Annales Societatis Geologorum Poloniae (2021), vol. 91: 327–345 doi: https://doi.org/10.14241/asgp.2021.20

NEW EVIDENCE FOR THE RANK OF THE WARTANIAN COLD PERIOD (THE PLEISTOCENE, MIS 6): A CASE STUDY FROM E POLAND

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Terpiłowski, S., Zieliński, T., Mroczek, P., Zieliński, P., Czubla, P. & Fedorowicz, S., 2021. New evidence for the rank of the Wartanian cold period (Pleistocene, MIS 6): a case study from E Poland. *Annales Societatis Geologorum Poloniae*, 91: 327–345.

Abstract: In the stratigraphic division of the Saalian (Middle Pleistocene) in Europe, the Wartanian cold period has the rank of a stadial of the Odranian Glaciation, correlated with MIS 6. The authors demonstrate the higher rank of this cold period, on the basis of an analysis of the sedimentary succession in eastern Poland, at an exposure of the terminal moraine of the Wartanian ice sheet. At the Wólka Zagórna site, three stratigraphic units were distinguished: A (lower glacigenic deposits – glaciofluvial deposits and subglacial till), A/B (fossil soil of lessivé type), B and C (a periglacial horizon with deflation pavement, involutions, frost-wedge structures and upper glaciofluvial deposits and flow till, with ice-wedge casts). Two distinct periods of climatic cooling, associated with the youngest Saalian ice sheets, were recorded in this succession in E Poland: Odranian (unit A, an ice-sheet transgression marked by the deposition of glaciofluvial deposits dated as 365–226 ka, ending with the deposition of subglacial till), and Wartanian (units B and C, an ice sheet transgression marked by development of a periglacial zone, dated as 180–126 ka, and then deposition of glacigenic sediments at the front of the ice sheet and formation of a marginal moraine). Each of these periods of ice-sheet transgression occurred at a different time (in the MIS 8 and MIS 6 positions) and were separated by a warm period. It is documented by unit A/B – a fossil soil with a very well developed B_t horizon – which attests to its formation in an illuviation process beneath a complex of mixed forests during an interstadial warming that occurred in MIS 7. From this palaeoclimatic reconstruction, it is inferred that the Wartanian cold period should be viewed as a separate glaciation in MIS 6 and the Odranian period should be assigned to MIS 8 in the stratigraphic schema of the Quaternary.

Key words: Stratigraphy, fossil soil, Luvisol, Saalian, Odranian.

Manuscript received 29 May 2021, accepted 12 October 2021

INTRODUCTION

The marginal zone of the Wartanian ice sheet has long been regarded as one of the most distinct landforms of the European Plain (Woldstedt, 1929). However, the rank of the transgression of this ice sheet remains unresolved. In accordance with the current stratigraphic division of the Saalian, the Wartanian cold period is treated as the younger, post-maximum ice-sheet transgression in Marine Isotope Stage (MIS) 6 (Fig. 1; Ehlers *et al.,* 2004; Meyer, 2005; Litt

ka	MIS	Sub-series	Western Europe		Poland	
	5	L P	E E M		Eemian	NPC
130	6	MIDDLE PLEISTOCENE	SAALIAN	Warthe Drenthe	Wartanian Odranian	MIDDLE POLISH COMPLEX
	7			Schöningen	Lublinian	
	8				Krznianian	
	9			Reinsdorf	Zbójnian	
	10			Fuhne	Liwiecian	
	11		HOLSTENIAN		Mazovian	
420	12		ELSTERIAN		Sanian 2	SOUTH POLISH COMPLEX
	13		CROMERIAN COMPLEX	Interglacial IV	Ferdynandovian	
	14			Glacial C		
	15			Interglacial III		
	16			Glacial B	Sanian 1	
	17			Interglacial II	Małopolanian	
	18			Glacial A	Nidanian	
781	19			Interglacial I	Augustovian	

L P – Late Pleistocene NPC – North Polish Complex

Fig. 1. Correlation of glaciations and interglacials in Poland with their equivalents in western Europe (Lindner *et al.*, 2013).

et al., 2008; Böse *et al.*, 2012; Lee *et al.*, 2012; Lindner and Marks, 2012; Lindner *et al.*, 2013; Stephan, 2014). The older ice-sheet transgression, with the maximum extent, occurred in the Odranian cold period. According to the authors quoted above, the Odranian and Wartanian cold periods occurred after the Lublinian Interglacial (MIS 7). In this stratigraphic approach, the Wartanian cold period is assigned at the most the rank of a stadial.

The proposed stratigraphic view of the Saalian seems to be clear in relation to the numerous cited proofs of the double or even triple transgression of the Drenthe (Saalian) ice sheet in western Europe (Lüttig, 1954, 1960; Eissmann, 1975, 2002; Beets *et al.*, 2005; Litt *et al.*, 2008; Meijer and Cleveringa, 2009; Kars *et al.*, 2012; Roskosch *et al.,* 2015; Lang *et al.*, 2018). The oldest of them already could have happened in MIS 8 (Beets *et al.*, 2005; Meijer and Cleveringa, 2009; Kars *et al*., 2012; Roskosch *et al*., 2015; Lang *et al*., 2018). This means that the cold period referred to as Odranian could have a double and, thus, equivocal palaeoclimatic meaning, i.e., not only as a cooling of stadial rank together with the Wartanian in an MIS 6 position, but also as an independent ice advance in an MIS 8 position. Therefore, should the term Odranian not be applied more narrowly to the ice-sheet transgression in MIS 8, as previously suggested (e.g., Lindner, 1992)? It then could be assigned the rank of a separate glaciation, as in the case of the Wartanian period in MIS 6 position. In the current state of knowledge, this proposal is supported to a significant extent by the results of petrographic investigations of Odranian and Wartanian tills that indicate a different source area for the ice sheets (e.g., Lüttig, 2007; Czubla *et al.*, 2019). There is still little unequivocal evidence, in particular palaeobotanical evidence, indicating the character of the warming period in the MIS 7 position, separating both ice-sheet transgressions. The small number of sites, where an interglacial flora has been recognized (e.g., Krupiński and Marks, 1986; Urban 1995; Gaigalas *et al.*, 2007; Litt *et al*., 2008; Urban *et al.*, 2011), arouses some doubts because of their ambiguously defined stratigraphic position. On the other hand, the sites with unequivocal stratigraphic positions, where, *inter alia*, traces of periglacial and pedogenetic processes or fluvial processes are documented, indicate a warming period with a rank that is merely interstadial (e.g., Krzyszkowski and Nita, 1995; Zieliński, 2007; Ehlers *et al.*, 2011; Guobyté and Satkũnas, 2011). This scarcity of evidence of climatic warming contrasts fundamentally with the common examples of fossil soil of interglacial rank, occurring in loess successions in the Pleistocene periglacial area of the Dnieper Upland and the Ukrainian Carpathians Foreland (e.g., Gozhik *et al.*, 2014; Komar *et al.*, 2018; Łanczont *et al.*, 2019).

The Wólka Zagórna study site is the only known one in this area, where Odranian deposits were documented and where their direct contact with Wartanian deposits can be observed (Fig. 2; Małek, 2004; Małek and Buczek, 2009). This contact is marked by manifestations of strong pedogenesis and cryogenesis in the upper part of the glacigenic Odranian deposits.

The objective of this study was to verify the stratigraphic schema, currently accepted in Poland and western Europe for the MIS 8–MIS 6 period. In particular, the study is intended to answer the question: did the Wartanian cold period had the rank of a stadial or that of a separate glaciation?

GEOLOGICAL SETTING

The stratigraphic position of the Saalian deposits in the Łuków area of eastern Poland has been very thoroughly identified palynologically (Figs 1, 2B). Their lower boundary is determined by the biogenic-mineral deposits of the Mazovian Interglacial (MIS 11; Małek and Pidek, 2007; Pidek *et al.*, 2011, 2014; Terpiłowski *et al.*, 2014; Zieliński *et al.*, 2016) and the upper boundary by the biogenic-mineral deposits of the Eemian Interglacial (MIS 5e; Pidek and Terpiłowski, 1993; Bińka and Nitychoruk, 2003). The boundary between the sites of the Mazovian and Eemian deposits, outcropping on the land surface, is determined by the line corresponding to the maximum extent of the Wartanian ice sheet.

The succession described at Wólka Zagórna (GPS: 51º58′49″N, 22º21′05″E) is exposed in a sandpit, located at the culmination of the Wartanian terminal moraine, about 5 km north of Łuków city (Fig. 2B). This contact is marked by manifestations of strong pedogenesis and cryogenesis in the upper part of glacigenic Odranian deposits (Fig. 2C).

The widespread till of the Wartanian ice sheet and the locally documented till of the Odranian ice sheet at Wólka Zagórna differ essentially in petrographic composition (Czubla *et al.*, 2019). In the Odranian till, alongside the very numerous rocks from the eastern part of the Baltic Basin (Åland boulders account for 51.5% of indicator erratics identified), there is a high proportion of rocks from central Sweden (Dalarna), i.e., 9.9%. The Wartanian till has a three

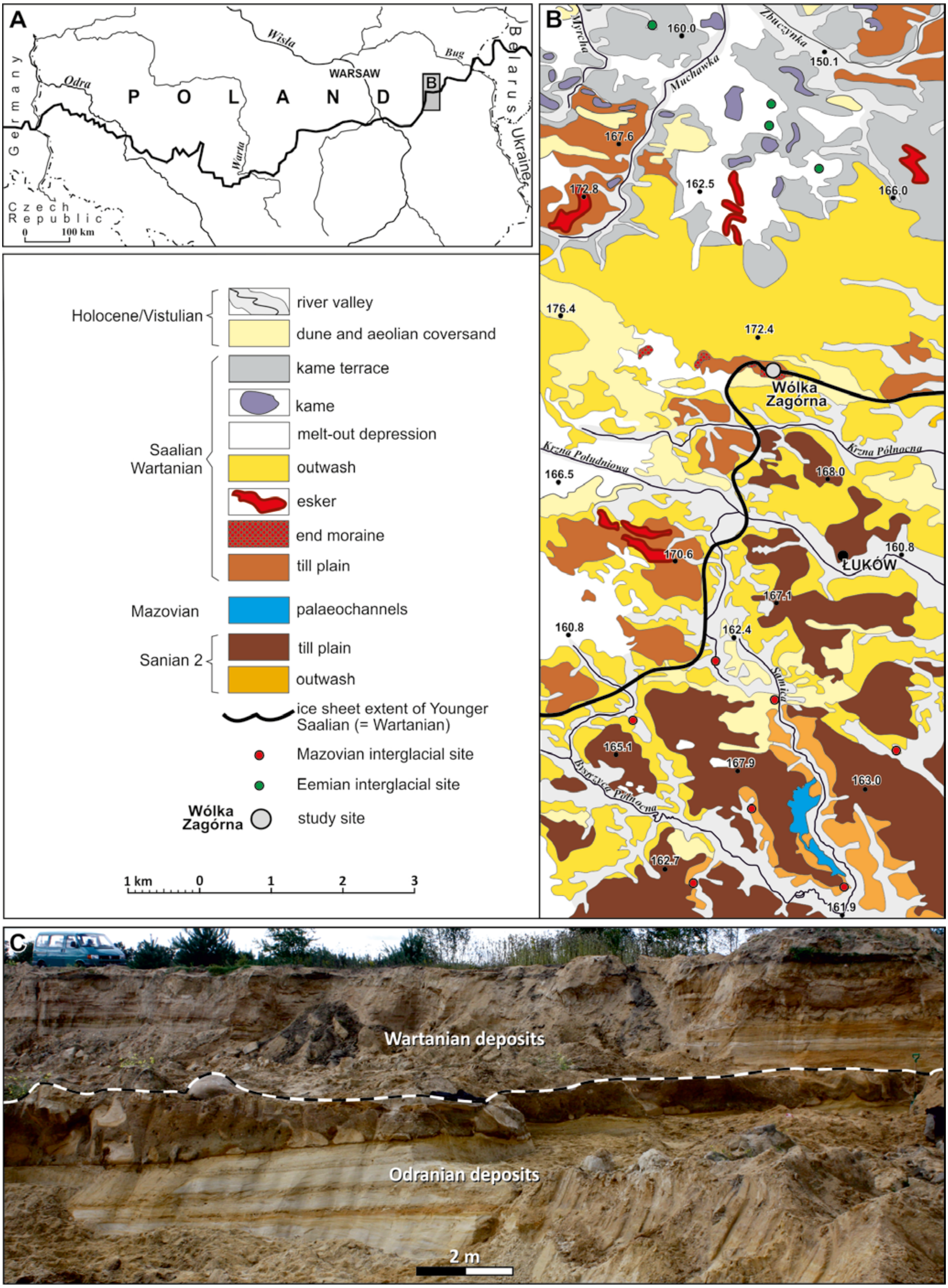

Fig. 2. Study area. **A.** Location in relation to the Wartanian ice-sheet extent (Marks, 2004). **B.** Wólka Zagórna site, described in detail in the text in relation to the main features of relief and geological structure (according to Terpiłowski, 2001; Małek, 2004; Małek and Buczek, 2009). **C.** Contact of Odranian and Wartanian deposits at the Wólka Zagórna site.

times lower proportion of rocks from central Sweden; only 3.7% of indicator erratics originate from Dalarna.

MATERIALS AND METHODS

The investigations of the sedimentary succession included a sedimentological analysis, a micromorphological analysis of fossil soil, and thermoluminescence (TL) dating.

Sedimentological analysis

The textural and structural features of the excavated deposits were documented in detail. The type, dimensions, shape, and contacts were recorded for all the depositional bodies (lithofacies). The lithofacies were labelled using Miall's (1978) code with some modifications (Tab. 1; Zieliński and Pisarska-Jamroży, 2012). The dip and dip direction of cross-laminae within the sandy stratified lithofacies were measured to estimate the palaeoflow direction. The same directional features were measured for elongated clasts in glacial diamictons to determine their origin (rheological properties) and the flow direction of the depositional medium. These measurements were carried out for deposits undisturbed by post-depositional processes. The dominant direction of clast orientation and its concentration were calculated according to the eigenvalue vector method (Davis, 2002). Deformational structures were analysed too, especially those that are typical of the periglacial environment. The analysis of them was based on the methodology proposed by French (2007) and the divisions according to Murton (2007) for thermal-contraction structures and Vandenberghe (2007) for load-cast structures. A palaeoclimatological interpretation took into account the views of Vandenberghe and Pissart (1993) and Murton and Kolstrup (2003) on that issue.

Table 1

Lithofacies code used in this study

Texture	
SG	gravelly sand
S	sand
SF	silty sand
D	diamicton (till)
SD	diamictic sand
Structure	
h	horizontal stratification/lamination
p	planar cross-stratification
t	trough cross-stratification
m	massive structure
(m_1)	matrix-supported, gravel content <15% (for till only)
d	deformed

Sandy glacigenic deposits and cryogenic structures, formed within diamictic deposits (till), were sampled for the morphoscopic analysis of quartz grains. This was performed according to the modified Cailleux method (Mycielska-Dowgiałło and Woronko, 2004); 100 grains of 710–1,000 μm were examined and divided into seven groups (Tab. 2). The analysis was conducted by means of a stereoscopic microscope at the general magnification of 20x.

Micromorphological analysis of fossil soil

The material for analysis was collected in Kubiëna boxes that preserve the undisturbed structure of the deposits sampled. Eight samples were collected from two soil parts with different colours, and additionally for comparison, one sample was taken from the deposits below the soil. For each

Table 2

Type of roundness and frosting of quartz sand grains according to Mycielska-Dowgiałło and Woronko (2004)

Type of grain	Roundness of grain (Krumbein, 1941)	Description	Processes responsible for grain formation
RM	0.7–0.9	Very well-rounded with completely matte surface	Very long duration of abrasion in aeolian environment
EM/RM	0.3–0.9	Moderately rounded, matte surface only on convex parts of grains	Short-time abrasion in aeolian environment
EL	0.7–0.9	Very well-rounded, entire surface smooth and shiny	Combination of abrasion and solution in fluvial or beach environment. 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; the process is shorter than for EL-type grains
C	–	Crushed/broken. Only crushed surface fresh, remaining parts with microstructures typical of transport or weathering	Crushing in all types of environments but with highest intensity in subglacial environment or as a result of frost weathering
NU	0.1–0.2	All surfaces fresh: corners sharp and angular	Crushing and abrasion in glacial environment; mechanical weathering *in situ*, e.g., frost weathering
O (other)	0.1–0.9	Very intensively weathered surface by silica precipitation or solution *in situ*; traces of transport not visible	Solution or precipitation in soil profile, hot desert or periglacial environment

sample, two thin sections were prepared (2 pieces for each sample; size: 7×5 cm, thickness: ca. 25 μm), according to the methodology described by Lee and Kemp (1992), with small modifications to permit analysis of them at the Lublin laboratory (Mroczek, 2008, 2013).

Luminescence dating

Only those samples were submitted for luminescence dating that met the basic conditions for obtaining the correct dates, i.e., before deposition, the dated grains were subjected to long transport and had contact with sunlight over relatively long periods of time. Eleven TL datings were carried out in accordance with the methodology used at the University of Gdańsk Laboratory. The detailed description of this is included in a study by Fedorowicz *et al*. (2013). This method was chosen because the expected age of the deposits often exceeded the capability and appropriate age range for the optically stimulated luminescence (OSL) method.

RESULTS

Sedimentology

As a result of this research, the authors distinguished three sedimentary units documenting the cold periods of the Pleistocene: A, B and C. Some of them were further subdivided into parts of lower rank, i.e., subunits (Fig. 3).

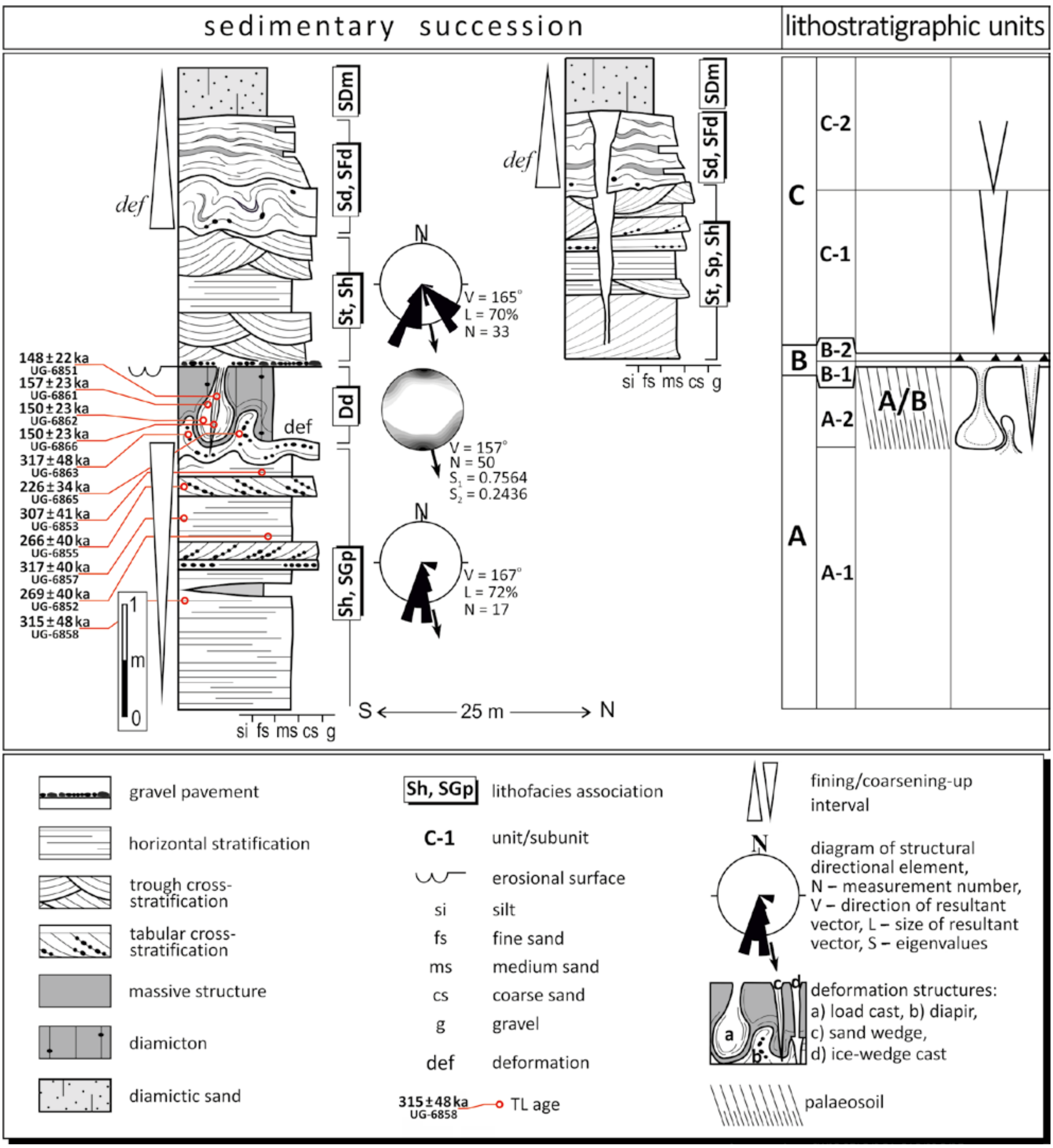

Fig. 3 Lithology and lithostratigraphy of the Wólka Zagórna site.

Unit A

This glacigenic unit consists of two subunits that differ in lithology (Fig. 3). In the lower part, sand predominates (subunit A-1), while the upper part consists of diamicton (subunit A-2).

Subunit A-1 is an association of two types of predominant lithofacies: medium-grained, horizontally stratified sand (Sh) and coarse-grained sand with interspersed granules and pebbles and with planar cross stratification (SGp; Fig. 4A). The frequency of the Sh lithofacies is higher and some beds attain a thickness of 1 m. Cross-stratified gravelly sands form relatively thin beds, developed as elongated lenses. Their average thickness is approximately 15 cm. A few lens-like intercalations of massive sandy silt, up to 10 cm thick, also were found in the Sh packages. Generally, the A-1 subunit shows reverse grading; the frequency of sandy-gravelly beds increases upwards. The orientation of cross-beds indicates that the palaeoflow was southward (mean vector = 167°). In morphoscopic terms, grains with shiny surfaces predominate (EL + EM/EL = 60–68%). There is a relatively high proportion of crushed and unrounded grains (C + NU = 12–19%) that increases upwards (Fig. 5).

Subunit A-2 is 0.5–0.8 m thick. The contact with the underlying subunit A-1 is sharp. Massive diamicton contains numerous, most frequently dispersed gravels, lithofacies Dm(m_1) (Fig. 4B). Only in the basal part, rolled up clusters occur, accompanied by ploughing marks in the glaciofluvial deposits. The long axes of gravels show a low spread of orientation (S_1 = 0.7564), with a strong SSE mode (mean vector = 157°).

Unit B

This unit consists of two subunits (Fig. 3): an assemblage of deformation structures (subunit B-1) and a pavement (subunit B-2).

Subunit B-1 consists of deformation structures developed in till (subunit A-2) and the top part of subunit A-1. These structures belong to two groups: type 2 involution structures (according to Vandenberghe, 2007) and thermal-contraction structures. Involution structures developed as load casts and diapir structures. The load casts were formed by sands sinking into the till (subunit A-2); locally they are connected with the till surface, although in many cases there is no connection (drop-like and ball-and-pillow structures; Fig. 6D, F, G). They are accompanied by the diapiric occurrence of glaciofluvial sands of subunit A-1 (Fig. 6G, H). In places, where the till is of minor thickness, these structures have completely transformed this layer (Fig. 2C). The group of thermal-contraction structures comprises veins and wedges. The following patterns in their distribution were found. The veins, up to 3 cm wide, are in a till layer (Fig. 6E), while the wedges, up to 20 cm wide, usually occur within sandy

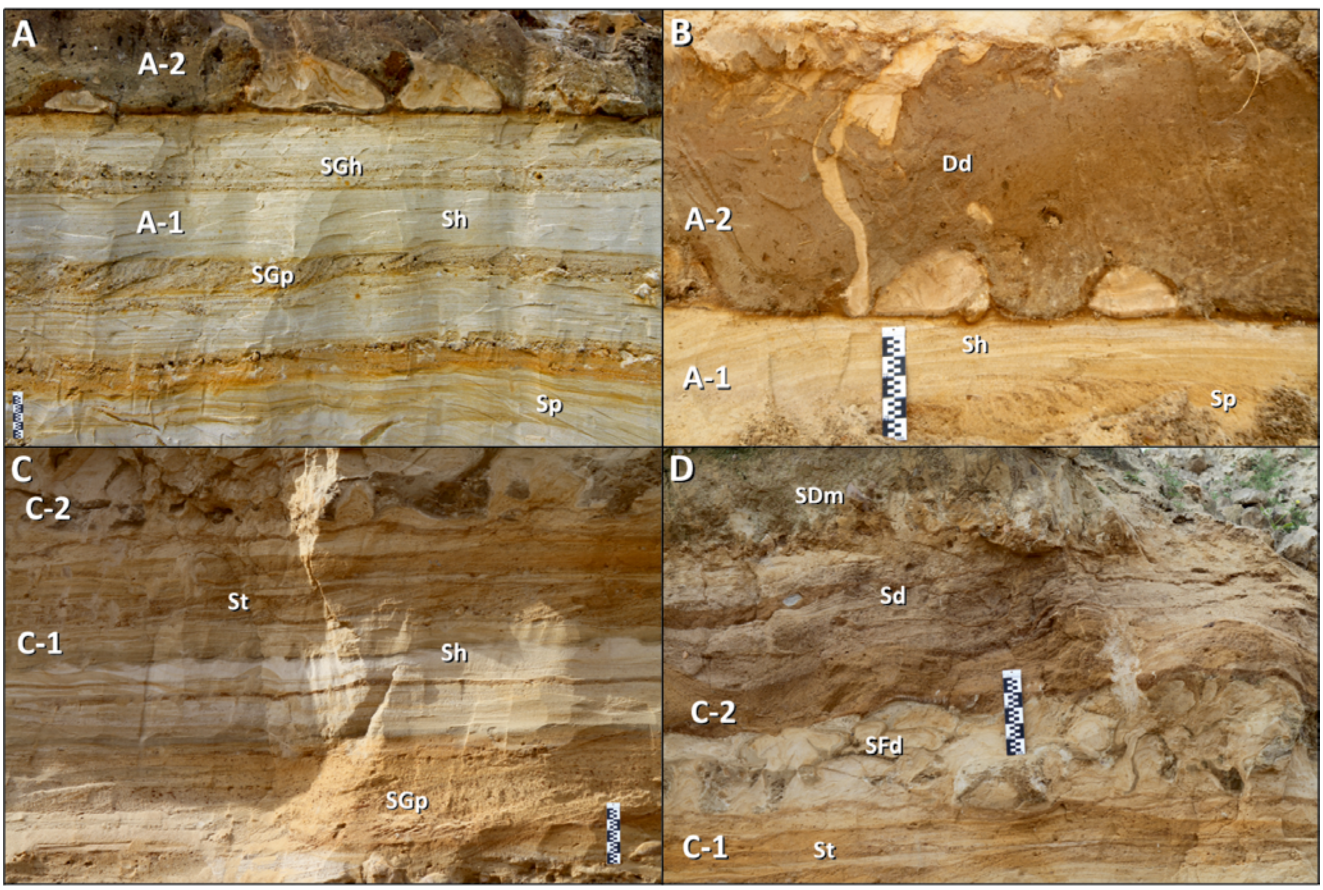

Fig. 4. Lithology of deposits at the Wólka Zagórna site. **A.** The uppermost part of glaciofluvial package of sands and gravelly sands (unit A-1). **B.** Massive diamicton – subglacial till (subunit A-2). **C.** Sand and gravelly-sand beds derived from shallow flows on terminoglacial fan (subunit C-1). **D.** Deformed silty-sand SFd and sand Sd beds are overlain by diamictic sand SDm – a result of morainic mass flow (subunit C-2). The scale bar in all photos is 25 cm long.

ball-and-pillow structures (Fig. 6F). Vertical lamination is clearly visible within them. Predominantly, the sand infilling of these structures is represented by grains that were subjected to aeolian reworking, mainly with a moderate degree of rounding (EM/RM up to 80%), while round, matte grains represent a smaller proportion (RM up to 20%). This feature is the main difference from the sands of the diapir structures, the morphoscopic composition of which is very similar to those of subunit A-1 (Fig. 5).

Subunit B-2 is a thin and discontinuous, but widely distributed layer of clasts of Fennoscandian rocks, with diameters of up to 20 cm. These clasts most frequently occur horizontally, above the pedogenically transformed till (subunit A-2 and unit B). In the planform, they form quasi-circles, 25–50 cm in diameter (Fig. 6C); 65% of the clasts have sharp edges and their surfaces are well polished. The basal parts of large clasts 'rooted' in the soil are not polished. The elongated clasts occurring below the pavement are characterized by the nearly vertical orientation of their long axes (Fig. 6D).

Unit C

This glacigenic unit consists of two subunits that differ in lithology (Fig. 3). Sands form the lower part of the succession (subunit C-1); the upper part is made up of diamictic deposits (subunit C-2).

Subunit C-1 starts from a sand package, 1.5–2.0 m thick and dominated by cross-stratified beds St (Fig. 4C). Coarse-grained sand forms trough sets up to 35 cm thick. In a more northerly location, St lithofacies occur with sand beds with planar cross-stratification Sp, the thickness of which is up to 80 cm. The cross-strata are intercalated with horizontally stratified, medium-grained sands Sh. Some beds, both horizontally stratified and cross-stratified, exhibit a graded texture. The directional distribution of cross-stratified laminae is bimodal and the mean vector is oriented to the south (165°). From the top of subunit C-1, ice-wedge pseudomorphs are developed (Fig. 6A), up to 1.5 m long and up to 25 cm wide. The distance between the structures reaches 6–8 m. In morphoscopic terms, the unit is mostly made up of sand grains with shiny surfaces (EM/EL = 45–63% and EL up to 16%). There is an upward increasing frequency of crushed (C = 2–14%) and unrounded grains (NU = 0–20%; Fig. 5).

Subunit C-2 consists of two parts. The lower one comprises the lithofacies association Sd, SFd (Fig. 4C). Medium- and fine-grained sands are intercalated with discontinuous (up to 1 m long), thin (up to 2 cm) lenses of fine-grained silty/clayey sand. The lowermost beds of this association contain some gravels. The frequency and thickness of silty-sandy laminae increases upwards. The primary sedimentary structure of the deposits is horizontal lamination. This part of the succession is deformed, with load casts and diapiric folds (Fig. 4D). Their intensity decreases toward the top of the succession. In this sandy subunit, ice-wedge pseudomorphs are also common (Fig. 6B). Their length and spacing are analogous to those of the structures in subunit C-1, while their widths are slightly greater (up to 20 cm). Frost structures are developed in the top sediments of the horizon, which are deformed by involutions. In morphoscopic terms, the subunit, especially its upper part, consists of similar proportions of shiny and matte grains (about 40% each; Fig. 5).

The upper part of subunit C-2 is diamictic sand SDm, 0.5 m thick, a very poorly sorted mixture of sand, silt, clay and a few gravels. The structure is massive. The basal contact is planar or slightly undulating, which may be depositional or deformational.

Generally, subunit C-2 is a fining-upwards succession of successive lithofacies: Sd → SFd → SDm (Fig. 3).

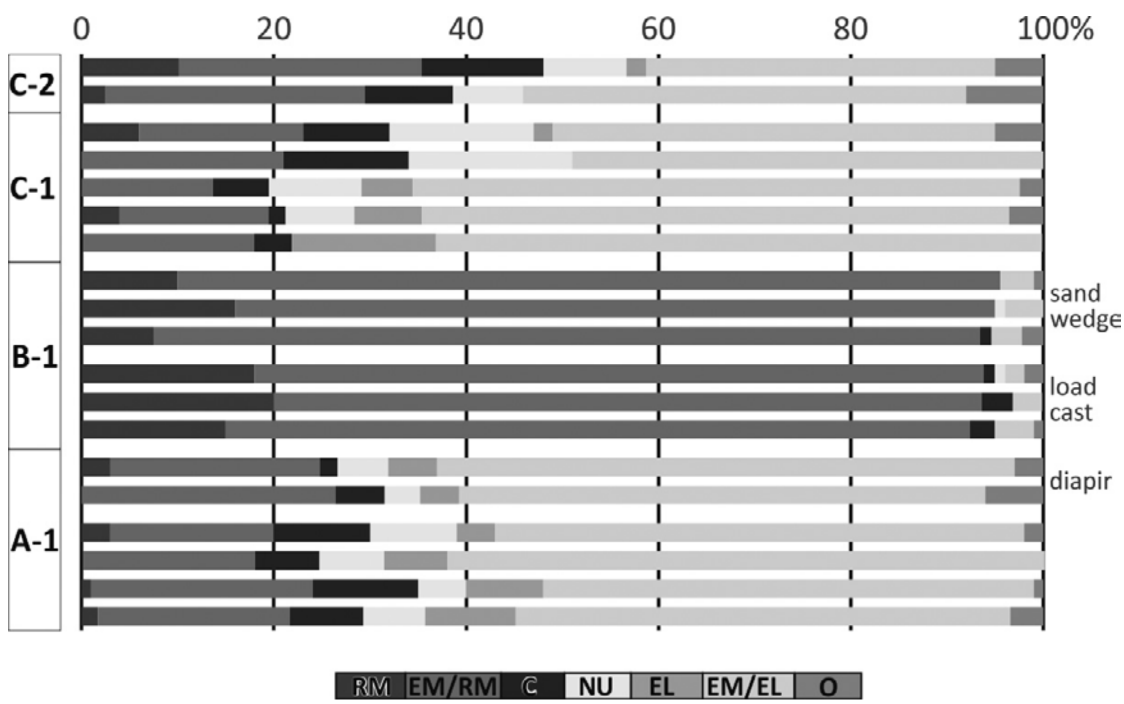

Fig. 5. Morphoscopic analysis results. Legend in Table 2.

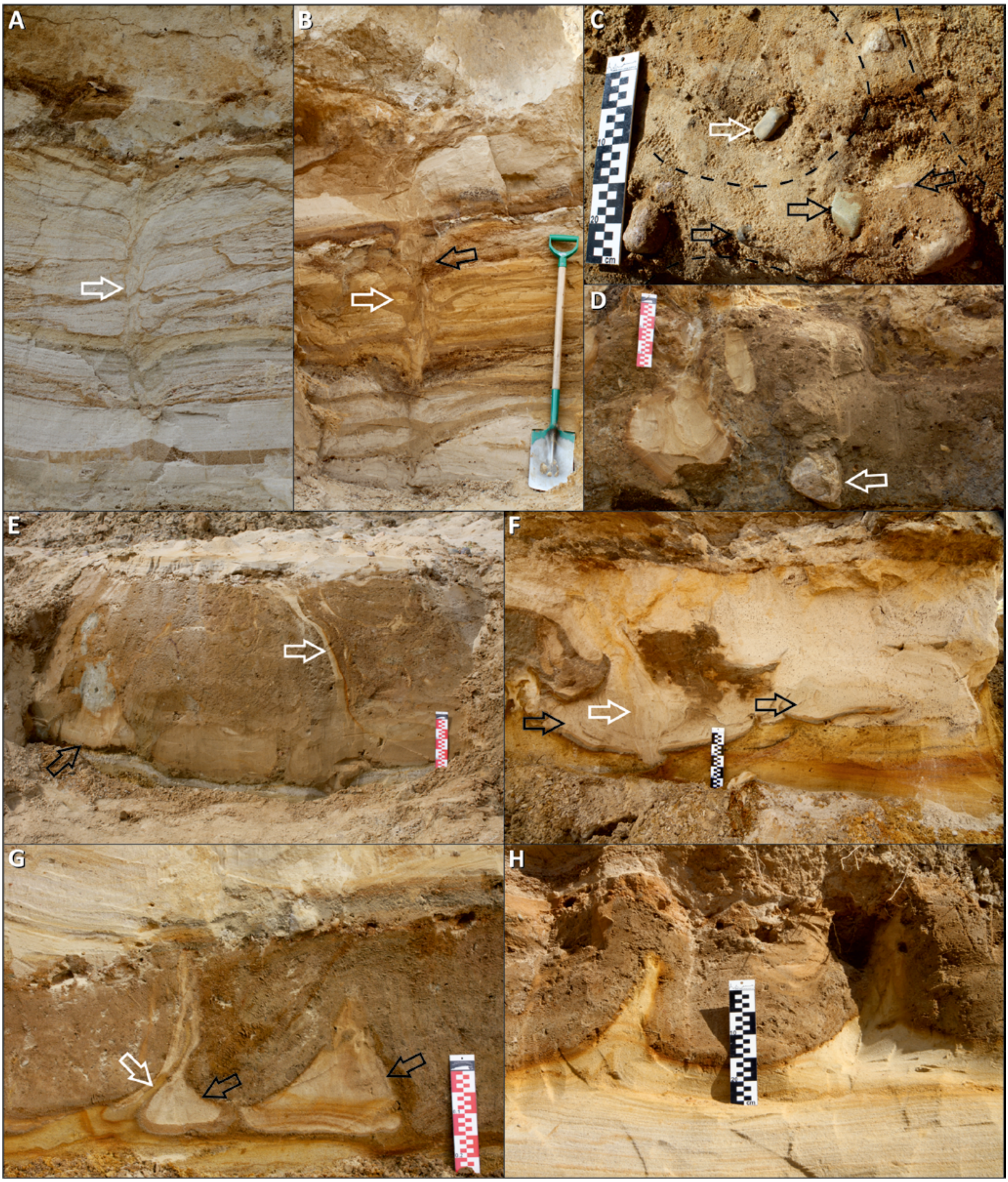

Fig. 6. Periglacial structures at the Wólka Zagórna site. **A.** Ice-wedge pseudomorph in unit C. **B.** Ice-wedge pseudomorph in unit C; after the first stage, the wedge melted completely or was only partially reduced, which is documented by the faults (white arrow); the second development stage occurred after the erosion of the upper part of the wedge, the eroded surface is marked with a black arrow. **C.** Surface of till (subunit A-2) with deflation pavement featuring ventifacts (black arrow), the dotted line indicates the zone of pavement concentration, some clasts are vertically oriented and are 'rooted' in the till (white arrow). **D.** Till with vertically oriented clasts (white arrow). **E–G.** Load-cast structures, sandy wedges and veins in subunit A-2; E – sandy vein (white arrow) and ball-and-pillow structure (black arrow); F – Extensive ball-and-pillow structures (black arrows) dissected with a sandy wedge (white arrow); G – Sandy load-cast structures (black arrows) disappearing at the contact with the underlying sandy subunit A-1; the load casts are accompanied by diapirs (white arrow). **H.** Diapir structures.

Micromorphology of fossil soil

The soil that developed on the subglacial till (subunit A-2), was formed during the hiatus between sedimentation of the A and B units (see unit A/B in Fig. 3).

The feature that stands out the most in the macroscopic view of the soil is the distinct duality of colour as well as the occurrence of free spaces in the form of biogenic channels and tiny fissures and concretions of Fe and Mn-Fe. The lower part of the soil is rusty-grey, while the upper part is brownish red (Fig. 7). The colour changes gradually. This pattern is reflected in the distribution of the basic, micromorphological characteristics, documented in the microscopic view of the soil, i.e., concentrations of manganese and iron compounds (the so-called nodules) and clay fraction <2 μm (Figs 7, 8). In the vertical soil profile (top to bottom), an increase in the concentration of manganese and iron compounds (Fig. 8A) and a decrease in the concentration of the clay fraction were observed (Fig. 8B–D). The Mn-Fe nodules most often occur in the form of homogeneous, spherical concretions with irregular walls, randomly distributed in the sediments (Fig. 8A). These forms are accompanied by concentrations of clay, usually in the form of deformed infillings, the distribution of which corresponds to the walls of fissures and bio-pores as well as infillings inside biogenic channels that fill free space, both in the subvertical and subhorizontal system (Fig. 8C–E). Concentrations of the micromorphological characteristics mentioned above were not found in the glacigenic deposits underlying the soil, in subunit A-1. In cross-section, this deposit has a massive, chaotic structure (Fig. 8F), completely devoid of pedogenic characteristics.

Geochronology

In accordance with the methodological assumptions for determining the absolute age, the dates obtained refer to the sandy sediments of the A-1 and B-1 subunits.

Two generations of dates were obtained. The TL-age of the deposits of the A-1 subunit was estimated at 365–226 ka, and the age of the deposits of the B-1 subunit was 180–126 ka (Fig. 3; Tab. 3).

DISCUSSION

Palaeoenvironmental scenario of succession studied

The results of the sedimentological and micromorphological analyses allow the recognition of two cold periods, separated by a warm one: an older cold period, a warm period, and a younger cold period.

Fig. 7. The presence of diagnostic redoximorphic ferro-manganiferous microfeatures (FM) and pedogenic concentrations of clay (CM) of fossil soil and glaciofluvial deposits at the Wólka Zagórna site. The occurrence of microforms: one square – single; two squares – numerous; three squares – very numerous; four squares – common.

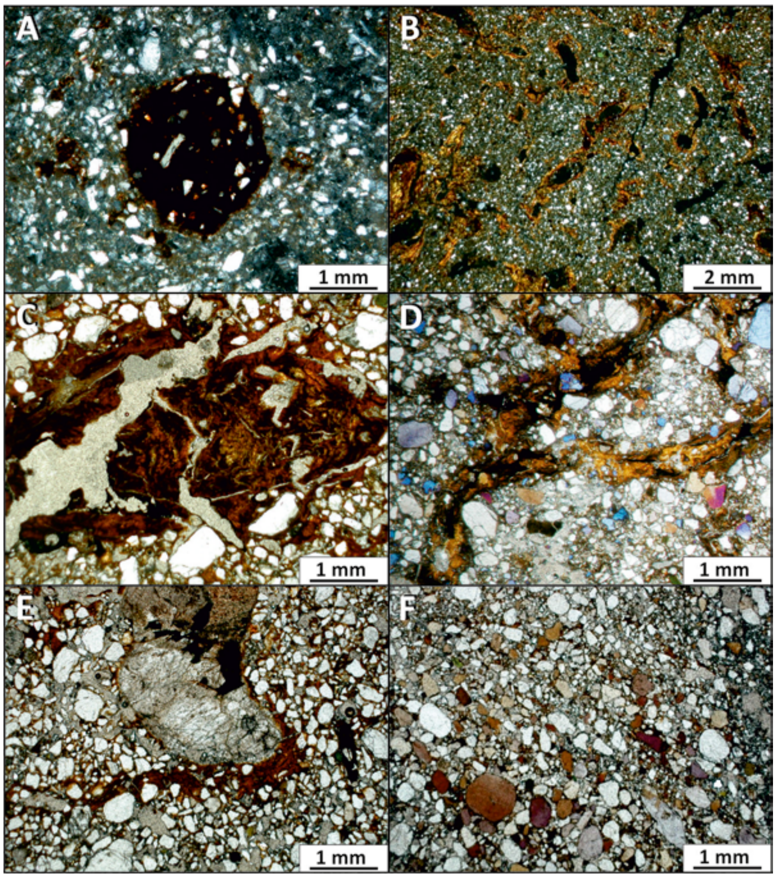

Fig. 8. Main diagnostic micromorphological features at the Wólka Zagórna site. **A.** Well- developed Fe-Mn nodule (XPL). **B.** Clay coatings inside the channels (XPL). **C.** Clay infilling inside the channel (PPL). **D.** Clay infillings inside the fissures (XPL). **E.** Deformed clay infilling (PPL). **F.** Groundmass of the unit C without pedogenic features (PPL). Types of light: PPL – plane-polarized, XPL – cross-polarized.

Table 3

Luminescence and radioactivity data for the analysed samples: Ra, Th, K refer to radium, thorium and potassium content in the sediments; d_r – total dose rate; d_e – equivalent dose

Sample	Sampling location	Depth [m]	No. Lab.	^{226}Ra [Gy/kg]	^{232}Th [Gy/kg]	^{40}K [Gy/kg]	d_r [Gy/ka]	d_e [Gy]	TL age [ka]
WZ-1	Sand wedge	2.3	UG-6851	14.2 ± 0.8	14.1 ± 0.8	459 ± 34	1.88 ± 0.16	277.5 ± 28.0	**148 ± 22**
WZ-2	Sand wedge	2.5	UG-6866	9.3 ± 0.4	15.5 ± 0.2	342 ± 14	1.50 ± 0.16	225.2 ± 22.0	**150 ± 23**
WZ-3	Load cast	2.3	UG-6861	12.1 ± 0.5	13.5 ± 0.6	392 ± 13	1.64 ± 0.16	256.8 ± 25.0	**157 ± 23**
WZ-4	Load cast	2.5	UG-6862	12.1 ± 0.5	13.5 ± 0.6	392 ± 13	1.64 ± 0.16	246.3 ± 24.3	**150 ± 23**
WZ-5	Diapir	2.8	UG-6863	4.7 ± 0.3	2.8 ± 0.2	200 ± 12	0.78 ± 0.08	247.6 ± 24.6	**317 ± 48**
WZ-6	Diapir	2.7	UG-6865	4.5 ± 0.3	3.8 ± 0.2	152 ± 10	0.66 ± 0.06	149.1 ± 15.0	**226 ± 34**
WZ-7	A-1	3.1	UG-6853	4.3 ± 0.3	2.6 ± 0.2	134 ± 10	0.55 ± 0.05	169.0 ± 16.2	**307 ± 41**
WZ-8	A-1	3.4	UG-6852	4.7 ± 0.3	2.7 ± 0.2	161 ± 11	0.64 ± 0.06	171.9 ± 18.0	**269 ± 40**
WZ-9	A-1	3.2	UG-6855	4.4 ± 0.3	2.7 ± 0.2	163 ± 13	0.65 ± 0.06	173.0 ± 17.0	**266 ± 40**
WZ-10	A-1	3.5	UG-6857	4.2 ± 0.3	2.4 ± 0.2	129 ± 12	0.54 ± 0.05	171.4 ± 17.2	**317 ± 48**
WZ-11	A-1	3.9	UG-6858	3.9 ± 0.2	2.4 ± 0.2	124 ± 12	0.54 ± 0.05	170.2 ± 17.0	**315 ± 47**

Older cold period

This older cold period is documented by the glacigenic deposits of unit A, i.e., the A-1 and A-2 subunits (Fig. 3).

The predominance of horizontal stratification in the sands indicates that subunit A-1 was deposited mainly from sheet flows. The flow was shallow. The deeper (up to 50 cm) zones of poorly developed channels were present only locally. Concentrated currents reached greater velocities there, enabling the transportation of pebble-sized material and the formation of low dunes. An analogous, sandy lithofacies association, dominated by horizontal stratification with secondary cross-stratified beds, was regarded as a typical outwash sedimentary record by Fraser (1982). In time, the velocity of flows increased, most probably as a result of higher meltwater discharges. The shiny (EL + EM/EL) grains that predominate in subunit A-1 are proof of fluvial transport. On the other hand, C- and NU-type (i.e., crushed and unrounded) grains are typical of a glacial environment. Taking into account these features, the authors concluded that the deposits originated in a glaciofluvial environment. The increasing frequency of C- and Nu-type grains towards the top of the subunit indicates that the transportation of meltwater streams was progressively shorter.

Subunit A-1 is a record of proglacial sedimentation, an outwash formed in front of the advancing ice. The ablational origin of the flow is proved by the north-to-south orientation of the cross strata, the typical regional direction of outwash sedimentation in lowland areas. Another line of evidence is the coarsening-upwards tendency within the subunit. It is a result of the gradual proximalization of the meltwater supply, i.e., an advance of the ice-sheet margin (see Ehlers and Grube, 1983; Miall, 1983; Marren, 2001). The predominance of sheet flows as the main depositional mechanism indicates that the origin of subunit A-1 should have been connected with the interchannel zone of outwash, not the main meltwater artery. Similar overbank glaciofluvial deposits were observed in central Poland by Kasprzak (1997).

The diamicton of subunit A-2 shows features characteristic of traction subglacial till (e.g., Evans *et al.*, 2006). The sharp basal contact and massive structure resulted from simultaneous lodgement (Dreimanis, 1989) and shear deformation in the lowermost part of the advancing ice sheet (Boulton and Hindmarsh, 1987; Hart and Boulton, 1991; Van der Meer *et al.*, 2003). The presence of rolled-up clusters in the basal diamicton is proof of deformation processes under the base of the advancing ice sheet (Jennings, 2006), and the accompanying ploughing marks in glaciofluvial deposits indicate the relatively fast flow of the ice (Jørgensen and Piotrowski, 2003; Lian *et al.*, 2003). The genetic interpretation of diamicton (traction subglacial till) is also supported by the clear orientation of the long axes of gravel clusters. This directional element also indicates that the ice sheet advanced from NNW to SSE, i.e., in accordance with the regional direction of ice-sheet transgression in eastern Poland, in various periods of the Pleistocene (e.g., Dobrowolski and Terpiłowski, 2006; Terpiłowski, 2007; Godlewska and Terpiłowski, 2012; Terpiłowski *et al.*, 2014; Czubla *et al.*, 2019).

The authors interpret unit A as a transgressive glacigenic succession that is the record of one advance of the Scandinavian ice sheet. The deposits of subunit A-1 indicate the proximalization of the glaciofluvial environment and evidence the approaching ice-sheet margin. Moreover, the deposits of subunit A-2 were derived from the subglacial environment, when the ice sheet covered the area of the study site.

Warm period

The warm period is recorded in the sedimentation gap between units A and B, which is documented with fossil soil developed on subglacial till, the unit A/B (Fig. 3).

The two parts of the fossil soil, clearly different in the macroscopic and micromorphological perspectives, indicate different processes in their development; the gradual transition between the parts is evidence that the change in processes was an evolution. The very numerous and widespread forms of iron and manganese concentration, found in the lower part of the soil, indicate the oxidation/reduction processes typical of hydrogenic Gleysols (Marcinek and Komisarek, 2015), formed in conditions of a shallow groundwater table. In the upper part of the soil, the numerous and widespread forms of colloidal clay concentration, found on the walls of fissures and channels, indicate the process of illuviation characteristic of a well-developed Luvisol (lessivé soil) with the enriched horizon Bt (e.g., Konecka-Betley, 2009; Świtoniak *et al.*, 2016). Furthermore, the layout of the fissures indicates a pedogenic origin and an association with the free spaces between polyhedric aggregates. In interpretations of Pleistocene fossil soils, it is commonly believed that the conditions for the development of typical hydrogenic soils existed below a poor vegetation cover, during relatively short and cold periods of low stratigraphic rank, i.e., interstadial and interphase (Konecka-Betley, 2002). The presence of colloidal clay concentrations unequivocally attests to the activity of advanced lessivage processes, typical of mature lessivé soils formed on glacigenic deposits (Manikowska and Konecka-Betley, 2002; Świtoniak *et al.*, 2016). The most common view is that the most favourable conditions for the development of Luvisols existed beneath a forest complex, during long, warm, and wet periods of interglacial rank (Retallack, 2001; Konecka-Betley, 2002). Recently, however, it has been suggested that Luvisols also could have developed during cold stratigraphic periods of interstadial rank. However, it occurred only locally, in particularly favourable geomorphological positions, i.e., on southern slopes with a warm exposure and, preferably, in depressions functioning as ecological niches (Mroczek, 2008, 2013). The interglacial character of soil-forming processes at the Wólka Zagórna site is supported by the clear development of illuviation characteristics. Their common occurrence in the upper part of the soils allows classification of the entire layer as a diagnostic B-argic horizon (Marcinek and Komisarek, 2015). In addition, with increasing depth, illuvial microforms give way to increasingly numerous concentrations of Mn-Fe compounds, which allows inferences to be made about the evolution of the entire pedon. This profile has the character of a succession of soil processes: the older micromorphological (oxidation/reduction) characteristics were replaced by younger ones (illuviation). This model of pedon development is in agreement with Iversen's (1958) model of environmental evolution in the interglacial, i.e., transition from periglacial (Gleysol) to optimum conditions (Luvisol). The deformations of illuvial microforms, commonly interpreted as secondary characteristics acquired in the periglacial environment at the post-pedogenic stage, are a micromorphological record of subsequent changes (e.g., Bullock and Murphy, 1979; Avery, 1985; Kemp, 1998).

Younger cold period

This younger cold period is documented by two genetically distinct units, B and C (Fig. 3).

Unit B (i.e., B-1 and B-2 subunits) is a record of periglacial processes (Fig. 3). Both types of deformation in subunit B-1 are characteristic periglacial structures. These are involution structures (load casts and diapirs) and contraction structures (wedges, veins) that are commonly regarded as evidence of the presence of permafrost (Murton *et al.*, 2000; French, 2007; Murton, 2007; Vandenberghe, 2007). Load casts form as a result of a reversed density gradient, related to the high degree of sediment liquefaction within the active layer of permafrost. Permafrost, as the main factor in the formation of the load casts, is supported by the sinking of deposits with a lower density (sands) into deposits with a higher density (till). Such conditions can occur, when the till is "loosened up" by lenses of ground ice (Vandenberghe, 1992, 2007; Vandenberghe and Pissart, 1993; Petera-Zganiacz and Dzieduszyńska, 2017). Another plausible line of evidence is the formation of diapirs as a result of hydrostatic pressure during the simultaneous upward-and-downward freezing of a liquefied layer. These forms indicate repeated freeze-thaw cycles. The thickness of the active layer of permafrost can be estimated at about 80 cm, i.e., it extended to 10–20 cm below the base of the till. The sandy wedges and dikes formed as a result of ground contraction, with a sudden and considerable decrease in temperature (Vandenberghe and Pissart, 1993; Murton *et al.*, 2000; French, 2007; Murton, 2007; Worsley, 2016). On the basis of the presence of the wedges among load casts, it can be inferred that there was a considerable decrease in temperature or/and a decrease of humidity (Vandenberghe and Pissart, 1993; Murton *et al.*, 2000). During the formation of both types of structures, processes of aeolian accumulation most probably occurred, which can be inferred from the properties of the deposits forming the load casts and infilling the sandy wedges and veins. Matte grains, characteristic of the aeolian environment, predominate and their morphoscopic characteristics are completely different from those of the sediments overlying unit B (Fig. 5).

In B-2 subunit, the destructive nature of aeolian processes is indicated by the character of reworking of the clasts. Owing to the sharp edges and very well-polished surfaces between the edges, the clasts can be regarded as ventifacts. Deflation also is indicated by the non-aeolized lower parts of the clasts 'rooted' in the clay. Thus, they constitute a deflation pavement (cf. Seppälä, 2004; French, 2007). The process of upfreezing cannot be excluded as a factor increasing the frequency of clasts in this unit. This is evidenced by the structures of stone rings, visible on the till surface, a result of segregation processes (Ballantyne, 2007) as well as the vertical orientation of elongated clasts (Goździk and French, 2004) in the till.

The authors interpret the origin of unit B as a record of the development of the periglacial zone as a consequence of a clear, progressive climatic cooling and increasing dryness. On the basis of the size of the wedges and frequency of the veins filled with sandy aeolian material, the authors infer that during the climatic pessimum, the annual temperature could have been in the range of –4 to –8°C, and the mean annual precipitation volume could have amounted to 100 mm (cf. Vandenberghe and Pissart, 1993; Murton *et al.*, 2000).

Unit C (C-1 and C-2 subunits) is a record of glacigenic depositional processes (Fig. 3). Subunit C-1 is derived from the meltwater channel environment. Horizontally stratified sands were deposited in upper plane-bed conditions. Sand beds with trough cross-stratification are the record of dunes, whereas the planar cross-beds represent larger channel forms – transverse bars. The coexistence of horizontally stratified and cross-stratified beds indicates that the flows were rather shallow. The sets of planar cross-strata are regarded as a good indicator of palaeoflow depth (Carling, 1990; Paola and Borgman, 1991). This estimation results in 1.0–1.1 m as the general depth of the palaeochannels. The dunes covered the bed in some deeper, inter-bar zones, in contrast with the upper plane bed formed on shoals, developed in the marginal parts of channels. Analogous lithofacies associations have been noted from sand-bedded braided channels by Tirsgaard and Oxenvad (1998), Ashworth *et al.* (2000) and Therrien (2006). The directional distributions of cross-stratification cover a range of 70–120° and represent bimodal azimuth roses (see Fig. 3). Such directional features were observed by Landvik and Mangerud (1985), Fielding and Webb (1996) and Khadkikar (2003) in deposits of a braided-river environment. Deposits with analogous lithofacies characteristics were found in relatively shallow braided channels on the small (up to 1 km long) alluvial fans, fed by meltwater (Ruegg, 1977; Russell *et al.*, 2001). The high frequency of ice-wedge pseudomorphs indicates the occurrence of polygons with a diameter of about 8 m. They have a character of synsedimentary structures, i.e., permafrost aggraded on parts of the fan, where flows disappeared. The morphoscopic features of sand grains in subunit C-1 are analogous to those in A-1: predominance of fluvially transported sediments, together with a significant frequency of glacially derived ones. The base-to-top increase in unreworked grains is also important here. Therefore, the genetic interpretation of subunit C-1 of the authors is glaciofluvial sediments, deposited in front of the advancing ice-sheet margin.

The lower, sandy part of subunit C-2 represents a low-energy fluvial environment. At first, sand-bed sheet flows took place. Shallow streams formed the sandy upper plane bed. These flows were highly unsteady; currents declined during short pulses, when bedload deposition was followed by the settling of the fine-grained material from suspension. Stream competency progressively decreased. Over time, the meltwater flows disappeared. Analogous fining-upwards, sandy-silty packages were interpreted as records of abandonment of shallow braided streams (Therrien, 2006). Then the shallow and wide stream arteries were filled with highly saturated morainic material, which moved from the ice by slurry debris flows (the upper part of subunit C-2). They underwent only minor, fluvial redeposition. In this way, the diamictic sand was deposited as the final stage of glaciomarginal sedimentation. This sediment is similar to the "heterolithic sand", documented by Krüger (1997) in small glaciofluvial fans in Iceland. The mass-flow origin of the subunit is confirmed by the "mixed" composition of various grain types, derived from both fluvial and aeolian reworking. On the basis of frost structures, analogous to those of subunit C-1, it can be inferred that the periglacial conditions continued in those fragments of the fan, from which the flows receded. On the other hand, silty sand with involutions permits inferences about the active layer of permafrost, the estimated thickness of which was about 30 cm.

The authors interpret unit C as the record of a terminoglacial fan, formed close to the ice-sheet margin. At first, deposition took place in relatively shallow channels, approximately 1 m deep. Within a short period, the channelized streams changed to sheet flows. The last depositional episode was the gravitational redeposition of supraglacial morainic debris, which underwent only slight fluvial washing. This sedimentary scenario indicates that deposition of unit D can be attributed to a relatively small terminoglacial fan, forming the end moraine (cf. Krzyszkowski and Zieliński, 2002). A poorly channelized, small-scale (shorter than 2 km) glaciofluvial fan, a so-called hochsander fan (*sensu* Krüger, 1994) and "transitional fan" (*sensu* Pisarska-Jamroży and Börner, 2011) can also be compared with the site studied. The terminoglacial conditions, in which the form developed, are also indicated by ice-wedge pseudomorphs. Their location in various horizons indicates that during the formation of the fan, its surface was periodically exposed to cryogenic processes, due to the avulsion of channels. On the basis of the dimensions and frequency of periglacial structures, the authors infer that during the formation of the terminoglacial fan, the mean annual temperature was low (from -4 to –8°C), and the daily amplitudes were considerable, up to 15° (Vandenberghe and Pissart, 1993; French, 2007). The thermal conditions were similar to those in the period of formation of unit C, but the humidity was much greater. However, this can be related to glaciofluvial outflow (cf. Ewertowski, 2009).

Palaeoclimatic and geochronological insights

As the analyses performed indicate, two distinct periods of climatic cooling, associated with the youngest Saalian ice-sheet advances in E Poland, were recorded in the Wólka Zagórna sedimentary succession, i.e., unit A (Odranian) and units B, C (Wartanian), separated by a warming period of interglacial rank, unit A/B. This is additionally indicated by the TL dates (Fig. 3; Tab. 3). On the basis of the present study and the previous work of the authors (Czubla *et al.*, 2019), the following chronology of events in the Odranian−Wartanian time interval can be assumed (Fig. 9). They correspond very well with the oxygen curve (Railsback *et al.*, 2015).

Odranian Glaciation (MIS 8)

The advance of the Odranian ice sheet is documented by glacigenic deposits (unit A). The transgressing ice sheet caused the proximalization of glaciofluvial sedimentation in its foreland: meltwaters became deeper and faster, which was recorded in the coarsening-upwards sedimentary succession (subunit A-1). The ice sheet advance was recorded in the deposition of subglacial till (subunit A-2). Its petrographic composition indicates that the source area of the ice sheet was central Fennoscandia, i.e., central Sweden and the Åland Islands area (Czubla *et al.*, 2019).

The period of glaciofluvial deposition was dated at 271 ± 30 ka, 281 ± 30 ka and 300±40 ka. It is convergent with the age of glaciofluvial deposition in Germany that took place during the first glacial phase of Saalian (analogue Alfeld Phase in NW Germany and Zeitz in Middle Germany): 248 ± 22 ka (Kars *et al.,* 2012), 250 ± 20 ka (Roskosch *et al.*, 2015), to 323 ± 70 ka (Kreutzer *et al.*, 2014).

Lublinian Interglacial (MIS 7)

In this period of a progressive climate warming, the exposed Odranian glacial till (subunit A-2) underwent pedogenetic processes with the formation of unit A/B.

Initially, Gleysol developed in cold-climate conditions, i.e., the presence of permafrost and poor, tundra vegetation with high levels of groundwater. Then, in warm climatic conditions (degradation of the permafrost and lower groundwater levels), the process of illuviation and development of a Luvisols took place beneath a forest complex. This evolution can be compared to the cataglacial and interglacial timespan between the Odranian and the Wartanian. It can correspond to the period of evident hiatus of Saalian glacigenic deposition that was documented in Germany after the older phase, the Alfeld/Zeitz of Drenthe (MIS 8; see Lang *et al.*, 2018).

Wartanian Glaciation (MIS 6)

The transgression and stabilisation of the Wartanian ice sheet were along the line of its maximum extent and fall in this cold period. The petrographic composition of subglacial till – a threefold decrease in the proportion of Central-Swedish erratics – indicates a shift in the source area of the ice sheet to the southeast in relation to the Odranian ice sheet (Czubla *et al.*, 2019). In the succession studied, this period initially was marked by the development of cryogenic and aeolian processes in the periglacial zone (unit B), and then, the deposition of glacigenic sediments in front of the ice sheet (unit C).

During the permafrost phase, in conditions of the periglacial zone and aeolian accumulation, the load casts and diapir structures initially developed, followed by wedge and vein structures (subunit B-1). These processes probably were accompanied by the frost-controlled, upward migration of clasts (Scandinavian rocks) from the till. Finally, the intensification of aeolian processes, deflation in particular, resulted in reduction of the fossil Luvisol to the B_t horizon and formation of the pavement layer (subunit B-2).

During the phase of sedimentation at the front of ice sheet, the formation of a terminoglacial fan (an end moraine in the geomorphological sense) took place. Initially, it was glaciofluvial deposition in sand-bed braided channels. The channels underwent frequent avulsion and cryogenic processes developed on their drained bottoms (subunit C-1). Over time, the channel flows were replaced by sheet flows of lower energy. Finally, the flows ceased and ice-contact mass flows dominated the terminoglacial fan (subunit C-2).

The thermal conditions were similar in both phases. The mean annual temperature could have ranged between –4 and –8°C. The humidity was greater than during the period of formation of unit B.

The succession of processes in both phases corresponded to the anaglacial and glacial Wartanian cycle. The anaglacial period was dated as 126–180 ka, which corresponds to

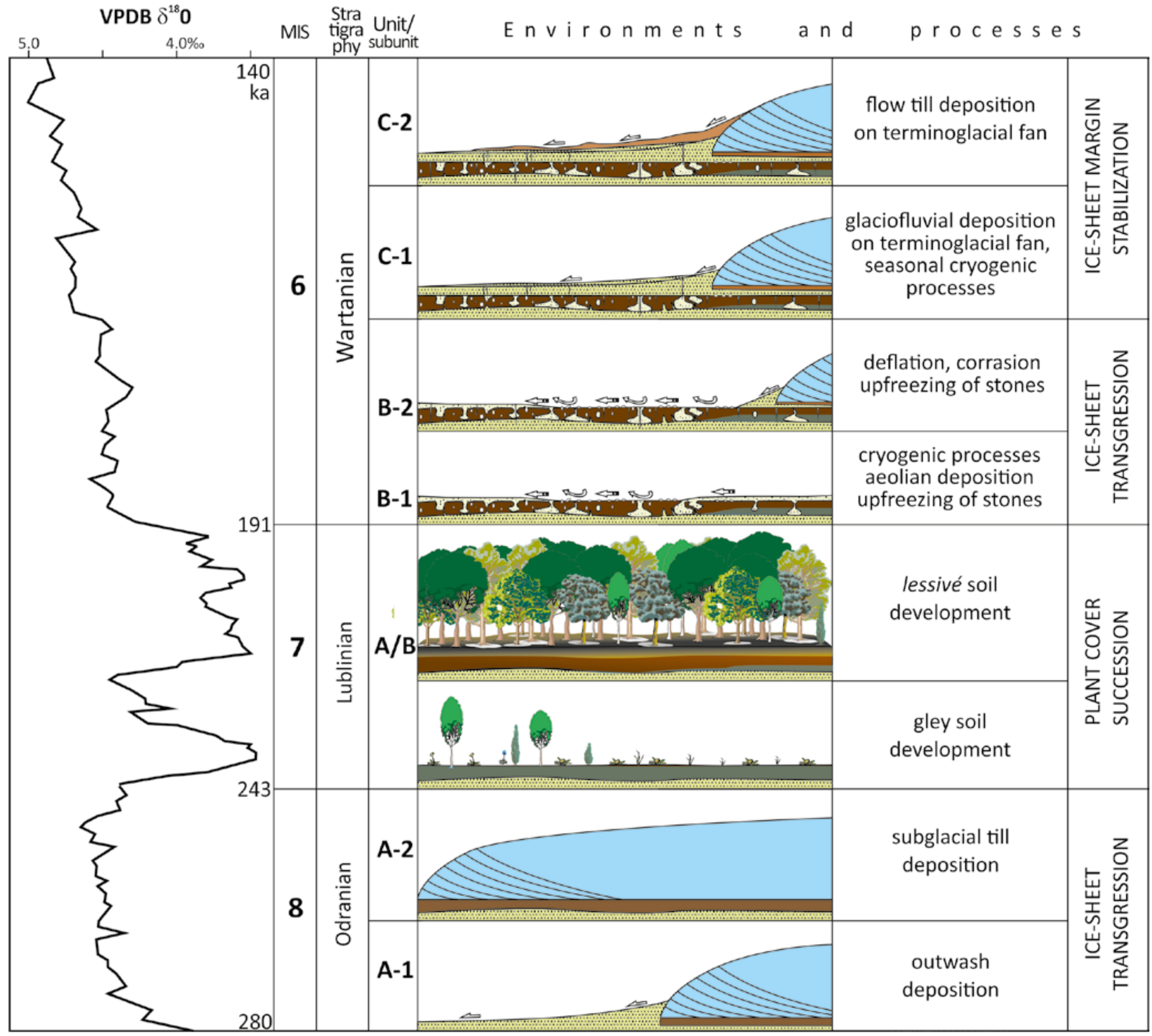

Fig. 9. Odranian – Wartanian at the Wólka Zagórna site – geochronology, lithostratigraphy and palaeogeography. $^{18}O/^{16}O$ ratio after Railsback *et al.* (2015).

the global climatic cooling in MIS 6, with the maximum cooling occurring between 150–130 ka (Shackleton and Opdyke, 1973). The age of the glaciofluvial delta deposits of the younger phase Freden/Leipzig of Drenthe and glaciofluvial Warthe deposits are within this timespan in Germany (see Lang *et al.*, 2018).

The rank of Wartanian cold period

According to the rules of Pleistocene stratigraphy, the rank of cold periods (glacials or stadials) depends on the rank of the intervening warm periods (interglacials or interstadials). In areas glaciated in the Pleistocene, the rank of warm periods is defined on the basis of palynological analyses of biogenic deposits, while in extraglacial areas, it is based on pedological analyses of the fossil soils in loess successions.

As noted in the introduction to this paper, evidence indicating the rank of the Wartanian cold period in areas glaciated in the Pleistocene is inconclusive. On the basis of the results of the investigations of the sedimentary succession at Wólka Zagórna – within the extent of the Saalian ice sheets – the authors suggest the possibility of recognizing the Wartanian cold period as a separate glaciation in position MIS 6, with well documented changes of environmental conditions during the ice-sheet transgression: development of the periglacial zone and then the terminoglacial zone in the forefield of its maximum extent. Its separateness is significantly manifested in the development of a Luvisol that occurred in MIS 7 on the Odranian till (MIS 8). This interpretation also is supported by the dating of deposits of the Wartanian and Odranian periods. The results of the present study are consistent with the most recent results of investigations of loess-soil successions in the stratotypical Dubrivka section (W Ukraine), i.e., in an extraglacial area. This section encompasses a full record of climate changes in the MIS 12–2 timespan. The Wartanian period (MIS 6) is marked by the thickest loess series, separated from the Odranian loess (MIS 8) by an interglacial Korshiv Luvisol, correlated with Lublinian (MIS 7; Łanczont *et al.*, 2019).

The results of the present study suggest a return to the stratigraphic scheme proposed earlier, e.g., by Lindner (1992), where the Wartanian period was a separate glaciation. It is important that in eastern Poland the Wartanian ice sheet had the largest extent among the Saalian ice advances (Czubla *et al.*, 2013, 2019; Terpiłowski *et al.*, 2013; Marks *et al.*, 2018). Moreover, its marginal zone is recorded by distinct landforms, such as end moraines, outwash plains, and the marginal valleys of present-day rivers Wieprz and Krzna (Terpiłowski, 2001; Harasimiuk *et al.*, 2004; Godlewska, 2014).

In the context of the well-preserved traces of Pleistocene climatic changes, recorded in the loess-soil successions of the extraglacial zone, the exceptional scarcity of palaeobotanical evidence for the existence of warmer periods in areas encompassed by Pleistocene ice sheets is particularly puzzling. Investigations in eastern Poland, with sites of lacustrine flora of the Ferdynandovian, Mazovian and Eemian interglacials, indicate that the abundance of these sites depends on their location in relation to the extent of the ice sheet in the successive glacial cycles. Sites of Ferdynandovian flora that were encompassed by glaciation and covered by till during the Sanian 2 are rare (Pidek and Poska, 2013; Stachowicz-Rybka *et al.*, 2017). On the other hand, there are numerous sites featuring the flora of the Mazovian Interglacial, located within the marginal zone of the Sanian 2 ice sheet and the forefield of the Wartanian ice sheet (Krupiński, 1995; Hrynowiecka and Winter, 2016; Hrynowiecka and Pidek, 2017). There are also numerous sites with the flora of the Eemian Interglacial, located within the marginal zone of the Wartanian ice sheet and in the forefield of the Vistulian ice sheet (Granoszewski, 2003; Kupryjanowicz, 2008; Kupryjanowicz *et al.*, 2018). In the latter case, the southern boundary of occurrence of Eemian "lakes" coincides with the boundary of the Wartanian ice sheet (Albrycht *et al.*, 1997). These patterns indicate that glacial exaration was not conducive to the preservation of interglacial lacustrine flora. In the view of the present authors, this is a sound explanation of the lack of biogenic deposits in the period between the Odranian and the Wartanian. In this context, the Wólka Zagórna site with the preserved B_t horizon of interglacial Luvisol should be recognized as particularly significant, because it was a proglacial and then terminoglacial zone of the Wartanian ice sheet. The removal of the O-A-E horizons from the soil section occurred in a periglacial environment, as a result of deflation processes. Thus, the pavement layer was formed. The deflation pavement protected the soil from further erosion by glaciofluvial waters during the formation of the terminoglacial fan (end moraine) of the Wartanian ice sheet.

CONCLUSIONS

The results of a detailed investigation of the Wartanian–Odranian (Saalian) sedimentary succession in the Wólka Zagórna site in eastern Poland lead to the following conclusions:

Three stratigraphic units were distinguished: A (lower glacigenic deposits), A/B (fossil soil), B and C (periglacial horizon and upper glacigenic deposits).

The lower glacigenic deposits (unit A) represent the succession from the base upwards: glaciofluvial sands and gravelly sands (subunit A-1), subglacial till (subunit A-2). This is a clear record of ice-sheet advance.

The fossil soil (unit A/B) developed on the till is bipartite: its lower part has the properties of a Gleysol, while its upper part has the properties of Luvisol with its characteristic B_t horizon. This succession indicates a progressive climate warming. During its optimum, the Luvisol developed in conditions of a warm climate, beneath a forest complex, with a low groundwater level. The most favourable conditions for its development occurred during the climate warming period of interglacial rank.

The periglacial horizon (unit B) comprises a set of deformation structures: cryogenic (involution structures, i.e., load casts and diapirs, and contraction structures, i.e., wedges and veins), subunit B-1, and the deflation pavement, subunit B-2. The periglacial structures indicate conditions of a gradual climatic cooling. Its pessimum is recorded in cryogenic structures, i.e., wedges and veins.

The upper glacigenic deposits (unit C) represent the following base-to-top sedimentary succession. Glaciofluvial sand beds, derived from shallow braided channels and sheet flows, are dissected by rare ice-wedge pseudomorphs (subunit C-1). They are capped by diamicton of mass-flow origin, i.e., flow till (subunit C-2). This is a record of sedimentation in front of the advancing ice sheet.

The lithostratigraphic units distinguished indicate a continuous record of climatic changes in the Odranian–Wartanian period. Unit A is a record of the Odranian glacial period, unit A/B of the cataglacial and interglacial period, unit B of the anaglacial period, and unit C of the Wartanian glacial period.

The time of glaciofluvial deposition of subunit A-1 was determined as 365–226 ka, while that of subunit B-1 – at 180–126 ka. This, alongside the interglacial soil separating them (unit A/B) and the previously mentioned petrographic distinctiveness of the Wartanian and Odranian glacial tills, indicate that the Wartanian cold period can be assigned the rank of an independent glaciation in position MIS 6; the same applies to the Odranian cold period, which is older and should be placed in position MIS 8.

Acknowledgements

This work was supported financially by the Polish Ministry of Science and Higher Education (Project No. N N306 198739 – *Climatic cycles of the Middle Pleistocene recorded in sedimentary sequence of the Łuków vicinity (E Poland)* – Head S. Terpiłowski) and by the University of Łódź (560/8442) and Maria

Curie-Skłodowska University (statutory means of both universities). We thank both reviewers – Andreas Börner and Antoni Wójcik for their constructive feedback to improve the manuscript.

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