Quaternary Science Reviews 193 (2018) 1–23

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

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 glaciotectonism (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 microfabrics 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.

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).

https://doi.org/10.1016/j.quascirev.2018.06.009
0277-3791/

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 glacitectonic 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; Gehrmann 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 glacigenic 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 microfabrics 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 km^2) is characterised by a suite of well-preserved NW-SE-trending megascale glacial lineations (MSGL) 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 km^2) is dominated by a suite of elongate (>16 km long), low-relief (2–4 m high) MSGL 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 glacifluvial 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 MSGL described from other palaeo-ice stream settings worldwide (Spagnolo et al., 2014).

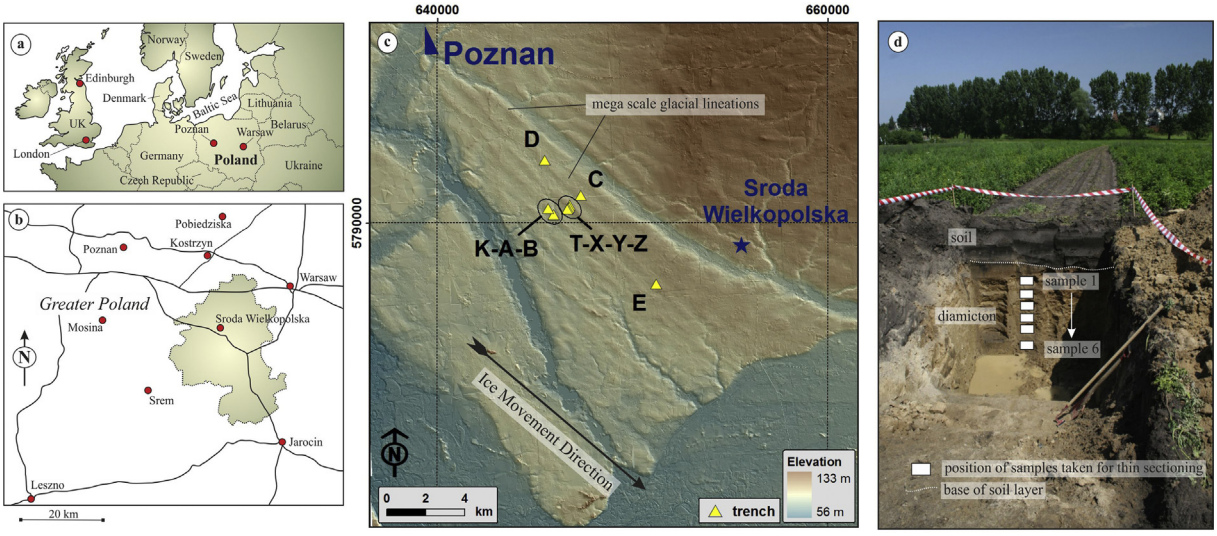

Fig. 1. **(a)** and **(b)** Maps showing the location of the study area in western Poland; **(c)** Digital Elevation Model (DEM) of the Środa Wielkopolska area showing the well-developed NW-SE-trending megascale glacial lineations and locations of the trenches excavated into these subglacial landforms. 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.