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Basal till and subglacial conditions at the base of the Upper Odra ice lobe (southern Poland) during the Odranian (Saalian) Glaciation

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The objective of this contribution is detail characteristics of the basal till and the conditions at the base of the Upper Odra ice lobe. The lobe was formed in a foremountain area. Its central part was a Niemodlin Plain and the W part of the Racibórz Basin, surrounded by areas that have a much more varied relief. Particular attention is paid to the conditions at the ice sheet base, generating the dynamics of glacier movement. The study is based on analysis of the basal till. Three sites with basal till lying on different types of substratum (typical for the study area) are presented. The basal till of the Upper Odra ice lobe is characterized by spatial variations. Different intensities of its deformation indicate that large lateral differences in conditions occurred in the lobe substratum. The lithology controlled the rate of basal water pressure, and thus the strength of both the subglacial sediments and the ice-bed coupling. Various strain rates in the till profiles indicate that the conditions at the ice sheet base also changed with time. The ice sheet was highly mobile, even on the coarse-grained substratum. The low permeability of the Quaternary substratum, and the relatively small thickness of the Quaternary sands and gravels resulted in a high water pressure at the ice sheet base. The movement of the Upper Odra ice lobe was concentrated in the basal zone of the ice sheet. The main mechanisms of motion were sliding and deformation of the subglacial sediments. The deformation occurred in restricted areas only, and did not have a pervasive character.

Key words: till, subglacial conditions, ice sheet dynamics, Upper Odra ice lobe, Pleistocene, S Poland.

INTRODUCTION

During the Odranian (Saalian) Glaciation the Scandinavian Ice Sheet advanced to the area of the Sudetes Mountains and the Middle Polish Uplands, which formed a morphological barrier. In the zones of open vast areas, like large river valleys (Odra River valley, Wisła River valley), the ice sheet formed distinct lobes. One of these lobes (the Upper Odra ice lobe) was developed in the southern part of the Silesian Lowland through which the ice sheet advanced to the zone of the Moravian Gate, the area separating the Sudetes from the Carpathians (Fig. 1). The Upper Odra ice lobe was formed in a foremountain area, but its central part was a region with relatively low relief. Just in its southern periphery, higher-lying areas occurred with more significant relief contrast. Undoubtedly the lobe development was determined by topography. The question is what conditions occurred at the ice sheet base, and whether they favoured the formation of the lobe. This problem needs a complex approach to determine the conditions at the glacier bed. Genetic identification of till is therefore essential for the proper assessment of the subglacial conditions and the dynamic state of the ice sheet.

It is known that the movement of glaciers may result from both internal ice deformation and basal motion (Paterson, 1994; Benn and Evans, 2010). In the case of warm-based glaciers, the ice deformation represents only a small percentage of the overall balance of their movement (Boulton and Jones, 1979; Alley et al., 1986, 1987; Blankenship et al., 1986; Boulton and Hindmarsh, 1987; Clarke, 1987; Iverson et al., 1995). Much more important are the mechanisms generated at the contact of the ice with the substratum, i.e. the subglacial sediment deformation or basal sliding (Boulton and Jones, 1979; Boulton and Hindmarsh, 1987; Brown et al., 1987; Clarke, 1987; Paterson, 1994; Benn and Evans, 2010). It is essential to realise that these mechanisms could occur not only on rigid bedrock (cf. Weerteman, 1957; Kamb, 1970), but also on soft, unconsolidated sediments, which constituted most of the Pleistocene ice sheets substrate. As a result, subglacial processes likely greatly influenced the ice-mass distribution in the former ice sheets, including their growth and decay during glaciation cycles, and thus the relation between palaeoglacier systems and the global climate (Alley, 1991; Clark, 1994; Hughes, 1996; Marshall, 2005).

Despite the significant progress in the research of basal tills made over the last three decades, still some not fully resolved issues remain, particularly the scale of subglacial sediment deformation and its role in the development of former ice sheets. According to the "soft deforming-bed" model, many researchers assume that in areas built of unconsolidated sediments, the main mechanism of glacier motion was continuous, pervasive deformation of subglacial sediments (Boulton and Jones, 1979;

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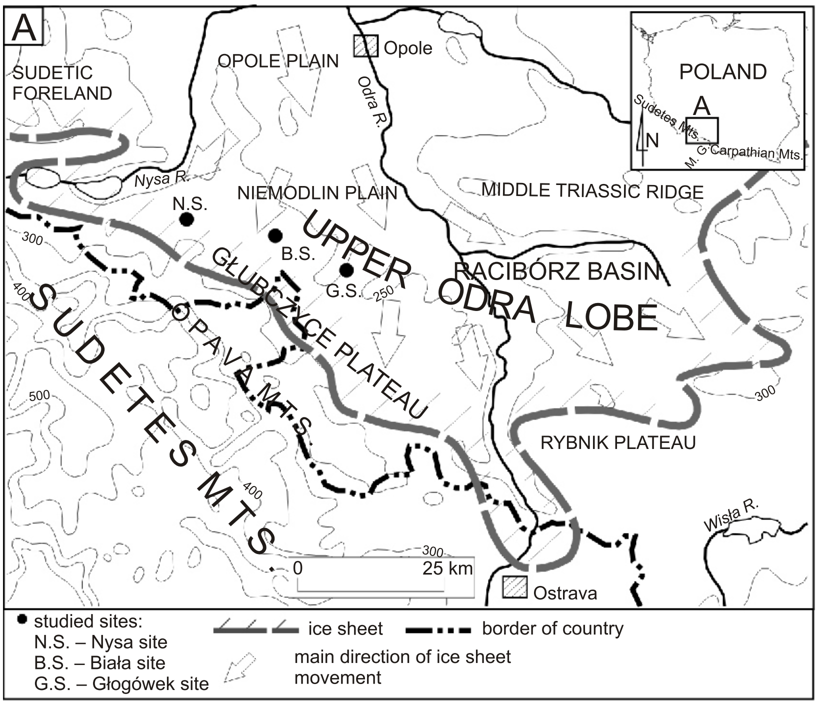

Fig. 1. Extent of the Upper Odra ice lobe and location of the sites under study

Main directions of ice sheet movement on the basis of Salamon (2012);
M. G. – Moravian Gate

Beget, 1986; Hicock et al., 1989; Hart et al., 1990; Alley, 1991; Hart and Boulton, 1991; Boulton, 1996; Clark and Walder, 1994; Van der Meer et al., 2003; Evans et al., 2006; Menzies et al., 2006). However, this concept does not always apply. For example, rapid movement of Ice Stream B in West Antarctica was initially attributed to the presence of thick, unconsolidated, strongly saturated deformed deposits at the ice sheet base (Alley et al., 1986, 1987), but subsequent studies have shown that the basal movement of the ice stream is concentrated within only a very thin layer of substrate (cf. Engelhardt and Kamb, 1998; Tulaczyk et al., 1998). Brown et al. (1987) pointed out that the Puget Lobe of the Pleistocene Cordilleran Ice Sheet moved mainly by sliding and that only local deformation was caused by clasts ploughing the substrate. A similar concept was presented by Piotrowski and Kraus (1997), Piotrowski and Tulaczyk (1999) and Piotrowski et al. (2001) for the Scandinavian Ice Sheet. They doubt the presence of continuous pervasive deformation at the ice sheet base, and assume that its movement was mainly due to basal sliding. In a later model, soft subglacial beds were presented as a mosaic of deforming and stable spots; the intensity of deformation varied in both time and space (Piotrowski et al., 2004). Concepts of spatially varied glacier bed characteristics have been described also by other authors (see Knight, 2002; Van der Meer et al., 2003; Larsen et al., 2004, 2007; Stokes et al., 2007; Narloch et al., 2012, 2013; Tylmann et al., 2013). The differences in assessment of the role and scale of subglacial deformation are largely due to the different rheological models for the behavior of basal till, i.e. viscous rheology (Alley, 1991, 2000; Hindmarsh, 1997) or the plastic rheology model (Kamb, 1991; Hook et al., 1997; Iverson et al., 1998; Tulaczyk et al., 2000, 2001; Tulaczyk, 2006). This complex, global issue aspect is still not fully resolved. Theoretical considerations on this topic have been mentioned in many works (cf. Murray, 1997; Boulton et al., 2001; Bennett, 2003; Menzies, 2012).

The objective of this contribution is the analysis of the lithological characteristics of the subglacial tills of the Upper Odra ice lobe and recognition of the style of sedimentation. The lobe was distinctly matched to the relief of the substratum, which was confirmed by its long and sinuous margin and by its division into several ice sublobes (Fig. 1). The topography must therefore have been an important factor in its development, but probably not the only one. It follows from the divergent pattern of ice sheet movement directions (Salamon, 2012) that the velocity of the ice flowage was high. Analysis of tills reflects the conditions in the glacier bed and the mechanisms of ice sheet movement.

This contribution presents three sites where till was deposited on different types of substratum, most typical for the study area, so the deposits underlying the till, i.e. spatial differences in the lithology of the substratum of the advancing ice sheet are analysed.

METHODS

The textural and structural features of the Upper Odra ice lobe basal till were studied. The grain size of the sediments was established on the basis of laboratory analyses: the sieving method and the areometric method of Casagrande with Pruszynski modification (Racinowski, 1973). The clast-fabric analysis was based on Krüger (1970). Measurements were carried out on at least 30 elongated clasts, which longer axis reaching a minimum of 1 cm and a-axis to b-axis ratio is at least 1.5–1.0. The measurements were analysed with the *StereoNet* program and are presented on rose diagrams and contour diagrams (the Schmidt equal-area grid). The eigenvalue vectors S_1 and S_3 and the parameter of isotropy ($I = S_3/S_1$) and elongation ($E = 1 - (S_2/S_1)$) were calculated (Mark, 1973, 1974; Benn, 1994; Benn and Evans, 1996). The analysis of the gravel fraction followed the standard petrographic procedure of Polish Geological Institute, i.e. at least 300 grains (5–10 mm in diameter) for each sample were identified. Lithifacies are coded with the modified code of Krüger and Kjær (1999; Table 1).

STUDY AREA

The Upper Odra ice lobe was formed in the southernmost part of the Silesian Lowland. In its maximum extent, the lobe was subdivided into four sublobes (Fig. 1). The central part of the area occupied by the lobe is the Niemodlin Plain and Racibórz Basin (Fig. 1).

The area is situated at 170–200 m a.s.l. Towards the south it passes into higher uplands with a more complex morphology: the Głubczece Plateau on the western side of Odra River valley and the Rybnik Plateau on the eastern one. The differences in elevation are 30–50 m there. The terrain slopes gently in the N–NE direction of the Głubczyce Plateau, and E of the Rybnik Plateau.

The pre-Quaternary basement is built mainly of marine and terrestrial sediments of Miocene and Pliocene age, deposited in a zone of fore-mountain basins (Fig. 2). The Miocene deposits are mainly clays, silts and sands (Alexandrowicz, 1963; Alexandrowicz and Kleczkowski, 1974; Kotlicki and Kotlicka, 1980), whereas the Pliocene sediments consist of thin, isolated patches of sand and gravel with intercalations of silts and clays

Table 1

Lithofacies code used to description of till and associated deposits, on the base of Krüger and Kjær (1999)

Diamict sediments	
D	diamicton
Structure	
m	massive homogeneous
b/s	banded/stratified
Granulometric composition of matrix	
C	coarse-grained, sandy-gravelly
M	edium-grained, silty-sandy
F	fine-grained, clayey-silty
Clast-matrix relationship	
c	clast-supported
m_1	matrix-supported, clast poor
m_2	matrix-supported, moderate
m_3	matrix-supported, clast rich
Sorted sediments	
Fh – fines (silt, clay), laminated Sr – sand, ripple cross-laminated Sh – sand, horizontally laminated Sp – sand, planar cross-bedded SGp – gravelly sand, planar cross-bedded Gm – gravel, massive	

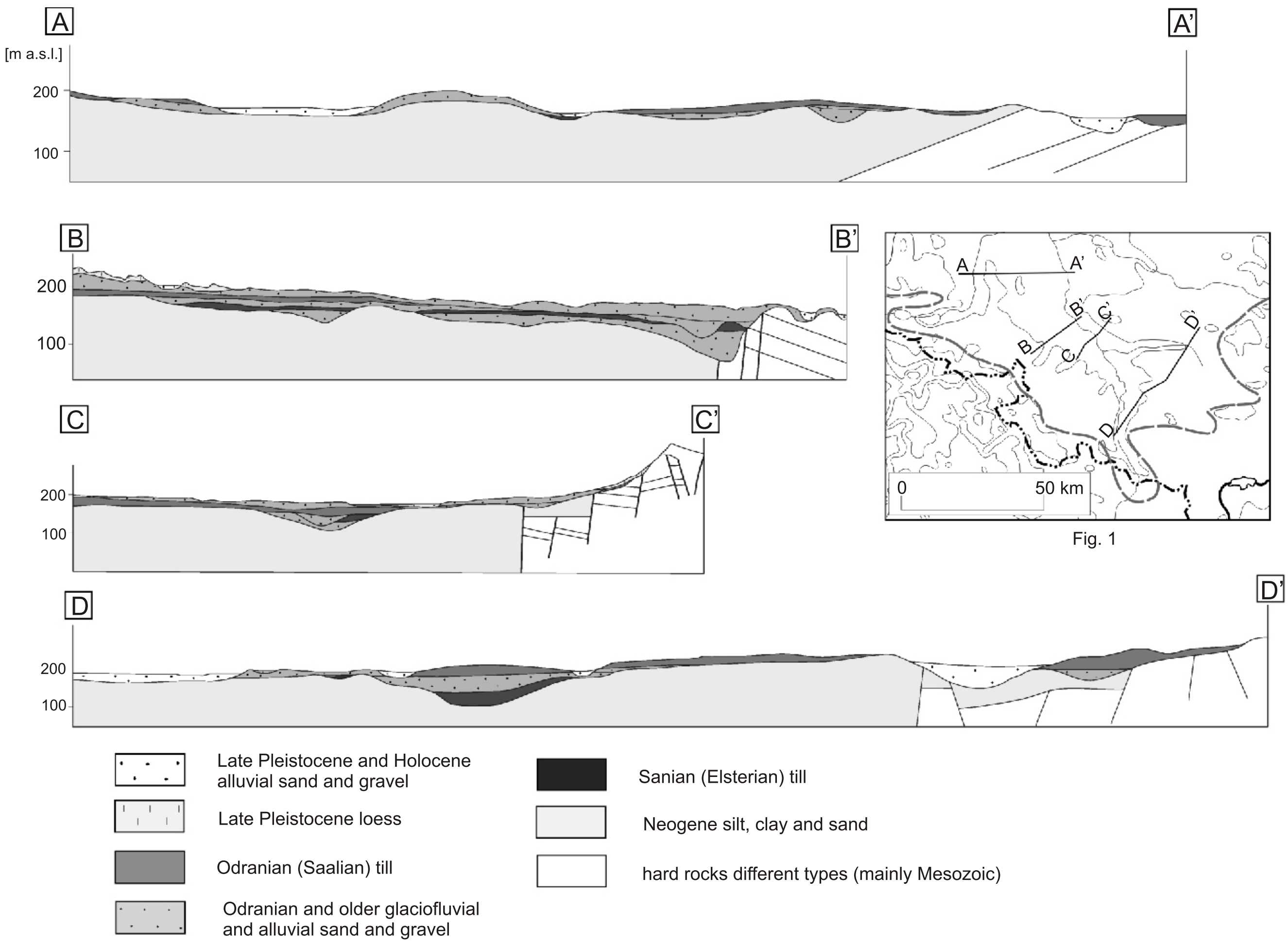

Fig. 2. Schematic and simplified geological cross-sections trough the study area; on the basis of cross-sections to geological maps in the scales 1:200,000 (Kotlicka and Kotlicki, 1979; Wroński and Kościówko, 1988) and 1:50,000 (Trzepla, 1999a, b)

(Kotlicki and Kotlicka, 1980; Badura et al., 1996, 1998). The Quaternary deposits form a thin cover of a few to locally more than 40 m thick (Fig. 2). In the river valleys, these are mainly fluvial sands and gravels. In the areas between the river valleys mainly glaciofluvial sands and tills are present. Some part of the study area is covered by loess, particularly on the Głubczyce Plateau.

According to Czech authors (Macoun, 1985; Macoun and Kralik, 1995), the ice sheet during the Odranian (Saalian) Glaciation reached the upper part of the Odra River valley, about 40 km SW from Ostrava, as far as during the Earlier (Elsterian) Glaciation. According to Lewandowski (1988, 2001, 2003) and Badura and Przybylski (2001) and Salamon (2008, 2009, 2012), the maximum extent of the ice sheet was much smaller during Saalian Glaciation.

SECTIONS UNDER STUDY

The Upper Odra ice lobe advanced over a substratum with different lithologies. Through the main valleys, it moved over alluvial sands and gravels, locally fluvioglacial and glaciolimnic deposits. In zones between the valleys, the ice sheet advanced over older Quaternary units, or immediately over Neogene sediments, mainly clays, silts and sands. The till was studied at a dozen or so sites located in different parts of the ice lobe. At the three sites dealt with here (Fig. 1), the till overlies sediments with different lithologies that are characteristic for the whole study area.

THE NIWNICA SITE

The Niwnica site is located in the NE part of the Głubczyce Plateau within a relatively flat terrain (230–240 m a.s.l.) at the foot of a small hill, which slopes gently toward the valley of the Nysa River (Fig. 3). In an excavation, a continuous bed of till of about 3.5 m thick is visible (Figs. 3 and 4). The till rests on a Neogene clay that has locally intercalations of sand and silt. Drilling data from nearby reveal that a thin sandy bed exists sometimes between the clay and the till.

The substratum is locally deformed. Large-scale deformation structures occur in the western part of the exposure (Fig. 4A). The Neogene clay and sand with the till atop are deformed. The clay forms an anticlinal fold inclined toward the W–SW, whereas the sand is enclosed in a synclinal structure. The dip of the fold axis is approx. 35–45°, but immediately under the till it gradually becomes subhorizontal. The fold axis dips toward 240–260°.

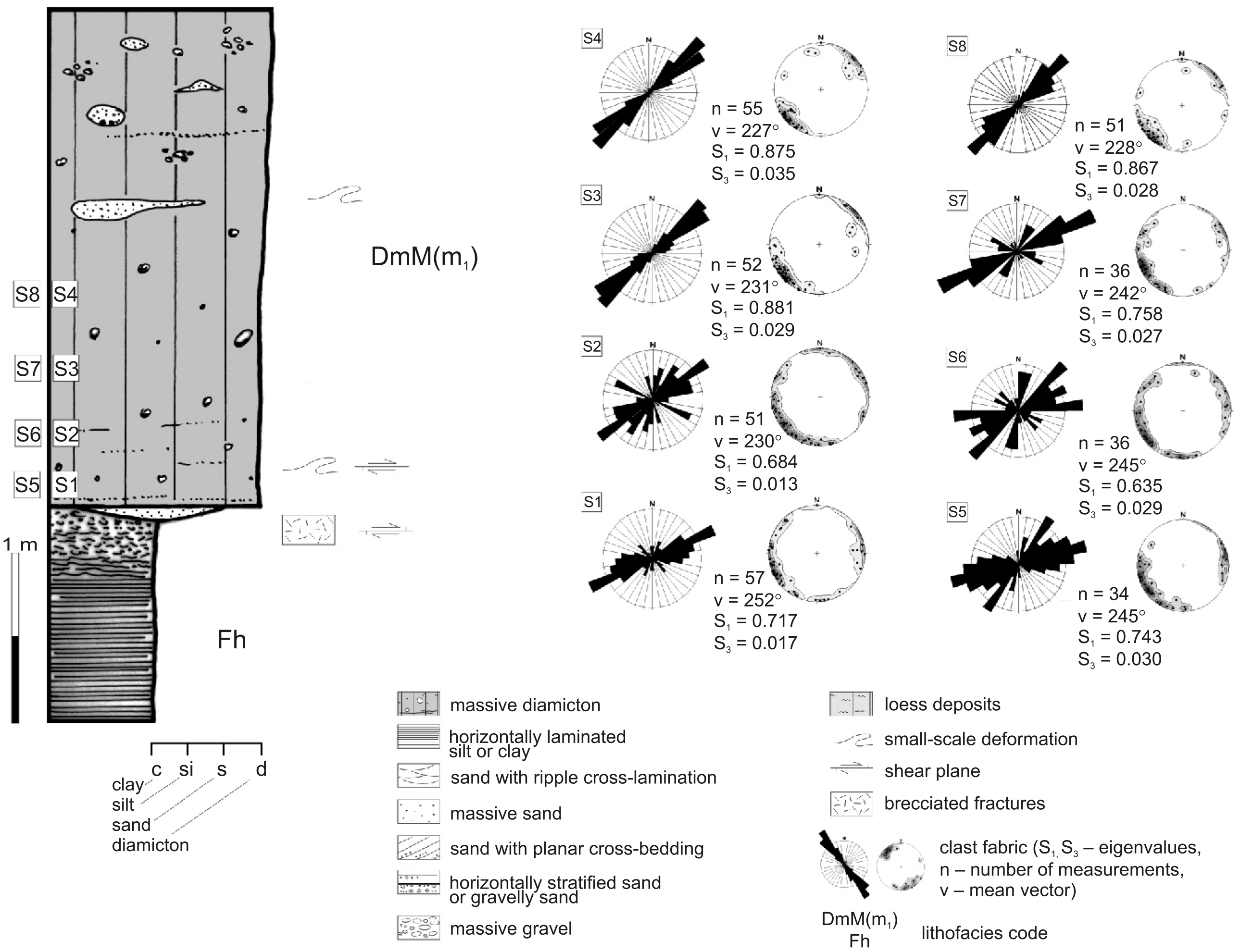

Fig. 3. Generalized sediment log and clast fabrics at the Niwnica site

Other explanations see Table 1

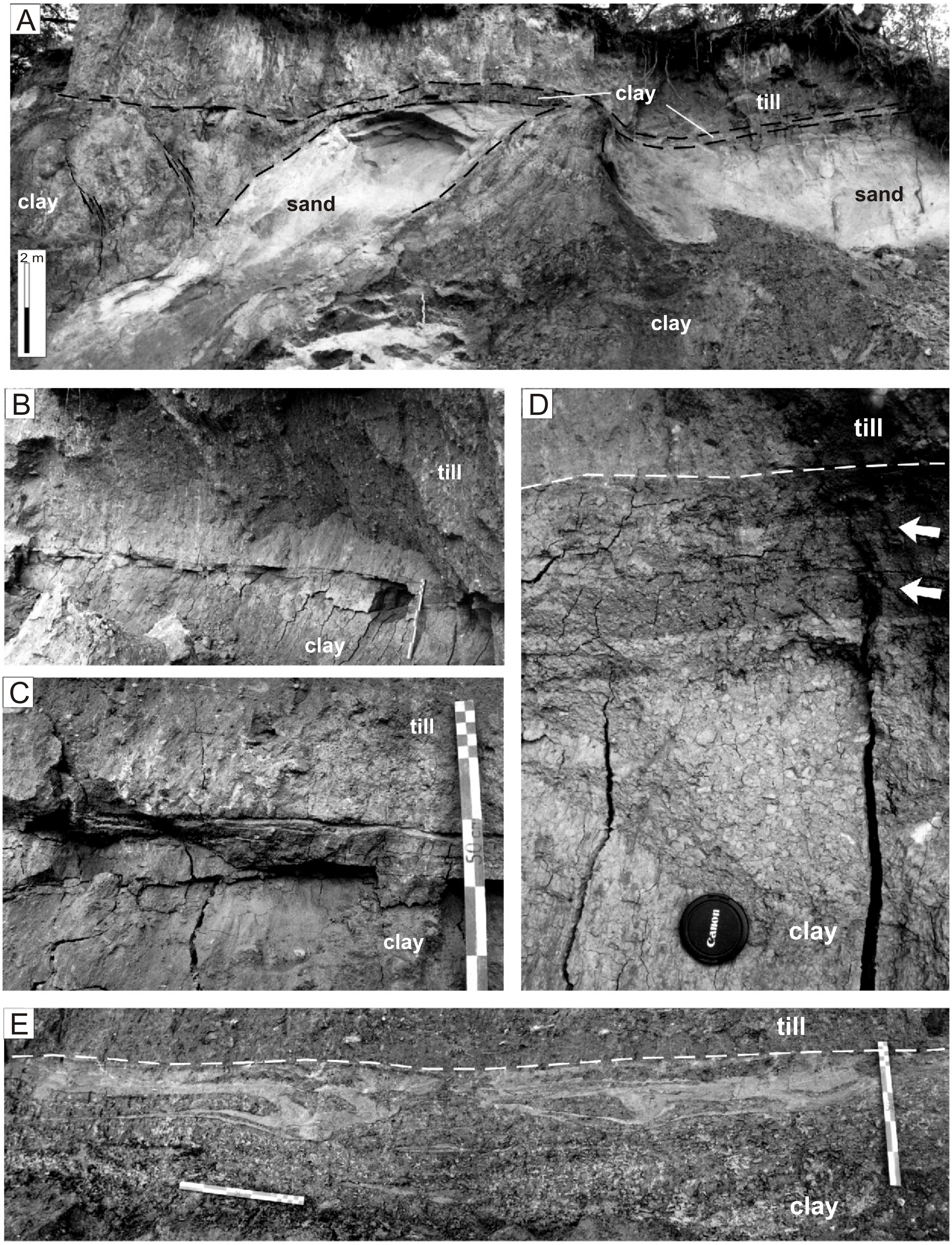

Fig. 4. Till at the Niwnica site

Sections in all photographs oriented approximately parallel to the former ice sheet movement direction, which was from left to right; **A** – glaciotectonic deformation in the SW part of the site; **B** – sharp contact of the till with underlying clay; **C** – sand laminae (arrows) visible along the contact surface; **D** – deformation structures in the clay bed just below the till, in the central part of the photo a marble-like structure is visible (angular clay clasts a dozen or so millimetres in diameter touch each other), in the upper part, the clay clasts are much smaller (a few millimetres), rounded and dispersed in the massive clay matrix (arrowed); **E** – melange of strongly deformed clay and sand below the till

LITHOFACIES DESCRIPTION

The till is a sandy, matrix-supported diamicton with brown colour. The average sand content in the matrix is more than 55%. The average amounts of silt and clay are about 20 and 24%, respectively. The sandy fraction increases upwards from 43 to 63%, whereas the silt and clay percentages increase downwards (silt: from 16 to 26%, clay: from 21 to 31%).

The basis of the till is commonly flat and the contact with the underlying clay is sharp (Fig. 4B). Immediately below the till, the primary sedimentary structures in the clay are not preserved. Deformation structures are visible there in a layer of at least 30–50 cm thick. The whole layer has a marble-like structure and is built of clayey, more or less spherical, aggregates (clasts) of up to several millimetres (Fig. 4D). Angular aggregates form the clast-supported texture in the lower part of the layer. Their size decreases upwards. In the upper, matrix-supported part of the layer, the more ovally shaped aggregates reach 1–3 mm in size, being scattered in a homogeneous, massive clay matrix (Fig. 4D).

The sand in the contact zone between the clay and the till is built of subhorizontal laminae of a few millimetres thick (Fig. 4B, C). The sand laminae are usually laterally extensive, but discontinuous and in some places they are absent. Most commonly it is a poorly sorted sand, sometimes with an admixture of fine gravel. Locally, in the contact zone, sands of several decimetres thick are also present. Sometimes they form small-scale structures with a trough shape. In other places they form, together with underlying clay, a melange with numerous deformation structures (Fig. 4E).

The contact of the till with the underlying sediments has a slightly different nature in the zone of large-scale glaciotectonic structures. A folded sand with a stretched clay layer atop is present under the till. The thickness of the clay layer is about 20 cm, gradually diminishing towards the SW, where it wedges out in the lower part of the till (Fig. 4A). The till has a massive structure. Occasionally, thin subhorizontal stringers of sand or gravelly sand occur in the lower part of the till. In the middle part some larger lenses with distinct traces of horizontal stretching are present. The upper part of the till is coarser. There are numerous inclusions of sorted sediments, mainly ovally shaped sand lenses. Irregular lenses of gravel without distinct boundaries are also visible.

The clast fabric is characterized by a very low spread of data (S_1 = 0.635–0.881; S_3 = 0.013–0.035). The parameter of isotropy is very low too (I = 0.013–0.046), whereas the parameter of elongation (E) is high or very high. In the lower part of the diamicton, E = 0.650; in the middle part it reaches its maximum (E = 0.890–0.909). In most cases the distribution is unimodal.

Petrographic analysis of the gravel shows that quartz is the most frequent (38%); the group of Sudetes crystalline rocks forms more than 30% and Scandinavian rocks (mainly crystalline) contribute approx. 7%.

INTERPRETATION

The relation of the large-scale deformation structures with the overlying till, i.e. between the co-directional axial surfaces of the folds in the Neogene deposits and the a-axes of the clasts in the till, indicates a glaciotectonic origin of the deformations. They were developed in a zone with laterally different lithologies. The marginal part of the sandy lithosome acted as a compression zone. The local stress concentrated there and consequently clay fold structures were formed. The upper parts of the folds became stretched out at the base of the moving ice sheet. It is possible that the deformations were initiated at the front of the advancing ice sheet and afterwards developed subglacially. Such deformation structures were probably common for a palaeoenvironmental situation where the ice sheet advanced immediately over Neogene sediments. This substratum was characterized in many places by a mosaic-like pattern of two lithologies, viz. clays and sands.

The clay overlain by till displays distinct traces of deformation. The marble-like structure of the clay close to the till base is a characteristic feature. Structures of this type are often recognized in till with a high content of clay (Hiemstra and Van der Meer, 1997; Van der Meer, 1997; Van der Meer et al., 2003). A network of small fractures was formed in the overloaded clay. The inter-fracture aggregates were rotated due to horizontal stress. They evolved from the larger, angular elements which are visible at a deeper position, to well-rounded ones dispersed in a homogeneous clayey matrix directly under the till. The variability of the vertical structure of the clay reveals a distinct gradient of the strain rate and increasing intensity of shearing towards the ice sheet bed (Iverson et al., 2003). The small thickness of the deformed horizon was partly a result of the fine-grained character of the deposit. The lack of a grain framework was the main reason for the limited downward transfer of the shear stress (Tulaczyk, 1999). As a result, the clay was intensively deformed only in a thin layer (<20 cm) directly below the ice sheet base. Moreover, the very low clay permeability prevented the downward penetration of basal meltwater into the substratum. It caused a rapid increase in water pressure at the base of the ice sheet and reduced the strength of the ice-bed coupling. As a consequence, basal sliding was triggered, and simultaneously the intensity of the subglacial shearing was reduced (cf. Brown et al., 1987; Iverson et al., 1994, 1995; Fischer and Clarke, 2001).

The very high water pressure at the glacier's base is evident from the sand deposits at the contact between the till and the clay. They indicate episodes of subglacial water flow. The effective pressure had to reach a value close to zero. The deposits released from the basal ice during ice sheet sliding became liquified and were subsequenly transported by the meltwater (cf. Boulton and Dobbie, 1993). The shape of the sand structures in the contact zone indicates that the water flow took place through a system of interconnected, very slight cavities or in slightly larger diffuse canals. The genetic connection of laminar structures of sorted deposits in basal till with subglacial water flows has been proved by many authors (Brown et al., 1987; Piotrowski and Kraus, 1997; Piotrowski and Tulaczyk, 1999, Munro-Stasiuk, 2000; Fuller and Murray, 2000; Wysota, 2002, 2007; Piotrowski et al., 2006; Lesemann et al., 2010). After the flow had stopped, the rate of the effective basal pressure increased so much that the strength of the ice-bed coupling for a short time again became higher than the strength of the subglacial deposits. At this phase the subglacial deformation took place, at least locally. This is expressed by the occurrence of sands folded together with clays of the substratum (Fig. 4E).

In contrast to the clay, there is no distinct evidence of intense deformation in the overlying till. Its flat base suggests that no significant mixing of diamicton with clay occurred. Mixing took place only locally, in zones where large contrasts of strain existed due to different lithologies in the substratum. The deposits underwent folding and thrusting there. The clast orientation does not indicate an increase of the strain rate toward the top of the bed either, which is characteristic for deformation till (Benn and Evans, 1996). The fabric is rather characteritic of lodgement till (cf. Hart, 1994; Hicock and Fuller, 1995; Hicock et al., 1996) and melt-out till (cf. Lawson, 1979). Only in the lowermost part of the layer the fabric is comparable with that of deformation till. Only some deformation structures in the form of horizontally stretched inclusions of sorted sediments within the middle part of the till indicate deformation. However, their preservation in the till suggests a not so high rate of subglacial shearing. The lower part of the unit is a basal till deposited from the base of a sliding ice sheet. Probably the till was only periodically subjected to a weak strain, although the pore-water pressure directly affecting the strength of the subglacial deposits was permanently very high, because of the clayey substratum. Under such conditions, the lack of intense deformation may therefore indicate that the shear stresses were not transferred to the till, but interceped by a water film on the ice-bed contact (see Iverson et al., 1994, 1995). In this way the ice was separated from the substratum, and ice sheet slip took place. Few subhorizontal sand laminae preserved in the lower part of the till confirm this view. Probably they were formed as a result of subglacial flows.

The upper part of the diamicton, which is characterized by numerous, oval or irregular inclusions of sorted sediments, is interpreted as a melt-out till. The till was deposited at the base of a stagnant ice sheet as a result of its passive melting. The inclusions of gravel and sand were probably derived from draining of the base of the stagnant ice or, alternatively, they are traces of englacial drainage (e.g., Shaw, 1982; Munro-Stasiuk, 2000). The larger grain size of the till also suggests a melt-out origin (Dreimanis, 1989).

THE BIAŁA SITE

The Biała site is located in the northern part of the Głubczyce Plateau (Fig. 1), approx. 1 km NW from Biała City. The terrain slopes towards the NE and is cut by the valleys of small rivers; therefore the area has a hilly relief. The culminations of the terrain in the vicinity of the site reach a height of 240–250 m a.s.l. The exposure under study is situated at an altitude of 238 m a.s.l. At this site the till overlays sands with a thickness of a few to more than twenty metres, covering the fine-grained Neogene deposits.

LITHOFACIES DESCRIPTION

The till exposed at the site is underlain by several metres of fine-grained glaciofluvial sands. The till is 4–5 m thick; it consists of two beds (B1 and B2; Fig. 5). The till is covered by a thin layer of loess.

The underlying sand is characterized by numerous deformation structures, among which the most common are subhorizontal shear plains (Y-type), and low-angle shear plains (P- and R-type; Fig. 6C). Rare boudins of coarser sand and small overthrown folds are present. In some places the primary depositional structures of the sand are completely destroyed. The deformed zone below the till base is up to several decimetres thick.

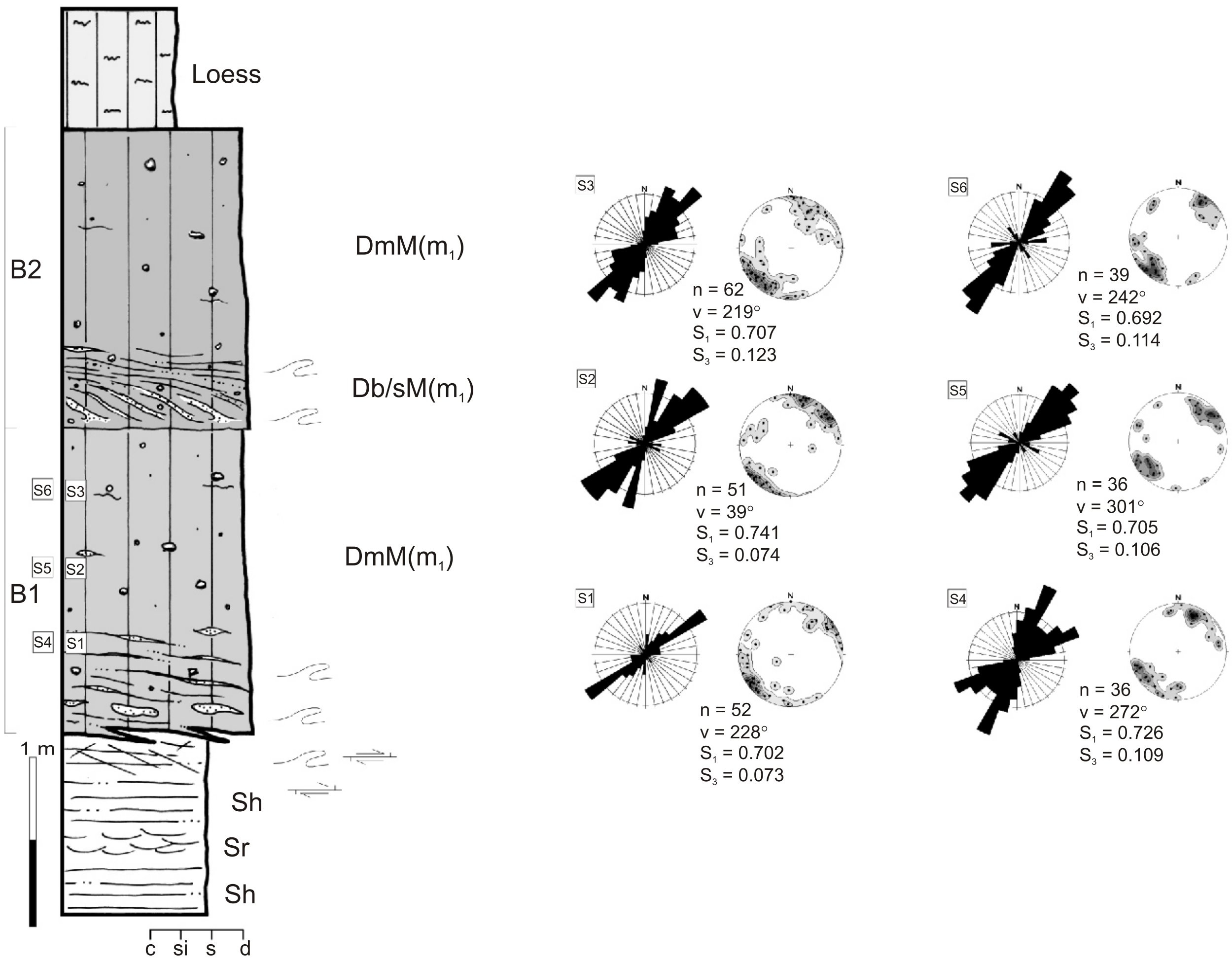

Fig. 5. Schematic sediment log and clast fabrics at the Biała site

For explanations see Figure 3 and Table 1

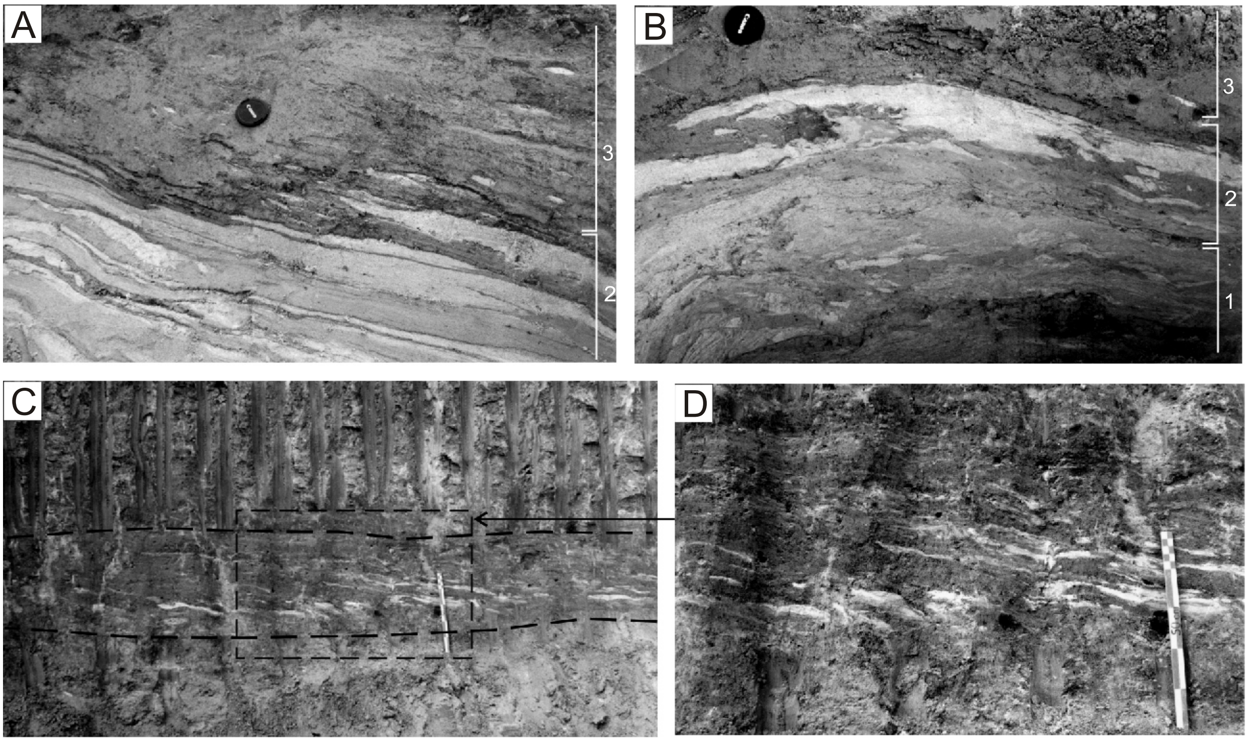

Fig. 6. Till at the Biała site

A, **B** – bottom part of till B1, visible contact zone with transitional character, varied structures in the vertical profile show an increased upward intensity of deformation: 1 – zone of brittle shearing with numerous small-scale shear surfaces, 2 – zone of brittle-plastic shearing with a much larger number of plastic structures, boudins and detached folds, 3 – zone of plastic shearing; massive diamicton with smaller amount of sand structures; sections oriented obliquely to the former ice sheet movement direction; **C**, **D** – bottom part of till B2, with a laminar structure, sand lenses and strings are slightly inclined, the thickness and inclination of the sand structures diminishes upwards, the laminar till gradually passes upwards into a massive till, sections oriented approximately parallel to the former ice sheet movement direction, which was from right to left

The contact between the till of unit B1 and the underlying deposits is gradational (Fig. 6A–C). Numerous till wedges extend from the till base into the sand. In the lower part of the till, many sand lenses and boudins are present. Sand occurs also in the form of laminae, giving locally a laminar structure to the till. This unhomogeneous diamicton passes gradationally upwards into a massive one (Fig. 6B). Unit B1 is some 2 m thick. It is a grey matrix-supported diamicton with a small amount of gravel. The composition of the matrix is, on average, 48% sand, 25% silt and 27% clay. In the lower part of the unit, the diamicton is more sandy (55% of sand). The content of sand gradually decreases upwards to 45%. The content of clay increases toward the top of the unit, from 20 to 30%.

The clast fabric is highly aligned (S_1 = 0.692–0.741; S_3 = 0.073–0.123). It is also confirmed by low values of isotropy (I = 0.099–0.175) and high values of the elongation parameter (E = 0.692–0.765). The mean vectors are oriented NW–SE. The clast orientation varies relatively little (Fig. 5).

Measurements of the kinematic structures in the underlying sand and in the basal part of the till indicate slightly different orientations, i.e. N/NE–S/SW.

Unit B2 is about 2 m thick (Fig. 5). This rust brown diamicton is a bit more sandy, with sand constituting 60%. The silt and clay fractions contribute 18 and 22%, respectively. The amount of sand gradually decreases upwards. Unit B2 is structurally similar to Unit B1. In its lower part a layer of 30–60 cm thick with numerous sandy structures is present (Fig. 6C, D). They form elongated lenses or stringers, sometimes turned into small boudins. All these structures are inclined toward the NE. Upwards they become thinner and give the diamicton a structure of very thin subhorizontal lamination, which gradually disappears and passes into a massive one. In other places the sandy diamicton with sand and sandy-gravelly intraclasts is an equivalent. The intraclasts have various shapes, usually lens-like, from centimetres to decimetres in size; they are dispersed in the strongly inhomogeneous till with numerous, irregular sand streaks and laminae. In the remaining part the B2 diamicton is homogeneous and massive. Due to the infrequent occurrence of gravel-sized clasts only few fabric measurements were performed. Generally, the axes of the clasts are arranged consistently with the direction of the deformations in the underlying laminated diamicton in the lower part of the unit, i.e. NE–SW.

Among the gravel particles quartz predominates (38%). The content of the Sudetic and Scandinavian crystalline rocks is similar (approx. 17%). Local Carboniferous sandstones are less frequent (about 8%).

INTERPRETATION

The numerous shear structures in the sediments underlying the till record deformation processes in the subglacial shear zone (cf. Benn and Evans, 1996; Van der Wateren et al., 2000). The subhorizontal and low-angle shear surfaces indicate brittle deformation. In turn, the small sand boudins, overturned folds and in places completely destroyed depositional structures of the sediments indicate local ductile shearing. The lower part of the diamicton was also formed under such conditions. Evidenced are the till wedges close to the base, and the numerous lenses, boudins and attenuated stringers of sand from the substrate incorporated in the till (see Van der Wateren, 2002). The massive structure of the diamicton in the middle and upper parts of unit B1 are probably attributable to more intensive deformation processes under the ice sheet base, which led to the homogenization of deposits in the ductile shear zone. Similar successions are commonly related to deformation tills (see Boulton and Hindmarsch, 1987; Hicock and Dreimanis, 1992; Van der Wateren, 2002). These deposits are characterized by a distinct gradient in the strain rate (Benn and Evans, 1996; Van der Wateren et al., 2000), due to changes in the shear strength, which depend mainly on the pore-water pressure. Usually the water pressure in subglacial deposits is higher close to the ice sheet base and consequently the rate of sediment deformation is there higher too (Van der Wateren, 2002; Iverson et al., 2003). Deformation origin of the till is also supported by the higher sand content in its lower part, resulting from of shearing and causing till enrichment with the underlying sandy deposits. This is supported by the clast orientation. Similar, quite low isotropy and high elongation values characterize the tills which underwent both brittle shear deformation and more intensive plastic shearing. However, in the second case mostly a weaker clast fabic was reported (Dowdeswall and Sharp, 1986; Benn, 1994; Hart, 1994, 1995; Benn and Evans, 1996). A similar clast-fabric pattern was also found in lodgement till (Hart, 1994; Benn and Evans, 1996).

The orientation of the kinematic structures in the basal part of the till and in the underlying deposits is slightly different than the fabric in the middle and upper parts of the till. It can be interpreted that, at a time when the till in the middle and upper parts of unit B1 were subjected to shear, its lower part was already outside the deformation zone and formed a more stable horizon (see Hart et al., 1990; Benn, 1995). The thickness of the deformed bed was presumably small (approx. 10–30 cm), much smaller than the thickness of unit B1 in its entirety, and probably its lower boundary moved steadily upwards while progressive deposition of till, took place. Gradual upward migration of a deformation zone as a result of accumulation of sediment beneath the glacier was postulated also by, among others, Hart and Boulton (1991) and Larsen et al. (2004). One of the arguments that support this interpretation is the similar value of the clast fabric in the whole till profile (cf. Larsen et al., 2004).

Unit B2 contains in its lower part also significant traces of deformation. Numerous attenuated lenses and stringers of sand were created as a result of folding and stretching of subglacial sediments in the shear zone (cf. Benn and Evans, 1996; Van der Wateren et al., 2000). Toward the top of the unit, the intensity of deformation increases, as expressed by smaller thicknesses of sorted sediment structures. Low-angle structures in the lower part passing into subhorizontal sandy lamination gradually disappear upwards resulting in a massive diamicton. The laminar character of the till and the higher sand content in its lower part indicate that intensive shearing took place at the contact of the two lithologically different beds. The laminar diamicton is similar to the glacitectonite described by Benn and Evans (1996) and Evans et al. (2006). The more finite strain can be attributed to the overlying massive diamicton. Probably it is the successive part of the same deformation horizon, where the more intense plastic shearing close to the ice sheet base led to sediment homogenization.

An important question is related to the origin of the sand in the bottom part of till B2. This type of sorted sediments within the till has often been interpreted in different ways (e.g., Ruszczyńska-Szenajch, 1987; Benn and Evans, 1996; Piotrowski et al., 2006). In this case it seems most probable that this deposit was connected with subglacial drainage. The structures of the sorted sediments related with subglacial water flows in the deformation till have been described by, among others, Brown et al. (1987), Benn and Evans (1996), Johnson and Hansel (1999). Initially the sand formed a much larger and more continuous lithosome within the till, but was later significantly destroyed as a result of shearing.

The till at the Biała site has most features of a deformation till. A distinct variation in the strain rate in the till succession indicates a complex formation process, evolving over time. The till was deposited mainly as a result of particles stabilizing from the base of the deformation horizon, which moved slowly upwards. However, this was not a continuous process. It seems that the changes in the intensity of the deformation were strongly related with the development of subglacial drainage. A meltwater flow at the ice-bed contact was possible when the effective pressure in the glacier base was close to zero. According to Iverson et al. (1994, 1995, 2003) the intensity of subglacial shearing decreases under such conditions as a result of decoupling of the glacier from its bed; thus the shear stresses affecting the till were significantly reduced. Consequently, the intensity of the deformation as well as the thickness of the deformation horizon had to decrease. Moreover, the drainage caused a temporal reduction of the pore-water pressure, which in turn gave rise to a local increase in sediment consolidation. The local increase of sediment shear strength probably was also derived from the presence of sand bodies (connected with subglacial meltwater flows) within the till. The sand was not equally intensively sheared as the till. Consequently it was not completely mixed with the diamicton and locally was preserved in the form of macroscopically visible structures.

THE GŁOGÓWEK SITE

The Głogówek gravel pit is situated on the outskirts of the town of Głogówek, approx. 1.5 km E of the Osobłoga River valley (left bank tributary of the Odra River). It is located close to the northern edge of the Głubczyce Plateau, on the wide accumulation plain that gently slopes toward the Odra valley (Fig. 1). The area is built of Quaternary deposits of 10–30 m thick, mainly alluvial gravel and sand, which cover the Neogene succession.

LITHOFACIES DESCRIPTION

In the lower part of the exposure a massive gravel occurs (Fig. 7). A 1.5–2.0 m thick layer of sand and gravelly sand covers the lower gravel. These deposits form a lithofacies with horizontal, trough or planar cross-stratification. Directional and petrographic data indicate that the sediments under the till were deposited by a river running from South. They were deposited prior to the ice sheet advance on the vast, gently sloping Osobłoga River alluvial plain. A till overlies the gravelly-sandy sediments (Fig. 7). Its erosional top is covered by loess.

The till in the exposure reaches a thickness of up to 2 m. It is a matrix-supported sandy diamicton of rusty brown colour, with a low content of gravel. The matrix contains on average 55% sand, 25% silt and 20% clay. Locally a thin (1–3 cm) layer of massive sand with destroyed sedimentary structures is present below the till. The underlying deposits are commonly not deformed. They contain only few low-angle or subhorizontal shear plains. The basal contact is sharp and flat (Fig. 8A). Only in a few places small till wedges and folds occur (Fig. 8B). The till has a massive structure. In the lower part of the unit rare elongated sand lenses are visible. These structures are slightly inclined toward the north (Fig. 8C). In the basal part of the till, an

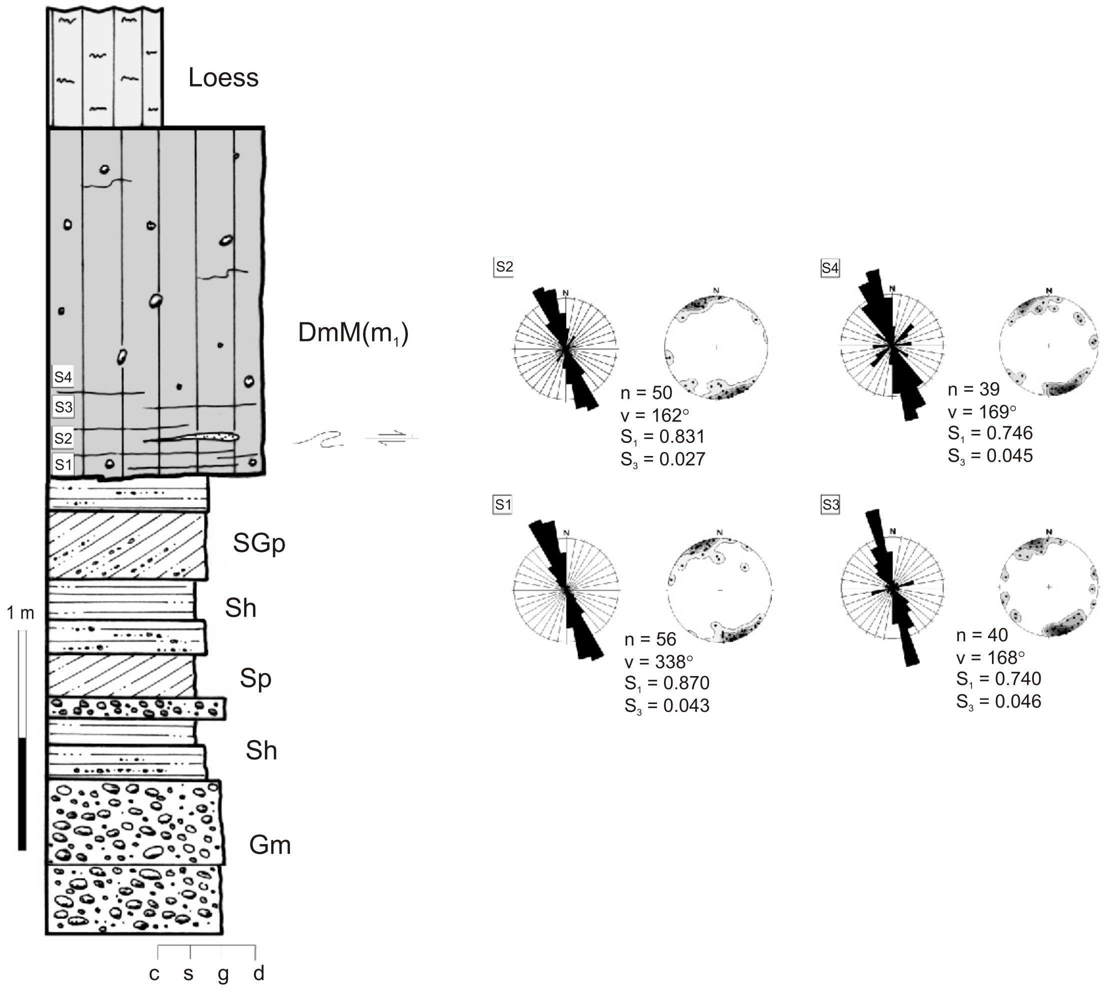

Fig. 7. Schematic sediment log and clast fabrics at the Głogówek site

For explanations see Figure 3 and Table 1

elongated granite boulder was found (Fig. 8D). It was situated inclined into the direction of the ice sheet movement toward the SSE and it dipped 40°. The basal part of the till below the boulder is slightly bent downwards so that the boulder does not protrude from the till into the underlying deposits (Fig. 8D).

The fabric shows a very strong orientation of the clasts. The values of the vectors are S_1 = 0.740–0.870, and S_3 = 0.027–0.046. The isotropy parameter is low (I = 0.03–0.062), whereas the elongation parameter, in turn, is high (E = 0.91–0.83). The mean direction of the long axis alignment is NNW–SSE (Fig. 6). The distribution is unimodal.

INTERPRETATION

The flat and sharp lower boundary, the massive structure, and especially the very high values of clast arrangement suggest that the diamicton is a basal till. The same features, together with the low frequency of deformation structures in the underlying sand, suggest lodgement as the main process of till formation. In turn, the individual attenuated sand lenses that are present in the lower part of till indicate at least local deformation. The sand lenses most probably represent deposits from the substrate incorporated in the till. A small number of these structures suggest that the folding occurred only locally, or that the intensity of deformation was so high that the incorporated sands became completely mixed with diamicton (cf. Boulton, 1996; Van der Wateren, 2002). The till origin can also be deduced from the orientation of the large boulder in the basal part of the till. The inclination of the boulder in the direction of ice sheet movement suggests that it was rotated as a result of shearing. In a lodgement till, large boulders usually are oriented subhorizontally (Hart, 1995). Before detachment from the ice, they usually plough the underlying deposits (Brown et al., 1987; Tulaczyk et al., 2001). In the case under study, however, the downward bending of the lower boundary of the till below the boulder suggests rather its vertical rotation than ploughing (Fig. 9). Moreover, the upper surface of the boulder shows no clear signs of abrasion as typical for lodgement till (Piotrowski et al., 2001). Hart (1994) claimed that the rate of clasts arrangement in thin deformation tills can also be very high. The same conclusion was reached by Hooyer and Iverson (2000) on the basis of laboratory experiments.

From this follows that an unequivocal identification of the till origin is difficult. For its formation, both lodging and deformation processes were presumably important. It seems that the lower part of the till probably formed a stable substrate for the glacier. This may have been caused by the highly permeable gravel and sand underneath. In this way the till could have been effectively drained, but in spite of this the basal pore pressure was probably high enough for at least local shear-induced deformation of a thin layer below the base of the ice sheet. It suggests that gravel and sand deposits of the substratum were not sufficient

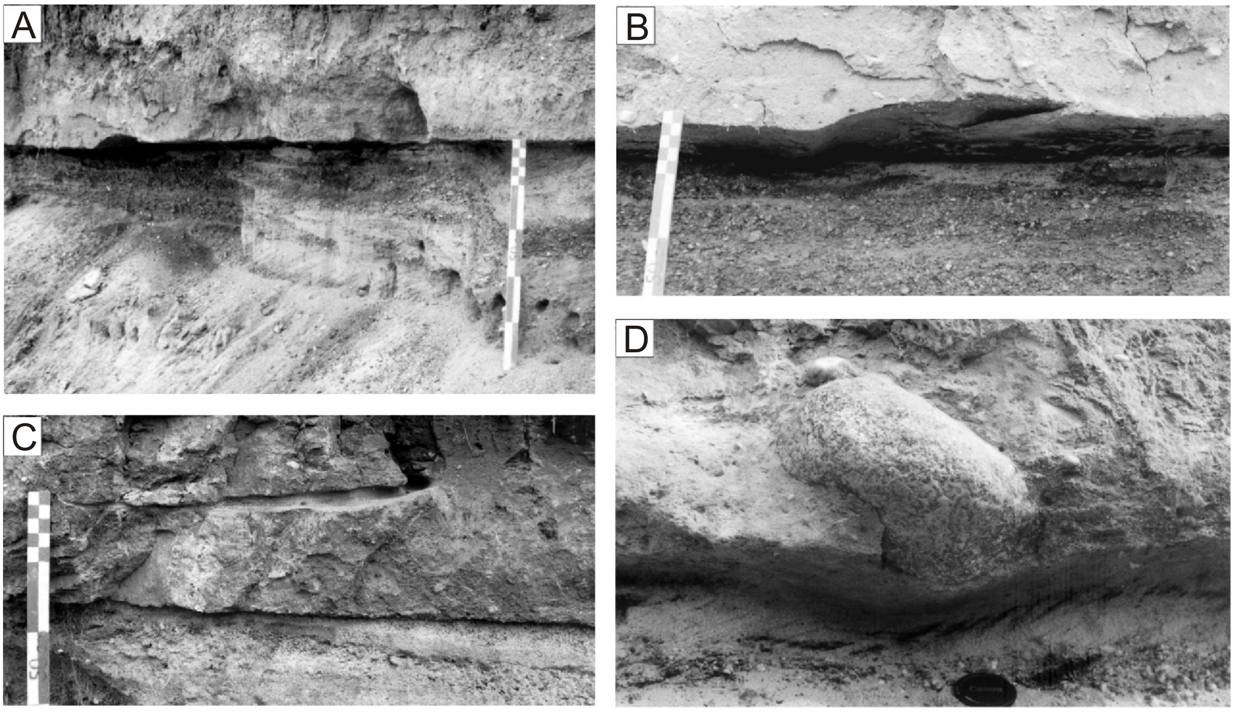

Fig. 8. Till at the Głogówek site

Sections in all photographs oriented approximately parallel to the former ice sheet movement direction, which was from left to right; **A** – sharp contact of the till with the underlying sandy-gravelly deposits; **B** – small deformation structure (recumbent fold) in the contact zone; **C** – single elongated sand inclusion in the bottom part of the till; **D** – granite boulder in the basal part of the till, the boulder dips into the direction of ice sheet movement, the lower boundary of the till just below the boulder is slightly bent downwards

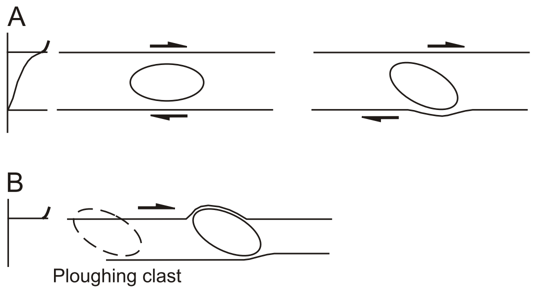

Fig. 9. Scheme of potential boulder behavior at the ice sheet base

A – in the deformation till, as a result of clast rotation the bottom till surface below the clast is bent downwards; **B** – in the lodgement till, clast ploughing preceded its deposition, the lower boundary of the till below the ploughing clast is flat

to evacuate total mass of meltwater produced at the ice-bed interface. This conclusion is supported by the small amount of brittle deformation, which would be expected if the till had covered a well drained substratum, thus preventing maintenance of a high basal water pressure.

DISCUSSION

SUBGLACIAL CONDITIONS AND MECHANISMS OF ICE SHEET MOVEMENT

The three sites under study provide some clues that help reconstructing the depositional and deformational conditions (thermal regime, basal pore water pressure) present at the base of the Upper Odra ice lobe. The till with few deformations and numerous traces of subglacial water flows at the ice-bed contact, and the deformation till indicate that the ice at the base of the Upper Odra ice lobe was in the melting point of ice under pressure (Fig. 10). Both types of till suggest a low effective pressure in the ice sheet base, as a consequence of the high pore-water pressure there. At least locally (see the Niwnica site) it had reached values equal to the overburden ice pressure.

The basal till without distinct deformations and with numerous traces of subglacial meltwater flows suggests that the ice sheet was mostly sliding (see Brown et al., 1987; Piotrowski and Tulaczyk, 1999). Horizontal laminae of sorted sediment in the basal part of the till at the Niwnica site record the process of hydraulic flow in the glacier's sole as a result of a very low effective pressure, causing ice sheet flotation. Separation of the ice sheet from its bed by a water film reduced both the friction in the contact zone and the shear stress affecting the subglacial deposits. The most extensive slip probably took place then. Piotrowski and Kraus (1997) and Piotrowski and Tulaczyk (1999) assumed that, if the effective pressure in the Scandinavian Ice Sheet base was permanently low (approx. 0), ice sheet movement as a result of sliding could occur all the time.

The presence of deformation till (the Biała site) indicates that in some areas the ice sheet also moved as a result of subglacial shearing of deposits. In that case, the ice-bed coupling had to be stronger. Presumably the effective pressure reached low values (which resulted in a low shear strength of the deposits), but as a rule higher than zero. These conditions enabled the transfer of the shear stress from the sole of the moving ice sheet to the underlying sediments and consequently their deformation (see Brown et al., 1987; Iverson et al., 1995, 2003; Piotrowski and Tulaczyk, 1999; Tulaczyk, 1999; Bennett, 2003). The different scales of finite shear strain in the vertical

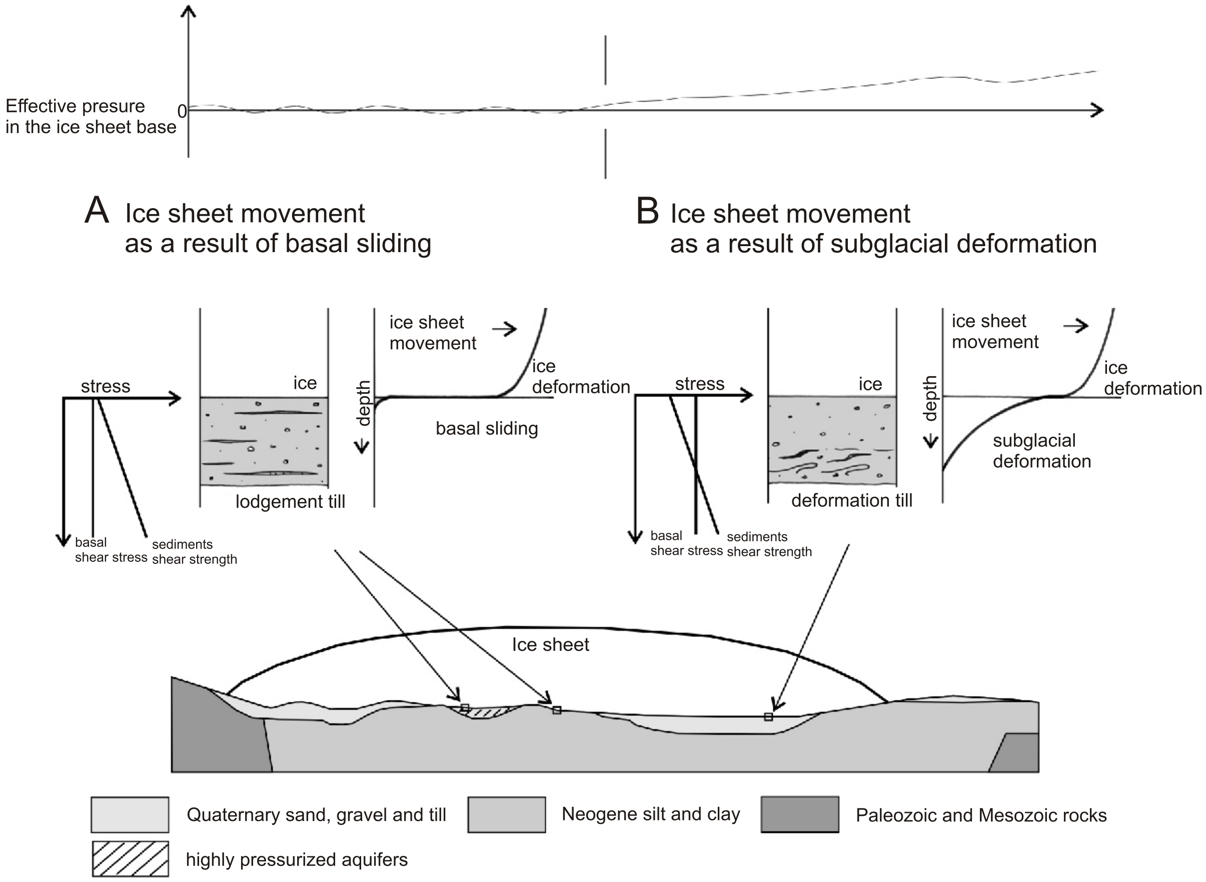

Fig. 10. Simplified diagram showing the main mechanisms of the Upper Odra ice lobe movement and their connection with subglacial conditions, which determine the strength of the substratum and the style of subglacial deposition

profile of till reflect the periodic variation of its intensity. The sands derived from unchannelized or poorly channelized subglacial meltwater flows, which were involved in the deformation structures, suggest that periodically conditions of significant reduction of deformation intensity could exist at the ice sheet base. The effective basal pressure was then close to zero, which could induce basal sliding. However, the drop of the pore-water pressure after an episode of drainage was probably much larger than in the case of the till with few deformations and with traces of subglacial water flows at the ice-bed contact. This indicates that a deformation till can archive the cycles of changes in strain rate, including their diminishing, ceasing and reactivation (see Boulton et al., 2001; Larsen et al., 2004; Piotrowski et al., 2004; Narloch et al., 2012, 2013). This conclusion is consistent with the observations of some modern glaciers, which indicate temporal variations of the basal movement type: from subglacial deformation to basal sliding as a result of changes in the basal water pressure (Blake et al., 1992, 1994; Fischer and Clarke, 1994, 1997, 2001; Iverson et al., 1994, 1995; Hooke et al., 1997; Fischer et al., 1999; Hart et al., 2009). If the water pressure at the base of the Upper Odra ice lobe fluctuated largely all the time, the just-mentioned changes of basal movement could occur often and even cyclically. However, it seems that these changes can be recorded rarely in the till, due to later deformation processes, which erase the sedimentary traces of slip phases (see Evans et al., 2006).

The till at Głogówek seems more difficult to interpret. It can be considered as a subglacial traction till resulting from a wide range of processes, including clast lodgement and sediment deformation (Evans et al., 2006). This example of till is very important for the study area, because similar quite coarse-grained deposits constituted mostly the ice sheet base in the axial part of Upper Odra ice lobe which advanced through a large valley filled with alluvial deposits. The highly permeable gravelly-sandy substrate suggests that relatively efficient drainage of basal meltwater could take place there through intergranular flow. On the other hand, the lack of distinct evidence of brittle deformations at the Głogówek site does not indicate a high stress in the subglacial sediments, which should have been recorded in the till under high-friction conditions. Presumably the basal meltwater pressure was relatively high there, despite the coarse-grained texture of the underlying sediments. This was probably an effect of the presence of poorly permeable sediments below the gravelly-sandy alluvial series, and probably also large quantity of subglacial meltwater which has been produced at the ice bed.

The three sites dealt with in the present study indicate a complex process of till deposition by the Upper Odra ice lobe. They prove spatial and temporal variations of the mechanisms involved in the basal ice sheet movement. It was mainly the effect of fluctuations in the subglacial pore-water pressure, which was strongly related with the geology of the ice sheet's substratum. The results of this study are consistent with the concept of a mosaic character of the substratum of former ice sheets, composed of stable, non-deformed, mostly sliding and deformed patches (Piotrowski et al., 2004). It seems that, in the case of the Upper Odra ice lobe, subglacial deformation was an important parameter for the ice sheet movement, although its role cannot be estimated precisely. The deformation did not have a pervasive character and was probably restricted to a thin bed, of which the thickness was changing with time.

THE INFLUENCE OF THE SUBSTRATUM'S LITHOLOGY ON THE LOBE DEVELOPMENT

The till deposition took place under spatially different conditions resulting largely from the different types of sediment of the ice sheet substratum (Figs. 2 and 10). The lithology of these sediments and the basal pore-water pressure, which affected the shear strength of the deposits of the bed and the strength of the ice-bed coupling, were directly related (see Kamb et al., 1985; Iverson et al., 1994, 1995; Piotrowski et al., 2004; Evans et al., 2006). The subglacial water pressure depended on the rate of meltwater supply, but also on the granulometry of the sediments, which influenced the permeability of the ice sheet substratum (Boulton and Jones, 1979; Boulton et al., 2001; Piotrowski et al., 2004; Roberts and Hart, 2005; Piotrowski et al., 2006). In the study area, the impact of the substratum lithology on the subglacial hydraulic conditions was, however, not always straightforward. It seems that very fine-grained sediments, such as clays, which can be regarded as aquitards, had a direct influence. It caused an immediate increase of the basal water pressure and triggered slip at the base of the ice. The Upper Odra ice lobe moved directly over a clayey bed only in restricted areas (Fig. 2), especially in some inter-valley regions. In the cases where the sediments at the base of the ice sheet were more permeable, such as in the case of sand and gravel, its relationship with the subglacial hydrology and basal pore-water pressure was more complex: in addition to the granulometry of the deposits also their thickness, lateral extent and the geometry of the aquifers were very important. The outflow from these water-bearing horizons could sometimes take place without problems, but in other cases the basal water could not flow out freely and thus became stored, with consequently an increase in pore-water pressure, in spite of the their coarse-grained nature. It appears from the present study that, in the zone of valleys where the ice flow was concentrated, probably conditions prevailed that favoured the maintenance of a high subglacial water pressure. This was caused by the presence of the low-permeability Neogene clay under the Quaternary sediments. Important were also the geometry and the size, e.g. the thickness and lateral extent of the deposits in the valleys; these deposits become thinner toward the south, which caused even a further increase of the pressure of the subglacial water.

The possible impact of permafrost in the study area is not known. Its occurrence at the ice sheet margin may have significantly affected the basal water pressure through a possibly significant reduction of ground water outflow from thin subsurface aquifer horizons onto the area in front of the ice sheet (see Piotrowski, 1997; Clayton et al., 1999; Cutler et al., 2000; Waller et al., 2009; Wysota et al., 2009; Narloch et al., 2013; Szuman et al., 2013). A single wedge structure, which could indicate the presence of permafrost before the ice sheet advanced, was present in the gravel under the till at the Głogówek site. This makes impact of this factor on the subglacial processes highly probable, although further study of this issue is required.

In comparison to the areas of the river valleys, it seems that in the inter-valley areas, where the thickness of the Quaternary deposits is small (Biała site) or where Neogene clays are exposed at the surface (Niwnica site) even higher pressure conditions could have occurred at the base of the ice sheet. The resistance that this substratum exerted on the advancing ice sheet was locally smaller here than in the valleys, which theoretically could have resulted in a faster movement of the ice sheet. The present study suggests that it was, however, just the opposite: a slightly lower rate of ice sheet movement in the inter-valley area, especially in the more outer zone of the lobe, must have resulted from the more varied relief of the substratum. Consequently, glaciotectonic deformations could have developed more frequently; these were the result of friction caused by morphological obstacles. As a result, the largest valleys remained the main pathways of the moving ice.

Another important and poorly recognized issue on the study area is the nature of the subglacial drainage system. It has become clear from numerous studies that the subsoil of the Scandinavian Ice Sheet was not able to drain the total mass of water through the sediments at the base in the form of groundwater flows (Piotrowski, 1997; Piotrowski et al., 2001, 2006). The most effective drainage took place through specific drainage systems, mainly large tunnel valleys (cf. Piotrowski, 1994; Clayton et al., 1999). However, subglacial drainage could take also another forms, for instance through a network of smaller channels, linked cavity systems or a thin water layer at the ice-bed interface (Benn and Evans, 1996; Evans et al., 2006).

In the area of Upper Odra ice lobe only few large subglacial tunnel valleys have been recognized, and these were almost all connected with older glaciations (Lewandowski, 1988). Only one erosive subglacial tunnel, with a system of eskers correlated directly with the Upper Odra ice lobe, was found in the northern part of the study area (Salamon, 2009). An important question is why no more large tunnel valleys were formed there. The lack of them can indicate the presence of a more diffuse drainage system in the form of linked cavities, canals or smaller braided channels (see Clark and Walder, 1994; Walder and Fowler, 1994) or sheet-like flows (see Piotrowski et al., 2001; 2006; Creyts and Schoof, 2009; Lesemann et al., 2010). It seems that this would favour the lobe development by continuous maintaining high-pressure conditions, which facilitated the relatively rapid flow of ice.

The tills under study indicate that the conditions at the base of the Upper Odra ice lobe favoured fast ice flow, suggesting that the lobe was continuously fed by the main ice stream (Salamon, 2012), especially that the tills were deposited in the more marginal part of the lobe, away from the central area where a higher ice velocity would be expected.

CONCLUSIONS

The till of the Upper Odra ice lobe is characterized by variations in space. As a rule, the lower part of the till profiles consists of a basal till with different intensities of deformation, associated with active ice movement.

The variety of basal tills indicates that a large lateral differentiation of conditions occurred in the substratum of the Upper Odra ice lobe. This was largely the result of the varying lithology of the ice sheet base. The lithology controlled the basal water pressure, and thus the strength of the ice-bed coupling, as well as the strength of the subglacial sediments themselves. The various strain rates in the till profiles indicate that the conditions at the ice sheet base also changed with time; the fluctuations of the basal water pressure were probably the main reason.

The low permeability of the Quaternary substratum, built mainly of Neogene clays, and the relatively small thickness of the Quaternary sands and gravels, which constitute the main aquifers, resulted in a high water pressure at the ice sheet base. Consequently the ice sheet was highly mobile, even on the coarse-grained substratum.

The movement of the Upper Odra ice lobe was concentrated at the basal zone of the ice sheet. The main mechanisms of basal motion were sliding and the deformation of subglacial sediments. Intensive subglacial deformation occurred only in restricted areas. Their intensity varied with time, together with changes of the effective pressure.

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