Geological Quarterly, 2016, **60** (3): 610–623
DOI: http://dx.doi.org/10.7306/gq.1280

Upper Pleistocene palaeoenvironmental changes at the Zwierzyniec site, central Poland

Edyta KALIŃSKA-NARTIŠA[1, *], Jan DZIERŻEK[2], Krzysztof BIŃKA[2], Andrzej BORKOWSKI[2],
Paweł RYDELEK[2] and Piotr ZAWRZYKRAJ[2]

[1] Lund University, Department of Geology, Sölvegatan 12, Lund 223 62, Sweden

[2] University of Warsaw, Faculty of Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland

Kalińska-Nartiša, E., Dzierżek, J., Bińka, K., Borkowski, A., Rydelek, P., Zawrzykraj, P., 2016. Upper Pleistocene palaeoenvironmental changes at the Zwierzyniec site, central Poland. Geological Quarterly, **60** (3): 610–623, doi: 10.7306/gq.1280

The paper presents the data on an Eemian–Late Glacial sedimentary sequence from the Zwierzyniec site, central Poland. A number of boreholes document one or two organic layers that occur beneath one or two horizons of clayey and silty deposits of ice-dammed lakes. This study demonstrates to which extent the Zwierzyniec site can contribute to a better understanding of the palaeoenvironmental changes during the Eemian–Vistulian time-frame in central Poland. To study it, a multi-proxy approach was applied, involving: palynological and plant macrofossil analysis, study of rounding of quartz grains and morphology of their surface, and investigations of sand mineralogy and till petrography. The results show that a till bed is overlain by a sandy series corresponding to the glacial-interglacial transition. Either one or two distinct peaks of organic accumulation are evidenced by peat horizons. The lower horizon records spectra with hazel and hornbeam, and did, therefore, accumulate in the Eemian. Observed only in some boreholes, the upper peat horizon marks the Brørup (or the lower part of the Rederstall stadial) represented by forest-steppe conditions with patchy mosaics of larch and further transition into sedges and herbaceous taxa. Localized in between the two peat sequences, the sandy horizon marks a long-lasting aeolian transformation with weathering by frost in the Early Vistulian. Again, significant changes of the palaeoenvironmental regime occurred, and are manifested in the one or two horizons of the glaciolacustrine sediments. This corresponded to the last glaciation in the region, when the ice-dammed lakes formed during the Main Stadial.

Key words: pollen, plant macrofossils, glaciolacustrine, Eemian–Vistulian sequence, palaeoenvironment, central Poland.

INTRODUCTION

A series of sediments of various origins and ages occur in the Warsaw region, central Poland. The area was covered by ice sheets several times during the Quaternary. The Wartanian (MIS 6) ice sheet was the last one (Marks, 2002, 2005a; Marks et al., 2006) and it was followed by the Eemian (MIS 5e) warming. The latter resulted in deposition organic sediments that have been found throughout the region (Karaszewski, 1972; Kenig, 1985; Krupiński, 1986). Although the area of central Poland was ice-free during the next Vistulian cold stage (MIS 5d-2), a number of cooler-warmer episodes took place (Klatkowa, 1997). Among these episodes, the development of an ice-dammed lake in the hypsometrically lower parts of central Poland (i.e. the Warsaw Basin) are of great palaeoenvironmental significance. This morphological depression is an important hydrographic junction of the major rivers of the Polish Lowlands, thus favouring lake development (Marks, 2005b). Vast flat areas typical for ice-dammed lakes prevail both west and east of Warsaw (Fig. 1).

Among sedimentary horizons in central Poland, some of them have a well-established age control and palaeoenvironmental reconstructions (cf. Weckwerth et al., 2011; Dzieduszyńska et al., 2014; Kalińska-Nartiša and Nartišs, 2016a). Others, in contrast, lack of sufficient investigation. To fill the existing knowledge gap, we present a new data on the Zwierzyniec sequence documented by a number of boreholes drilled in the vicinity of Radzymin, 30 km north-east of Warsaw, during a routine geological survey. Therefore, this study aims to distinguish the sedimentary-environmental signature of the Zwierzyniec sequence and offers a better understanding of the palaeoenvironmental changes of the region. A combination of two peat horizons separated by fine-grained sands and superimposed by varved clay-sandy alternations makes the Zwierzyniec area ideal for a new study on environmental history. The profiles span warmer and colder periods and provide a potential insight into palaeoclimatic changes of the region during the Late Pleistocene. The latter is synchronous with the North-Polish complex (MIS 5e-2; Lindner et al., 2013). In our study, we apply a multi-proxy methodological approach involving palynological and plant macrofossil analysis, study of rounding of quartz grains and morphology of their surface, and investigations of sand mineralogy and till petrography.

---

* Corresponding author, e-mail: edyta.kalinska-nartisa@geol.lu.se

Received: October 15, 2015; accepted: January 20, 2016; first published online: February 22, 2016

Fig. 1. Location map showing the main glacial limits during the Late Vistulian in Poland and adjacent areas (adopted from Marks, 2012)

Ga – Gardno Phase; Le – Leszno Phase, Pz – Poznań Phase, Pm – Pomeranian Phase, Main Vistulian ice-dammed lakes (grey) and location of selected Eemian and Vistulian organic profiles (after Bruj and Roman, 2007): B – Błonie, G – Gołków, H – Horoszki, I – Iłów, K – Kubłowo, O – Ossów, P – Piaseczno, U – Ustków, Z – Zakroczym, ZR – Zgierz-Rudunki; black square – area shown in Figure 2

THE UPPER PLEISTOCENE SEDIMENTS IN CENTRAL POLAND

Glacial deposits of Wartanian (MIS 6) age cover vast areas of central Poland and form the higher elevations and topographically distinct morainic plateaux (Marks et al., 2006). Glacial recession resulted in degradation of sediments (Lindner and Marks, 2012), and further development of local ice-dammed lakes. This is documented at numerous sites, i.e. at Mochty, ca. 40 km north-west of Warsaw (Marks et al., 1996) and at Plecewice, ca. 50 km west of Warsaw (Kalińska, 2015). In the post-Wartanian landscape, small-sized lakes or/and peatlands prevailed, where organic accumulation took place during the Eemian. In central Poland, several sections of Eemian organic deposits were palynologically documented, i.e. at Ossów (Sarnacka, 1992), ca. 10 km south of Zwierzyniec (Fig. 2), Komorów (Krupiński, 1986), Pass (Janczyk-Kopikowa, 1974; Karaszewski, 1974), and at the Żoliborz subglacial tunnel valley in Warsaw (Morawski, 1980; Pietrzykowski, 2011). The Eemian–Vistulian transition with a full record of sediments representing the Amersfoort, Brørup (MIS 5c) and Odderade (MIS 5a) interstadials is documented by the profiles at the Zgierz–Rudunki (Jastrzębska-Mamełka, 1985), Kubłowo (Roman and Balwierz, 2010) and Ustków (Kołaczek et al., 2012) sites, all of them located west of Warsaw (Fig. 1). It is also well established that during the Eemian–Vistulian transition the periglacial processes dominated in the higher elevations, with limited accumulation of the sediments in the valleys and increased slope-driven processes (Roman et al., 2014). Similarly, a significant ice advance (MIS 4) in northern Poland (Wysota, 2002; Dzierżek, 2009; Marks, 2012; Dzierżek and Szymanek, 2013) intensified periglacial processes in the extraglacial area of Poland (Dzierżek and Stańczuk, 2006; Roman et al., 2014). During the Last Glacial Maximum (LGM), the ice sheet blocked river valleys and the Warsaw ice-dammed lake developed (Marks, 2012). After the final drainage of the ice-dammed lake,

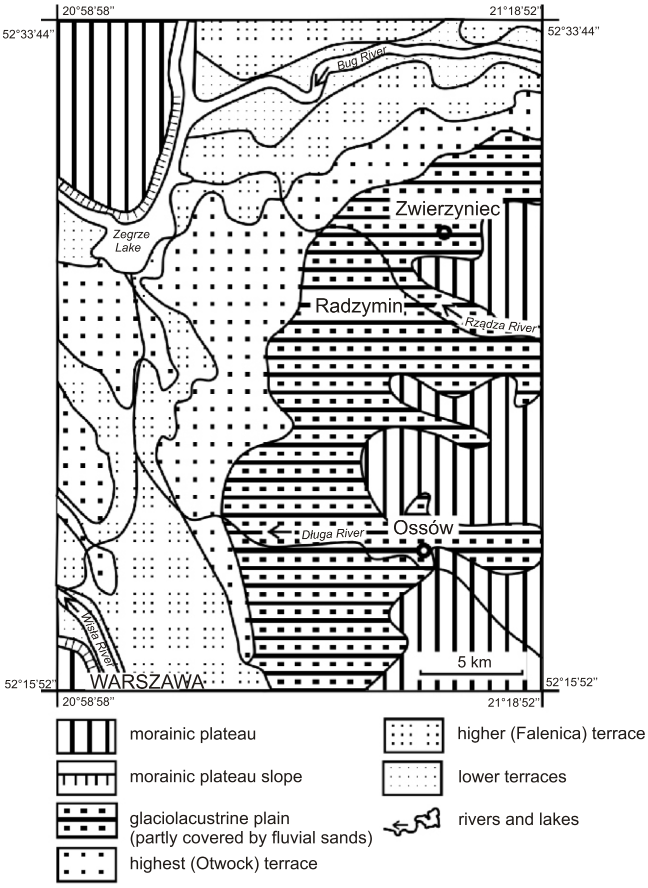

Fig. 2. Geomorphology of the eastern Warsaw Basin

a few Vistula River terraces formed, largely covered by Late Glacial dunes (Różycki, 1967; Baraniecka and Konecka-Betley, 1987; Starkel et al., 2015).

THE WARSAW ICE-DAMMED LAKE

The Zwierzyniec site is located on a vast glaciolacustrine plain named the Radzymin–Marki level. Varved clays of the ice-dammed lake are covered by a thin sandy horizon (Fig. 2). A similar sandy layer covers the Błonie level, west of Warsaw (Kalińska, 2012). The varved clays of the Warsaw ice-dammed lake, as established by Halicki (1933), occur also north of Warsaw in the Zakroczym area, as well as in Piaseczno and Gołków, south of Warsaw (Fig. 1). The uppermost horizon of the varved clays is hipsometrically roughly uniform and the varvograms reveal a similar pattern.

Originally, the Warsaw ice-dammed lake was positioned in the northern part of the Warsaw Basin (Samsonowicz, 1922). The spatial range of the ice-dammed lake varied from 25 to 130 km in its widest place, with a complex shoreline and narrow bays stretching into the valleys of the tributaries of the Vistula and Narew rivers (Fig. 1). Its development was correlated with the Middle Polish Glaciation (MIS 6; Lencewicz, 1927; Halicki, 1933; Różycki, 1967).

The discovery of peat horizons intercalated with sands at the Błonie site (Janczyk-Kopikowa, 1974; Karaszewski, 1974) and sands with organics at the Ossów site (Sarnacka, 1982) changed the ice-dammed lake age-model radically. This organic sequence occurs directly beneath the varved sediments and appeared to be of Eemian age. Such interpretation positioned the ice-dammed lake in the Vistulian Glaciation.

As yet, very few direct age determination of the ice-dammed lake exists. A very early thermoluminescence (TL) study yielded an age of 44 ka (Prószyńska-Bordas et al., 1988). This placed the Warsaw ice-dammed lake in the middle part of the last (Vistulian) Glaciation (Baraniecka and Konecka-Betley, 1987), and contradicted the general palaeogeographical outline, because no direct record of the glaciation have been found in central Poland at that time. Only the Płock lobe of the Vistulian ice sheet, correlated with the Poznań Phase at 19–20 ka (Marks, 2012) and located ca. 100 km west of Warsaw, could dam up the water. If it is true, the Warsaw ice-dammed lake developed at 19–20 ka. A similar large ice-dammed lake occurred also in the vicinity of Grodno (Belarus) in a similar palaeogeographic position (Fig. 1), and was linked by Marks and Pavlovskaya (2007) with the maximum advance of the Late Vistulian ice sheet.

Giving confidence to the above-mentioned interpretations, the varved deposits from boreholes and outcrops in the vicintity of Warsaw do not represent one glaciolacustrine depositional event in one ice-dammed lake as stated previously. The tectonically affected depression-like area of the Warsaw Basin favoured, therefore, several glacially-controled ice-dammed lakes. An accurate determination of the age and distribution of the Warsaw ice-dammed lake remains, however, debatable.

METHODS

To determine the palaeoenvironmental record, 10–20 m long sediment cores and a few tens of metres apart from each other were acquired in the Radzymin area. The H-15 50 cm drill with a 9 cm inner tube diameter chamber assembled on a UAZ452 chassis was used. Additionally, drillings were also performed with a hand auger. This allowed recognition of one to two peat intervals, as well as one or two glaciolacustrine horizons. The electrical resistivity tomograph (ERT) was tested across the profile and details can be found in Kowalczyk et al. (2015).

The four borehole logs (Zw 1–4) were examined for (1) palynological and plant macrofossil evidence in peats and gyttjas, (2) rounding of quartz grains and character of their surface together with their mineral content in sands, and, finally, (3) petrography of gravelly fractions in the tills. The details on those are given in the following sub-chapters.

ORGANIC SEDIMENTS

Plant pollen and macrofossil data can be used to reconstruct climate variations during deposition of peat (cf. Kalnina et al., 2015) and, therefore, were employed in our study. A total of 25 samples of ca. 3 cm thick and 5 cm in diameter were available for palaeobotanical survey: 1 for the gyttja layer (960 cm) in the Zw-1 borehole, 3 for peats (1000–1030 cm), and 3 for the gyttja layer (1160–1190 cm) in the Zw-2 log, 5 for the upper peat layer (415–430 cm), and 11 for the lower peat layer (815–855 cm) in the Zw-3 log (Table 1), and finally 2 for organic matter (560 and 1730 cm) in the Zw-4 borehole. In every pollen sample, hydrofluoric acid and the standard Erdtman acetolysis were applied. Approximately 1000 pollen grains per sample were counted. Prior to the macrofossil analysis, the samples were boiled in 10% KOH solution. Occasionally, boiling had to be repeated due to a high degree of peat compaction preventing sample dissolution. Plant macrofossils were also extracted by wet sieving on a 200 μm mesh screen.

CLASTIC SEDIMENTS

Quartz is ubiquitous in nearly all clastic sediments and its grain rounding and character of its surface are of great importance in determination of the environment in which the grain has been transported and preserved (Vos et al., 2014). Similarly, the mineral composition of clastic sediments can be a powerful tool in ascertaining i.e. mineralogical maturity and sediment sources (Muhs et al., 2013). Having two clastic (fine medium-grained sand) horizons, we can classify rounding of quartz grains and character of their surface and determine their mineral composition. Preliminarily, two sandy samples from depths of 6.7 and 10 m (Zw-3) in two grain-size fractions (0.5–0.8 and 0.8–1.0 mm) were analysed. The classification of the grain shape and the surface character was done according to the Cailleux (1942) method modified by Mycielska-Dowgiałło and Woronko (1998) and accompanied with depositional environments according to Woronko et al. (2015). Six groups of grains were determined: (1) RM – well-rounded frosted (long-term abrasion in aeolian environment), (2) EM/RM – partially-rounded and frosted (short-term abrasion in aeolian environment), (3) EL – well-rounded shiny (long-term transformation in fluvial/beach environment), (4) EL/EM – partially-rounded and shiny grains (short-term transformation in fluvial/beach environment), (5) C – broken with at least 30% of the original grain surfaces (crushing in all types of environments), and (6) NU – fresh, angular. Within the latter, the following subgroups were distinguished: (i) NU/L shiny grains with sharp edges that result from crushing and abrasion in a glacial environment (Woronko et al., 2015), and (ii) NU/M – outwardly frosted grains with sharp edges without effect of transport. The NU/M grains could correspond with "other" group as established by Woronko et al. (2015) and exposed to, e.g., a periglacial environment. However, in our studies these grains are only of non-rounded outline and are, therefore, similar to quartz grains observed by Kalińska-Nartiša et al. (2015) in aeolian settings of Lithuania. Subsequently, mineral-petrographic composition was determined from both the 0.5–0.8 and 0.8–1.0 mm fractions, as the amount of quartz increases in the deposits due to numerous redeposition events (Mycielska-Dowgiałło, 2007). A random selection of 200–250 grains was made and four groups were distinguished: quartz, feldspars, particles of crystalline rocks, and micaeous minerals.

MORAINIC TILL

Morainic till was found in several boreholes at a depth of 17–18.5 m (Fig. 3). Two till samples were taken for petrographic analysis from the Zw-2 and Zw-3 boreholes. Because of the low frequency of gravel, we took additional samples from other nearby boreholes (Zw-combine). Because the petrographic analysis allows a prompt examination of the vertical petrographic differenation of tills (Woźniak and Czubla, 2015), we consider it as an adequate technique in our study. The deposits were wet-sieved to obtain only the 5–10 mm gravel fraction. The number of gravels varied between 64 and 345 (Table 2). The relation of crystalline rocks, Paleozoic limestones, dolomites, quartzites, quartz) was used for calculation of the petrographic indices (O/K, K/W, A/B), where: O – total of sedimentary rocks, K – total of lithic fragments and quartz, W – total of carbonate rocks, A – total of non-resistant rocks, B – total of resistant rocks (Table 2). Additionally, the relation between Paleozoic limestons and dolomites (Wp/Dp) was also counted. Details of the methodology can be found, e.g., in Woźniak and Czubla (2015). The values of petrographic indices have been analysed with regard to regional characteristics (lithotype) of the tills (Lisicki, 2003).

RESULTS

LITHOLOGY

At Zwierzyniec the following units can be classified in the boreholes (Fig. 3). The fine-grained 0.4–1.0 m thick sands lie directly under the present-day soil horizon. Sands are underlain by one (in the Zw-1, Zw-2 and Zw-3) or two (in the Zw-4) glaciolacustrine horizons: brown-grey varved clays separated by a thin sandy layer, or a sandy silt layer on top of varved clays. Varves represent numerous alternations between the dark grey to brown and light grey laminae towards the top of the profile. The thickness of a single varve lamina varies between 0.1 and 1.5 cm, however, no direct correlation between colour and thickness was observed. Locally, the brown laminae intercalates with the dark grey laminae. Deeper in the profile, under the glaciolacustrine sequence, one (in the Zw-2) or two (in the Zw-1 and Zw-3, Zw-4) peat horizons occur. The upper peat layer is 0.9–1.4 m thick and is documented in the Zw-1 and Zw-3. Sands with organic fragments occur in the Zw-4. Beneath the upper peat layer, there is a thick (up to 4 m) grey fine-grained sandy layer. The lower layer of peat is 2–3 m thick. In the Zw-4 profile, an additional peat layer was documented between a 13.0–14.5 m depth, underlain by 4.5 m thick gyttja (Fig. 3). Thin layers of gyttja beneath the peat layers were also drilled in the Zw-1 and Zw-2. The organic-rich sediments are underlain either by medium-grained sands (Zw-4) or grey morainic till (Zw-2 and Zw-3).

PALAEOBOTANICAL STUDIES OF ORGANIC SEDIMENTS IN THE ZW-3

Three local pollen assemblage zones (LPAZ) and five local macrofossil zones (LMZ) were distinguished in the Zw-3 profile based on visual evaluation.

LOCAL POLLEN ASSEMBLAGE ZONES

In the lower part of peat (samples 6–16; 814–854 cm depth), LPAZ Z-1 was distinguished (Fig. 4 and Table 1). This zone is characterized by the high number of pollen grains, that decreases slightly towards its top. The pollen of pine and, to a lesser extent, birches become common among trees. The lower samples from the zone reveal the occurrence of *Picea*, *Alnus* and *Calluna vulgaris* as well as single pollen of deciduous trees. Additionally, pollen grains of *Buxus* are noted within the lower part of the profile. However, *Betula nana* pollen is present at the top of the zone (Fig. 4)

LPAZ Z-2 is distinguished in the upper peat of the Zw-3 profile (samples 3–5; 420–430 cm depth). In this zone, the pollen frequency indicates the existence of forest patches. The arboreal pollen (AP) is dominated by pine and, to a lesser extent, by birch and larch. A high and increasing amount of the non-arboreal pollen (NAP) is caused by the sedges (Cyperaceae). These represent local vegetation.

The upper peat of the Zw-3 profile at a depth of 414–420 cm (samples 1–2) represents the LPAZ Z-3 zone, in which the pollen reveals a relatively low frequency. The AP, dominated by birch and pine, falls rapidly to about 50%. There is a scant record of *Larix*, *Juniperus* and *Salix.* Among the NAP, grasses and sedges are abundant. In part, however, they are undoubtedly local in origin. *Artemisia*, Chenopodiaceae and a large number of herbaceous taxa are also distinctive for this zone.

POLLEN ANALYSIS OF THE OTHER SAMPLES

Sample from a depth of 560 cm from sand with organic matter in the Zw-4 profile (Figs. 3 and 5) shows a treeless phase (somewhat similar to that of LPAZ Z-3 in the Zw-3 profile; Fig. 4). However, a horizon with a pollen spectrum abundant in *Quercus*, *Corylus* and *Pinus* pollen is found in gyttjas at a depth of 1730 cm in the same profile. Samples taken from the peat layer in the Zw-2 profile (Fig. 5) show that the pollen spectra from a depth of 1000–1020 cm are dominated by hornbeam, and from a depth of 1030 cm by hazel with an admixture of hornbeam (R 2 LPAZ). In gyttja at depths of 1160, 1180, 1190 cm we have documented the presence of hazel pollen with a low amount of *Tilia* and *Alnus* (R 1 LPAZ). Finally, sample from gyttja at a depth of 960 cm in the Zw-1 profile (Fig. 5) shows a high frequency of hornbeam pollen. The hornbeam and oak levels, noted in the three above-mentioned profiles, represent part of the widely recognised climatic optimum, in which pollen of plants with a more southerly present-day range have the greatest frequency in the sequence (Bińka and Nitychoruk, 2011).

LOCAL MACROFOSSIL ZONES

The MZ-1 from the Zw-3 profile (samples 10–16; 830–854 cm depth; Fig. 6) shows a low frequency of *Andromeda polifolia, Scheuchzeria palustris, Oxycoccus, Triglochin palustre, Potentilla palustre, Menyanthes trifoliata, Carex riparia, Cicuta virosa*; all of them either inhabit raised and transitional bogs or form microhabitats in raised bogs (Fig. 6).

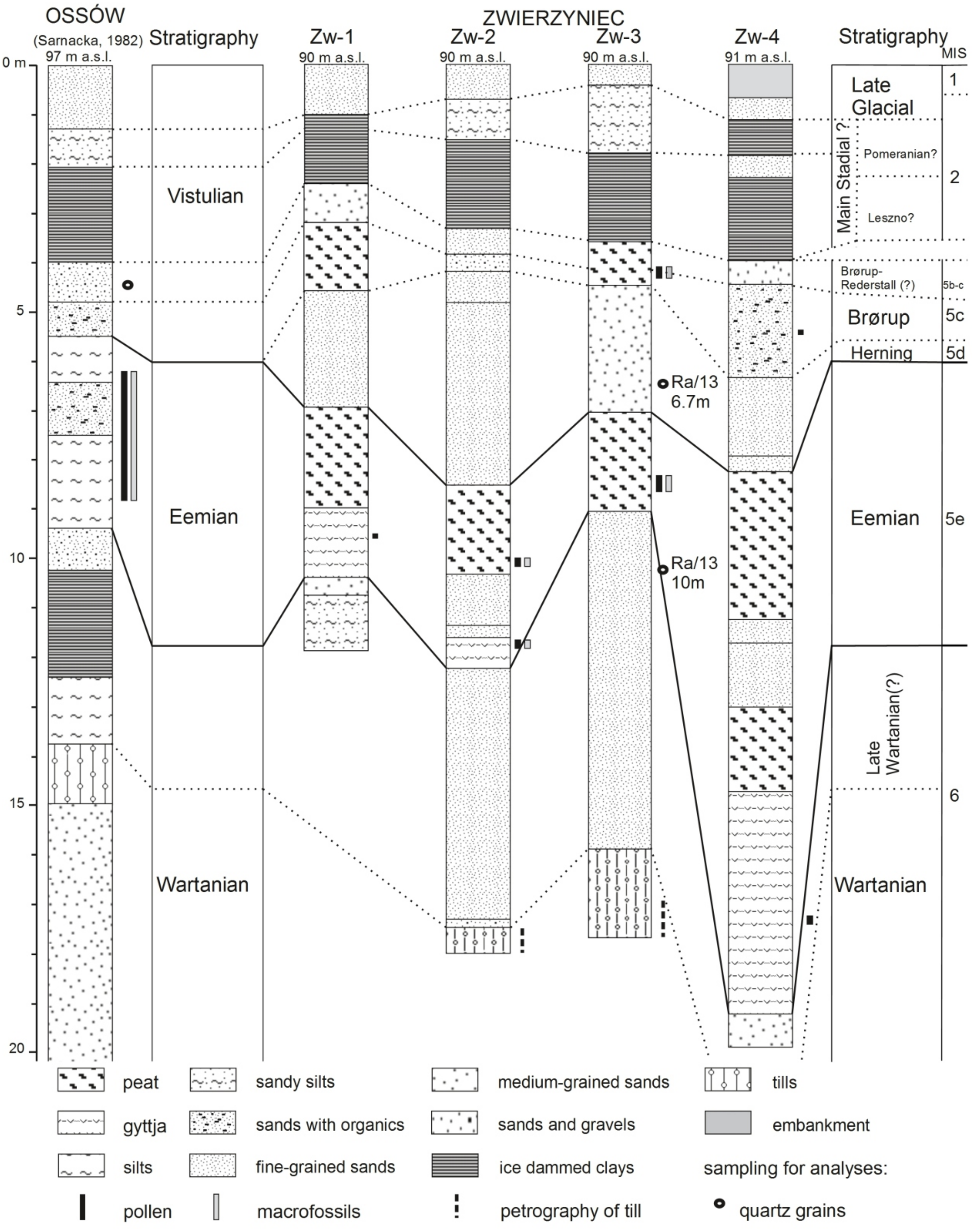

Fig. 3. Details on the boreholes of the Zwierzyniec and Ossów area

Table 1

Lithology of peats following the Tröels-Smith (1955) classification and the local palaeobotanical zones in the Zw-3 profile

Lithology	Sample number	Depth [cm]	Material	LPAZ	LMZ
Upper peat	1	414	4Th (radic.)/2 [*trunki et rami salici/II*]	Z-3	MZ-5
	2	418	4Th (radic.)/2		
	3	422	2Th (Sphagn.)/2, 2Th(radic.)/2	Z-2	MZ-4
	4	426	4Th (Sphagn.)/2		
	5	430	4Th (Sphagn.)/1		
Lower peat	6	814	4Dg [*stripes pini*]	Z-1	MZ-3
	7	818	4Th (radic.)/1 [*trunki et rami*]		
	8	822	3Dg, 1Th (radic.)2 [*trunki et rami*]		MZ-2
	9	826	2Th (Sphagn.)/2, 2Th (radic.)/1		
	10	830	2Th (radic.)/1, 2Dg		MZ-1
	11	834	2Th (radic.)/1, 1Th (Sphagn.)/1,1Dg		
	12	838	3Th (radic.)/1, 1Th (brown mosses,Sphagn.)/1		
	13	842	2Th (Sphagn.)/1, 1Th(radic.)/1, 1Dg		
	14	846	3Th (radic.)/1, 1Dg		
	15	850	4Th (Sphagn.)/1		
	16	854	4Th (Sphagn.)/1		

LPAZ – Local pollen assemblage zones; LMZ – Local macrofossil zones

Table 2

Petrography of tills at Zwierzyniec

Profile	Depth [m]	Number of gravels	O/K	K/W	A/B	Wp/Dp
Zw-2	17.5–18.0	189	0.49	2.59	0.40	1.33
Zw-3	17.0–17.5	64	0.88	1.36	1.21	0.78
Zw-combine	17.5–18.5	345	0.67	1.72	0.54	1.61

O – sedimentary rocks, K – lithic fragments, W – limestones (Wp) and dolomites (Dp), A – mechanically non-resistant rocks, B – mechanically resistant rocks

Macroremains of pine and tree birches as well as plants from dry habitats (*Arctostaphylos uva-ursi* and *Rumex acetosella)* occur regularly.

The MZ-2 (samples 8–9; 822–826 cm depth) shows a lower variety of taxa than the MZ-1. *Betula nana*, as well as *Andromeda polifolia* and *Potentilla palustre* occur abundantly.

The MZ-3 (samples 6–7; 814–818 cm depth) reveals a decline of *Betula nana* (Fig. 7) and *Andromeda,* and generally has less frequent remains than as compared to the MZ-2. Abundant pine wood fragments are noted towards the top of the zone (Table 1).

In the MZ-4 (samples 3–5; 42–430 cm depth), numerous types of *Carex* nuts prevail in the spectra. Other plants from subaqueous habitats are rare. Only *Menyanthes*, *Potentilla palustre* appear singly. The remains of pine and tree birches are present in small numbers.

Lastly, in the MZ-5 (samples 1–2; 414–418 cm depth), needles of larch, nuts of *Betula* sect. *Albae, Carex rostrata* and *Stellaria palustris* are the most abundant remains. Fragmented wood of willow is significant towards the top of the zone (Table 1).

CLASTIC SEDIMENTS

The number of well-rounded frosted (RM) grains varies between 27 and 32% in the 0.5–0.8 mm fraction, and 24–38% in the coarser fraction. This is followed by partially-rounded frosted (EM/RM) grains that account for 18–29% and 23–25% in the 0.5–0.8 and 0.8–1.0 mm fractions, respectively. The investigated sediments are, therefore, characterized by abundantly aeolian-transported quartz grains which both have the highest roundness (RM), and with the signs of aeolian activity visible on the edges and corners of the grains (EM/RM). High-energy subaqueous grains reach as high as 4–7% (well-rounded shiny EL grains), and 11–13% (partially-rounded shiny EM/EL grains) in the 0.8–1.0 mm fraction, as well as *ca.* 8% (EL), and 12–17% (EM/EL) in the 0.5–0.8 mm fraction. The number of broken (C) grains, formed from breakage of the EL, EM/EL, RM and EM/RM types, is relatively high – *ca.* 16–18% in both of the fractions. Both the fresh (NU/L) and weathered (NU/M) grains occur sparsely. However, the sample from a depth of 10 m contains *ca.* 10% of fresh grains (NU/L).

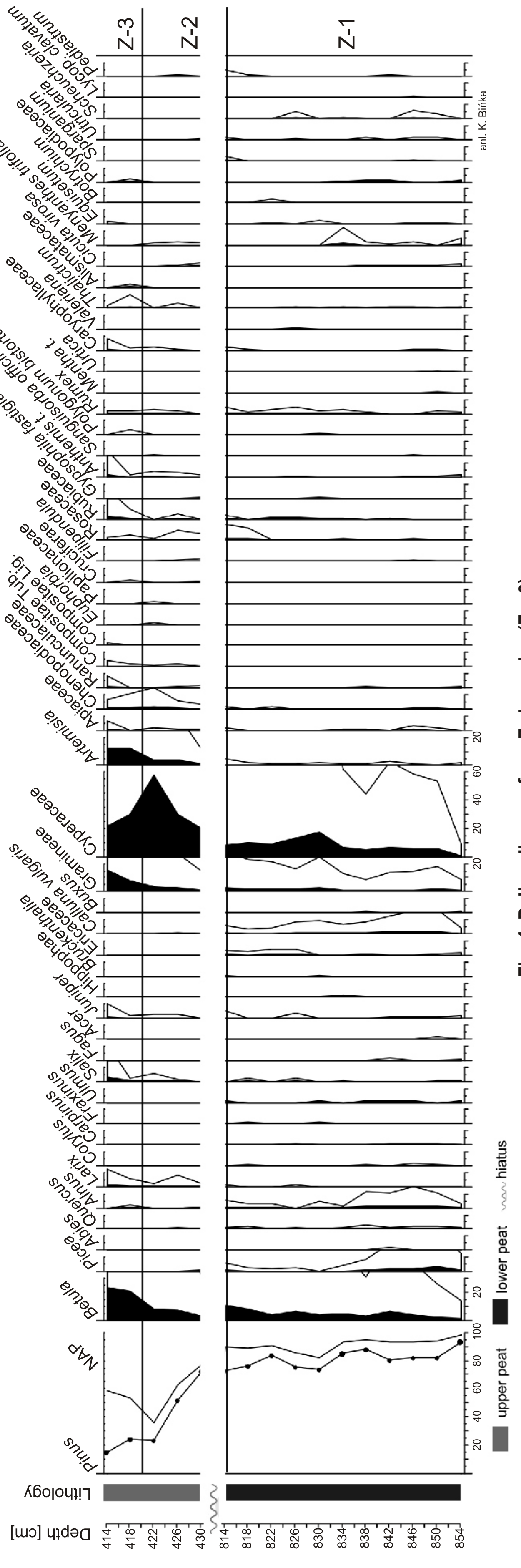

Fig. 4. Pollen diagram from Zwierzyniec (Zw-3)

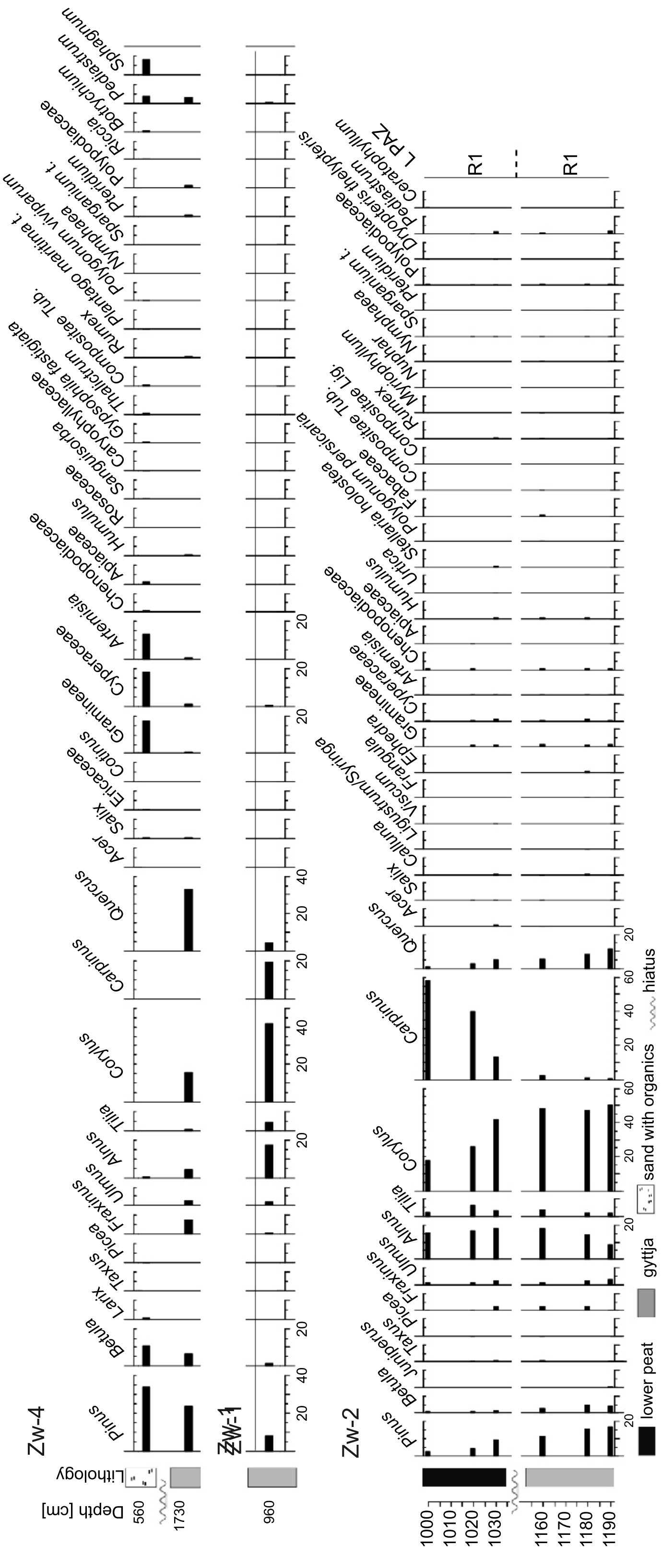

Fig. 5. Pollen diagram from Zwierzyniec (Zw-4, Zw-1, Zw-2)

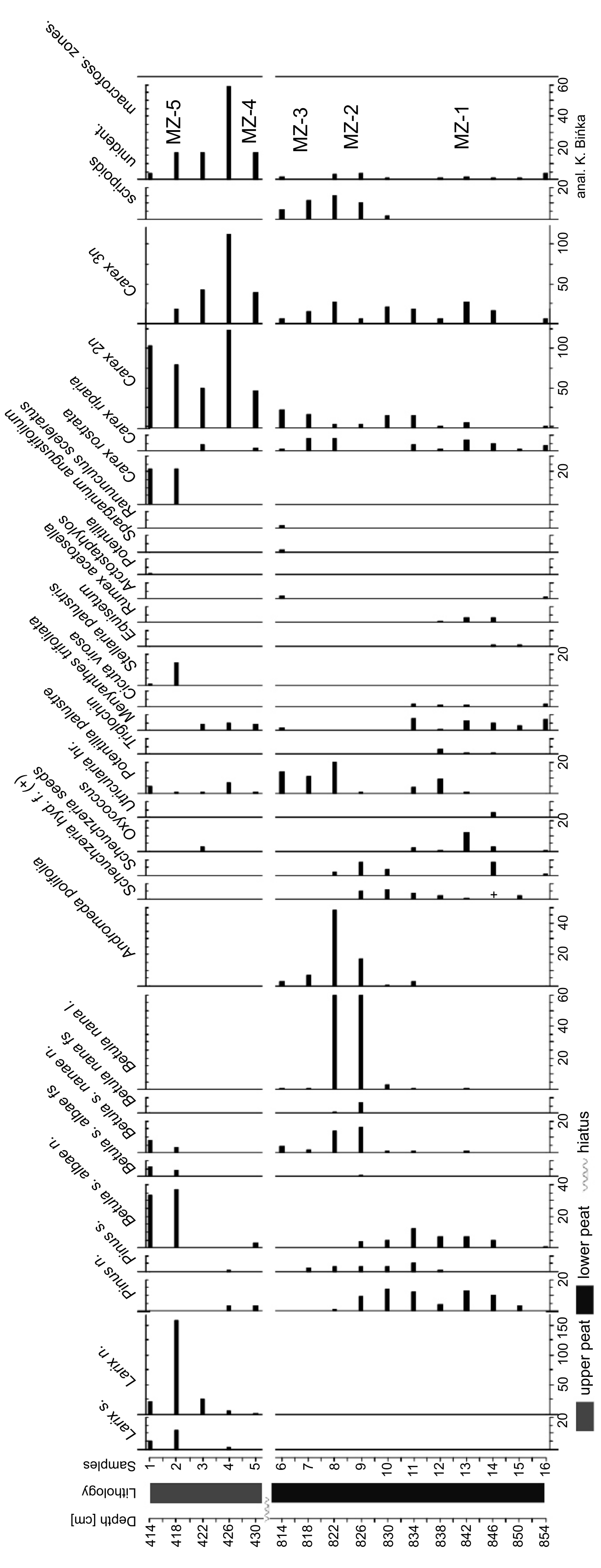

Fig. 6. Macrofossil diagram from Zwierzyniec (Zw-3)

hr – hairs; h – hydathode; fr – fruit; fs – fruit scales; l – leaves; n – needles; c – cone; f – follicle; s – seeds; 2n – two-stigmal nuts; 3n – three-stigmal nuts; scirpoids – *Carex* group non-assigned to genus or species

The highest content of quartz (92%) is found in the 0.5–0.8 mm fraction of the sample from a depth of 6.7 m. The 0.8–1.0 mm fraction and the sample from a depth of 10 m seem to be depleted in quartz content, which varies from 74 to 80%. Simultaneously, a relatively high content of both rounded feldspars (4–8%) and lithic fragments (11–20%) are observed. No micaceous minerals are found.

THE PETROGRAPHIC CHARACTERISTICS OF TILL

The composition of gravel in all samples is dominated by lithic fragments. The K/W index of 2.59 for the Zw-2 profile (Table 2) is very high and is not compatible with any tills in the region. The low frequency of limestones in the fine-gravely fraction of till can be explained by strong weathering. The latter is supported by the presence of Paleozoic limestones and dolomites (Table 2). A high content of dolomite is typical of the Wartanian tills in central Poland. However, the low frequency of limestones in tills, which build the bottom of lakes, is very common (D. Gałązka, pers. comm.).

DISCUSSION

PALAEOENVIRONMENTAL INTERPRETATION OF POLLEN AND MACROFOSSIL DATA

At least two peat layers have been distinguished in the geological cross-section in the Zwierzyniec area (Kowalczyk et al., 2015). However, the upper peat layer is not preserved in the Zw-2 and Zw-4 boreholes. It was presumably eroded and replaced by fine sand with the high content of organic material that could represent another sediment facies of the same age (Fig. 3). The lower organic layer is represented by peat and gyttja, which overlie the sandy layer.

Pollen spectra from the three fragmentarily analysed profiles indicate the presence of pine-oak forest (gyttja at 1730 cm in the Zw-4), forest communities dominant by hazel (gyttja at 1160–1190 cm in the Zw-2) and, finally, by hornbeam (gyttja at 960 cm in the Zw-1).

The LPAZ Z-1 (Zw-3 profile) pollen concentration and the low content of herbaceous taxa (excluding local elements) suggest dense boreal pine forests that existed until the end of the zone; a wood of pine was identified in the topmost sample. Therefore, we observe a gradual decline of interglacial condition. This is expressed by rare *Buxus* that requires more maritime climate, and single pollen of deciduous trees in the lower samples (Fig. 4). In the Eemian, *Buxus* occurred in a hornbeam zone and persisted until the end with Picea, and the beginning of the pine phase (Bińka and Nitychoruk, 2011; Bińka et al., 2011; Mamakowa, 1989; Zagwijn, 2000). More abundant remains of *Betula nana* (Fig. 6) indicate a progressive decrease in temperature at the end of the zone.

Locally, the MZ-1 represents initially a vegetation of raised or transitional bog overgrowing by *Sphagnum* moss (Table 1). The more demanding plants dominate in the hollows or in small permanent and

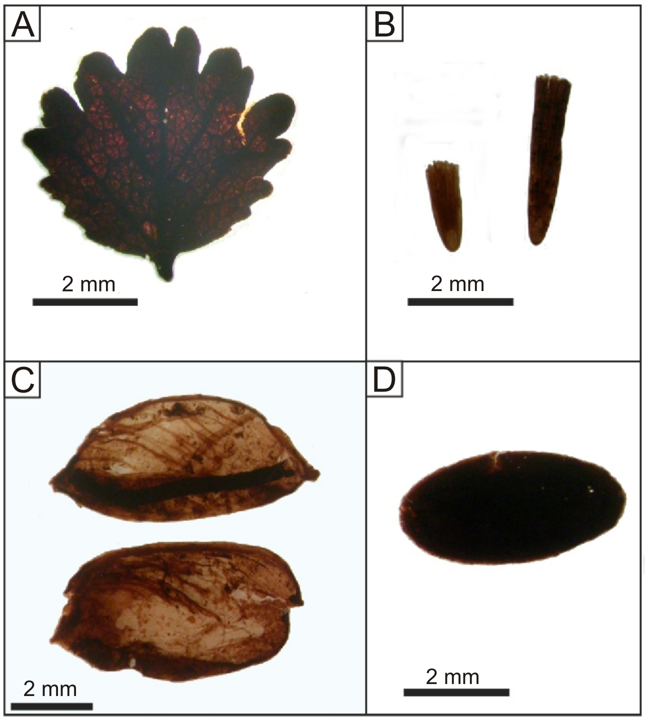

Fig. 7. Macrofossils from Zwierzyniec (Zw-3)

A – leaf of *Betula nana* (depth 826 cm in Table 1); **B**–**D** – *Scheuchzeria palustris*: B – ends of leaves with hydathodes (depth 854 cm), C – follicle (depth 846 cm), D – seed (depth 830 cm)

temporary water bodies, including *Triglochin, Carex riparia, Menyanthes, Cicuta virosa* and *Potentilla palustris*, as revealed at a depth of 850–855 cm in the Zw-3. It was rapidly followed by a peat bog with sedge communities and of lower water level, because the remains of pine and tree birches were found *in situ*. The MZ-2 (820–830 cm in the Zw-3 profile) represents a successive retreat of trees from the bogs, the abundance of dwarf birch, and its further disappearance in the next zone (Fig. 6). A similar pattern is observed in the Linie relict bog in northern Poland (Ejankowski and Kunz, 2006), wherein the dwarf birch occurs in the dwarf shrub communities *Ledo-Sphagnetum magellanici,* and further retreats. This is caused by a low groundwater level, that could potentially be triggered by waterlogging of the ground, as observed by Ejankowski (2004, 2008). The dwarf birch decline is recorded at a depth of 815–820 cm in the Zw-3 profile. A satisfactory explanation of this cannot be found at the present stage of research. Of significance, some plants such as *Carex riparia* can indicate an even higher water level. Simultaneously, a well-decomposed peat layer with particles of wood suggests a period of drought.

Throughout the period of sedimentation of the upper peat layer, forest represents the isolated type only in the LPAZ Z-2, where pine dominates in communities. The lower pollen frequency and abundant herbaceous plants, especially *Artemisia*, associated with steppe vegetation mark open conditions in the LPAZ Z-3. The presence of remains of tree birches and abundant needles of larch, however, shows the existence of forest. It seems that the vegetation was forest-steppe with patchy mosaics of larch. Abundant remains of larch and low percentages of its pollen also attract attention. A very similar pattern is known from the neighbouring Eemian sequence at Horoszki (Fig. 1; Granoszewski, 2003). Observations of modern pollen of larch in the Altai Mountains (Pelánková and Chytrý, 2009) support these discrepancies and show that the correspondence between *Larix* pollen in the modern spectra and real tree abundance was often tenuous.

The upper organic level (MZ-4 and MZ-5) also begins with a *Sphagnum* peat bog (Table 1), before being rapidly replaced by transitional or minerotrophic mires with many species of sedges, *Potentilla palustris*, *Menyanthes*, *Stellaria palustris* and *Carex rostrata.* Abundant larch needles and a higher degree of peat decomposition indicate frequent episodes when the bog dried up in summer.

PRESUMABLE AGE OF THE DEPOSITS

The formation of the lower peat layer and the gyttjas at Zwierzyniec may have started during the Eemian. This is supported by the presence of spectra with hazel (at a depth of 1160–1190 cm; Zw-2), oak, pine and hazel (at a depth of 1730 cm; Zw-4) as well as of pollen spectra dominated by hornbeam at a depth of 1000–1030 cm (Zw-2) and at 960 m (Zw-1) representing the Carpinus zone (Fig. 5). In the Zw-3 profile, the lower peat layer (LPAZ Z-1) represents probably part of the final zone of the Eemian. This is supported by the occurrence of *Buxus*, low curve of *Picea* and rare pollen of deciduous trees. The same pattern has been observed regionally in the numerous Eemian pollen diagrams in Poland (Granoszewski, 2003; Kupryjanowicz, 2008; Bińka and Nitychoruk, 2011; Bińka et al., 2011). This period lasted from ca. 1500 to 2000 years (Caspers et al., 2002).

Following the superposition, the upper peat layer in the Zw-3 profile at a depth of 414-430 cm (Fig. 4), and the fine material with organics in the Zw-4 profile at a depth of 560 cm (Fig. 5) represent the upper or lower part of the Brørup interstadial (LPAZ Z-2 zone), and the first part of the Rederstall stadial (LPAZ Z-3) or the lower part of the Brørup and a part of a part of intra-interstadial cold fluctuation.

PALAEOENVIRONMENTAL IDENTIFICATION OF QUARTZ GRAINS

The quartz grain morphology relates to the mode of transportation, distance from source, and timing, but it is equally a function of the original grain shape in the parent rock (Mahaney et al., 2001; Kleesment, 2009; Costa et al., 2013; Kalińska and Nartišs, 2014; Vos et al., 2014). In this study, a preliminary analysis of the roundness of quartz sand grains and the character of their surface combined with mineralogical composition open up great opportunities for future work at higher resolution. So far, two sediment samples revealed a great variability of grain types, representing not only aeolian (RM and EM/RM) and fluvial (EM/EL) sedimentary environments, but also cracked grains (C) and totally fresh grains with no traces of transportation (NU/L). However, the predominance of matt grains with perfectly spherical shapes was noted in particular in the upper part of the profile (sample taken from a depth of 6.7 m). These grains represent the long-lasting aeolian transformation. Simultaneously, the abundance of shiny (EM/EL+EL) quartz grains is attributed to fluvial environments (Krinsley and Doornkamp, 1973), and such deposits could be typical of river floodplains (Marks et al., 2014). It is acknowledged that a relatively high (>5%) number of grains with well-rounded outlines observed in the sediments refer either to the underlying deposits (Woronko,

2001) or results from the long-lasting fluvial cycles (Weckwerth et al., 2011). Similarly, the high content of cracked grains (C) indicates the post-sedimentary weathering due to freeze-thaw (Woronko and Hoch, 2011; Woronko, 2012) and have been reported from the former periglacial areas in northeastern Poland (Woronko et al., 2013). It is apparent from this study that the textures reflect not only the influence of fluvial/aeolian associations by the supply of aeolian material into the river valleys, but also the reworking of pre-existing sediments, as noticed within the periglacial zone of the last glaciation (Zieliński et al., 2009; Velichko et al., 2011). The contribution of the latter could be explained by the presence of the underlying morainic complex. Noteworthy is the prevalence of aeolian-type grains in the sample from a depth of 6.7 m; these could only result from longer-term aeolian activities caused by increasing climate aridity. The 0.8–1.0 mm quartz grains tend to reveal the strongest aeolian abrasion (Mycielska-Dowgiałło and Dzierwa, 2003). In our study, however, similar numbers of both well-rounded (RM) and partially-rounded (EM/RM) matt grains are observed and, therefore, it argues that aeolian action has no significant role in abrading the coarser fraction.

The mineralogical maturity, defined as composition where there is a dominance of quartz (Pettijohn et al., 1972), is stated as being achieved from extended periods of aeolian activity (Muhs, 2004). It is likely, given by the relatively large amount of feldspars and lithic particles, particularly in the sample from a depth of 10 m, that their source was from a combination of igneous or metamorphic rocks. Such a composition appears to be similar to the fluvioglacial sediments of central Poland, with 70–75% of quartz, exclusively (Mycielska-Dowgiałło, 1993). Feldspars, however, are mostly of rounded outline, meaning the whole material underwent aeolian transformation (cf. Weckwerth et al., 2011). The feldspar depletion in the sample from a depth of 6.7 m was likely overlapping with the deterioration of climate conditions recorded in the upper part of the profile.

PALAEOENVIRONMENTAL IDENTIFICATION OF TILLS

Based on the petrographic indices of the Zwierzyniec till, it cannot unambiguously be established whether or not the till is of the Wartanian age. Although the Wartanian tills have been observed in the area (Lisicki, 2003; Marks et al., 2006), our O/K, K/W and A/B petrographic indices correspond neither to the regional lithotype for Wartanian till nor the older tills. The cause of this is likely due to a strong weathering.

PALAEOENVIRONMENTAL RECONSTRUCTION

The sediment cores to a maximum depth of 20 m at the Zwierzyniec site represent a sedimentary record of the Eemian–Late Glacial sequence in central Poland. This data combined with the multi-proxy approach applied in this study allow the evaluation of the palaeoenvironmental pattern of the sequence, which is discussed below.

Based on petrographic composition of the lowermost morainic till, we assume that, although strongly weathered, it is probably of Wartanian age. An uneven upper boundary of the till ranges between 70 to 74 m a.s.l. Either this is inherited after the primary-preserved uneven surface of the morainic plateaus, or eroded by the proglacial water.

Accumulation of fine- and medium-grained sands postdates the glacial conditions. Sands are presumably of fluvial origin; this is supported by the abudance of the shiny well- and partially-rounded quartz grains (EL+EM/EL) and lack of mica. This mineral, due to its platy habit (Marcinkowski and Mycielska-Dowgiałło, 2013), contradicts with water flowing conditions. The numerously cracked quartz grains coincide with the glacial-interglacial transition and could be possibly inherited from the underlying till. The continuous organic deposits, termed as the lower peat, cover the sands. Formation of the organic deposits occurred probably during the late Eemian, and coincides with the end of spruce and beginning of the pine phase (Mamakowa, 1989; Zagwijn, 2000; Bińka and Nitychoruk, 2011; Bińka et al., 2011), when continental conditions prevailed. Locally, the lower peat is replaced by two peat horizons alternated by a sandy horizon and underlain by gyttja (Zw-4; Fig. 3). That complex combination cannot be explained at this stage of research. However, colder-interglacial interval cannot be excluded. Macrofossil record at the Horoszki Duże site (Granoszewski, 2003) provides the minimum mean July temperature estimates of 17–18°C, and January temperatures between –1 and –5°C for the late Eemian (cf. Helmens, 2014). These are lower than the estimates from continental Europe (Klotz et al., 2003), but slightly higher than in the Eastern Baltic region (Šeirienė et al., 2014).

Rapid environmental changes are inferred for the lower peat-sand transition; this is well-documented in all boreholes, where the total thickness of sands between the lower and the upper peat is occassionally up to 5 m (Kowalczyk et al., 2015). In sand the fluvial-aeolian grain mixing prevails, giving evidence of a fluvioperiglacial environment (Mycielska-Dowgiałło and Woronko, 2004). Collectively, the cracked (C-type) and aeolian-type (EM/RM+RM) grains demonstrate intense frost weathering and long-lasting aeolian processes. As such, aeolian deposition is likely to coincide with stadials of the early Vistulian (MIS 5d and b), when a general trend towards colder temperatures and dryer conditions in Central Europe is observed (Brewer et al., 2008); the plant cover sharply decreased and even cold-resistant species did not form dense forests (Novenko et al., 2008). Assuming the Brørup age of the overlying upper peat horizon (see below), the timeframe of sand deposition can be narrowed to the cold Herning stadial (MIS 5d), when the fluvial activity and ocassionally solifluction prevailed in Poland (Marks et al., in press). However, only a sufficient dating can stratigraphically position that sandy horizon.

The upper peaty sequence documented in the Zw-1 and Zw-3 profiles is discontinuous. For example, no peat is recorded in the Zw-2 and Zw-4 boreholes, which seems to be replaced by the sandy series with organic matter. A plant record of the Zw-3 profile coincides with the Brørup onset (the LPAZ Z-2 zone), and probably represents either its intra-interstadial cold fluctuation or the first part of the Rederstall stadial (LPAZ Z-3). This stadial is considered to be the coolest period during the Early Vistulian (Šeirienė et al., 2014). A fragmentary nature of the Zw-3 profile does not allow stating whether the plant record is of intra-interstadial fluctuation or the first part of Rederstall stadial age. However, prevalance of pine (LPAZ Z-2) combined with a strong steppe continental phase documented by larch in the LPAZ Z-3 (and similar to that found in the Zw-4; Fig. 5) supports rather the late Brørup and the Rederstall stadial age. A similar pollen pattern, assigned to the Brørup onset, has been reported from central and eastern Poland (Granoszewski, 2003; Bińka and Nitychoruk, 2011; Kołaczek et al., 2012). Given the arid continental steppe conditions with larch in the wetter location, the minimum mean temperature between –27 and –34°C and from 16 to 18°C of January and July, respectively, together with an annual precipitation <400 mm, were established (Kuneš et al., 2008). In our study the temperatures must have been slightly higher due to the presence of *Betula*. Meadow steppe formations with patches of *Betula* provided the temperatures between 20 and 21°C for July and the annual precipitation between 300–350 mm (Pelánková et al., 2008). According to Granoszewski (2003) the temperatures of the warmest and the coldest months varied between 15–17°C and –8 to –14°C.Winter temperatures in Western Europe seem to be, in contrast, milder with an annual preciptitaion of ca. 600 mm (Kühl et al., 2007). The peaty horizon in our study was probably continuous, however, eroded partially by a water flow. This is supported by the presence of a thin gravelly horizon that occurs in the overlying sandy sequence.

Widely distributed varved clays occur in the Warsaw Basin. Between two glaciolacustine horizons a thin 0.5 m thick fine-sandy layer occurs; this is documented by the Zw- 4 borehole and allows us to establish two phases of ice-dammed lake development within the likely short drainage event in between. It is supported by lithological differentation of sediments in Zw-2 and Zw-3 boreholes. Owing to the unique alternation of the interglacial/interstadial-glacial/stadial sedimentary record, the Zwierzyniec sequence allows us to correlate the varved clays, and consequently the ice-dammed lake with the last glaciation. Two damming events likely coincide with the Main Stadial, when the ice positioned ca. 100 km west of Warsaw. The Leszno and Poznań phases of the maximum Vistulian ice-sheet advance (MIS 2) are of similar range in central Poland (Skompski, 1969; Marks, 2002; Mojski, 2005; Wysota et al., 2009), and can be, therefore, linked with the development of the lower and upper glaciolacustrine horizons, respectively. The thin sandy horizon reflects a relatively short time gap when the ice-dammed lake did not exist, which could coincide with an up to 5 ka difference between the phases, as indicated by the cosmogenic isotope ages and calibrated radiocarbon data (Marks, 2012).

The total thickness of the glaciolacustrine sequence, as observed in Zwierzyniec east of Warsaw, differs significantly from west of Warsaw, wherein 12 to 18 m profiles were examined in Plecewice and Iłów (Fig. 1), respectively (Dzierżek, 2015). Thus, the Zwierzyniec site is likely to represent a more peripheral zone of the ice-dammed lake/lakes.

The sandy sequence overlies the varved clays, thus dominating the Radzymin–Marki level landscape. The fine-gravelly horizon in the lowermost part of the sandy sequence is due to erosion and gravels, that originate presumably from the adjacent morainic plateau. The fluvial origin of the sands was proposed by Sarnacka (1982), and Baraniecka and Konecka-Betley (1987). However, west of Warsaw at the Plecewice site, the aeolian character of sediments prevails (Kalińska, 2012). Additionally, sandy aeolian-like deposition took place at 15–16 ka and 12 ka only 15 km SE of the Zwierzyniec site (Kalińska-Nartiša and Nartišs, 2016b). A stepwise ice recession together with simultaneous variations in the water level resulted in the formation of the terraces of the Vistula River. The Otwock terrace is adjacent to the investigated area (Fig. 2) and considered to have been formed in the Late Weichselian (Vistulian; Baraniecka and Konecka-Betley, 1987; Sarnacka, 1992), After surface drying, aeolian activity formed dune fields observed throughout the Warsaw Basin (Manikowska, 1982, 1991).

FINAL REMARKS AND CONCLUSIONS

1. This study was the first to provide a sedimentary record of the Zwierzyniec site, where two glaciolimnic sequences are underlain by two organic horizons. The multi-proxy approach reveals the Wartanian(?)–Eemian–Vistulian sequence, in which the Late Eemian and the Brørup seem to be well-expressed.
2. The Eemian optimum is manifested in the gyttjas and lower peats; the uppermost part of the lower peat, however, reveals gradual climate deterioration.
3. The Early Vistulian climate, as inferred from the lithology and the sedimentary pattern recorded in the quartz grains, reveals both its deterioration and dryness. This was later followed by the accumulation of the upper peat in the warmer Brørup.
4. Climatic deterioration is characteristic for the onset of glaciation, and thus indicates erosion. The uppermost part of the upper peaty sequence was therefore eroded, and subsequently replaced by the sandy accumulation.
5. The varved sequence of the Radzymin–Marki level corresponds to the last glaciation. A scenario of the Leszno–Poznań phases is supported by the general palaeogeographical outline in central Poland.
6. Our study demonstrates to which extent the Zwierzyniec profile can contribute to a better understanding of the palaeoenvironmental changes during the Wartanian–Eemian–Vistulian sequence. As such, its further detailed exploration remains open.

Acknowledgements. We are grateful to Dr. M. Nartišs (University of Latvia) for comments on text and discussion. A.P. Gumsley (Lund University) is thanked for his English proof-reading. Our appreciation is expressed to Dr. O. Borisova (Russian Academy of Sciences), anonymous reviewer and Dr. W. Granoszewski (Geological Quarterly) who helped to improve our manuscript.

REFERENCES

Baraniecka, M.D., Konecka-Betley, K., 1987. Fluvial sediments of the Vistulian and Holocene in the Warsaw Basin. In: Evolution of the Vistula River Valley during the Last 15000 Years (ed. L. Starkel): 151–170. Zakład Narodowy im. Ossolińskich, Wrocław.

Bińka, K., Nitychoruk, J., 2011. Cyclicity in the Eemian climate? A case study of the Eemian site at Czaple, Eastern Poland. Review of Palaeobotany and Palynology, **164**: 39–44.

Bińka, K., Nitychoruk, J., Dzierżek, J., 2011. Climate stability during the Eemian – new pollen evidence from the Nidzica site, northern Poland. Boreas, **40**: 342–350.

Brewer, S., Guiot, J., Sánchez-Goñi, M.F., Klotz, S., 2008. The climate in Europe during the Eemian: a multi-method approach using pollen data. Quaternary Science Reviews, **27**: 2303–2315.

Bruj, M., Roman, M., 2007. The Eemian lakeland extend in Poland versus stratigraphical position of the Middle Polish Glaciations (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **425**: 29–36.

Cailleux, A., 1942. Les actiones éoliennes périglaciaires en Europe (in French). Mémoires de la Société Géologique de France, **41**: 1–176.

Caspers, G., Merkt, J., Müller, H., Freund, H., 2002. The Eemian Interglaciation in Northwestern Germany. Quaternary Research, **58**: 49–52.

Costa, P.J.M., Andrade, C., Mahaney, W.C., Marques da Silva, F., Freire, P., Freitas, M.C., Janardo, C., Oliveira, M.A., Silva, T., Lopes, V., 2013. Aeolian microtextures in silica spheres induced in a wind tunnel experiment: comparison with aeolian quartz. Geomorphology, **180–181**: 120–129.

Dzieduszyńska, D.A., Kittel, P., Petera-Zganiacz, J., Brooks, S.J., Korzeń, K., Krąpiec, M., Pawłowski, D., Płaza, D.K., Płóciennik, M., Stachowicz-Rybka, R., Twardy, J., 2014. Environmental influence on forest development and decline in the Warta River valley (Central Poland) during the Late Weichselian. Quaternary International, **324**: 99–114.

Dzierżek, J., 2009. Palaeogeography of selected areas of Poland during the last glaciation. Acta Geographica Lodziensia, **95**: 1–112.

Dzierżek, J., 2015. Nizina Mazowiecka i obszary przyległe – 43 stanowiska geologiczne (in Polish). Wydział Geologii Uniwersytetu Warszawskiego, Warszawa.

Dzierżek, J., Stańczuk, D., 2006. Record and palaeogeographical implications of Pleistocene periglacial processes in the Drohiczyn Plateau, Podlasie Lowland (Eastern Poland). Geological Quarterly, **50** (2): 219–228.

Dzierżek, J., Szymanek, M., 2013. Interplenivistulian (MIS 3) environmental changes recorded in sub-till lake deposits at Wildno, Dobrzyń Lakeland (Polish Lowland). Quaternary International, **294**: 99–107.

Ejankowski, W., 2004. The influence of ground water level on the demography and population structure of the dwarf birch *Betula nana* L. Ecological Questions, **5**: 63–68.

Ejankowski, W., 2008. Effect of waterlogging on regeneration in the dwarf birch (*Betula nana*). Biologia, **63**: 670–676.

Ejankowski, W., Kunz, M., 2006. Reconstructing of vegetation dynamics in “Linie” peat bog (N Poland) using remote sensing method. Biodiversity Research and Conservation, **1.2**: 111–113.

Granoszewski, W., 2003. Late Pleistocene vegetation history and climatic changes at Horoszki Duże, eastern Poland: a palaeobotanical study. Acta Palaeobotanica Supplement, **4**: 1–95.

Halicki, B., 1933. Iły wstęgowe w Plecewicach nad Bzurą (in Polish). Zabytki Przyrody Nieożywionej, **2**: 86–90.

Helmens, K.F., 2014. The last interglacial-glacial cycle (MIS 5-2) re-examined based on long proxy records from central and northern europe. Quaternary Science Reviews, **86**: 115–123.

Janczyk-Kopikowa, Z., 1974. The Eemian Interglacial sediments at Błonie near Warsaw. Bulletin of the Polish Academy of Sciences, Earth Sciences, **22**: 147–150.

Jastrzębska-Mamełka, M., 1985. The Eemian Interglacial and the Early Vistulian at Zgierz-Rudunki in the Łódz Plateau. Acta Geographica Lodziensia, **53**: 1–75.

Kalińska, E., 2012. Geological setting and sedimentary characteristics of the coversands distributed in the western part of the Blonie glaciolacustrine basin (Central Poland) – preliminary results. Bulletin of the Geological Society of Finland, **84**: 33–44.

Kalińska, E., 2015. Plecewice I (in Polish). In: Nizina Mazowiecka i obszary przyległe (ed. J. Dzierżek): 26–27. Wydział Geologii Uniwersytetu Warszawskiego, Warszawa.

Kalińska, E., Nartišs, M., 2014. Pleistocene and Holocene aeolian sediments of different location and geological history: a new insight from rounding and frosting of quartz grains. Quaternary International, **328–329**: 311–322.

Kalińska-Nartiša, E., Nartišs, M., Thiel, C., Buylaert, J.-P., Murray, A.S., 2015. Late-glacial to Holocene aeolian deposition in northeastern Europe – the timing of sedimentation at the Iisaku site (NE Estonia). Quaternary International, **357**: 70–81.

Kalińska-Nartiša, E., Nartišs, M., 2016a. The fan-like forms in the southern margin of the Mazovian Lowland area (Central Poland): a new high-resolution textural-timing study. International Journal of Earth Sciences, **105**: 885–903.

Kalińska-Nartiša, E. and Nartišs, M., 2016b. Sandy fan-like forms in the central-eastern Mazovian Lowland (Central Poland): textural record and chronology. Geografiska Annaler Series A Physical Geography, **98**: 111–127.

Kalnina, L., Stivrins, N., Kuske, E., Ozola, I., Pujate, A., Zeimule, S., Grudzinska, I., Ratniece, V., 2015. Peat stratigraphy and changes in peat formation during the Holocene in Latvia. Quaternary International, **383**: 186–195.

Karaszewski, W., 1972. The Eemian interglacial at Skierniewice (Central Poland) and its significance for the knowledge of the younger Pleistocene palaeogeography (in Polish with English summary). Kwartalnik Geologiczny, **16** (3): 724–732.

Karaszewski, W., 1974. Age of the Warsaw ice dammed lake sediments. Bulletin of the Polish Academy of Sciences, Earth Sciences, **22**: 151–156.

Kenig, K., 1985. Eemian interglacial sediments at the background of history of Pleistocene sedimentation in the section at Lisówek near Grodzisk Mazowiecki (in Polish with English summary). Przegląd Geologiczny, **33**: 64–70.

Klatkowa, H., 1997. Zagłębienia bezodpływowe w Polsce Środkowej i przydatnosć analizy ich wypełnień do interpretacji paleogeograficznych (in Polish). Acta Universitatis Lodziensis, **1**: 23–44.

Kleesment, A., 2009. Roundness and surface features of quartz grains in Middle Devonian deposits of the East Baltic and their palaeogeographical implications. Estonian Journal of Earth Sciences, **58**: 71–84.

Klotz, S., Guiot, J., Mosbrugger, V., 2003. Continental European Eemian and early Würmian climate evolution: comparing signals using different quantitative reconstruction approaches based on pollen. Global and Planetary Change, **36**: 277–294.

Kołaczek, P., Karpińska-Kołaczek, M., Petera-Zganiacz, J., 2012. Vegetation patterns under climate changes in the Eemian and Early Weichselian in Central Europe inferred from a palynological sequence from Ustków (central Poland). Quaternary International, **268**: 9–20.

Kowalczyk, S., Zawrzykraj, P., Mieszkowski, R., 2015. Application of electrical resistivity tomography in assessing complex soil conditions. Geological Quarterly, **59** (2): 367–372.

Krinsley, D.H., Doornkamp, J.C., 1973. Atlas of Quartz Sand Surface Textures, 1st ed. Cambridge University Press, Oxford.

Krupiński, K., 1986. Sediments of the Eemian interglacial at Komorów near Pruszków (Mazowian Lowland). Bulletin of the Polish Academy of Sciences, Earth Sciences, **34**: 387–397.

Kuneš, P., Pelánková, B., Chytrý, M., Jankovská, V., Pokorny, P., Libor, P., 2008. Interpretation of the last-glacial vegetation of eastern-central Europe using modern analogues from southern Siberia. Journal of Biogeography, **35**: 2223–2236.

Kupryjanowicz, M., 2008. Vegetation and climate of the Eemian and Early Vistulian lakeland in northern Podlasie. Acta Palaeobotanica, **48**: 3–130.

Kühl, N., Litt T., Schölzel, C., Hense, A., 2007. Eemian and Early Weichselian temperature and precipitation variability in northern Germany. Quaternary Science Reviews, **26**: 3311–3317.

Lencewicz, S., 1927. Glaciation et morphologie du bassin de la Vistule moyenne (in French with Polish summary). Prace Państwowego Instytutu Geologicznego, **2**: 66–226.

Lindner, L., Marks, L., 2012. Climatostratigraphic subdivision of the Pleistocene Middle Polish Complex in Poland (in Polish with English summary). Przegląd Geologiczny, **60**: 36–45.

Lindner, L., Marks, L., Nita, M., 2013. Climatostratigraphy of interglacials in Poland?: Middle and Upper Pleistocene lower boundaries from a Polish perspective. Quaternary International, **292**: 113–123.

Lisicki, S., 2003. Lithotypes and lithostratigraphy of tills of the Pleistocene in the Vistula drainage basin area, Poland (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **177**: 1–105.

Mahaney, W.C., Stewart, A., Kalm, V., 2001. Quantication of SEM microtextures useful in sedimentary environmental discrimination. Boreas, **30**: 165–171.

Mamakowa, K., 1989. Later Middle Pleistocene Glaciation, Eemian and Early Vistulian vegetation at Imbramowice near Wrocław and the pollen stratigraphy of this part of the Pleistocene in Poland. Acta Palaeobotanica, **29**: 11–179.

Manikowska, B., 1982. Fosil soils in dunes of central Poland (in Polish with English summary). Rocznik Gleboznawczy, **33**: 119–133.

Manikowska, B., 1991. Dune processes, age of dune terrace and Vistulian decline in the Vistula Valley near Wyszogród, Central Poland. Bulletin of the Polish Academy of Sciences, Earth Sciences, **39**: 137–148.

Marcinkowski, B., Mycielska-Dowgiałło, E., 2013. Heavy-mineral analysis in Polish investigations of Quaternary deposits: a review. Geologos, **19**: 5–23.

Marks, L., 2002. Last Glacial Maximum in Poland. Quaternary Science Reviews, **21**: 103–110.

Marks, L., 2005a. Pleistocene glacial limits in the territory of Poland. Przegląd Geologiczny, **53**: 988–993.

Marks, L., 2005b. Pleistocene river systems in the southern peribaltic area as indication of interglacial sea level changes in the Baltic Basin. Quaternary International, **130**: 43–48.

Marks, L., 2012. Timing of the Late Vistulian (Weichselian) glacial phases in Poland. Quaternary Science Reviews, **44**: 81–88.

Marks, L., Pavlovskaya, I.E., 2007. Development of meltwater system ourflow during last glacial maxiumum in the middle Neman valley region, central Europe. Quaternary International (suppl.) , **2**: 167–168.

Marks, L., Dzierżek, J., Gadomski, M., Gałązka, D., Pochocka, K., 1996. Stanowisko stratotypowe plejstoceńskich osadów lodowcowych w Mochtach na NW od Warszawy (in Polish). Stratygrafia Plejstocenu Polski: 69–78.

Marks, L., Gogołek, W., Piotrowska, K., 2006. Geological Map of Poland 1:50 000, with Explanatory Text. Państwowy Instytut Geologiczny, Warszawa.

Marks, L., Gałązka, D., Krzymińska, J., Nita, M., Stachowicz-Rybka, R., Witkowski, A., Woronko, B., Dobosz, S., 2014. Marine transgressions during Eemian in northern Poland: A high resolution record from the type section at Cierpięta. Quaternary International, **328–329**: 45–59.

Marks, L., Gałązka, D., Woronko, B., in press. Climate, environment and stratigraphy of the last Pleistocene glacial stage in Poland. Quaternary International, doi: 10.1016/j.quaint.2015.07.047

Mojski, J.E., 2005. Ziemie Polskie w czwartorzędzie (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Morawski, W., 1980. Objaśnienia do Szczegółowej mapy geologicznej Polski 1:50 000, arkusz Warszawa Zachód (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Muhs, D.R., 2004. Mineralogical maturity in dunefields of North America, Africa and Australia. Geomorphology, **59**: 247–269.

Muhs, D.R., Roskin, J., Tsoar, H., Skipp, G., Budahn, J.R., Sneh, A., Porat, N., Stanley, J-D., Katra, I., Blumberg, D.G., 2013. Origin of the Sinal-Negev erg, Egypt and Israel: mineralogical and geochemical evidence for the importance of the Nile and sea level history. Quaternary Science Reviews, **69**: 28–48.

Mycielska-Dowgiałło, E., 1993. Estimates of Late Glacial and Holocene aeolian activity in Belgium, Poland and Sweden. Boreas, **22**: 165–170.

Mycielska-Dowgiałło, E., 2007. Research methods for textural features of clastic deposits and the significance of interpretational results (in Polish with English summary). In: Badania cech teksturalnych osadów czwartorzędowych i wybrane metody oznaczania ich wieku (eds. E. Mycielska-Dowgiałło and J. Rutkowski): 95–189. WSWPR, Warszawa.

Mycielska-Dowgiałło, E., Dzierwa, K., 2003. Reconstruction of the dynamics of aeolian processes and of their duration on the basis of selected textural features of the deposits within the dune at Cięciwa (eastern Poland) (in Polish with English summary). Przegląd Geologiczny, **51**: 163–167.

Mycielska-Dowgiałło, E., Woronko, B., 1998. Rounding and frosting analysis of quartz sand-grain surfaces and their interpretative significance (in Polish with English summary). Przegląd Geologiczny, **46**: 1275–1281.

Mycielska-Dowgiałło, E., Woronko, B., 2004. The degree of aeolization of Quaternary deposits in Poland as a tool for stratigraphic interpretation. Sedimentary Geology, **168**: 149–163.

Novenko, E.Y., Seifert-Eulen, M., Boettger, T., Junge, F.W.M., 2008. Eemian and Early Weichselian vegetation and climate history in Central Europe: a case study from the Klinge section (Lusatia, eastern Germany). Review of Palaeobotany and Palynology, **151**: 72–78.

Pelánková, B., Chytrý, M., 2009. Surface pollen–vegetation relationships in the forest-steppe, taiga and tundra landscapes of the Russian Altai Mountains. Review of Palaeobotany and Palynology, **157**: 253–265.

Pelánková, B., Kuneš, P., Chytrý, M., Jankovská, V., Ermakov, N., Svobodová-Svitavská, H., 2008. The relationships of modern pollen spectra to vegetation and climate along a steppe-forest-tundra transition in southern Siberia, explored by decision trees. The Holocene **18**:1259–1271.

Pettijohn, F.J., Potter, P.E., Siever, R., 1972. Sand and Sandstones. Springer-Verlag, Cambridge.

Pietrzykowski, P., 2011. Eemian gyttja and lacustrine chalk from Warsaw as an example of „hard" organic soils (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **446**: 385–396.

Prószyńska-Bordas, H., Stańska-Prószyńska, W., Prószyński, M., 1988. TL dating of partially bleached sediments by the regeneration method. Quaternary Science Reviews, **7**: 265–271.

Roman, M., Balwierz, Z., 2010. Eemian and Vistulian pollen sequence at Kubłowo (Central Poland): implications for the limit of the Last Glacial Maxiumum. Geological Quarterly, **54** (1): 55–68.

Roman, M., Dzieduszyńska, D., Petera-Zganiacz, J., 2014. Łódź Region and its northern vicinity under Vistulian Glaciation conditions. Quaestiones Geographicae, **33**: 155–163.

Różycki, S.Z., 1967. Plejstocen Polski Środkowej (in Polish). Państwowe Wydawnictwo Naukowe, Warszawa.

Samsonowicz, J., 1922. Zastoiska lodowcowe nad górną i środkową Wisłą (in Polish). Sprawozdania Państwowego Instytutu Geologicznego, **1**: 373–403.

Sarnacka, Z., 1982. Age revision of the Warsaw proglacial lake in the Warsaw region. Biuletyn Instytutu Geologicznego, **343**: 59–70.

Sarnacka, Z., 1992. Stratigraphy of Quaternary sediments of Warsaw and its vicinity (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **138**: 1–88.

Skompski, S., 1969. Stratigraphy of Quaternary deposits of the eastern part of the Płock Depression (in Polish with English summary). Biuletyn Instytutu Geologicznego, **220**: 175–258.

Starkel, L., Michczyńska, D.J., Gębica, P., Kiss, T., Panin, A., Perşoiu, I., 2015. Climatic fluctuations reflected in the evolution of fluvial systems of Central-Eastern Europe (60–8 ka cal BP). Quaternary International, **388**: 97–118.

Šeirienė, V., Kühl, N., Kisielienė, D., 2014. Quantitative reconstruction of climate variability during the Eemian (Merkinë) and Weichselian (Nemunas) in Lithuania. Quaternary Research, **82**: 229–235.

Tröels-Smith, J., 1955. Karakterisaring af Løse jordarter (in Danish). Danmarks Geologiska Undersoegelsa IV Reakke Bd., **3**: 1–73.

Velichko, A.A., Timireva, S.N., Kremenetski, K.V., MacDonald, G.M., Smith, L.C., 2011. West Siberian Plain as a late glacial desert. Quaternary International, **237**: 45–53.

Vos, K., Vandenberghe, N., Elsen, J., 2014. Surface textural analysis of quartz grains by scanning electron microscopy (SEM): From sample preparation to environmental interpretation. Earth-Science Reviews, **128**: 93–104.

Weckwerth, P., Przegiętka, K., Chruścińska, A., Woronko, B., Oczkowski, H.L., 2011. Age and sedimentological features of fluvial series in the Toruń Basin and the Drwęca Valley (Poland). Geochronometria, **38**: 397–412.

Woronko, B., 2001. Znaczenie analizy obtoczenia i zmatowienia powierzchni ziarn kwarcowych frakcji piaszczystej w interpretacji genetycznej osadów czwartorzędowych (in Polish). In: Eolizacja osadów jako wskaźnik stratygraficzny czwartorzędu (ed. E. Mycielska-Dowgiałło): 33–38. Wydział Geografii i Studiów Regionalnych, Uniwersytet Warszawski, Warsaw.

Woronko, B., 2012. Micromorphology of quartz grains as a tool in the reconstruction of periglacial environment. In: Contemporary Issues in Polish Geography (ed. P. Churski): 111–131. Bogucki Wydawnictwo Naukowe, Poznań.

Woronko, B., Hoch, M., 2011. The development of frost-weathering microstructures on sand-sized quartz grains: examples from Poland and Mongolia. Permafrost and Periglacial Processes, **227**: 214–227.

Woronko, B., Rychel, J., Karasiewicz, M.T., Ber, A., Krzywicki, T., Marks, L., Pochocka-Szwarc, K., 2013. Heavy and light minerals as a tool for reconstructing depositional environments: an example from the Jałówka site (northern Podlasie region, NE Poland). Geologos, **19**: 47–66.

Woronko, B., Zieliński, P., Sokołowski, R.J., 2015. Climate evolution during Pleniglacial and Late Glacial as recorded in quartz grain morphoscopy of fluvial to aeolian successions of the European Sand Belt. Geologos, **21**: 89–103.

Woźniak, P.P., Czubla, P., 2015. The Late Weichselian glacial record in northern Poland?: A new look at debris transport routes by the Fennoscandian Ice Sheet. Quaternary International, **386**: 3–17.

Wysota, W., 2002. Stratygrafia i środowiska sedymentacji zlodowacenia Wisły w południowej części dolnego Powiśla (in Polish). Wydawnictwo UMK, Toruń.

Wysota, W., Molewski, P., Sokołowski, R.J., 2009. Record of the Vistula ice lobe advances in the Late Weichselian glacial sequence in north-central Poland. Quaternary International, **207**: 26–41.

Zagwijn, W.H., 2000. An analysis of Eemian climate in Western and Central Europe. Quaternary Science Reviews, **15**: 451–461.

Zieliński, P., Fedorowicz, S., Zaleski, I., 2009. Sedimentary succession in Berezno in the Volhynia Polesie (Ukraine) as an example of depositional environment changes in the periglacial zone at the turn of the Vistulian and the Holocene. Geologija, **51**: 97–108.