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Subglacial conditions and Scandinavian Ice Sheet dynamics at the coarse-grained substratum of the fore-mountain area of southern Poland

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ABSTRACT

The fore-mountain areas of southern Poland are locally composed of the coarse-grained sediments of alluvial fans, which created unusual conditions under the advancing Scandinavian Ice Sheet during the Elsterian glaciation. This highly permeable substratum potentially enabled rapid outflow of meltwater from the ice sheet base, thereby reducing the water pressure and strongly influencing the ice sheet dynamics. The subglacial conditions and the relationship between the ice sheet behaviour and its coarse-grained substratum were studied at the foreland of the western Carpathian Mountains. The sedimentological and structural analysis of the till and related sediments that were deposited above the alluvial gravel of the fore-mountain fans are presented.

The study indicates that despite the high permeability of the coarse-grained substratum, it did not slow the ice sheet movement. Conversely, the ice sheet moved mainly due to basal slip and locally shallow deformations. This was a consequence of very high basal water pressure, which resulted largely from the presence of permafrost that restricted subglacial groundwater outflow. In addition, the ice sheet substratum was inclined opposite to the direction of its movement, increasing the pressure of the subglacial water. Numerous subhorizontal sandy laminae within the till indicate that the meltwater from the ice sheet base was drained by a water film along the ice/bed interface. The water escape structures within the till and subtill sediments indicate the occasional instability of the ice sheet hydrological system and suggest that the meltwater was periodically stored in the ice sheet base. Temporal changes occurring in the ice sheet hydrological system might indicate variations in the ice sheet behaviour; i.e. phases of relatively fast ice flow and phases of ice stagnation. The latter were probably correlated with the freezing of the ice margin to its base. The study shows how the coarse-grained substratum could potentially influence ice sheet behaviour and provides a broader look on the factors controlling the dynamics of the Pleistocene ice sheets, which soft-sediment substrata in many areas were texturally varied.

1. Introduction

The crucial role of soft-sediment substrata in the development of ice sheets has remained undisputed for many decades (Boulton and Jones, 1979; Alley, 1991; Hicock and Dreimanis, 1992; Clark, 1994). However, in this universal concept less attention has been placed on spatial textural variation of substrata sediments and potential impact of this factor on ice sheet behaviour. From most studies it follows that Pleistocene ice sheets were overriding mostly medium-to fine-grained sediments such as sands, silts and tills and the majority of models representing subglacial deposition are developed for such cases (e.g. Hicock and Dreimanis, 1992; Johnson and Hansel, 1999; Piotrowski et al., 2004, 2006; Maclachlan and Eyles, 2011). Much less is known regarding relationship of ice sheets with coarse-grained substrata, which also occurred at the base of ice sheets, although less commonly so (e.g. Rijsdijk et al., 1999).

During the Elsterian glaciation, the Scandinavian Ice Sheet reached the margin of the Sudeten and Carpathian Mountains (cf. Mojski, 2005) (Fig. 1). The foreland of these central European mountains created notably different conditions for the overriding ice sheet than those that occurred in other regions, especially in the lowlands. As a rule, the ice sheet substratum was constructed at

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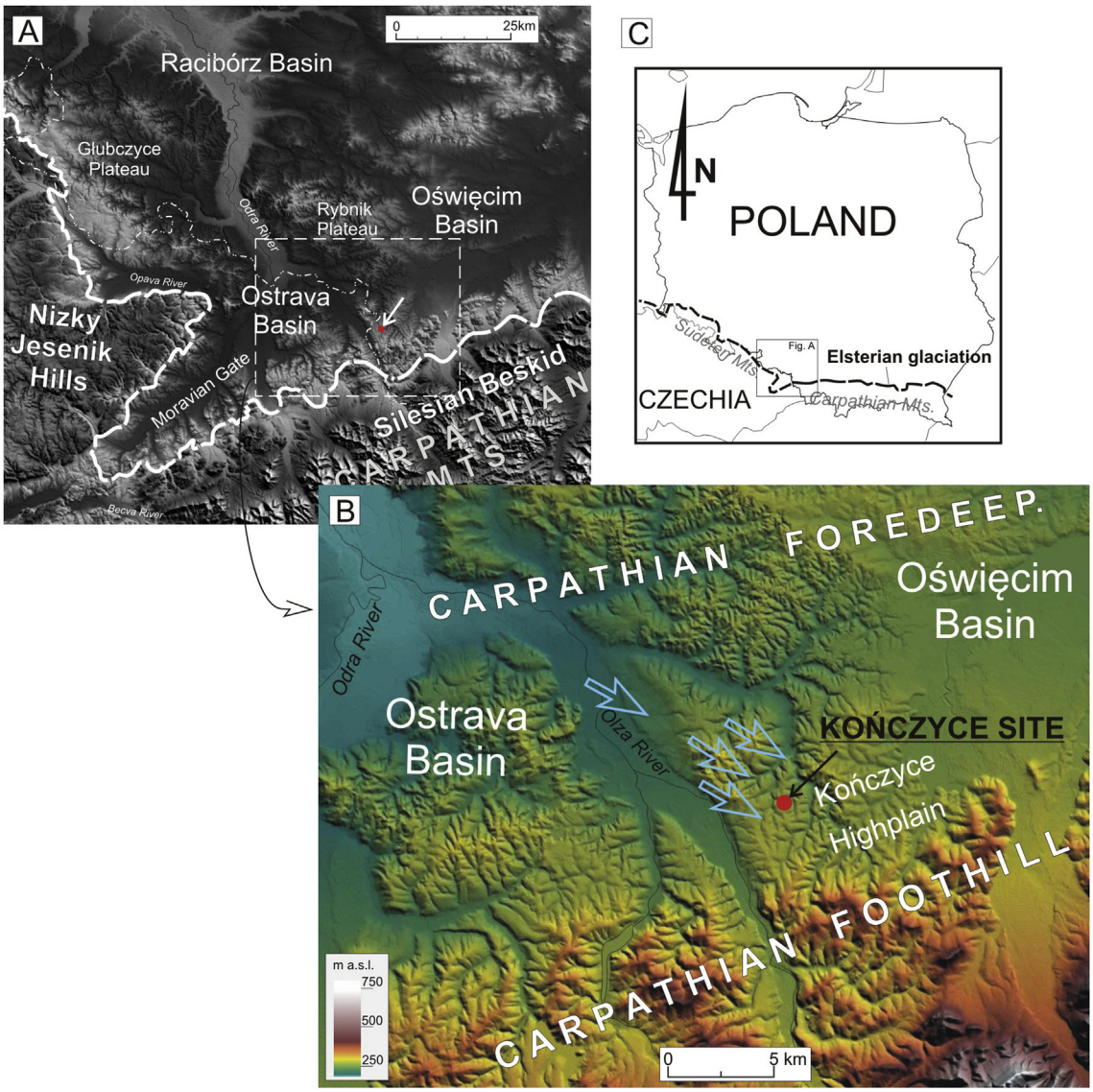

Fig. 1. A) Location of the study area and extent of the Scandinavian Ice Sheet during Elsterian glaciation (white dashed line) based on Mojski (2005). B) Relief map of the nearest area of the Kończyce site. Blue arrows indicate general ice flow direction interpreted from the till macrofabric analysis. C) Label for the country-wide index map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that location from more coarse-grained sediments, mostly gravels, which were deposited by rivers flowing from the mountains. The length of these depositional zones composed of alluvial fans or alluvial plains could reach from a few to several tens of kilometres. Due to the high permeability of the substratum sediments, they potentially allowed relatively rapid drainage of the water that was produced in the ice sheet base (cf. Boulton et al., 1995). This phenomenon might have effectively reduced the basal water pressure, increasing the strength of the ice/base coupling, and thereby affected the glacier dynamics (Iverson et al., 1999, 2003). However, many more factors might be important, including the thickness and lateral extent of the coarse-grained sediments and the presence or lack of permafrost (Boulton and Caban, 1995; van der Meer et al., 1999; Tylmann et al., 2013; Salamon, 2015a).

Coarse-grained sediments are found in the substratum of some present day glaciers that flow down over proglacial deposits. At the mountain foreland, such sediments are often characterized by a gravel texture (Benediktsson et al., 2009; Denis et al., 2009; Fleisher et al., 2010). A good example of glaciers that exist in such conditions are some Icelandic glaciers, like Brúarjökull (Benediktsson et al., 2009). Studies of contemporary glaciers show that the dynamics of glaciers can vary widely as they override coarse-grained substratum. The efficient drainage of subglacial meltwaters can cause low pore-water pressure, resulting in a strong ice/bed coupling (cf. Boulton and Caban, 1995; Boulton et al., 2001) and thereby a distinct slowing of basal ice movement. Conversely, on a gravel substratum, glaciers may move much more rapidly and even surge (Benediktsson et al., 2009; Denis et al., 2009). In this case, however, an appropriately high water supply in relation to the rate of intergranular outflow is necessary to generate an increase in the fluid pressure. The existence of till in the glacier base and its characteristics are also crucial.

The base of the Pleistocene ice sheets consisted only at few locations of coarse-grained sediments, which were generally small in extent. The sediments were conditioned by high energy proglacial deposition before the ice sheet advance and by local factors that were related to the geology of the substratum and its topography. The ice sheets that advanced toward the mountains of southern