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The Late Weichselian glacial record in northern Poland: A new look at debris transport routes by the Fennoscandian Ice Sheet

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ABSTRACT

The area of the Kashubian Coastland and areas adjacent to the northern part of the Lower Vistula Valley (northern Poland) were involved in the major transgressive phases distinguished in Poland during the Late Weichselian. Due to the small scale of the regressions between the different phases of the Late Weichselian, the ice sheet usually deposited only one till, but with a complex vertical profile. Based on the studies of the directional properties, petrographic composition of the fine gravel fraction and the analysis of indicator erratics, the dichotomy of the till bed was demonstrated. The petrographic composition of the gravel fraction in tills together with the analysis of the indicator erratics and delimitation of the Theoretical Boulder Centres were used to determine the direction of the influx of ice masses. This allowed speculation on the reasons for the different dynamics of the Fennoscandian Ice Sheet (FIS) as well as the operation and time variability of the Baltic Ice Stream (BIS). It was emphasised that the delivery system of debris by the ice sheet might have been complex and multidirectional (more than one route). It has been suggested that changes in the petrographic composition of the gravel fraction of the glacial sediments did not have to be associated only with shifting the centre of glaciation, but may have resulted from a change in the thermal regime of the ice sheet's bed in the source area (especially with the spread of the cold regime zone), and depended on the dynamics of the ice sheet (stream or sheet flow) as well as the spatial and temporal conditions of its development in the deposition area.

1. Introduction

One of the key issues of the Quaternary studies in northern and central Europe is the reconstruction of thermodynamics of the Pleistocene ice sheets. It influenced the amount and type of debris retrieved in Fennoscandia and in the area occupied today by the Baltic Sea, and then transported in the ice and deposited within the range of the last glaciations. This means that based on the qualitative and quantitative characteristics of glacial deposits the directions and routes of the ice masses inflow can be reconstructed. The most suitable fraction for this purpose is gravel because it not only allows identification of the types of rocks represented by individual clasts, but in many cases a particular outcrop from which a given rock comes (in the case of indicator erratics). Knowing the origin of erratics found in glacial sediments allows tracing their presumed path to the place of deposition. Additional data is provided by textural features of glacial deposits and striae left on the bedrock. The disadvantage of the latter is that they are limited to the areas built of solid rock and document only the last advance of the ice sheet. The directions of the striae representing older advances are in most cases gradually erased by younger ice sheets.

The main factor conditioning the presence of the debris in the ice is exaration. It depends primarily on the thermodynamic conditions in the sole of the ice sheet, which most often are described in a synthetic manner by identifying their thermal regime (e.g. Payne and Baldwin, 1999; Kleman and Glasser, 2007). Including debris into basal facies of the glacial ice is possible only when the ice moves relative to the basement. The size of erosion is significantly impacted by the ice thickness, velocity of the basal sliding, debris content in the basal ice, subglacial water presence and its pressure variability, subglacial drainage and others (Embleton and King, 1975; Sugden and John, 1976; Drewry, 1986; Hildes et al., 2004; Fu and Harbor, 2011).

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Basal freezing-on (cold thermal regime) led to the cessation of erosion (cf. Jonsson, 1983; Drewry, 1986; Dyke, 1993; Kleman, 1994). However, even the ice sheets located in the polar zone, such as the Antarctic Ice Sheet, have very large areas with warm thermal regimes (Takeda et al., 2002; Pollard et al., 2005; Jamieson et al., 2010; Pattyn, 2010). Thus, spatially and temporally the Fennoscandian Ice Sheet (FIS) must have shown variable thermal regimes (cf. Kleman and Stroeven, 1997; Boulton et al., 2001; André, 2004; Kleman and Glasser, 2007).

The thermal regime of the ice sheet, together with the location of the ice divide, range and rate of movement as well as the amount of sub- and englacial water, determined the temporal variability of exaration of the substrate and the accumulation of sediment (e.g. Kleman et al., 1997). This means the possibility of varying the composition of the glacigenic sediments deposited during the subsequent FIS advances of different ranks, and even during a single advance (see Lagerlund et al., 1995; Kjær et al., 2003). This assumption is the basis of petrographic analyses of the glacigenic sediments undertaken by the authors.

In recent years, the glacier stream model of the FIS has become widespread (incl. Punkari, 1993; Boulton et al., 2001; Arnold and Sharp, 2002; Marks, 2002, 2005; Wysota, 2002; Kjær et al., 2003; Ottesen et al., 2008; Wysota et al., 2009). The development of paleo-ice streams was determined by the thermodynamic conditions in the bed, mainly driven by its relief (e.g. Payne and Baldwin, 1999; Kleman and Applegate, 2014), and the key role was played by the quantity of water at the ice-bed interface (e.g. Piotrowski and Tulaczyk, 1999; Tulaczyk et al., 2000; Christoffersen and Tulaczyk, 2003; Stearns et al., 2008; Lesemann et al., 2010; Clason et al., 2014).

Rapid movement of paleo-ice streams allowed distant transport of the debris, sometimes in a direction different from the dominant at the main stage of the ice sheet development (Kjær et al., 2003). This could have led to the formation of the petrographic duality of till profiles documenting a local change in the ice sheet dynamics.

The petrographic duality of the till led the authors to do more research to obtain the detailed characteristics of the petrographic variability of the glacial deposits and explain the causes. Based on the petrographic analysis, the following research tasks were possible:

- indicating the processes that led to the creation of a till bed with complex vertical profile,
- analysing the directions of the ice flow in various stages of development of the ice sheet in the Late Weichselian,
- analysing the regional diversity of petrographic composition of the till,
- comparing local and regional transport directions (from till fabric, striae orientation or ploughing marks as well as erratics of local provenance) and trans-regional transport directions, recorded in the composition of the fine-gravel fraction and the ratios of indicator erratics, and
- verifying the stream model of the ice sheet activity for the southern part of FIS in the Late Weichselian.

2. Regional setting

One of the areas influenced by the Late Weichselian paleo-ice stream is located along the northern section of the Vistula valley. The glacigenic sediments developed there have an atypical form. Isolated till beds found in its southern part represent subsequent phases of the Late Weichselian (Leszno Phase = Brandenburg Phase and Poznań Phase = Frankfurt Phase, see Wysota et al., 2009). Considerably further to the north, the limit of the Pomeranian Phase ice sheet can be found (Fig. 1). The extent of the ice-sheet in the study area during the Gardno Phase remains unclear. Some authors locate it far to the south (cf. Kaulbarsz, 2005; Marks, 2005), but in our research suggests that, in the area of the Gulf of Gdańsk, there is no evidence of the ice sheet advance during this time. The detailed recession of the ice sheet, following an advance in each of the above-mentioned phases, remains questionable. The northern part of the considered area was under ice cover regardless of the fluctuation of the ice sheet's range. Consequently, the number of the observed Late Weichselian till units decreases northward, finally to one, though often revealing a complex vertical profile (see Woźniak et al., 2009, 2012). Glacial deposit sequences observed in this region undoubtedly show the evidence of ice sheet readvances following periods of its stagnation, which most likely took place without clearing of the occupied land from the ice cover (sequences of till-on-till type). Most common in the area is a single till unit, which represents the glacial deposition during the entire Late Weichselian. Occasionally, when studying macroscopic features, subunits formed in the succeeding phases of the Late Weichselian can be distinguished. Such subunits are often distinguishable only in the laboratory analysis of petrographic composition of tills and the examination of till fabric. An appropriate examination strategy is required to separate them (Woźniak and Czubla, 2011; Woźniak et al., 2012), based on high resolution analysis within a vertical profile.

The complexity of the upper part of the Weichselian sediment profile, including uncertainty about the stratigraphic position of the tills and the complexity of their profiles, both in the areas around the Gulf of Gdańsk and the Lower Vistula Valley, was stressed by the authors of the older monographs (incl. Olszewski, 1974; Drozdowski, 1986) and in the explanations to the sheets of the Detailed Geological Map of Poland at the scale of 1: 50 000 (see e.g. Mojski, 1979, 1981). There is often a reference there to the duality of the youngest till bed.

The Vistula paleo-ice stream was narrow and covered the pre-Vistula river valley together with the restricted strips of land along both sides, and the velocity of the ice flow in its southern part could have reached over 500 m/y (cf. Morawski, 2009; Wysota et al., 2009; Narloch et al., 2012). The research results from the northernmost part of the area, where two zones of significantly different glacial transport directions are documented, also indicate the spatially-limited extent of the ice stream impact (Woźniak et al., 2009). The influence of different ice masses is reflected not only in the till fabric differentiation within the profile of a particular till but also in the petrographic composition of the distinguished till subunits. Moreover, the published results of petrographic composition studies of the fraction >20 mm (Woźniak et al., 2009) indicate that the differentiation of this composition is much higher than could be expected from the comparison of the dominant debris transport routes, which can be determined on the basis of the main paleo-ice streams layout (cf. Punkari, 1993, 1997; Boulton et al., 2001).

3. Methods

The previous research experience of the authors (Woźniak et al., 2009) enabled the preparation of a sensible course of studies (Woźniak and Czubla, 2011; Woźniak et al., 2012). The results from the eight key exposures were considered in the present paper. The first step of field works was geological mapping of individual sections, which was followed by determining the macroscopic features and facies characteristics of the corresponding sediments and sedimentary units. The lithofacies code based on Miall (1978) and Eyles et al. (1983) was used for the description of sedimentary units, their contacts and textural characteristics. The analysis of the