Record of the Vistula ice lobe advances in the Late Weichselian glacial sequence in north-central Poland

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A B S T R A C T

During the Last Glacial Maximum (LGM), the Vistula ice lobe was one of the key morphological elements at the southern margin of the Scandinavian Ice Sheet in north-central Poland. The area of the Vistula ice lobe experienced two ice sheet advances of varied extent: the older one is correlated with the Leszno (Brandenburg) Phase and the younger one is correlated with the Poznań (Frankfurt) Phase. Sedimentological research and luminescence dating of the Late Weichselian glacial sequence in the Vistula ice lobe area was conducted. A new scenario of the Late Weichselian ice events in the area is presented. The limit of the Leszno Phase within the Vistula ice lobe was much smaller than had been accepted previously, and its age is estimated to be about 20,300 BP. Significant ice sheet retreat was followed by an ice re-advance during the Poznań Phase, overriding the extent of the Leszno Phase. The Poznań re-advance reached the maximum limit in the Vistula ice lobe area about 18,400 BP. The rapid ice sheet transgression, especially during the Poznań Phase (on average 400 m/a), was connected with the Vistula palaeo-ice stream.

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1. Introduction

Ice lobes were characteristic elements in the morphology of Weichselian land-based ice sheet margins. They were particularly clearly visible in the geological and geomorphological signature at the southern periphery of the Laurentide Ice Sheet during the Last Glacial Maximum (LGM) and the later stages (e.g. Mickelson and Colgan, 2004). The lobes were dynamic parts of the ice sheet margins and are interpreted as surges or terminations of terrestrial palaeo-ice streams (e.g. Clayton et al., 1985; Patterson, 1997, 1998; Stokes and Clark, 2001; Jennings, 2006).

The southern margin of the Scandinavian Ice Sheet (SIS) during the LGM on the Central European Lowland was also a lobate configuration (Woldstedt, 1935, 1954; Boulton et al., 2001; Houmark-Nielsen, 2004). In northern Poland there were a few larger ice lobes, including the Vistula ice lobe in central Poland (Fig. 1). Nowadays, the functioning of these lobes is studied in connection with former terrestrial palaeo-ice streams (Punkari, 1993; Boulton et al., 2001; Marks, 2002; Wysota, 2002).

It is now accepted that the southern maximum extent of the ice sheet during the LGM in Poland is asynchronic (see Marks, 2002, 2004). In western Poland it was associated with the Leszno (Brandenburg) Phase, and in central and eastern Poland with the younger Poznań (Frankfurt) Phase. These extensions were predominantly based on the morphostratigraphic criteria but in some areas they are also indicated by lithostratigraphic, biostratigraphic and geochronological data. In accordance with the research, it is assumed that the maximum extent of the last ice sheet in the Late Weichselian did not take place before 21 ka BP (Kozarski, 1986, 1988, 1995; Stankowska and Stankowski, 1988).

The number and the age of the advances (the Leszno or Poznań Phase) as well as the dynamics of the ice sheet during the LGM remain controversial issues, especially in the case of the Vistula ice lobe (Wysota and Molewski, 2007). Moreover, the conditions in which the Vistula ice lobe functioned and its role in the ice dynamics of the southern sector of the SIS during the LGM are also key issues.

The paper presents the course of the glacial events in the Vistula ice lobe during the Late Weichselian in accordance with the authors’ research. The records in the glacial sequence of the given period of time in the selected regions of north-central Poland are included. The stratigraphy of the deposits in the key sections together with their palaeoenvironmental interpretation is shown. A discussion referring to the extent and the age of the Vistula ice lobe advances during the Late Weichselian was undertaken.

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2. Regional setting

The study area is located in the north-central part of Poland. It includes compact areas of morainic plateaus cut by the Vistula Valley (Fig. 2). Its southern limit is the maximum extension of the SIS during the LGM. The south-western part of the study area is the eastern part of the Great Poland and the Kujawy, which are limited by the channel of Lake Gópło and the Notec Valley. The north-eastern part of the research area includes the Dobrzyń and Chełmno Plateaus which are separated by the Drwęca Valley. The northern part of the analysed area, located along the Vistula Valley, is known as the Lower Vistula Region.

The elements which dominate in the landscape of the study area are till plains (Galon, 1964). Their surface is cut by tunnel valleys and valley landforms of various origins which developed during both the presence and waning of the last ice sheet (Majdanowski, 1947; Niewiarowski, 1983, 1995). The research area includes a number of glaciomarginal features, mainly morainic hills and hummocks which, together with tunnel valleys and small outwash plains, have been used to determine the maximum extent of the ice sheet as well as its early retreat phases during the LGM (Galon and Roszkówna, 1961; Kozarski, 1988; Stankowska and Stankowski, 1988).

The Vistula Valley constitutes the morphological axis of the study area. Within the analysed area the Vistula Valley partly follows the course of the buried valley from the Eemian Interglacial (Wiśniewski, 1976; Makowska, 1980). It was formed by the river and meltwater during the retreat and waning of the last ice sheet. The Vistula Valley cuts the neighbouring morainic plateaus and thus the Pleistocene deposit sequences, including those from the Weichselian Glaciation, become exposed in numerous sections.

The Weichselian deposit complex in the research area includes up to three till layers which are separated from each other by glaciofluvial, glaciolacustrine and/or fluvial series. They are correlated with the three advances of the SIS: the Toruń advance in the Early Weichselian, the Świecie advance in the Middle Weichselian and the main advance in the Late Weichselian; they are separated from each other by ice-free interstadials (Drozdowski, 1980; Makowska, 1980, 1992; Drozdowski and Fedorowicz, 1987; Mojski, 1992, 1995). Some researchers suggest the ice sheet might have advanced into the Vistula ice lobe area during the Early and Middle Weichselian (Makowska, 1986; Marks, 1988). However, the idea of the ice advance into this area in that time has been criticised (Wysota, 2002). The presence of the SIS to the south of the Lower Vistula Region before the Late Weichselian has not been proved to date (Stankowska and Stankowski, 1988; Stankowski, 2000; Wysota, 2002). As a result, the authors of the paper refer the issue of the ice sheet advances into the Vistula ice lobe area only to the Late Weichselian.

In accordance with the recent research, various scenarios are accepted in terms of the glacial events within the Vistula ice lobe during the Late Weichselian. On the basis of the geomorphological criteria Galon (Galon, 1961; Galon and Roszkówna, 1961) assumed that the maximum of the last glaciation in the Vistula ice lobe took place during the Leszno Phase (Fig. 3A). Galon determined the limit of the maximum extent of the ice sheet advance of the Poznań Phase. Kozarski (1986, 1988, 1991), based mainly on morphostratigraphic criteria, assumed that after the maximum advance during the Leszno Phase the ice sheet’s margin retreated to the new stationary line in the central Great Poland (the Poznań Phase). However, further to the east, towards the Vistula Valley Region, the Poznań Phase ice advance crossed the limit of the Leszno Phase (Fig. 3B). Thus, according to Kozarski, the southern side of the Vistula ice lobe experienced another ice advance during the Poznań Phase. This concept referred to the earlier views of Woldstedt (1925, 1954) and Mojski (1968, 1969). Kozarski’s scenario (Kozarski,
(1986, 1988, 1991, 1995) of the course of glacial events within the Vistula ice lobe during the LGM was adopted by other authors (e.g. Boulton et al., 2001; Houmark-Nielsen and Kjær, 2003). According to other views, the limit of the ice sheet to the east of Konin was similar during both phases (Stankowska and Stankowski, 1988, 1991). However, to the west of Konin the limit of the maximum extent of the last ice sheet during the Leszno Phase is hypothetical (Stankowska and Stankowski, 1988, 1991; Petera and Forysiak, 2003).

Most of the opinions regarding the extent of the last glaciation in the Vistula ice lobe were based on ambiguous morphostratigraphic criteria, although a few lithostratigraphic data referring to the glacial events in this area do exist. In the Konin area there is mainly one till, which overlies glaciofluvial deposits connected with the maximum ice advance during the LGM (Stankowski and Krzyszkowski, 1991; Stankowski et al., 1999). Below those deposits, in the Maliniec site (Fig. 2), the fluviolacustrine series was documented (the Maliniec series). It includes organic interbeddings which were deposited shortly before the LGM. Radiocarbon dating of those deposits indicated ages of 22,050 ± 450 14C BP and 22,230 ± 480 14C BP (Pazdur et al., 1980). The conversion of the above radiocarbon ages to calendar ages, based on the Fairbanks calibration program (Fairbanks et al., 2005), gave the following results: 26,507 ± 555 cal BP and 26,720 ± 580 cal BP, respectively. The Mikorzyn site (Fig. 2) is the only one which revealed two separate tills interbedded by the glaciofluvial deposits and with ice-wedge casts developed in the lower till above the Maliniec series (Kozydra and Skompski, 1996; Stankowski et al., 1999).

In Kaliska and Ruszkówek in the southern part of the Kujawy (Fig. 2) the sections of the Eemian Interglacial deposits were documented. They are overlain by one till, which suggests one ice advance in the area during the last glaciation (Domosiawska-Baraniecka and Mojski, 1960; Domosiawska-Baraniecka, 1961; Kozydra and Skompski, 1995). This is also indicated by the studies undertaken by Roman (2003, 2007a, 2007c) in the south-eastern part of the Kujawy.

Two Late Weichselian tills separated by sand deposits were recorded in the southern part of the Dobrzyn Plateau (Ber, 1960, 1968; Łyczewska, 1960; Skompski, 1969) (Fig. 2). According to Mojski (1984), those tills refer to the Leszno Phase (the lower till) and the Poznań Phase (the upper till). Moreover, Mojski (2005) assumes that the maximum ice sheet extent during the Late Weichselian took place at the Leszno Phase. The two tills exposed on the Drwęca Valley slopes and in the northern part of the Dobrzyń Plateau, are interpreted as the record of two advances of the Last ice sheet in the north-eastern side of the Vistula ice lobe (Niewiarowski and Wysota, 1994; Wysota, 1999). According to the recent interpretation, however, those tills show ice advances of the Leszno Phase and the Poznań Phase during the Late Weichselian (Wysota, 2002). It is also assumed that the maximum extent of the
ice sheet in the north-eastern side of the Vistula ice lobe took place during the Poznań Phase.

Thus, taking into consideration all the research carried out so far, the following questions referring to the glacial events in the Vistula ice lobe during Late Weichselian may be put forward:

- Do the Leszno and Poznań Phases show lithostratigraphic separation from each other in the study area?
- What are the spatial relations between the ice sheet maximum extensions of the Leszno and Poznań Phases in the Vistula ice lobe?
- Did the Poznań Phase in the north-central Poland form a pan-regional transgression?
- What was the age of the ice sheet advances in the Vistula ice lobe area during the Late Weichselian?

3. Methods

The investigations were based on conventional sedimentological techniques combined with luminescence dating methods. Sedimentological studies were conducted at 14 key exposures located in four regions (Fig. 2): the southern part of the Lower Vistula Region, the north-eastern Great Poland, the north-eastern Kujawy, and the western Kujawy. The lithofacial analyses at the exposures were carried out to identify sedimentary units within each section and to recognise sedimentary environments. Till fabric data were collected by measuring the orientation of a-axes of at least 25 elongated pebbles of the length ranging from 1 to 10 cm and with an a/b ratio > 1.5. Measurements of deformation structures (faults, minor folds) beneath the till units and the orientation of striae on the top surfaces of stones in the till were taken. The orientation of palaeocurrents in both fluvial and glaciofluvial facies was measured.

Petrographic characteristics of the till facies were also examined. Gravel petrography was analysed for 5–10 mm size clasts. At least 300 pebbles from each sample were identified. Gravel components were subdivided into two major petrographic groups: rocks of the northern provenance (the Scandinavian and the Baltic depression: crystalline rocks; Palaeozoic limestones, dolomites, sandstones and shales; older quartzitic sandstones, quartzites, and quartz), and rocks of the local provenance (the South Baltic depression and Northern Poland: Mesozoic limestones, sandstones, marls, flint, chert; Neogene mudstones).

Due to the lack of organic material, samples for luminescence dating (TL and OSL) were collected from the sediment exposures. The samples were taken from glaciofluvial, fluvial and glaciolacustrine sand/silt. A few samples were also taken from the sand infilling of ice-wedge casts. A total 14 TL samples and 25 OSL samples from 14 sections were subjected to dating (Table 1). The TL samples from the southern part the Lower Vistula Region and the OSL samples from the Kujawy area were analysed at the laboratory of the Luminescence Dating of the Nicolaus Copernicus University in Toruń, Poland. The OSL samples collected from the north-eastern part of the Great Poland were analysed at the Luminescence Dating Laboratory of the Silesian University of Technology in Gliwice, Poland.

In both laboratories, 0.1–0.2 mm quartz grains (Toruń laboratory) and 0.09–0.125 mm (Gliwice laboratory) size intervals extracted from sand samples were used for TL/OSL dating. In the case of the TL measurements the regenerative procedure was used in the Toruń laboratory. The single-aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2000) was applied to OSL measurements both in Toruń and Gliwice laboratories. All the TL and OSL measurements in the Toruń laboratory were carried out by the Riso TL/OSL reader, model TL/OSL-DA-12. The OSL equipment Daybreak 2200 was used to the OSL measurements in the Gliwice laboratory. The annual dose rates were measured with the help of the Canberra gamma spectrometer in Toruń and Gliwice laboratories. The details
of the measurement and computational procedures (TL and OSL) applied in both laboratories were published previously (Oczkowski and Przęgijka, 1998; Bluszcz, 2000; Oczkowski et al., 2000; Molewski et al., in press). Simplified sediment logs of the investigated exposures with distinguished lithostratigraphic units, results of macrofabric data (till fabric, palaeocurrent and structural data) presented as single arrows (resultant vectors), and the results of the luminescence dating are presented in Figs. 4, 7 and 8.

4. Results

4.1. The southern part of the Lower Vistula Region

In the southern part of the Lower Vistula Region there is a thick (in some cases up to 70 m) sedimentary succession, which formed during the Weichselian Glaciation and overlies terrestrial formations of the Eemian Interglacial (Makowska, 1976, 1980). The Weichselian complex in this area has recently been studied in detail (Wysota, 2002, 2007; Wysota et al., 2002). In the upper, exposed part of the sedimentary succession, two major lithostratigraphic units have been distinguished: the Rzeczckowo Formation and the Starogrod Formation. The Rzeczckowo Formation (unit L1 in Fig. 4) is composed of fluvial sediments. Overlying it, the Starogrod Formation consists of four glaciogenic elements: L2 – the Unistaw clays, L3 – the Łazyń till, L4 – the Kiep clays, and L5 – the Starogrod Zamek till (Fig. 4).

4.1.1. Unit L1

Unit L1 (Rzeczckowo Formation) is composed of well-sorted fine-grained and medium-grained sands, predominantly with planar cross-bedding and horizontal lamination as well as ripple or climbing-ripple cross-lamination (Fig. 4). In some places there are thin interbeddings of horizontally or ripple cross-laminated silty sands and silts, sometimes with deformations such as loads and pseudonodules. In those deposits scattered plant detritus was recorded. The thickness of the Rzeczckowo Formation in the studied profiles reaches up to 23 m.

The sediments of the Rzeczckowo Formation were deposited in a sand-bed braided river environment (Wysota et al., 1996; Wysota, 2002). The sedimentation took place in periglacial conditions with sparse or tundra vegetation. The palaeocurrents indicate a southern direction of palaeotransport.

A total of 10 TL samples related to the Rzeczckowo Formation were dated from 7 sections (see Fig. 4 and Table 1). The ages obtained suggest that the Rzeczckowo Formation originated during the Middle Weichselian, between 65 and 30 ka (Wysota, 2002; Wysota et al., 2002). The mean age of 42.9 TL ka with standard uncertainty of ± 1.7 ka was obtained by the weighted averaging method.

4.1.2. Unit L2

Unit L2 (Unistaw clays) includes glaciolacustrine clays and silts, generally 2–6 m, but sometimes up to 12 m thick (Wysota, 2002).
Locally, they interfinger with glaciofluvial sands. In the Unistaw section they overlie fluvial deposits of the Rzeczkwowo Formation and underlie the glacial unit L3 (Fig. 4). Those are mainly structureless and horizontally laminated clays and silts 2.1 m thick. They were accumulated in a shallow glaciolacustrine basin during the ice sheet advance.

4.1.3. Unit L3

Unit L3 (the Łazyn till) is commonly 1.5–10 m thick, locally thicker (Fig. 4). It overlies fluvial sands of the Rzeczkwowo Formation (Fig. 5A), and rests in some places on glaciolacustrine clays and silts (the Unistaw clays). Three basal till facies were distinguished in the Łazyn till (Wysota, 2002, 2007). The lowest facies consists of a yellow-brown sandy till (0.5–2.5 m thick) with characteristic sand inclusions forming detached and attenuated folds (Fig. 5A). Usually, fluvial sands beneath the till commonly show soft-sediment deformations in the form of small recumbent folds and shear planes. This facies is overlain by a bedded till (up to 0.7 m thick) characterised by alternating diamictons and sorted sediment layers. Locally, the bedded till is covered by a horizontally laminated or massive clay of 20 cm up to 2.2 m thick. The uppermost facies is a homogeneous, commonly brown sandy till that covers bedded till, but locally it overlies the lowest till facies or fluvial sands of the Rzeczkwowo Formation.

The petrographic composition of the L3 till reveals a predominantly northern provenance (Fig. 6); limestones (52%) and crystalline rocks (32%) dominate. Palaeozoic dolomites also occur (6%). The portion of rocks of local provenance is small (6%).

The Łazyn till facies records complex depositional processes during the first Late Weichselian ice advance (the Leszno Phase) in the southern part of the Lower Vistula Region (Wysota, 2002). The lowest till facies is interpreted as a deformation till, the middle facies was formed during recurrent periods of subglacial melt-out followed by meltwater sedimentation, and the upper till facies was deposited by subglacial melt-out (Wysota, 2007). Till fabric data and orientation of subtil facies show predominantly the NE ice flow direction in the area.

4.1.4. Unit L4

Unit L4 (the Kiep clays) is represented by clays and silts, commonly up to 5 m thick, locally thicker (Wysota, 2002). They consist mainly of rhythmically laminated, mostly varved clays and silts (Fig. 5B). The soft-sedimentary deformations such as loads, pseudonodules, small scale slumps and clayey diamicton intercalations were found in the deposits. In places, they are underlain and/or covered by ripple and climbing ripple-cross laminated glaciofluvial sands.

The Kiep clays were deposited in marginal and proglacial lakes that developed during ice sheet retreat and wastage (Wysota, 2002). The settling from suspension was a predominant type of sedimentation. Locally, in basin-margins, sedimentary facies associated with meltwater inflows and re-sedimentation by gravity flows was produced.

Four TL samples were taken from glaciolacustrine silts and glaciofluvial sands of the unit 4 at two sections (see Fig. 4 and Table 1). Three (TOR-35, TOR-36 and TOR-41) yielded similar ages: 19 ± 3 TL ka, 20 ± 2 TL ka and 21 ± 3 TL ka (Wysota, 2002; Wysota et al., 2002). For the sample TOR-40 an age of 27 ± 5 TL ka was obtained. According to these data, the Kiep clays were deposited at the time of the ice sheet recession between 21 and 19 ka, after the first Late...
Weichselian ice advance in the southern part of the Lower Vistula Region (Wysota, 2002).

4.1.5. Unit L5

Unit L5 (the Starogrod Zamek till) is commonly up to 10 m thick (Fig. 4). It covers glaciolacustrine rhythms or glaciofluvial sediments of the Kiep clays. The basal contact of the unit is commonly sharp and conformable. The till consists of a brown clayey or sandy diamicton. Although the diamicton is generally massive, local thin layers or lenses of sorted sediments (mainly sand and silt) were found. The petrographic composition of the L5 till reveals also prevailing far-travelled clasts (Fig. 6). Northern limestones (46%) and crystalline rocks (30%) clearly predominate. Their amount is lower than in the L3 till. The portion of dolomites (5%) is also slightly lower. The amount of local rocks is large (14%).

The Starogrod Zamek till records the ice sheet’s re-advance during the Late Weichselian (the Poznań Phase) in the southern part of the Lower Vistula Region (Wysota, 2002). Till fabric shows that the ice advanced from the NNE direction. It is suggested that lodgement and melt-out depositional processes were mostly responsible for the formation of the till unit (Wysota, 2002). During deglaciation basal till facies were locally covered by flow till and silt–clay deposits of shallow supraglacial lakes.

4.2. North-eastern Great Poland

The Pleistocene deposits are accessible for research in the Wapienno quarry and the sandpits in Barcin and Modocin, located in the north-eastern part of the Great Poland (Rzdowalski and Wysota, 2004; Sokolowski, 2007a). In the sequence up to 30 m in thickness two formations have been distinguished: the Wapienno Formation and the Barcin Formation (Fig. 7). The Wapienno Formation (unit W1) consists of fluvial deposits. It is overlain by the Barcin Formation which includes 5 units: W2 – till, W3 – fluvial and glaciofluvial sediments, W4 – till, W5 – till, and W6 – glaciofluvial deposits.

4.2.1. Unit W1

Unit W1 (the Wapienno Formation) is composed mainly of trough cross-bedded medium-sorted and poorly sorted sands with a sparse gravel admixture. They are commonly overlain by ripple-cross laminated fine-grained sands as well as structureless clayey silts. Those deposits include some pseudonodules and syngenetic ice-wedge casts and veins. Unit W1 is up to 20 m thick (Fig. 7), and is overlain by the till of unit W2.

The sediments of the unit W1 were deposited in a sand-bed braided river environment in periglacial conditions with distinctive cycles of deposition (Sokolowski, 2007a). The measurements of the palaecurrents indicate the water flow in the NW direction.

Seven OSL samples of the W1 unit deposits were collected in both the Wapienno and Barcin exposures (Fig. 7 and Table 1). The ages obtained suggest that the deposits of the Wapienno formation originated during the Saalian Glaciation, between 268 and 154 (1377) ka (Sokolowski, 2007a).

4.2.2. Unit W2

Unit W2 comprises brown till up to 4 m thick (Fig. 7). It overlies the sediments of the Wapienno formation; locally, in the eastern part of the quarry, it overlays directly the Upper Jurassic limestones. At the contact with the sandy deposits there is a discontinuous deformation zone up to 2 m thick. Overlying it is the brown sandy till, predominantly massive, with poorly visible bedding in the top. Its basal part includes a boulder pavement with clearly visible ploughing marks (Sokolowski, 2007a, 2007b). Locally, the uppermost part of the unit, up to 40 cm, is represented by a characteristic reddish clayey till.

The W2 till is characterised by a large content of northern limestones (41%) and crystalline rocks (37%) (Fig. 6). The amount of dolomites is small (4%), while the portion of local rocks is large (13%).

It is suggested that the unit W2 records the ice sheet advance during the Late Saalian Glaciation (Sokolowski, 2007a, 2007b). Till facies formed as a result of subglacial deformation combined with ploughing, lodgement and melt-out processes. The orientation of the striae on faceted boulders and till fabric measurements indicates the west to the east ice movement direction. The reddish layer in the top of the till unit possibly originated as a result of chemical weathering during the Eemian Interglacial and/or the Early Weichselian.

4.2.3. Unit W3

Unit W3 consists of a discontinuous layer of fluvial and glaciofluvial deposits of the thickness up to 2 m (Fig. 7). Fluvial deposits are composed of trough cross-bededded and ripple cross-laminated medium-grained and fine-grained sands. The glaciofluvial sediments are represented by predominantly structureless, less commonly low-angle bedded sandy gravels with coarse-grained sand inclusions (Sokolowski, 2007a, 2007b).

Fluvial sediments were deposited in a sand-bed braided river environment in cool climate conditions. Glaciofluvial deposits were connected with more energetic proglacial meltwater flows during the ice sheet transgression. The palaecurrents indicate the SW (fluvial series) and SE (glaciofluvial series) directions of palaeo-transport (Fig. 7). Two OSL samples taken from fluvial sands yielded similar ages: 62.4 ± 2.6 OSL ka and 57.7 ± 3.7 OSL ka (Fig. 7). The single OSL sample collected in the glaciofluvial deposits showed an age of 18.5 ± 0.7 OSL ka.

4.2.4. Periglacial structures in units W2 and W3

In the deposits of units W2 and W3, well developed periglacial structures were found. Those are mainly primary sand wedges, as well as ice-wedge pseudomorphs (Fig. 5C). The earlier structures, up to 2 m deep and 50 cm wide, make a polygonal pattern. Besides ice-wedge casts, numerous pseudonodules were recorded. The top surface of the units W2 and W3 contains numerous ventifacts, deflation lag and some traces of an initial periglacial palaesoal.

Six OSL samples of the sand infilling of ice wedges found in the exposures of both Wapienno and Barcin were collected (Fig. 7 and Table 1). The dating results show those sand wedges developed between 29 and 19 ka.

4.2.5. Unit W4

Unit W4 is composed of clays, sand gravels and till facies up to 4.5 m in thickness (Fig. 7). They overlie the sediments of units W3 or W2. The contact of unit W4 with the underlying deposits is mainly sharp with minor deformations in places. The bottom of unit W4 contains 1-m thick grey-brown laminated clays with...
dropstones. Locally, they interfinger with sand gravels and sands up to 3 m thick. Above, there is a brown sandy till, bedded at the top, and 2.5 m thick. The contact with underlying sediments is transitional and contains visible deformations. In places, the till is overlain by structureless and horizontally laminated sandy silts, while locally with sandy gravels of 1-m thickness. At the top of unit W4 records of periglacial processes were found: primary sand wedges, ventifacts, deflation lag, as well as some pseudonodules (Fig. 5D). Wedges of up to 1-m depth and 30-cm width (10 cm on average) form a polygonal pattern.

The petrographic composition of the W4 till predominantly reveals rocks of northern provenance (Fig. 6). The average amount of limestones (44%) is slightly higher than in till W2, while the content of crystalline rocks (33%) is lower than in till W2. The portion of dolomites (6%) is slightly higher. The amount of local rocks (12%) is similar to the till W2.

The unit W4 originated during the first ice advance into the studied area during the Late Weichselian (Sokołowski, 2007a, 2007b). Clay and sandy-gravel facies at the bottom of the unit formed as a result of deposition in small subglacial ponds and channels. The overlying till facies were first deposited due to lodgement, and later due to melt-out processes. The overlying sediments record supraglacial deposition during ice sheet stagnation and wastage. Till fabric data indicate SW as a predominant direction of regional ice movement (Fig. 7). Once the ice sheet retreated, permafrost aggradation was followed by the development of both frost and aeolian processes.

4.2.6. Unit W5

Unit W5 contains brown sandy till, commonly of bedded structure, locally structureless, 6 m thick (Fig. 7). At the contact with the sediments of unit W4 minor deformations are found. Those include drag folds and deformed primary sand wedges.

The petrographic composition of the till W5 is different from the petrographic composition of till W4 (Fig. 6). The till W5 shows a larger content of crystalline rocks (38%), and a similar content of limestones (43%). The portions of dolomites (4%) and local rocks (10%) are slightly lower than in till W4.

Till W5 records the second ice advance during the Late Weichselian (Sokołowski, 2007a, 2007b). The formation of the till was dominated by subglacial melt-out processes. Till fabric data show the dominant ice movement was to the SSW direction (Fig. 7).

4.2.7. Unit W6

The unit W6 is found locally and reaches up to 2 m of thickness (Fig. 7). It consists of horizontally and trough cross-bedded sands and gravels, locally with structureless sand diamicton intercalations (Sokołowski, 2007a). The contact with till unit W5 is erosive with a gravel pavement. In places, ice-wedge casts and deflation lag were found in the top part of the unit.

The sediments were formed due to shallow meltwater flows during the stagnation and waning of the ice sheet. Once the deglaciation was completed, ice wedges and deflation lag originated in dry periglacial conditions. A single OSL sample collected from those deposits indicated the age of 18 ± 0.7 OSL ka (Sokołowski, 2007b).

4.3. North-eastern Kujawy

The Vistula Valley slope in the north-eastern part of the Kujawy exposes a sequence of sand–silt deposits (units N2 and N4 in Fig. 8). It is 7 to over 10 m thick and is overlain by tills (N3 and N5). In the Nieszawa exposure the sediments of the unit N2 overlie the Neogene clays, while in the Raciszew exposure the till N1 (Molewski, 2007).

4.3.1. Unit N1

Unit N1 is composed of structureless grey till over 10 m thick. The top part of the till contains an erosional pavement. The till N1 is referred to as the Odra Stage (=Drenthe) of the Older Saalian Glaciation (Kucharski, 1966; Jeziorski, 1991).
4.3.2. Unit N2

Unit N2 commonly consists of trough and planar cross-bedded sands. In the top part of the unit horizontally laminated sands, as well as ripple cross-laminated silts, sandy silts and silty sands with lenses of massive silt and clay were found. Locally, scattered plant detritus is recorded. The top of unit N2 in the Nieszawa section includes clastic dykes and deformations in the form of inclined minor folds and complementary shears.

The interpretation of the above deposits varied: either they were classified as glaciofluvial sediments of the Weichselian Glaciation (Kucharski, 1966; Kurlenda, 1971), or fluvial sediments from the Eemian Interglacial (Wiśniewski, 1976), or as the deposits from the Saalian Glaciation (Jeziorski, 1991).

Lithofacies associations indicate that the N2 sediments were deposited in a sand-bed braided river environment of unstable flow conditions. The palaeocurrents show water flow in the sectors from NW to N (Jeziorski, 1991; Wysota et al., 2004; Wysota and Molewski, 2007). The origin of deformations and clastic dykes in the top of unit N2 probably is related to a high pore-water pressure at the base of the overriding ice sheet. Two OSL samples collected from the top of the unit yielded ages: 144 ± 11 OSL ka and 110 ± 5 OSL ka (Fig. 8 and Table 1).

4.3.3. Unit N3

The N3 unit contains two till layers (N3a and N3b) of various lithofacies. The lower till (N3a) is mainly a homogeneous, silty–sandy brown till up to 2 m thick. The contact of the layer with the underlying deposits is sharp with ploughing marks and embedded elongated boulders oriented consistent with the ice flow. The topmost part of the lower till layer consists of 60-cm thick yellow-brown sandy till with numerous inclusions of sand and silty sand. The till contains a number of minor folds. The fabric in both till layers is similar and indicates the average NNW-SEE direction. The orientation of striae on the upper surface of boulders is consistent with the till fabric maximum.

The petrographic composition of the lower till (N3a) reveals prevailing rocks of northern provenance (Fig. 6). Limestones (42%) and crystalline rocks (34%) clearly predominate. The large portion of dolomites (12%) is very characteristic. The local rocks amount to 9%.
The upper layer (N3b), 60 cm thick, is composed of brown-grey clayey till. At the bottom of the till clearly visible boulder pavement was found (Fig. 5E). The upper faceted surfaces of boulders have one system of striae. In the top part of this till occur deformed primary sand wedges (Fig. 5F), which are up to 60 cm deep and 15 cm wide. Till fabric data and the orientation of striae indicate N–S ice flow.

The petrographic composition of the upper till (N3b) differs from the petrographic composition of the lower till (N3a). It is characterised by a larger content of limestones (45%) and crystalline rocks (39%). The portions of dolomites (3%) is clearly lower than in the till N3a (Fig. 6), while the amount of local rocks (9%) is similar.

The till N3 layers predominantly resulted from subglacial ploughing and lodgement processes (Wysota et al., 2004; Wysota and Molewski, 2007). Possibly, the top part of the lower till layer formed as a result of the melt-out deposition.

So far, the tills of the unit N3 were correlated with the Weichselian Glaciation (Wiśniewski, 1976) or the Warta Stage of the Younger Saalian Glaciation (Jeziorski, 1991). The lower till unit (N3a) is considered as Younger Saalian (Warta) (Wysota and Molewski, 2007). The upper till unit (N3b) might have been connected with the ice sheet oscillation during the Warta Stage or even an ice advance in the Late Weichselian.

### 4.3.4. Unit N4

In the Raciążek exposure, unit 4 constitutes of ripple cross-laminated and climbing-ripple cross-laminated fine-grained sands and silty sands up to 2 m thick. Those sediments were probably deposited in a sand-bed braided river environment (Molewski, 2007). The palaeocurrents indicate the western direction of the water flow.

The OSL dating results of the two samples collected from the deposits of the unit show a very similar age: 20.2 ± 0.6 OSL ka at its base, and 20.9 ± 0.6 OSL ka at its top. These ages indicate that the deposition of unit N4 probably took place during the Leszno Phase of the Late Weichselian.

### 4.3.5. Unit N5

Unit N5 is commonly composed of light brown sandy till, 2.2 m thick in Nieszawa and almost 5 m thick in Raciążek (Fig. 8). Locally, the till is strongly weathered. At the Nieszawa section in the bottom of the unit a 20-cm layer with minor folds was found. This layer also contains embedded boulders with a single system of striae on their upper faceted surfaces. At the Raciążek exposure in underlying sediments of unit N4, minor folds and subhorizontal shears were observed.

The N5 till contains a large amount of northern limestones (42%) and crystalline rocks (38%). Their amounts are similar to tills N3a and N3b (Fig. 6). The portion of dolomites is clearly lower (3%) than in the till N3a and similar to the till N3b. The large amount (13%) of local rocks is very characteristic.

The till originated due to subglacial deposition processes of lodgement, deformation and ploughing (Wysota et al., 2004; Wysota and Molewski, 2007; Molewski, 2007). The till fabric analysis indicates the WNW-ESE direction, which is consistent with the striae orientation (Fig. 8). However, this is opposite if compared to the fabric and striae orientation in till layers of the unit N3.

According to Jeziorski (1991), the till N5 in the Nieszawa exposure formed during the main stage of the Wechselian Glaciation. However, in the Raciążek section, it is correlated with the Warta Stage of the Younger Saalian Glaciation (Jeziorski, 1991). The research of the authors indicates that the till N5 originated during the Late Weichselian and is correlated with the ice re-advance during the Poznań Phase (Wysota et al., 2004; Molewski, 2007; Wysota and Molewski, 2007).
4.4. Western Kujawy

The slope of the Pakoś Lake tunnel valley as well as the slope and the vicinity of the Gopło Lake tunnel valley, both located in the western part of the Kujawy, contain till layers (the unit M4). They overlie sand–silt deposits of various ages, a few to a dozen m thick (units M1–M3). Those sediments fill buried valley depressions, the orientation of which is followed by the tunnel valleys (Molewski, 1999, 2007).

4.4.1. Unit M1

The bottom part of unit M1 at the Koćuda Mała exposure consists of large scale (up to 80 cm) beds of planar cross-bedded varied-grained sands with fining upward cycle. The top part of the unit includes beds of varied-grained horizontally laminated sands and silty sands with thin interbeddings of clay breccia. Those deposits contain scattered plant detritus.

Previously, the deposits were interpreted as glaciofluvial sediments connected with the ice sheet advance during the Poznań Phase (Listkowska, 1991). However, according to Molewski (2007), the deposits of the unit M1 originated in a meandering river environment. The average orientation of the palaeocurrents indicated the water flow in the SW direction (Fig. 8).

The OSL dating of the two samples of sands collected at the top part of this unit shows the ages: 278 ± 33 OSL ka and > 197 OSL ka. This suggests the Saalian age of the unit.

4.4.2. Unit M2

The M2 unit at the Mielnica exposure is composed of facially homogeneous planar and trough cross-bedded sands and gravels 10 m thick. In the top of the unit an erosive surface, locally with gravel and stone pavement, was observed (Fig. 8). Those deposits contain scattered plant detritus. At the Gocanówko exposure unit M2 consists mainly of planar cross-bedded fine-grained and medium-grained sands at the bottom, and trough cross-bedded varied-grained sands with gravel at the top.

Locally, mainly in the topmost part of this unit, there are beds of horizontally laminated medium-grained sands and ripple cross-laminated fine-grained sands.

The lithofacial features indicate that the deposits of the unit M2 were deposited in a sand-bed braided river environment (Molewski, 1999, 2007). It was a river with deep and stable main channel and high energy flows. The palaeocurrents indicate the water flow in the sectors NW to S.

The OSL dating of three samples collected from the top of the unit yielded the following ages: 85 ± 12 OSL ka at Mielnica, and about 60 OSL ka and 37 OSL ka at Gocanówko (Table 1). These results indicate that the river functioned in this area during the Early and possibly the Middle Weichselian.

4.4.3. Unit M3

At the Mielnica exposure the deposits of unit M3 overlie unit M2 sediments which had been eroded. At the bottom part of the unit there are horizontally laminated clayey silts, as well as silts and silty sands with massive or disturbed primary structure. There are discontinuous beds with loads and pseudonodules of up to 60 cm in diameter. Those deposits also include continuous lamina of clay breccia.

Above these deposits in the middle part of the exposure occur horizontally laminated fine-grained sands, which are overlain by ripple and climbing-ripple cross-laminated fine-grained sands. Locally, at the top part of the unit there are foreset cross-bedded fine-grained sands.

The bottom part of unit M3 formed in a reservoir where settling of fines from suspension was a predominant type of sedimentation (Molewski, 1999, 2007). The structure of these deposits, massive and deformed inside, suggests that they originated as a result of a subaqueous slump. The fact that the deposits include clay breccia indicates that the deposition took place in a shallow reservoir which dried up periodically. Foredelta cross-bedded and ripple laminated sand lithofacies in the top part of the unit are connected with progradation to a basin of a small fan delta. The measurement of palaeocurrents indicates the southern direction of palaeotransport. The OSL dating of one sample from the top of the unit indicated the age of 49 ± 4 OSL ka.

4.4.4. Unit M4

Unit M4 is composed of structureless, light brown or brown till up to 2 m thick. The bottom part of the till at Mielnica section consists of a bedded till. At the exposure of Gocanówko and Koćuda Mała the till is characterised by subvertical and subhorizontal fractures.

At the Mielnica exposure, the contact of this till with the underlying unit M3 is clearly visible. Locally, it is deformed and contains attenuated folds and subhorizontal shears (Fig. 5 G). At the Gocanówko exposure, the contact of the till with the underlying sediments shows ploughing marks with specific rib structures (Ehlers and Stephen, 1979) of nearly N–S orientation. Beneath the till, down to 1.5 m depth, large scale subhorizontal shears and accompanying minor folds were observed. The orientation of the fold axes indicated the SE direction of the deformation (Molewski, 1999).

The petrographic composition of the till M4 reveals a large amount of northern limestones (47%). The content of crystalline (26%) is clearly lower than in other studied till units (Fig. 6). A very small content of dolomites and a very large amount (22%) of local rocks is characteristic.

The till M4 originated mainly due to a lodgement process (Molewski, 2007). The basal part of the till at the Mielnica might have developed as a result of a combination of subglacial melt-out, deforming and lodgement processes.

The till M4 shows a sedimentation record of the one ice sheet advance during the Late Weichselian, which is correlated with the Poznań Phase. Till fabric data at the analysed exposures indicate S to SSW ice movement.

5. Discussion

5.1. A new scenario of ice advances

It is possible to undertake a new interpretation of the glacial events within the Vistula ice lobe area during the Late Weichselian. The research in the southern part of the Lower Vistula Region, north-eastern the Great Poland and the northern part of the Dobrzyń Plateau indicate that there exists a distinct lithostratigraphic separateness in the Late Weichselian glacial sequence in these areas. These two till layers found there are interpreted as evidence of two ice advances into the Vistula ice lobe area during the Late Weichselian (Fig. 9A), which are correlated with the Leszno Phase (the lower till) and the Poznań Phase (the upper till). Such an interpretation is supported by the results of the OSL and TL dating.

At the western, southern and, possibly, north-eastern parts of the Kujawy there exists a lithostratigraphic signature of a single ice advance into the Vistula ice lobe area during the Late Weichselian (Fig. 9A). Only the Mikołajyn section documents two ice advances during the last glaciation (Kozyra and Skompski, 1996; Stankowski et al., 1999). Similarly, two ice advances into the Vistula ice lobe are suggested by the research sites in the southern part of the Dobrzyń Plateau (Ber, 1960, 1968; Łyczewska, 1960; Skompski, 1969). These sites, however, lack detailed till studies and, most of all, the dating
of intertill deposits. This does not enable the authors to interpret them stratigraphically with no uncertainty. Moreover, in accordance with the observations made in this area, the idea that there are two separate till layers of the last glaciation does not find support.

The Vistula ice lobe area experienced two ice advances of various ranges during the Late Weichselian. The older one, correlated with the Leszno Phase, included the eastern Great Poland, possibly only a part of the northern Kujawy (Molewski, 2007), and the northern part of the Dobrzyński Plateau (Fig. 9B). At the foreground of the advancing ice sheet permafrost developed, indicated by ice-wedge casts found at some sites (Fig. 9A). Thus, it is suggested that the limit of this ice advance within the Vistula ice lobe area was about 60 km to the north of the maximum ice sheet extent during the Late Weichselian, which took place during the ice re-advance related to the Poznań Phase. In the southeastern part of the Great Poland the older ice advance (the Leszno Phase) reached much further south. Its limit there, however, remains unclear (Stankowska and Stankowski, 1988, 1991; Petera and Forysiak, 2003). It is probable that in the eastern part of the Dobrzyński Plateau the limits of the ice advances during both phases were similar (Niewiarowski and Wysota, 1994; Wysota, 1999, 2002). The analysis of directional data (e.g. till fabric, striae, deformations) indicates that during the ice advance the direction towards SW-S predominated, while in the eastern part of the study area it turned towards SE (Fig. 9A). In the northern part of the Great Poland and the north-western part of the Kujawy there probably existed a divergent zone in which the ice movement split towards SW and SE.

The research sites in the north-eastern part of the Great Poland, the southern part of the Lower Vistula Region and the northern part of the Dobrzyński Plateau indicate that after the maximum of the Leszno Phase a retreat of the ice sheet took place at least towards the line of the Noteć Valley, central part of the Lower Vistula Region and to the north of the Drwęca Valley (Fig. 9B). This is indicated by thick (locally up to 5 m) glaciofluvial and glaciolacustrine deposits which separate the tills of both phases in the numerous exposures. Once the ice sheet of the Leszno Phase retreated, permafrost developed in the ice-free area. The size of primary sand wedges (the Wapienno exposure) as well as slight aeolian modification of the deposits which infill them indicate that periglacial processes took at least a few hundred years (Sokołowski, 2007a).

At the next stage, the ice re-advanced at the Poznań Phase. It crossed the limit of the older ice advance (the Leszno Phase) and thus marked the maximum of the last glaciation to the east of Konin. The ice sheet re-advance was pan-regional and showed spatial diversity of its extension. Possibly, it also included the northern part of the Great Poland (Czerwonka and Krzyszkowski, 1994; Krzyszkowski and Czerwonka, 2007) and the area to the east of the Vistula ice lobe (Wysota, 2002). During the transgression stage the distribution of the ice flow directions was a fan pattern. Locally, the ice flow directions and the morphology of the marginal part of the ice sheet were determined by the topography of both its bed and foreground (Roman, 2003, 2007b; Molewski, 2007). The main routes of the ice distribution went along the Vistula Valley depression and, possibly, along the buried depression along the Lake Gopowál tunnel valley. As a result, two sublobes formed: the Gopów ice sublobe and the Plock ice sublobe (Fig. 9B). Along the Vistula Valley depression the ice flowed from NE towards SW in the northern part and from NW towards SE in the southern part of the Vistula ice lobe. In the western part of the Kujawy the N to S ice flow direction dominated. At the sides of the lobe the ice flowed from NE to SW (the western side) and from NW to SE (the eastern side).

5.2. Aspects of chronology and ice dynamics

Until recently, the age of the maximum extent of the last ice sheet during the LGM in Central Poland was based on the
radiocarbon and luminescence dating (the TL and OSL) in the vicinity of Konin. They suggest that the maximum of the last ice sheet extent in this area did not take place before 21 ka, or even 20–19 ka (Kozarski, 1986, 1988, 1995; Fedorowicz and Olszak, 1987; Stankowska and Stankowski, 1987, 1988, 1991; Stankowski and Krzyszkowski, 1991). As the time–distance diagram shows (Fig. 10), the ice advance in the Vistula ice lobe area during the Leszno Phase possibly reached its maximum about 20,300 BP. The ice re-advance in this area at the Poznań Phase reached its maximum extent about 18,400 BP. As there are no dates of the Late Weichselian deposits in the areas neighbouring the Vistula ice lobe, it is impossible to carry out wider correlation of the glacial events during both phases.

Chronology of ice advances and retreats based on the location of the ice sheet margin and on the radiocarbon and luminescence datings enable the authors to define the possible rate of those advances and retreats. Until recently, the rate of advance and retreat of the last ice sheet were estimated for north-western Poland between the central part of the Polish Baltic seacoast and its maximum extent during the Leszno Phase in the southern part of the Great Poland (Stankowski, 1983; Kozarski, 1986, 1988, 1995; Rotnicki and Borówka, 1995). It was assumed that the rate of the ice margin advance was at least 150–180 m/a, while the rate of the ice retreat was about 44–50 m/a, or even 70 m/a (Wysota, 2002). Those calculations did not consider, however, the episodes of a retreat followed by a re-advance of the ice sheet margin during a few minor phases.

The calculation for the Vistula ice lobe indicates that the rate of both the advance and retreat of the ice sheet margin during the Late Weichselian was much faster. During the Leszno Phase the rate of the ice sheet margin advance might have been on average 250 m/a, while during the retreat it was about 300 m/a. At the time of the ice re-advance of the Poznań Phase, the ice margin possibly moved at the rate of on average 400 m/a; during the retreat the rate was about 450 m/a.

Convincing sedimentological records are found in the Vistula ice lobe area, which support the idea of the fast ice movement, especially during the Poznań Phase. They include: small and generally similar thickness of a basal till, deformation till facies, boulder pavements with striae, ploughing marks and erosive hiatuses (Wysota, 2002, 2007; Wysota et al., 2004; Molewski, 2007; Wysota and Molewski, 2007; Sokotowska, 2007). Such features are accepted as the evidence of terrestrial palaeo-ice streams (e.g. Patterson, 1998; Jørgensen and Piotrowski, 2003; Lian et al., 2003; Jennings, 2006). Other signatures of rapid ice movement in the Vistula ice lobe are great-scale glacial lineaments (Molewski, 2007) found in the northern part of the Kujawy.

Fast ice flow in this area was the effect of the previously suggested the Vistula palaeo-ice stream (Punkari, 1993; Boulton et al., 2001; Marks, 2002; Wysota, 2002). It is supposed this palaeo-ice stream was especially active during the Poznań Phase re-advance (Wysota, 2002). The Vistula ice lobe, which at that time developed at the ice sheet margin, was a termination of the terrestrial palaeo-ice stream. The large low angled lobe protruding from the ice sheet margin was created. Possibly, the fast ice movement at the Poznań Phase resulted in partial exaration of the basal topography. Moreover, the possible smaller thickness of ice within a lobe (Stokes and Clark, 2001) might have favoured the survival of some older landforms of the Kujawy (Molewski, 2007).

6. Conclusions

The glacial sequence of the Late Weichselian in the area of the Vistula ice lobe contains the sedimentological record of the two ice advances of diverse extent. The older one is correlated with the Leszno Phase (Brandenburg) while the younger one with the Poznań Phase (Frankfurt). The limit of the Leszno Phase advance in this area was probably smaller that had been assumed before. The maximum of the Leszno Phase was followed by the ice sheet recession at least to the Notec Valley, central part of the Lower Vistula Region and to the north of the Drwęca Valley. An ice re-advance during the Poznań Phase crossed the limit of the earlier phase and reached its maximum in the Vistula ice lobe. This transgression was pan-regional and possibly included the neighbouring areas as well.

Fig. 10. Time–distance diagram showing the Vistula ice lobe advances during the Late Weichselian. Representative radiocarbon and luminescence age (Table 1) control is shown. The dates from the Maliniec and Mikorzyn sites according to Pazdur et al. (1980), Stankowska and Stankowski (1987), Fedorowicz and Olszak (1987), and Stankowski et al. (1999). Location of the transect line is shown in Fig. 9B.
Both ice sheet advances in the Vistula ice lobe area probably took place between 21,000 and 18,000 BP. The maximum of the ice sheet advance during the Leszno Phase is estimated to have taken place about 20,300 BP, while during the Poznań Phase about 18,400 BP. During both phases the ice movement was fast, especially during the Poznań Phase. The rate of the advances and recessions of the ice sheet margin during the above phases was much faster than had been assumed before. It is estimated that it reached 250 m/a and 300 m/a respectively during the Leszno Phase, and on average 400 m/a and 450 m/a respectively during the Poznań Phase. The rapid ice sheet re-advance during the Poznań Phase was probably related to ice streaming along the Vistula Valley depression. The Vistula ice lobe, which developed at that time, was a termination of terrestrial palaeo-ice stream.

It remains unclear, however, whether the ice sheet extents during both phases of the Late Weichselian on the outside of the Vistula ice lobe area in northern Poland were synchronous or asynchronous. Thus, it is an oversimplification to introduce a vast timespan and spatial correlation of the extents of the southern SIS ice sheets (e.g. Boutron et al., 2001; Houmark-Nielsen and Kjaer, 2003). Once the new scenario of the advances of the last ice sheet in the Vistula ice lobe is accepted, views of the palaeogeographical events in central Poland during the Late Weichselian will need to be reviewed.

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