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Postglacial evolution of a small lake in the South Baltic coastal zone based on geochemical, pollen and subfossil Cladocera analysis

by

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Abstract

The paper presents sedimentary records acquired as part of the research on the coastal cliff located between 221.3 and 221.4 km of the Slovincian (Słowińskie) Coast near Dębina. Palynological and subfossil Cladocera analysis of sediments combined with geochemical data proves the existence of varying environmental conditions that occurred depending on the climate fluctuation. The Dębina reservoir was formed in the Late Glacial period. Mud and gyttja were deposited in an initially cold proglacial lake. Species of Cladocera identified in this period indicate a deeper oligotrophic reservoir. The end of the Late Glacial cooling inhibited the development of fauna in the reservoir. Climate change at the beginning of the Holocene improved the habitat conditions in the Dębina paleolake, which is reflected in the growth of zooplankton biodiversity and enrichment of the aquatic pollen content. We distinguished three phases that illustrate the evolution of the studied aquatic-mire ecosystem. In the following periods, the trophic level in the reservoir increased and significant water-level fluctuations led to periodic transformations of reservoirs into peat bogs. Gradually, the water-level lowering and the intensification of eolian processes led to terrestrialization of the paleolake.

Key words: Late Glacial-Holocene transition, multi-proxy analysis, cliff paleolake, Polish Baltic Coast

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Introduction

Numerous natural exposures of sediments occur in coastal cliffs of the Southern Baltic, in the region of Middle Pomerania. They were the subject of mainly geological, geomorphological and stratigraphic studies. The stratigraphy of the Late Glacial and Holocene deposits is available for the cliff section located to the east of Ustka (Tomczak 1993; Olszak et al. 2008; 2012; Wróblewski et al. 2013). The Late Glacial sediments accumulated in shallow water reservoirs located near Orzechowo were described by Marsz & Tobolski (1993), Olszak et al. (2012), Wojciechowski (2012), and Kruczkowska et al. (2017). As part of the work related to the dynamics of the seashore, palynological studies of marine sediment cores taken from the central coastal zone of the Southern Baltic were carried out (Zawadzka 2001; Miotk-Szpiganowicz 2005). Despite adequate knowledge of geological structure and geomorphologic processes as a good basis for interpretation, comprehensive multi-proxy studies covering the period of lake formation and its evolution in the Holocene, which would provide information on fossil aquatic and terrestrial ecosystems as well as changes in the biological, climatic, and hydrological environment, are relatively rarely carried out. One of the well-known sites in the Pomerania region is the cliff in Niechorze. Two fossil lakes were studied: Niechorze I – outcropped in the cliff, and Niechorze IV – a fossil bog depression. Niechorze has been studied for many years, mostly by K. Kopczyńska-Lamparska who prepared a geological map of the area and described in detail organogenic deposits outcropping in the cliff (Kopczyńska-Lamparska et al. 1983). In addition, ^{14}C dating, pollen analysis (Brykczyńska 1978), Cladocera analysis (Szeroczyńska 1985), diatom analysis (Kopczyńska-Lamparska et al. 1983) and others were performed for these sediments. These sites provide very valuable information on the development of the area from the Oldest Dryas to the Subboreal.

Fossil cliffs containing lake and bog organic deposits are natural archives. Such reservoirs occur on cliffs relatively rarely, which is an additional difficulty in research. Their lifetime on the cliff wall is also relatively short. Depending on the season and the rate of abrasion processes, such reservoirs exposed on cliffs after the stormy period last from several months to several years. The average rate of cliff abrasion was estimated at 0.2–2.7 m/year at the coast near the study area, excluding catastrophic storms, which can cause a loss of 7–8 m (Florek et al. 2010).

Geochemical, palynological and subfossil Cladocera surveys make it possible to supplement our knowledge about the development of the area during the Late Glacial and the Holocene, which is now a border

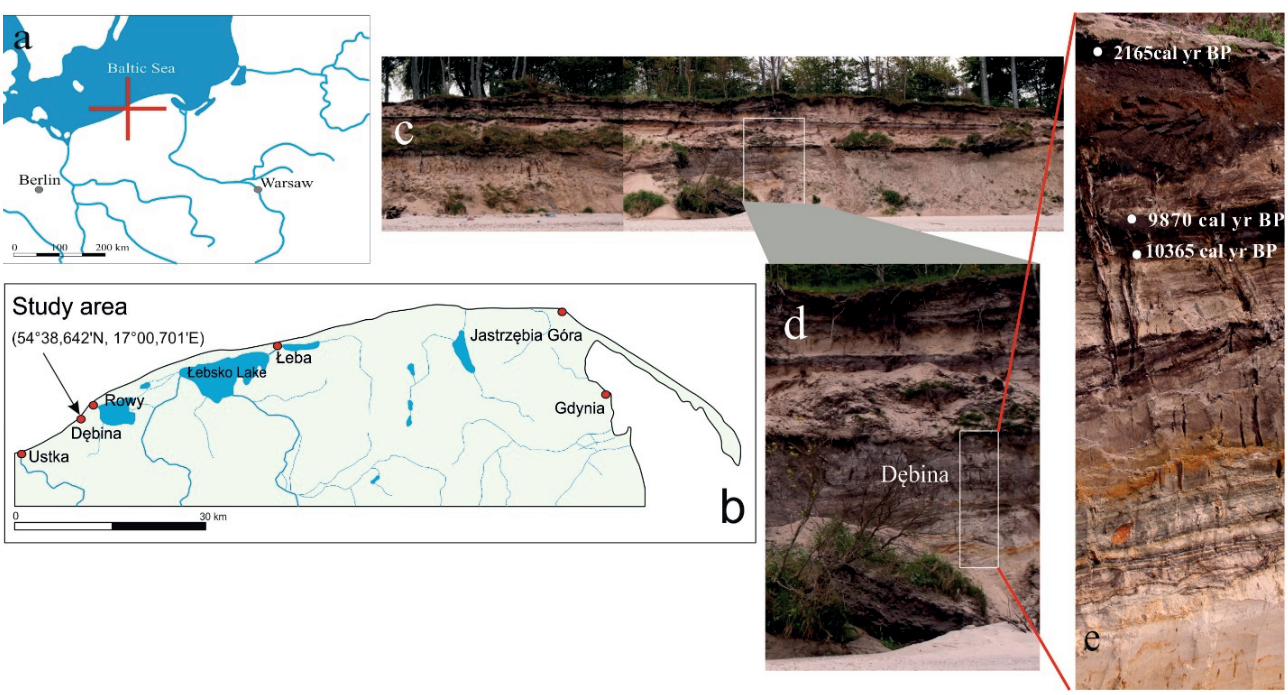

Figure 1

Location of the site (a, b), morphology of the cliff (c, d), location and morphology of the paleolake profile and its calibrated radiocarbon age (e) zone of the land and sea, formed during the period of receding glaciation and progressive warming, and will create a much more complete picture of the past environments. Pollen analysis supported by the results of radiocarbon dating plays a key role in the reconstruction of vegetation associated with water reservoirs and makes it possible to establish the chronostratigraphy of sediments (Latałowa 1982; Latałowa & Tobolski 1989).

This paper presents the results of interdisciplinary research on a small natural paleolake located near the village of Dębina. Our research aimed to reconstruct the main phases of the development of the lake and mire ecosystem and the environmental conditions, with emphasis on paleohydrological events based on multi-proxy (geochemical, pollen, and subfossil Cladocera) analysis of the Dębina profile. We have the opportunity to discover the history of this paleolake from its origin in the Late Glacial, through its development, to its decline and transformation into a mire in the middle Holocene.

Materials and methods

Study site

The investigated profile is located within the section of the coastal cliff between 221.3 and 221.4 km of the Polish Baltic coast, near the village of Dębina (54°38.642'N, 17°00.701'E) in the central part of the Slovincian Coast mesoregion (Fig. 1). The base consists of glacial till and glaciolimnic sediments of the Middle and Upper stadials of the Vistula Glaciation. The age of glacial till and glaciolimnic sediments is assigned to the Świecie Stadial (Olszak et al. 2008), the Pomeranian Phase and the Gardno Phase (Petelski 1985; 2006; Jasiewicz 2005). The contemporary landscape of this area was shaped in the Late Glacial during the Gardno Phase of the Vistula Glaciation, 14500–14300 yr ^{14}C BP (Rotnicki & Borówka 1994), and by the Holocene litho-morphogenetic processes, including the eolian activity (Olszak et al. 2008) and coastal abrasion (Florek et al. 2010), whose intensity varied over time. Eolian sands are the major type of superficial deposits within the investigated site and its surroundings. They usually lie on stratified shallow covers of fluvioglacial sands, which in some layers are enriched with organic matter, or on lacustrine sediments (lacustrine mud and calcareous gyttja). Coastal dunes are covered with forests of spatially varied species composition, usually with a dominance of pine. At the investigated site, it is a mixed forest with beech as the main component.

The climate of the studied area is strongly influenced by the sea. The average annual temperature is about 8.1°C, with the maximum in July (average 17°C) and the minimum in January (average 0.3°C). Mean annual precipitation amounts to about 641 mm (Baranowski 2008). There are 10–32 days with storms during the year.

Fieldwork was carried out in May 2015. A 250 cm profile was collected for the research, which included lake bottom sediments (200–250 cm – fluvioglacial sands) and lake-bog sediments: non-calcareous lacustrine mud, calcareous gyttja, sand with organic matter, peat (0–200 cm). The entire profile was subjected to geochemical analysis. Part of the profile containing lacustrine and peat deposits (8–200 cm) was used for palynological and Cladocera analysis.

Radiocarbon dating

Radiocarbon dates were obtained for three samples collected from the Dębina profile. Dating was performed in the Laboratory of Absolute Dating in Cianowice. Conventional dates were calibrated using the OxCal 4.2.3 software (Bronk Ramsey 2013) and the IntCal13 calibration curve (Reimer et al. 2013). In this paper, dates are given in calibrated years BP. Detailed information on dating is included in Table 1.

Geochemical analysis

One disturbed and two volumetric (using 100 cm^3 steel rings) samples were collected from each sedimentary layer. In the volumetric samples, the bulk density and total porosity were determined by the dry weight method. Disturbed samples were dried at 40°C and sieved through a 2.0 mm sieve to remove the skeleton fraction. The particle size distribution was analyzed by the mixed pipette and sieve method, pH was measured potentiometrically in suspension with

Table 1

Results of radiocarbon dating of the Dębina profile

Depth (cm)	Laboratory number	Dated material	Result of dating in ^{14}C yr BP	Calibrated ages in ^{14}C cal yr BP (95.4%) probability	Calibrated ages in ^{14}C cal yr BP (Median)
5–10	MKL-2590	bark	2160 ± 60	2318–2001	2165
70–72	MKL-2591	organic remains	8810 ± 90	10 173–9596	9870
83–85	MKL-2592	organic remains	9170 ± 110	10 663–10 160	10 365

water at the soil:water ratio of 1:2.5 (Elmetron CPC-401 pH-meter), the content of $CaCO_3$ was determined according to Scheibler's method, total organic carbon (TOC) – by the Tyurin method in mineral samples and by the Alten method in organic samples (Dziadowiec & Gonet 1999), and total nitrogen (TN) – by the Kjeldahl method (van Reeuvijk 2002). The content of phosphorus was analyzed by the molybdenum blue method (van Reeuvijk 2002) after sample digestion in a mixture of 40% HF and 60% $HClO_4$. In the same solutions, the total content of iron, aluminum, potassium, calcium, magnesium and manganese was determined using the microwave plasma atomic emission spectrometry (Agilent 4100 MP-AES). Based on the results of particle size distribution analysis, we calculated logarithmic graphical measures after Folk & Ward (1957) using Gradistat 5.11 software (Blott & Pye 2001) (Fig. 2).

Pollen analysis

We collected 24 samples of 1 cm³ at intervals of 8 cm from a depth of 200 cm to 8 cm to analyze pollen from the Dębina profile. The samples were boiled in 10% KOH, treated with 10% HCl or soaked for several days in HF (depending on sediment composition), and subsequently acetolyzed (Faegri & Iversen 1989; Dybova-Jachowicz & Sadowska 2003). The total number of pollen grains counted in each sample up to a minimum of 200 grains of arboreal pollen (AP; low pollen frequency) was used to calculate the concentration of trees, shrubs, aquatic plants and non-pollen palynomorphs (NPPs) (Fig. 3). The identification of microremains of fungi and faunal organisms (NPPs) followed van Geel & Bohncke (1978; 1981) and Barthelmes et al. (2012). Zonation was carried out visually based on changes in the dominant pollen,

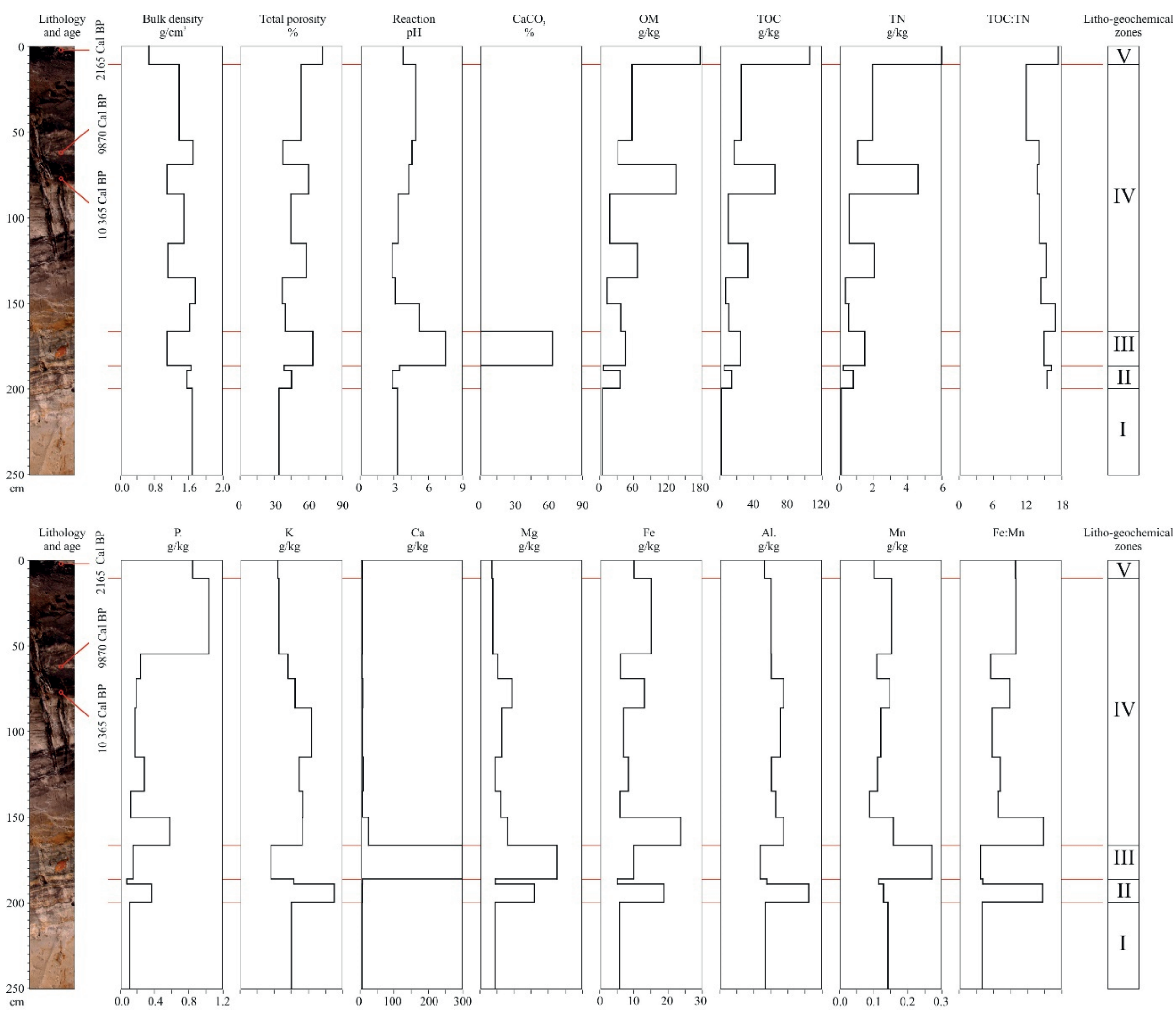

Figure 2

Lithology, age (in calibrated years BP) and selected physical and chemical properties of the Dębina profile

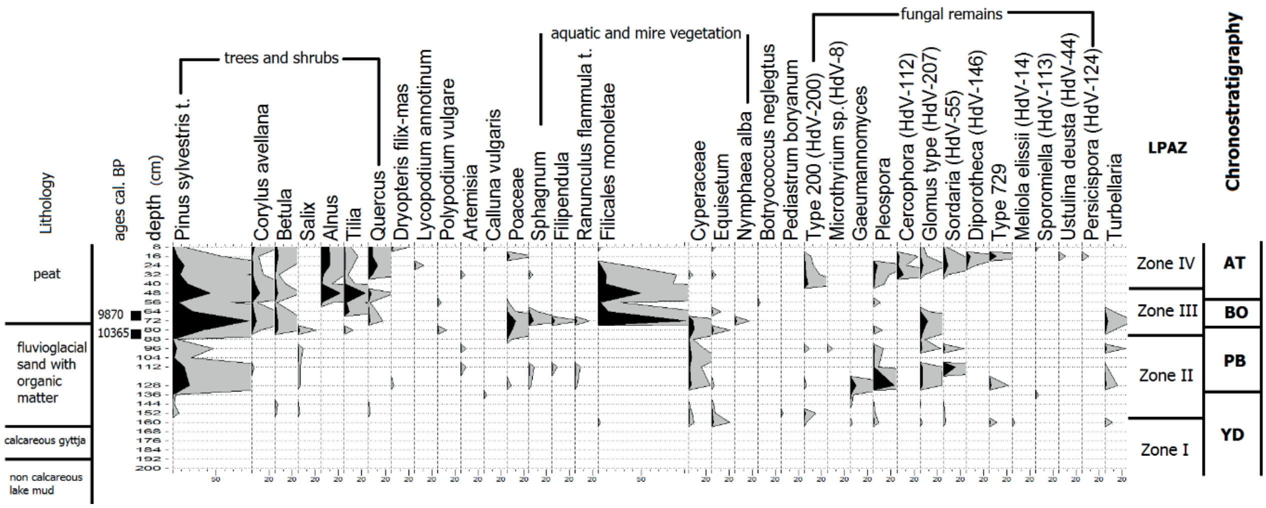

Figure 3

Pollen concentration diagram, of non-pollen palynomorphs (NPPs), aquatic and marsh plants from the Dębina profile

spores, and NPP taxa. The diagram was constructed using the POLPAL software (Nalepka & Walanus 2003). For the purpose of determining the aquatic concentration of trees, shrubs, and pollen/NPPs (Stockmarr 1971), Lycopodium tablets produced by the Department of Quaternary Geology, University of Lund, were added.

Cladocera analysis

The Cladocera analysis was performed in 48 samples collected every 4 cm from a depth of 200 cm to 8 cm from the Dębina profile. Samples of 1 cm^3 were prepared using a standard procedure (Frey 1986; Korhola & Rautio 2001). After the removal of carbonates using 10% HCl, each sample was boiled in 10% KOH for 30 min, washed with distilled water, and sieved through a 40 μm mesh sieve. The fine material was transferred into a polycarbonate test tube. Prior to counting, the remains were colored with safranin T. The analysis was performed under a Nikon model Eclipse Ci-L microscope with magnifications of 10, 40, and 60×. A minimum of 200 remains of Cladocera (3–8 slides) were examined in each sample. First, all remains from each slide were counted (headshields, shells, postabdomens, postabdominal claws, and antennules) and then converted to one Cladocera specimen and all ephippia together.

Identification and ecological interpretation of the Cladocera remains were based on Goulden (1964), Szeroczyńska (1985; 1998), Hofmann (1986; 2000), Korhola (1990), Duigan (1992), Flössner (2000), and Szeroczyńska & Sarmaja-Korjonen (2007). The results are shown in Figure 4, including the percentage diagram, the total number of Cladocera individuals, the number of species and their biodiversity. The numerical analysis was performed using the POLPAL software (Nalepka & Walanus 2003). The Cladocera species were classified into four habitat-preference groups: bottom-dweller species, species associated with or restricted to vegetation, planktic (offshore) and littoral (meiobenthic) species (Flössner 1964; Whiteside 1970; Whiteside & Swindoll 1988; Korhola 1990).

Results

Radiocarbon age and stratigraphy

The radiocarbon age of organic materials collected from the investigated profile ranged from 10 365 to 2165 yr cal BP (Table 1). The calibration results are presented for each date with a median (Table 1). The youngest date (2165 yr cal BP) obtained for bark particles from the roof (5–10 cm) of the profile determines the period of burial of lacustrine deposits by eolian sands. The remaining two C14 dates, 10 365 and 9870 yr cal BP for depths of 85 and 70 cm, respectively, confirm the proglacial nature of the investigated paleolake. The sedimentation rate in the period of lake development was about 0.27 mm yr^{-1}.

Lithology and geochemistry of sediments

Based on lithological and chemical properties, we distinguished five litho-geochemical zones, which developed as a result of various geomorphological processes (Fig. 2).

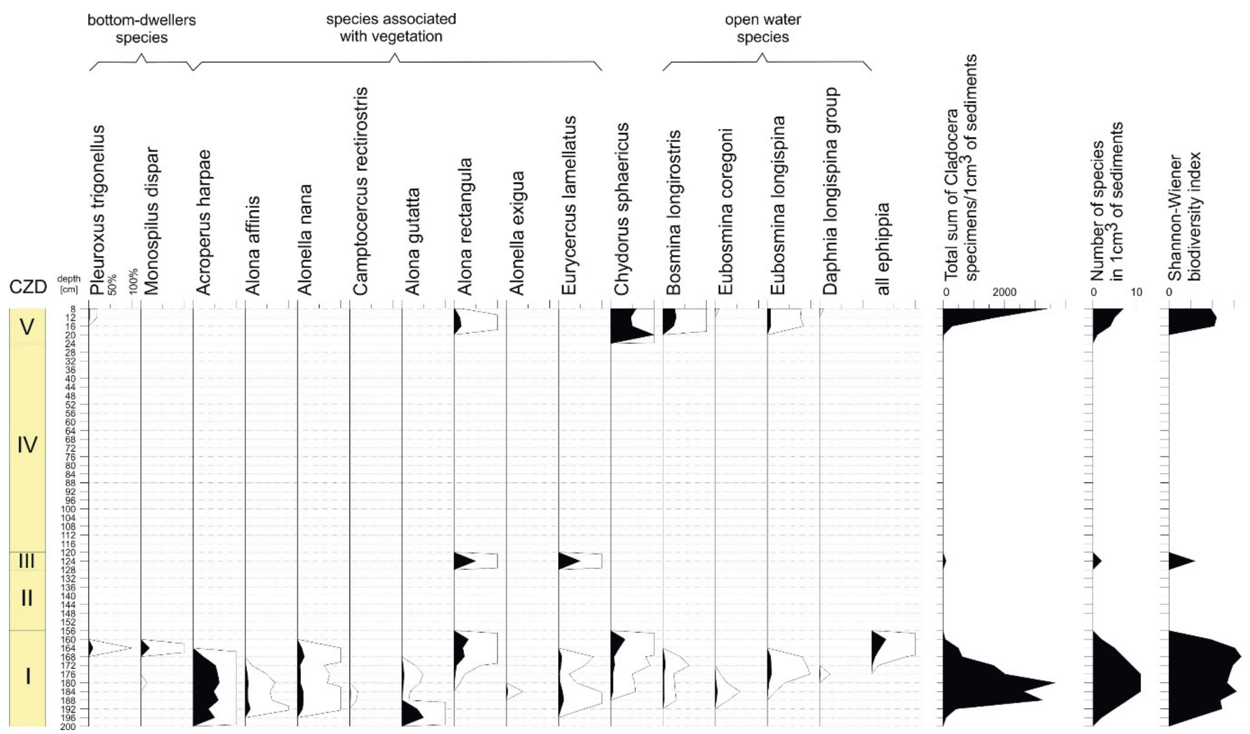

Figure 4

Relative abundance diagram of subfossil cladoceran taxa, the total number of Cladocera specimens, and the number of species in the Dębina profile

Zone I (250–200 cm) is the base part of the reservoir formed as a result of fluvioglacial processes and represents moderately sorted, fine fluvioglacial sand (Table 2). It is characterized by relatively low total porosity (33.8%), strongly acidic pH (3.2), as well as low content of P (0.09 g kg^{-1}), K (9.0 g kg^{-1}), Ca (1.9 g kg^{-1}), Mg (0.8 g kg^{-1}), Fe (5.5. g kg^{-1}) and Al (13.9 g kg^{-1}). TOC and TN occur in trace amounts.

Zone II (200–186 cm) is a record of sedimentation in a newly developed lake. Sediments are non-calcareous lacustrine mud (sandy loam) with sandy layers. These are strongly acidic (pH 2.7–3.4) sediments, slightly enriched with TOC (1.42–11.13 g kg^{-1}) and TN (0.09–0.71 g kg^{-1}). The content of P (0.36 g kg^{-1}), K (16.7 g kg^{-1}), Mg (3.2 g kg^{-1}), Fe (19.0. g kg^{-1}) and Al (31.2 g kg^{-1}) in lacustrine mud is higher than in the sandy layers and deposits of Zone I.

Zone III (186–166 cm) consists of stratified, calcareous gyttja. This highly porous (63.8%) material contains 64.6% of $CaCO_3$ and 4.5% of organic matter. We can observed a considerable increase in the content of TOC (21.49 g kg^{-1}), TN (1.41 g kg^{-1}), Ca (300.1 g kg^{-1}) and Mg (4.6 g kg^{-1}) compared to lacustrine mud (Zone II). The concentrations of P (0.12 g kg^{-1}), K (5.3 g kg^{-1}), Fe (9.9. g kg^{-1}) and Al (11.7 g kg^{-1}) decreased.

Zone IV (166–10 cm) is a sequence of stratified, poorly and moderately sorted fluvioglacial sands enriched with organic matter. The sands from the shoreline zone of the lake were eroded and deposited at its bottom. This process probably occurred in the lake catchment in cold climate (tundra vegetation). Sediments of this zone show large variability in terms of physical and chemical properties, however, some temporal trends are clearly visible (Fig. 2). Total porosity ranged from 36.5 to 60.4% and was positively correlated with the content of organic matter (0.7 to 13.6%). TOC amounted to 2.88–65.09 g kg^{-1}, TN – 0.18–4.66 g kg^{-1} and P – 0.07–1.05 g kg^{-1}. The content of elements increased with time but strongly varied among the distinguished sedimentary layers. The observed trend suggests a gradual increase in the trophic state of the lake, which is also confirmed by vertical variability in the TOC:TN ratio. Fe (2.9–23.9 g kg^{-1}) and Mn (0.05–0.16 g kg^{-1}) also showed increasing temporal trends. The content of K and Mg decreased and varied from 6.7 to 12.7 g kg^{-1} and from 0.6 to 1.9 g kg^{-1}, respectively. The concentrations of Al were relatively stable over time.

Zone V (10–0 cm) represents the final stage in the lake development. It is composed of peat-like materials containing numerous remains of trees. The

Table 2

Particle size distribution and logarithmic measures of the studied deposits

Depth (cm)	% of				Logarithmic measures (ϕ)			
	gravel	sand	silt	clay	M_G	σ_G	Sk_G	K_G
0–10	0.0	90.7	5.1	4.3	2.83	1.49	0.22	1.42
10–56	0.8	91.4	6.1	2.5	2.46	1.29	0.30	1.13
56–70	0.0	93.8	4.6	1.6	2.24	1.15	0.21	1.16
70–87	1.4	90.3	6.0	3.7	2.55	1.74	0.22	1.54
87–115	0.0	93.8	4.5	1.7	3.00	0.98	0.14	1.13
115–125	4.6	93.0	4.1	2.8	2.57	1.50	-0.07	1.47
125–135	0.0	100.0	0.0	0.0	1.34	0.81	0.00	1.38
135–150	0.0	91.3	7.1	1.6	2.53	1.42	0.23	1.30
150–166	1.2	93.9	4.5	1.6	2.44	1.26	-0.03	1.26
166–186	0.0	27.3	71.4	1.3	5.31	1.67	0.02	0.96
186–190	0.0	100.0	0.0	0.0	2.36	0.76	-0.11	0.91
190–200	0.0	67.9	25.7	6.4	4.21	2.18	0.35	1.29
200–250	0.0	97.8	1.5	0.7	2.26	0.88	0.04	0.90

piece of bark was dated by the radiocarbon method at 2002 ± 60 cal yr BP. This date determines the period of sediment burial by eolian sands. Sediments of this zone are relatively rich in TOC (107.35 g kg^{-1}) and TN (6.05 g kg^{-1}). The content of remaining elements did not differ significantly from sediments in the roof of Zone IV.

Pollen analysis

Based on pollen analysis of trees, shrubs, herbaceous, aquatic and mire vegetation, as well as other macrofossil NPPs, we distinguished three zones illustrating the evolution of the studied aquatic-mire ecosystem (Fig. 3). The most important findings in specific zones are described below.

Zone I (200–156 cm). Pollen plants and non-pollen palynomorphs have not been preserved in the studied lacustrine sediments.

Zone II (156–84 cm). *Pinus* pollen dominates in this zone. Rushes with representatives of the Cyperaceae family and *Equisetum* sp. predominated around the lake. The significant presence of fungal spores *Glomus* is correlated with the increasing frequency of animal remains of *Turbellaria*. A significant amount of fungal spores *Pleospora* is present at a depth of 128 cm.

Zone III (84–44 cm). *Pinus* sharply increases but decreases towards the top. *Corylus*, *Alnus*, *Quercus* and *Tilia* start to appear in this zone, and the abundance of *Alnus* and *Tilia* rapidly increases. The NAP percentage is high in the bottom part and lower in the upper part of the zone. *Thelypteris palustris* predominated in rush vegetation. *Filipendula ulmaria* and *Ranunculus flammula* occurred at the bottom of the zone in some places of wetlands. Macrophytes were represented in the reservoir by *Nymphaea alba*. We observed increasing frequencies of fungal spores *Glomus* and animal remains of *Turbellaria*.

Zone IV (44–8 cm). The zone is characterized by the maximum value of *Quercus*, stable and low values of *Tilia* and *Corylus* and the decline of *Pinus*. The content of *Alnus* pollen is smaller compared to the previous pollen zone. Fungal remains of Type-729 and Poaceae clearly increase in the upper part of the zone, while ascospores of *Cercophora* sp., *Sordaria* sp., *Diporotheca*, *Pleospora* and chlamydospores of *Glomus* sp. decline. *Filicales monolete* occurred in plant communities, which is reflected in the frequency of *Thelypteris palustris* spores.

Cladocera analysis

The subfossil cladoceran fauna of sediments in the Dębina profile is represented by 15 species that belong to three families: Bosminidae, Chydoridae, and Daphniidae. Most of the remains belong to the family of Chydoridae (11). Cladocera remains were identified in only three sections of the core – at depths of 200–156 cm (Zone I), 128–120 cm (Zone III) and 24–8 cm (Zone V) (Fig. 4). In the first zone, *Acroperus harpae* from the Chydoridae family was dominant. In the second zone, only two species were found, both from the Chydoridae family. In the third zone, species associated with the eutrophic state of the reservoir predominated, including *Chydorus sphaericus* and *Bosmina longirostris*. The distinguished Cladocera zones are described in detail below.

Zone I (CZD 200–156 cm). Fourteen species of Cladocera were identified in the sediments (Fig. 4). The total number of individuals was about 3650 per 1 cm^3 of sediments. This zone was the most abundant in Cladocera species and their individuals. The dominant species were *Acroperus harpae* (max 60%), *Alona guttata* (max 35%), *Alonella nana* (max 14%) and, at the end of this zone, *Chydorus sphaericus* (max 23%) and *Alona rectangular* (max 33%); the number of all ephippia also increased (33%). The largest group of species comprised those associated with water: *Eurycercus lamellatus, Acroperus harpae, Alonella nana, Alona guttata*. A high abundance of species typical of open water zones (max 15% of all species) and the highest index of biodiversity (0.82) were determined.

Zone II (CZD 156–128 cm). Lack of Cladocera remains in the sediments.

Zone III (CZD 128–120 cm). Remains of only two Cladocera species – *Alona rectangular* (33%) and *Eurycercus lamellatus* (33%) – and ephippia (33%) were identified in this zone. These species are closely related to the macrophyte zone. The total number of individuals in the sediments was about 100 per 1 cm^3 and the biodiversity index reached the lowest value of 0.3.

Zone IV (CZD 120–24 cm). Lack of Cladocera remains in the sediments.

Zone V (CZD 24–8 cm). A slight improvement in the zooplankton development conditions was observed in this zone, which is reflected in the increasing frequency of species – up to six species, and the increased number of Cladocera individuals of up to 3397 ind. per 1 cm^3 of sediments. The dominant species are *Chydorus sphaericus* (max 59%), *Alona rectangula* (17%), and *Bosmina longirostris* (31%). Species from the open water zone occurred too: *Eubosmina longispina* and *Eubosmina coregoni* and the *Daphnia longispina* group. The index of biodiversity was 0.54.

Discussion

The investigated profile constitutes an archive of fragmentary environmental changes during the Late Glacial and the Early Holocene. Physical and chemical properties, radiocarbon dating, Cladocera, and pollen analysis were used to interpret this information and to reconstruct the major phases of the evolution and processes of the lake-peatbog ecosystem and factors influencing them. Based on the obtained data, we distinguished three main phases of the development of the Dębina paleolake (Fig. 5). The first phase includes the formation of a lake basin in the Late Glacial, which is a typical lacustrine phase with lacustrine mud and gyttja accumulation. The second transition phase involves the further development of the basin during the Late Glacial (Younger Dryas) and the Early Holocene. The third and final phase covers the decline of the lake and its transformation into a peat bog at the end of the Preboreal period. The characteristics of each phases involve a description

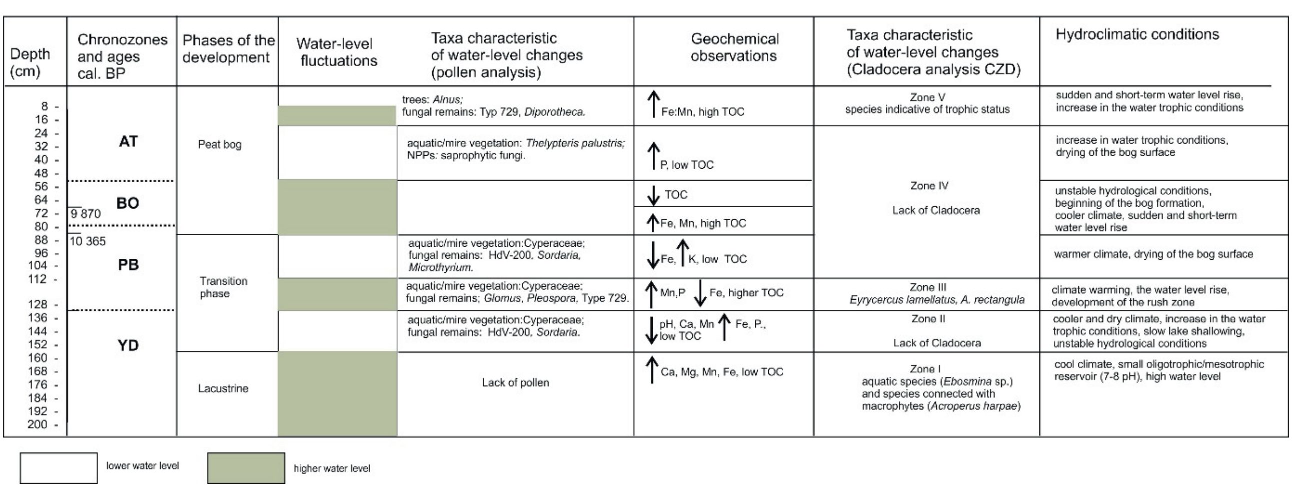

Figure 5

Reconstruction of the hydroclimatic conditions in the Dębina paleolake during the Late Glacial and the Early Holocene of environmental conditions prevailing in the Dębina paleolake, in particular changes in vegetation, the Cladocera community, geochemical composition, the trophic state, water temperature, and water level.

During the Late Glacial, stratified fluvioglacial sand accumulated in the foreland of the disappearing ice sheet, in which a small paleolake – Dębina developed (250–200 cm). These sediments were enriched with small amounts of weakly humified organic matter and were poor in nitrogen and phosphorus. The results of studies by Pienitz & Smol (1993) demonstrate that the degree of humification of sediments is strongly influenced by climatic conditions, especially temperature, showing a positive correlation.

First phase of the Dębina paleolake evolution (200–156 cm): the initial lacustrine phase (Late Glacial: litho-geochemical Zones II–III, L PAZ I, CZD I)

At the beginning of this period, starting from a depth of 200 cm, a small oligotrophic reservoir developed in the cold and dry climate. This was likely followed by further cooling and moistening of the climate, as indicated by the increasing content of TOC, N and P. The high varying content of Mn in sediments suggests surface water runoff into the reservoir. The presence of open water species: *Eubosmina longispina,* the *Daphnia longispina* group and *Bosmina longirostris,* as well as species typical of reservoirs with reduced fertility: *Alona guttata*, *Eurycercus lamellatus*, *Acroperus harpae* and *Alonella nana*, suggest the presence of a relatively deep, cold and oligotrophic water reservoir (Korhola 1990; Hofmann 2000). These species also show tolerance to low water temperature (Hofmann 2000). The existence of lakes of similar genesis has been documented, among others, at the site in Niechorze (Kopczyńska-Lamparska 1976) and in the Szczecin Lagoon (Latałowa & Święta 2003; Borówka et al. 2005). At these sites, the lake sediments occurred in depressions located between an upland built of fluvioglacial sands or glacial till and, similarly to the Dębina paleolake, lying on fluvioglacial sand (Mianowicz & Cedro 2013). From a depth of 186 cm, a high content of Mn and Ca in sediments suggests surface and ground water runoff into the reservoir (Borówka 2007). At the same time, there was a gradual increase in primary production (increase in TOC content). This period, corresponding to the accumulation of calcareous gyttja (186–166 cm), was the most favorable for the development of Cladocera, which is reflected in the highest value of the biodiversity index and the largest number of species and individuals. A similar species composition was also found in the sediments in a fossil reservoir located near Mrzeżyno (profile T28) from the Late Glacial period (Zawisza & Cedro 2012). In this period, the presence of species associated with various habitats, including an open water zone, was determined.

With time (from a depth of 168 to 156 cm), the lake evolved toward a mesotrophic state, which is evidenced by the occurrence of *Pleuroxus trigonellus* and *Monospilus dispar* (Duigan 1992) and other species requiring nutrient-rich conditions, i.e. *Alona rectangula* and *Chydorus sphaericus*. Most of these species are associated with bottom sediments. The presence of *P. trigonellus* and *M. dispar* may also indicate the increase in water temperature. At the end of this phase, species typical of open waters withdrew from the reservoir, which should be associated with water-level lowering as a result of climate change during the Younger Dryas. The deterioration of living conditions due to the climate cooling is also reflected in the increased production of Cladocera ephippia (Sarmaja-Korjonen 2003).

The species composition of Cladocera is typical for lakes developed during the Late Glacial in northern Poland [Lake Biskupin (Szeroczyńska 1995), Lake Niechorze and Lake Woryty (Szeroczyńska 1985)]. During the warm episodes of the Late Glacial (Bølling/Allerød), species typical of warmer waters occurred (Szeroczyńska 2003), whereas in cold periods (the Oldest Dryas and Older Dryas), the species composition of Cladocera was limited to 3–5 taxa and the frequency of individuals was low (Szeroczyńska & Zawisza 2007).

Second phase of evolution of the Dębina paleolake (156–84 cm): the transition phase (the end of the Late Glacial and the Early Holocene (Preboreal): litho-geochemical Zone IV, L PAZ II, CZD II, III, IV)

This phase is associated with the destabilization of hydrological conditions in the lake. Stratified fluvioglacial sands enriched with amorphous organic matter have accumulated in the reservoir. This process probably occurred in cold climate and could be associated with scarce vegetation cover in the surrounding area, for example, the occurrence of tundra vegetation and, consequently, greater erosion of material from the catchment. It is likely that there was a slow decrease in the water level and water temperature, as indicated by the lower content of Fe in the sediments and low TOC values. The high variability in the types of accumulated material may indicate the instability of hydrological conditions, with periods of alternating lower and higher water levels. Rush vegetation (pollen grains of Cyperaceae and spores of *Equisetum* sp.) occurred in the marginal part of the reservoir to a small extent. No Cladocera remains and very few pollen were identified at a depth

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of 156–128 cm, which should be related to the periodic disappearance of the reservoir and probably periodic fluvial conditions.

At the beginning of the Preboreal period, the sea level rose as a result of the ice sheet melting and the glaciotectonic lifting of Scandinavia. In the southern parts of the Baltic, the coastline moved southward, but it was still several kilometers north of today's coast. In the paleolake, the change in hydrological conditions was recorded in sediments at a depth of 128 cm. High abundance of the HdV-729 type and spores from the genus *Pleospora* can be regarded as indicators of a water level rise. The presence of hyphopodia from the genus *Gaeumannomyces* indicates the presence of Cyperaceae among species of the lake shore (Pals et al. 1980; van Geel et al. 1989). A few Cladocera remains representing two species (*Alona rectangula* and *Eurycercus lamellatus*) associated with aquatic vegetation were found at a depth of 128 cm, which may suggest the presence of a shallow water reservoir (Korhola 1990). The beginning of the Preboreal period (128–112 cm) was associated with a water level rise in the reservoir, which resulted from the melting of dead ice and increased melting processes related to climate warming (Błaszkiewicz 2011). There was also an increase in the TOC content, which means an increase in primary production associated with an increase in the trophic state. Palaeogeographical data indicate a gradual lowering of the water level at the end of the Preboreal period (112–84 cm), suggested by lower values of Mn and Fe in the sediments. Lower water levels also confirm the presence of fungal remains – *Sordaria, Microthyrium* and Type-200, and are reflected in the lack of Cladocera remains in the sediments.

Third phase of evolution of the Dębina paleolake (84–8 cm): the peat bog phase (Boreal and Atlantic period): litho-geochemical Zones IV, V; L PAZ III, VI; CZD IV, V)

In the first part of the third stage (84–52 cm) in the Boreal period, there is evidence of a wet period at about 10 300 cal BP, similarly to other sites of Northern Europe (Magny 2004), for example in the southern part of the Gulf of Riga (Grudzinska et al. 2017) and northern Poland (Pędziszewska et al. 2015). This phase probably corresponds to the climate cooling identified as IRD-7 in the Bond cycle. On the other hand, it is most likely that the Ancylus Lake transgression ca. 10 300 cal BP (Saarse et al. 2003) induced a rise in the groundwater table in some areas, which in turn caused an increase in the reservoir's water depth. This phase is characterized by unstable hydrological conditions. The presence of *Glomus* remains confirms intensive erosion in the catchment and the fluvial character of the material in the profile. The animal remains – Turbellaria – indicate the supply of mineral matter to the reservoir. The productivity of the ecosystem and consequently the trophic status of the waters increased. The prevailing conditions favored the development of peat bogs (depth 76 cm) characterized by rushes with a dominance of swamp fern (*Filicales monolete*) spores as well as pollen (Cyperaceae). During this period, the lake was characterized by mesotrophic conditions with numerous nymphoides (*N. alba*). The increasing water level is also reflected in the expansion of *Filipendula ulmaria* and *Ranunculus flammula*-t. A short-term slight increase in the water level recorded at 68–52 cm, as indicated by the low TOC content, also confirms the presence of planktic species, including *Botryococcus* sp. The Boreal period is characterized by the expansion of hazel (*Corylus*) at this time. The undergrowth of pine forests was primarily hazel. There are no Cladocera remains in this period. Furthermore, only very few Cladocera remains were found in the sediment core T28 (Zawisza & Cedro 2012) in this period, which was connected with the drying of peat bogs. In this stage (depth: 70–10 cm), the textural measures of sediments show some differences compared to those lying below, which is probably a result of their enrichment with eolian material. The presence of eolian sands in the roof of swampy deposits was also recorded by Olszak et al. (2012) in the Orzechowo cliff.

In the second part of the third phase in the Atlantic period (44–8 cm), the Baltic Sea transformations became relatively stable. In the last 6000 years, the rate of changes in sea level and shoreline has decreased. Erosion processes on the cliffs and gradual peneplanation of the coastal zone, initiated in the Atlantic period, predominated (Uścinowicz 2003; 2006). Despite the intensive processes and evolution of the coast, there were periods of relative stabilization.

In the first part of the Atlantic period, water levels decreased. This was caused by increases in air temperature and evaporation and is reflected in the presence of fungal spores of *Sordaria* and *Cercophora* growing on decaying plant remains, including dead wood (Barthelmes et al. 2012). The HdV-200 type are specific agglomerations of fungal cells inhabiting the surface of dried organic sediments (van Geel et al. 1989; Miola et al. 2006). During this period, a swampy forest with alder (*Alnus*) grew in the vicinity of the site. Such a situation was also determined in the cliff reservoir Niechorze I, in which the water-level lowering with the advent of the Atlantic period caused the disappearance of Cladocera fauna (Szeroczyńska 1985).

The expansion of Cladocera is observed anew from a depth of 22 cm, indicating an increase in the water level. In this period, species specific to shallow and eutrophic waters occurred in the lake, such as *Alona rectangula*, *Chydorus sphaericus,* and *Bosmina longirostris* (Szeroczyńska 1985). Such a species composition is typical of lakes rich in nutrients and characterized by a higher trophic status, which existed in the Atlantic period (Szeroczyńska & Zawisza 2007). It is interesting that at the same time we can observe a small proportion of species associated with deeper and more nutrient-poor waters, which can be explained by periodic supplies of fresh water to the reservoir. The characteristic increase in the presence of the HDV-729-type fungus and a decrease in HDV-200 type fungal spores in the roof of the profile (20–8 cm) again indicate an increased moisture content. The roof part of the Dębina profile consists of peat-like material, rich in organic matter and moderately rich in nitrogen and phosphorus, containing numerous pieces of bark.

The termination of the peat bog was connected with its burial by eolian sands. The burial of the peat bog probably took place in the Early Subatlantic period, which is confirmed by the radiocarbon age of bark pieces from the roof of the Dębina profile: 2165 cal yr BP. The intensification of eolian processes in this period was also determined at other sites along the coastal cliffs of Middle Pomerania. On the other hand, it should be taken into account that the date 2165 is clearly "rejuvenated" and palynological data indicate that there is a hiatus in the top part of the profile.

Conclusions

The results of this research represent one of the most detailed studies of the reservoir discovered on the cliffs, thus complementing the knowledge on the development of the Central Pomerania region during the Late Glacial and the Early and Middle Holocene period. The results of our studies confirm the importance of paleolakes as an archive of environmental conditions and their importance in palaeoenvironmental reconstructions.

The Late Glacial origin of the lake was confirmed by the results of pollen and Cladocera analysis. Unstable ecological conditions occurred in the lake. The subsequent significant changes in water level and trophic status can be explained by temporal variability of climate conditions. At that time, a small cliff lake developed, at the bottom of which lacustrine mud and then calcareous gyttja accumulated. In the Late Glacial and the Early Holocene, the lake basin was almost completely filled with stratified sediments, enriched with organic matter, constituting the products of soil erosion in the catchment.

The results of the multi-proxy research enabled the identification of three main stages in the development of the reservoir: the first initial stage associated with the development of a cold oligotrophic lake covering the late Glacial period, and the second – the transition stage – associated with the destabilization of hydrological conditions when periods of erosion and filling of the reservoir with fluvioglacial sands alternated with periods of stabilization and deposition of organic matter and stages of stabilization of hydrological conditions, water-level lowering and transformation of the lake into a peat bog. The functioning of the peat bog ceased with its burial by eolian sands. The history of the development of the Dębina paleolake also resembles the evolution of other cliff paleolakes (Niechorze, Trzebielino T28).

In general, the results of subfossil Cladocera reconstruction based on radiocarbon dating and pollen analysis as well as the analysis of the sequence of physical and chemical properties of litho-morpho--geological processes correlate well with the dynamics of geomorphological processes established by other authors. However, the multi-proxy approach provides more comprehensive information regarding the evolution of the studied area.

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