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Fluvial processes under late Pleni-Weichselian environmental conditions: a case study from the Warenka site in central Poland

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Abstract

Strong aggradational tendencies during the late Pleni-Weichselian have been noted in river valleys in central Europe. Thick series of mineral deposits were laid down, but also organic or mineral-organic horizons were formed under favourable conditions. The study area is located in the central section of the valley of the River Warta within an extraglacial area of the last glaciation. At the Warenka site alluvia, that attain thicknesses of 16 m, were analysed. Lithofacies analysis, OSL dating of mineral sediments and radiocarbon dating of organic and mineral-organic strata were performed. Organic and mineral-organic deposits were also subjected to pollen and Cladocera analyses. Together this set of analyses was used to determine fluvial processes and environmental conditions during the late Pleni-Weichselian. The results obtained allow the conclusion that these levels were deposited in the sedimentary environment of a low-energy, sand-bed braided river, which operated in the period from approximately 30 to 24 cal kBP – the late Pleni-Weichselian. During this time, there were periods when shallow water bodies were formed on the valley bottom, where deposition of organic material was possible. The presence of this type of sediment made it possible to reconstruct the vegetation cover; this had the character of a steppe-tundra, periodically shrubby steppe-tundra. Short-lived reservoirs were characterised by shallow-water settings with weakly developed vegetation and temporary influence of floodwaters as indicated by changes in cladoceran assemblages. Pollen spectra, low concentration of cladocerans, as well as the presence of the cold-tolerant Cladocera taxa are indicative of cold climatic conditions.

Keywords: sand-bed braided river, pollen analysis, Cladocera analysis, OSL and ^{14}C dating, palaeoenvironmental reconstruction, Warta River valley

1. Introduction

The response of fluvial systems to climate change was clearly visible during the glacial-interglacial transition (e.g., Turkowska, 1988; Kasse et al., 1995; Kaiser et al., 2012), but also changes on a smaller scale – such as those occurring during the Pleni-Weichselian – are expressed in the functioning of river valleys (e.g., Krzyszkowski, 1990; Petera, 2002; Kasse et al., 2003; Busschers et al., 2005). In response to climate fluctuations there were phases of erosion, accumulation or stabilisation of fluvial systems (e.g., Turkowska, 1988; Busschers et al., 2005; Kaiser et al., 2012; Starkel et al., 2015), changes in river regimes (Kasse, 1998) or changes of channel pattern (e.g., Turkowska, 1988; Krzyszkowski, 1990; Van Huissteden, 1990; Gębica, 1995; Mol, 1995; Kasse, 1998; Zieliński, 2007).

During the Pleni-Weichselian, a phase of intense erosion, dated between 40 and 35 kBP (Turkowska, 1988; Van Huissteden & Kasse, 2001; Petera, 2002; Van Huissteden et al., 2003), was followed by intense aggradation, commonly recorded from mid-latitude extraglacial river valleys in Europe, usually lasting until the end of the time interval indicated (e.g.,Turkowska, 1988; Eissmann, 2002; Kasse et al., 2003; Zieliński, 2007; Starkel et al., 2015). Under favourable conditions organic or mineral-organic horizons developed. These constitute an important source of information enriching our knowledge of the overall conditions of functioning of fluvial systems during the Pleni-Weichselian (e.g., Krzyszkowski, 1990; Van Huissteden, 1990; Kasse et al., 1998; Petera, 2002; Kasse et al., 2003; Engels et al., 2008).

The aim of the present research was to reconstruct how the fluvial sedimentary environment functioned under the severe conditions of the late Pleni-Weichselian based on the example of the Warenka site in central Poland and by checking whether or not organic or mineral-organic sediments preserved in alluvium may provide information on other elements of the palaeoenvironment. For this reason, we provide pollen and Cladocera (water fleas) analyses, because these methods have been successfully used in palaeoenvironmental and palaeohydrological reconstructions of river valleys (Dzieduszyńska et al., 2014; Kittel et al., 2016, 2021; Pawłowski, 2017).

2. Outline of regional setting

The study area is located in the Central Poland Lowlands, within the middle, meridional course of the River Warta – the largest tributary of the River Odra. The valley of the River Warta in the study area runs within the zone of the Adamów Graben (Widera, 1998; Widera et al., 2022). During the last glaciation, this area remained in the extraglacial zone (Fig. 1A). The line of maximum extent was marked by the limit of the Poznań phase (Stankowski, 1982).

The River Warta valley cuts into plains formed during the Saalian glaciation, widening significantly in the study section where it joined the Warsaw–Berlin ice-marginal valley. During the Weichselian, two terraces were formed, i.e., the Pleni-Weichselian high terrace and the late Weichselian low terrace (Fig. 1B). Longitudinal profiles of terraces show an inclination from the south to the north (Forysiak, 2005).

3. Material and methods

Two locations were selected for detailed analysis at the Warenka site, situated on the high terrace of the River Warta valley (Fig. 1B). Access to the entire section of Weichselian strata was possible on quarry faces at the Adamów lignite opencast mine, closed in 2021 (Widera et al., 2022). At both sites, two sections were analysed: in one, lithofacies analysis was carried out directly in the field, and in the other, material for laboratory analysis was collected from organic and mineral-organic sediments (Fig. 2; Table 1). This procedure was opted for in order to select proper places for the use of individual methods, e.g., collecting material for palaeobiological analysis from undisturbed layers.

Features of sedimentary environment and process dynamics were determined on the basis of textural and structural properties of deposits. Lithofacies analysis was carried out following the Miall (1978) code, as modified by Zieliński (2014). The lithofacies recognised were grouped into lithofacies associations, which have a considerable lateral extent.

Five samples of mineral material taken from the A-4′ section were dated using the optically stimulated luminescence (OSL) method. Age determination was performed in the Gliwice Luminescence Laboratory (Poland) according to the procedure outlined by Moska et al. (2021). Dating results according to laboratory recommendation are given in years before 1950 (marked as BP – before present). Six samples of bulk material collected from organic or mineral-organic horizons were analysed using the radiocarbon method AMS technique: three analyses were conducted in the Gliwice Radiocarbon Laboratory, Poland (Piotrowska, 2013), and three in the Laboratory of Absolute Dating in Skała, Poland. Radiocarbon ages were recalculated with the IntCal 20 calibration curve (Reimer et al., 2020) using OxCal v4.4.4. software (Bronk Ramsey, 2009).

The pollen analyses covered 11 samples from the A-1 section (depth 6.20–6.00 m) and 13 samples from the A-4 section (depth 5.20–4.96 m). Material was prepared according to standard maceration procedures (Berglund & Ralska-Jasiewiczowa, 1986) using the Erdtman acetolysis method (Faegri & Iversen, 1975). Pollen grains of individual taxa were counted in the prepared samples using an optical microscope Optek Labor Digital Infinity 3MP, with 400x optical magnification. For samples from the A-1 section, at least 500 pollen grains of trees, shrubs and herbaceous plants (AP+NAP) were

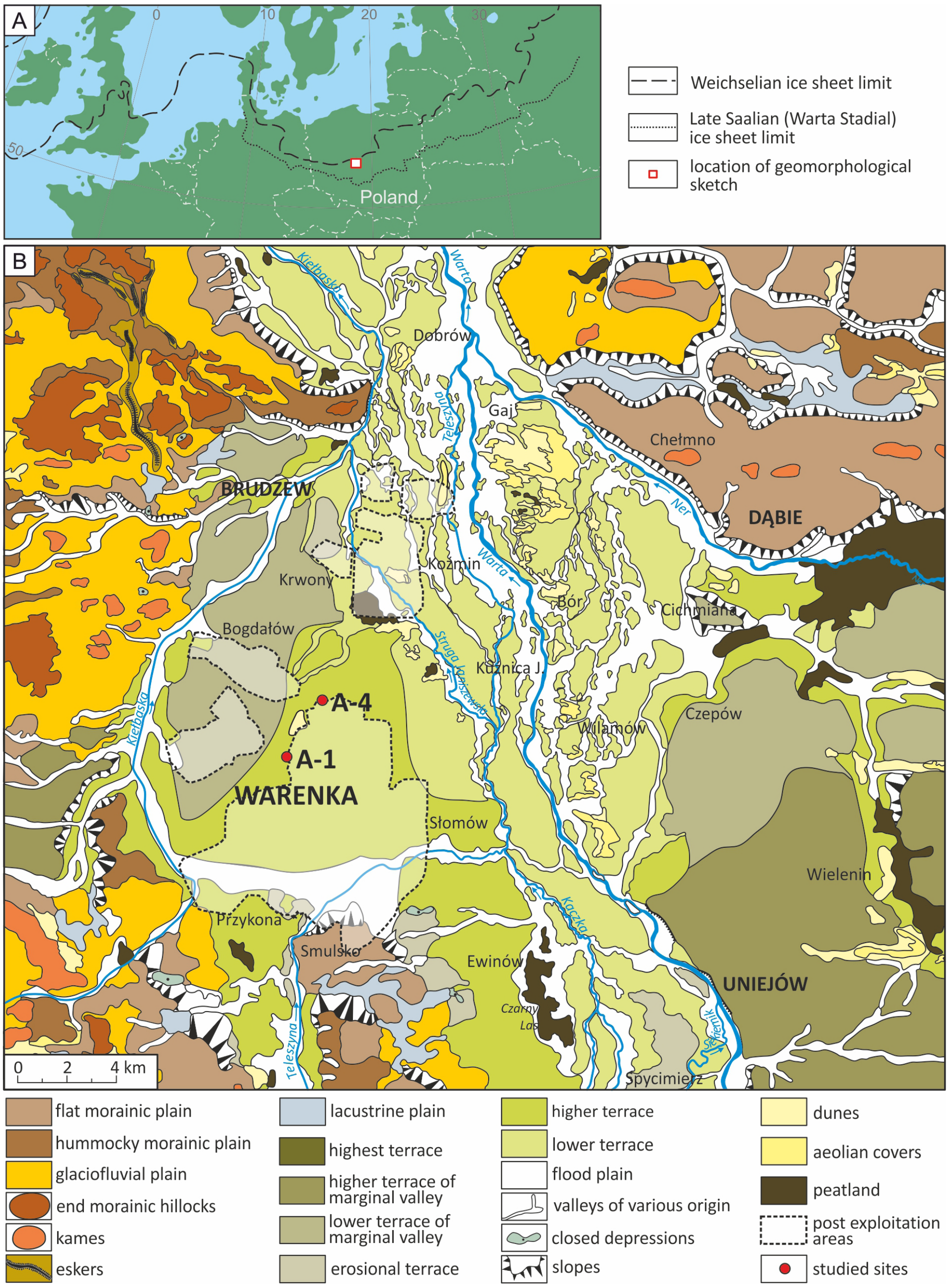

Fig. 1. Study area. **A** – Selected glacial limits (after Marks et al., 2018; Palacios et al., 2023); **B** – Geomorphological sketch (modified from Forysiak, 2005).

counted. The pollen material from the A-4 section was significantly degraded, and the frequency of pollen grains was very low, which is why less than 300 pollen grains were counted in each sample. Pollen diagrams were prepared using the POLPAL software (Nalepka & Walanus, 2003).

Analysis of subfossil Cladocera was done in sediment layers of the A-1 (10 samples; depth 6.19–6.01 m) and A-4 sections (16 samples; depth 5.22–4.91 m) at 2-cm-intervals. Each sample of 1 cm^3 of deposit was processed according to standard procedure (Frey, 1986). The residue was washed, sieved and finally coloured with safranine dye before counting. A solution of 0.1 ml was used for each microscope slide. All Cladocera remains (e.g., head shield, shell, postabdomen, claw, ephippium) were counted and percentage frequency of species are presented using POLPAL software (Nalepka & Walanus, 2003). The taxonomy of cladoceran remains in the present paper follows that presented by Szeroczyńska & Sar-

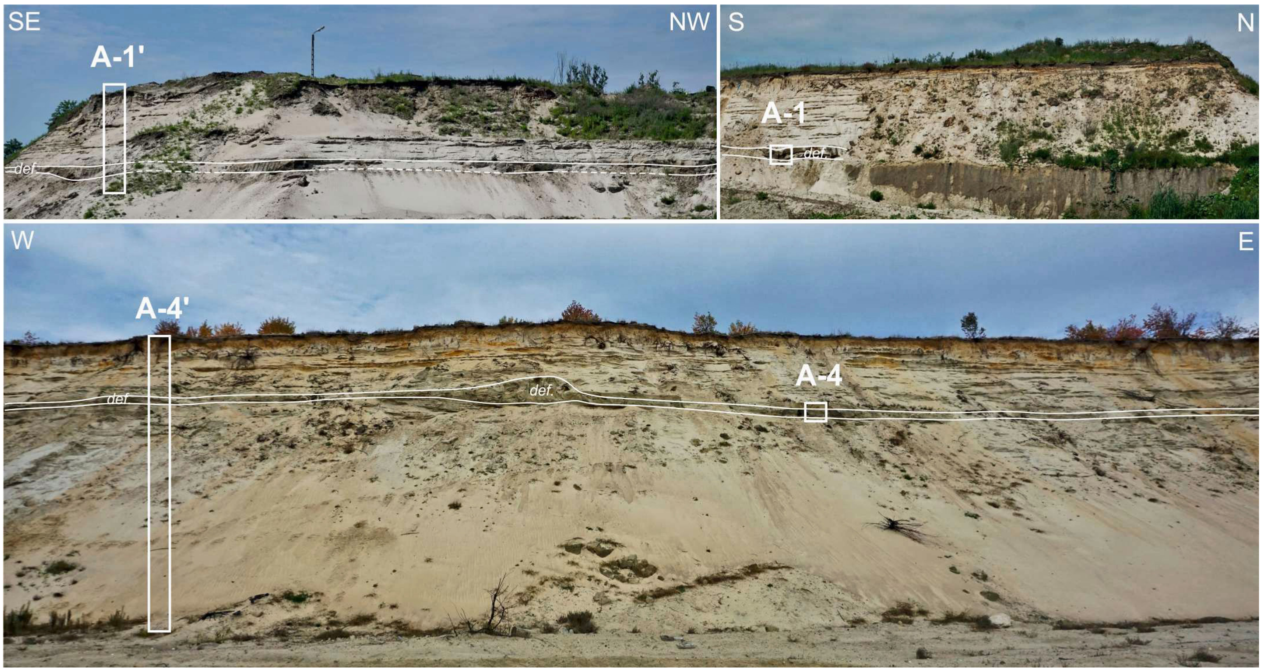

Fig. 2. Localities of sections studied on excavation faces, white lines showing the extent of mineral-organic series, in places intensely deformed (photographs by J. Petera-Zganiacz, 2018, 2019).

Table 1. Basic information on sections studied.

Profile symbol	Geographical coordinates	Altitude	Type of analysis
A-1	52°01′53.6′′N; 18°36′39.5′′E	106 m a.s.l.	Pollen analysis, Cladocera analysis, Radiocarbon dating
A-1′	52°01′50.4′′N; 18°36′42.7′′E	106 m a.s.l.	Lithofacial analysis
A-4	52°02′47.2′′N; 18°37′42.7′′E	105 m a.s.l.	Pollen analysis, Cladocera analysis, Radiocarbon dating
A-4′	52°02′46.7′′N; 18°37′38.6′′E	105 m a.s.l.	Lithofacial analysis, OSL dating, Radiocarbon dating

maja-Korjonen (2007), Van Damme et al. (2010) and Faustová et al. (2011). Classification of Cladocera habitat preferences is indicated following Flössner (1972, 2000), Bjerring et al. (2009) and Błędzki & Rybak (2016).

4. Results

The alluvia observed in the westerly face of the outcrop in the part where sections A-1 and A-1′ were documented rest on glacial till and are approximately 7 m thick. Towards the north, their thickness increases to almost 16 m (15.5 m in the A-4′ section) and glaciofluvial sands with gravels, as well as glaciolacustrine deposits, occur in the substrate.

4.1. Lithofacies analyses

4.1.1. Sections A-4′and A-4

The lower part of section A-4′ is dominated by sands of various fractions and structural features (Fig. 3). This set of lithofacies (I) is crowned by a mineral-organic horizon, the top of which has been washed away. Radiocarbon dating yielded 25,460±200 BP (Table 2). Another set of lithofacies (II) formed in higher-energy flow conditions and comprises sands with gravels, which change into medium-grained sands planar or low-angle cross-stratified (SGp, Sp, Sl). The gap in the section resulting from an inability to collect data makes it impossible to determine whether the sediments lying above are a continuation of the set of lithofacies or whether it is part of another association. Above the gap, horizontally stratified sands (Sh) dominate (III), the age of which was determined by the OSL method at 29,300±2,000 BP (Table 2). The next set of lithofacies (IV) consists of mainly fine-grained sands horizontally (Sh) or planar cross-stratified (Sp), alternating with lithofacies of sands ripple cross-laminated (Sr). Above, sediment structure changes noticeably. On an approximately metre-long section of the profile (V) there are medium- and coarse-grained sands trough cross-stratified (St). In the next set of lithofacies (VI), the textural features do not change, while the structural features are characterised by the predominance of horizontal stratification (Sh) and planar cross-stratification (Sp). For these sediments, an age of 17,400±1,400 BP was obtained using the OSL method (Table 2). The next set (VII) consists of sandy lithofacies of small thickness, with alternating trough and horizontal stratification, as well as ripple cross-lamination (St, Sh, Sr). The surface developed as a result of slight erosion highlights the transition to the next lithofacies complex (VIII), which begins with trough cross-stratified sands (St). In the bottom part of these deposits, the age determined by the OSL method is 26,700±1,700 BP. Towards the top the sediments changed into finer sands with horizontal and ripple lamination, which are covered with a layer of massive silt containing organic matter. These sediments constitute a continuous horizon observed over several hundred metres, and in some places they are subject to involution-like deformations.

In section A-4 (Fig. 3), which was selected in view of the undisturbed condition of the sediment, material was collected for palaeobiological analyses and age determination using the ^{14}C method. The following dating results were obtained: 19,480±120 BP for the base and 22,370±150 BP for the top of the layer (Table 2). The next set of lithofacies in section A-4′ (IX) is dominated by horizontally stratified sands of various gradations (Sh), the age of which was determined by the OSL method at 24,900±1,500 BP (Table 2). Above (set of lithofacies X), sediments formed that illustrate a high variability of depositional conditions, ranging from lithofacies of coarse sands trough or planar cross-stratified (St), through ripple lamination (Sr), to flaser lamination in silty sand (SFf). For sediments from a depth of 0.65 m, the OSL method obtained an age of 24,100±1,600 BP (Table 2).

4.1.2. Profile A-1 and A-1′

In section A-1 (Fig. 3), on the glacial till lies lithofacies (II) of sand trough cross-stratified and horizontally stratified (St, Sh). Above, there is a horizon in which organic and mineral-organic levels are represented by an approximately 20 cm layer of peat covered with lithofacies of horizontally laminated sands and silts (III). These pass upwards into a lithofacies with a greater share of finer fractions and organic matter. For the base and top of the peat layer, the following radiocarbon dates were obtained: 22,540±210 BP and 23,170±230 BP, respectively, and for the layer of mineral-organic sediments 19,970±260 BP (MKL-4280) (Table 2). From the peat layer material for pollen analysis was collected. The entire horizon is approximately 2 m thick in the A-1 section (III), while in section A-1′(II) it is reduced to approximately 80 cm (Fig. 3). The set of lithofacies above in section A-1′ (III) is dominated by lithofacies of ripple cross-laminated sands (Sr). From a depth of 3.75 m the share of lithofacies typical of a higher-energy environment with participation of cross-stratification types (Sp, St, Sl) increases (IV and V). At the top of individual lithofacies sets there are fine or medium sands ripple laminated with participation of climbing ripple cross-lamination and wavy lamination (Sr, Scr, Sw). The near-surface set of lithofacies (VI) includes planar cross-stratified sands and massive sands (Sp, Sm). In the sections analysed there are continuous levels with involutions and ice wedge pseudomorphs (Fig. 3).

Table 2. Results of age determinations.

Method	Depth (m)	Laboratory code	Results (BP)	Results of calibration in case of ^{14}C method – 68.3% probability (cal BP)	Results of calibration in case of ^{14}C method – 95.4% probability (cal BP)
A-4′ profile					
^{14}C	14.37	GdA-6447	25,460±200	30,000–29,350	30,064–29,235
OSL	12.85	GdTL-3532	29,300±2,000	-	-
OSL	8.65	GdTL-3440	17,400±1,400	-	-
OSL	6.00	GdTL-3531	26,700±1,700	-	-
OSL	3.80	GdTL-3530	24,900±1,500	-	-
OSL	0.65	GdTL-3529	24,100±1,600	-	-
A-4 profile					
^{14}C	5.20	GdA-6446	19,580±120	23,785–23,371	23,827–23,222
^{14}C	4.96	GdA-6445	22,370±150	26,929-26,462	27,116–26,343
A-1 profile					
^{14}C	6.20	MKL-4278	22,540±210	27,147–26,487	27,247–26,393
^{14}C	6.00	MKL-4279	23,170±230	27,640–27,281	27,796–27,137
^{14}C	4.95	MKL-4280	19,970±260	24,343–23,754	24,771–23,336

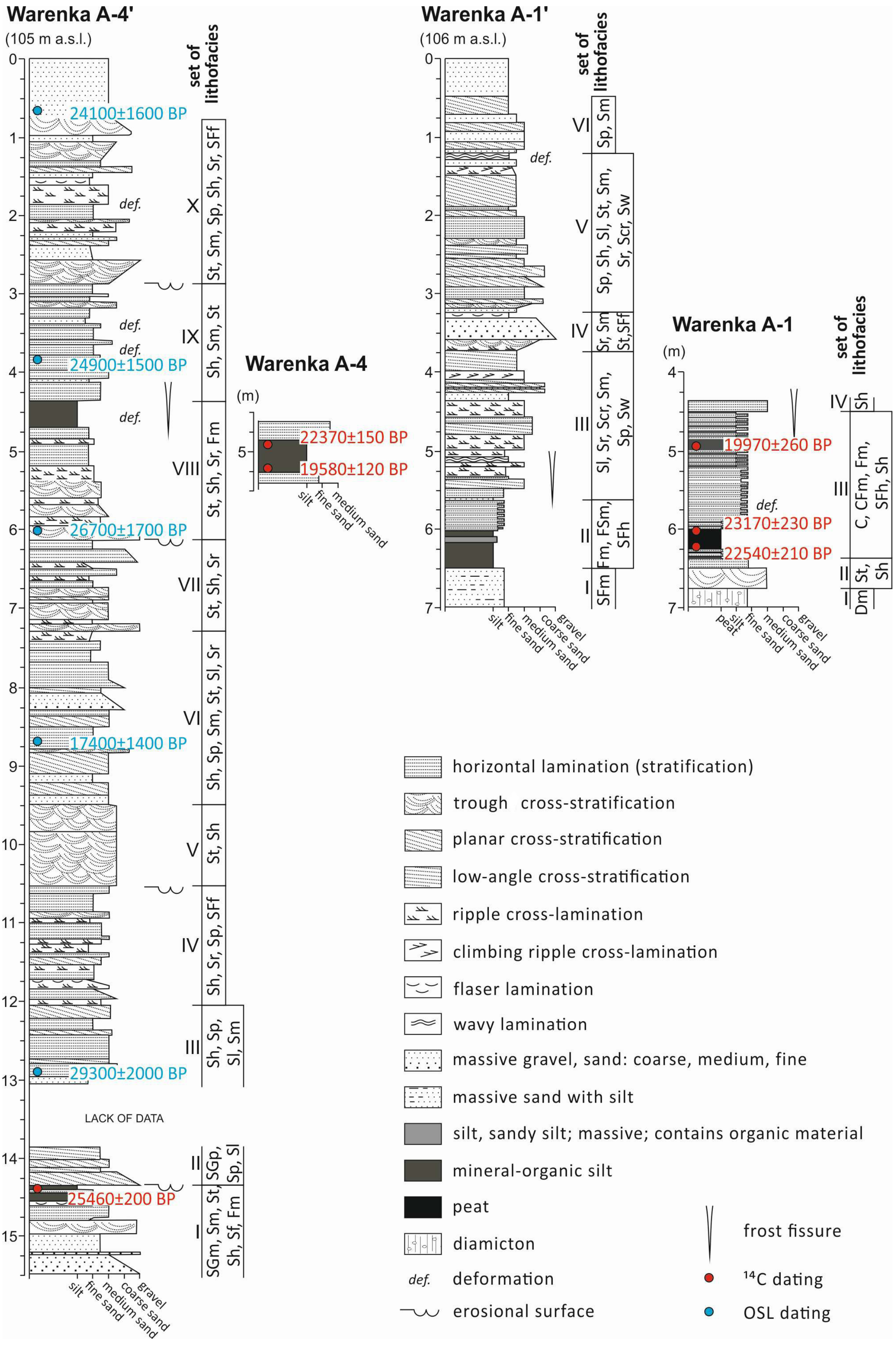

Fig. 3. Lithofacies of sections A-4′ and A-1′ (modified from Gładys, 2020).

4.2. Pollen analyses

Results of pollen analyses are shown in Tables 3 and 4. On the basis of changes in percentages of the most important taxa, the diagrams are divided into local pollen assemblage zones (L PAZ). In the A-1 section four L PAZs were distinguished, while in section A-4 it proved possible to identify three (Fig. 4). In section A-4, the share of NAP (non arboreal pollen) is similar and amounts to approximately 50 per cent. Here, the share of degraded grains exceeds 20 per cent (Fig. 5).

4.3. Cladocera analyses

Results of Cladocera analysis are shown in Tables 5 and 6. The organic sediments from section A-1 contain only three Cladocera species of the family Chydoridae (Table 5; Fig. 6). In turn, in the mineral-organic deposits of the A-4 section, seven species, respresenting three families (Bosminidae, Daphniidae and Chydoridae) were documented (Table 6; Fig. 6).

5. Interpretation and discussion

The fluvial sedimentary environment is developed in two facies associations, i.e., channel and overbank. In the channel facies, material from the bottom-load is deposited, and migrating bottom forms are built as a result of lateral accretion. In the overbank facies, sediment is deposited from vertical accretion, most often accumulated from suspension on the valley bottom during floods (Allen, 1965).

Lithofacies associations identified in the sections studied indicate a channel subenvironment in which inter-bar channels functioned. On the bottoms of these 3D megaripples wandered, yielding trough cross-stratification (St) in the sedimentary record. Lithofacies associations dominated by pla-

Table 3. Results of pollen analysis of section A-1 at Warenka.

Local pollen assemblage zones (L PAZ)	Depth [m] and number of samples	Characteristic features of pollen spectra
L PAZ A-1-1 *Cyperaceae-Betula*	6.20–6.11 (5 samples)	The share of NAP reaches up to 90%. *Cyperaceae* pollen dominates, up to 80%. The share of *Betula* pollen drops from 15% to 5%. The share of *Poaceae* reaches 8%, only in the sample from a depth of 6.16 m the share increases to approx. 20%. The share of *Pinus sylvestris* pollen is constant at 5%. Occasionally appear pollen grains of: *Betula nana t., Larix, Picea abies, Salix and Artemisia*. There are also remains of algae from the genus *Pediastrum* and *Botryococcus*.
L PAZ A-1-2 *Cyperaceae-* *-Pinus-Betula*	6.11–6.07 (2 samples)	NAP reaches 80%. The share of *Cyperaceae* pollen decreases from 70 to 55%. The share of *Poaceae* and *Pinus sylvestris* increases to 15%. *Potamogeton* appears and the share of *Pediastrum* and *Botryococcus* algae increases.
L PAZ A-1-3 *Selaginella-Pinus*	6.07–6.03 (2 samples)	The NAP share drops to approximately 65%. The share of *Pinus sylvestris* increases to 20%. *Selaginella selaginoides* appears, its share reaches over 30%. The share of *Betula* and *Poaceae* is decreasing.
L PAZ A-1-4 *Cyperaceae-* *-Selaginella*	6.03–6.00 (2 samples)	The share of NAP is up to approx. 80%. The share of *Cyperaceae* increases to 70%. The share of *Selaginella selaginoides* decreases to 5%. *Pinus sylvestris* decreases as well to 8%.

Table 4. Results of pollen analysis of section A-4 at Warenka.

Local pollen assemblage zones (L PAZ)	Depth [m] and number of samples	Characteristic features of pollen spectra
L PAZ A-4-1 *Pinus-Picea*-NAP	5.20–5.17 (2 samples)	*Pinus sylvestris* dominates, reaching up to 40%. The share of *Cyperaceae* decreases from 25 to 15%, *Poaceae* increases from 10 to 15%. *Picea abies* approx. 5%. The share of *Musci* and *Pediastrum* algae is significant.
L PAZ A-4-2 *Pinus*-NAP	5.17–4.96 (2 samples)	*Pinus sylvestris* dominates up to 30%. The share of *Cyperaceae* ranges from 15 to 25%, *Poaceae* reaches up to 20% and *Betula* up to 5%. Occasionally, pollen from *Betula nana t.*, *Larix* and *Juniperus communis* appear. *Sphagnum* is also recorded.
L PAZ A-4-3 *Pinus-Poaceae*	4.96–4.90 (2 samples)	The share of *Pinus sylvestris* is approx. 30%, *Poaceae* up to 15%. *Cyperaceae* periodically drops from 25 to 10% and increases again to 25%. *Musci* share increases to 30%.

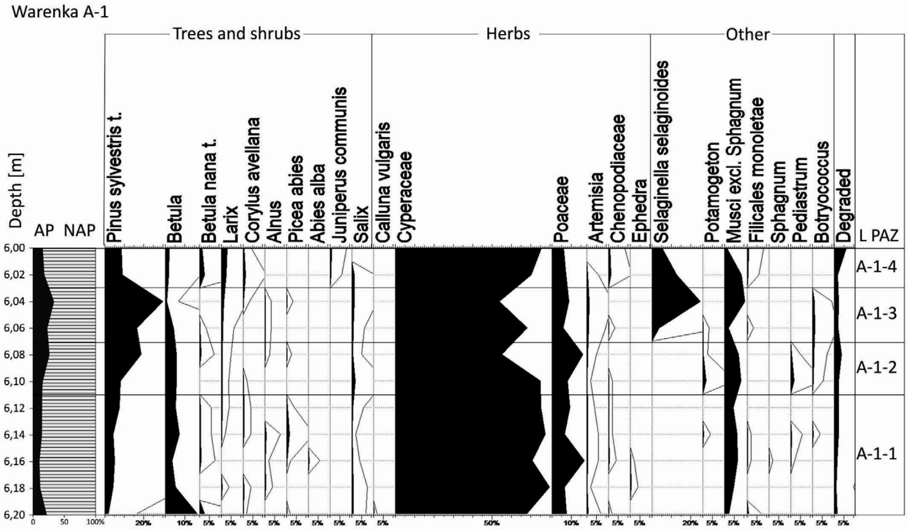

Fig. 4. Percentage pollen diagram for the section A-1 at Warenka.

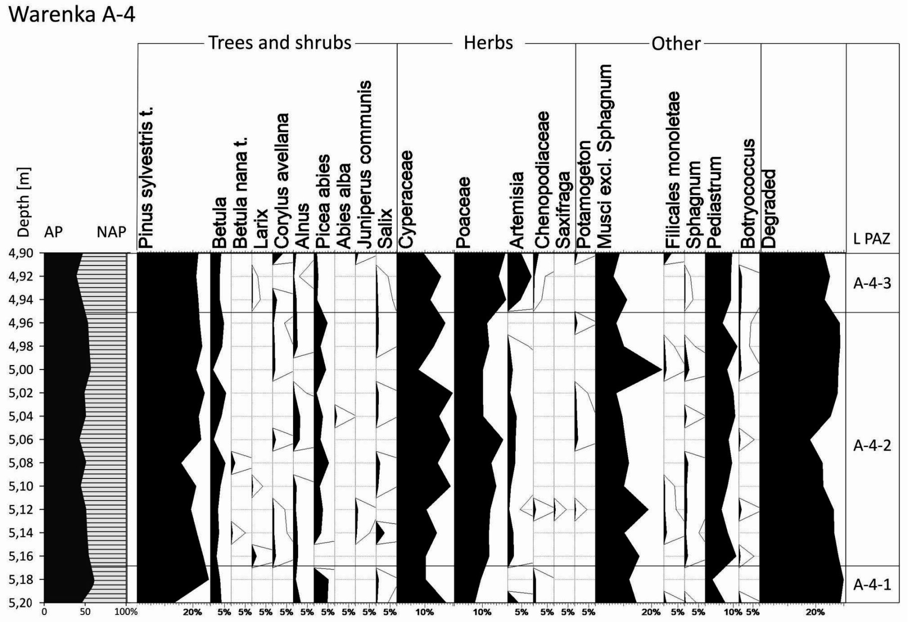

Fig. 5. Percentage pollen diagram for the section A-4 at Warenka.

nar and low-angle cross-stratification developed in sands and occasionally in sands with gravels (Sp, SGp, Sl) transverse bars formed. They are the most characteristic channel forms for sand-bed braided rivers with a prominent bar sedimentation style (Zieliński, 1997, 2007, 2014). At times, these are

Table 5. Results of Cladocera analysis of section A-1 at Warenka.

Local Cladocera Assemblage Zones (L CAZ)	Depth [m]	Characteristic features
L CAZ A-1-1	6.19–6.11 (5 samples)	The frequency of cladoceran specimens increased to 480/cm^3. The littoral, macrophyte-associated taxon, *Acroperus harpae* was dominant species exceeding 50% frequency of all water fleas at the end of zone. The macrophyte/sediment-associated taxa, *Alona affinis* and *Chydorus sphaericus*, were less numerous
L CAZ A-1-2	6.11–6.01 (5 samples)	The frequency of cladocerans decreased, not exceeding 140 specimens/cm^3. Littoral taxa, *Alona affinis* and *Chydorus sphaericus* increased. In turn, *Acroperus harpae* was rare.

Table 6. Results of Cladocera analysis of section A-4 at Warenka.

Local Cladocera Assemblage Zones (L CAZ)	Depth [m]	Characteristic features
L CAZ A-4-1	5.21–5.05 (8 samples)	The frequency of cladoceran specimens increased to 1320/cm^3. The planktonic taxa, *Eubosmina* sp., and *Daphnia pulex*-group were dominant, especially at the onset of the zone. The littoral, macrophyte-associated taxa, *Acroperus harpae* and the macrophyte/sediment-associated taxa, such as *Alona affinis* and *Chydorus sphaericus*, were also numerous. The *Eurycercus lamellatus* and *Alona quadrangularis* appears occasionally.
L CAZ A-4-2	5.05–4.91 (8 samples)	The frequency of Cladocera decreased to 330 specimens/cm^3. The one planktonic taxon, *Eubosmina* sp. was dominant species, exceeding 70% of all Cladocera. The littoral, macrophyte/sediment-associated taxa, such as *Alona affinis* and *Chydorus sphaericus*, were not numerous and the macrophyte-associated taxa (*Acroperus harpae* and *Eurycercus lamellatus*) appear occasionally.

overlain by sediments of a finer fraction with ripple, wavy or horizontal lamination (Sr, SFw, Sh), which represents bar-top subfacies.

An important component of the sedimentary record of the alluvium studied is formed by lithofacies associations in which there are alternating horizontally or low-angle stratified sands (Sh, Sl) and massive fine-grained sands with silt and clay (Sm, FSm), as well as ripple-cross, climbing ripple, flaser or wavy lamination. These represent an overbank subenvironment in which flash floods occurred; after such events the flow significantly reduced the dynamics until the phase of deposition from suspension was reached (Zieliński, 1997, 2014). The

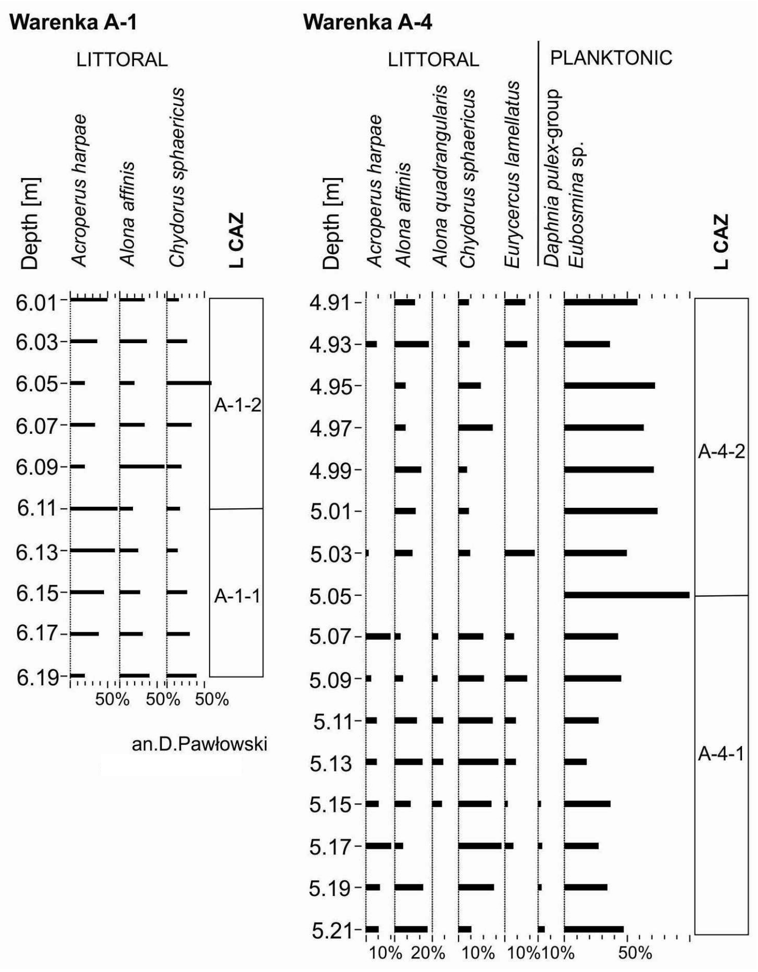

Fig. 6. Cladocera percentage diagram for the sections A-1 and A-4 at Warenka.

repeatability of the channel and overbank facies, with predominance of lithofacies indicating low dynamics of the sedimentary environment, provides grounds for comparing the documented sediment sequences with the depositional features of the modern South Saskatchewan River described by Cant & Walker (1978). Those authors classified alluvia with such features as the lithotype of braided rivers with the lowest energy.

The results of dating sediments at the Warenka site allow the conclusion that the stage of accumulation responsible for their formation most likely began slightly earlier than 30,000 BP, as indicated by the oldest 14C result obtained from section A-4′: 30,000–29,350 cal BP (Table 2; Fig. 3). The final stage of deposition is indicated by the OSL date of 24,100±1,600 BP obtained for near-surface sediments. One of the OSL dating results, i.e., 17,400±1,400 BP, does not match the others, which can be explained by younger material entering the sampler. The faces at the opencast lignite mine may have been subject to gravitational movements, which could have resulted in the formation of cracks and allowed material to migrate (Pulinowa, 1972). In section A-4, an inversion of ^{14}C dates was noted; the base is dated as interval 23,785–23,371 cal BP and the top as 26,929–26,462 cal BP. However, when comparing these age assessment with results of OSL dating and taking into account the given error range, it may be assumed that the results obtained are not mutually exclusive. The inversion of ^{14}C dates could have resulted from redeposition of material in the river valley environment, even within the same mineral-organic horizon. In the case of radiocarbon dating of the base and top of the peat layer in section A-1, inversion also occurred, but the difference is small and the calibrated age ranges overlap. This suggests that organic deposits formed over a relatively short period of time. Sediments from the upper layer of mineral-organic sediments in section A-1 are younger, dating back to approximately 24,000 cal BP (Table 2; Fig. 3). The alluvium studied was deposited over a period of approximately 6,000 years, during the coldest part of the Weichselian, i.e., the beginning of late Pleni-Weichselian, but prior to the moment when the ice sheet reached its maximum extent in central Poland during the last glaciation (Stankowski, 1982; Marks, 2023).

The presence of organic sediments in the sections studied made it possible to reconstruct some aspects of the functioning of the biotic sphere under the severe environmental conditions of the onset of late Pleni-Weichselian. Results of pollen analysis in the A-1 section document that the immediate vicinity of the river valley was occupied by shrub steppe-tundra with a very large share of herbs and *Musci* and individual shrubs such as *Betula nana t.* and *Salix* which could grow solitarily (Tobolski, 1986) and *Ephedra*, which prefers well-lit habitats (Mamakowa, 2003). At the bottom of the valley, where a shallow but extensive reservoir was formed, probably fed by floods, occurred *Potamogeton*, which prefers habitats with standing or slow-flowing water (Kłosowski & Kłosowski, 2006) and algae of the genera *Pediastrum* and *Botryococcus* (L PAZ A-1-2) (Fig. 4). The wet localities also favoured the presence of *Selaginella selaginoides*, the occurrence of which suggests that temperatures in the warmest and coldest months of the year did not exceed +20°C and –12°C, respectively (Mamakowa, 1997; Granoszewski, 2003) (L PAZ A-1-3). The gradual disappearance of the reservoir is evidenced by the diminishing percentage of algae of the genera *Pediastrum* and *Botryococcus* and of the aquatic plant *Potamogeron*, but also by the disappearance of *Selaginella selaginoides* and *Musci* in favour of taxa that preferred dry habitats, such as *Juniperus communis*, *Betula nana t.* or *Corylus* (L PAZ A-1-4). The pollen picture obtained from section A-4 also indicates the existence of a steppe-tundra landscape dominated by Poaceae and Cyperaceae, which could periodically transform into shrubby steppe-tundra with *Betula nana t.*, *Taxus*, *Salix* and *Juniperus communis* (L PAZ A-4-1, L PAZ A-4-2) (Figs. 4, 5). As in the case of section A-1, the valley bottom remained swampy, with stagnant water in which *Pediastrum* developed, and *Sphagnum* was also present, indicating the existence of wetlands (L PAZ A-4-2). Towards the end of the reservoir's existence, shrubby plants withdrew from its surroundings (L PAZ A-4-3), which could have been linked to the increasingly severe climatic conditions. The tree pollen recorded during the analysis most likely comes from long-distance transport in an open landscape that functioned during the beginning of late Pleni-Weichselian.

The results of the Cladocera analysis are in agreement with those obtained in pollen studies and confirm biotic and hydrological conditions prevailing during the onset of late Pleni-Weichselian on the valley bottom. The low species diversity of cladoceran assemblages confirms the cold climate during the existence of reservoirs documented in both sections (A-1 and A-4; see Fig. 6). In section A-1 highly adaptable littoral taxa (*Acroperus harpae*, *Alona affinis* and *Chydorus sphaericus* s.) were found; these may inhabit reservoirs of different depths and extreme conditions since they have a wide tolerance to environmental conditions, especially temperature (Flössner, 2000; Nevalainen, 2011). These cold-tolerant taxa are also pioneer species that dominated in the initial phase of development in many lakes across central and northern Europe (Lotter et al., 2000; Bennike et al., 2004). Additionally, the abundant littoral cladoceran taxa provide evidence for a shallow-water setting with weakly developed vegetation cover (Płóciennik et al., 2020). Similar conditions have been documented in section A-4 by the presence of more phytophilous species such as *Eurycercus lamellatus*. The cladoceran assemblages from section A-4 reflect cold climate conditions during existence of this floodplain's water body as most of the Cladocera taxa noted tolerate cold water. Additionally, the fluctuated presence of planktic species, especially *Eubosmina* sp., suggest river input, which modified water-level changes.

The upper Pleni-Weichselian sediments constitute a very important element of river valley infills across extraglacial European Lowlands (Krzyszkowski, 1990; Van Huissteden & Kasse, 2001; Petera, 2002; Van Huissteden, et al. 2003; Kaiser et al., 2012), often forming sediment bodies of high terraces (e.g., Turkowska, 1988; Forysiak, 2005; Wachecka-Kotkowska & Ludwikowska-Kędzia, 2007). The severe climate-forced changes in the functioning of river valleys, which led to an increase both in average flows and in size of episodic flood flows, as well as to a reduction in infiltration through permafrost presence and an increase in the supply of mineral material (Turkowska, 1988). As shown by results of the present research at the Warenka site in the River Warta valley, the thick sediments of which the Weichselian high terrace was formed were deposited over a period of approximately 6,000 years in the sedimentary environment of a sand-bed braided river. Ice-wedge pseudomorphs and involutions developed in the levels studied indicate that formation took place under periglacial conditions. Aggradation of mineral material was periodically inhibited and large, shallow reservoirs were formed at the bottom of the valley, where organic or mineral-organic material accumulated. The lifespan of these reservoirs was probably limited, but they lasted long enough to be colonised by vegetation and aquatic and marsh organisms. The radiocarbon dating results for the mixed sediments, although consistent with other research results, do not allow to determine the time frame for the existence of reservoirs.

The formation of organic or mineral-organic horizons in alluvium is not a direct indicator of warmer climatic fluctuations. Their formation could have resulted from the migration of the channel – also of a braided river – along a vast valley bottom and could merely indicate formation of a distal flood plain rarely reached by floods. Thus, the formation of these organic or mineral-organic horizons was influenced by local factors (Behre, 1989; Manikowska, 1996). Nevertheless, the palaeogeographical importance of such levels is great because, apart from the Horoszki site (Granoszewski, 2003), there are no continuous sections of biogenic sediments covering the late Pleni-Weichselian. However, they do provide fragmentary, yet valuable, data on the functioning of the biotic sphere in that period, for instance at the following sites: Konin-Maliniec (Pazdur et al., 1980), Lublinek (Turkowska, 1988), Bełchatów (Manikowska, 1992; Balwierz, 1995), Kobbelgård (Kolstrup, 1993) and Koźmin (Petera, 2002).

6. Conclusions

The climatic changes occurring during the Pleni-Weichselian period were of small amplitude, but they left noticeable traces in the environment. A major problem in palaeoenvironmental reconstructions of this period results from the paucity of continuous records in sedimentary environments. Therefore, it is of great importance to collect data for even short periods with the most precise location of the reconstructed events on the time scale.

The research results discussed here show that fluvial deposits were formed in the very cold onset of late Pleni-Weichselian, between about 30 to 24 kBP. In the sedimentary record there is a predominance of lithofacies Sp, St, Sh and Sr, indicating that deposition occurred in an environment of a low-energy sand-bed braided river. Despite its low energy, the river had very strong aggradational tendencies.

At the bottom of the valley, shaped by a low-energy river, conditions appeared for the deposition and preservation of organic and mineral-organic sediments. These deposits became geoarchives, in which the biotic features of past environments were recorded. The research results showed that the surroundings of the valley were covered with steppe-tundra, periodically with shrubs, and on its marshy bottom, wet meadows and peat bogs developed. In addition, there were periodic conditions favourable to the development of aquatic invertebrates.

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