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MIDDLE WEICHSELIAN PLENIGLACIAL SEDIMENTATION IN THE KRASÓWKA RIVER PALAEOVALLEY, CENTRAL POLAND

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Abstract: This study from the Szczerców field of the Bełchatów open-cast mining complex, central Poland, reveals the local geomorphic and stratigraphic history of the Krasówka river palaeovalley – a major western tributary of the river Widawka. The data are from the western flank of the N-trending palaeovalley and the study combines detailed lithofacies analysis of outcrop sections, sediment petrology, AMS measurements and palynological evidence. Radiocarbon dates are of crucial importance for the reconstruction of the palaeovalley history. The study contributes to a better understanding of the response of the Central European river systems to the Vistulian Pleniglacial conditions.

The Vistulian Pleniglacial sedimentation in the study area commenced with the accumulation of the latest Eemian to earliest Weichselian (≥45 ka) deposits by sheetwash processes in a local karstic topographic depression. The Krasówka river then formed to the east and shifted farther eastwards, but later approached twice the study area with a net aggradation prior to 43 ka BP – flooding it with overbank deposits. The river subsequently incised by nearly 20 m around 40 ka BP and began to fill in its valley by aggradation around 35 ka BP, while migrating eastwards and markedly decreasing its flooding capacity from 33 to 24 ka BP. The fluvial system was rejuvenated around 21 ka BP, with some initial erosion, and kept filling its valley by aggradation while flooding the valley flank. The river after filling its valley continued to aggrade, but gradually ran out of vertical accommodation and migrated westwards. The fluvial activity at this stage was increasingly accompanied by aeolian sedimentation. Once the Mid-Weichselian Pleniglacial came to an end around 14.5 ka BP, the Krasówka river had re-incised by nearly 5 m and assumed its present-day altitude in response to the post-glacial regional isostatic rebound of crustal basement.

Key words: alluvial deposits, MIS 3, sedimentary petrology, AMS, palynology, radiocarbon dates, Bełchatów mine.

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INTRODUCTION

Two main NW-directed Quaternary fluvial systems are crossing the area of the Bełchatów open-cast lignite mine complex in central Poland (Fig. 1): the Widawka river and the smaller Krasówka river, a major western tributary of the former. Their topographic drainage divide is related to a subsurface salt diapir near Dębina, which also separates the eastern Bełchatów and western Szczerców Miocene lignite fields (Fig. 1). The alluvial deposits of the Widawka river drainage system have been extensively studied in the Bełchatów mining field (e.g., Krzyszkowski, 1990, 1991, 1992, 1996, 1998; Goździk and Zieliński, 1996; Manikowska, 1996; Kasse *et al.*, 1998; Goździk and Skórzak, 2011). The new Szczerców mining field to the west (Fig. 1) has now allowed also the deposits of the Krasówka river valley to be studied in comparable detail, as reported in the present paper.

The Krasówka valley-fill deposits crops out in the SE corner of the Szczerców excavation field and are considered to represent the Piaski Formation (as defined by Krzyszkowski, 1990, 1991; see also Allen and Krzyszkowski, 2008) deposited during the Middle Weichselian Pleniglacial (Fig. 2). The latter has been correlated with the Marine Isotope Stage (MIS) 3, dated to 59–24 ka (Chappell and Shackleton,

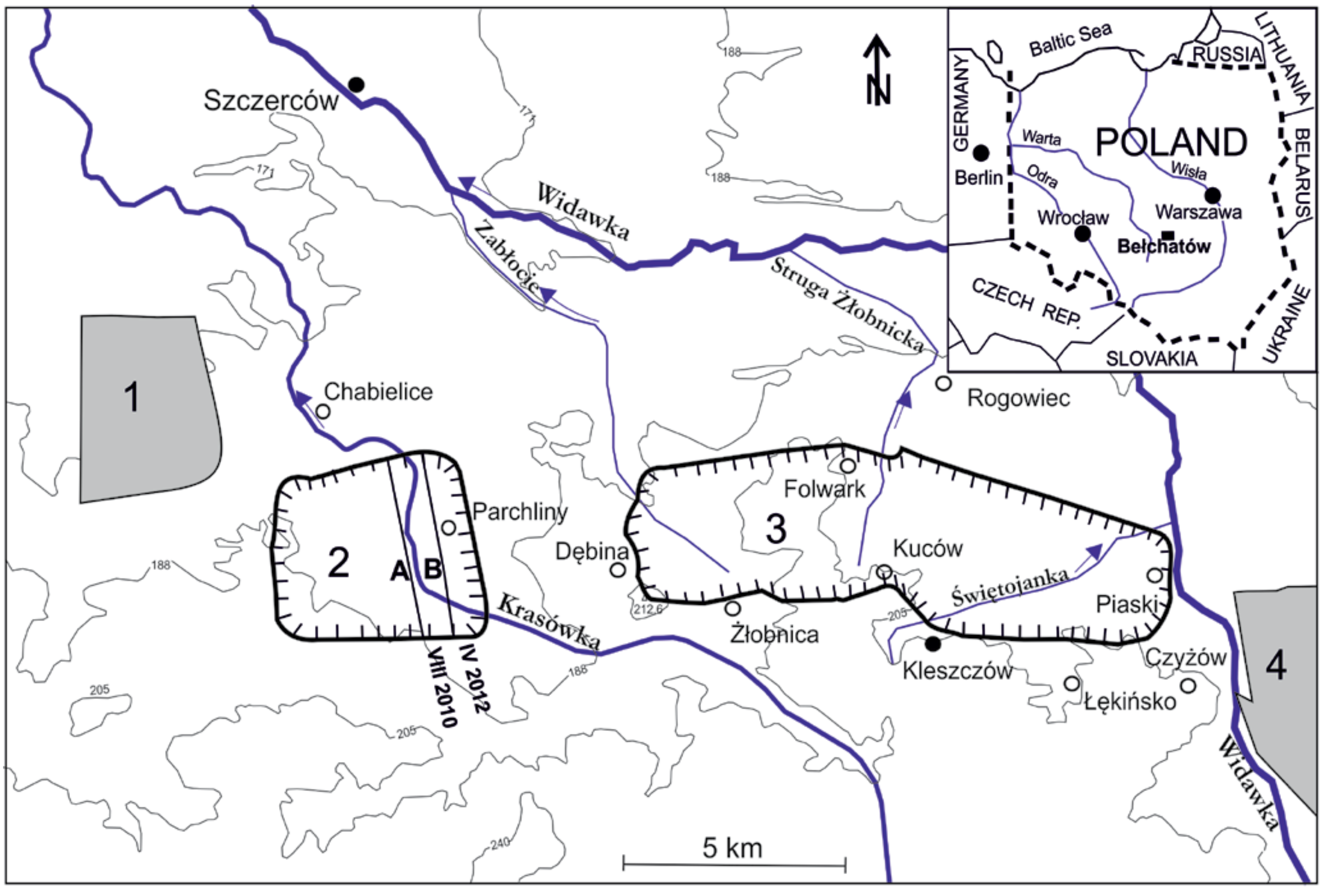


Fig. 1. Location of the Bełchatów open-cast mine complex and its present-day drainage pattern in central Poland (see inset map). The numbers indicate the Szczerców spoil dump (1) and mining field (2), and the Bełchatów mining field (3) with Kamieńsk spoil dump (4). The mining fields are within the E-trending Kleszczów Graben. Note the Szczerców mining-front outcrop sections: A – Parchliny A (August 2010); and B – Parchliny B (April 2012).

1996), with evidence of several glacial stadials and interstadials (Bos *et al.,* 2001). The sedimentary record of interstadials, although well-documented in other parts of Europe and particularly in the Netherlands (e.g., Zagwijn and Paepe, 1968; Bos *et al.,* 2001; Kasse *et al*., 2003; Wohlfarth, 2009; Sarala and Eskola, 2011), is poorly exposed and thus far little-evidenced in Poland (Manikowska, 1996; Petera, 2002; Krzyszkowski and Kuszell, 2007). The general aim of the present study is to close this gap in the regional knowledge by linking the Weichselian events in the Krasówka valley to those in the Widawka valley and to the climatic and vegetation history of Central Europe during the MIS 3 and subsequent MIS 2 (Last Glacial Maximum).

The Weichselian climatic changes and their impact on fluvial systems in the non-glacial zone of Central Europe have been extensively studied (e.g., Kuydowicz--Turkowska, 1975; Turkowska, 1988; Goździk, 1995; Balwierz, 1996; Manikowska, 1996; Kasse *et al.,* 1998, 2003; Vandenberghe, 1999, 2002, 2003; Bridgland, 2000; Bos *et al.,* 2001; Vandenberghe and Maddy, 2001; Petera, 2002; Cordier *et al.,* 2004; Wachecka-Kotkowska, 2004; Forysiak, 2005). The vegetation cover during the Weichselian Pleniglacial is recognized as the most important factor translating climate change into changes in fluvial-system dynamics, especially sediment yield, water discharges and river-bed morphodynamics (e.g., Bos *et al.,* 2001; Maddy *et al.,* 2001; Petera, 2002; Kasse *et al.,* 2003; Vandenberghe, 2003; Krzyszkowski and Kuszell, 2007; Bridgland and Westaway, 2012).

The present paper focuses on the Weichselian Pleniglacial history of the Krasówka river valley, deciphered on the basis of sedimentological observations, palynological data and radiocarbon dates from the Szczerców field. Special emphasis is on the river behaviour and its phases of incision and aggradation. The stratigraphic development of the Krasówka valley is compared with that of the adjacent valleys of Widawka river and its small tributaries documented in the Bełchatów field (Fig. 1), although these fluvial systems differ slightly in their geological and geomorphological settings. The north-trending Widawka and Krasówka rivers are cross-cutting the east-trending Kleszczów Graben, whereas the smaller tributaries of Widawka in the Bełchatów field are within the graben and roughly parallel to its axis.

STUDY AREA

The Weichselian succession of terrestrial siliciclastic deposits forms the upper, tectonically undisturbed lithostratigraphic unit in the Kleszczów Graben (Krzyszkowski, 1989). These deposits overlie the Eemian Aleksandrów

Formation (dated to MIS 5e) and the late Saalian Rogowiec Formation (dated to MIS 6) of the Wartanian Mid-Polish Complex. Their sedimentary cover is the late Weichselian to Holocene Widawka Formation (Figs 2, 3).

The study area is in the Szczerców field of the Bełchatów open-cast lignite mining complex (Fig. 1), located about 60 km to the SSW of Łódź in central Poland. The alluvial deposits studied belong to the Piaski Formation (Fig. 2) which buried the Chabielice fault system of the Kleszczów Graben (Fig. 3). The study was conducted in two phases, in August 2010 and April 2012, focusing on exposures in the south-eastern corner and eastern face of the Szczerców mining field (Fig. 1). The two mine-face outcrop sections studied in detail are referred to as Parchliny A (studied in 2010) and Parchliny B (studied in 2012) (see Fig. 3).

The Scandinavian ice-sheet limit at the Weichselian (Vistulian) Last Glacial Maximum was located about 150 km to the north of the present-study area in central Poland, which then hosted extensive fluvial, lacustrine and aeolian sedimentation (Turkowska, 1988; Goździk, 1991, 1995, 2007; Petera, 2002; Wachecka-Kotkowska, 2004; Forysiak, 2005). The unique extensive exposure of these deposits in the Bełchatów open-cast mine complex has long been intensely studied. Studies from the Bełchatów field (Fig. 1) have indicated a bipartite Weichselian cycle of sedimentation in the river valleys of central Poland, recording two episodes of regional climatic cooling (Krzyszkowski, 1990; Manikowska, 1996). Studies of the alluvial deposits of the left-bank small local tributaries of the Widawka river (Fig. 1), particularly the Świętojanka and Struga Żłobnicka streams (Krzyszkowski, 1991; Goździk and Zieliński, 1996), have documented three main lithofacies associations: sandy, muddy and heterolithic mud-sand deposits.

The lithofacies complexes of the Krasówka river valley exposed in the Szczerców field are comparable to those of the Widawka tributary valleys in the Bełchatów field. All these deposits are considered to represent the Middle Weichselian Pleniglacial and belong to the Piaski Formation (Fig. 2; *sensu* Krzyszkowski, 1990, 1991; Allen and Krzyszkowski, 2008). However, their accumulation may not have been fully synchronous, as the geomorphic signal of the Widawka behaviour probably migrated upstream and into its small/short and large/long tributaries, such as the Krasówka. For example, the alluvial succession in both fields commences with a unit of grey silty deposits, 80 cm thick and rich in plant detritus. In the Bełchatów field, these basal deposits are interpreted to be Eemian in age (Goździk and Balwierz, 1994; Goździk and Skórzak, 2011), but the present study suggests them to be of the latest Eemian to earliest Weichselian age in the Szczerców field. Similar short-term diachroneity can be expected for the episodes of river-system incision and aggradation.

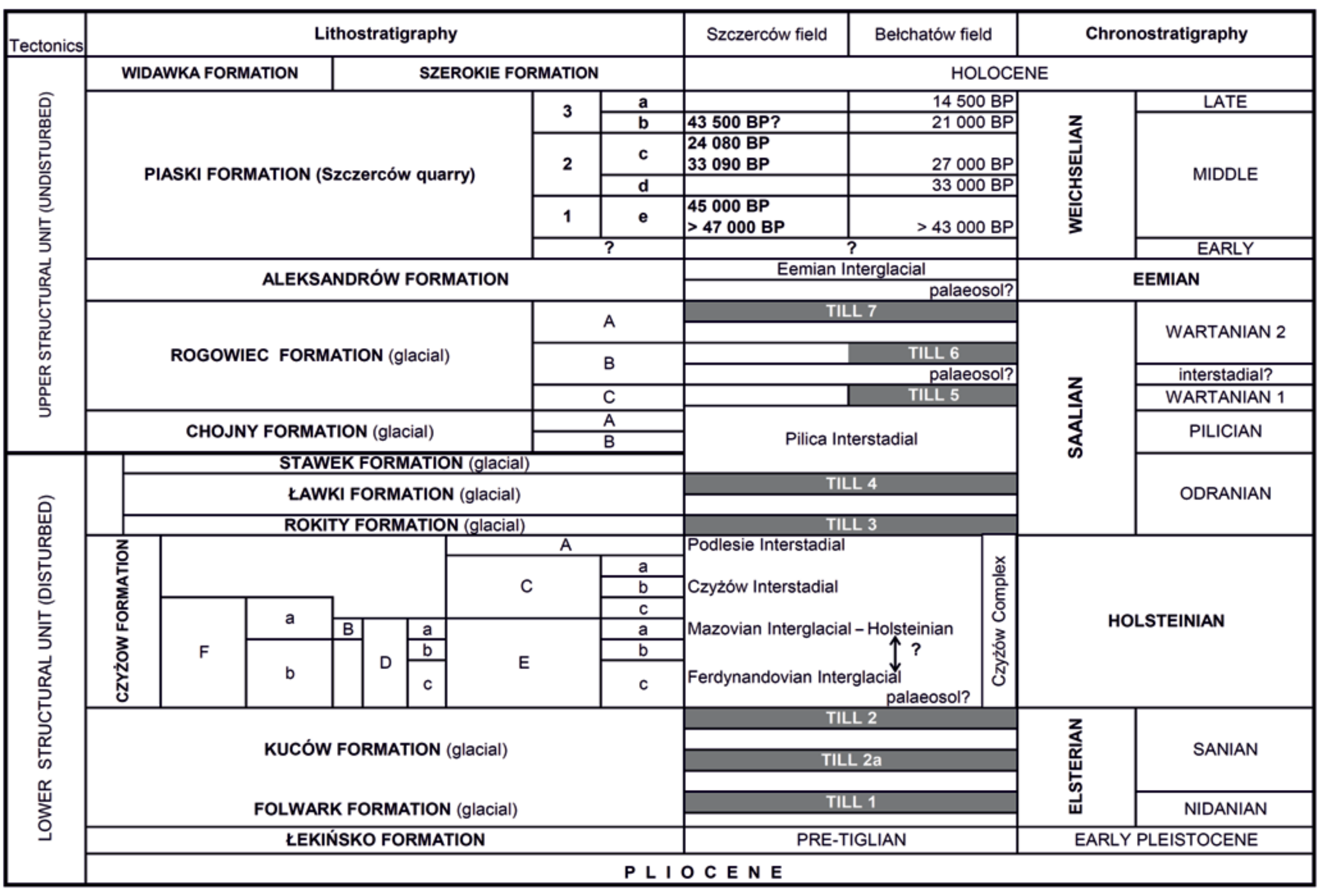


Fig. 2. The stratigraphic position of the Weichselian Piaski Formation in the context of the Quaternary succession of the Kleszczów Graben. The numbers and letter symbols refer to lithostratigraphic subdivisions (as used further in Figs 4–7).

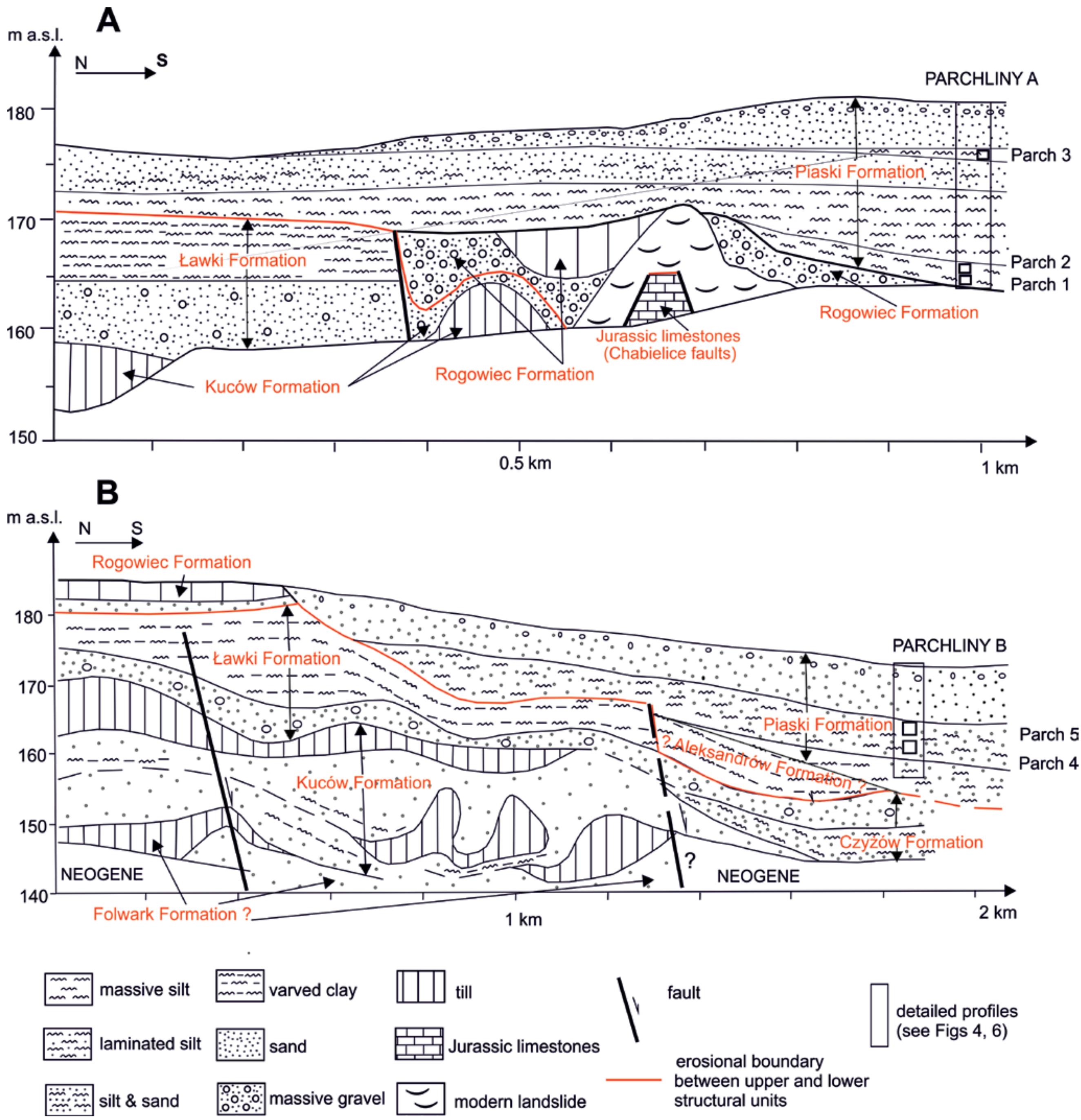


Fig. 3. Outcrop cross-sections from the Szczerców mining field (see location in Fig. 1). **A**. Section Parchliny A (August 2010). **B.** Section Parchliny B (April 2012). Note the Weichselian Piaski Formation and the location of its detailed logs (shown in Figs 4, 6). The red line is the boundary between lower, tectonically-deformed sedimentary succession and the upper, non-deformed succession.

The Weichselian Piaski Formation in the Bełchatów field was divided into five lithofacies assemblages labelled "a" to "e" in a descending stratigraphic order; these were grouped further into three lithocomplexes labelled 1–3 in an ascending stratigraphic order (Fig. 2). The same nomenclature is used herein for the Szczerców field (see Figs 4–7), but without an implication that the local lithocomplexes and their component lithofacies assemblages, even when descriptively similar, are necessarily time-equivalents.

METHODS

Conventional field methods of sedimentological analysis (Tucker, 1996) were used, with a detailed logging of outcrop sections and a lithofacies code after Zieliński and Pisarska-Jamroży (2012) (see caption to Fig. 4). For the sake of objectivity, the descriptions of lithofacies assemblages are separated from their interpretations in the text.

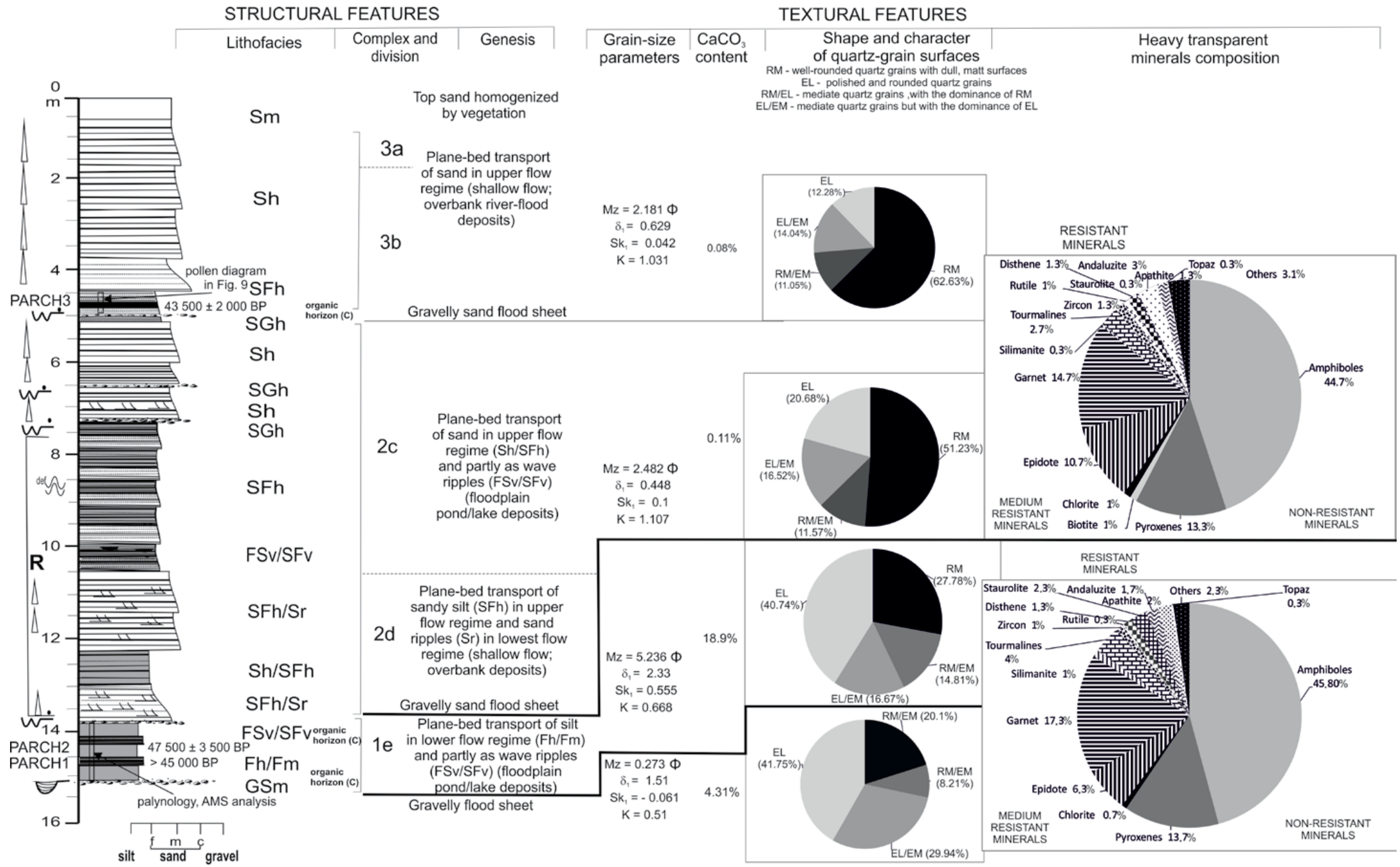


Fig. 4. Detailed sedimentological log Parchliny A (see location in Fig. 4A) with lithofacies interpretation, structural and textural features and heavy-mineral composition of samples. Lithofacies code: Sm – massive sand; C – organic horizon (plant detritus); Fm – massive silt/mud; Fh and SFh – horizontally laminated mud and sandy silt; SFv and FSv – wavy-laminated sandy silt and silty sand; Fv – wavy-laminated mud or silty mud; Sr – ripple cross-laminated sand; Sh – sand with planar parallel stratification, horizontal or inclined; SGh – planar parallel-stratified sandy gravel; GSm – massive gravelly sand.

Table 1

Samples taken for palynological analysis and ^{14}C dating.

Sample number	**Altitude** (m)	**Depth** (m)	**Sample details** (samples PARCH 1–5 were subject to ^{14}C dating)
PARCHLINY A section (sampled in August 2010) Basal part of the Piaski Formation (unit 1e)			
1	165.3	13.8	Upper grey muddy-organic series, top of organic horizon I
2	163.9	14.2	Upper grey mud, base of organic horizon I (^{14}C PARCH 2)
3	163.85	14.25	Upper grey mud
4	163.8	14.3	Base of upper grey mud
5	163.7	14.4	Sandy-muddy sediments
7	163.6	14.5	Top of middle part of grey mud
7	163.5	14.6	Middle part of grey mud
8	163.4	14.7	Bottom of middle part of grey mud
9	163.3	14.8	Top of organic horizon II
10	163.25	14.85	Middle part of organic horizon II (^{14}C PARCH1)
11	163.15	14.95	Base of organic horizon II
12	163.1	15.0	Top of lower grey mud
13	162.9	15.2	Base of lower grey mud
Top part of the PIASKI Formation (unit 2c/3b)			
14	175.1	5	Sandy-muddy deposits with organic horizon III (^{14}C PARCH3)
PARCHLINY B section (sampled in April 2012) Ławki Formation (unit 2c)			
15	164.4	13.6	Basal upper part of sand-mud with organic horizon (^{14}C PARCH4)
16	164.7	13.3	Grey mud with organic admixture
17	165.1	12.9	Black clay
18	165.5	12.5	Grey mud with organic admixture
19	165.7	12.3	Top part of sand-mud with organic horizon (^{14}C PARCH5)
20	165.9	12.1	Sandy gravel pavement (unit 2c/3b)

Twenty samples were collected for palynological analysis, five samples (PARCH 1–5) for radiocarbon dating (Table 1; see location in Figs 4–7), five other samples for grain-size analysis and three samples for heavy-mineral analysis. Laboratory data included grain-size distribution parameters (after Folk and Ward, 1957), non-opaque heavy mineral content, the morphoscopy (surface texture) and roundness of quartz sand grains (method after Cailleux, 1942; modified by Mycielska-Dowgiałło and Woronko, 2004), and bulk calcium-carbonate content.

These data were supplemented with measurements of the anisotropy of magnetic susceptibility (AMS) in order to determine grain fabric and the direction of fine-grained sediment transport. For this purpose, 10 accurately-oriented block samples were taken systematically from the profile of a 70-cm thick silt bed in the lowest part of the Piaski Formation in the Parchliny A section (Figs 3, 4). The anisotropy tensor of magnetic susceptibility (Tarling and Hrouda, 1993) was calculated statistically for each sample on the basis of the three principal axes of the ellipsoid of magnetic susceptibility anisotropy (Fig. 8). The AMS measurements were conducted with the use of a modern, multifunction bridge MFK1-FA (produced by AGICO Ltd., Czech Republic) at the Palaeomagnetic Laboratory of the Institute of Geophysics of the Polish Academy of Sciences in Warsaw. All specimens were closed in plastic boxes (volume 8 cm^3) to avoid rapid drying and mechanical deformation of sediment, and the measurements were taken in 15 different positions for high precision. The numerical results and their plotting on stereonets were obtained by using the AGICO software ANISOFT 42.

In the interpretation of AMS data, it has been taken into account that it may be either the axis of maximum magnetic susceptibility (κ_{max}) or the intermediate axis (κ_{int}) of the AMS ellipsoid that is parallel to the sediment transport direction (Tarling and Hrouda, 1993). The magnetic fabric of grains pivoted by flow or aligned by laminar shear will be parallel to the transport direction (e.g., Shumway and Iverson, 2009). However, grains deposited by rolling will show the κ_{max} of magnetic fabric transverse to their transport direction (Allen, 1982), and the transport axis will then be indicated by κ_{int}.

RESULTS AND INTERPRETATION

The thickness of the Weichselian Pleniglacial alluvial succession at the western flank of the Krasówka river palaeovalley exposed in the Parchliny sections reaches 16 m (Fig. 3). The lowest deposits are silty to muddy, with occasional interlayers of pebbly sand, peat and organic-rich mud (Table 1). They pass upwards into a package of sandy and muddy deposits, 5–10 m in thickness, with organic-rich fine-grained sand at the top.

The outcrop section Parchliny A (Fig. 3A) shows the most complete local succession of the Piaski Formation, which comprises three lithocomplexes and is about 15 m thick (Fig. 4). The lowest lithocomplex 1(e) consists of a thin basal layer of pebbly sand overlain by silt with horizons rich in plant detritus (see Figs 4, 5A, B), whereas the overlying lithocomplexes 2 and 3 are considerably richer in sand (Fig. 4). The fine-grained basal division is lacking in the section Parchliny B, where it is replaced by a deep-incised basal erosional surface (see Figs 6, 7A). The Piaski Formation there comprises sand-rich lithocomplexes 2 and 3 (Fig. 6) and has a measured thickness of slightly more than 16 m, but its actual thickness is probably greater, as the full depth of the basal incision is unexposed (Figs 3B, 7A).

The lithofacies assemblages of the Krasówka palaeovalley deposits in the Szczerców field are comparable to those of the Early to Middle Weichselian Pleniglacial deposits in the nearby small palaeovalleys of Struga Żłobnicka and Świętojanka streams in the Bełchatów field (Fig. 1; see Krzyszkowski, 1990; Goździk and Zieliński, 1996; Manikowska, 1996; Kasse *et al.*, 1998), but their time-equivalence is uncertain. For example, one may be tempted to correlate the basal gravelly layer in Parchliny A with the basal erosional surface in Parchliny B and consider them as representing the Weichselian Pleniglacial pavement widely recognized in the LGM fluvial successions in central Poland (e.g., Kuydowicz-Turkowska, 1975; Turkowska, 1988; Petera, 2002; Wachecka-Kotkowska, 2004; Forysiak, 2005). However, the present study shows further that this is not the case.

In this chapter, the results of the present study of the Piaski Formation in the Szczerców field are reviewed and interpreted, including sedimentological characteristics of the deposits, their carbonate and heavy-mineral content, AMS properties, palynological evidence and radiocarbon dates. Lithostratigraphic complexes are distinguished on a purely descriptive basis and are numerically labelled in a hypothetical analogy to those in the Bełchatów field (Fig. 1), but their actual chronostratigraphic and palaeogeomorphic correlation is discussed further in a subsequent chapter.

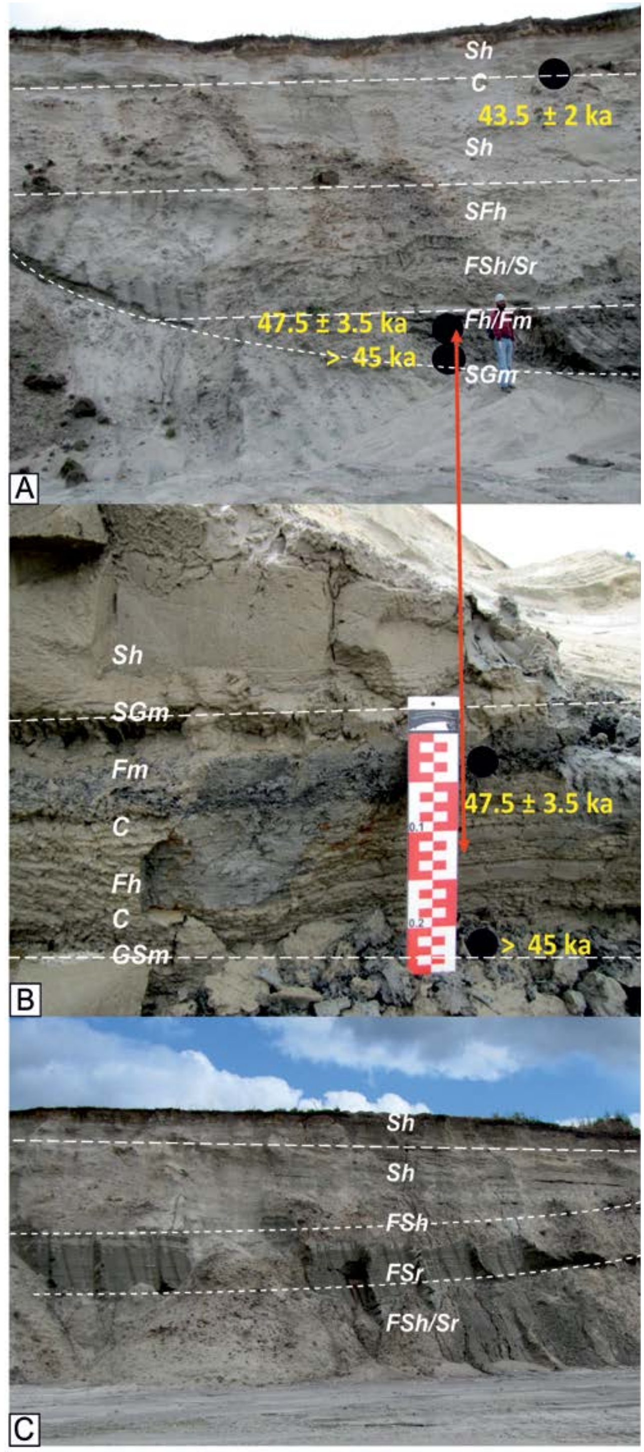


Fig. 5. Outcrop section Parchliny A (as seen in August 2010), showing the Krasówka valley-fill in Szczerców field. **A.** Broad view of the main part of the Piaski Formation. **B**. The lower part of the formation. **C.** The middle to upper part of the formation. Note the radiocarbon dates. Lithofacies code as in the caption to Fig. 4.

Lithofacies successions

Section Parchliny A

The Piaski Formation in the outcrop section Parchliny A (Fig. 3A) commences with a sandy gravel pavement (lithofacies Gm, GSm and SGm), 5–10 cm thick, overlying unconformably Saalian to Eemian deposits (Fig. 5A, B). It is covered with a package of grey muds, massive (lithofacies Fm) to variously laminated (lithofacies Fv, FSv and Fh), including two horizons rich in plant detritus (Figs 4, 5B, Table 2). The middle part of the succession consists of laminated silt (lithofacies FSh), planar parallel-stratified sand (lithofacies Sh) and fine-grained to silty ripple cross-laminated sand (lithofacies Sr and FSr). Organic interlayers are rare, whereas cryoturbation structures and ice-wedge

Table 2

Main structural and textural characteristics of the Weichselian deposits in the Krasówka palaeovalley in outcrop section Parchliny A (Fig. 4).

Piaski Fm.:	Basal lag	Lower part	Middle part	Upper part
General description				
Deposit type	Sandy gravel (24.5% gravel, 75.5 % sand)	Silt, mud and silty sandy (47.9 % sand, 52.1% mud)	Fine-grained sand with organic matter (99.2% sand, 0.8% mud)	Fine-grained sand (98.6% sand, 1.4% mud)
Thickness	0.1–0.25 m	0.8–1.5 m	5–10 m	2–5 m
Lithostratigraphic unit	Boundary of Aleksandrów & Piaski fms	Unit e	Unit d/c	Unit b/a
Structural characteristics				
Main lithofacies	GSm (massive)	Fv/FSv (varved) Fm (massive)	Sh (planar laminated) Sr (ripple cross-laminated)	Sh (planar laminated)
Occurrence of organic layers	Absent	Present	Present at the top	Absent
Genetic complex	CF/GS (sheetwash gravel pavement)	SS (products of suspension fallout)	SU/SB-RM (non-channelized sheetflow)	SU (non-channelized sheetflow)
Textural characteristics				
Grain-size distribution parameters				
Mean (Mz, phi)	0.273 very fine gravel	5.236 coarse silt	2.482 fine sand	2.182 fine sand
Standard deviation (δ_1)	1.519 poorly sorted	2.330 poorly sorted	0.448 very well sorted	0.629 very well sorted
Skewness (Sk_1)	–0.061 symmetrical	0.555 very coarse skewed	0.100 coarse skewed	0.042 symmetrical
Kurtosis (K)	0.510 very platokurtic	0.668 very platokurtic	1.107 mesokurtic	1.031 mesokurtic
Quartz-grain morphoscopy				
Well rounded matt (RM)	20.10%	27.78%	51.23%	62.63%
Shiny rounded (EL)	41.75%	40.74%	20.68%	12.28%
Intermediate (EM: RM/EM & EL/EM)	8.21% RM/EM 29.94% EL/EM	14.81% RM/EM 16.67% EL/EM	11.57% RM/EM 16.52% EL/EM	11.05% RM/EM 14.04% EL/EM
Bulk $CaCO_3$ content				
Content	4.31%	18.91%	0.11%	0.08%

casts are locally observed. The upper part of the succession (lithocomplex 3, Fig. 4) shows an erosional basal surface covered with a pebbly sand lag (lithofacies SGm), a few centimetres thick, overlain by thin sandy mud with plant detritus (lithofacies SFh) and a thicker (2 m) package of planar parallel-stratified sand (lithofacies Sh). The topmost sand layer in lithocomplex 3 is homogenous, nearly massive (lithofacies Sm).

The deposition of the lowermost part of the formation (lithocomplex 1, Fig. 4) is attributed to non-channelized overland waterflow (sheetwash) processes, with the sediment accumulation in a post-Wartanian local topographic low, presumably a karst depression. The topographic depression was pre-washed and lain with a sandy gravel pavement, before accumulating sediment from a low-energy sheetwash (Fh) and fine-grained suspension fallout (Fm) in slack-water conditions, with sporadic weak wave action (SFv and FSv).

The middle part of the formation (lithocomplex 2, Fig. 4) represents an increase in tractional transport (SFh and Sr), followed by wave-influenced slack-water conditions (FSv/SFv) and a prolonged pulsating tractional deposition of silty to increasingly sandy lithofacies (SFh and Sh) (lithocomplex 2c, Fig. 4). The lack of large-scale cross-stratification (dune bedforms) implies non-channelized flow and suggests river overbank deposits. The bulk upwards-coarsening trend in lithocomplex 2c and the associated sheets of sandy gravel (SGh) suggest repetitive overbank flooding from a little-incised river channel located to the east, beyond the outcrop section. The uppermost part of the formation (lithocomplex 3, Fig. 4) is another package of fine-grained silty sand

(SFm) with at least one organic horizon, passing upwards into medium-grained sand (Sh). These sandy deposits with fining-upwards strata sets indicate a cyclic non-channelized shallow tractional flow, similarly attributed to overbank flooding (see McKee *et al.*, 1967; Bridge, 2003).

The deposition of lithocomplexes 2 and 3 is thought to have occurred on a floodplain adjacent to the Krasówka river palaeochannel. This interpretation is supported by the flat base of the Piaski Formation in the area (Fig. 3A). The river channel coeval with lithocomplex 2 is inferred to have first migrated away from the study site and markedly decreased its discharge, thereby resulting in a fining-upwards succession of overbank deposits (see the lower part of lithocomplex 2d in Fig. 4). The river then sharply increased its overbank flooding capacity, perhaps by also shifting its channel closer to the study area (see the upper part of lithocomplex 2d in Fig. 4). The river subsequently shifted away from the study area and gradually approached it again (see the coarsening-upwards lithocomplex 2c in Fig. 4). After another shift away from the study area and gravel-lag deposition (possibly a hiatus), the river approached the study area again with a strong overbank flooding (see lithocomplex 3 in Fig. 4). The top layer of massive sand (lithofacies Sm, Fig. 4) is attributed to sediment homogenization by sub-recent surface vegetation.

Section Parchliny B

The Piaski Formation in the Parchliny B outcrop section (Figs 6, 7) reaches a lower altitude and shows the infill deposits of an incised fluvial valley cut in the Saalian–Eemian sedimentary substrate (Figs 3B, 7A). Lithocomplex 1 (Fig. 4) is apparently lacking here, although the full depth and thickness of the valley-fill are not exposed.

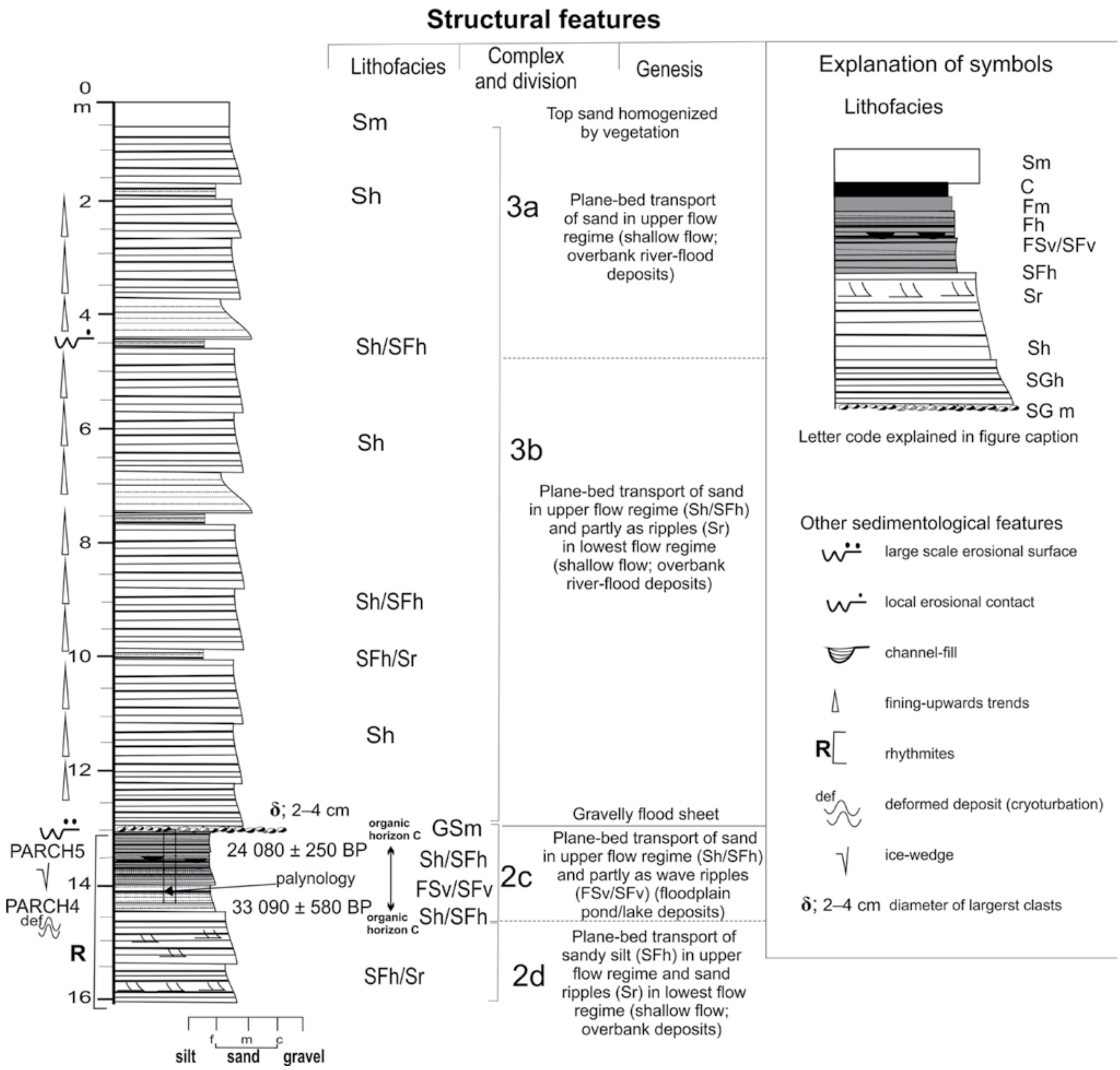


Fig. 6. Detailed sedimentological log Parchliny B (see location in Fig. 4B) with lithofacies interpretation. Lithofacies code as in the caption to Fig. 4.

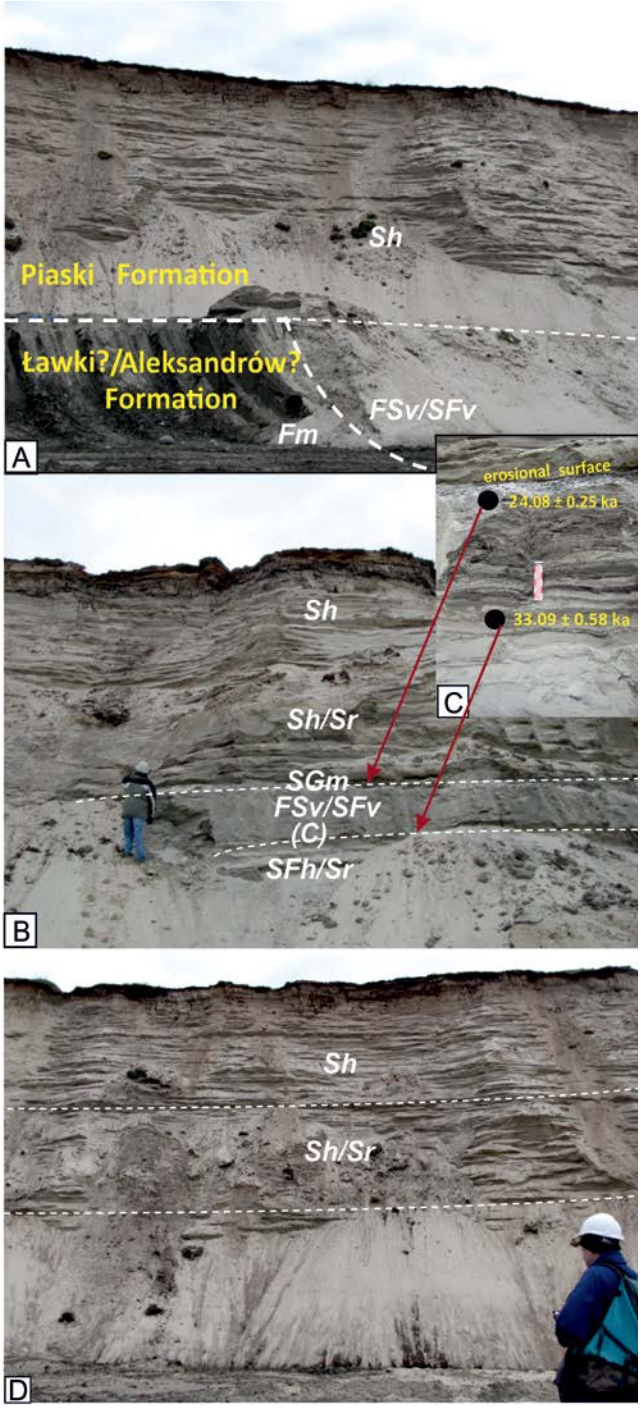


Fig. 7. Outcrop section Parchliny B (as seen in April 2012), showing the Krasówka valley-fill in Szczerców field. **A**, **B.** Broad views of the main part of the Piaski Formation. **C.** The middle part of the formation. **D.** The upper part of the formation. Note the radiocarbon dates. Lithofacies code as in the caption to Fig. 4.

The succession commences with deposits tentatively considered as lithocomplex 2, whose lower part comprises planar parallel-stratified and ripple cross-laminated, fine-grained to silty sands (lithofacies Sh and Sr/FSr) with small-scale (up to 5 cm) cryoturbation structures (see lithocomplex 2d in Fig. 6). The upper part (lithocomplex 2c, Fig. 6) contains similar sandy lithofacies, but is richer in laminated silty layers (lithofacies FSh/SFv and FSv/SFv) with organic-rich laminae and shows rhythmic minerogenic-organic alternations. Lithocomplex 2c shows also ice-wedge casts up to 1 m deep (Fig. 7C).

An erosional surface with gravel pavement 5–10 cm thick (lithofacies GSm) separates lithocomplex 2 from the overlying lithocomplex 3 (Figs 6, 7B; see also Fig. 3B). Lithocomplex 3 consists of fining-upwards sand packages, around 1 m thick, dominated by lithofacies Sh and including subordinate lithofacies Sr and SFh (Figs 6, 7). A minor erosional surface separates its lower part (lithocomplex 3b) from the upper part (lithocomplex 3a) (Fig. 6).

The lithofacies in the Parchliny B section are still overbank deposits, as evidence of channelized flow and dune bedforms (large-scale cross-stratification) is lacking. The river palaeochannel must have been located outside this section, farther to the east. Lithocomplex 2d (Fig. 6) indicates sedimentation in a sand-prone, shallow-flow overbank environment. The river-flood hydraulic energy then significantly declined, which implies the river shifting farther to the east and/or decreasing its water discharges (lithocomplex 2c, Fig. 6). Although the admixture of plant material increased, the ice-wedge casts in lithocomplex 2c indicate periglacial conditions with permafrost. The fluvial system probably shrank at this time, with the vegetation cover being seasonally removed by snowmelt.

Lithocomplex 3, with its gravel-paved erosional base and thick accumulation of sandy deposits (Fig. 6), indicates a marked rejuvenation of the fluvial system. The river channel apparently came very close to the study area, as the lithofacies here are similar to channel-proximal overbank fluvial-flood deposits (McKee *et al.*, 1967; Bridge, 2003). Nevertheless, the cyclic pattern of river flooding differs markedly from that in the section Parchliny A (Fig. 4), which puts in doubt possible time-equivalence of lithocomplexes 3 in the two Parchliny sections.

It is also worth emphasis that no fluvial channel-fill deposits were found in either of the two sections within their vertical outcrop limits, which means that the river channel had shifted into the study area and assumed its present-day location (Fig. 1) relatively late.

Detailed textural characteristics

The pebbly gravel pavement at the base of the Weischelian Pleniglacial succession in the Parchliny A section (Fig. 4) has a coarse-grained ($Mz = 0.273\ \Phi$) and poorly sorted ($\delta_1 = 1.519$) sand matrix (Table 2). The overlying sandy silt (Fig. 4), with $Mz = 5.236\ \Phi$, shows a very poor sorting ($\delta_1 = 2.33$) and strong positive skewness ($Sk_1 = 0.555$), which indicates an excess of fines and suggests rapid deposition by fallout from turbulent suspension (Folk, 1980).

The basal part of lithocomplex 2 comprises sand and silty sand (Fig. 4). The sand is fine-grained ($Mz = 2.482\ \Phi$), well sorted ($\delta_1 = 0.629$) and moderately positively skewed ($Sk_1 = 0.1$), which is consistent with sediment segregation by river overbank spill-out (Bridge, 2003). Similar grain-size characteristics are shown by sand samples from lithocomplex 3.

The shape and morphoscopic characteristics of sand quartz grains indicate further some textural differences between the lithocomplexes (Table 2, Fig. 4). Polished and rounded grains of EL-type abound (42%) in the basal gravel pavement and the overlying deposits of lithocomplex 1e (Fig. 4). These grains come probably from reworked Eemian fluvial deposits. Higher in the profile, the proportion of EL grains decreases to 12% in favour of well-rounded RM-type grains with dull, matt surfaces (from 51% RM and 11% RM/EM in lithocomplex 2c to 62% RM and 11% RM/EM in lithocomplex 3b). In lithocomplexes 2 and 3, most grain surfaces appear to have been "frosted" by aeolian abrasion (Goździk, 1991; Mycielska-Dowgiałło and Woronko, 2004). This evidence is consistent with the notion of periglacial fluvio-aeolian conditions for the upper part of the Piaski Formation.

Heavy-mineral composition

Heavy-mineral analysis of samples from the basal pavement and middle part (lithocomplex 2c) of the Piaski Formation in Parchliny A section shows their similar composition (Fig. 4). Dominant in are non-durable minerals, highly susceptible to weathering, such as amphiboles (~45%) and pyroxenes (13%) of low hydro- and aero-dynamic susceptibility (Racinowski, 2010). There is a significant admixture of medium-durable minerals, particularly garnets (14–17%) and epidotes (6.3–10.7%), whereas resistant minerals are relatively rare (e.g., 2.3–4% tourmaline and 1.7–3% andalusite).

The composition of heavy-mineral fraction suggests that the deposits of the Weischelian succession comprise sediment eroded from the Saalian–Eemian part of the Pleistocene (Wachecka-Kotkowska and Ludwikowska-Kędzia, 2013). The local provenance and redeposition of sediment in karstic and tectonic depressions, such as the Kleszczów Graben, would alter little the heavy-mineral assemblages inherited from a fresh glacial substrate (cf. Bateman and Catt, 2007). However, any direct comparison with the substrate heavy-mineral assemblages is difficult, because the pre-Quaternary bedrock lithology varies on a local scale, whereas fluvial recycling of sediment even over short distances inevitably homogenizes its mineral composition (Wachecka-Kotkowska and Ludwikowska-Kędzia, 2013).

Carbonate content

The $CaCO_3$ content in the basal gravelly pavement of the Weischelian Pleniglacial succession in Parchliny A section is only 4.31%, but increases to 18.91% in the overlying silts with organic horizons defined as lithocomplex 1e (Fig. 4, Table 2). This upward change can be attributed to the derivation of $CaCO_3$ from erosion of glacial and Eemian deposits, namely the Wartanian diamictons and fluvioglacial sediments of the Rogowiec Formation (Figs 2, 3A). The primary source of carbonate was the Jurassic limestones exposed to erosion along the Chabielice marginal faults of the Kleszczów Graben (Fig. 3A; Krzyszkowski, 1989, 1991, 1992). An extremely low content of $CaCO_3$ (<0.1%) characterizes the middle and upper parts of the Piaski Formation (Fig. 4, Table 2). These younger fluvio-aeolian sands and sandy silts were deposited in cold climatic conditions, which did not favour carbonate preservation.

AMS measurements

Directions of the main anisotropy axes of magnetic susceptibility (κ_{max}, κ_{int} and κ_{min}) and their mean direction (with a corresponding confidence angle) for the AMS ellipsoid were calculated for the 10 samples taken from the Parchliny A section. These data and related other parameter values are summarized in Figure 8B. For the sake of laboratory measurements, the sampling was limited to the most cohesive, finest-grained deposits.

The κ_{min} directions have high inclination (mean 81.3°), which indicates that the sediments were not deformed after deposition and that the κ_{max} and κ_{int} axes can be expected to lie in an almost horizontal plane (i.e., the primary bedding plane). The stereographic plot of the main axes of the AMS ellipsoids (Fig. 8A) is an equal-area projection in geographic coordinates system, with the confidence angle of each mean direction given as an ellipse. The confidence ellipses for κ_{min} axes are highly elongate (Fig. 8A), with an azimuth trend of 348–168°. This trend is close to the average declination of the κ_{int} axes for the samples (324 ± 13.6°). The spatial imbrication of the κ_{min} axes is a good argument for taking the κ_{int} direction as parallel to that of the depositing current.

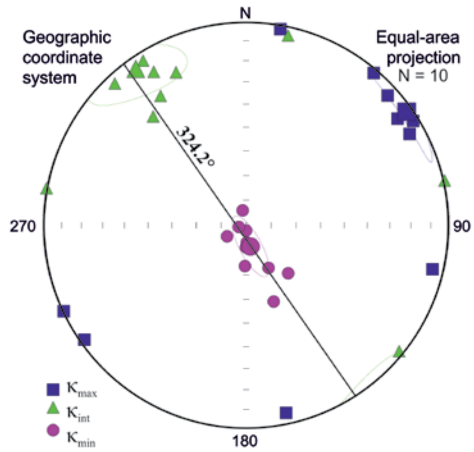
The finest-grained deposits in the Weichselian succession have magnetic susceptibility (κ) in the range of 167.0 to 269.0×10^{-6} SI (average $206.0 \pm 29.5 \times 10^{-6}$ SI), which indicates a high content of ferromagnetic mineral grains. The primary fabric of these deposits indicates "foliation" (planar lamination) better developed than lineation, but the anisotropy parameter P` is high (5.4 to 10.1%, averaging 7.2%; Fig. 8C) and allows a reliable estimation of the directions of the main axes of AMS ellipsoids. The oblate shape of the AMS ellipsoids is related to the positive value of parameter U (Fig. 8D). The mean direction of sediment transport would then appear to be 324 ± 17.6°.

The present-day direction in the Krasówka river in the study area is towards the north (Fig. 1). The river Weichselian palaeochannel, although located more to the east, seems to have had a similar northward trend (see discussion in a subsequent chapter). The estimated mean direction of overbank flow, obliquely away from the channel (Bridge, 2003), would then be consistent with this palaeogeographic scenario.

Palynological data

Most of the 19 samples taken for palynological analysis (Table 1) showed degraded pollen, unsuitable for detailed determination. Only sample 14 from the basal part of lithocomplex 3b in the Parchliny A section (Fig. 4, profile depth 5 m) yielded a relatively well-preserved pollen assemblage (Fig. 9). It is dominated by the tree species *Alnus glutinosa* (21%), *Picea abies* (17%) and *Abies alba* (13%), accompanied by deciduous species *Corylus avellana* (7.5%) and *Carpinus betulus* (8%). Other numerous species are *Pinus sylvestris* (9%) and *Betula pendula* (7%). Subordinate are *Tilia cordata* (1%) and *Quercus* sp. (0.5%), with sporadic *Fraxinus excelsior*, *Larix* sp. and *Salix* sp. Shrub pollen is represented by *Ilex incana* (0.5%). Herb species are mainly grasses (graminoids) Poaceae (4%), with subordinate Cyperaceae (0.5%), *Humulus lupulus* (0.25%) and representatives of the Apiaceae family (0.25%).

A

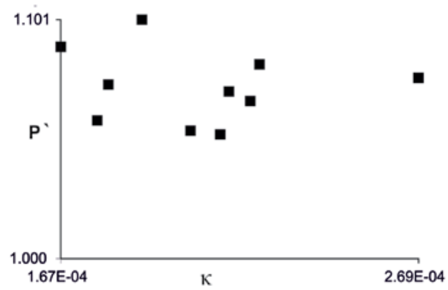


B

Samples no	κ (E-06)	L	F	P`	U	κ_{max} D[°]	κ_{max} I[°]	κ_{int} D[°]	κ_{int} I[°]	κ_{min} D[°]	κ_{min} I[°]
P24	223	1.004	1.069	1.082	0.880	*47.4*	*6.0*	*316.7*	*6.3*	*180.7*	*81.2*
P25	190	1.012	1.079	1.101	0.718	*168.0*	*6.1*	*77.9*	*0.1*	*347.1*	*83.9*
P26	269	1.011	1.059	1.076	0.679	*9.9*	*2.1*	*279.9*	*0.3*	*181.5*	*87.9*
P27	221	1.017	1.047	1.066	0.456	*40.0*	*2.4*	*130.0*	*1.8*	*356.9*	*87.0*
P29	215	1.011	1.054	1.070	0.633	*103.3*	*6.4*	*12.6*	*6.0*	*239.7*	*81.2*
P30	204	1.017	1.035	1.054	0.322	*58.0*	*3.4*	*327.6*	*6.0*	*177.6*	*83.1*
P32	212	1.022	1.029	1.052	0.116	*60.7*	*8.6*	*328.6*	*13.8*	*181.7*	*73.6*
P33	167	1.019	1.064	1.089	0.514	*244.7*	*0.9*	*335.1*	*19.3*	*152.2*	*70.7*
P34	180	1.016	1.053	1.073	0.520	*54.8*	*9.7*	*318.9*	*31.0*	*160.6*	*57.2*
P35	177	1.009	1.045	1.058	0.657	*234.7*	*2.8*	*326.0*	*25.5*	*138.9*	*64.3*
Mean value	**206 ± 29.5**	**1.014**	**1.053**	**1.072**	**0.550**	***54.7*** *c.a.* ***16.5***	***3.5*** *c.a.* ***3.5***	***324.2*** *c.a.* ***17.6***	***7.9*** *c.a.* ***11.5***	***168.2*** *c.a.* ***13.6***	***81.3*** *c.a.* ***4.4***

c.a. – confidence angle

C



D

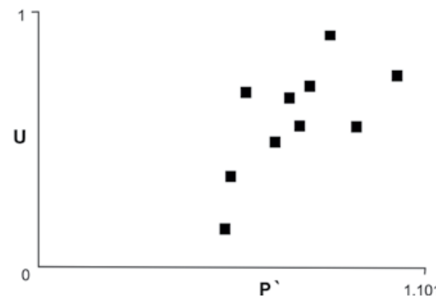


Fig. 8. Review of sample data on the anisotropy of magnetic susceptibility from the outcrop section Parchliny A (Fig. 4). **A.** Spatial distribution of the main axes of AMS ellipsoids; the enlarged symbols indicate mean orientation. **B.** Summary of the numerical values of all main parameters determined on 10 samples. **C.** Relationship between parameter P` and the individual values of magnetic susceptibility κ. **D.** Relationship between parameters U and P`**;** the positive U-values indicate an oblate shape of the AMS ellipsoids. Explanation of symbols: κ – susceptibility per unit volume; κ_{max}, κ_{int} and κ_{min} – the longest, intermediate and shortest AMS axes for each sample; L – magnetic lineation; F – magnetic foliation; P` – corrected anisotropy degree; U – shape parameter (with -1<U< 0 indicating prolate/rod shape and 0<U<1 oblate/disc shape); D – declination; I – inclination. For parameter definitions, see Tarling and Hrouda (1993, pp. 18–19).

The pollen spectrum from this sample (Fig. 9) thus shows a high proportion of trees and indicates a fairly warm climate. The degraded pollen in the other samples (Fig. 4) supports the notion of a weathered and reworked plant material.

Radiocarbon dating

The radiocarbon dates obtained from the outcrop sections Parchliny A (Figs 4, 5A) and Parchliny B (Figs 6, 7B) are reviewed with laboratory details in Table 3.

The lowest sample of plant detritus from the Weichselian succession at the Parchliny A site (sample PARCH1) yielded a date of >45 ka BP. Sample PARCH2 from the uppermost part of lithocomplex 1e gave a date of 47.5 ± 3.5 ka. These two dates imply a minimum age of about 45 ka for the succession's basal lithocomplex 1e (Fig. 4). Sample PARCH3 from the top of lithocomplex 2c yielded a date of 43.5 ± 2 ka (calibrated age 42.8 ka), which should similarly be regarded as a minimum age of the lithocomplex 2/3 boundary (Fig. 4).

At the Parchliny B site (Fig. 6), sample PARCH4 from the lower part of lithocomplex 2c yielded a date of 33.09 ± 0.58 ka, whereas sample PARCH5 from the top part of this lithocomplex gave a date of 24.08 ± 0.25 ka (calibrated age 29.25–28.62 ka). These dates correlate with the Mid-Weichselian Pleniglacial (MIS 3). No radiocarbon dates were obtained from lithocomplex 3 at either site.

The radiocarbon dates, although limited, provide some important constraints for the local palaeogeomorphic development and stratigraphic correlations. The basal lithocomplex 1e of the Piaski Formation in the Parchliny A section (Fig. 4) was deposited before 45 ka BP. Its deposition was followed by marked fluvial erosion with the formation of gravel lag and subsequent deposition of the much thicker and sand-richer lithocomplex 2 (Fig. 4) prior to about 43 ka BP. Lithocomplex 3 in this outcrop section is then younger than the latter date.

In the Parchliny B section (Fig. 6), the basal sandy lithocomplex 2d was deposited before 33 ka BP and the overlying thin silt-sand lithocomplex 2c was formed before about 24 ka BP. Their deposition was terminated by a phase of strong erosion that left a gravel lag and was followed by deposition of the thick (>13 m) and sand-dominated lithocomplex 3 (Fig. 6).

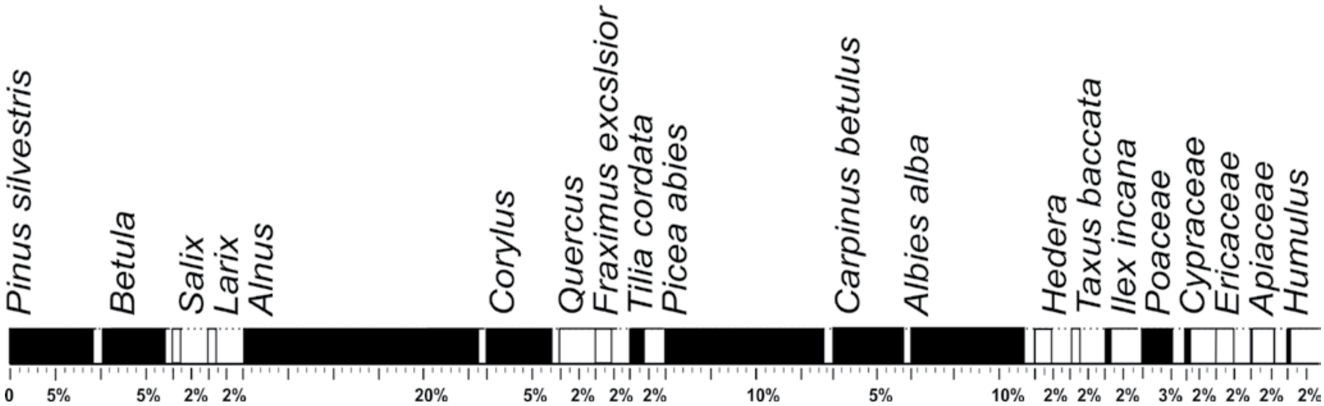


Fig. 9. Pollen diagram from the outcrop section Parchliny A (see samples location in Fig. 4).

It would thus appear that the lithocomplex 2 in Parchliny B section (Fig. 6) is considerably younger than the lithocomplex 2 in Parchliny A section (Fig. 4) and that they thus cannot be regarded as time-equivalents. Similarly, the thick lithocomplex 3 in Parchliny B section (Fig. 6), as a whole, does not seem to match chronostratigraphically the much thinner lithocomplex 3 in Parchliny A section (Fig. 4). The chronostratigraphic and palaeogeomorphic correlation of lithocomplexes is discussed in the next chapter.

DISCUSSION

This chapter first summarizes the main implications of the present study for the Weichselian Pleniglacial conditions of sedimentation in the study area and then discusses the stratigraphy and geomorphic development of the Krasówka palaeovalley as reconstructed in the Szczerców mining field.

The Weichselian sedimentation conditions

The Weichselian regional vegetation cover is broadly considered to have been a moderate-climate grassy tundra with bushes and minor trees (e.g., Balwierz, 1996), but the climate is thought to have been considerably colder during the infilling of the fluvial valleys from 33 to 20 ka BP, with the central Poland turning into a cold arctic desert from 20 to 14 ka BP (Goździk, 1995; Manikowska, 1996). The dry climate then became warmer around 14 to 10 ka BP, when aeolian sands tended to accumulate at the top of sediment-filled valleys (Goździk, 1991, 2007).

The Middle Weichselian Piaski Formation appears to contain pollen and spores from a range of trees and lower plants that are characteristic of a warmer climate, although most of the pollen is strongly degraded. The warm-climate flora contrasts with the evidence of cryoturbation and ice-wedges in the Krasówka palaeovalley (e.g., Turkowska, 1999; Petera, 2002). This intriguing fact may indicate intra-Weichselian climatic fluctuations or be due to a redeposition of Eemian sediments in the Weichselian alluvium.

The Middle Weichselian Pleniglacial (MIS 3) in Central Europe was characterized by a cold climate with tundra vegetation and development of periglacial sedimentary features (Huisink, 2000; Kasse *el al.,* 2003), but was punctuated by several brief warming events, such as the Denekamp, Hengelo and Moershof interstadials (Bos *et al.,* 2001; van

Table 3

Radiocarbon dates obtained from the outcrop sections Parchliny A and B in the Szczerców mining field (for sample details, see Table 1).

Sample label	Depth (m)	Lab. code	Age (^{14}C yrs BP)	Calibrated age (68% range)	Calibrated age (95% range)	Remarks
Profile PARCHLINY A, geographic location: j = 51°14`00``N l = 19°08`12``E						
PARCH1	14.85	GdC-476	> 45 000	—	—	Sample older than ^{14}C 45 ka
PARCH2	14.2	GdS-1127	47 500 ± 3 500	—	—	Out of calibration curve range
PARCH3	5.0	GdS-1128	43 500 ± 2 000	46 757–43 468	42 813	See Figs 4, 5
Profile PARCHLINY B, geographic location: j = 51°13`58.2``N, l = 19°08`50.8``E						
PARCH4	13.6	GdS-1366	33 090 ± 580	38 530–37 080	39 140–36 530	See Figs 6, 7
PARCH5	12.3	GdS-1371	24 080 ± 250	29 250–28 620	29 480–28 370	

Huissteden *et al.,* 2003; Ashkenazy and Tziperman, 2004; Vandenberghe *et al.*, 2004; Ganopolski and Calov, 2011). An erosional sweeping of plant remains might then explain their mixture contrasting with the periglacial features.

On the other hand, there is also a strong evidence of the redeposition of Eemian substrate sediments in the Weichselian periglacial conditions (e.g., see Vandenberghe, 1999; Vandenberghe *et al.,* 2004). The heavy-mineral data in the present case indicate local-scale fluvial erosional reworking of little-mature older sediments. The degraded pollen flora supports the notion of a weathered sediment reworking. Likewise, the sand-grain roundness and surface morphoscopic characteristics clearly indicate the fluvial system strong propensity for reworking even contemporaneous aeolian deposits (Goździk, 1991; Wachecka-Kotkowska, 2004).

Development of the Krasówka palaeovalley

The Parchliny outcrop sections (Fig. 3) revealed only the western flank of the Krasówka palaeovalley, onlapped by the river overbank deposits (Figs 4, 6), which means that the river channel throughout most of the Weichselian Pleniglacial was located to the east of the study area and trending northwards. The overbank deposits show transport direction towards 324° (± 17.6°), which is consistent with the inferred channel location and spatial trend (cf. Bridge, 2004). The eastern margin of the palaeovalley is recognizable as an incompletely buried topographic escarpment of a glacial plateau, standing at nearly 10 m above the mining field's top land surface. On this basis, the hypothetical location and spatial orientation of the river palaeovalley in the Szczerców field has been reconstructed (Fig. 10A).

The Weichselian Pleniglacial lithofacies of the Krasówka palaeovalley resemble those of the Widawka tributary palaeovalleys in the adjacent Bełchatów field, particularly of the Świętojanka valley (Krzyszkowski, 1990, 1991, 1992; Kasse *et al.,* 1998). Therefore, the lithocomplexes distinguished in the Parchliny sections were tentatively labelled with numbers (Figs 4, 6) in analogy to those in the Bełchatów field. However, their lateral correlation between the Parchliny sections A and B remained unclear (Fig. 10B, upper diagram). Any of the three gravel-lag horizons in Parchliny A section could theoretically be correlated with the gravel pavement in Parchliny B section. The radiocarbon dates have shed an important light on the chronostratigraphy of the lithocomplexes, allowing the following four main depositional stages to be distinguished in the geomorphic history of the Krasówka palaeovalley (Fig. 10B, lower diagram). They are described below.

Stage 1 – Accumulation of the latest Eemian to early Vistulian (≥45 ka) deposits occurred in a local topographic depression by overland sheetflow processes (lithocomplex 1 in Parchliny A section, Fig. 4). The formation of such enclosed or semi-enclosed depressions in the Wartanian (Saalian) time was structurally facilitated by the Chabielice fault zone and was due to karstic or thermokarstic processes (Goździk and Skórzak, 2011), with the sedimentation driven by rain-wash and probably snowmelt water flow.

Stage 2 – The Krasówka river formed to the east and shifted farther eastwards, but then approached twice the study area with a net aggradation prior to 43 ka BP – flooding the area with overbank deposits (lithocomplex 2 in Parchliny A section, Fig. 4). The river had subsequently incised by nearly 20 m. This erosion event correlates with the marked incision of the Widawka river tributaries in the adjacent Bełchatów field around 40 ka BP, with the early infilling of their valleys dated to 33.9 ka in the lower reaches and to 32.6 ka in the middle reaches (Manikowska, 1992, 1996). A similar behaviour characterized virtually all rivers in the central Poland (Goździk and Zieliński, 1996).

Stage 3 – The Krasówka river began to fill in its valley by aggradation (lithocomplex 2 in Parchliny B section, Fig. 6) while migrating eastwards and probably shrinking, as the river flooding capacity markedly declined from 33 to 24 ka BP. The fluvial valley-filling process in the Bełchatów field is similarly considered to have commenced around 34 ka BP (Goździk, 1995; Manikowska, 1996).

Stage 4 – The Krasówka river system became rejuvenated after 24 ka BP and kept filling its valley by aggradation while flooding the valley flank (lithocomplex 3 in Parchliny B section, Fig. 6). Some initial erosion probably occurred, as indicated by the gravel pavement at the base of lithocomplex 3 (Fig. 6) and a regional incision of rivers around 21 ka BP, but strong aggradation subsequently prevailed, evidenced also from other river palaeovalleys in the central and south-western Poland (Turkowska, 1988; Petera, 2002; Wachecka-Kotkowska, 2004; Forysiak, 2005; Krzyszkowski and Kuszell, 2007). The Krasówka river after filling its valley continued to aggrade, but once the Widawka river had regulated its profile and ceased to aggrade – also the vertical accommodation for the Krasówka tributary began to decrease rapidly, whereby this river channel migrated westwards seeking lateral accommodation (Fig. 10B, lower diagram). The fluvial activity at the late stage 4 was increasingly accompanied by aeolian sedimentation.

The Weichselian Pleniglacial came to an end around 14.5 ka BP. The Krasówka river subsequently re-incised by nearly 5 m and assumed its present-day altitude (Fig. 10B, upper diagram), apparently in response to the post-glacial regional isostatic rebound of the crustal basement.

CONCLUSIONS

The present study from the new Szczerców field of the Bełchatów open-cast mining complex, central Poland, revealed the local geomorphic and stratigraphic history of the Krasówka river palaeovalley – a main western tributary of the river Widawka. The outcrop data are from the western flank of the palaeovalley. Radiocarbon dates have been of crucial importance for the reconstruction of the palaeovalley history.

The Weichselian Pleniglacial sedimentation in the study area commenced with the accumulation of the latest Eemian to earliest Weichselian (≥45 ka) deposits by overland sheetwash processes in a local karstic topographic depression. The Krasówka river then formed to the east and shifted farther eastwards, but later approached twice the study area with a net aggradation prior to 43 ka BP – flooding the area with overbank deposits.

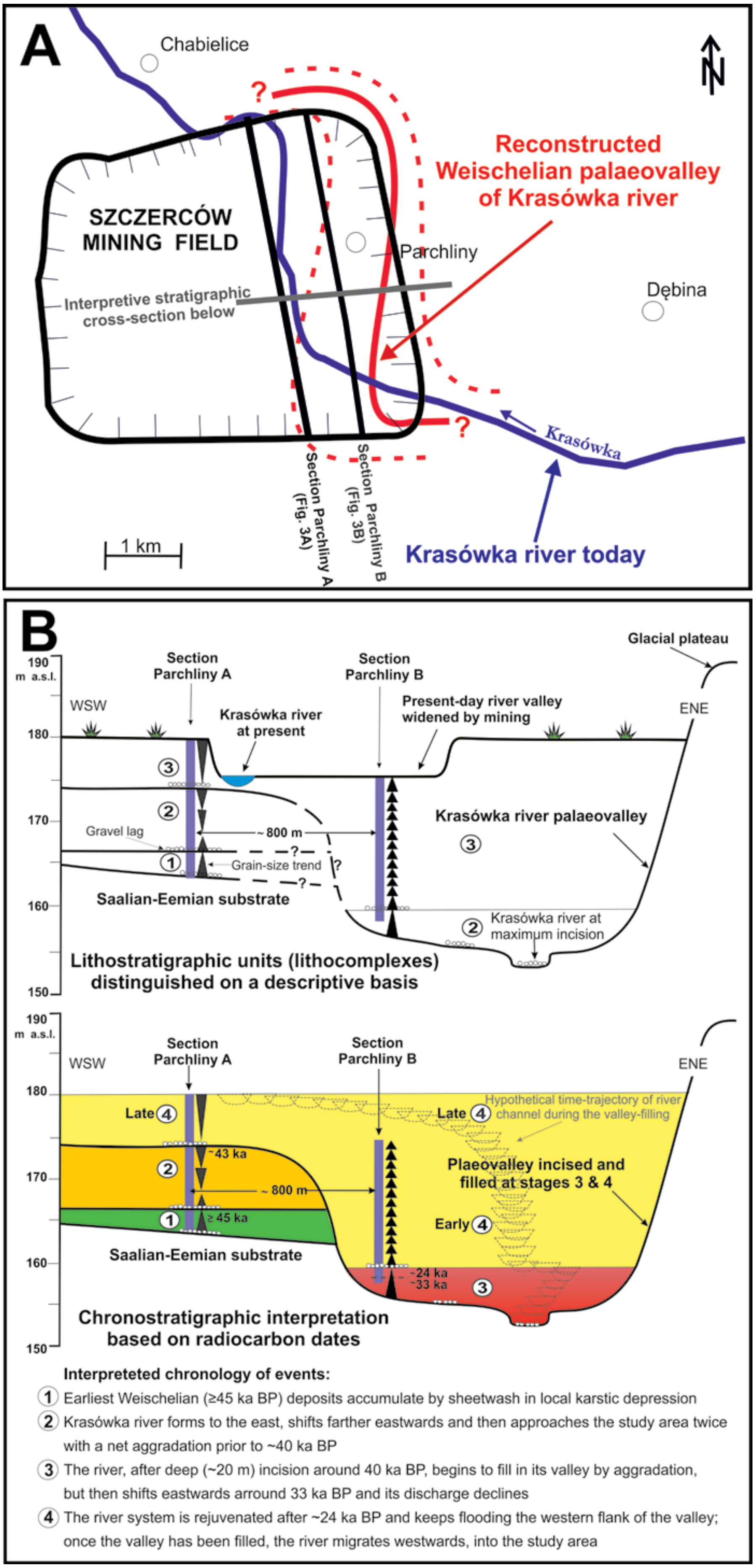


Fig. 10. Geomorphic history of the Krasówka palaeovalley. **A.** Hypothetical reconstruction of the Weichselian palaeovalley of Krasówka river in the Szczerców mining field (for discussion, see text). **B.** A west–east cross-section through the study area showing the descriptively distinguished lithocomplexes (upper diagram) and their chronostratigraphic interpretation based on ^{14}C dates (lower diagram); for further discussion, see text.

The Krasówka river subsequently incised by nearly 20 m around 40 ka BP and began to fill in its valley by aggradation around 35 ka BP, while migrating eastwards and markedly decreasing its flooding capacity from 33 to 24 ka BP.

The river system was rejuvenated around 21 ka BP with initial erosion and kept filling its valley by aggradation while flooding the valley flank. The river after filling its valley continued to aggrade, but gradually began to run out ran of vertical accommodation and migrated westwards. The fluvial activity at this stage was increasingly accompanied by aeolian sedimentation.

Once the Middle Weichselian Pleniglacial came to an end around 14.5 ka BP, the Krasówka river had re-incised by nearly 5 m and formed its present-day valley in response to the post-glacial regional isostatic uplift.

Acknowledgements

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REFERENCES

Allen, J. R. L., 1982. *Sedimentary Structures: Their Character and Physical Basis*. *Developments in Sedimentology*, 30. Elsevier, Amsterdam, 1256 pp.

Allen, P. & Krzyszkowski, D., 2008. Till base deformation and fabric variation in Lower Rogowiec (Wartanian, Younger Saalian) Till, Bełchatów outcrop, central Poland. *Annales Societatis Geologorum Poloniae,* 78: 19–35.

Ashkenazy, Y. & Tziperman, E., 2004. Are the 41 kyr glacial oscillations a linear response to Milankovitch forcing? *Quaternary Science Reviews,* 23: 1879–1890.

Balwierz, Z.,1996. Vegetation of Upper Vistulian cold phases in Central Poland. *Biuletyn Peryglacjalny*, 34: 21–36.

Bateman, R. M. & Catt, J. A., 2007. Provenance and palaeoenvironmental interpretation of superficial deposits, with particular reference to postdepositional modification of heavy mineral assemblages. In*:* Mange, M. A. & Wright, D. T. (eds), *Heavy Minerals in Use. Developments in Sedimentology,* 58. Elsevier, Amsterdam, pp. 151–188.

Bos, J. A. A., Bohncke, S. J. P., Kasse, C. & Vandenberghe, J., 2001. Vegetation and climate during Weichselian Early Glacial and Pleniglacial in the Niederlausitz, eastern Germany – macrofossils and pollen evidence. *Journal of Quaternary Science*,16: 269–289.

Bridge, J. S., 2003. *Rivers and Floodplains: Forms, Processes, and Sedimentary Record*. Blackwell Publishing, Malden, 491 pp.

Bridgland, D. R., 2000. River terrace systems in north-west Europe an archive of environmental change, uplift, and early human occupation. *Quaternary Science Reviews*, 19: 1293–1303.

Bridgland, D. R. & Westaway, R., 2012. The use of fluvial archives in reconstructing lanscape evolution: the value of sedimentary and morphostratigraphical evidence. Netherlands Journal of Geosciences. *Geologie en Mijnbouw*, 91: 5–24.

Cailleux, A., 1942. Les action éoliennes periglaciares en Europe. *Mémoires de la Société Géologique de France*, 46, 1–176.

Chappell, J. & Shackleton, N. J., 1996. Oxygen isotope and sea level. *Nature*, 324: 137–140.

Cordier, S., Harmand, D., Losson, B. & Beiner, M., 2004. Alluviation in the Meurthe and Moselle valleys (Eastern Paris Basin, France): Lithological contribution to the study of the Moselle capture and Pleistocene climatic fluctuations. *Quaternaire*, 15: 65–76.

Folk, R. L., 1980. *Petrology of Sedimentary Rocks*. Hemphill, Austin (Texas), 184 pp.

Folk, R. L. & Ward, W. C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology*, 27: 3–26.

Forysiak, J., 2005. Development of the Warta Valley between Burzenin and Dobrów after the Wartanian glaciation. *Acta Geographica Lodziensia*, 90, 160 pp. [In Polish, with English summary.]

Ganopolski, A. & Calov, R., 2011. The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles. *Climate of the Past*, 7: 1415–1425.

Goździk, J. S., 1991. Sedimentological record of aeolian processes from the upper Pleni-vistulian at the turn of Pleni- and Late Vistulian in central Poland. *Zeitschrift für Geomorphologie, Supplementbände*, 90: 51–60.

Goździk, J. S., 1995. Vistulian sediments in the Bełchatów open cast mine, Central Poland. *Quaternary Studies in Poland,* 13: 13–23.

Goździk, J. S., 2007. The Vistulian aeolian succession in central Poland. *Sedimentary Geology*, 193: 211–220.

Goździk, J. S. & Balwierz, Z., 1994. Kuców. Upper units of the Wartian complex, the Eemian and Vistulian sediments. In: *Excursion Guidebook, INQUA SEQS Symposium The Cold Warta Stage: Lithology, Paleogeography, Stratigraphy, Łódź, 11–5 October 1994*. University of Łódź, Łódź, pp. 45–48.

Goździk, J. S. & Zieliński T., 1996. Sedimentology of the Weichselian deposits in the small valleys in Central Poland – examples from Bełchatów. *Biuletyn Państwowego Instytutu Geologicznego* 373: 67–77. [In Polish, with English summary.]

Goździk, J. S. & Skórzak, A., 2011. Zmienność akumulacji jeziorno-bagiennej od interglacjału do holocenu w obszarze odkrywki Bełchatów. In: *Warsztaty Naukowe Torfowiska dorzecza Widawki, Łódź, 1–3 czerwca 2011*. Wydawnictwo Uniwersytetu Łódzkiego, Łódź, pp. 19–32. [In Polish.]

Huisink, M., 2000. Changing river styles in response to Weichselian climate changes in the Vecht valley, eastern Netherlands. *Sedimentary Geology*, 133: 115–134.

Huissteden van, K., Vandenberhe, J. & Pollard, D., 2003. Palaeotemperature reconstructions of the European permafrost zone during marine oxygen isotope Stage 3 compared with climate model results. *Journal of Quaternary Science*, 18: 453–464.

Kasse, C., Huijzer, A. S., Krzyszkowski, D., Bohncke, S. J. P. & Coope, G. R., 1998. Weichselian Late Pleniglacial and Late-glacial depositional environments, Coleoptera and periglacial climatic records from central Poland (Bełchatów). *Journal of Quaternary Science*, 13: 455–469.

Kasse, C., Vandenberghe, J., Van Huisstenden, J., Bohncke, S. J. P. & Bos, J. A. A., 2003. Sensitivity of Weichselian fluvial systems to climate change (Nochten mine, eastern Germany). *Quaternary Science Reviews*, 22: 2141–2156.

Krzyszkowski, D., 1989. The tectonic deformation of Quaternary deposits within the Kleszczów Graben, central Poland. *Tectonophysics* 163: 285–287.

Krzyszkowski, D., 1990. Middle and Late Weichselian stratigraphy and palaeoenvironments in central Poland. *Boreas*, 19: 333–350.

Krzyszkowski, D., 1991. Vistulian fluviatile sedimentation near Bełchatów, central Poland. *Bulletin of the Polish Academy of Sciences, Earth Science*, 39: 311–329.

Krzyszkowski, D., 1992. Quaternary of the Kleszczów Graben, lithostratigraphy and tectonics. Some problems on the basis of investigations of the Bełchatów Open Cast Mine. *Acta Universitatis Wratislaviensis* 1252, *Studia Geograficzne* 54, 158 pp. [In Polish, with English summary.]

Krzyszkowski, D., 1996. Climatic control on Quaternary fluvial sedimentation in the Kleszczów Graben, central Poland. *Quaternary Science Reviews*, 15: 315–333.

Krzyszkowski, D., 1998. Stratigraphy and sedimentology of Weichselian deposits at Folwark, Bełchatów Outcrop, Central Poland. *Quaternary Studies in Poland*, 15: 3–25.

Krzyszkowski, D. & Kuszell, T., 2007. Middle and Upper Weichselian Pleniglacial fluvial erosion and sedimentation phases in southwestern Poland, and their relationship to Scandinavian ice-sheet built-up and retreat. *Annales Societatis Geologorum Poloniae*, 77: 17–38.

Kuydowicz-Turkowska, K., 1975. Rzeczne procesy peryglacjalne na tle morfogenezy doliny Mrogi. *Acta Geographica Lodziensia,* 36: 1–122. [In Polish, with English summary.]

Maddy, D., Bridgland, D. R. & Westaway, R., 2001. Uplift-driven valley incision and climate-controlled river terrace development in the Thames Valley, UK. *Quaternary International*, 79: 23–36.

McKee, E. D., Crosby, E. J. & Berryhill, H. L., Jr., 1967. Flood deposits, Bijou Creek, Colorado, June 1965. *Journal of Sedimentary Petrology*, 35: 829–851.

Manikowska B., 1992. Ewolucja suchych dolin na terenie kopalni Bełchatów w plenivistulianie. *Acta Universitas Lodziensia, Folia Geographica*, 15: 115–130.

Manikowska, B., 1996. Dwucykliczność ewolucji środowiska peryglacjalnego w Polsce środkowej podczas vistulianu. *Biuletyn Państwowego Instytutu Geologicznego* 373: 97–106. [In Polish, with English summary.]

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

Petera, J., 2002. Vistulian valley deposits in the Uniejów Basin and its palaeogeography. *Acta Geographica Lodziensia* 83: 174 pp. [In Polish, with English summary.]

Racinowski, R., 2010. Main transparent heavy minerals in Quaternary deposits of Poland. *Biuletyn Państwowego Instytutu Geologicznego*, 438: 99–106. [In Polish, with English summary.]

Sarala, P. & Eskola, T., 2011. Middle Weichselian interstadial deposit at Petäjäselkä, Northern Finland. *Quaternary Science Journal,* 60: 488–492.

Shumway, J. R. & Iverson, N. R., 2009. Magnetic fabrics of the Douglas Till of the Superior lobe: exploring bed-deformation kinematics. *Quaternary Science Reviews*, 28: 107–119.

Tarling, D. H. & Hrouda, F., 1993. *The Magnetic Anisotropy of Rocks*. Chapman and Hall, London, 257 pp.

Tucker, M. E., 1996. *Sedimentary Rocks in the Field*. 2nd ed., Wiley, Chichester, 275 pp.

Turkowska, K., 1988. Development of the river valleys in the Late Quaternary on the Łódź Upland. *Acta Geographica Lodziensia*, 57: 1–157. [In Polish, with English summary.]

Turkowska, K., 1999. Some reflections on the Łódź contribution to periglacial research and evaluation criteria of periglacial morphogeny in the middle Poland. *Biuletyn Peryglacjalny*, 38: 43–61.

Vandenberghe, J., 1999. Periglacial research: jumping between process and environment. *Biuletyn Peryglacjalny*, 38: 27–36.

Vandenberghe, J., 2002. The relation between climate and river processes, landforms and deposits during Quaternary. *Quaternary International*, 91: 17–23.

Vandenberghe, J., 2003. Climate forcing of fluvial system development: an evolution of ideas. *Quaternary Science Reviews*, 22: 2053–2060.

Vandenberghe, J., Lowe, J., Coope, R., Litt, T. & Zöller, L., 2004. Climatic and environmental variability in the mid-latitude Europe sector during last interglacial-glacial cycle. In: Battarbee, R., Gasse, F. & Stickley, C. (eds), *Past Climate Variability through Europe and Africa*. Springer, Dordrecht, pp. 394–416.

Vandenberghe, J. & Maddy, D., 2001. The response of river system to climate change. *Quaternary International*, 79: 1–3.

Wachecka-Kotkowska, L., 2004. Evolution of the Luciąża river valley – local and climatic conditions. *Acta Geographica Lodziensia*, 86: 1–161 pp. [In Polish, with English summary.]

Wachecka-Kotkowska, L. & Ludwikowska-Kędzia, M., 2013. Spectrum of heavy minerals in the Vistulian Pleniglacial sediments in the fluvial levels in the Luciąża and Belnianka river valleys, Central Poland – a comparative study. *Geologos*, 19: 131–146.

Wohlfarth, B., 2009. *Ice-free Conditions in Fennoscandia during Marine Oxygen Isotope Stage 3?* Department of Geology and Geochemistry, Stockholm University, Technical Report, TR-09-12, 48 pp.

Zagwijn, W. H. & Paepe, R., 1968. Die Stratigraphie der weichselzeitlichen Ablagerungen der Niederlnade und Belgiens. *Eiszeitalterbund Gengenwart*, 19: 129–146.

Zieliński T., 1995. Lithofacies and genetic codes: construction and application. In: Mycielska-Dowgiałło, E. & Rutkowski, J. (eds), *Research into the Textural Features of Quaternary Sediments and Some Dating Methods.* Wydawnictwo Uniwersytetu Warszawskiego, Warszawa, pp. 220–235. [In Polish, with English summary.]

Zieliński, T. & Pisarska-Jamroży, M., 2012. Which features of deposits should be included in code and which not? *Przegląd Geologiczny*, 60: 387–397. [In Polish, English summary.]