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Sedimentological record of subglacial conditions and ice sheet dynamics of the Vistula Ice Stream (north-central Poland) during the Last Glaciation

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ABSTRACT

Deposits of the Vistula Ice Stream draining the Scandinavian Ice Sheet during the Last Glaciation were investigated at four field sites in north-central Poland using micro- and macroscale features. The study reveals several till units with specific structural, textural and lithological characteristics. The individual till units are either macroscopically massive or bedded, and the contacts between the units are either sharp or transitional. The nature of the contacts with the underlying sediments, ductile deformation structures, largely undeformed clayey clasts, tectonic lamination, thin horizontal stringers of sorted sediments, ploughing marks, boulder pavements, and striated upper surfaces of pebbles in the till indicate both bed deformation and enhanced basal sliding under high subglacial water pressure conditions. It is suggested that the till is a hybrid deposit generated by some combination of lodgement, deformation and ploughing punctuated by periods of basal decoupling. The depth of deformation at any point in time was thinner (up to several decimetres) than the maximum till thickness (c. 2.5 m). The ice sliding velocity estimations indicate velocities of less than 100 to over 2000 m yr^{-1}, which suggests an unstable and highly dynamic ice lobe, consistent with spatial variability of till characteristics. Sand wedges in the deposits beneath the till and the nature of the till/bed interface indicate permafrost under the advancing ice sheet. We suggest that under the increasing ice thickness, a layer of thawed, water-saturated sediment formed on top of the still-frozen ground due to inefficient drainage, and contributed to ice streaming by promoting pervasive deformation and basal sliding.

1. Introduction

Modern-day ice sheets of Greenland and Antarctica lose their mass mainly by ice stream drainage (c. 70–90%) (Bennett, 2003). The behaviour of ice streams influences global sea level and contributes to abrupt climatic shifts (Heinrich, 1988; Oppenheimer, 1998). However, despite their profound impact on the Earth system both at present and in the past, ice streams are still poorly understood (Bennett, 2003; Winsborrow et al., 2010).

Ice streams are arteries of fast ice flow within ice sheets in which the flow velocity is orders of magnitude greater than in the surrounding ice (Echelmeyer and Harrison, 1990; Echelmeyer et al., 1991; Whillans and van der Veen, 1993; Holland et al., 2008). Ice-stream parameters such as lateral migration and changes of width (Jacobel et al., 1996; Bindschadler and Vorenberger, 1998), changes in flow velocity (including stoppage) (Retzlaff and Bentley, 1993) or changes in ice-flow directions are temporarily and spatially variable (Conway et al., 2002).

Pleistocene ice streams that terminated on land have no modern analogues (Stokes and Clark, 2001; Bennett, 2003; Jennings, 2006). They extended hundreds of kilometres beyond the main body of the ice sheet and formed lobes (e.g., Clayton et al., 1989; Colgan and Mickelson, 1997; Stokes and Clark, 2001; Mickelson and Colgan, 2004; Jennings, 2006; Thomason and Iverson, 2009). Highly lobate, palaeo-ice sheet margins are known from northern Europe (Kleman and Borgström, 1996; Punkari, 1997; Houmark-Nielsen, 2004; Johansson et al., 2011), the British Isles (Boulton and Hagdorn, 2006) and North America (Clayton et al., 1985, 1989; Mickelson and Colgan, 2004). Topography, bed lithology, geothermal heat flux, and meltwater under and in front of advancing ice sheets played an important role in the formation of ice streams (Winsborrow et al., 2010). Most studies point to elevated water pressure in subglacial sediments and along the ice–bed interface as triggers of fast ice flow (Boulton and Jones, 1979; Clayton et al., 1985; Brown et al., 1987; Clayton et al., 1989; Hicock and Fuller, 1995; Colgan and Mickelson, 1997; Lian et al., 2003; Mickelson and Colgan, 2004; Kehew et al., 2005; Boulton and Hagdorn, 2006; Jennings, 2006; Thomason and Iverson, 2009). Under warm-based ice that was generating meltwater (Paterson, 1994; Clarke, 2005; Hooke, 2005), bed deformation varied in time and space with enhanced basal sliding on top of a pressurised water layer (Piotrowski et al., 2004), which is reflected in the properties of tills formed under variable basal conditions (Piotrowski and Tulaczyk, 1999; Evans et al., 2006; Piotrowski et al., 2006; Menzies et al., 2012; Phillips et al., 2013).

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Studies of modern subglacial environments are typically conducted under warm-based glaciers (e.g., Alley et al., 1986; Iverson et al., 1995; Hart et al., 2009) and the importance of permafrost, especially in the early stages of ice overriding, has possibly been underestimated (Clarke, 2005; Evans et al., 2006; Waller et al., 2009). Accordingly, deformation models involving unfrozen bed conditions were typically applied to the reconstructions of past continental ice sheets under which such conditions did not necessarily prevail (Boulton et al., 2001b; Piotrowski et al., 2004). Some researchers have addressed the interactions between subglacial permafrost and ice sheets (e.g., Hughes, 1992; Cutler et al., 2000) and in most cases such studies were limited to narrow ice-marginal zones (Piotrowski, 2006; Waller and Murton, 2006) and specific geographical regions such as Siberia (Astakhov et al., 1996), British Isles (Waller et al., 2009) or Greenland (Waller and Murton, 2006).

This paper follows upon the pilot study by Narloch et al. (2012) that investigated the strain signature in till deposited by the Vistula Ice Stream in Poland. The aim of the present study is to further constrain subglacial processes under this palaeo-ice stream with focus on the origin of the till and ice-movement dynamics using an approach involving till sedimentology, structural geology, petrography and micromorphology from four field sites located within the outermost 130 km of the ice sheet.

2. Study area

The area covered by the Vistula ice lobe area is located in north-central Poland (Fig. 1). The southern boundary of the lobe is the maximum ice-sheet extent during Poznań (=Frankfurt) phase of the Weichselian glaciation (Wysota et al., 2009; Wysota and Molewski, 2011).

The stratigraphy of the Weichselian glaciation includes at least two till complexes deposited in the Middle and Late Weichselian. The two youngest tills in the Vistula ice lobe area are of Late Weichselian age (e.g., Marks, 2002; Wysota, 2002; Marks, 2005; Molewski, 2007; Wysota et al., 2009; Wysota and Molewski, 2011; Marks, 2012). The lower till belongs to the Leszno (=Brandenburg) phase, which reached its maximum extent about 20.5 ka BP (Fig. 1). After retreating from the area, the ice sheet re-advanced as the Vistula ice lobe during the Poznań (=Frankfurt) phase and reached its maximum 60 km to the south-east of the Leszno phase limit about 18.5 ka BP (Fig. 1) (Wysota et al., 2009; Wysota and Molewski, 2011) and this marks the terminus of the Vistula Ice Stream. This ice stream is a major land-based palaeo-ice stream of the southern Scandinavian Ice Sheet (named ice stream B3 by Stokes and Clark, 2001) fed by the Baltic Ice Stream further to the north (Punkari, 1997; Boulton et al., 2001b; Marks, 2002; Wysota, 2002; Marks, 2005; Wysota, 2007; Wysota et al., 2009).

3. Methods

We investigated the Poznań phase till together with the upper part of the underlying deposits at four field sites (Fig. 1B). The Mielnica and Obórki sites are located on either flank of the Vistula ice lobe, Nieszawa is in the centre and Kozłowo furthest up-ice. In most cases, the Poznań phase till is underlain by sand, similar to sites elsewhere in the ice stream area (e.g., Wysota, 2002; Molewski, 2007; Wysota, 2007; Wysota et al., 2009).

At each field site, sedimentary characteristics, bed contacts, facies geometry, texture and lithology of the deposits were recorded, and an up to 3.5-m-high vertical profile was selected for detailed investigations (Fig. 2). The sedimentary successions in all sites have been subdivided into units of local range (within each site): K1–K4 (Kozłowo site), M1–M4 (Mielnica site), N1–N2 (Nieszawa site) and O1–O5 (Obórki site) based on their spatial, structural and textural characteristics. Lithofacies codes of Eyles et al. (1983) were used for logging the deposits. In each profile, till segments 20 cm high and 30 cm wide separated by approximately 10 cm gaps were designated for till-fabric measurements and sampling for grain-size and lithologic analysis. In each segment, undisturbed oriented till samples were taken for thin-section production to study sediment micromorphology.

Till fabrics were determined in each segment by measuring the orientation of 35 elongated pebbles with a-axis lengths between 1 and 7 cm and a/b axes ratios of ≥1.5. The results are presented as contours on an equal-area Schmidt projection, lower hemisphere. Eigenvectors (V_1) and eigenvalues (S_1) are calculated according to Mark (1973).

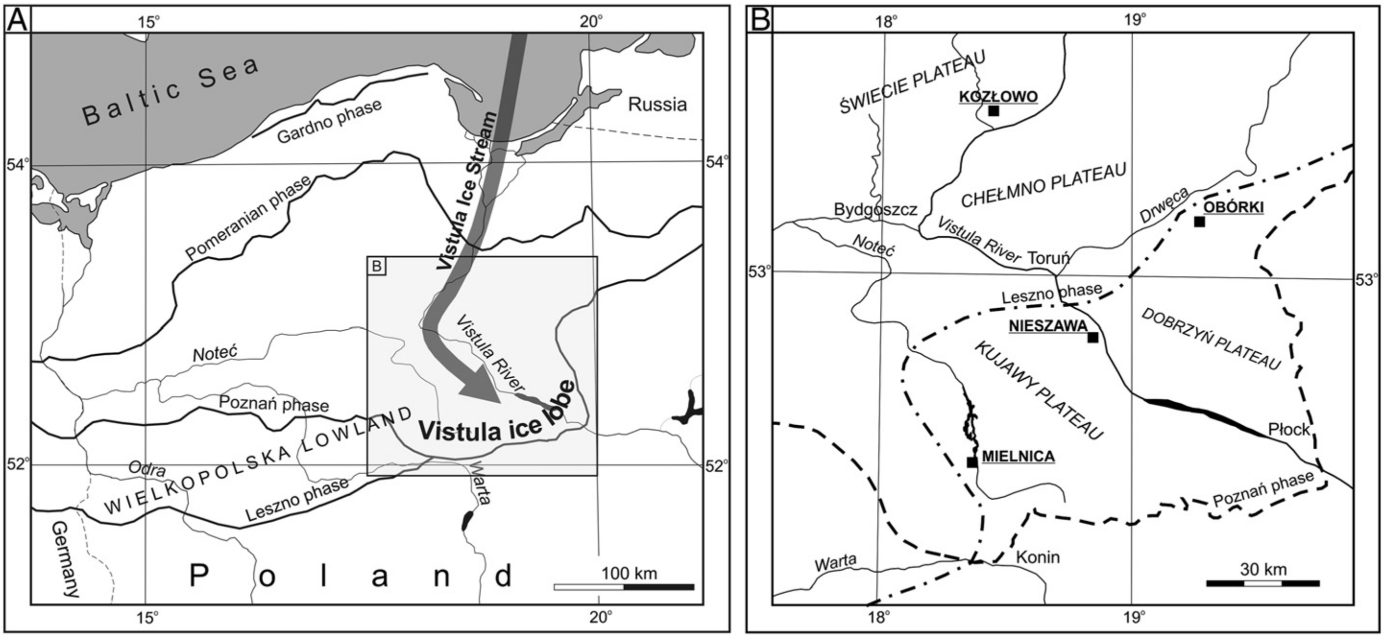

Fig. 1. Location of the study area. A — The Vistula ice lobe area and the main trunk of Vistula Ice Stream in relation to the Late Weichselian maximum ice sheet extent in north-central Poland. B — Study area and the location of field sites.