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Palaeogeographical significance of the Eemian biogenic sediments at the Bór site (Warta River valley, central Poland)

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An investigated area is located in the middle reach of the Warta River valley. During drillings in the Bór site organic deposits such as detrital calcareous gyttja and calcareous detrital gyttja has been documented in a depth between 14.9 and 16.6 m. The organic deposits are covered by mineral, mostly sandy deposits. The accumulation took place in the small lake formed as an abandoned channel. Palynological analysis led to the conclusion that biogenic accumulation began at the end of Wartanian and took place at least to the Eemian Interglacial optimum. Results of palynological, Cladocera and geochemical analyses indicate water level changes and the increasing of the trophy status of the reservoir. Presence of Mesozoic substratum very close to the palaeolake bottom influenced significantly the chemical features of the organic deposits. As Eemian organic deposits are uncommon in the Warta River valley, the Bór site seems important for palaeogeographical reconstructions of the Warta River valley during Eemian Interglacial.

Key words: gyttja, palynology, Cladocera, geochemistry, Warta River valley deposits.

INTRODUCTION

In central Poland, there are a lot of well-documented sites of biogenic sediments from the Late Wartanian and Eemian Interglacial (e.g., Klatkowa, 1990; Bruj and Roman, 2007), which are located in the morainic plateau, while not numerous were found in river valleys. This situation provides solid background for the palaeogeographical interpretation of the plateaus, but it does not enable a successful reconstruction of the river valley floors of the period in question.

The data presented is a contribution to the knowledge about the functioning of the river system in central Poland during the Eemian Interglacial. The Vistula drainage system from that period is recognized much better (Marks and Pochocka, 1999; Marks, 2005b) than those known from the Odra and Warta rivers. Most of the information comes from drillings, and palaeogeographical reconstructions are based on analysis of properties of the mineral deposits due to the shortage of organic material suitable for pollen analysis and reliable dating (Marks, 2005b). For this reason each site, where Eemian Interglacial organic deposits are documented is very important and allow us to verify the interpretation based on mineral material. It is obvious that the sites where age was determined palynologically have the greatest value as presented in this paper Bór site or e.g., Krzyżówki (Noryśkiewicz, 1999), but the mollusc analysis can be also sufficient to confirm Eemian age of fluviolacustrine deposits (e.g., Skompski, 1983; Szałamacha and Skompski, 1999; Meng et al., 2009).

Until recently, the palaeogeography of the middle reach of Warta River valley during Eemian Interglacial was reconstructed on the base of the mineral, mostly sandy deposits (Czarnik, 1972; Trzmiel, 1996). The situation has greatly improved, when lake deposits and peat have been found in the Krzyżówki site, near Koło (Szałamacha and Skompski, 1999) and on the basis of palynological data were determined as belonging to the late glacial of the Wartanian and the Eemian Interglacial (Noryśkiewicz, 1999). Their deposition took place in a shallow lake, perhaps an oxbow lake, which has gradually transformed into a mire. Investigations in the Bór site bring (Fig. 1A, B) new data about the palaeogeography of the meridional section of the Warta River valley close to Uniejów during the Wartanian termination and Eemian Interglacial.

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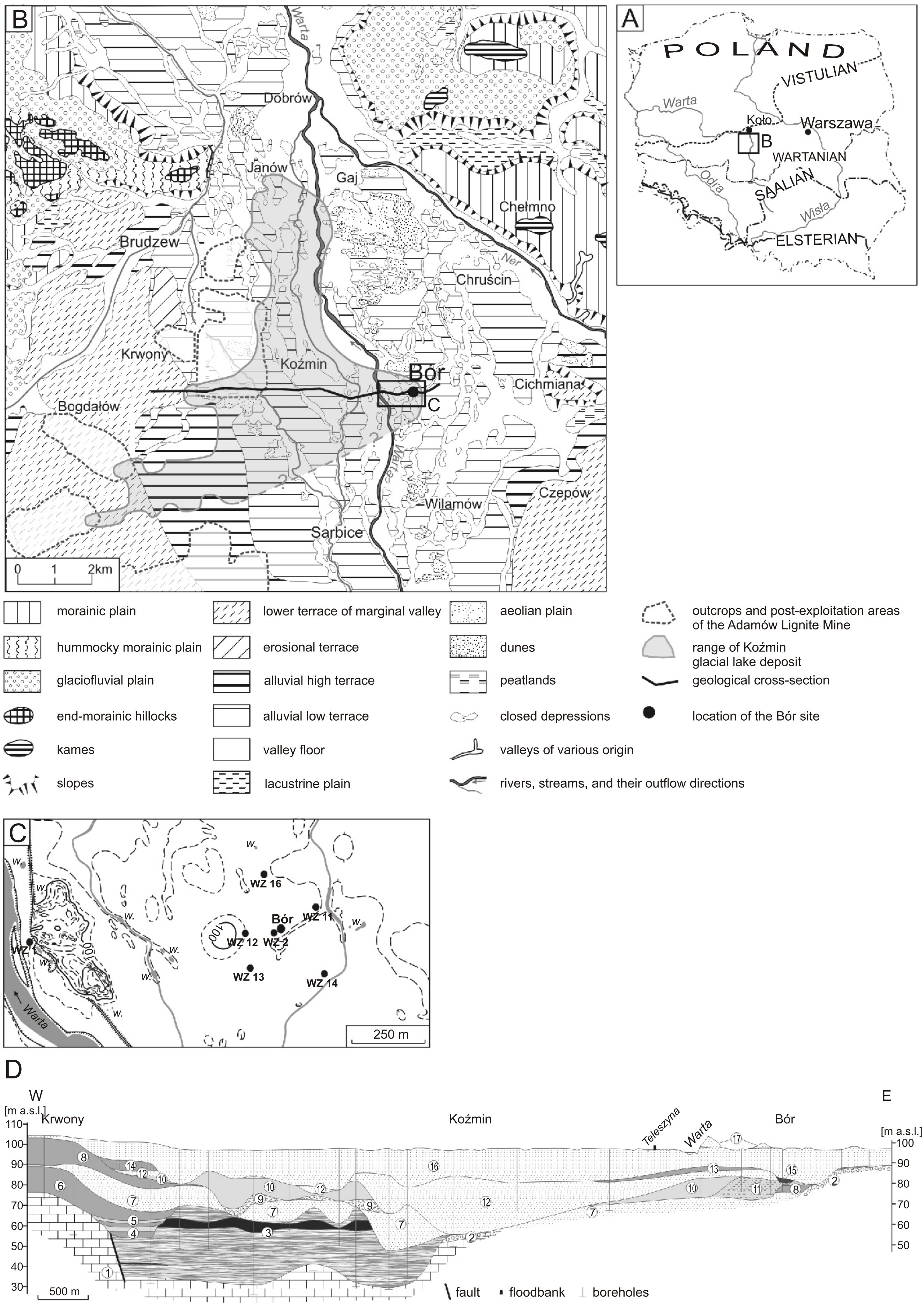
B
Warta
Dobrów
Janów
Gaj
Chełmno
Brudzew
Ner
Chruścin
Krwony
Koźmin
Bór
C
Cichmiana
Bogdałów
Czepów
Wilamów
Sarbice
0 1 2km
A
POLAND
VISTULIAN
Warta
Koło
Warszawa
B
WARTANIAN
Odra
SAALIAN
Wisła
ELSTERIAN
morainic plain
hummocky morainic plain
glaciofluvial plain
end-morainic hillocks
kames
slopes
lower terrace of marginal valley
erosional terrace
alluvial high terrace
alluvial low terrace
valley floor
lacustrine plain
aeolian plain
dunes
peatlands
closed depressions
valleys of various origin
rivers, streams, and their outflow directions
outcrops and post-exploitation areas of the Adamów Lignite Mine
range of Koźmin glacial lake deposit
geological cross-section
location of the Bór site
C
WZ 16
Bór
WZ 11
WZ 12
WZ 2
WZ 1
WZ 13
WZ 14
Warta
250 m
D
W
E
[m a.s.l.]
Krwony
Koźmin
Teleszyna
Warta
Bór
[m a.s.l.]
500 m
fault
floodbank
boreholes

GEOLOGICAL SETTING

The Bór site is located in the middle section of the Warta River valley (Fig. 1A), in area where the valley joins with the Warsaw–Berlin ice-marginal streamway. Between Sarbice and Dobrów it widens and reaches a width of several km. The study area lies within the Middle Polish Glaciations extent. During the Last Glacial Maximum the Bór site was situated in an extraglacial zone (Kozarski, 1981; Stankowska and Stankowski, 1988; Stankowski and Krzyszkowski 1991).

In the Mesozoic substratum of the investigated area the Adamów graben occurs. It belongs to the system of grabens of the Konin elevation, formed within the Szczecin–Łódź–Miechów Trough (Widera, 1998). Within the graben, thick Neogene deposits, including brown coal, and Quaternary series were accumulated.

The oldest Quaternary deposits are represented by tills and other glaciogenic deposits of South Polish Complex (based on stratigraphy postulated by Ber et al., 2007; Lindner and Marks, 2012), which filled deep erosional forms developed in the sub-Quaternary surface (Fig. 1D). The upper till of South Polish Complex (probably Sanian 2), are more widespread and deformed by glaciotectonic processes. Fluvial sands and sands with gravels representing beginning of the Middle Polish Complex lie above. Two horizons of the Middle Polish Complex tills were found (Czubla et al., 2010). Outside the Adamów graben the tills are thick, and dominate the Quaternary series, while in the graben their thickness decreases or they are completely eroded or/and separated by glaciolacustrine deposits of the Koźmin glacial lake and glaciofluvial sand and gravels (Fig. 1D). The glacigenic deposits of the Middle Polish Complex form uplands: morainic and glaciofluvial plains as well as the Warsaw–Berlin ice-marginal streamway terraces (Kłysz, 1981; Klatkowa, 1993; Nowacki, 1995; Trzmiel, 1996; Czubla, 2001; Forysiak, 2005).

Fluvial sands lying at a depth of 14–24 m were described as Eemian deposits by Czarnik (1972) and Trzmiel (1996). The organic sediments of Eemian age were recognized only at the Bór site. Nowadays, the site is located in the wide valley but in the Eemian, it was located in very distal part of the valley. The bottom of the Bór reservoir was close to the Adamów graben east edge (Fig. 1D).

The thick Weichselian alluvia, exceeding locally 20 m in thickness, cover older deposits (Fig. 1D). Morphologically, Weichselian deposits form two levels: the alluvial high terrace and lower terrace. The great part of the valley is occupied by the lower terrace (Fig. 1B). The lower terrace is cut by remains of the multichannel river system which developed in the Younger Dryas and also functioned in the Holocene. Some of the channels are still occupied by small streams (Petera, 2002; Turkowska et al., 2004; Forysiak, 2005).

The Holocene fluvial deposits usually occupy narrow fragments of the valley, along the numerous small streams and Warta River. They are represented by sands with silt and alluvial clay (Forysiak, 2005). The aeolian sands and dunes occur, the most frequently in the right side of the valley.

MATERIAL AND METHOD

The organic series were documented during drillings in the Bór site. There were undertaken drillings around the site (Fig. 1C) to establish their spread and geological context. At the Bór site the drilling reached a depth of 18.5 m, and the vertical profile is as follows:

Depth [m]	Lithology
0.0–0.3	sandy soil, brown
0.3–1.1	medium sand, grey beige
1.1–8.5	medium and coarse sand, grey beige
8.5–10.0	fine sand with silt, grey beige
10.0–14.0	medium and coarse sand, grey beige
14.0–14.6	sand with gravel
14.6–14.85	gravel
14.85–16.35	detrital calcareous gyttja
16.35–16.60	calcareous detrital gyttja
16.60–16.75	silt mixed with gravel
16.75–17.45	gravel
17.45–17.95	fine and medium sand with silt
17.95–18.50	till

ANALYSIS OF MINERAL DEPOSITS

21 samples of mineral deposits (Fig. 2) were examined by grain-size analysis: sieve and aerometric method (Mycielska-Dowgiałło, 1995), and standard Folk and Ward coefficients were counted using *GRADISTAT* software. The quartz-grain abrasion analysis was performed for the fraction 0.8–0.63 mm, using modified Cailleux method (Klatkowa, 1991; Manikowska 1993). Moreover, the calcium carbonate content was determine for all mineral samples using the Scheibler method.

ANALYSIS OF GYTTJA

The gyttja from the Bór profile was analysed by means of pollen, Cladocera, granulometric and geochemistry analyses. The samples from detrital calcareous gyttja were collected in intervals of 10 and 5 cm from calcareous detrital gyttja, within the depth range of 14.9–16.6 m.

The pollen analyses were done for 20 samples. For the microscopic investigations the samples were prepared using Faegri and Iversen (1978) and Berglund (1979) methods. The results are presented as percentage pollen diagram drawn using *POLPAL* software.

The analysis of Cladocera was based on 21 samples of 1 cm^3 volume and were processed according to the standard procedure (Frey, 1986). The taxonomy of cladoceran remains follows that presented by Frey (1962) and Szeroczyńska and

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Fig. 1. Location of the Bór site in Poland with geological sections

A – location of the investigated area in relation to extents of the ice-sheets (after Marks, 2005a); **B** – geomorphological map (after Forysiak, 2005); **C** – location of the boreholes in Bór village; **D** – geological cross-section: Cretaceous: 1 – marl, 2 – weathered marl; Neogene: 3 – clay, silt, sand and lignite; Quaternary, Elsterian: 4 – the oldest till and glaciolacustrine silt, 5 – older till and glaciolacustrine silt, 6 – younger till; Saalian: 7 – fluvial sand and gravels; Wartanian: 8 – lower till, 9 – lower glaciofluvial sand and gravels, 10 – glaciolacustrine silt and fine sand, 11 – glaciolacustrine sand and sand with silt, 12 – upper glaciofluvial sand and gravels, 13 – upper till, 14 – glacial loamy sand; Eemian Interglacial: 15 – gyttja; Weichselian and Holocene: 16 – fluvial sand, sand and gravel, and sand with silt, 17 – aeolian sand

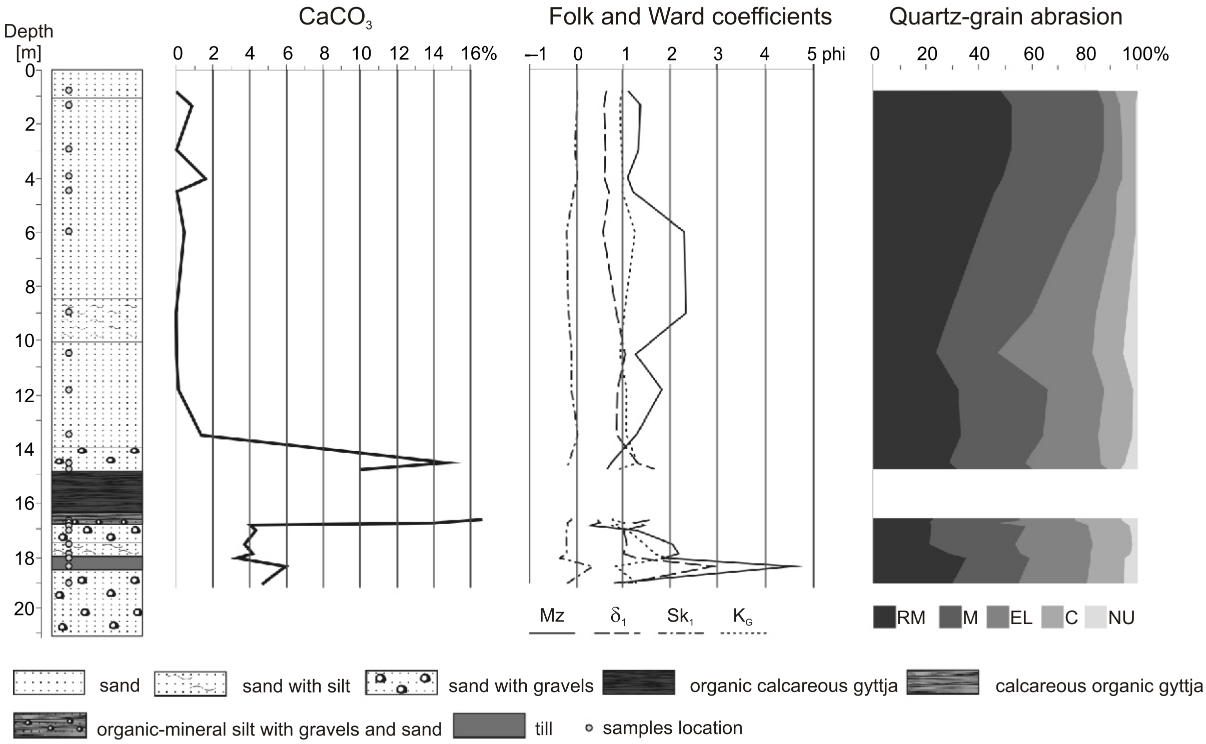

Fig. 2. Lithology and textural features of deposits in Bór site

Mz – mean grain-size, δ_1 – standard deviation, Sk_1 – skewness K_G – curtosis, RM – round mat, M – intermediate, EL – shiny, C – crushed, NU – unabraded (fresh)

Sarmaja-Korjonen (2007). Ecological preferences of cladoceran taxa were determined on the basis of Whiteside (1970) and Szeroczyńska (1998).

Sediment granulometry and geochemistry was analysed in 21 samples. Individual samples were freeze-dried in lyophiliser and samples were mineralised in the process of combustion (550°C) to calculate per cent contribution of organic and mineral parts of each sample. The ash produced by combustion was analysed for grain-size related and geochemical characteristics.

Grain-size analysis of the mineral part was carried out in a laser analyser which processes samples of 300–0.3 μm mean grain-size. Standard Folk and Ward coefficients were calculated using the *GRADISTAT* software. Percent contributions of individual fractions were calculated as well.

In order to perform geochemical assays, the ash samples were dissolved in Teflon bombs using a microwave mineraliser. Mineralisation was carried out in two microwave cycles: the first one in concentrated nitric acid with 2 ml 10% chloric acid and the second one in hydrogen peroxide. The solution obtained was analysed for concentrations of Na, K, Ca, Mg, Fe, Mn, Cu, Zn, and Pb with atomic absorption spectrometry. All the analyses were conducted at the Geochemical Laboratory in University of Szczecin.

Part of the geochemical analyses were conducted in Laboratory of the Earth Science Institute, University of Łódź. Twenty samples of sediment were analysed using the following methods: Scheibler volumetric method in order to determination of the carbonate content in the sediment, potentiometric method for measurement of pH, conductivity and voltage.

RESULTS

TEXTURAL FEATURES OF MINERAL DEPOSITS

The till documented at the Bór site has typical textural features: high value of mean grain diameter, is poorly sorted, positive skewness coefficient and low value of kurtosis (Fig. 2). The quartz grain abrasion is representative for tills: RM (round mat) ~35%, M (intermediate) ~25% and EL (shiny) ~23% with high content of the broken grains. The $CaCO_3$ content varies from about 4 to 6%, which is typical as well. The top of the till has sand admixture, is better sorted and negatively skewed, probably due to fine fraction remove. Above, medium and fine-grained sands with silt occur. The deposits are medium or poorly sorted, with negative skewness and $CaCO_3$ content of about 4%. These sediments have been classified as glaciolacustrine deposits of the Koźmin glacial lake.

The next series consists of medium and poorly sorted coarse sand and gravels. The gyttja is underlain by organic-mineral silt with gravels and sand and covered by the Weichselian alluvia, represented by sand, sand with gravels, and fine sand with silt (Fig. 2). The content of $CaCO_3$ in Weichselian deposits is low (about 1%) except at the base where it reaches almost 15%. At the base, the quartz grain abrasion is characterized by a relatively small amount of RM grains and a significant content of EL grains. At depths of about 8 m the proportions of RM and M grains increase towards the top, and reach, respectively about 50 and 35%. Considerable content of wind-abraded grains is typical for Weichselian alluvia, as well for Warta River deposits (Petera, 2002; Forysiak, 2005).

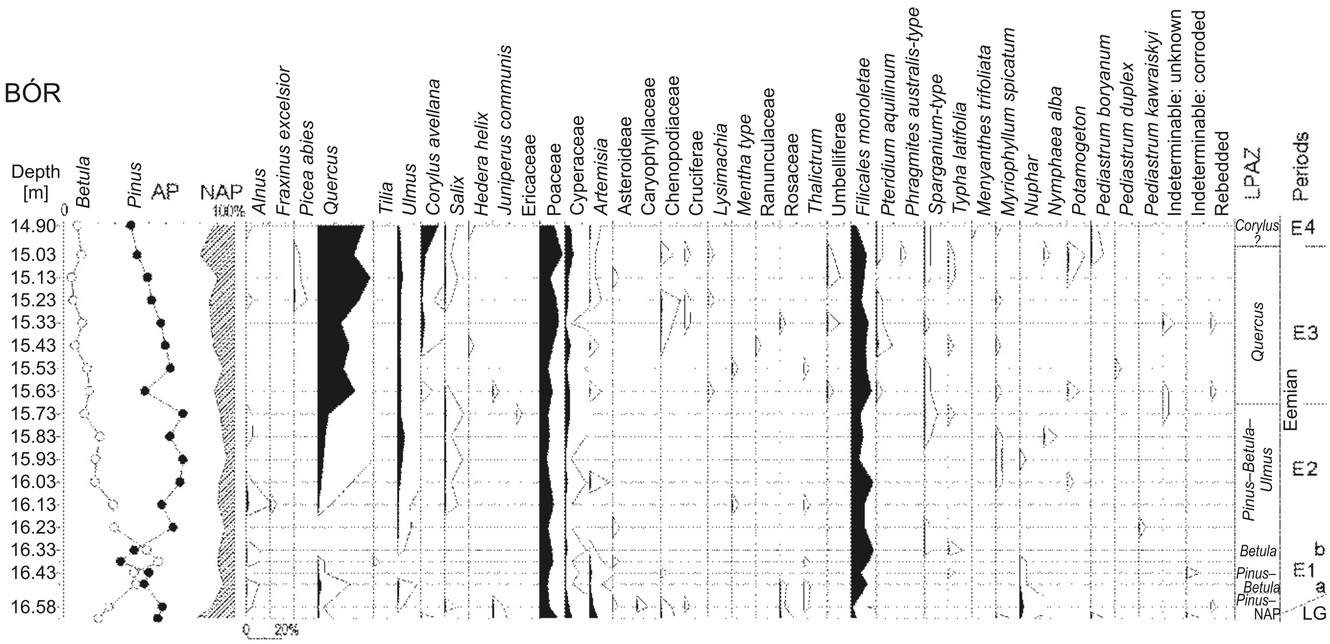

Fig. 3. Percentage pollen diagram

PROPERTIES OF ORGANIC DEPOSITS

POLLEN ANALYSIS

Changes of the percentage share of taxa in creation of vegetation associations in Bór borehole, allow for the distinction of six local pollen assemblage zones (LPAZ), according to Janczyk-Kopikowa (1987; Fig. 3).

Pinus–NAP LPAZ (16.48–16.63 m). *Pinus* (55.3–58.0%) as the dominating taxon is accompanied by *Betula* (20.0–26.3%) and in small amounts – *Juniperus* (0.8%). Of the herbal plants (NAP: 23%) the main constitutents are Cyperaceae and Poaceae and species of steppe-like associations (*Artemisia,* Chenopodiaceae). Predominance of non-forest associations in the vegetation shows that the sediments of this zone have been accumulated during the cold climate, probably in the period between the Late Glacial and the oldest Eemian.

Pinus–*Betula* LPAZ (16.38–16.48 m). A decrease of *Pinus* to 47.5% and an increase of *Betula* + *Betula nana* up to 42.4% is observed. The amount of NAP also decreases, especially Cyperaceae, Chenopodiaceae and *Artemisia*. It indicates the development of birch shrub associations and open birch-pine forests and shows the improvement of climate conditions proved also by presence of *Typha latifolia* pollen.

Betula LPAZ (16.23–16.38m). The dominance of *Betula* (to 55.6%) over *Pinus* (33.2–41.3%), shows the development of birch and birch-pine forests.

The zones *Betula* and *Pinus*–*Betula*, as well as probably the younger part of *Pinus*–NAP zone, we can correlate with the oldest regional pollen zone of Eemian – E1 (Mamakowa, 1988, 1989).

Pinus–*Betula*–*Ulmus* LPAZ (15.73–16.23 m). A high amount of *Pinus* (57.5–70.1%) accompanied with a lower amount, in comparison to the previous zone, of *Betula* (11.9–29.5%). Small amounts of pollen grains of *Ulmus* (max. 4.3%) and *Quercus* (max. 6.5%) are also present. The presence of new species proves the improvement of climate and edaphic conditions allowing the development of mixed forest with *Ulmus* and *Quercus*. The general palynological picture of this zone allows for its correlation with the zone E2 in stratigraphic division of the Eemian (Mamakowa, 1988, 1989).

Quercus LPAZ (15.03–15.73 m). *Quercus* (15.2–30.9%) is dominant and accompanied by *Pinus* (42.0–62.7%), *Betula* (4.7–14.9%) and *Ulmus* (1.9–3.1%), as well as the continuous percentage curve (up to 2.2%) of *Corylus* in the middle part. The pollen of *Hedera* proves the existence of a warm and humid climate (Iversen, 1958). The pollen spectra of this zone allow for its correlation it with the E3 zone in the Eemian vegetation succession (Mamakowa, 1988, 1989).

Corylus LPAZ (14.90–15.03 m). The characteristic feature is the significant amount of *Corylus* pollen grains (up to 10.5%). Although this zone was distinguished on the basis of pollen spectrum of only one sample, we can associate it, with high probability, with the beginning of E4 zone in the Eemian succession (Mamakowa, 1988, 1989).

Summing up, the obtained palynological results are similar to previously described Eemian series known from other sites of central Poland (Noryśkiewicz, 1978; Stankowski and Tobolski, 1981; Jastrzębska-Mamełka, 1985; Tobolski, 1986, 1991a, b; Klatkowa and Balwierz, 1990; Klatkowa and Winter, 1990; Kotarbiński and Krupiński, 1995; Malkiewicz, 2002), which allows for a strong indication of the age of deposition of investigated sediments.

CLADOCERA ANALYSIS

In the Bór profile, 23 Cladocera species were recognized (Fig. 4), belonging to four families. The most numerous were the littoral species of the Chydoridae family. The number of pelagic forms (from the Bosminidae, Daphnidae and Sididae families) in places exceeds 30% of all Cladocera individuals.

On the basis of the Cladocera communities and the changes in frequency of the various species, five zones of Cladocera development were distinguished and connected with the Eeemian Interglacial period.

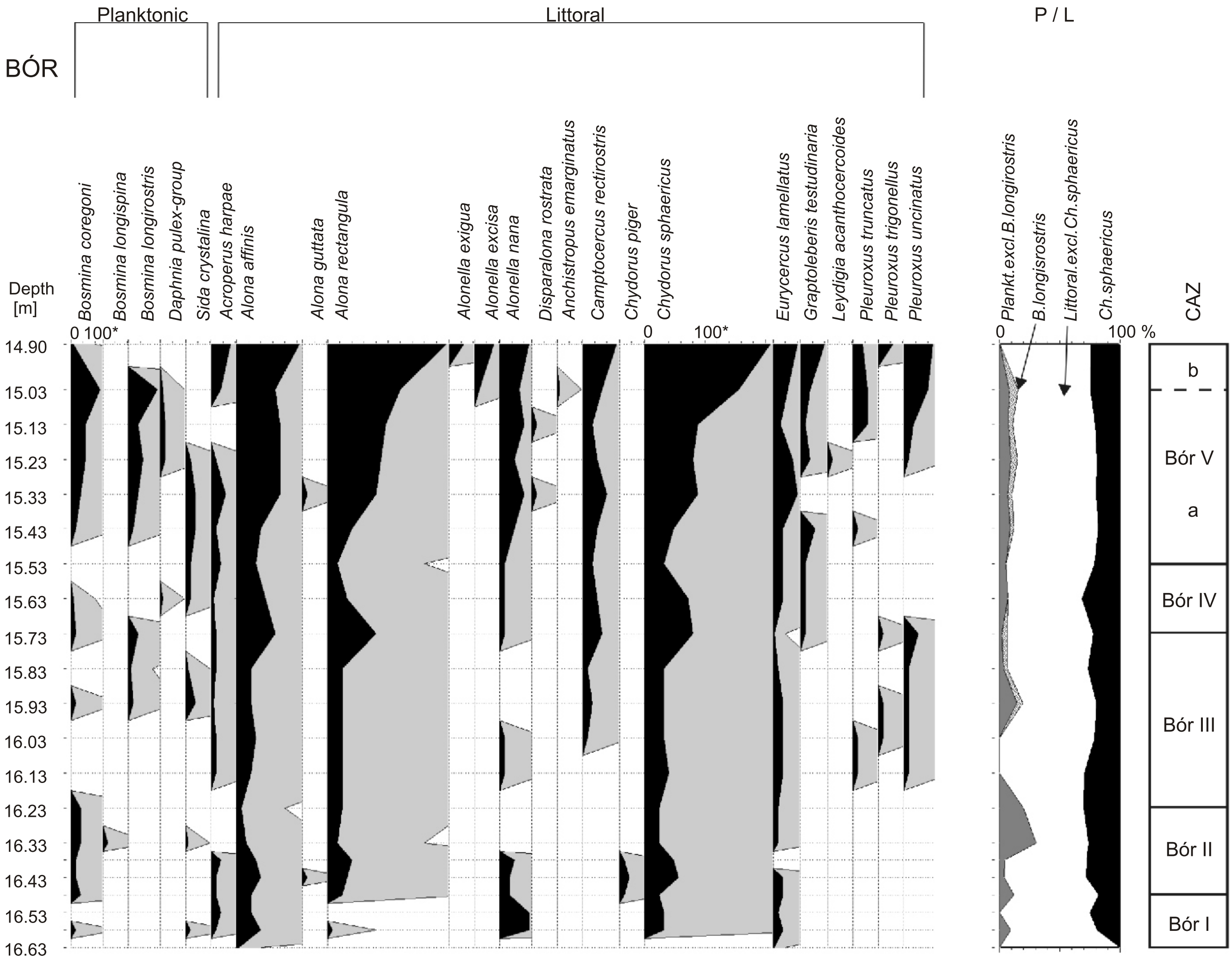

Fig. 4. Absolute number of Cladocera individuals, ratio of planktonic (P) to littoral (L) forms and proposed Cladocera zones (CAZ) in the sediments of Bór palaeolake

* – scale on diagram shows specimens in 1 cm^3 of fresh sediments

Zone Bór I (16.48–16.63 m). At the beginning a low diversity of Cladocera is noted, comprising only two initial species: *Alona affinis* and *Eurycercus lamellatus*. Later the diversity of Cladocera species increases to 8. The most numerous are *Chydorus sphaericus*, *Alona affinis*, *Alonella nana* and *Acroperus harpae* which tolerate cold water in the lake.

Zone Bór II (16.23–16.48 m). The planktonic form is noted up to 30% frequency of all Cladocera. The diversity of Cladocera species increases at the beginning to 9 species but later decreases to 5 species.

Zone Bór III (15.73–16.23 m). The diversity of Cladocera species increases to 12 species. These include species indicating warmer water: *Camptocercus rectirostris, Pleuroxus trigonellus*, *P. truncatus* and *P. uncinatus,* as well as macrophyte-associated species are present. Planktonic forms occur in middle part of this zone.

Zone Bór IV (15.53–15.73 m). The most numerous species are *Chydorus sphaericus* and *Alona affinis.* The diversity of Cladocera species decreases to 8 species at the end of the zone. *Daphnia pulex* and *Graptoleberis testudinaria* appear for the first time.

Zone Bór V (14.90–15.53 m). This zone is characterized by the maximum of zooplankton development. Fourteen species of Cladocera have been found, and two subzones have been distinguished. In subzone Bór Va (15.03–15.53 m) the diversity of Cladocera species systematically increases. Planktonic forms frequent reach 15% of all Cladocera. Among planktonic forms *Bosmina longirostris* dominates during periods of increased supply of nutrients. Among littoral forms *Chydorus sphaericus* and *Alona rectangula* dominate and *Leydigia acanthocercoides* and *Disparalona rostrata* appear for the first time. Species indicating warmer water e.g., *Camptocercus rectirostris, Graptoleberis testudinaria* and *Pleuroxus* spp., are also present accompanied by *Acroperus harpae, Eurycercus lamellatus* and *Alona affinis*, which are often associated with a high density of water plants. Subzone Bór Vb (14.90–15.03 m) is characterized by the highest frequency and diversity of Cladocera remains and species. *Chydorus sphaericus* and *Alona rectangula* dominate in this zone. The planktonic forms disappear and the presence of *Graptoleberis testudinaria, Camptocercus rectirostris* and *Pleuroxus* spp. suggests that the warm climatic conditions continued.

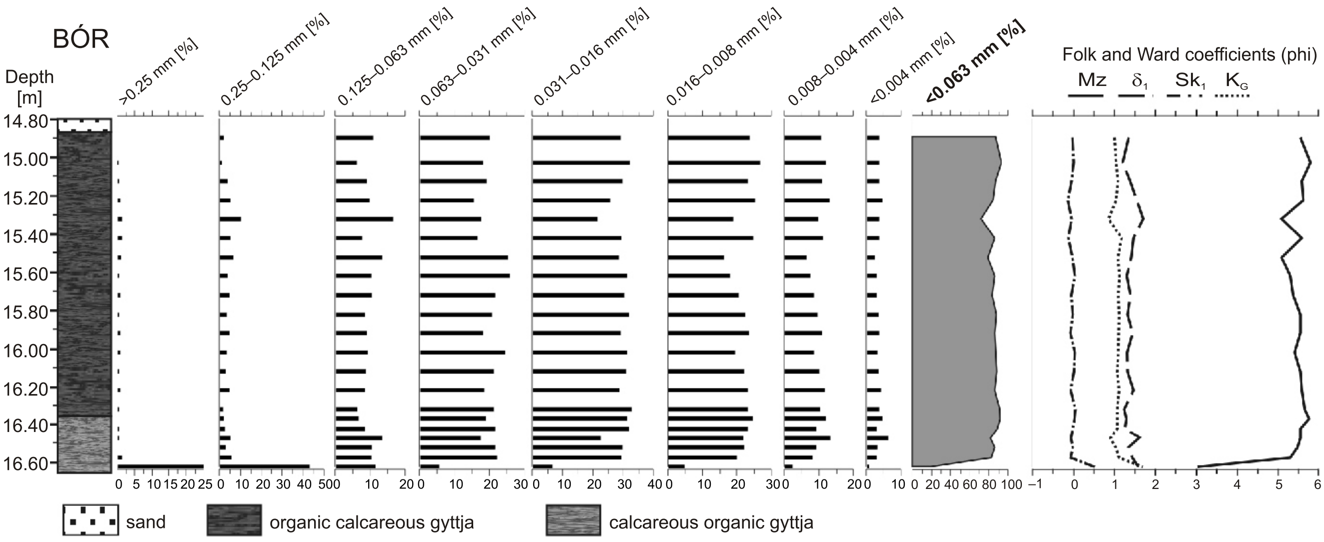

Fig. 5. Grain-size composition and Folk and Ward coefficients of the mineral matter in gyttja

Explanations as in Figure 2

GRAN-SIZE ANALYSIS OF GYTTJA

The grain-size distribution varied only slightly along the studied profile. Excluding the lowest sample, the sediment consists of silts dominated by the coarse silt fraction (0.031–0.016 mm) which makes up, on the average, about 30% of the sample weight. The very coarse silt (0.063–0.031 mm) and moderately coarse silt (0.016–0.008 mm) account for 20 and 22%, respectively (Fig. 5). The total content of silt-clay fraction (<0.063 mm) is 85% on average.

The grain-size variability in the profile was relatively low. It was noticed (on depth 15.5–16.5 m) that there is a tendency towards a gradual increase of the mean grain-size (Fig. 5). The tendency is primarily related to a reduction of moderate- and fine-grained silt fractions (0.016–0.008 and 0.008–0.004 mm, respectively; Fig. 5). The standard deviation (δ_1), a measure of sediment sorting, varied from 1.1 to 1.7 phi, indicating poor sorting. Grain-size distribution skewness varied slightly only, from –0.1 to +0.1, a range typical of symmetrical distributions (Racinowski et al., 2001).

GEOCHEMISTRY

In the organic deposits content of the $CaCO_3$ is much higher than in mineral deposits and is 25.9% on average (Fig. 6). The highest value was obtained in the base part – in the calcareous detrital gyttja – almost 50%. Determination of the reaction allows for the classification biogenic deposits as neutral and slightly alkaline (Okruszko, 1976). The lowest values were estimated in the base part while in the middle and top part of the organic deposits, reaction ranges from 7.2 to 7.5. The conductivity of deposits is characterized by considerable variability. The value of that parameter exceeds 1200 μS in the base, decreases in the middle part of the profile to 540 μS and at the top again increases to 1280 μS.

Contents of sodium, potassium, magnesium and lead in the chemical composition of analysed sediment is, on average, much lower than those recorded in silty formations or sandstones (Table 1). Contents of copper and zinc is within the range typical to sandstones, whereas the content of calcium, iron, and manganese is distinctly higher, compared to contents known from silty deposits.

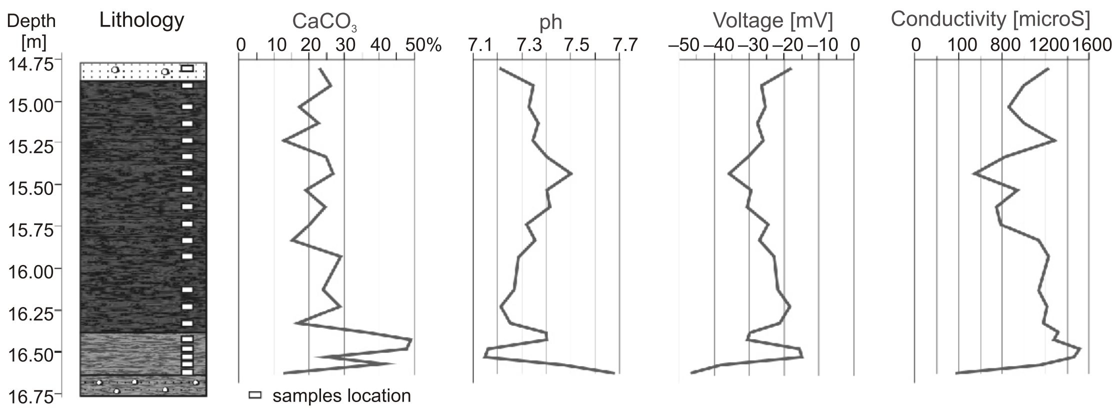

Fig. 6. Physicochemical properties of organic deposits from the Bór site

Explanations as in Figure 2

Table 1

Average concentration of mineral material (MO) and average contents of elements analysed in the profiles and geochemical intervals (cf. Fig. 5)

Geochemical interval	MO [%]	Na [mg/g]	K [mg/g]	Ca [mg/g]	Mg [mg/g]	Fe [mg/g]	Mn [mg/g]	Cu [µg/g]	Zn [µg/g]	Pb [µg/g
Bór; average	17.1	0.16	1.37	108.9	3.20	48.92	1.34	7.48	35.53	1.20
Silty deposits*	–	7–15	22	22	15	33–47	0.4–0.8	40–60	80–120	20–40
Sandstones *	–	10–15	12	27	7–10	9–30	0.1–0.5	5–30	15–30	5–10
Bór III	15.7	0.15	1.35	95.1	3.15	52.24	1.36	6.92	32.88	0.62
Bór II	22.9	0.17	1.60	96.4	3.53	47.78	1.75	8.68	45.82	1.93
Bór I	7.1	0.13	0.91	150.5	2.58	47.21	0.47	5.76	18.14	0.46

* – contents most frequently found in silty deposits and sandstones (according to Kabata-Pendias and Pendias, 1993)

Table 2

Bór profile: coefficients of correlation between metal contents and per cent contribution of silt-clay fraction (<0.063 mm) and organic matter concentration (bold characters denote highly significant correlations, as shown by Student's t test)

R	0.063	MO	Na	K	Ca	Mg	Fe	Mn	Cu	Zn	Pb
0.063	1										
MO	0.51	1									
Na	0.67	0.62	1								
K	0.52	0.60	**0.88**	1							
Ca	0.43	–0.14	0.02	–0.15	1						
Mg	0.57	0.64	**0.84**	0.88	0.12	1					
Fe	0.63	0.24	0.53	0.42	0.46	0.53	1				
Mn	0.46	**0.93**	0.52	0.49	–0.11	0.52	0.23	1			
Cu	0.42	**0.81**	0.56	0.60	–0.27	0.52	0.12	0.66	1		
Zn	0.54	**0.88**	0.70	0.72	–0.03	**0.79**	0.24	**0.78**	0.73	1	
Pb	0.39	0.48	**0.74**	0.82	–0.08	**0.76**	0.15	0.28	0.51	**0.74**	1

The analysed sediments show a statistically significant (at the level of 0.1%) positive correlation between the concentration of organic matter and the contents of manganese, zinc, and copper as well as weak correlation in case of magnesium, sodium, and potassium (Table 2). Moreover, significant connections are observed in contents of Zn and Mg, Cu and Mn, and some lithophilous metals: Na and K, Na and Mg, and K and Mg (Table 2). Calcium and iron do not show stronger correlations with other assayed elements. The percentage content of silt-clay fraction (<0.063 mm), correlates the strongest with content of sodium and iron (Table 2), although the significance of those correlations is at the level of 1%.

Analysis of geochemical diagrams (Figs. 7 and 8) allow for the identification of three geochemical intervals, which are markedly different in their chemical composition.

Interval Bór I (16.43–16.63 m) shows the highest content of mineral material (>92%), and calcium (150.5 mg/g) but the lowest values of the remaining elements, particularly potassium, manganese and zinc (Table 1). The highest Fe/Mn ratio (80–180) as well as somewhat elevated Cu/Zn and Ca/Mg are observed (Fig. 8).

Interval Bór II (15.5–16.43m) contain on average 22.9% organic matter (up to about 30%). This level is characterized by relatively the highest concentrations of all metals except iron, while the high contents of Ca and Zn in the base of interval distinctly decreases to the top. In the case of the other elements there are only some slight variation of the contents, which are associated only to a small extent with subtle changes in lithology, what is visible, inter alia, in correlations of organic matter content and percentage of clay-silty fraction with each metal.

Throughout the interval the Fe/Mn and Cu/Zn ratios are uniform and low. On the other hand, the Fe/Ca ratio was clearly higher than in the Interval Bór I, indicating an increasing trophic status of the basin. Minor variations of Ca/Mg ratio are observed, what probably reflect subtle changes in the supply of mineral deposits.

Interval Bór III (14.90–15.50 m) was identified on the base of changing in the trend of the calcium and zinc contents in the profile (Fig. 7). Contents of individual metals, except iron, are lower than those in Interval Bór II. In addition, the interval shows initially a growing and then a decreasing trend in the content of almost all elements, which reflects changes in grain-size of the mineral fraction (Fig. 5) which attain, on average, ca. 85%. In the top part of the interval the Fe/Mn ratio increases.

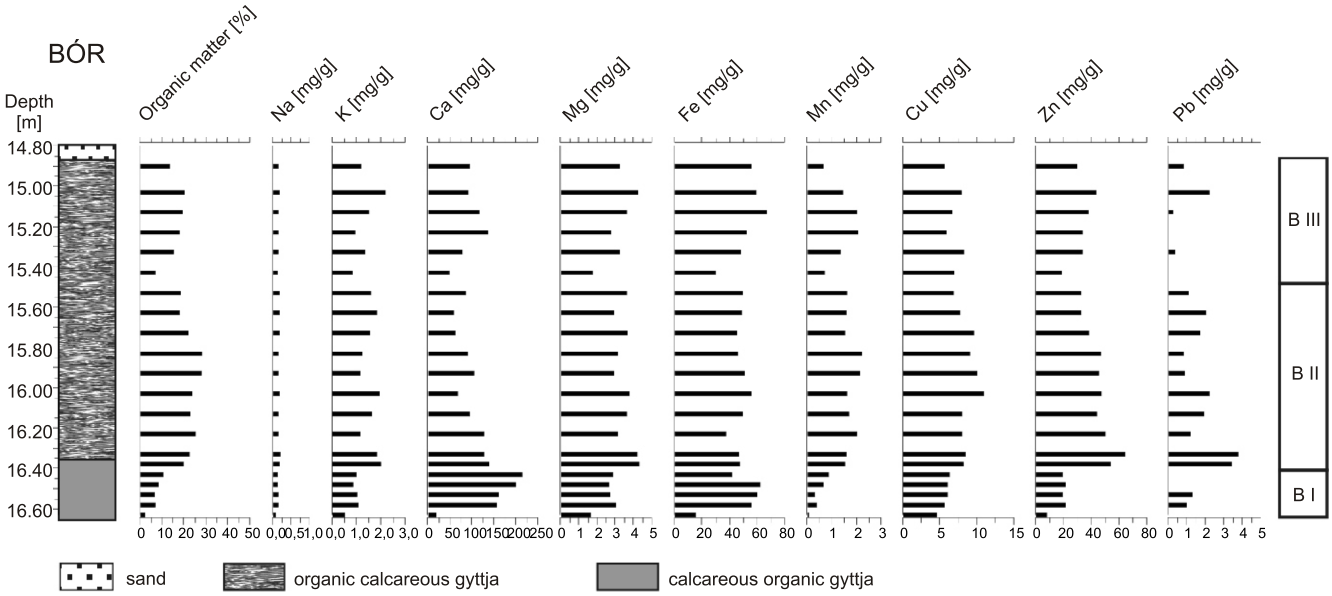

Fig. 7. Geochemical diagram

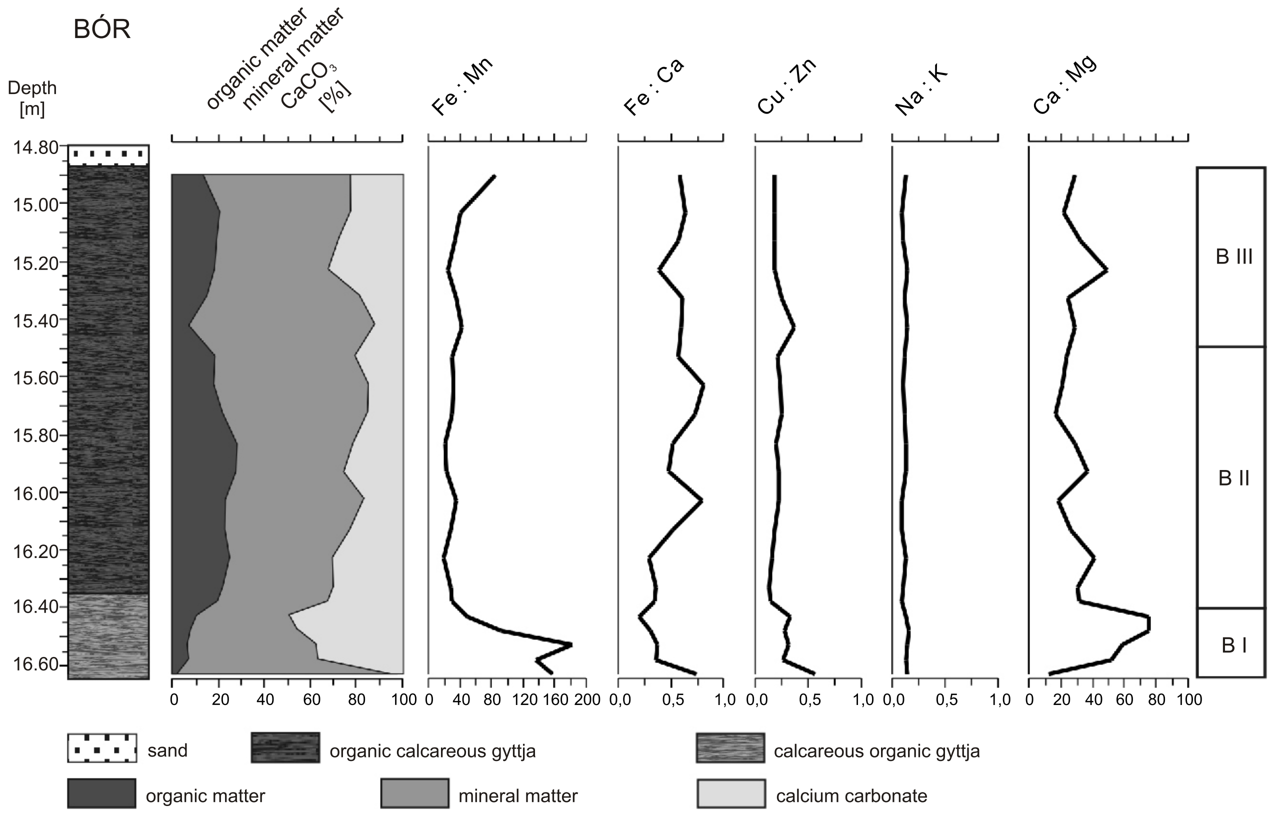

Fig. 8. Vertical differentiation of selected geochemical parameters

PHASES OF THE BÓR PALAEOLAKE DEVELOPMENT

The obtained results allow to distinguish four phases of the lake development in the Bór site (Fig. 9):

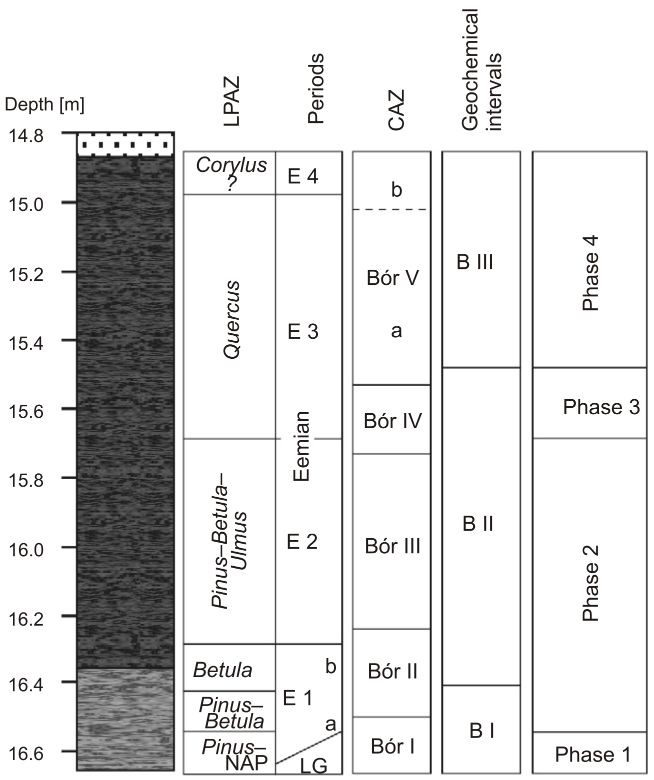

Fig. 9. Phases of the Bór palaeolake development

Phase 1 (16.53–16.63 m)

The lowest part of the investigated sediments was deposited in the final part of the Wartanian, in a cold climate when tundra associations were present and intensive calcium carbonate supply to the sedimentary basin took place. That period was also characterized by a high, although gradually decreasing, intensity of mechanical denudation processes indicated by more than 90% contribution of the mineral fraction, at first sandy and then silt-clay (Fig. 5) and the high Fe/Mn ratio with the simultaneous high Fe contents (Mackereth, 1966). It may be concluded that sedimentation at Phase 1 proceeded during a cool climate when the plant cover was sparse, which is in agreement with the pollen analysis results. The conditions were most probably analogous to those prevalent in the Late Glacial in the European Lowland, when intense mechanical denudation was accompanied by carbonate deposition in sedimentary basins, particularly as a result of hydrocarbonate iron supply with groundwater (Nowaczyk and Tobolski, 1980; Kowalkowski, 1988; Borówka, 1992; Borówka and Tomkowiak, 2010; Forysiak et al., 2010). At the beginning Cladocera species tolerating cool, oligotrophic water existed in the lake. The slightly higher amount of Cladocera and presence of planktonic forms might be a consequence of favorable conditions like an increase in the amount of water in the reservoir and/or better thermal conditions. The sediments of the upper part of this phase, probably developed in the very beginning of Eemian Interglacial.

Phase 2 (15.68–16.53 m)

The characteristic feature of the Phase 2 is the highest content of the organic material (>20%) and significant amount of $CaCO_3$ (15–30%). This phase include three LPAZ: *Pinus–Betula, Betula,* and *Pinus–Betula–Ulmus*, which are correlated with the oldest regional pollen zones of Eemian – E1 and E2. The beginning of the Eemian Interglacial was expressed by a greater diversity of Cladocera (Fig. 4) and the initially high frequency of planktonic forms (Cladocera zone Bór II). It is possible that this situation was respond to increase of water table. The diversity of Cladocera species increased at the beginning but later decreased to rise again (Cladocera zone Bór III). Species indicating warmer water, *Camptocercus rectirostris, Pleuroxus trigonellus, P. truncatus* and *P. uncinatus* are present. Also species associated with a high density of water plants, occur there. Lack of planktonic forms which is observed in middle part of this zone, probably indicates a short-term shallowing, but can also be a response to geochemical changes in water (Fig. 7) or reflect subtle changes in the supply of mineral deposits (Fig. 5).

Higher organic matter concentration, accompanied by a simultaneous increase of the Fe/Ca ratio, which indicate a raising of the trophic level, most likely associated with warming of the climate. In the base part of the Phase 2 (lower part of the geochemical Interval Bór II), the highest Zn and Pb contents are observed, likely as a result of bioaccumulation of those elements. The increase in Zn content could have been associated with the appearance of the light-requiring birch characterized as having a strong ability to bioconcentrate zinc (Fortescue, 1980; Reimann et al., 2007). The relatively low Fe/Mn ratios evidenced persistence of oxidative conditions in the water body (Mackereth, 1966; Borówka, 2007).

Phase 3 (15.50–15.68 m)

In the Phase 3 the percentage of the mineral material increases and values of the Mz coefficient decreases, what indicates that the basin became a recipient of a fairly high amount of mineral material, including fine sands. It may thus be contended that the water body was either a flow-through. The Phase 3 is connected with the beginning of the *Quercus* LPAZ with characteristic rapid increase amount of *Quercus* pollen and increased percentage of the NAP, including plants of wet communities. The diversity of Cladocera species decreases at the end of phase, the most numerous were *Chydorus sphaericus* and *Alona affinis. Daphnia pulex* and *Graptoleberis testudinaria* appears for the first time. The occurrence of *Daphnia pulex*, which is a species typical of the open-water zone, suggests a slight raise of the water level in the reservoir, perhaps due to the inflow of flood waters into the basin.

The vegetation cover was dense in this part of the Eemian Interglacial, which excludes the intensification of the denudation or aeolian processes. The increasing of humidity and water level in the lake can by accounted for flood activity.

The gradual reduction of calcium carbonate content (Fig. 8) can indicate a decreasing rate of leaching of that compound from the former drainage area, which could have been associated with: exhaustion of $CaCO_3$ resources in the drainage area, more compact vegetation cover which can inhibit leaching $CaCO_3$ from soil by binding the compound via biochemical processes, or a change in the precipitation-evapotranspiration relationships in favour of evapotranspiration, which is associated with reduced infiltration of precipitation and in consequence leaching of carbonates, characterized by high solubility in water. An intake of water during floods can be take into consideration as well.

Phase 4 (14.90–15.50 m)

The Phase 4 is correlated with the upper part of the level *Quercus* LPAZ (E 3) and *Corylus* LPAZ (E 4) which determine the climatic Eemian Interglacial optimum (Mamakowa, 1988, 1989). The increase of the sum of the herbs and plants characteristic for wet communities probably reflect local conditions in the river valley bottom, whereas in case of high groundwater level a larger role could have been played by open, treeless communities.

In the Phase 4 the number of Cladocera species rapidly increased (Cladocera zone Bór Va). The presence of "thermophilic species" shows the continued warm climatic conditions. An increase in the number of phytophilous cladocerans indicates the rich macrovegetation in the lake. Presence of species which have bigger requirements, suggests a higher trophic level of the lake. Occurrence of planktonic species, which living in open-water zone suggests sufficient of water level, but finally a reduction of planktonic forms took place (Cladocera zone Bór Vb).

The high trophic level is indicated by results of analysis of changes in the Fe/Ca ratio in Interval Bór III (Fig. 8). At the same time, the supply of mineral matter, including $CaCO_3$, increased. There is also a tendency towards an increase in the Fe/Mn ratio accompanying the high iron content (Figs. 7 and 8), which also evidences the domination of allochthonous mineral matter supply (Mackereth, 1966; Boyle, 2001). It may be thus inferred that the study site located in a river valley, was experiencing an increased frequency of floods. The basin itself accumulated not only the flood-borne sediment, but also deposited plant remains (mainly leaves), which would explain the persistence of rather high $CaCO_3$ concentrations.

DISCUSSION AND PALAEOGEOGRAPHICAL CONCLUSIONS

The Bór palaeolake was a small and shallow reservoir located in the distal part of the former valley, rather far from the active river channel and close to the valley edge, where the Mesozoic substratum lays relatively high. The lake appeared as a result of abandonment of one of the channels or subchannels of the braided river which developed in the Warta River valley during the Wartanian termination. The beginning of the lake infilling took place during that time and lasted, at least to the Eemian Interglacial optimum. The top part of the organic deposits were – most probably – eroded due to intensive fluvial processes in Weichselian.

The palynological record starts from the end of the Wartanian. During that period the cladoceran succession comprises a very rich frequency which might be mirrored by a favourable conditions for zooplankton. The sediments of the Bór palaeolake were accumulated in a humid environment, most probably on the shore, which is supported by the presence of pollen grains originating from: rushes (*Sparganium, Typha latifolia*), water plants (*Nuphar*, *Potamogeton, Myriophyllum)* and large amounts of fern spores (Filicales) in the sediments. The Cladocera species indicate the oligotrophic status of the lake initially and then an increase of the trophic status in Eemian optimum. At the beginning of the Eemian optimum the water level increased, which is indicated by the increasing amount of pollen grains of the water plants and planktonic Cladocera forms. Next, the reservoir became shallower, but probably the ground water level was high, what effected in places on development of the treeless, wet communities. Generally, conditions in Bór reservoir are similar to other Polish Eemian palaeolakes (e.g,. Tobolski, 1991a; Malkiewicz, 2002; Mirosław-Grabowska et al., 2009; Pawłowski, 2011).

The impossibility of a reconstruction of the former topography made an estimation of the intensity of denudation processes difficult. The obtained results point to a lake mostly fed by calcium carbonate-rich groundwater, which is understandable in the case of nearby Mesozoic substratum. However, the sediments also contain a high proportion of carbonate-free mineral fraction, therefore it has to be assumed that it was supplied to the basin via surface transport. It is most probable that the accumulation proceeded in a small lake developed from an abandoned channel located close to a valley margin, periodically fed by surface waters and at the same time experiencing conditions amenable to groundwater transport. Physicochemical properties of deposits from Bór palaeolake are comparable to results obtained for contemporary peatland in the Bartochów site, located in the Warta River valley at the base of the Warta Hills, possibly, in an analogous situation.

The applied methods like pollen, Cladocera, geochemistry, and lithological analyses, as well as palaeogeomorphological analyses allowed for the reconstruction of an image of the functioning of the reservoir during time from Wartanian termination to Eemian Interglacial optimum. A key point of the studies was to establish the spatial relation between the Mesozoic substratum and the palaeolake location. The influence of the Mesozoic substratum manifested in the geochemical properties of the deposits and results led to the conclusion about the methods of feeding the lake. The results of investigations in the Bór site shows how important are detailed multi-proxy analyses of the organic deposits in order to establish an as wide as possible geological context which confer the possibility of reconstruct the various elements of the palaeoenvironment. It is worth investigating the river valleys, because such an investigation can provide valuable and various information.

It is worth paying attention to the estimated level of the valley beds of the sections of Warta and Vistula rivers within the Warsaw–Berlin ice-marginal streamway in Eemian Interglacial. On the west side there are two sites with Eemian Interglacial biogenic sediments: Krzyżówki (located about 2 km to the north-west from Koło, on the right bank of the Warcica River – right tributary of the Warta River) and Bór (located in the Warta River valley about 3 km south from the contemporary mouth of the Ner River) which is presented here. The base of the biogenic deposits at altitudes of 80.8 m a.s.l. in the Bór and about 71 m a.s.l. in the Krzyżówki confirm a similarity to the present course of the Warta River. On the east side the Vistula River bed in the Bzura River mouth area is located at about 54 m a.s.l. (Marks and Pochocka, 1999) and the bed of Eemian alluvia in Łęczyca vicinity lay at altitudes about 75 m a.s.l. (Jewtuchowicz, 1967). The implications of these facts are connected with the direction of the flow of the rivers drained the Łódź Plateau in the sections within Warsaw–Berlin ice-marginal streamway – to the east or to the west as Jewtuchowicz (1967) claimed. Taking into account the altitude of the Lower Bzura Valley in the Eemian Interglacial, the valleys of the rivers, which flowed through the edge zone of the Łódź Plateau should be incised deeper. Assuming that the Lower Ner Valley bed has dropped gradually similarly to those in the present day, the base level of erosion of the valleys mentioned above, should have lie on altitude 80–90 m a.s.l. and raising to the east. It corresponds well with the position of Eemian Interglacial and Early Weichselian biogenic sediments, deposited in the valley beds or wide basins in Piaski Stare (Jewtuchowicz, 1970), Walewice (Dylik, 1967), in Moszczenica Valley near Gieczno (Kamiński, 1993) and in Bobrówka Valley (Klajnert and Piechocki, 1972). These facts point to different from the present, direction of outflow of the river within the Warsaw–Berlin ice-marginal streamway in the Eemian Interglacial.

The reconstructed image of the Warta River valley during the Eemian Interglacial, compared with its contemporary image shows, how big is the transformation of fluvial relief in the past 130,000 years. Topographic differences in the valley between the edge and the bottom of the valley declined, in some parts, more than twofold (e.g., in Dobrów). The Warta River valley was a transitional valley, running through the Eemian lakeland (Klatkowa, 1990). The source area was certainly beyond the reach of the Middle Polish Glaciations, to the Koło vicinity running in a similar way as it does currently. Its downstream course is not entirely explained, however, there are suggestions that the river flowed directly north, to the Baltic Basin (Mojski, 2005).

It is also worth paying attention to the lack of an upper part of the interglacial profile (from the upper part of the Eemian Interglacial optimum) at the Bór site and in Peene Valley (Meng et al., 2009), and a hiatus in the top of the Eemian optimum in Krzyżówki site (Noryśkiewicz, 1999). One may wonder if there is a general tendency of some climate change after optimum, resulting in erosion, lowering of the groundwater level and the end of the deposition of organic sediments. However, current state of research lead to interpretation of absence of the upper parts of profiles, as an effect of Weichselian erosion.

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