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Palaeogeographic reconstruction of the North Podlasie region in the Sokółka area during the Late Pleistocene (NE Poland)

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A new palaeogeographic reconstruction from the end of the Odranian Glaciation to the end of the Weichslian Glaciation (MIS 2) is based on research carried out at the Knyszewicze site, NE Poland, focusing on the dynamics of the Wartanian Glaciation (MIS 6) and showing the lobed nature of this ice sheet. Reconstruction of deglaciation in the research area was supplemented by analysis of postglacial morpholineaments (MMA). Research carried out at the Jałówka site enabled reconstruction of the processes affecting lake processes during the Eemian (MIS 5e) Interglacial and transformation of this area during the Weichselian Glaciation. The results obtained indicated that the study area was not covered by Weichselian ice, the sediments formerly considered as glacial being slope-related and providing evidence of periglacial conditions. A new conceptual model for the evolution of this area is put forward, showing the polygenetic nature of the relief. The glacial landforms developed during the Warta Stadial and transformed during the Eemian Interglacial were further affected by periglacial processes, which significantly remodelled the relief.

Key words: palaeogeographic reconstruction, Late Pleistocene, North Podlasie, ice sheet dynamics, periglacial zone.

INTRODUCTION

This article reviews research on palaeogeographic reconstruction of the northern Podlasie region in the Sokółka area during the younger Pleistocene, from the end of the Odranian Glaciation to the end of the Weichselian Glaciation, based on the author's Ph.D. thesis, published in 2013–2017. It also contains previously unpublished data, including the location of key sites on a geological map, aggregate MMA results for the study area, a new conceptual model of the evolution of the study area, and comprehensive results of physicochemical and palynological tests. The key issues here are as follows:
– presence of the Weichselian (Vistulian) Glaciation ice sheet during the Middle Stadial (MIS3);
– maximum glacial extent during this glaciation;
– nature and dynamics of processes that have influenced the present shape of the northeastern part of the Podlasie Lowland.

Over 70 sites with Eemian Interglacial deposits (MIS 5e) have been described from the Podlasie Lowland (Kupryjanowicz, 2000, 2008; Kupryjanowicz et al., 2011), and it is possible to stratigraphically assign the overlying glacial deposits to the Middle Stadial (Świecie) of the Weichselian Glaciation. To this end, fieldwork was carried out at the Jałówka site (issues 1 and 2 above). The distribution of landforms and characteristics of their deposits were determined based on fieldwork, which involved drilling shallow boreholes (20 manual up to a depth of 2 m) and geophysical studies (total length of 518 m and a depth of up to 15 m) (Rychel et al., 2013, 2015; Woronko et al., 2013, 2017). Additionally, two Geoprobe boreholes (4.5 and 8.3 m deep) and one excavation pit (4 x 4 x 4 m) were made. Samples were collected to analyse textural properties, which involved analysis of grain size distribution (Rychel et al., 2015; Woronko et al., 2017), roundness and frosting of quartz grains (Woronko et al., 2013, 2017) as well as the content of heavy minerals (Woronko et al., 2013). Samples for physicochemical and geochemical analysis were also collected (Rychel et al., 2013; Woronko et al., 2013, 2017). Palynological analysis and analysis of plant macroremains were made on biogenic deposits (Rychel et al., 2013; Woronko et al., 2017). Selected mineral deposits were dated using the OSL (Optically Stimulated Luminescence) method (Woronko et al., 2017).

Based on the analysis of linear landforms (Multistage Morpholineament Analysis MMA) in the vicinity of the Knyszewicze site, an attempt was made to reconstruct the dynamics of the Warta Stadial ice sheet (MIS 6), directions and stages of its advance and the nature of deglaciation (issue 3). Based on topographic and geological maps as well as a terrain model (DT2), multistage morpholineament analysis (MMA) (Rychel et al.,

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2015; Rychel and Morawski, 2017) was carried out in the GIS environment (ArcGIS). Profiling of three walls in the Knyszewicze outcrop (up to 8 m high), were made during the fieldwork.

LOCATION

The study area is located in the northeastern part of the North Podlasie Lowland (NE Poland) bordering the territory of Belarus. It consists of the Sokółka Hills and the adjacent eastern part of the Białystok Plateau (Kondracki, 2009) up to the environs of Suchowola, Korycin and Janów. The area is located between the Biebrza, Neman and Świsłocz River valleys and extends beyond the range of the last Weichselian ice sheet (Fig. 1). In geological terms, it is one of the northernmost upland patches formed during the retreat of the Warta Stadial ice sheet (Marks and Karabanov, 2011). It represents the old glacial landscape, with large topographic height differences and distinct glacial landforms (Musiał, 1992). The peaks of hills with a relative height of up to 20 m rise ~70–120 m above the bottom of the Biebrza Valley. These are sandy and gravelly elevations of kames and end moraines, locally also including push moraines (Wrotek, 2009), with a height ranging from 190 to 240 m a.s.l., e.g. Wojnowska Mount located south-east of Sokółka (Fig. 2A). The highest elevations in the area of the Sokółka Hills are located in the village of Gliniszcze Wielkie (236.6 m a.s.l.) and Horczaki Knoll near the village of Wojnowice. The lowest locations are the bottoms of river valleys south-west of the village of Janów (Kumiałka River) or north of the village of Sidra (Sidra

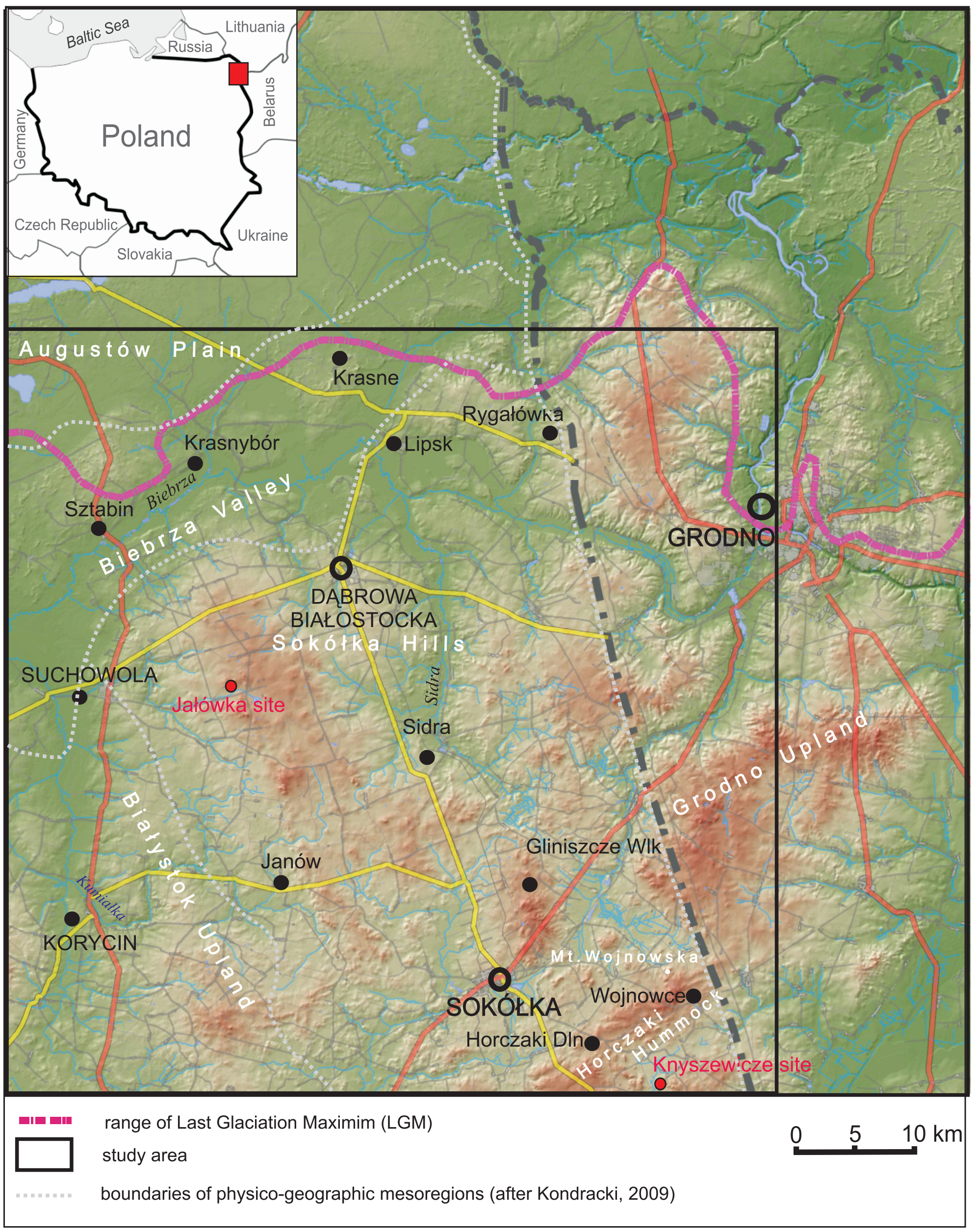


Fig. 1. Location of the study area

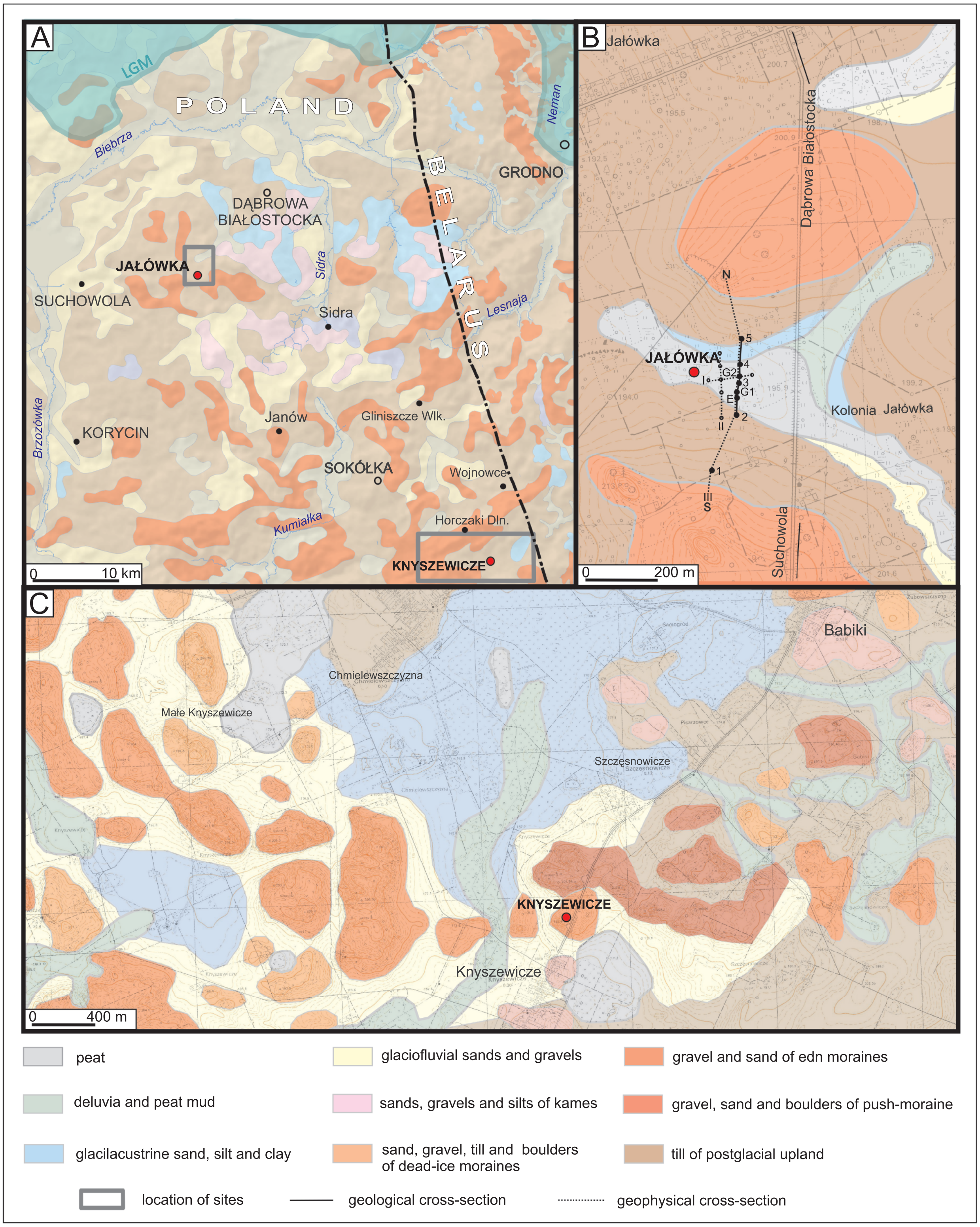


Fig. 2. Geological map of: A – study area (based on Marks, 2006); B – Jałówka site (based on Wrotek, 2009); C – Knyszewicze site (based on Boratyn, 2006)

River), thus the height differences in this area are ~100 m. The sites selected for detailed research are located in the northern (Jałówka) and southeastern (Knyszewicze) parts of the Sokółka Hills.

The Jałówka site is located 10 km south-west of the town of Dąbrowa Białostocka and 60 km north of the city of Białystok, at an altitude of 194.5 m a.s.l., at the foot of the end moraine in an extensive, currently dry NW–SE valley. The valley cuts through the hills; its bottom profile is irregular, with scattered small waterlogged depressions (Fig. 2B).

The site at Knyszewicze is located in an arch-shaped zone of end moraines, with a height of ~180 m a.s.l. and open towards the north-east. The arch of end moraines is developed in the form of a lobe, which stretches from the environs of Wojnowice in the north-east, through Horczaki Dolne to Knyszewicze in the south-west and then continues south-east (Fig. 2C).

LANDFORM ANALYSIS

Detailed analysis of postglacial morpholineaments was carried out first at the Knyszewicze site and next across the whole study area. Eight different positive and negative genetic forms of terrain relief were distinguished, directly or indirectly related to the glacial environment (Rychel and Morawski, 2017; Fig. 3). The quantitative analysis involved the count of morpholineaments (vectors) at intervals of 5 and 10 up to 180° every kilometre along their length, within the groups examined. The results of accidental vectors of each morpholineament group were shown graphically as rose diagrams in order to obtain the cumulative distribution of morpholineaments by direction and geomorphic feature (Fig. 3). The qualitative analysis consisted of a detailed analysis of the arrangement of the individual morpholineament types in order to define sectors where the individual morpholineament groups had a similar orientation (Table 1). The study area was divided into segments. The test area around the Knyszewicz site is located in the L1 segment (Fig. 4A). Two different azimuths, representing the strongest ice- sheet movement directions, were found: 171° (Horczaki Knoll Domain) and 23° (Knyszewicze Domain). In order to further constrain the ice mass movement directions, a comprehensive analysis of linear landforms – morpholineaments (MMA) – was conducted for the whole study area (Fig. 4B). Orientations of the glacial forms of the marginal zone system of the whole study area showed the existence of two groups of glacier ice mass movement directions (~290 and 330° as well as ~40 and 5°; Rychel and Morawski, 2017). The resultant directions of the first group (NNW) are concentrated in the central and western part of the area surveyed and the second group (NE) in the east.

GEOLOGY

The walls of the in Knyszewicze are built of three, slightly varied lithofacies units (Rychel et al., 2015). Measurements of two groups of faults – dip-slip (normal) faults, very common, with dip angles ranging 46 to 83°, and reversed (thrust) faults, with dip angles ranging from 11 to 44° – were made for a gravelly and sandy rhythmite forming large tilted planes where maximum particle size (MPS) increases upwards (Gh, Gm, SGh, Sh; Fig. 4). The sediments are strongly disturbed, with monoclines dipping at an angle of 40–50° to the north. Their total thickness reaches 30 m. The Knyszewicze site measurements of the angles of overthrust fault plane dips are within the range of 11–44° and demonstrate the NNE overthrust direction (Szymczuk et al., 2014; Rychel et al., 2015; Fig. 4C).

The geophysical profiling and field mapping (excavating pits and drilling) enable visualisation of the spatial outline of the valley along with the distribution of its sedimentary deposits (Fig. 5).

A cross-section was drawn based on the interpretation of the electrical resistivity tomography image made along the cross-sectional line and the geological data collected from the excavation pit, two Geoprobe boreholes and archival data. The northern exposure slope is built of glacial till (up to a depth of 4 m), overlain by sands (0.5 m). In the past, the present-day dry valley was incised as a tunnel valley (subglacial channel; 250 m wide) in sandy gravel and fine-grained sands and silts, which have been preserved in the lateral parts of the valley. Two former lakes with biogenic sediments were found within the valley. One was located in the lateral parts of the valley, where the excavation pit and boreholes were made, and a deeper one was located in the thalweg where peat was present up to a depth of 5.6 m.

SEDIMENTARY ANALYSIS

At the Jałówka site, two Geoprobe boreholes were drilled in the thalweg and on the slope of the currently dry valley, at depths of 4.5 and 8.3 m respectively, and one excavation pit was dug to a depth of 4.5 m in the marginal zone of this valley (Fig. 2B). Sedimentary and genetic units were distinguished based on grain size (Folk and Ward, 1957) and lithofacies analysis, respectively.

Unit I was recognized in the excavation profile <4.46 m depth (Fig. 6). This comprises fine-grained massive sands (Sm), the occurrence of which in the adjacent profile (Geoprobe 1) was supported by the results of electrical resistivity tomography profiling. Analysis using a modified Cailleux method (Table 2) showed a significant dominance of O grains (73%). Their surfaces are chemically weathered, seen as intense encrustations. EM/EL (EM – aeolian moderately rounded; EL – fluvial very well rounded) and EL grains account for a small proportion, accompanied by cracked (C) and completely angular (NU) grains. No EM/RM (RM – aeolian very well rounded) grains were found (Fig. 7).

Unit II was recognized in all three boreholes in the excavation pit as well as in the Geoprobe 1 and 2 profiles at depths of 4.13–4.46 m, 3.60–4.50 m and 2.47–8.29 m, respectively. This unit is represented by gyttja and peat (Fig. 8A), while the Geoprobe 2 profile also revealed clay with organic matter.

Unit III was documented in the Geoprobe 2 profile in the thalweg at a depth of 1.90–2.47 m as grey, massive clay with minor involutions and in the Geoprobe 1 profile at a depth of 3.40–3.60 as clayey silt (Fig. 6).

Unit IV as recognized in the excavation pit at a depth of 3.9–4.13 m comprises silty sands with climbing ripple-lamination (Src). In the Geoprobe 2 profile at a depth of 1.75–1.83 m, it is represented by fine-grained sands, and in the Geoprobe 1 profile by sands with pebbles up to 1 cm in diameter at a depth of 3.23–3.40 m.

Unit V was seen in the excavation pit and the Geoprobe 1 profile depths of 2.0–3.90 m and 2.70–3.60 m respectively, as fine-grained and silty loess-like sands. The modified Cailleux analysis showed a clear dominance of EM/EL (64.6%) and EL grains (18.5%), with a very high content of cracked grains (C = 11.3%; Fig. 7).

Unit VI consists of massive clayey silt seen in the excavation pit at a depth of 0.7–2.0 m, in the Geoprobe 1 profile at 1.45–2.70 m depth, and in the Geoprobe 2 profile at 1.39–1.75 m depth. The base of this unit includes pebbles up to 5 cm in diameter, the contact with the underlying units V and IV being erosive. Basal deposits of this unit show cubic structure (Fig. 8B) and include two generations of pseudomorphs after ice wedges (Fig. 8C) with primary sand infills found in the excavation pit. A very high content of cracked grains (up to 39.3%) was recorded in unit VI with individual EM/RM grains (1.8%) at its base, while EL and EM/EL grains form a very high percentage. A high proportion of O grains is present (from 12.7 to

28.9%). Completely fresh and angular NU grains were also found.

Unit VII, documented at a depth of 0.8–1.45 m only in the Geoprobe 2 profile drilled in the thalweg, comprises sandy gravels and fine sands (Fig. 6).

Unit VIII, at a depth of 0.5–0.7 m in the profile of the excavation pit and from a depth of 0.65–0.85 m in the Geoprobe 2 profile, is composed of massive silty sands, characterized by a very high content of cracked (C = 30.7%) and NU grains (3.5%).

The deposits at the Jałówka site are decalcified and extremely poor in Na, Mg, Ca, K, Fe and Mn, which may indicate

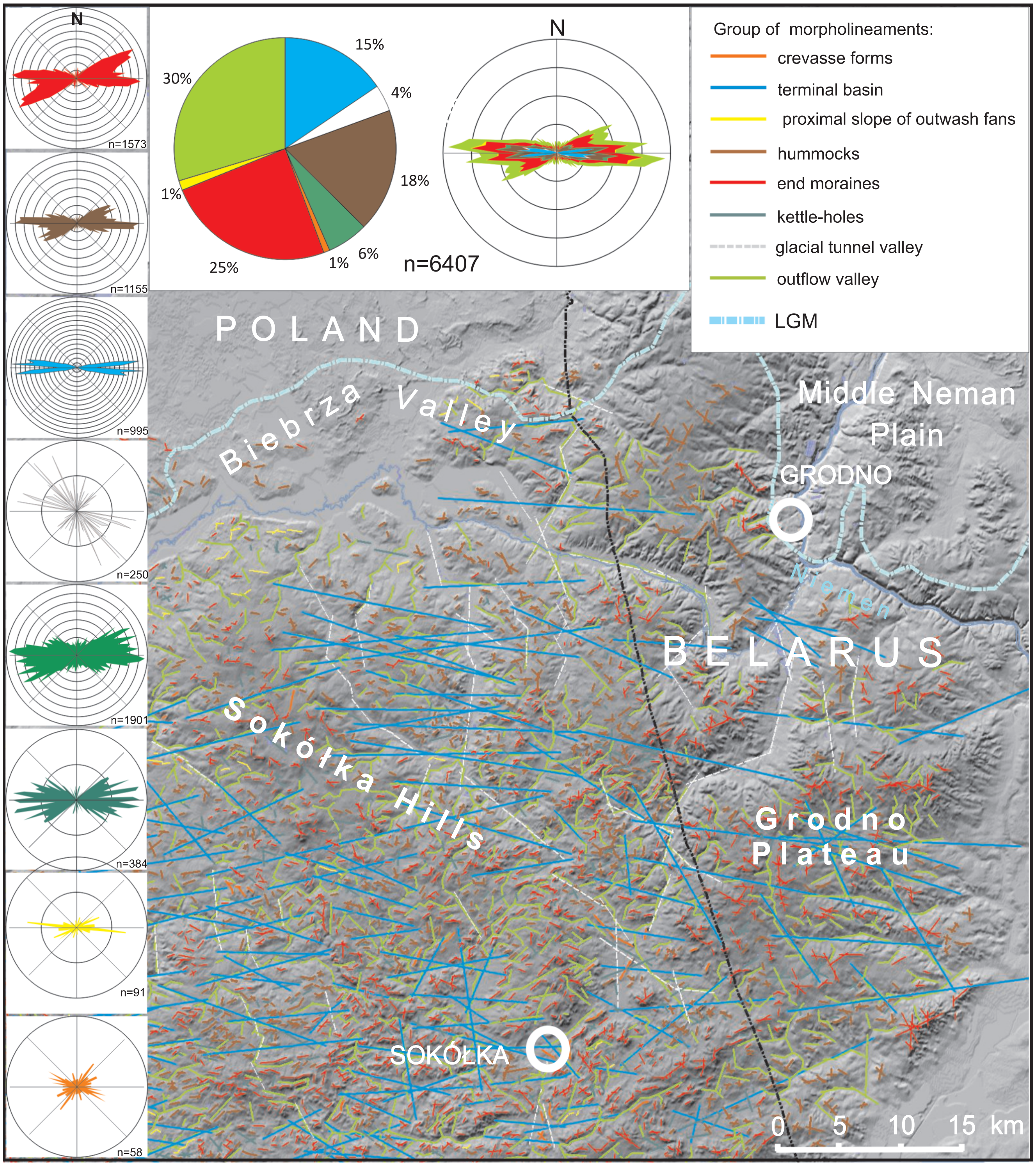


Fig. 3. Quantitative distribution of morpholineament groups for the study area (description after Rychel and Morawski, 2017)

strong weathering (Fig. 7). Their reaction varies from alkaline (unit IV) to neutral (units V and VI) and slightly acid (unit VIII).

The content of non-opaque heavy minerals is very similar in all units. Amphiboles and garnets dominate with a small proportions of zircon, rutile, tourmaline, staurolites and disthene. The zircon content in the sand wedge infills is slightly higher. Highly weathering-resistant minerals are present in the central part of unit VI. Primary iron oxides (ilmenite and magnetite) dominate among the opaque heavy minerals, with the highest content in unit VI. Secondary iron oxides (limonite and goethite) occur in very small amounts in units I, II and IV, while in unit II they account for almost 20%. The coefficient of weathering has a similar value in units IV and V, is slightly higher in unit VIII, varies in the sand wedges and unit VI, with greater values at top and base. By comparing the frequency of heavy minerals with those recorded from Lithuania and northern Germany for glacial deposits of the same age (Saale MIS 6), an analogous supra-regional source of material may be inferred (cf. Vareikienė et al., 2007; Fig. 7).

Results of physicochemical analysis indicate changes in oxidation-reduction conditions, the variability and intensity of denudation, the level of biological production and fertility of the environment (Rychel et al., 2014). The stable isotope (δ^{13}C and δ^{18}O) profiles have different shapes, which indicates an open water body (Fig. 7). The lower parts of the organic sediment profile indicate the sedimentation of allochthonous material from glacial deposits, while the top includes authigenic carbonates, probably reflecting higher air temperatures and more reducing conditions and consequently, a higher content of organic matter.

OSL dating of mineral sediments lining the bottom of the dry valley show that the accumulation of unit V sediments took place from 82.7 ±5.6 ka to 50.9 ±2.8 ka. Deposits of unit VI were dated at 60.4 ±5.6 ka, whereas sandy deposits of unit VIII were dated at 12.75 ±0.81 ka. Deposits of unit VIII in Geoprobe 2 were dated at 3.96 ±0.29 ka (Fig. 6).

PALAEOGEOGRAPHIC INTERPRETATION

The results obtained help reconstruct the geological history of the area surveyed area over the last 130,000 years, with six intervals distinguished:

1. Warta Stadial of the Odranian Glaciation (Saalian, MIS 6). Approximately 130,000 years BP (MIS 6), the area surveyed was covered by a continental ice sheet of heterogeneous structure. The area of northern Podlasie is characterized by a varied relief. Height differences (denivelation) are up to 100 m. A correlation between linear morphological elements and the activity of the ice sheets (e.g., Punkari, 1997; Boulton et al., 2001; Morawski, 2009) allowed reconstruction of the two main ice sheet movement directions. Two glacial areas were distinguished in the vicinity of the Knyszewicze site: Horczaki Knoll and Knyszewicze (Fig. 4C). A comprehensive analysis of linear landforms – morpholineaments (MMA) – was conducted for the whole study area (Rychel and Morawski, 2017), indicating that two ice sheet lobes coexisted in the study area (Narloch et al., 2013; Czubla, 2015), covering its eastern (Neman lobe) and western (Biebrza lobe) parts (Ber et al., 2012; Fig. 3). In the central part of the Sokółka region, the two lobes overlapped. The ice sheet entered through extensive depressions, today used by the river valleys of the Biebrza River in the west and the Niemen River in the east. It transgressed onto heterogeneous substrate, overcoming various types of barrier (Karabanov, 1987). The Horczaki Knoll was probably one such barrier, which

Table 1

Qualitative analysis of selected groups of morpholineaments for the study area divided into 15 segments (results direction in degrees)

SECTOR	terminal basins	tunnel valleys 1	tunnel valleys 2	marginal system 1	marginal system 2	succession
	I	II	III	IV	IV	older?younger (I? V)
L1	2			346	23	I? IV?V
L2	2			344		II?IV
L3	1	294		353		I?II??IV
L4	3	335		355		I?II?IV
L5	5			347		I???IV
L6	8	292	36	340	31	I?II?IV?III?IV
L7	10	40		338	40	I?II?IV?V
L8	3	345		359		I?II?IV
L9	2	287		352		I?II?IV
L10	14?	4?		0		I?II?IV
L11	353?	282?		352		IV
L12	4	332	45	355		I?II?IV for W part I?II?III?IV for NE part
L13		317?		3		IV
L14	5?	5?		354		I?II?IV
L15				355		IV

Division of ice-masses flow into two glacial lobs based on hypothetical direction of transgression: Neman lobe - western (sectors from L1 to L4, L8 and L9, L12); Biebrza lobe - eastern (sectors from L5 to L7, L10 and L 14)

Restored subglacial drainage systems for both lobes: older / younger — Neman lobe, Biebrza lobe

Stage of deglatiation of study area dased on marginal system analysis: eldest — youngest

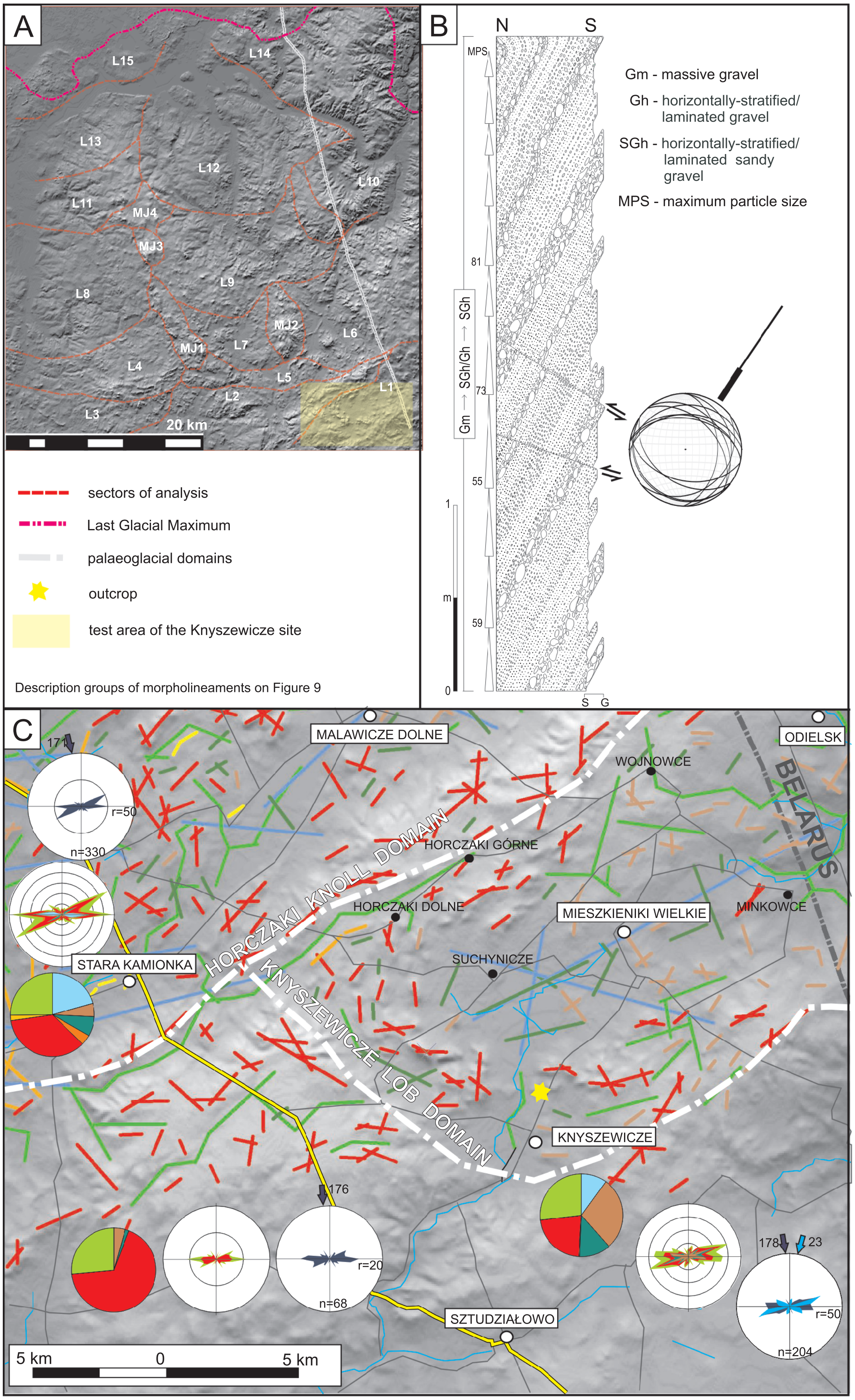


Fig. 4. Knyszewicze site

A – division of the study area into sectors for analysis; **B** – lithological log (after Rychel et al., 2015; description lithology after Zieliński and Pisarska-Jamroży, 2012); **C** – results of MMA

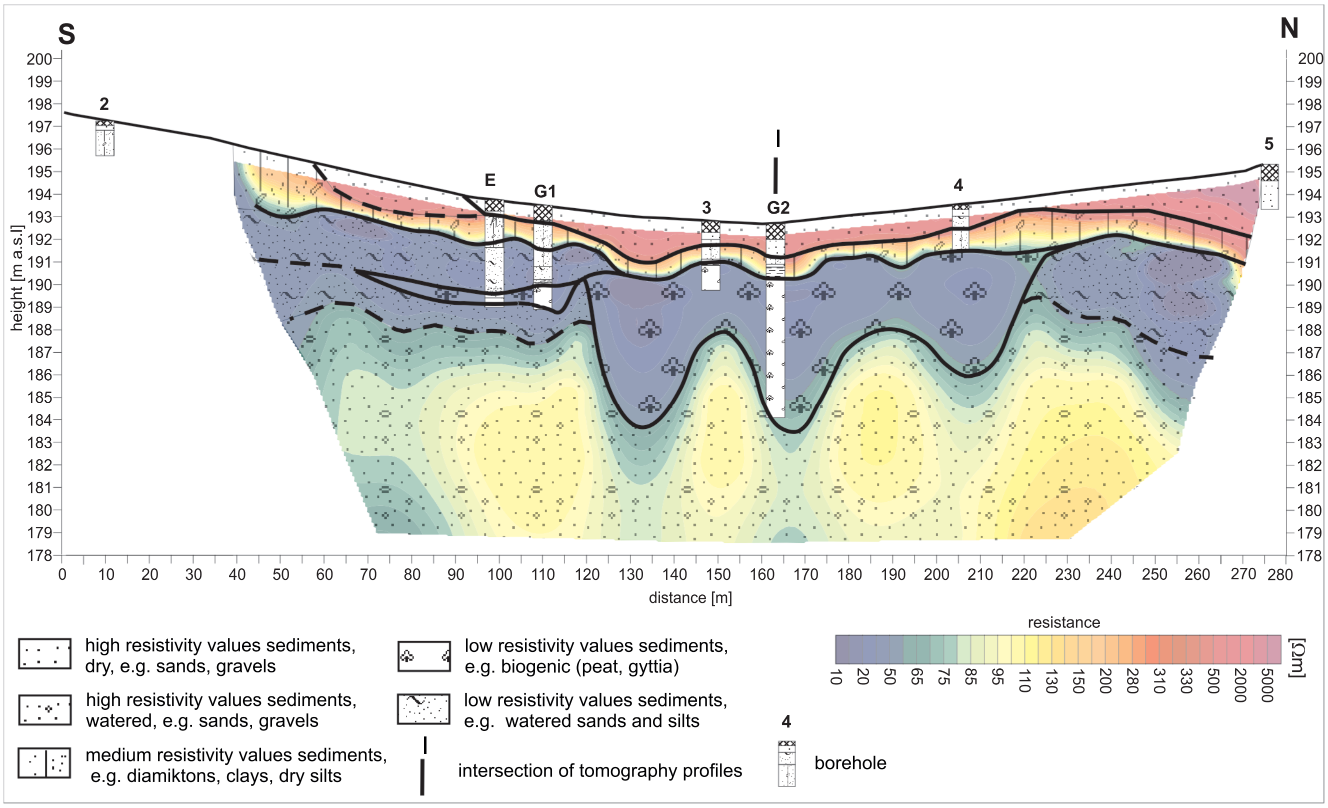


Fig. 5. Geological cross-section of the Jałówka sites based on ERT measurements

contributed to the activity of a small ice lobe near Knyszewicze (Rychel et al., 2015). Palaeoglaciological inversion model assumptions (Kleman and Borgstrom, 1996; Clark, 1997; Napieralski et al., 2007; cf. Benn and Evans, 2010) were used in reconstructing the varying ice sheet dynamics of the inferred Biebrza and Neman ice sheet lobes and in setting the relative chronology of glacial events during deglaciation in the Sokółka Hills area (Table 1). The variability in subglacial drainage directions indicates multiple changes in dynamics of the functioning and interactions of both glacial lobes and allows reconstruction of their ranges. Changes in the subglacial drainage system indicate the pulsatory nature of the ice movement and the presence of episodes with increased subglacial drainage, particularly well-developed in the western sector. The complex orientation of postglacial forms of the marginal zone system in particular sectors enables interpretation of the chronology of glacial events. The prevailing direction from the NNW (~290°) reflects climatic and glacio-dynamic factors. The continuing amelioration of climatic conditions led to a horizontal sequence of deglaciation, which was slightly modified by active ice movement or re-advance of some parts of the ice sheet. Possible traces of glacio-dynamic impact from the NE, ~40° (corresponding to the Neman lobe), are marked in the system of marginal morpholineaments as a secondary coupled system of morpholineaments with lower frequency. Based on the analysis of resultant directions of the marginal morpholineament system, a likely scheme of deglaciation isochrons was reconstructed.

The glacial lobes were connected to the early stages of ice advance. The azimuth of the greatest glacier basal shear stress (171°) is consistent throughout the study area and likely corresponds to the main NNW direction of transgression. Then, the rate of the Biebrza lobe advance increased from the WNW, while the Neman lobe stagnated. This was followed by activation of the Biebrza ice lobe masses by continued inflow of ice (Rychel and Morawski, 2017). These changes are manifested by glaciotectonic deformations in the marginal zone of the Knyszewicze (23°) area, which are evidence of NNE glacier advance (Rychel et al., 2015). The process of deglaciation began in the area covered by the Neman lobe, while ground depressions in the area covered by the Biebrza lobe were still receiving ice masses.

The formation of the valley in the Jałówka area can be associated with erosion by subglacial water, whereas the size and depth of the valley indicate that it may have originally been a narrow tunnel valley (Atkinson et al., 2013; Stewart et al., 2013). The bottom of the valley varies in altitude and the differences can reach up to 8 m, which may indicate the presence of two channels in the trough. After the ice sheet retreated and dead-ice blocks melted, small depressions of various depths were formed in the floor of the valley. They were formed through periglacial processes (thermokarst) as a result of ground ice melting (Klatkowa, 1990; Rdzany, 1997; Morgenstern, 2012). The massive sands of Unit 1 accumulated within them (Figs. 5, 6 and 9).

2. Eemian Interglacial (MIS 5e)*.* Gradual climate amelioration after the glaciation led to the development of vegetation cover. During the Eemian Interglacial (MIS 5e), the study area was a lakeland, the bodies of water being mostly shallow and small and functioning independently of each other, alternately as lakes and peat bogs with fluctuating water levels. In the Geoprobe 2 borehole (192.5 m a.s.l.) at a depth of 1.5–7.0 m, biogenic deposits (Unit 2) occur, formed in the Eemian Interglacial (Figs. 6 and 8). The water body was deeper and all phases

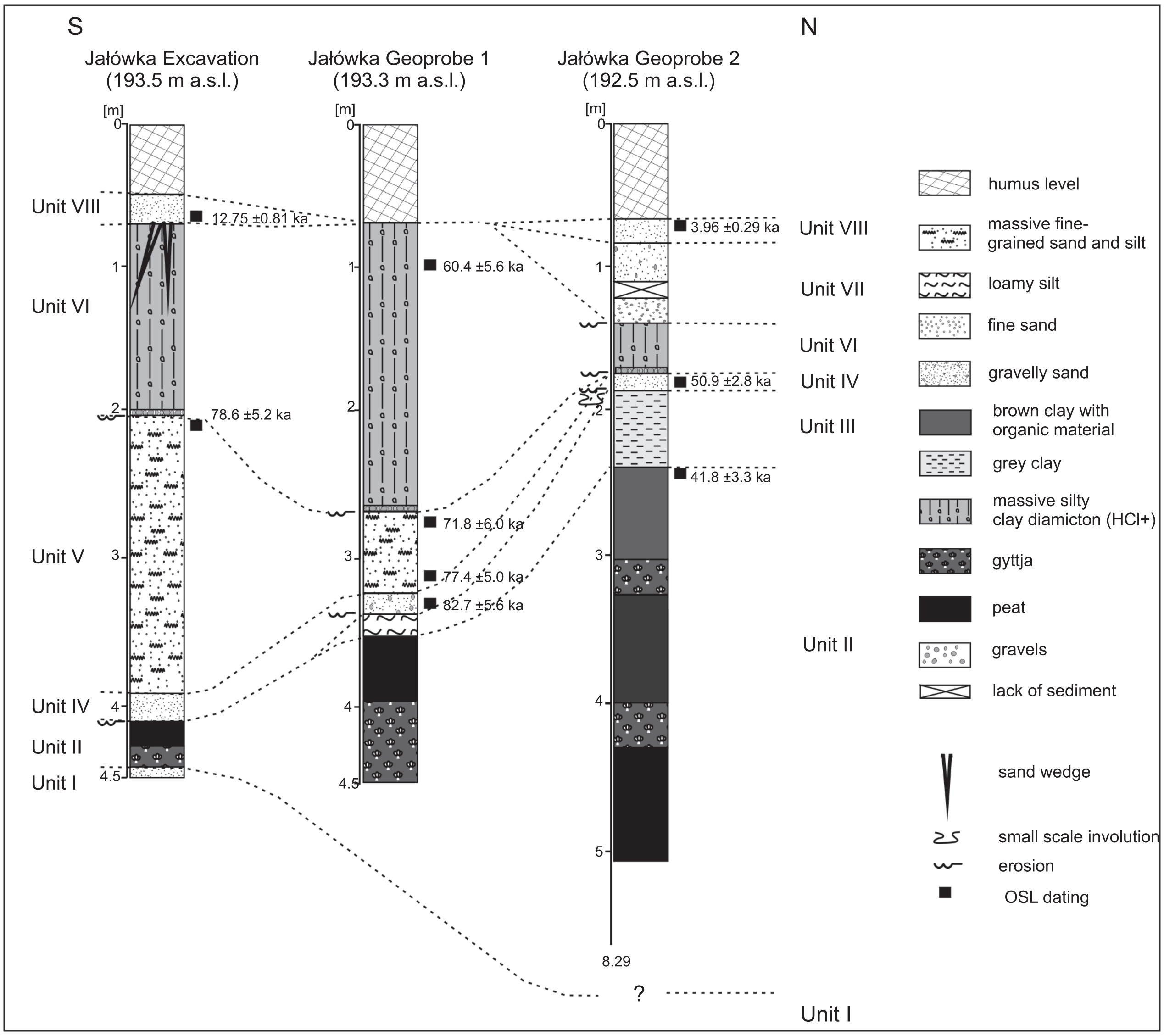


Fig. 6. Sedimentary profiles in the Jałówka site (after Woronko et al., 2017, changed)

of the Eemian Interglacial are recorded in the deposits. Based on palaeobotanical studies, a continuous record of climate change was identified in the Jałówka succession, from the Late Glacial Period at the end of the Warta Stadial (MIS6) through the Eemian Interglacial (MIS 5) to the Early Weichselian Glaciation (MIS 5 a–d).

In the marginal zone of the water body (excavation pit), sedimentation of the Eemian unit started with gyttja (initial phase E1), which then turned into peat with preserved pine-oak (E2), oak (E3), hazel (E4), hornbeam (E5), spruce (E6) and finally pine (E7) phases. At the end of the Eemian Interglacial (~115 ka), the water body were gradually transformed into a peat bog (Fig. 10). Pollen analysis performed on the profile of the excavation pit delineated five local pollen zones (L PAZ), which were correlated with regional zones (R PAZ) of the Eemian in northeastern Poland (Kupryjanowicz, 2008; Fig. 5). J/1 L PAZ *Juniperus–Artemisia* (4.36–4.47 m) belongs to the late glacial period of the Middle Polish (Wartanian/Saalian) Glaciation and is correlated with the Lw1 R PAZ. The J/2 L PAZ *Pinus–Betula–Picea* (4.28–4.36 m), J/3 L PAZ *Pinus–Betula–Ulmus* (4.18–4.28 m), J/4 L PAZ *Quercus–Ulmus–Fraxinus* (4.16–4.18 m) and J/5 L PAZ *Corylus–Quercus–Alnus–Tilia* (4.13–4.16 m) are assigned to the Eemian Interglacial and are correlated with regional zones E1, E2, E3 and E4, respectively. Eleven pollen zones (L PAZ) were distinguished based on pollen analysis performed on the Geoprobe 2 profile, which correlate well with the regional pollen zones distinguished for the territory of Poland. The six lowest zones – from J-1 to J-6 (E2–E7 R PAZ; depth 3.95–8.25 m) – correspond to the zones obtained for the excavation pit and represent the Eemian Interglacial vegetation succession (MIS 5e) (Fig. 10).

3. Early Weichselian (MIS 5d–5a). During colder stadials of the Early Weichselian Glaciation (Herning and Redelstall: MIS 5d and 5b), gyttja accumulated in the water bodies as a result of rising water level, whereas in warm stadials (Brörup and Odderade: MIS 5c and 5a) the water bodies became shallower and turned in peat bogs (Kupryjanowicz, 2008; Fig. 9). The J-7 L PAZ (depth 3.78–3.95 m) features the first post-Eemian climate cooling, i.e. the Herning Stadial, which corresponds to the C23 stadial in the North Atlantic cores and the younger part of MIS 5d (EV1 R PAZ). The J-8 L PAZ (depth 3.25–3.78 m) correlates with the first interstadial of the Early Weichselian, i.e. the

Table 2

Classes of rounding and frosting of quartz grains according to Mycielska-Dowgiałło and Woronko (1998)

Class of grain	Roundness of grain acc. to Krumbein (1941)	Description	Processes responsible for the formation of grain
RM	0.7–0.9	very well rounded with completely mat surface	very long duration abrasion in aeolian environment
EM/RM	0.3–0.6	moderately rounded, mat surface only on convex parts of grains	short abrasion in aeolian environment marked only on convex parts of grains
EL	0.7–0.9	very well rounded with smooth, shiny the entire surface	combination of abrasion and solution in fluvial or beach environment; very well roundness of grains indicates long duration of processes
EM/EL	0.3-0.6	moderately rounded, smooth and shiny surface	combination of abrasion and solution in fluvial or beach environment
C	–	crushed/broken	crushing in all type of environments but the most intensive in subglacial environment or as an effect of frost weathering
NU	0.1–0.2	all surface are fresh, corners are sharp and angular	crushing and abrasion in glacial environment; mechanical weathering *in situ* e.g., frost weathering
O	0.1–0.9	*in situ* very intensive weathered surface by silica precipitation or solution; no visible transport trails	solution or precipitation in soil profile, hot desert environment or periglacial environment

For explanations see text

Brörup Interstadial (MIS 5c) (EV2 R PAZ). The J-8a L PASZ (depth 3.65–3.78 m) corresponds to the birch phase and the J-8c L PASZ (depth 3.25–3.55 m) to the pine phase of this interstadial, while the J-8b L PASZ (depth 3.55–3.65 m) corresponds to the Brörup cold oscillation. The second stadial of the Early Weichselian (Rederstall, MIS 5b) is documented by the J-9 L PAZ (depth 3.18–3.25 m; EV3 R PAZ). Its record is the accumulation of brown clay (unit III), noted in the Geoprobe 2 and Geoprobe 1 profiles (Figs. 6 and 9). The local zone of J-10 (depth 2.53–3.18 m) represents the Odderade Interstadial (MIS 5a; EV4 R PAZ) (Fig. 10).

4. Early Middle Weichselian Glaciation. The climate cooled significantly in the Middle Weichselian (MIS 4), which may have resulted in the formation of permafrost (Delisle et al., 2003; Jary, 2007; Satkunas et al., 2009). As a result of decreased water supply and evapotranspiration, the shallow lake in Jałówka was drained. This was followed by a channelized flow of water in the former tunnel valley, accumulation of fine-grained sand with cross-lamination of Unit IV, climbing ripple marks and erosion of material in the marginal zone of the valley, which is marked by the lack of sediments from the Late Eemian Interglacial and the Early Weichselian Glaciation (Fig. 9). This was related to an increase of water supply and decrease of apotranspiration (Kasse et al., 2003). The results of the modified Cailleux method performed on the sediments collected from the excavation pit show a dominance of quartz grains representing an aquatic environment (EL and EM/EL) (Fig. 7), which suggests deposition as a result of a clear, low-energy channel flow, which may also be indicated by the erosive nature of contact between this unit and the deposits below. Erosion took place in the valley bottom and marks the MIS 5a to MIS 4 transition, as in the bottoms of river valleys in Western Europe (Mol et al., 2000). The uppermost pollen zone of J-13 L PAZ (depth 2.47–2.53 m) corresponds to the Early Plenivistulian (early MIS 4), i.e. the Schalkholz Interstadial (Woronko et al., 2017). From this moment onwards, the dry valley began to function as a valley and not as a series of isolated depressions located along the ancient subglacial trough. Sediments of unit V infilled the channel. The large thickness (~2 m), fine-grained and uniform character, lacking a gravel fraction, indicate similarity to the type of sediment described by Baltrūnas et al. (2007) in the periglacial zone of the Weichselian in south-east Lithuania. Their aeolian or solifluction genesis is suggested by the results of the Cailleux analysis. The lack of EM/RM types of quartz grains in the sediment (Fig. 7) indicates that the conditions favouring the development of aeolian processes were short term. Aeolian transport was over a short distance because distinct grain segregation of the particles into fractions did not occur. The accumulation of sediments of unit V was preceded by erosion, as observed in many Central European loess regions correlated with MIS 4 (Frechen et al., 2003).

5. Late Middle Weichselian Glaciation. Slope processes were initiated on the valley slopes and sediments of unit VI were displaced through lobes and solifluction covers (MIS 3), as shown by results of the Cailleux analysis, therefore their thickness on the slopes is the smallest and increases in marginal parts of the valley (Fig. 9). The slope processes commenced at the end of MIS 4 or in MIS 3 as indicated by OSL dates (Fig. 6). Large thickness of diamicton may indicate the imposition of successive solifluction lobes on top of each other. Investigations in current cold zones indicate that when the thickness of the transported layer exceeds 60 cm, two-sided freezing occurs. This phenomenon requires the presence of continuous permafrost and MAAT <6°C (Matsuoka, 2001).

6. Late Weichselian Glaciation (MIS 2). In the late Weichselian, the study area was located ~20 km south of the maximum range of the Weichselian (Vistulian) Glaciation (MIS 2), in the periglacial climate zone (Dylik, 1953; Jahn, 1970), as shown by the presence of two generations of ice wedges and cubic structure in the roof part of slope deposits (Fig. 8C). This indicates the presence of an active layer of relict permafrost (Goździk, 1995). The presence of two wedge generations suggests that they developed at different times and represent different climate conditions (Murton et al., 2000). The width of the wedges and their lengths indicate that the processes related to their formation were short-term. The thickness of the active layer was most probably restricted to the sand layer (unit VII).

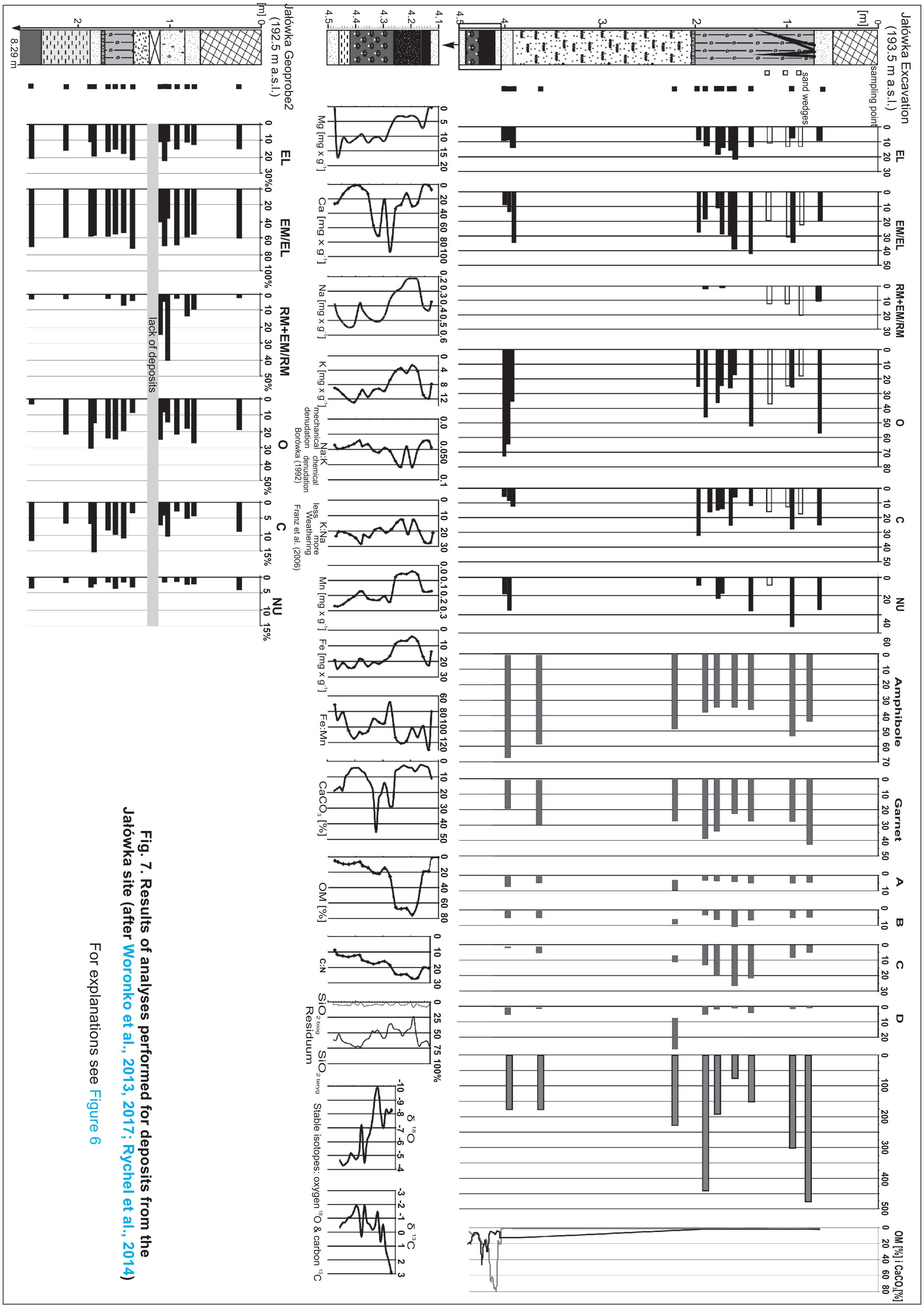


Fig. 7. Results of analyses performed for deposits from the Jałówka site (after Woronko et al., 2013, 2017; Rychel et al., 2014)

For explanations see Figure 6

With a subsequent increase in climate aridity, aeolian processes were activated (unit VIII) (Mycielska-Dowgiałło, 2001; Jary, 2007). The results of the Cailleux analysis (1942) performed on quartz grains from sandy sediments filling the wedges show almost an identical spectrum of grain types as in unit VI. Differences are only observed in the content of cracked grains (C), which does not exceed 7% at the bottom of wedges. In the upper parts of wedges, grains of aeolian genesis are found: up to 21%. The content of cracked grains also increases to 15–21%. This unit does not show a record of aeolian abrasion effects on the surface of quartz sand grains. Aeolian processes were short-lived and the transport took place over very short distances. Sediments of this unit could be periodically redeposited through aeolian processes during dry periods, while the dispersed sediment in humid periods could be incorporated into slope runoff. The upper parts of the filled wedges and sediments of this unit contain quartz grains that represent an aeolian environment (EM/RM and RM), with the effects being visible only on the edges and corners, suggesting short transport (Fig. 7). Aeolian transport was short-lived and of low intensity, manifested by a minimal degree of abrasion of the quartz grains (Woronko et al., 2013, 2017), but had a significant effect on the structure and texture of sediments (i.a. Pisarska-Jamroży, 2015).

According to the authors of the Detailed Geological Map of Poland (Krzywicki, 2002; Kasprzak and Lisicki, 2007; Wrotek, 2009) as well as Banaszuk and Micun (2014), the ice sheet during the Middle Weichselian (MIS 3) covered the central part of the Podlasie Lowland. Banaszuk (2010) based his views on geomorphological observations and primarily on the results of TL dating of fluvioglacial and glacial deposits of the North Podlasie Lowland. Analysis of the Jałówka deposits excluded

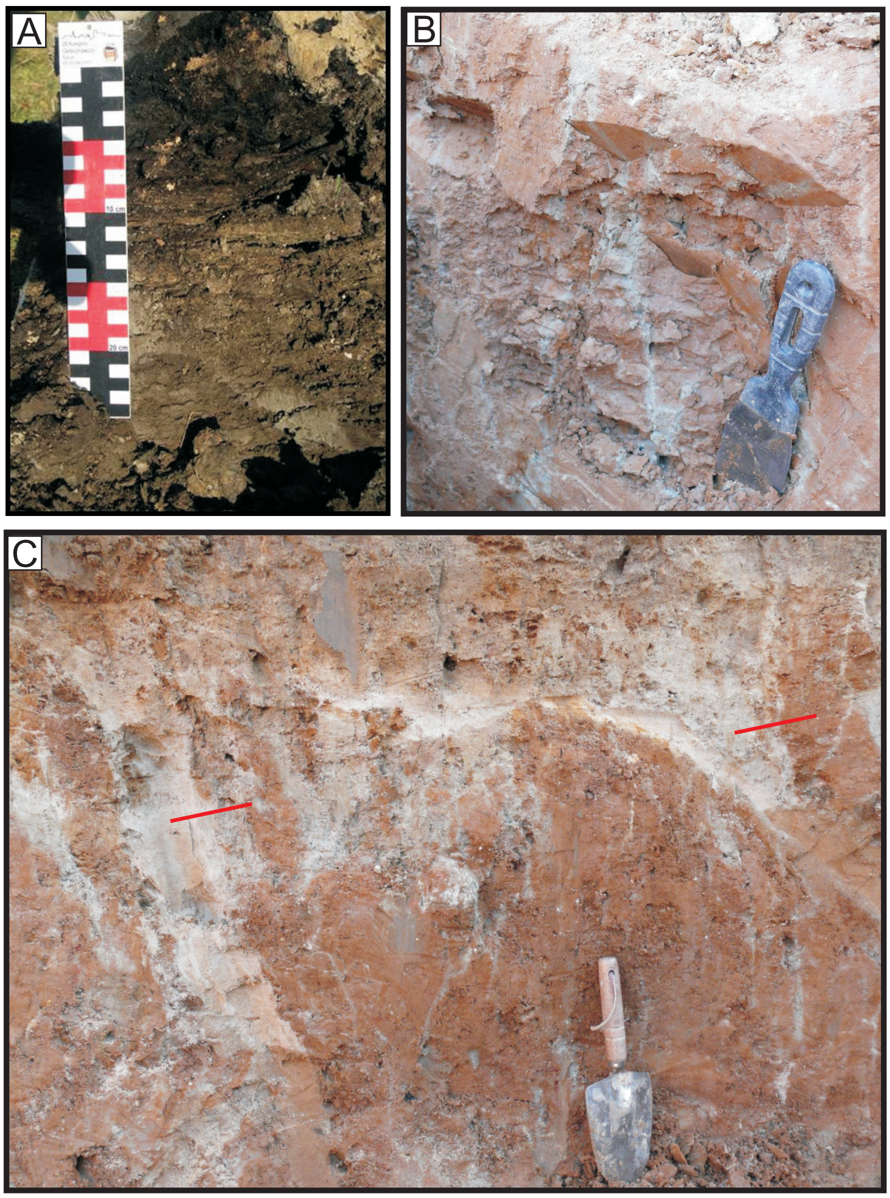


Fig. 8. Jałówka sites

A – peat; **B** – cubic structure of massive silty clay diamicton; **C** – epigenetic ice wedges with a primary sand infill

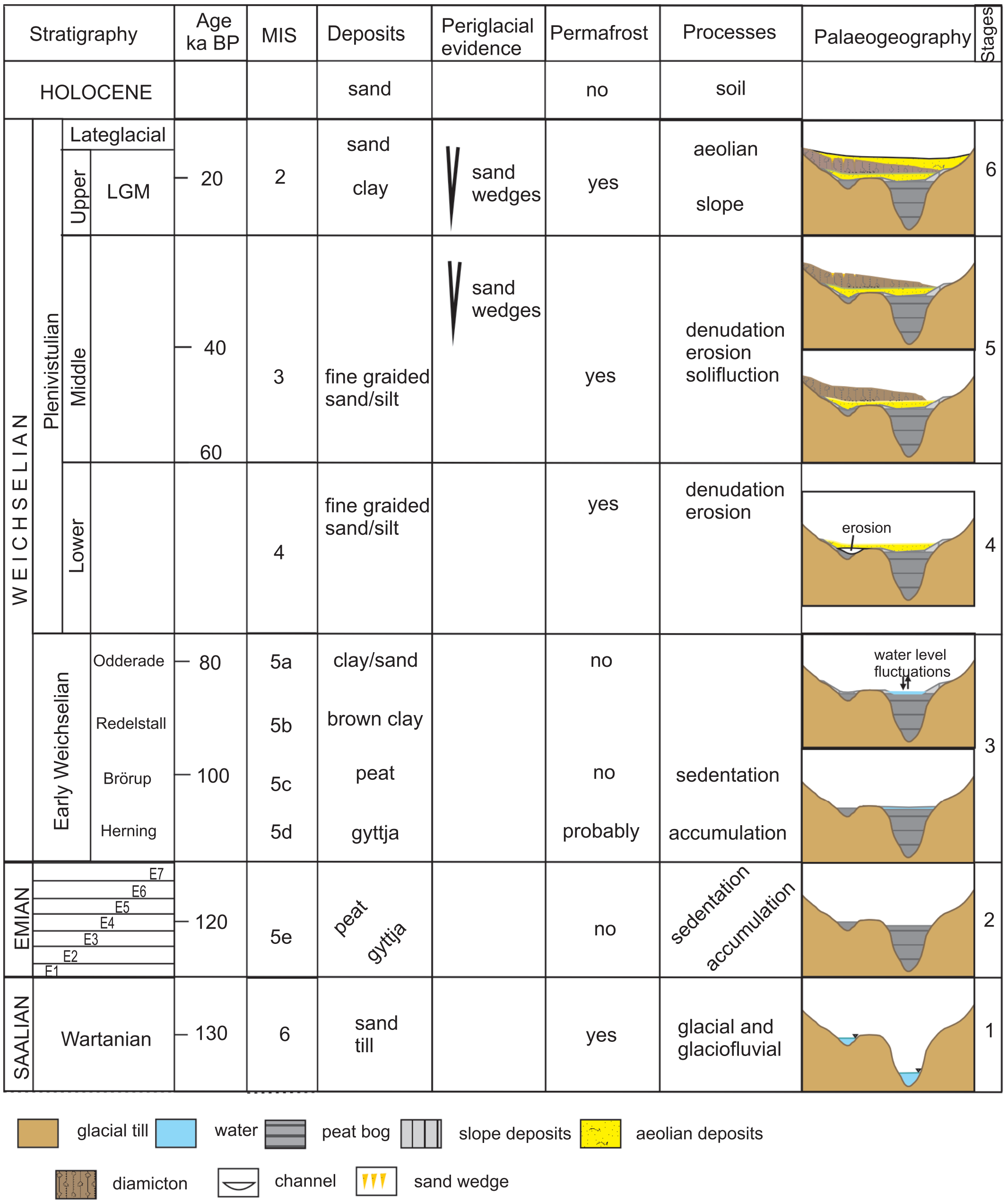


Fig. 9. Conceptual model explaining the landscape development at the Jałówka site

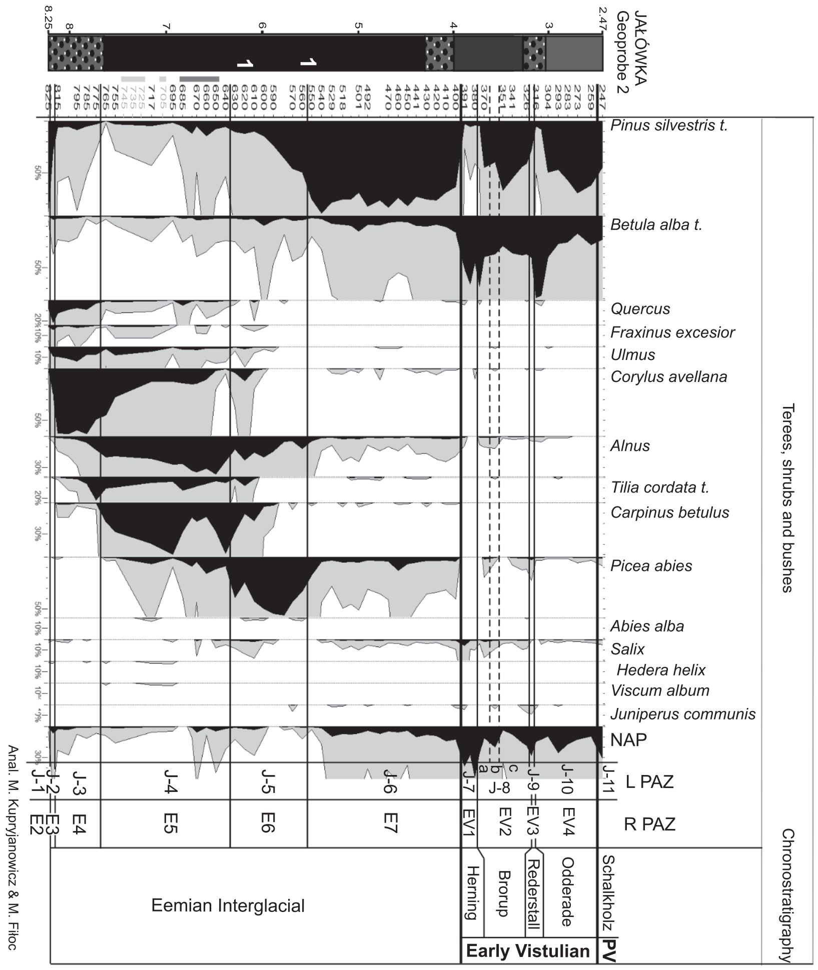
1 – glacial till, 2 – water, 3 – peat bog, 4 – slope deposits, 5 – aeolian deposits, 6 – diamicton

the occurrence of glacial sediments of the Weichselian Glaciation and showed the importance of periglacial processes (Jahn, 1970).

The palaeogeographic development of the area surveyed area is consistent with Dylik's thesis (1953) regarding the polygenetic character of the relief, because the glacial relief developed during the Warta Stadial and transformed by processes during the Eemian Interglacial was affected by a number of periglacial processes, which contributed to its further transformation.

CONCLUSIONS

The MMA analysis conducted, and detailed examination of biogenic deposits, allowed the palaeogeographic reconstruction of the study area in the period encompassing the Late Odranian (Saale) Glaciation, the Warta Stadial (Saale MIS 6) and the Late Pleistocene (MIS 2), constraining hypotheses concerning the polygenetic nature of its relief.



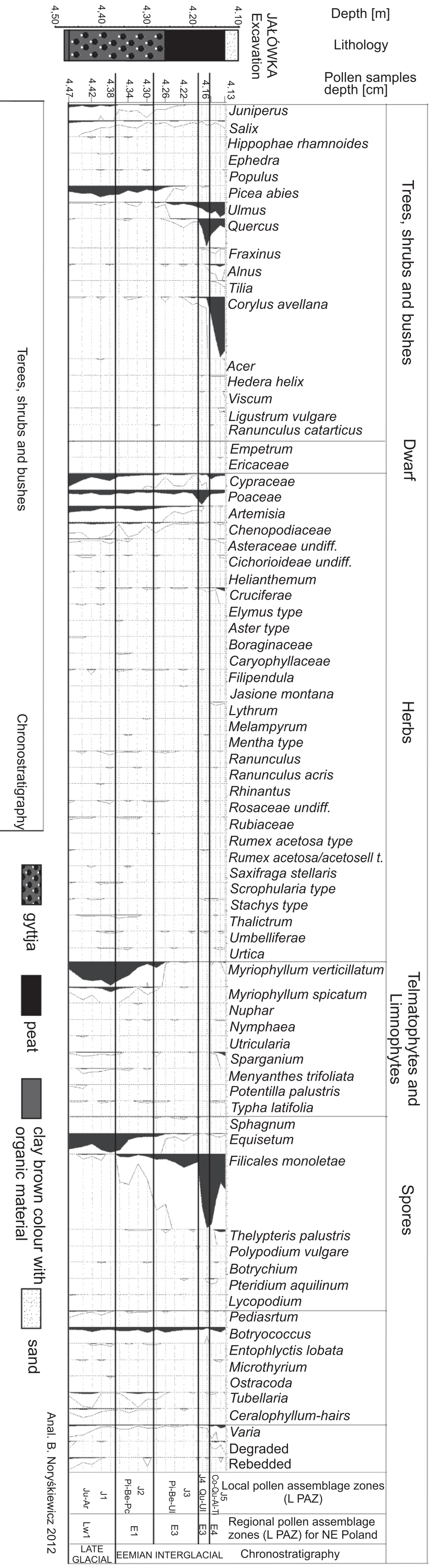


Fig. 10. Pollen diagrams from the Jałówka outcrop and the Jałówka Geoprobe 2 profile (after Rychel et al, 2014; Woronko et al, 2017)

For explanations see Figure 6

A continuous profile of sediments deposited between the Late Odranian (Saale) Glaciation, the Warta Stadial and the Late Glacial period, has been documented at the Jałówka site. The lack of a glacial till cover on biogenic deposits of the Eemian Interglacial at Jałówka and other sites described in the literature (Kupryjanowicz, 1991, 2000, 2008) demonstrates that the Weichselian ice sheet did not extend on to the study area.

In the Late Weichselian (MIS 2), the study area was located in the foreland of the Weichselian ice sheet (~20 km south of its maximum range), i.e. in the zone of periglacial climate. This period is associated with the presence of two generations of ice wedges and a cubic structure in the slope deposits. Older wedges were transformed by slope processes (inclination consistent with the slope exposure) and they are wide in their upper parts, while younger ones are straight throughout their length. The cubic structure testifies to the functioning of an active layer of the relict permafrost. Increased climate aridity resulted in the activation of aeolian processes.

Therefore, the last Scandinavian ice sheet that entered this area was the Odranian ice sheet, of the Warta Stadial. It had a lobed nature and ice masses of particular lobes advanced at different rates, occupying extensive ground depressions, which are currently used by river valleys: the Biebrza in the west and the Neman in the east. During the transgression, it crossed various types of rheological barriers one of which was Horczaki Knoll, the presence of which contributed to the development of a small projecting lobe in the Knyszewicze area. Glaciotectonic deformation structures occurring in the marginal zone of the lobe, and recorded at this site, testify to the variable activity of glacier masses.

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