evans et al., 2006; Phillips et al., 2013; Spagnolo et al., 2016). Evidence of the latter is potentially provided by the rotational turbate

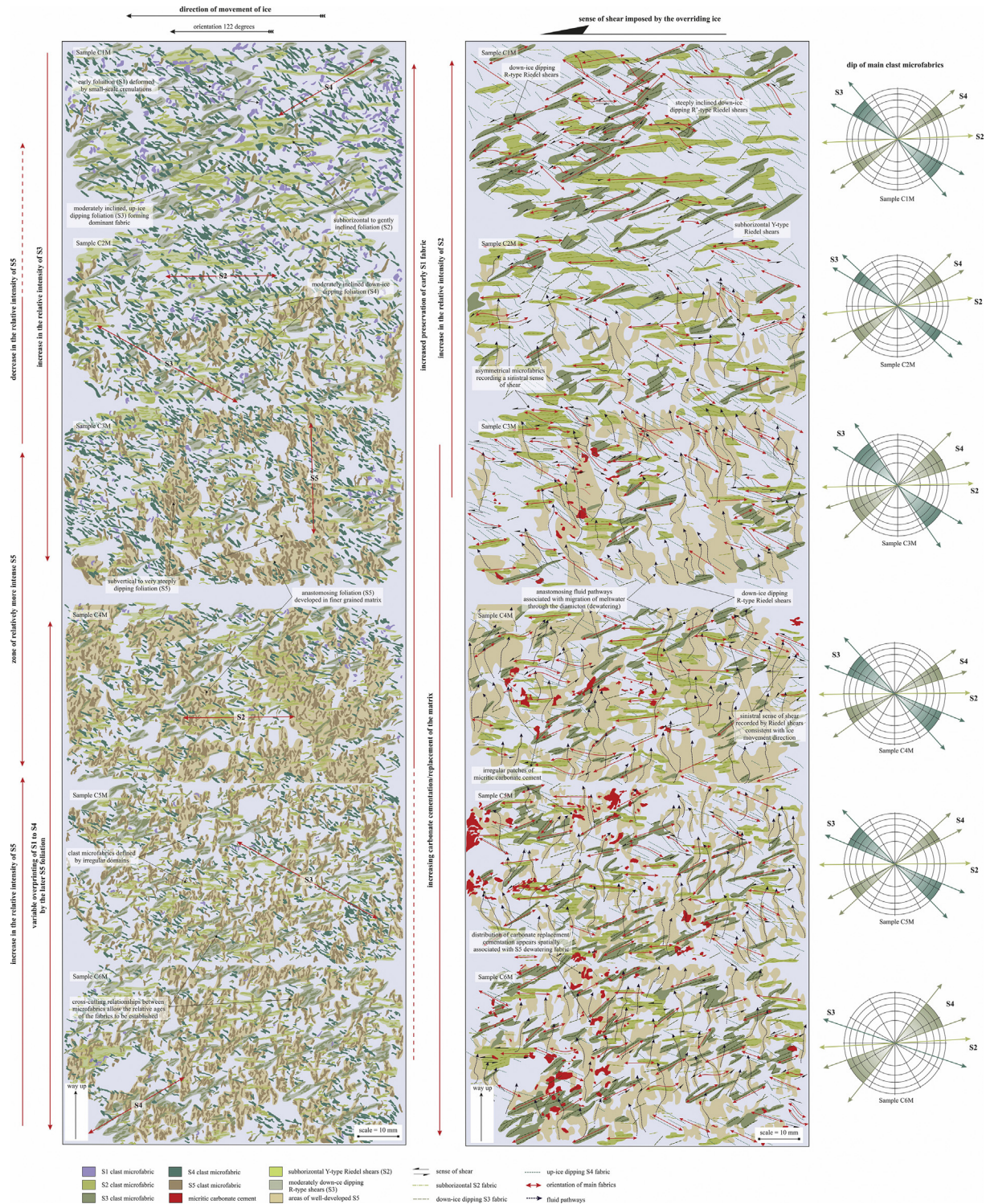


Fig. 15. Diagram showing the variation in clast microfabric development at site C.

structures (van der Meer, 1993, 1997; Menzies, 2000; Hiemstra and Rijdsdijk, 2003). These structures are truncated by the shear fabrics, indicating that rotational deformation occurred prior to foliation development within the OPIS till. Turbate structures form where larger clasts are able to rotate through angles of up to, or >360°, entraining the adjacent finer grained matrix (van der Meer, 1993; Menzies, 2000; Lachniet et al., 2001; Hiemstra and Rijdsdijk, 2003; Phillips, 2006; Lea and Palmer, 2014). This requires either very high

shear strains or the lowering of the strength of the sediment enabling clast rotation at the much lower strains (Evans et al., 2006), the latter being more likely due to the very low shear strain estimates obtained for the OPIS till. The presence of an active layer at the top of the bed would have markedly reduced or even prevented transmission of the shear into the underlying till. Furthermore, this layer is likely to have been highly mobile, facilitating the advection of well-mixed, far-travelled sediment down-

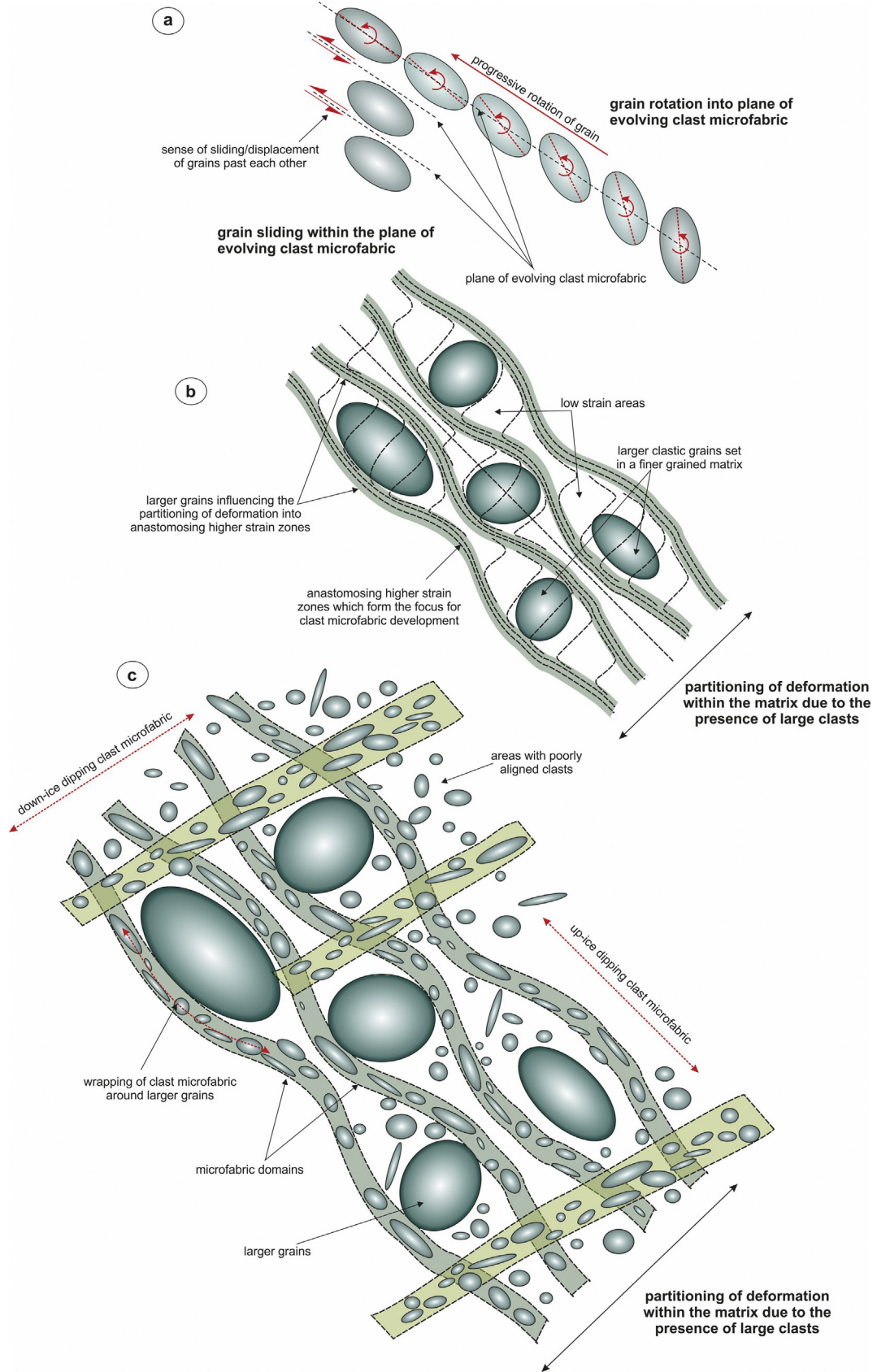


Fig. 16. (a) Cartoon showing the passive rotation of elongate clasts into the plane of the developing microfabric. Further deformation of clasts aligned within this fabric is thought to occur in response to grain sliding; (b) Strain field diagram modified from Bell et al. (1986) used here to show the proposed geometry of the strain field formed in response to the presence of large immobile clasts within a weaker deforming matrix; and (c) Schematic diagram showing the development of anastomosing clast microfibrils within a till defined by the preferred shape alignment of finer grained clasts. The spacing of the microfabric domains is controlled by the grain size and spacing of the larger sand to pebble sized clasts in response to deformation partitioning within the till.

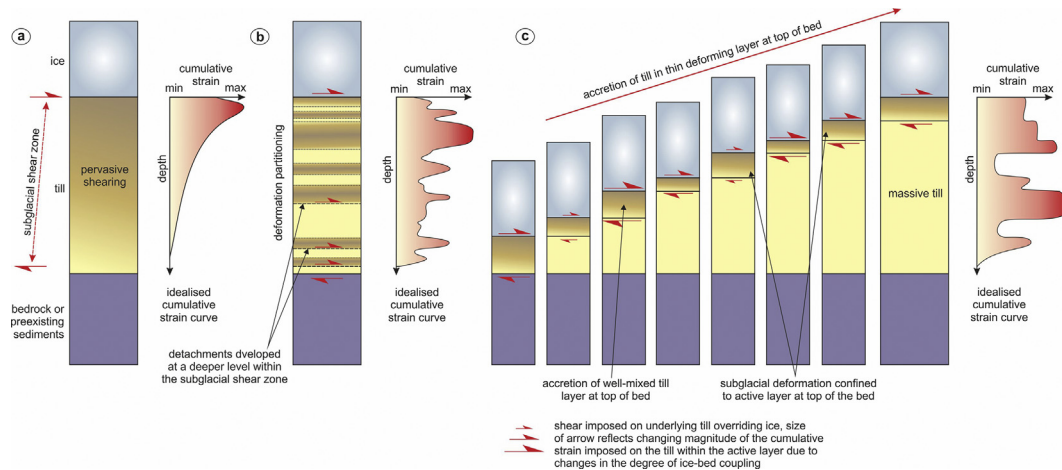


Fig. 17. Schematic profiles through the bed of a glacier and the resulting idealised cumulative strain curves: (a) Pervasive deformation throughout the subglacial shear zone with the amount of strain increasing upwards towards the ice-bed interface; (b) Deformation partitioning within the subglacial shear zone with localised detachments forming at deeper levels within the bed; and (c) Deformation confined to the “active” layer located at the top of the bed with shearing migrating upwards keeping pace with till accretion (cf. Larsen et al., 2004).

ice and the continuous accretion of till at the top of a shallow deforming bed (Spagnolo et al., 2016). Spatial and temporal fluctuations in the water content within this active layer will have affected the degree of ice-bed coupling, leading to the observed complex pattern of cumulative strain (Figs. 13–15).

Microtextural evidence (sections 5 and 6) indicates dewatering, consolidation and cementation of the OPIS till. These processes could have led to an increase in the shear strength of the till potentially resulting in the increased “stabilisation” of the sediment within the cores of the MSGL as they grew beneath the OPIS. Till consolidation or the presence of a relatively hard/stiff core has been invoked in the initiation of some subglacial landforms (e.g. Menzies and Brand, 2007; Menzies et al., 2016), although this concept is challenged by the regular spatial distribution of these landforms (e.g. Spagnolo et al., 2016). In specific case presented here, the results suggest that till consolidation may have been initiated at a lower level within the MSGL whilst till deformation and accretion continued above (see sections 6.3. and 6.4), thus providing no support for the idea that a stiffened core is required for MSGL initiation.

Although it is acknowledged that the detailed micromorphological/microstructural study presented here has largely focused upon a single site (site C), the results are applicable to the wider footprint of the OPIS as well as other contemporary and palaeo-ice streams. Deformation beneath glaciers and ice sheets is widely viewed as being dominated by simple shear within a subglacial shear zone (e.g. van der Wateren et al., 2000; Hart and Boulton, 1991; Lee and Phillips, 2008; Benn and Evans 2010). The style of deformation identified within the bed of the OPIS is consistent with this assumption, with comparable microscale shear fabrics being recognised in subglacial traction tills (sensu Evans et al., 2006) from other glaciated terrains (e.g. Germany - van der Wateren et al., 2000; England (Norfolk) - Vaughan-Hirsh et al., 2013; British Columbia, Canada - Neudorf et al., 2013; Central Poland - Narloch et al., 2012, 2013; Baltic Coast, northern Germany - Brumme, 2015; Gehrmann et al., 2017; Scotland - Phillips et al., 2011, 2018; Switzerland - Phillips et al., 2013). In structural geology, Pumpelly’s rule states that small deformation structures are a key to understanding the structural evolution of an area as they mimic the styles and orientations of a larger-scale structures of the same generation. Consequently, the geometry and the relationships displayed between the range of microscale (and macro-) structures found

within subglacially deformed sediments can not only be used to establish the overall stress regime responsible for deformation (e.g. van der Wateren et al., 2000; Vaughan-Hirsh et al., 2013; Gehrmann et al., 2017), but also aid in the reconstruction of the regional pattern of ice movement (e.g. Brumme, 2015). The bed of the OPIS across the Wielkopolska Lowland region is very gently undulating (Fig. 1c) (Przybylski, 2008; Spagnolo et al., 2016) and can, in general, be considered by an essentially subhorizontal ductile-brittle shear zone. The thick (c. 30 m) sequence of Quaternary sediments which blanket the area result in an absence of any major bedrock highs which would have imposed significant changes on the stress regime active within the bed of this palaeo-ice stream. Furthermore, gravel to cobble-sized clasts, which would have locally influenced (modified) microscale fabric development, are rare with the OPIS till. Consequently, the proposed model of progressive ductile shearing during till accretion is considered to be applicable across the bed of the Odra palaeo-ice stream with changes in microfabric geometry reflecting local changes in the physical properties of the sediment (e.g. grain size, porewater content) during fast ice flow.

7. Conclusions

The detailed microstructural study of the thick subglacial traction till formed within the bed of the Weichselian Odra palaeo-ice stream contributes to our understanding of the deformation processes occurring within its bed and it how it evolved over time.

- The massive, compositionally homogenous nature of the till indicates that the sediment being accreted to the bed was well-mixed and included far travelled material derived from Palaeozoic rocks of the Baltic Basin and crystalline basement of Scandinavian, consistent with the till being laid down by ice advancing from the NE.
- Deformation within the bed of the ice stream was dominated by foliation development (S1 to S5) recording progressive ductile shearing within a subhorizontal subglacial shear zone. Cross-cutting relationships displayed by these shear fabrics (S2, S3 and S4) reflect temporal changes in the style of deformation being accommodated within the till during a single progressive shear event as the till accreted vertically. Kinematic indicators (S-C and ECC-type microfabrics) within the till record a

consistent SE-directed (sinistral) sense of shear coincident with the regional pattern of ice flow across the Wielkopolska Lowland.

- The clast microfabrics reflect the stress field imposed by the overriding ice and form as a result of the passive rotation of detrital grains into the plane of the developing foliation(s). Larger clasts (pebbles, cobbles) become “locked” into position at an earlier stage within the deformation history and with subsequent shear being partitioned into the matrix of the till. These larger clasts then control the partitioning of deformation within the till and the spacing of the evolving microfabric domains.
- Evidence of intergranular pore water flowing through the bed of the OPIS is provided by the presence of clay-filled pore spaces within the till matrix having potentially occurred during or shortly after deposition. Further evidence of fluid flow through the bed is provided by the anastomosing, subvertical S5 fabric which formed in response to the dewatering and consolidation of the till in response to deposition from the deforming layer and final shutdown of the ice stream. Dewatering of the bed was accompanied by the growth of diagenetic micritic carbonate indicating that the escaping fluid contained dissolved CaCO_3 derived from the dissolution of detrital limestone.
- Bed deformation beneath the OPIS occurred in response to incremental progressive simple shear during till accretion. The relative age of deformation was diachronous (younger towards the top of the bed) as a thin deforming layer migrated progressively upwards in response to till accretion at the top of the ice stream bed. Focusing of deformation into this “active” layer or “transient mobile zone” effectively switched off deformation deeper within the bed. Variations in the relatively intensity of the microfabrics may record changes in the magnitude of the cumulative strain being imposed on the till during this accretion-deformation process and the degree of coupling between the ice and the underlying bed. Preliminary estimates of the shear strains involved are low, indicating that the amount of shear being transmitted into the bed of the OPIS was relatively small. This has implications for the mechanism responsible for the forward motion of this palaeo-ice stream.

Acknowledgements

The authors would like to thank various colleagues for numerous discussions on the nature of glacier bed deformation over the years, in particular Dave Evans, Jaap van der Meer, Jonathan Lee, Clive Auton, Jon Merritt, Chris Clark, Chris Stokes, Wojciech Wysota, Iza Szuman and Adriano Ribolini. Adrian Palmer (Royal Holloway University of London) is thanked for his expertise in making the thin sections. David J.A. Evans and one anonymous reviewer are thanked for their constructive reviews of this paper. ERP publishes with the permission of the Executive Director of the British Geological Survey, Natural Environment Research Council. The sampling and thin section preparation was funded by the NERC NE/J004766/1 grant awarded to MS.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.quascirev.2018.06.009>.

References

- Alley, R.B., 1989. Water pressure coupling of sliding and bed deformation: 1. Water system. *J. Glaciol.* 35, 108–118.
- Alley, R.B., Blankenship, D.D., Bentley, C.R., Rooney, S.T., 1986. Deformation of till beneath ice stream B, West Antarctica. *Nature* 322, 57–59.
- Alley, R.B., Blankenship, D.D., Bentley, C.R., Rooney, S.T., 1987a. Till beneath ice

stream B: 3. Till deformation: evidence and implications. *J. Geophys. Res.* 92, 8921–8929.

- Alley, R.B., Blankenship, D.D., Rooney, S.T., Bentley, C.R., 1987b. Till beneath ice stream B: 4. A coupled ice-till flow model. *J. Geophys. Res.* 92, 8931–8940.
- Bamber, J.L., Vaughan, D.G., Joughin, I., 2000. Widespread complex flow in the interior of the Antarctic ice sheet. *Science* 287, 1248–1250.
- Baroni, C., Fasano, F., 2006. Micromorphological evidence of warm-based glacier deposition from the Ricker hills tillite (Victoria Land, Antarctica). *Quat. Sci. Rev.* 25, 976–992.
- Bell, T.H., 1985. Deformation partitioning and porphyroblast rotation in metamorphic rocks: a radical reinterpretation. *J. Metamorph. Geol.* 3, 109–118.
- Bell, T.H., Rubenach, M.J., 1983. Sequential porphyroblast growth and crenulation cleavage development during progressive deformation. *Tectonophysics* 92, 171–194.
- Bell, T.H., Rubenach, M.J., Fleming, P.D., 1986. Porphyroblast nucleation, growth and dissolution in regional metamorphic rocks as a function of deformation partitioning during foliation development. *J. Metamorph. Geol.* 4, 37–67.
- Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. *Earth Sci. Rev.* 61, 309–339.
- Benn, D.I., Evans, D.J.A., 2010. *Glaciers and Glaciation*. Hodder, London.
- Bingham, R.G., Vaughan, D.G., King, E.C., Davies, D., Cornford, S.L., Smith, A.M., Arthern, R.J., Brisbourne, A.M., Rydt, J., Graham, A.G., Spagnolo, M., 2017. Diverse landscapes beneath Pine Island Glacier influence ice flow. *Nat. Commun.* 8, 1618.
- Boulton, G.S., 1996. Theory of glacial erosion, transport and deposition as a consequence of subglacial deformation. *J. Glaciol.* 42, 43–62.
- Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and geological consequences. *J. Geophys. Res.* 92, 9059–9082.
- Boulton, G.S., Dobbie, K.E., Zatzepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quat. Int.* 86, 3–28.
- Boyce, J.I., Eyles, N., 2000. Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. *Bull. Geol. Soc. Am.* 112, 98–118.
- Brumme, J., 2015. Three-dimensional Microfabric Analyses of Pleistocene Tills from the Cliff Section Dwasieden on Rügen (Baltic Sea Coast): Micromorphological Evidence for Subglacial Polyphase Deformation. PhD thesis. Ernst-Moritz-Arndt-Universität, Greifswald, 210pp.
- Clarke, G.K.C., 1987. Subglacial till: a physical framework for its properties and processes. *J. Geophys. Res.* 92, 9023–9036.
- O Cofaigh, C., Evans, J., Dowdeswell, J.A., Larter, R., 2007. Till characteristics, genesis and transport beneath Antarctic paleo-ice streams. *J. Geophys. Res.* 112, F03006.
- Cuffey, K.M., Paterson, W.S.B., 2010. *The Physics of Glaciers* Fourth Edition. Academic Press, Oxford.
- Denis, M., Guiraud, M., Konaté, M., Buoncristiani, J.-F., 2010. Subglacial deformation and water-pressure cycles as a key for understanding ice stream dynamics: evidence from the Late Ordovician succession of the Djado Basin (Niger). *Int. J. Earth Sci.* 99, 1399–1425.
- Dyke, A.S., Morris, T.F., 1988. Drumlin fields, dispersal trains, and ice streams in Arctic Canada. *Can. Geogr.* 32, 86–90.
- Evans, D.J.A., 2018. *Till: a Glacial Process Sedimentology*. John Wiley and Sons Ltd, UK.
- Evans, D.J., Phillips, E.R., Hiemstra, J.F., Auton, C.A., 2006. Subglacial till: formation, sedimentary characteristics and classification. *Earth Sci. Rev.* 78, 115–176.
- Evans, D.J.A., Roberts, D.H., Evans, S.C., 2016. Multiple subglacial till deposition: a modern exemplar for Quaternary palaeoglaciology. *Quat. Sci. Rev.* 145, 183–203.
- Fairchild, I.J., Bradby, L., Spiro, B., 1993. Carbonate diagenesis in ice. *Geology* 21, 901–904.
- Fairchild, I.J., Bradby, L., Spiro, B., 1994. Reactive carbonate in glacial systems: a preliminary synthesis of its creation, dissolution and reincarnation. In: Deymoux, M., Miller, J.M.G., Domack, E.W., Young, G.M. (Eds.), *International Geological Correlation Project 260: Earth's Glacial Record*. Cambridge University Press, pp. 176–192.
- Fuller, S., Murray, T., 2002. Sedimentological investigations in the forefield of an Icelandic surge-type glacier: implications for the surge mechanism. *Quat. Sci. Rev.* 21, 1503–1520.
- Gehrmann, A., Hüneke, H., Meschede, M., Phillips, E., 2017. 3D microstructural architecture of deformed glacial sediments associated with large-scale glaci-tectonism, Jasmund Peninsula (NE Rügen), Germany. *J. Quat. Sci.* 32, 213–230. <https://doi.org/10.1002/jqs.2843>.
- Hart, J.K., Boulton, G.S., 1991. The interrelation of glaciotectionic and glaciodepositional processes within the glacial environment. *Quat. Sci. Rev.* 10, 335–350.
- Hiemstra, J.F., Rijdsdijk, K.F., 2003. Observing artificially induced strain: implications for subglacial deformation. *J. Quat. Sci.* 18, 373–383.
- Hiemstra, J.F., van der Meer, J.J.M., 1997. Pore-water controlled grain fracturing as an indicator for subglacial shearing in tills. *J. Glaciol.* 43, 446–454.
- Hiemstra, J.F., Rijdsdijk, K.F., Evans, D.J.A., van der Meer, J.J.M., 2005. Integrated micro- and macro-scale analyses of last glacial maximum Irish sea diamicts from Abermaw and treath y Mwnt, Wales, UK. *Boreas* 34, 61–74.
- Hindmarsh, R.C.A., 1998. The stability of a viscous till sheet coupled with ice flow, considered at wavelengths less than the ice thickness. *J. Glaciol.* 44, 285–292.
- Hindmarsh, R.C., 2009. Consistent generation of ice-streams via thermo-viscous instabilities modulated by membrane stresses. *Geophys. Res. Lett.* 36 (6).
- Hodgson, D.A., 1994. Episodic ice streams and ice shelves during retreat of the northwestern most sector of the Late Wisconsinan Laurentide Ice Sheet over the central Canadian Arctic archipelago. *Boreas* 23, 14–28.

- Humphrey, N., Kamb, B., Fahnestock, M., Engelhardt, H., 1993. Characteristics of the bed of the lower Columbia glacier, Alaska. *J. Geophys. Res.* 98, 837–846.
- Iverson, N.R., 2011. Shear resistance and continuity of subglacial till: hydrology rules. *J. Glaciol.* 56, 1104–1114.
- Iverson, N.R., Hooyer, T.S., Baker, R.W., 1998. Ring-shear studies of till deformation: coulomb-plastic behaviour and distributed strain in glacier beds. *J. Glaciol.* 44, 634–642.
- Johnson, S.E., 1990. Lack of porphyroblast rotation in the Otago schists, New Zealand: implications for crenulation cleavage development, folding and deformation partitioning. *J. Metamorph. Geol.* 8, 13–30.
- Khatwa, A., Tulaczyk, S., 2001. Microstructural interpretations of modern and Pleistocene subglacially deformed sediments: the relative role of parent material and subglacial processes. *J. Quat. Sci.* 16, 507–517.
- King, E.C., Hindmarsh, R.C., Stokes, C.R., 2009. Formation of mega-scale glacial lineations observed beneath a West Antarctic. *Nat. Geosci.* 2, 585–588.
- Kjaer, K.H., Houmark-Nielsen, M., Richardt, N., 2003. Ice-flow patterns and dispersal of erratics at the southwestern margin of the last Scandinavian Ice Sheet: signature of palaeo-ice streams. *Boreas* 32, 130–148.
- Kjaer, K.H., Larsen, E., van der Meer, J.J.M., Ingólfsson, Ó., Krüger, J., Benediktsson, I.O., Knudsen, C.G., Schomacker, A., 2006. Subglacial decoupling at the sediment/bedrock interface: a new mechanism for rapid flowing ice. *Quat. Sci. Rev.* 25, 2704–2712.
- Kozarski, S., 1988. Time and dynamics of the last Scandinavian ice-sheet retreat from northwestern Poland. *Geographica Polonica* 55, 91–101.
- Kyrke-Smith, T.M., Katz, R.F., Fowler, A.C., 2015. Subglacial hydrology as a control on emergence, scale, and spacing of ice streams. *J. Geophys. Res.: Earth Surface* 120, 1501–1514.
- Lachniet, M.S., Larson, G.J., Lawson, D.E., Evenson, E.B., Alley, R.B., 2001. Microstructures of sediment flow deposits and subglacial sediments: a comparison. *Boreas* 30, 254–262.
- Larsen, N.K., Piotrowski, J.A., Kronborg, C., 2004. A multiproxy study of a basal till: a time-transgressive accretion and deformation hypothesis. *J. Quat. Sci.* 19, 9–21.
- Larsen, N.K., Piotrowski, J.A., Christiansen, F., 2006. Microstructures and microshears as proxy for strain in subglacial diamicts: implications for basal till formation. *Geology* 34, 889–892.
- Larsen, N.K., Piotrowski, J.A., Menzies, J., 2007. Microstructural evidence of low-strain, time transgressive subglacial deformation. *J. Quat. Sci.* 22, 593–608.
- Lea, J.M., Palmer, A., 2014. Quantification of turbate microstructures through a subglacial till: dimensions and characteristics. *Boreas*. <https://doi.org/10.1111/bor.12073>. ISSN 0300–9483.
- Lee, J.R., Phillips, E.R., 2008. Progressive soft sediment deformation within a subglacial shear zone – a hybrid mosaic-pervasive deformation model for Middle Pleistocene glaciotectionised sediments from eastern England. *Quat. Sci. Rev.* 27, 1350–1362.
- Leighton, I.D., Hiemstra, J.F., Weidman, C.T., 2012. Recognition of micro-scale deformation structures in glacial sediments – pattern perception, observer bias and the influence of experience. *Boreas*. <https://doi.org/10.1111/j.1502-3885.2011.00246.x>. ISSN 0300–9483.
- Margold, M., Stokes, C.R., Clark, C.D., 2015. Ice streams in the Laurentide ice sheet: identification, characteristics and comparison to modern ice sheets. *Earth Sci. Rev.* 143, 117–146.
- Marks, L., 2012. Timing of the late vistulian (weichselian) glacial phases in Poland. *Quat. Sci. Rev.* 44, 81–88.
- McGillen, M.R., Fairchild, I.J., 2005. An experimental study of incongruent dissolution of CaCO₃ under analogue glacial conditions. *J. Glaciol.* 51, 383–390.
- Menzies, J., 1982. Till hummock (proto-drumlin) at the ice glacier bed interface. In: Davidson-Arnott, R., Nickling, W., Fahey, B.D. (Eds.), *Research in Glacial, Glaciofluvial and Glacio-lacustrine Systems*. Proceedings of the 6th Guelph Symposium on Geomorphology, pp. 33–47.
- Menzies, J., 2000. Micromorphological analyses of microfibrils and microstructures indicative of deformation processes in glacial sediments. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), *Deformation of Glacial Materials*. Geological Society of London, vol 176, pp. 245–257. Special Publication.
- Menzies, J., 2012. Strain pathways, till internal architecture and microstructures – perspectives on a general kinematic model – a ‘blueprint’ for till development. *Quat. Sci. Rev.* 50, 105–124.
- Menzies, J., Brand, U., 2007. The internal sediment architecture of a drumlin, Port Byron, New York State, USA. *Quaternary Science Reviews* 26, 322–335.
- Menzies, J., Maltman, A.J., 1992. Microstructures in diamictites - evidence of subglacial bed conditions. *Geomorphology* 6, 27–40.
- Menzies, J., Zaniewski, K., Dreger, D., 1997. Evidence from microstructures of deformable bed conditions within drumlins, Chimney Bluffs, New York State. *Sediment. Geol.* 111, 161–175.
- Menzies, J., van der Meer, J.J.M., Rose, J., 2006. Till – a glacial “tectonict”, a microscopic examination of a till’s internal architecture. *Geomorphology* 75, 172–200.
- Menzies, J., Hess, D.P., Rice, J.M., Wagner, K.G., Ravier, E., 2016. A case study in the New York Drumlin Field, an investigation using microsedimentology, resulting in the refinement of a theory of drumlin formation. *Sediment. Geol.* 338, 84–96.
- Meriano, M., Eyles, N., 2009. Quantitative assessment of the hydraulic role of subglaciofluvial interbeds in promoting deposition of deformation till (Northern Till, Ontario). *Quat. Sci. Rev.* 28, 608–620.
- Narloch, W., Piotrowski, J.A., Wysota, W., Larsen, N.K., Menzies, J., 2012. The signature of strain magnitude in tills associated with the vistula ice stream of the scandinavian ice sheet, central Poland. *Quat. Sci. Rev.* 57, 105–120.
- Narloch, W., Wysota, W., Piotrowski, J.A., 2013. Sedimentological record of subglacial conditions and ice sheet dynamics of the Vistula Ice Stream (north-central Poland) during the Last Glaciation. *Sediment. Geol.* 293, 30–44.
- Neudorf, C.M., Brennand, T.A., Lian, O.B., 2013. Till-forming processes beneath parts of the Cordilleran Ice Sheet, British Columbia, Canada: macroscale and microscale evidence and a new statistical technique for analysing microstructure data. *Boreas*. <https://doi.org/10.1111/bor.12009>. ISSN 0300–9483.
- Palmer, A.P., 2005. *The Micromorphological Description, Interpretation and Palaeoenvironmental Significance of Lacustrine Clastic Laminated Sediments*. Unpublished PhD thesis. University of London.
- Passchier, C.W., Trouw, R.A.J., 1996. *Microtectonics*. Springer.
- Patterson, C.J., 1997. Southern Laurentide ice lobes were created by ice streams: des Moines Lobe in Minnesota, USA. *Sediment. Geol.* 111, 249–261.
- Patterson, C.J., 1998. Laurentide glacial landscapes: the role of ice streams. *Geology* 26, 643–646.
- Phillips, E.R., 2006. Micromorphology of a debris flow deposit: evidence of basal shearing, hydrofracturing, liquefaction and rotational deformation during emplacement. *Quat. Sci. Rev.* 25, 720–738.
- Phillips, E.R., Auton, C.A., 2000. Micromorphological evidence for polyphase deformation of glaciolacustrine sediments from Strathspey, Scotland. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), *Deformation of Glacial Materials*. The Geological Society of London, vol 176, pp. 279–291. Special Publication.
- Phillips, E.R., Auton, C.A., 2008. Microtextural analysis of a glacially ‘deformed’ bedrock: implications for inheritance of preferred clast orientations in diamictites. *J. Quat. Sci.* 23, 229–240.
- Phillips, E., Merritt, J., 2008. Evidence for multiphase water-escape during rafting of shelly marine sediments at Clava, Inverness-shire, NE Scotland. *Quat. Sci. Rev.* 27, 988–1011.
- Phillips, E., Merritt, J.W., Auton, C.A., Gollidge, N.R., 2007. Microstructures developed in subglacially and proglacially deformed sediments: faults, folds and fabrics, and the influence of water on the style of deformation. *Quat. Sci. Rev.* 26, 1499–1528.
- Phillips, E.R., van der Meer, J.J.M., Ferguson, A., 2011. A new ‘microstructural mapping’ methodology for the identification and analysis of microfibrils within glacial sediments. *Quat. Sci. Rev.* 30, 2570–2596.
- Phillips, E., Everest, J., Reeves, H., 2013a. Micromorphological evidence for subglacial multiphase sedimentation and deformation during overpressurized fluid flow associated with hydrofracturing. *Boreas* 42, 395–427.
- Phillips, E.R., Lipka, E., van der Meer, J.J.M., 2013b. Micromorphological evidence of liquefaction and sediment deposition during basal sliding of glaciers. *Quat. Sci. Rev.* 81, 114–137.
- Phillips, E., Evans, D.J.A., van der Meer, J.J.M., Lee, J.R., 2018. Microscale evidence of liquefaction and its potential triggers during soft-bed deformation within subglacial traction tills. *Quat. Sci. Rev.* 181, 123–143.
- Piotrowski, J.A., 1994a. In: Warren, W.P., Croot, D. (Eds.), *Formation and Deformation of Glacial Deposits*. Balkema, Rotterdam, pp. 3–8.
- Piotrowski, J.A., 1994b. Tunnel-valley formation in northwest Germany—geology, mechanisms of formation and subglacial bed conditions for the Bornhöved Tunnel Valley. *Sediment. Geol.* 89, 107–141.
- Piotrowski, J.A., Kraus, A.M., 1997. Response of sediment to ice sheet loading in northwestern Germany: effective stresses and glacier bed stability. *J. Glaciol.* 43, 495–502.
- Piotrowski, J.A., Tulaczyk, S., 1999. Subglacial conditions under the last ice sheet in northwest Germany: ice-bed separation and enhanced basal sliding? *Quat. Sci. Rev.* 18, 737–751.
- Piotrowski, J.A., Mickelson, D.M., Tulaczyk, S., Krzyszkowski, D., Junge, F., 2001. Were subglacial deforming beds beneath past ice sheets really widespread? *Quat. Int.* 86, 139–150.
- Piotrowski, J.A., Larsen, N.K., Junge, F., 2004. Soft subglacial beds: a mosaic of deforming and stable spots. *Quat. Sci. Rev.* 23, 993–1000.
- Piotrowski, J.A., Larsen, N.K., Menzies, J., Wysota, W., 2006. Formation of subglacial till under transient bed conditions: deposition, deformation, and basal decoupling under a Weichselian ice sheet lobe, central Poland. *Sedimentology* 53, 83–106.
- Przybylski, B., 2008. Geomorphic traces of a Weichselian ice stream in the Wielkopolska Lowland, western Poland. *Boreas* 37, 286–296.
- Spagnolo, M., Clark, C.D., Ely, J.C., Stokes, C.R., Anderson, J.B., Andreassen, K., Graham, A.G.C., King, E.C., 2014. Size, shape and spatial arrangement of mega-scale glacial lineations. *Earth Surf. Process. Landforms* 39, 1432–1448.
- Spagnolo, M., Phillips, E., Piotrowski, J.A., Rea, B.R., Clark, C.D., Stokes, C.R., Carr, S.J., Ely, J.C., Adriano Ribolini, A., Wysota, W., Izabela Szuman, I., 2016. Ice stream motion facilitated by a shallow-deforming and accreting bed. *Nat. Commun.* <https://doi.org/10.1038/ncomms10723>.
- Stokes, C.R., Clark, C.D., 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Ann. Glaciol.* 28, 67–75.
- Stokes, C.R., Clark, C.D., 2001. Palaeo-ice streams. *Quat. Sci. Rev.* 20, 1437–1457.
- Stokes, C.R., Clark, C.D., 2002. Are long subglacial bedforms indicative of fast ice flow? *Boreas* 31, 239–249.
- Stokes, C.R., Clark, C.D., 2003. The Dubawnt Lake palaeo-ice stream: evidence for dynamic ice sheet behaviour on the Canadian Shield and insights regarding the controls on ice stream location and vigour. *Boreas* 32, 263–279.
- Stokes, C.R., Fowler, A.C., Clark, C.D., Hindmarsh, R.C.A., Spagnolo, M., 2013a. The instability theory of drumlin formation and its explanation of their varied composition and internal structure. *Quat. Sci. Rev.* 62, 77–96.

- Thomason, J.F., Iverson, N.R., 2006. Microfabric and micro-shear evolution in deformed till. *Quat. Sci. Rev.* 25, 1027–1038.
- Truffer, M., Harrison, W.D., Echelmeyer, K.A., 2000. Glacier motion dominated by processes deep in underlying till. *J. Glaciol.* 46, 213e221. <https://doi.org/10.3189/172756500781832909>.
- Tulaczyk, S., 1999. Ice sliding over weak, fine-grained tills: dependence of ice-till interactions on till granulometry. *Spec. Pap. Geol. Soc. Am.* 337, 159–177.
- Tulaczyk, S., Kamb, B., Scherer, R.P., Engelhardt, H.F., 1998. Sedimentary processes at the base of a West Antarctic ice stream: constraints from textural and compositional properties of subglacial debris. *J. Sediment. Res.* 68, 487–496.
- van der Meer, J.J.M., 1987. Micromorphology of glacial sediments as a tool in distinguishing genetic varieties of till. *Geological Survey of Finland Special Paper* 3, 77–89.
- van der Meer, J.J.M., 1993. Microscopic evidence of subglacial deformation. *Quat. Sci. Rev.* 12, 553–587.
- van der Meer, J.J.M., 1997. Particle and aggregate mobility in till: microscopic evidence of subglacial processes. *Quat. Sci. Rev.* 16, 827–831.
- van der Meer, J.J.M., Menzies, J., Rose, J., 2003. Subglacial till, the deformable glacier bed. *Quat. Sci. Rev.* 22, 1659–1685.
- van der Meer, J.J.M., Kjær, K.H., Krüger, J., Rabassa, J., Kilfeather, A.A., 2009. Under pressure: clastic dykes in glacial settings. *Quat. Sci. Rev.* 28, 708–720.
- van der Wateren, F.M., Kluiving, S.J., Bartek, L.R., 2000. Kinematic indicators of subglacial shearing. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), *Deformation of Glacial Materials*. Geological Society of London, vol 176, pp. 259–278. Special Publication.
- Vaughan-Hirsch, D.P., Phillips, E., Lee, J.R., Hart, J.K., 2013. Micromorphological analysis of poly-phase deformation associated with the transport and emplacement of glaciotectionic rafts at West Runton, north Norfolk, UK. *Boreas* 42, 376–394.
- Vernon, R.H., 1989. Porphyroblast-matrix microstructural relationships: recent approaches and problems. In: Daly, et al. (Eds.), *Evolution of Metamorphic Belts*. Geological Society of London, vol 43, pp. 83–102. Special Publication.