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Environmental changes during the MIS 6a–MIS 5e transition: the Parchliny 2016 profile, central Poland

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We describe the penultimate glacial – last interglacial transition from the one of the numerous palaeolake successions in central Poland, which have yielded many documented Eemian and Early Weichselian floral records. In the new profile, Parchliny 2016, the lacustrine deposits were analysed lithologically, botanically, zoologically, and geochemically, providing new data that illustrate the environmental transition from the Late Saalian (MIS 6a) to the Eemian interglacial (MIS 5e). Five phases of palaeolake development have been distinguished. The first phase was related to the rapid melting of a dead ice block buried in the tills to form a lake. The second phase documented a Late Saalian initial succession, with the dominance of open steppe communities (Stadial 1), followed by a third phase with gradual increasing density of vegetation, the spread of boreal forests (Zeifen interstadial) and further increase in open communities and the retreat of pine (Kattegat stadial). The fourth phase reflected the beginning of Eemian interglacial by the expansion of pioneering birch-pine and purely birch forests and an increasing proportion of deciduous trees, including oak (Vth phase). Diatom, cladoceran and geochemical studies indicate at least two stages of lake development. The first stage (Late Saalian) was of an open lake (2–4 m deep), in relatively cold conditions and nutrient-poor water with the lowest amounts of organic carbon and nitrogen. The second stage (Eemian interglacial), shows warmer, shallower conditions in which the lake's primary production increased, the water was well oxygenated, and there were more trophic levels.

Key words: Eemian interglacial, glacial-interglacial transition, lacustrine deposits, Late Saalian, palaeoenvironment, central Poland.

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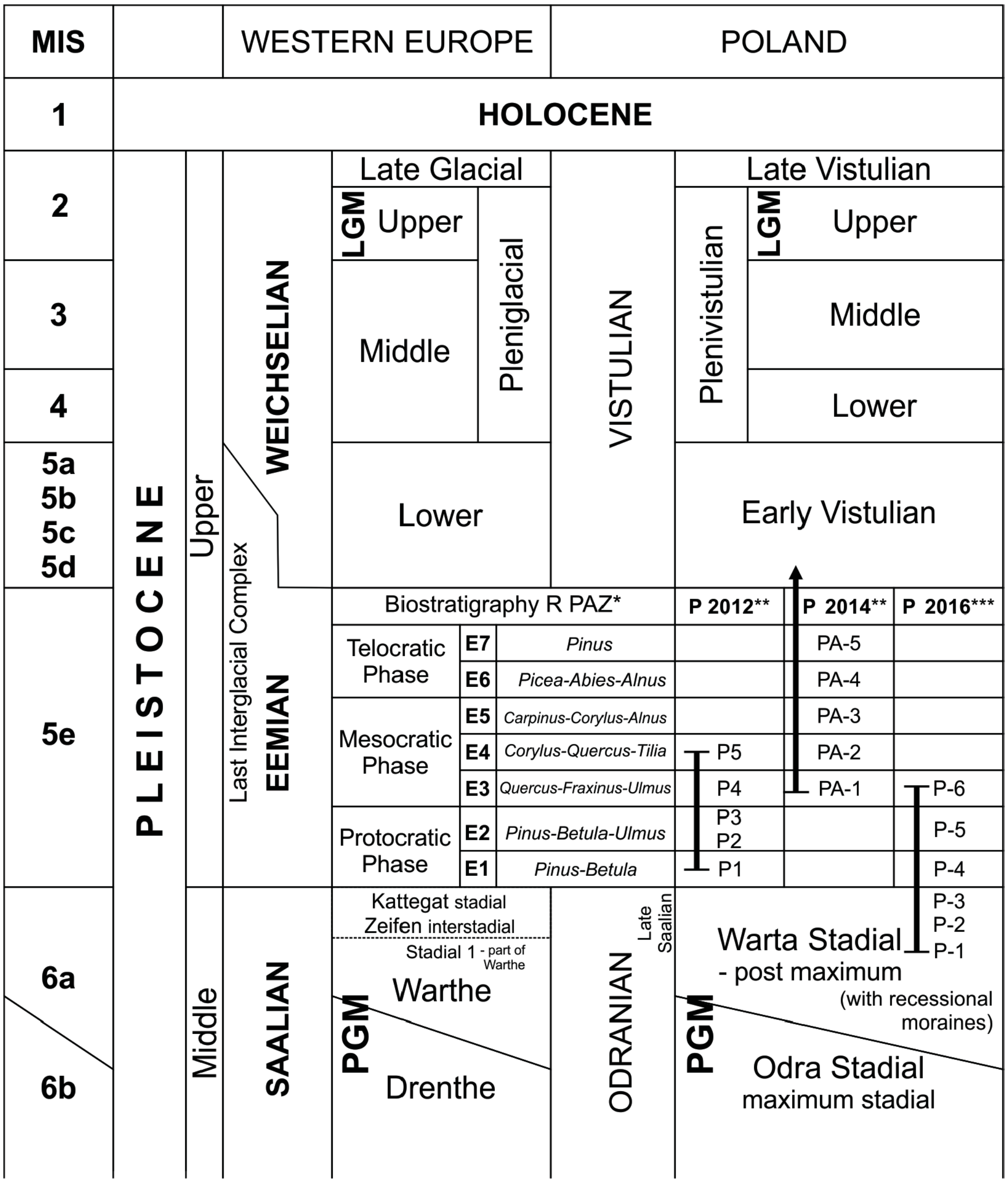
INTRODUCTION

The Eemian interglacial represents the marine isotope stage (MIS) 5e (Shackelton et al., 2002; Bińka and Marks, 2018). This last warm stage of the Pleistocene has been well documented, most of all in numerous terrestrial profiles in Europe (e.g., Guiot et al., 1989; Reille et al., 2000; Granoszewski, 2003; Helmens, 2013; Bińka and Marks, 2018). It was preceded by a cold stage of the Saalian Glaciation corresponding to MIS 6 (Marine Isotope Stage). In Polish stratigraphy, the younger part of the Saalian is referred to the Warta stadial of the Odranian Glaciation (Marks et al., 2016a, b, 2018), correlated with MIS 6a within the Penultimate Glacial Maximum. The name Late Saalian is also used for the decline of the Warta stadial as used in the present paper (cf. Railsback et al., 2015; Table 1).

In central Poland, palaeoflora of the Eemian interglacial have been found in numerous palaeolake profiles associated with the "Eemian Lakeland" (e.g., Klatkowa, 1990a, b; Roman et al., 2021). These former lakes, that existed and declined in the Early Weichselian, are known from at least 58 sites in this region (Bruj and Roman, 2007; Kupryjanowicz et al., 2016; Roman et al., 2021). However, pollen records of the Late Saalian

Table 1

Scheme of subdivision of the Upper Pleistocene with the correlation to Marine Isotope Stages (MIS) for western Europe (cf. Helmens, 2013) and Poland (Marks et al., 2016a, modified)



MIS			WESTERN EUROPE		POLAND	
1	HOLOCENE					
2	PLEISTOCENE	Upper	WEICHSELIAN	Late Glacial LGM Upper (Pleniglacial)	VISTULIAN	Late Vistulian Plenivistulian LGM Upper
3				Middle (Pleniglacial)		Plenivistulian Middle
4				Middle (Pleniglacial)		Plenivistulian Lower
5a 5b 5c 5d				Lower		Early Vistulian
5e		Last Interglacial Complex	EEMIAN	Biostratigraphy R PAZ*		P 2012** / P 2014** / P 2016***
6a		Middle	SAALIAN	Kattegat stadial Zeifen interstadial Stadial 1 - part of Warthe Warthe	ODRANIAN Late Saalian	Warta Stadial - post maximum (with recessional moraines) P-3 P-2 P-1
6b				PGM Drenthe		PGM Odra Stadial maximum stadial

		Biostratigraphy R PAZ*	P 2012**	P 2014**	P 2016***
Telocratic Phase	E7	*Pinus*		PA-5	
	E6	*Picea-Abies-Alnus*		PA-4	
Mesocratic Phase	E5	*Carpinus-Corylus-Alnus*		PA-3	
	E4	*Corylus-Quercus-Tilia*	P5	PA-2	
	E3	*Quercus-Fraxinus-Ulmus*	P4	PA-1	P-6
Protocratic Phase	E2	*Pinus-Betula-Ulmus*	P3 P2		P-5
	E1	*Pinus-Betula*	P1		P-4

LGM – Last Glacial Maximum **PGM** – Penultimate Glacial Maximum

An inserted table of * – Eemian interglacial biostratigraphy (Mamakowa, 1989) and documented adjacent sites: ** – Parchliny 2012, Parchliny 2014 (Wachecka-Kotkowska et al., 2018) and *** – Parchliny 2016 (this study) to Eemian interglacial transition are rare (see Guiot et al., 1989; Mamakowa, 1989; Granoszewski, 2003) and, in most cases, short, probably due to sedimentary disturbance or erosion. Bińka and Nitychoruk (2001) noted that in most Polish profiles the Late Saalian record is represented only by single samples. As a result, and because of pollen reworking and redeposition, the record may give a false image of the palaeoflora of this interval. Most Eemian profiles documented from central Poland generally extend from the Late Saalian (Jastrzębska-Mamełka, 1985; Krupiński and Morawski, 1993; Urbański and Winter, 2005; Majecka, 2014; Malkiewicz, 2018a, b) and show the gradual evolution of plant communities from open vegetation in the Late Saalian throughout the gradual appearance of trees to a closed forest at the beginning of the Eemian (Bińka and Nitychoruk, 2001). However, knowledge of the palaeoenvironmental lake conditions and vegetational transformation at the end of the Odranian Glaciation is incomplete. Many sites have been documented palynologically in other regions of Poland. Well-known areas include the Podlasie region (Bińka and Nitychoruk, 2001; Kupryjanowicz, 2008), Lower Silesia (e.g., Mamakowa, 1989; Kuszel, 1998), Mazovia (Winter et al., 2008; Żarski et al., 2018) and the Konin region (Tobolski, 1991). In western Europe the end of Saalian Glaciation showing climate oscillations of stadial-interstadial rank have been documented in profiles from e.g. Zeifen in southern Germany (Jung et al., 1972; Beug, 1973; Grüger, 1979), Austria i.e. Mondsee (Klaus, 1975, 1987), Denmark (Seidenkrantz, 1993), as well as in France at La Grande Pile (Woillard, 1975, 1978, 1979) and Les Echets (de Beaulieu and Reille, 1984). In Poland, attempts have been made to search for appropriate profiles, reflecting relatively long and with stable deposition, for possible correlation with western Europe.

A new site in central Poland is Wola Starogrodzka, where a record of climate oscillations at the end of the Late Saalian has been recognized, corresponding with the Zeifen interstadial and the Kattegat stadial recorded in western Europe (see Fig. 1B; Kupryjanowicz et al., 2021). Similarly, some proxies from the Parchliny 2016 profile described show correlation with these interstadial/stadial oscillations.

One of the areas rich in palaeolakes is the Szczerców Basin in the Bełchatów Lignite Opencast Mine. 17 profiles have been documented there representing several melt-out kettle or trough lakes (Fig. 1C). Most of the documented profiles represent lacustrine deposits spanning more or less complete succession of the Eemian, the Early Weichselian (MIS 5d–5a) and Middle Weichselian (MIS 4, MIS 3), but without an obvious record of palaeoflora of the Late Saalian (Sarnacka, 1970; Baraniecka and Sarnacka, 1971; Janczyk-Kopikowa, 1987; Balwierz, 2003; Goździk and Skórzak, 2011; Wachecka-Kotkowska et al., 2018). These studies showed the formation of several palaeolakes along a zone of tectonic structures, such as the Kleszczów Graben, in the sub-Cenozoic basement, (Fig. 1C). During the Late Saalian, there were favourable conditions for the prolonged deposition and preservation of lake sediments within the Kleszczów Graben area, within melt-out kettle holes (Baraniecka and Sarnacka, 1971) or subglacial channels (Wieczorek and Stoiński, 2019).

Research in the western part of Kleszczów Graben was possible because of the existence of the extensive Szczerców exposure, in which lignite is mined using the open-pit system (Fig. 1C). Mining has exposed various types of Quaternary deposits (Krzyszkowski et al., 2015; Wieczorek et al., 2015) and in August 2016, the contact between lacustrine deposits and underlying tills and glaciofluvial sands was exposed. The profile spanning this transition has been named Parchliny 2016 (Figs. 1 and 2). On the basis that this profile could complete the record of Late Saalian palaeoenvironmental change in this area, 21 samples were taken for research at intervals of 2–10 cm. A total of 1.17 m of the bottom part of the lacustrine deposits was sampled. They were analysed to reconstruct the pattern of palaeoenvironmental change during the Late Saalian/Eemian interglacial transition period and to reconstruct the evolution of the Early Eemian lake.

GEOLOGICAL SETTING AND THE STUDY AREA

The Parchliny 2016 profile (51°14'38.2"N; 19°09'46.5"E) is from the lower part of a former lake that formed within a subglacial channel, in part a melt-out kettle hole (Fig. 2). During MIS 6a (end of the Odranian Glaciation, i. e. Warta Stadial – see Table 1), the research area was covered by the Scandinavian ice sheet which left a relatively varied land relief in this area. Over distances of several kilometres, there are frontal moraines, kames, eskers, subglacial channels, terminal depressions and melt-out kettles. It is a very distinct ice-marginal zone with several strings of terminal moraines (Baraniecka and Sarnacka, 1971; Wieczorek and Stoiński, 2019).

Following excavation on levels I and II on the eastern wall of the Szczerców exposure, the lacustrine deposits were revealed (Fig. 1C). This succession has been previously documented as a relict of the "Eemian Lakeland", in the Podlas 18/21.5 (Goździk and Skórzak, 2011), Parchliny 2012 and Parchliny 2014 profiles (Wachecka-Kotkowska et al., 2018; Wieczorek and Stoiński, 2019). The last two sites are considered to be a record of the same palaeolake as the Parchliny 2016 profile discussed in this paper (Fig. 1C and Table 1).

The top of the Parchliny 2016 profile was determined at a depth of 23.33 m, while its base was at 24.5 m below the ground surface. The elevation of the ground surface in this area, before excavation commenced, was ~178–181.5 m a.s.l. At the base of the profile, there was the Odranian glacial till layer (Ławki and Rogowiec Formations, see Allen and Krzyszkowski, 2008; Wachecka-Kotkowska et al., 2021), currently associated with the Warta Stadial (MIS 6a). Above the profile studied, the thickness of the lake deposits (Aleksandrów Fm., Eemian) was ~4–6 m; however, these were located on a very steep part of the wall and are beyond the scope of this work. An even higher position was occupied by sandy and silty deposits of the Piaski Formation (Weichselian; MIS 5d-2; Fig. 2 and Table 1).

MATERIALS AND METHODS

FIELDWORK

The fieldwork mainly included lithopetrographic analyses and macrofossil sampling of the deposits. These were exposed by mining at level II on the eastern wall (Figs. 1C and 2). From the Parchliny 2016 profile, 21 samples of lacustrine sediments were collected from a depth of 23.33–24.50 m (~158.1 m a.s.l., Fig. 3), and four samples of tills were collected from the bedrock (~150 m a.s.l., Fig. 3). The research was carried out in terms of lithology, palaeobotany (pollen and diatom analyses, plant macroremain analysis), palaeozoology (cladocerans, gastropods, ostracods), and geochemistry (chemical elements and isotopic composition). The palaeobiological material helped to set the boundaries within the glacial/interglacial transition.

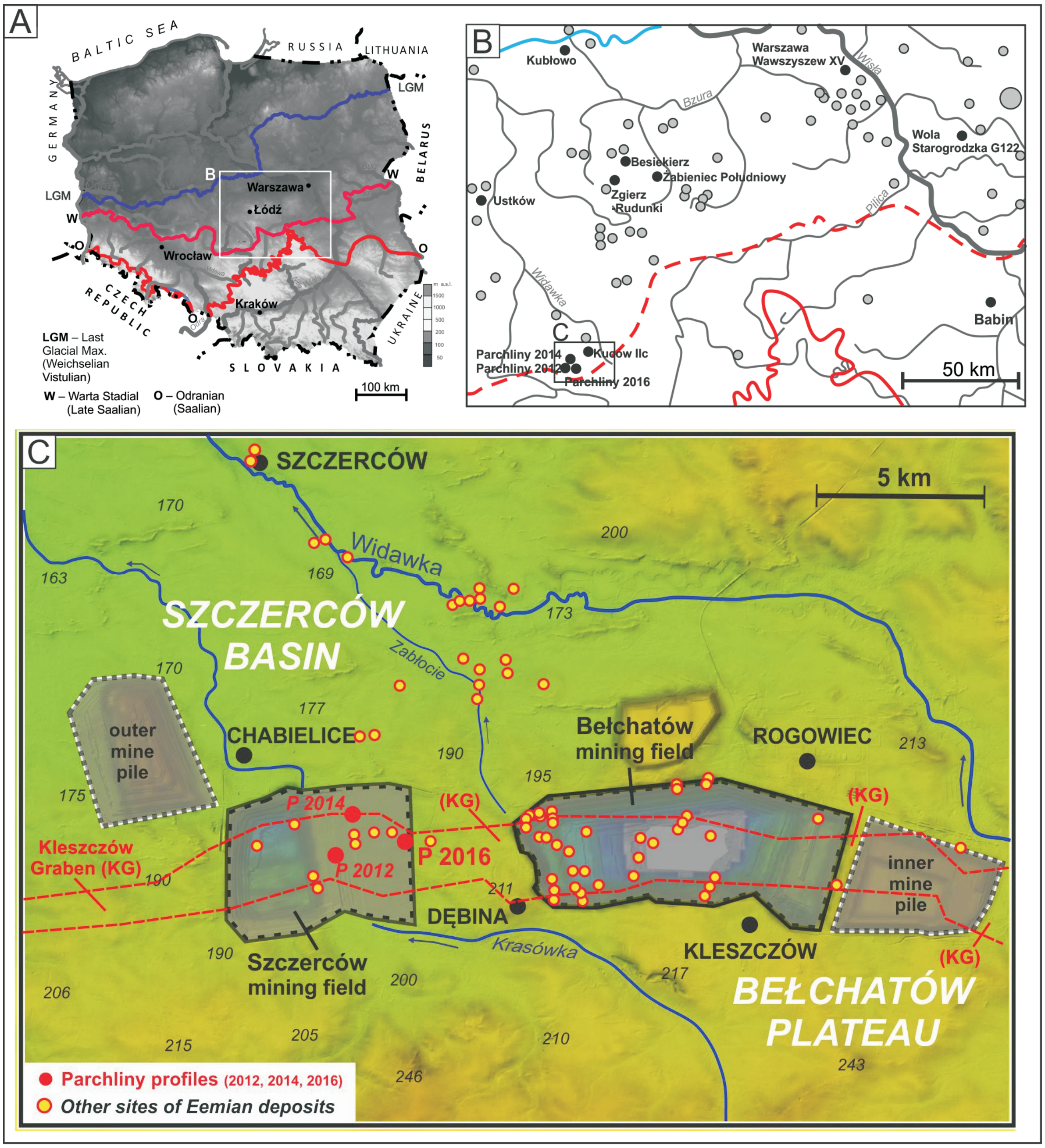


Fig. 1A – extents of the Pleistocene glaciations in Poland (after Marks, 2011; Wachecka-Kotkowska et al., 2015); B – documented sections of the Eemian interglacial in central Poland (grey dots), with specified locations cited in the text (black dots) based on (Bruj and Roman, 2007); C – locations of the Eemian sites in the Szczerców Basin (based on Sarnacka, 1970; Baraniecka and Sarnacka, 1971; Goździk and Skórzak, 2011; Wieczorek and Stoiński, 2019), P – Parchliny

SEDIMENTOLOGICAL AND PETROGRAPHICAL ANALYSIS

The Parchliny 2016 profile and its bedrock have been described in lithological/petrographic terms. These are O/K, K/W A/B, and D/LPI (O – total of sedimentary rocks; K – total of crystalline rocks; W – total of carbonate rocks; A – total of non-resistant rocks; B – total of resistant rocks; see Wachecka-Kotkowska et al., 2021). The indices used are in accordance with, the standard specified by the Polish Geological Institute – National Research Institute in Warsaw (Marks and Ber, 1999).

PALAEOBIOLOGICAL METHODS

Analyses of diatoms, pollen, plant macrofossils, and woody remnants as well as palaeozoological analyses (cladocerans, malacofauna) were the most important methods in the study.

DIATOM ANALYSIS

Diatom analysis was conducted according to standard methods (Battarbee, 1986). At least 300 diatom valves per sample were counted using a *Nikon Eclipse 200* light micro-

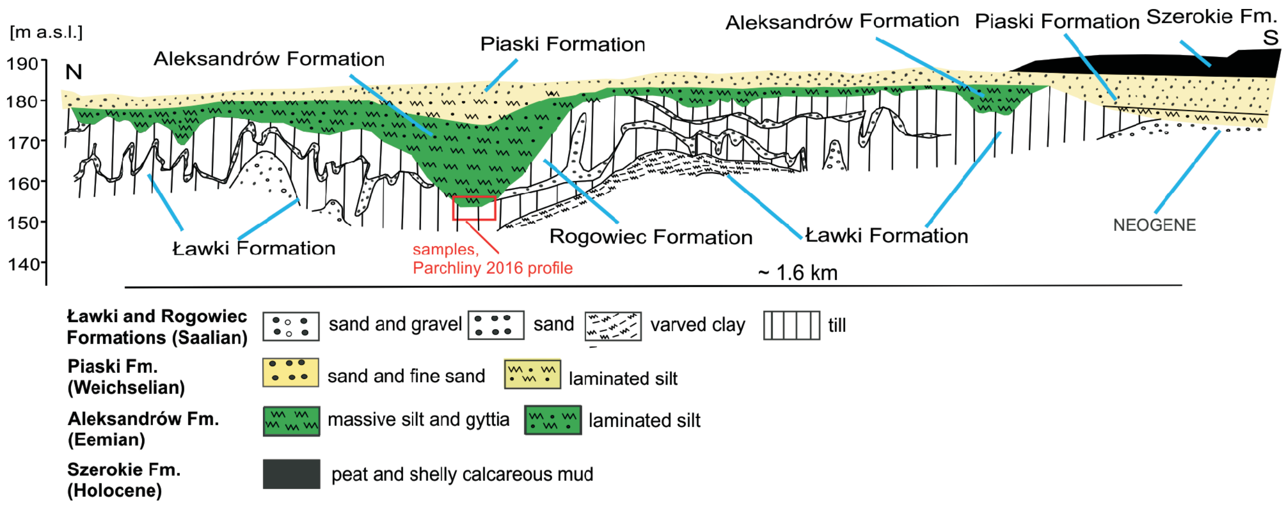


Fig. 2. Location of the Parchliny 2016 profile on the eastern wall of the Szczerców exposure

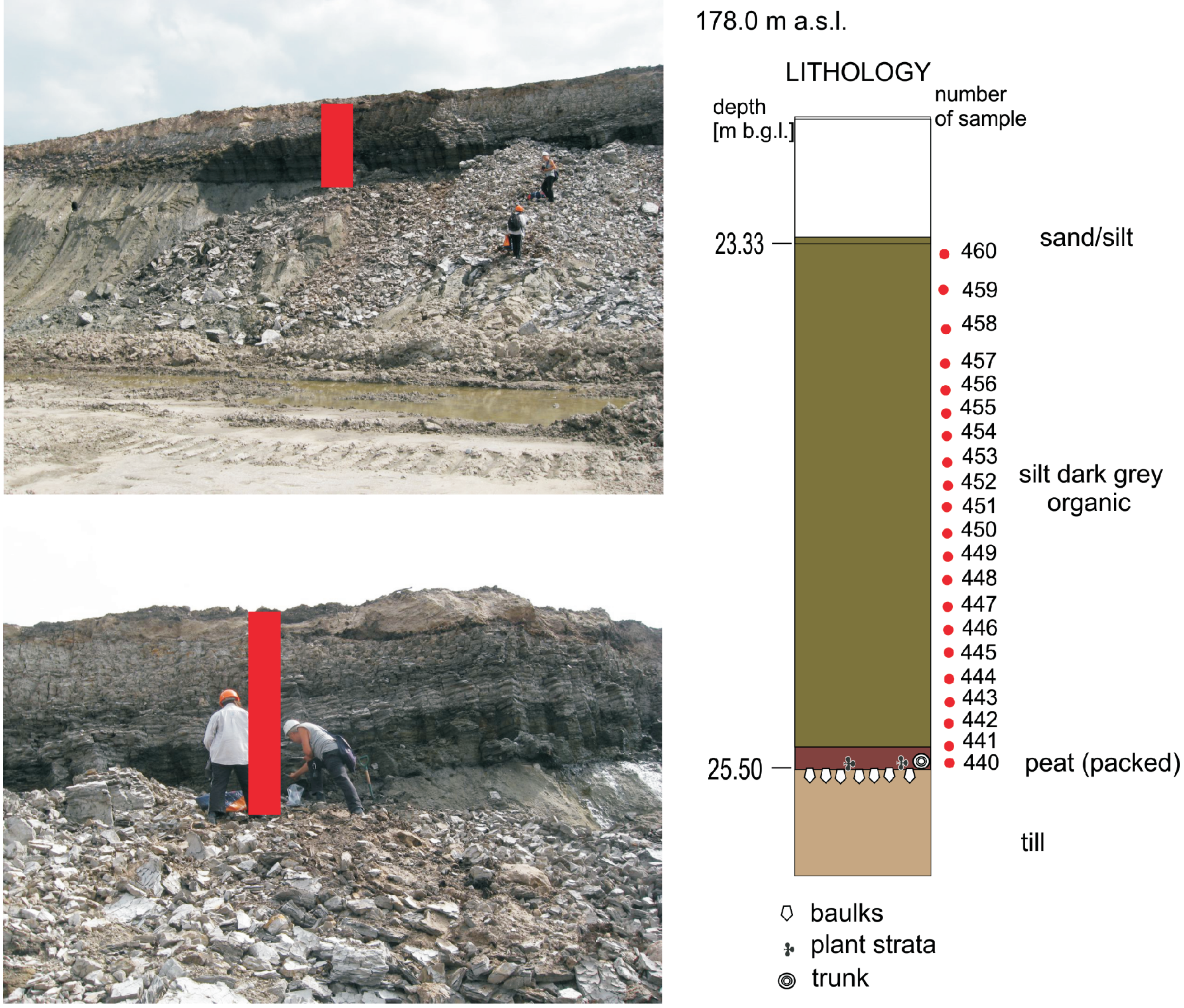


Fig. 3. General view of the Parchliny 2016 profile, marked by a red rectangle and its lithological log, including the sampling sequence

scope (x1,000 magnification). For the identification, Krammer and Lange-Bertalot (2008a, b, 2010, 2011), Hoffmann et al. (2011), Lange-Bertalot et al. (2011), Lange-Bertalot and Genkal (1999), Lange-Bertalot and Metzeltin (1996) and AlgaeBase (www.algaebase.org) were used. The diatom ecological groups were determined using *OMNIDIA* software (Version 4.2; Lecointe et al., 1993). The resulting groups were distinguished according to Denys (1991) and van Dam et al. (1994). We considered the following indicator parameters: habitat category (Denys, 1991), dominant taxa (abundance >2%), and preference for pH and trophic state (van Dam et al., 1994). The percentage diatom diagram was prepared using *Tilia software* (Grimm, 2012).

Recent taxonomic advances have split many diatom taxa of the former genus *Fragilaria* into several new genera, including *Fragilaria, Pseudostaurosira, Staurosira*, and *Staurosirella* spp. (Williams and Round, 1987). These new names herein collectively referred to as *Fragilaria sensu lato*. *Cyclotella sensu lato* taxa have included the genera *Cyclotella* and *Pantocsekiella*.

POLLEN ANALYSIS

For the pollen analysis, 21 samples from the depth interval of 23.33–24.50 m were prepared by a standard procedure, and acetolysis was applied (Berglund and Ralska-Jasiewiczowa, 1986). From 20 samples (except the sample from a depth of 24.50 m, no sporomorphs noted), at least 500 AP pollen grains and all NAP grains, and sporomorphs of water and reedswamp plants, ferns and algae were counted. Pollen taxa were determined using keys and atlases (Moore et al., 1991; Reille, 1992). The pollen percentage values are based on the total sum (AP+NAP), which includes trees, shrubs (AP), and herbaceous terrestrial plants (NAP). Water, reedswamp and spore plants were excluded from the total sum. POLPAL palynological software was used to construct a percentage pollen diagram (Nalepka and Walanus, 2003). The percentages of algal taxa, and concealed, degraded, corroded and indeterminate specimens, were calculated in relation to the total pollen sum. ConSLink numerical analysis (cluster analysis showing similarities between the spectra of the samples analysed) was used to justify the local pollen assemblage zones L PAZ distinguished (Nalepka and Walanus, 2003).

Palaeoclimate reconstructions were carried out on the basis of plant climate indicators identified in the pollen spectra. Plant indicators provide palaeoclimate data such as mean temperatures of the warmest (MTWM) and the coldest (MTCM) month on the basis of present plant tolerance (Iversen, 1954; Kolstrup, 1980; Mamakowa, 1989; Ran and van Huissteden, 1990; Zagwijn, 1996; Isarin and Bochncke, 1999)

ANALYSIS OF MACROSCOPIC PLANT REMAINS

For the analysis of plant macroremains, including seeds and fruits, individual samples (21 pieces) were treated with 3% NaOH and then rinsed under running water on a sieve with a mesh diameter of 0.3 mm. The seeds and fruits were extracted from the prepared material. For the peat sample (depth 24.48 m), slides with plant tissues and additional macrofossils were additionally made. To identify the seeds and fruits we referred to Katz et al. (1965), Velichkevich and Zastawniak (2006), Cappers et al. (2012), and for the vegetative remains we used the study by Katz et al. (1977).

Five large fragments of woody macrofossil were used for anatomical analyses. From the wood remnants, hand-made transverse, radial, and tangential sections were prepared, analysed, and documented according to standard protocols (Myśkow et al., 2016; Wachecka-Kotkowska et al., 2018). The characteristic features of wood were analysed and compared with available keys (Greguss, 1955; Schweingruber, 1990; InsideWood, 2004) to identify the plant genera to which the wood remains belonged.

CLADOCERA

The cladoceran samples were prepared in 20 samples of 1 cm^3 according to standard procedure (Frey, 1986; Korhola and Rautio, 2001) using a lower temperature of sample maceration: max. 60°C. An *Olympus BX53* microscope (10; 20; 40 magnification) was used to identify the remains. Identification and ecological interpretation of the cladoceran remains were based on Goulden (1964), Hofmann (1986, 2000), Korhola (1990), Duigan (1992), Flössner (2000), and Szeroczyńska and Sarmaja-Korjonen (2007). The results are shown in figures including the absolute diagram, the total number of cladoceran individuals, the number of species and their biodiversity being determined by the Shannon-Wiener index (Krebs, 1989). The numerical analysis was performed using *POLPAL* software (Nalepka and Walanus, 2003).

MOLLUSCS, AQUATIC FAUNA, OSTRACODS STUDY

The study of molluscs, aquatic fauna and ostracods was carried out at the Polish Geological Institute – National Research Institute, Marine Geology Branch in Gdańsk according to standard preparation. The sediment was treated with hydrogen peroxide (H_2O_2) to remove organic matter, and washed with water on a sieve with a mesh diameter of 0.1 mm. Each sample was examined under the binocular to identify the species.

GEOCHEMICAL ANALYSES

The geochemical mineral content and stable isotope analyses of sediments from the Parchliny 2016 profile included organic carbon and nitrogen concentrations, and carbon and nitrogen isotopes. Stable isotope analyses were performed at the Stable Isotope Laboratory, Institute of Geological Sciences PAS, in Warsaw, Poland.

Mineral content analyses were performed on 21 sediment samples using X-ray fluorescence (XRF; Weltje and Tjalingii, 2008). Measurements were made on an XRF *Tiger S8* device (Bruker Corporation 40 Manning Road Billerica, MA 01821) at the Bruker PD Instruments laboratory in Toszek. The selected samples were dried at 105°C for 24 hours. Then the samples (weight 5 g) were burned in a muffle furnace at 1000°C for 1 hour to calculate the loss on ignition (LOI) (Heiri et al., 2001). From the burned sample 5 g of material was taken and mixed with flux (lithium borate). The mixture was melted in a platinum crucible in the muffle furnace at 1000°C. Nine main elements were determined (K, Na, Mg, Fe, Mn, Ca, Si, Al, Ti) and three geochemical indicators (Fe/Mn, Na/K, Ca/Mg) were calculated. Our analytical results were controlled compared with standards, i.e. loess indications certified reference materials ISE 934 and ISE 974 Dutch company Wepal.

RESULTS

SEDIMENTOLOGICAL CONDITIONS

The palaeolake basement is represented by glacial tills with a ventifact pebble layer at its top (Fig. 4C). The tills are disturbed and contain sand interlayers (Fig. 2). The till in the base-

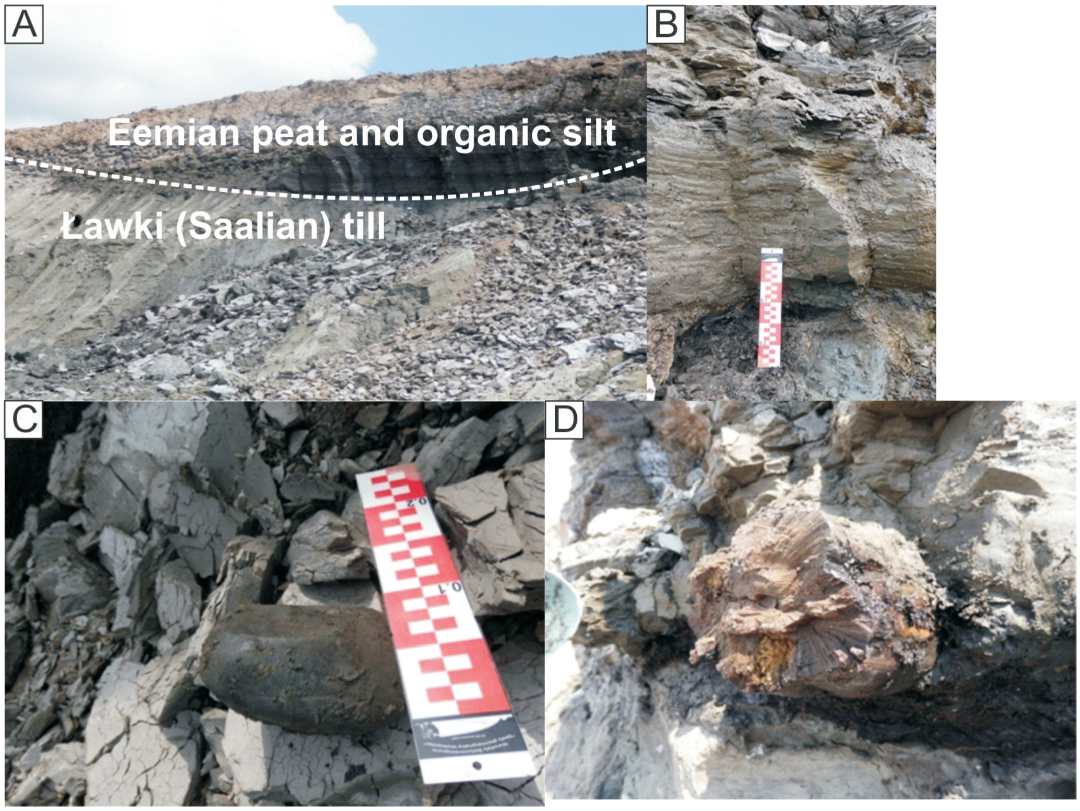


Fig. 4. Parchliny 2016 profile

A – general view of the profile; **B** – research profile; **C** – a pebble with traces of abrasion with three ridges, found at the top of the till; **D** – tree limbs embedded in the peat layer at the bottom of the depression

ment of the profile is a typical basal till with a relatively large amount of gravel (sample No. 464, see Fig. 3). Lithological studies of the gravel indicate the prevalence of fragments of northern rocks (58.5%) over local ones (41.5%). The tills contain many lignite clasts. The lithological/petrographic indices are as follows: O/K = 0.81; K/W = 1.69; A/B = 0.70; D/LPI = 0.11 (Wachecka-Kotkowska et al., 2021). At the top of the till, there is a thin gravel/boulder pavement and individual ventifact pebbles, a tree bough, and tree branch remains were found (Fig. 4C, D).

The contact between the till and overlying deposits is sharp. The till is overlain by biogenic deposits containing a tree bough fragment (Fig. 4D). At the depth of 24.48 m, there is a compact peat layer with organic debris at the top (Figs. 3 and 4B). The largest part of the profile studied is represented by layered organic clayey gyttja and organic silt, dark grey in colour, found at the depth interval of 24.44–23.33 m (Fig. 3). Just above the top of the Parchliny 2016 profile, a change in the lithology of the lacustrine deposits is observed, as sandy silt and silty sand deposits ~5–20 m thick appear.

PALAEOBOTANICAL DATA

DIATOM

In total, 114 diatom taxa (species and varieties) were identified in the material studied. The diatom frustule state of preservation was particularly good. Based on the species composition and differences in the ecological groups of diatoms, the core was divided into two diatom assemblage zones (P-1 and P-2 DAZ; see Fig. 5). Within zone P-1, three subzones were distinguished (P-1a, P-1b, P-1c). Indicator parameters, such as habitat category, diatom pH preference and trophic conditions, were considered.

The bottom part of the profile (P-1a; 24.48–24.50 m) is dominated by littoral (periphyton and benthic) diatoms. The proportion of planktonic diatoms in subzone P-1a is ~40%. *Cyclotella cyclopuncta, Pantocsekiella comensis* and *P. schumannii* dominate among planktonic species, whereas the dominant benthic species are *Amphora inariensis, A. pediculus, Staurosira construens* and *Pseudostaurosira brevistriata*. These planktonic and benthic species were widely distributed in the littoral zone, mainly in freshwater basins, and many were epiphytic species. As regards pH, alkaliphilic and circumneutral species were dominant. Moreover, oligotrophic, oligo-mesotrophic, mesotrophic and eutrophic species were also present.

At the beginning of subzone P-1b, at a depth of 24.43 m, we observed a change in the palaeolake's environmental conditions. The percentage of benthic taxa increased to 100%, and towards the top of the core, it decreased to 80% at the top of subzone P-1b, and further to a minimum value of 25% at the top of subzone P-1c, and decreased to 5.3% in P-2 DAZ. The dominant diatom species were the benthic *Amphora pediculus, Pseudostaurosira brevistriata, Stauroneis construens* and *S. lapponica*. Analysis of the proportion of diatom pH groups showed an increase in and dominance of the alkalophilous species. As regards trophic state, the dominant mesoeutrophic species were accompanied by eutrophic and hypereutrophic species.

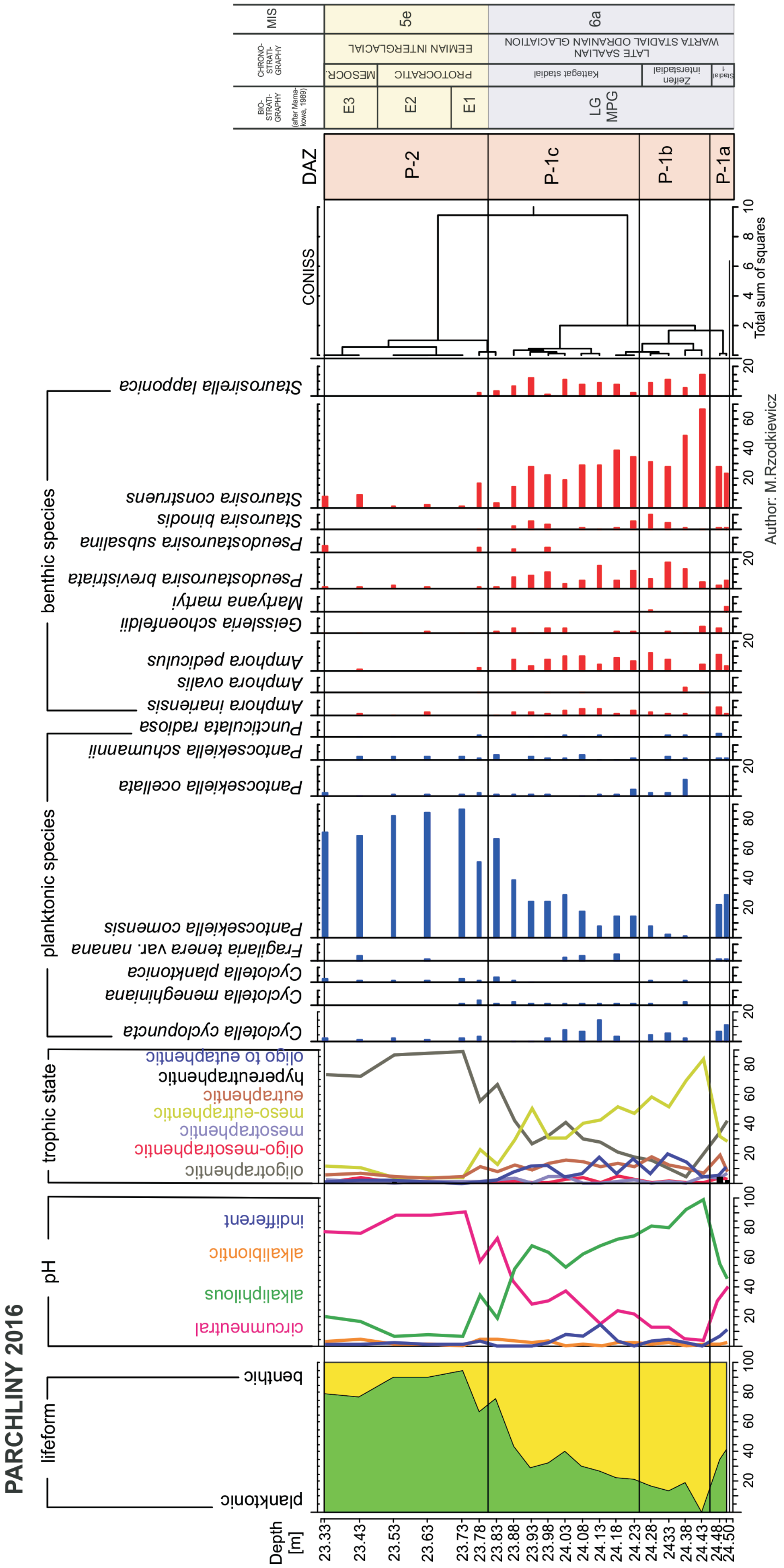


Fig. 5. Parchliny 2016 profile, diatom diagram of deposits collected from the floor of the former lake

Local diatom assemblage zones are abbreviated as P (Parchliny)

Table 2

Characteristics of local pollen assemblage zones (L PAZ) distinguished in the Parchliny 2016 profile in stratigraphic order from the bottom up

L PAZ	L PAZ name	Sample depth	Description
P-6	*Quercus*	23.33–23.43	AP dominates (max. 93%) with the maximum share of *Quercus* 48.5%. *Pinus sylvestris* and *Betula* undiff. decrease. *Ulmus* falls to 3.4% and *Alnus* undiff. reaches 0.72%. *Corylus avellana and Hedera helix* appear.
P-5	*Pinus-Betula-Ulmus-Quercus*	23.53–23.63	AP still high (max. 94%). *Pinus sylvestris* shows a distinct increase (max. 35.5%), while *Betula* undiff. falls to 44%. *Ulmus* reaches 5.5% and *Alnus* undiff. 1.8%. *Quercus* increases to 5.1%. *Picea abies*, *Fraxinus excelsior* and *Larix* appear. Values of NAP reach an average of 6%.
P-4	*Betula-Ulmus*	23.73–24.78	AP dominates (94-96%), with the maximum share of *Betula* undiff. 60.5%. *Pinus sylvestris* decreases to 25%. *Picea abies* occurs and reaches 0.2%. *Betula nana* reaches 0.9% and falls, and *Salix* reaches 0.7%. Other trees appear: *Ulmus, Quercus* and *Alnus* undiff. NAP decrease to 4%.
P-3	*Pinus-Betula*-NAP	23.83–24.23	AP range from a minimum value of 77% to a maximum value of 90% at the boundary between P-3 and P4 (NAP 23%-10%). *Betula* undiff. shows a steady increase from 23% to 48%, while *Pinus sylvestris* falls from 54.5% to 38%. Continuous presence of *Juniperus communis, Betula nana* and *Salix* Among the NAP group, Poaceae are most frequent (from 5 to 10%) and *Artemisia* (7%); Cyperaceae (3 %) are still present.
P-2	*Pinus-Betula*	24.28–24.43	AP values increase to an average of 82-86%; High proportion of *Pinus sylvestris* oscillates from 51 to 61.5%, *Betula* undiff. oscillates from 19.5 to 28.5%. The curves of *Betula nana* (max. 1.7%), *Juniperus communis* (max. 2%) and *Salix* (max. 1.8%) are continuous. *Picea abies* is present (0.8%). Among the NAP group, Poaceae (max. 10%), *Artemisia* (max. 5.3 %) and Cyperaceae (2.7%) are most common. Pollen of *Dryas octopetala* is found.
P-1	Poaceae-*Pinus-Betula*	24.48	NAP are over 35%; the highest pollen shares are those of Poaceae (up to 24.5%), Cyperaceae (up to 4.5%) and *Artemisia* (up to 3%). *Juniperus communis* (max. 1.3%), *Salix* (1.3%) and *Betula nana* (3.36%) show relatively high values. *Pinus sylvestris* reaches 38%, while *Betula* undiff. – 20%. *Ephedra* are noted. Single pollen grains of higher thermal demands taxa also appear (*Quercus, Fraxinus excelsior, Tilia, Corylus avellana* and *Carpinus betulus*), which are most likely redeposited.

Subzone P-1c is characterised by an increase in the proportion of planktonic species, ranging from 20 to 43.4%, and even 80% at the zone top. In terms of pH, the proportion of alkaliphilous diatoms decreased, while the proportion of circumneutral diatoms increased. The trophic analysis showed an increase in oligotrophic species.

In the second diatom zone P-2 DAZ (depth 23.78 m), planktonic taxa increased, ranging from 66.7 to 95.0%. The pH analysis showed a clear dominance of circumneutral species. There was an increased percentage of oligotrophic diatom trophic preferences, ranging from 54.9 to 88.8%. The most common genera was *Pantocsekiella*.

POLLEN

Detailed results from the Parchliny 2016 profile are included in Table 2 and in a pollen diagram (Fig. 6). Pollen analysis of 20 samples from depths of 24.48–23.33 m enabled the subdivision of the succession into six local pollen assemblage zones (L PAZ). L PAZs were determined according to the rules of Birks and Birks (1980), and Janczyk-Kopikowa (1987).

45 pollen taxa were identified: 16 trees and shrubs, 17 herbs, 8 aquatic and reedswamp plants, 2 spore plants and 2 algae.

PLANT MACROFOSSILS

From the 20 samples studied from the Parchliny profile from depths of 23.33–24.48 m (the sample from 24.50 m was barren), 13 taxa were identified, including six at the species level and six at the genus level. Three local macrofossil assemblage zones (L MAZ) were identified (Table 3). Macrofossil plants include taxa of mosses and higher plants, determined from seeds, fruits, wood, needles, and other remains. In the 24.03–24.28 m depth zone, no carpological material was recorded, but small fragments of damaged Bryales moss leaves were present; however, species determination was impossible.

WOODY MACROFOSSILS

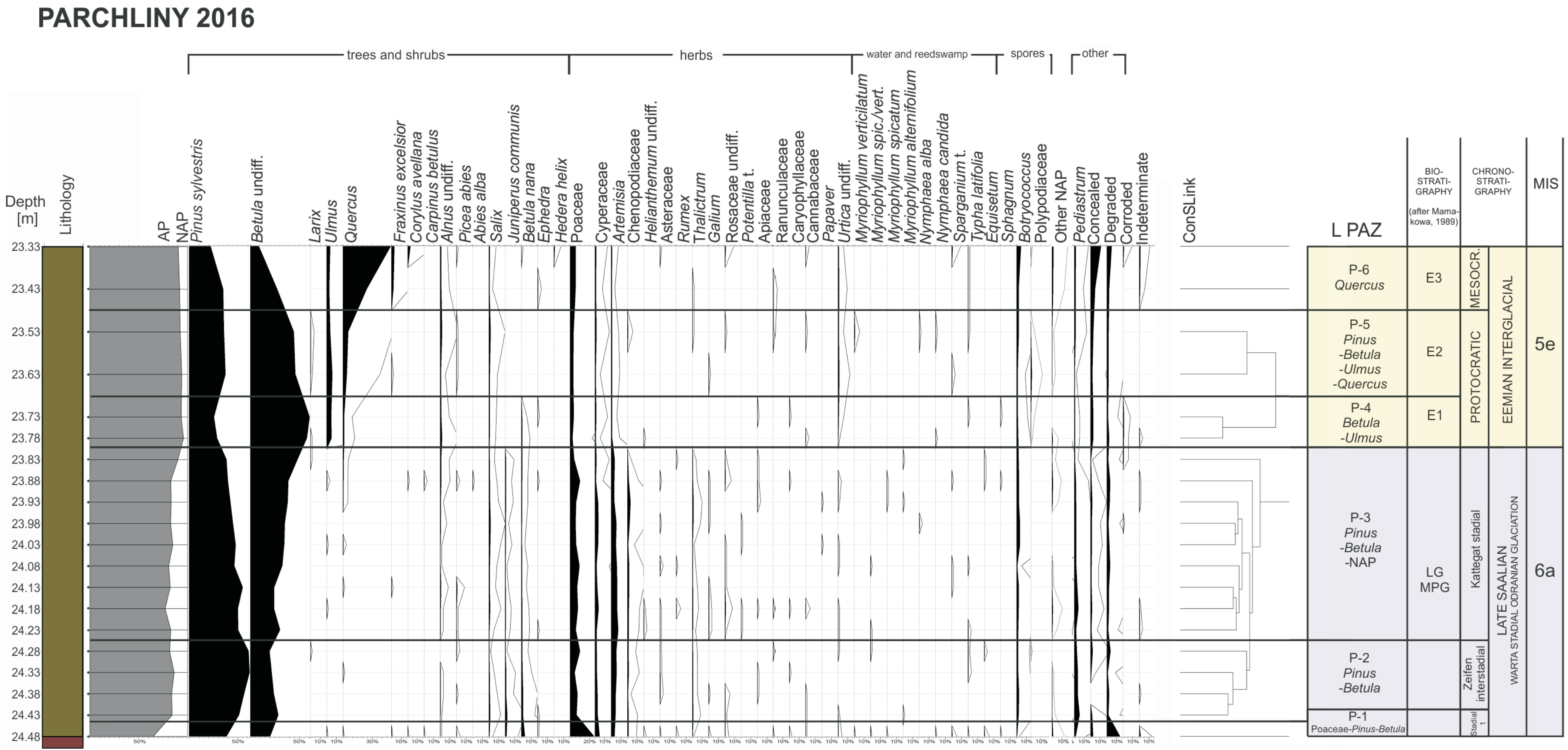
Microscopic analyses of the remains of a large stem (Fig. 4D) and two other smaller stem and root fragments showed that these macrofossils were composed of tracheids (Fig. 7A). The resin canals were present and lined with thin-walled epithelial cells (Fig. 7B). The heterocellular rays contained tracheids at the margins and parenchyma cells in the centre of a ray. Large fenestriform pits were also visible (Fig. 7C). All these features point to pine (*Pinus*) wood.

Two remaining woody macrofossils were derived from deciduous trees. One was still covered by a white periderm and the wood was diffuse-porous with vessels located in radial multiples of 2–4 pores (Fig. 7D). The rays were 2–4-seriated (Fig. 7E). Scalariform perforation plates in the vessels were clearly visible (Fig. 7F). The anatomical features of the wood and the presence of a white periderm clearly indicate that these remains belong to birch (*Betula* sp.).

PALAEOZOOLOGICAL DATA

CLADOCERA

The subfossil cladoceran fauna of sediments in the Parchliny 2016 profile is represented by 12 species belonging to two families: *Chydoridae* and *Sididae*. Most of the remains



Author: A. Majecka

Fig. 6. Pollen percentage diagram of the Parchliny 2016 profile

Local pollen assemblage zones (L PAZ) understood as phases; abbreviated as P – Parchliny; sediment layers in lithological column as in Figure 3

Table 3

Characteristics of local macrofossil assemblage zones (L MAZ) distinguished in the Parchliny 2016 profile in stratigraphic order from the bottom up

Depth	Ash content [%]	Vegetative remains [%]									Seeds and fruits (pieces)							L MAZ
		Meesia sp.	*Calliergonella cuspidata*	*Cratoneurum* sp.	*Climacium dendroides*	*Polytrichum* sp.	*Bryales*	*Betula* wood/bark	*Pinus* needle	*Pinus* bark	*Potamogeton* sp.	*Typha* sp.	*Carex rostrata*	*Betula nana*	*Betula pendula*	*Betula* sp.	*Pinus sylvestris* husk	
23.43	77.2	.	.	.	.	.	.	.	.	+	.	.	.	.	.	1	2	Pa-3
23.53	72.8	.	.	.	.	.	.	.	.	+	.	.	.	.	.	.	.	
23.63	67.4	.	.	.	.	.	.	.	.	+	.	.	.	.	6	.	.	
23.73	62.6	.	.	.	.	.	.	.	.	+	1	.	.	.	1	.	.	
23.78	64.9	.	.	.	.	.	.	.	.	+	.	.	.	.	9	1	.	
23.83	70.9	.	.	.	.	.	.	.	.	+	.	1	.	.	.	1	.	Pa-2
23.88	82.2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	8	
23.93	85.9	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	
23.98	85.3	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	
24.03	85.7	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	
24.08	84.1	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	
24.13	87.7	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	
24.18	89.3	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	
24.23	90.7	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	
24.28	87.1	.	.	.	.	.	+	.	.	.	.	1	.	.	.	.	.	
24.33	88.2	.	.	.	.	.	.	.	.	+	.	.	.	.	.	.	.	
24.38	88.1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	
24.43	85.7	.	+	+	.	.	.	.	.	+	.	.	.	.	.	.	.	
24.48	61.4	+	.	.	+	+	15	70	+	15	.	.	25	5	11	.	.	Pa-1

belonged to the *Chydoridae*. The dominant species were those living in shallow waters associated with aquatic plants. The most abundant remains represented the species *Alona affinis*. No cladoceran remains of open-water species were found. The faunal quantitative and qualitative composition enabled the distinction of two zones and six subzones of the cladoceran succession, marked by the symbol CAZ (Cladocera Assemblage Zones) and the letters A-C (Table 4 and Fig. 8).

The first zone is characterised by both a lower frequency of individuals (max. 563 ind./cm^3 of sediment – I-C CAZ) and a smaller number of species (9), which results in a low biodiversity index (max. 0.81). Species living in shallow waters associated with aquatic plants were dominant. In the second zone, the number of species (12) and the abundance of individuals (2,000 ind./cm^3 – II-C CAZ) increases significantly. The composition of species changed, with the assemblage containing species that require more fertile and warmer water. The cladoceran zones are described in detail in Table 4.

MOLLUSCS, AQUATIC FAUNA, OSTRACODS

The deposits studied did not contain mollusc or ostracod fossils. The lack of shells of these organisms has been also noted in the Parchliny 2014 profile, where this phenomenon was discussed (Wachecka-Kotkowska et al., 2018). One reason may be the inflow of large amounts of humic acid from the soil to the lake waters, which may have dissolved the calcareous mollusc and ostracod shells. The high content of humic acid and carbon dioxide gives a pH below ~6.2–6.5. Therefore, the low pH of the water prevented the development of mollusc and ostracod assemblages, even if the thermal and trophic conditions were suitable. An important reason for the lack of such

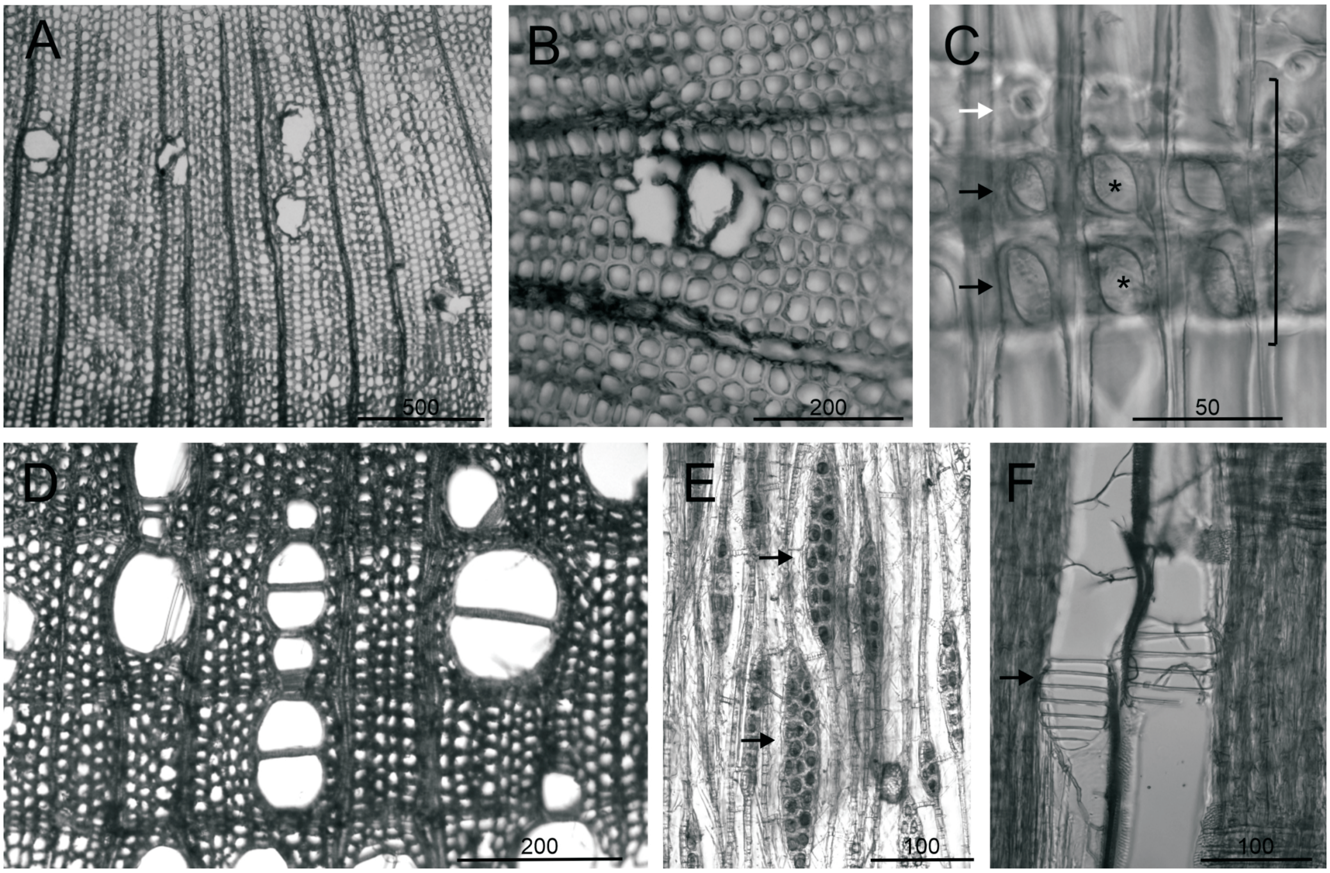


Fig. 7. Woody macrofossils

A–**C** – anatomical features of *Pinus* sp. wood: A, B – transverse sections, A – arrangement of tracheids, B – resin canals with thin-walled epithelial cells, C – radial section; heterocellular ray (enclosed in brackets) composed of tracheids (white arrow) and parenchyma cells (black arrows), fenestriform pits marked by stars; **D–F** – microscopic features of *Betula* wood: D – transverse section, diffuse-porous wood with vessels in radial multiples, E – tangential section, 2–4 seriate rays (marked with arrows), F – radial section – vessels with scalariform perforation plates; bar in μm

Table 4

Characteristics of Cladocera assemblage zones (CAZ) distinguished in the Parchliny 2016 profile in stratigraphic order from the bottom up

CAZ		Sample depth [m]	Description
II	C	23.33–23.43	Progressive increase in the number of species to 12 and the frequency of Cladocera remains up to 2000 ind./cm^3 of sediment; *Alona affinis* and *Acroperus harpae* are predominant; new species of *Camptocercus rectirostris* and *Leydigia leydigi* appear. *Leydigia* and *Pleuroxus* prefer high nutrient content in water; *Monospilus dispar* and small *Alona* reappear. *Pleuroxus* and *Camptocercus* need warmer water. At the end of this zone, the frequencies of almost all species increase; the biodiversity was higher and reached 0.93.
	B	23.53–23.63	In this zone, only 8 Cladocera species are identified; the frequency of Cladocera individuals significantly decreases (max 528 ind./cm^3 of sediment, Fig. 7); *Alona affinis* and *Chydorus sphaericus* are predominant. *Monospilus dispar* periodically withdrew from the lake The biodiversity index decreases to 0.82.
	A	23.73–23.78	Increase in the number of species to 9 and a significant rise in the number of individuals to 2383 ind./cm^3 of sediment, which is the profile's maximum; predominant species are *Alona affinis, Acroperus harpae, Pleuroxus uncinatus, Eurycercus lamellatus, Chydorus sphaericus* and *Alona quadrangularis*; a new species of *Monospilus dispar* appears, which needs more fertile and warmer water, similarly to *Pleuroxus*; The biodiversity index increases to 0.86.
I	C	24.23–23.83	The number of species remained at the same level (9); the number of individuals increased to a max. of 563 ind./cm^3 of sediment; the lake was inhabited by the same species as in the previous zone, except for the species *Alonella nana*; at the end of the zone, *Alona quadrangularis* also appeared. The dominant species is *Alona affinis*. The biodiversity index was higher than in the previous zone and reached 0.98.
	B	24.28–24.43	The number of species increases to 9 and the number of individuals to 482 ind./cm^3 of sediment; predominant species are *Alona affinis, Eurycercus lamellatus, Chydorus sphaericus* and *Sida crystallina*. *Alona quadrangularis* occurs at the beginning of this zone. The biodiversity index is higher than in subzone A – 0.91.
	A	24.48–24.50	Identification of 3 species; total number of Cladocera individuals reaches 233 ind./cm^3 of sediment; predominant species are: *Alona affinis* and *Eurycercus lamellatus*; only cold water tolerant species occur. At the beginning of this zone, the biodiversity was low and then increased to 0.38.

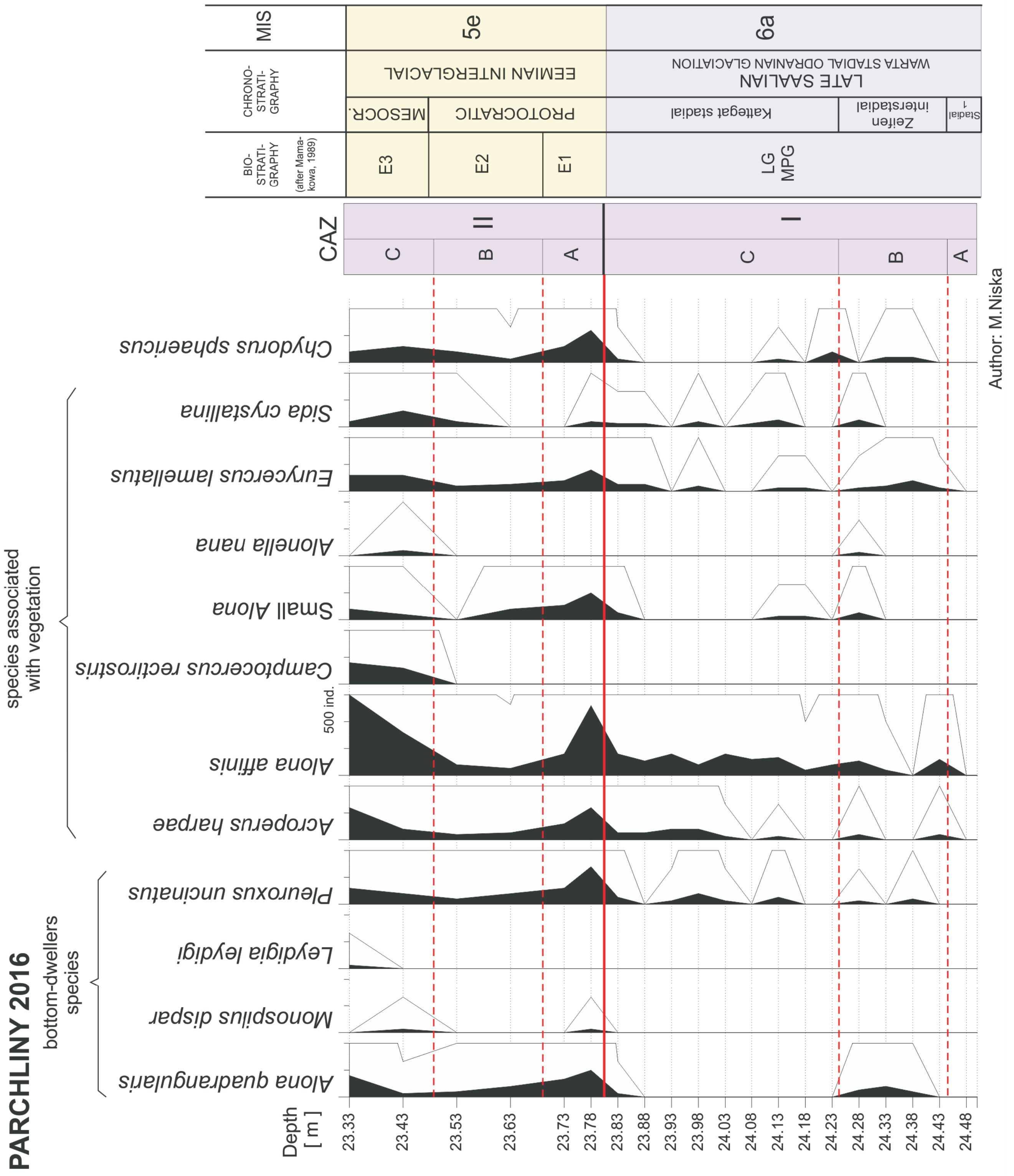


Fig. 8. Diagram of cladoceran species in deposits of the Parchliny 2016 profile

CAZ – local cladoceran assemblage zones

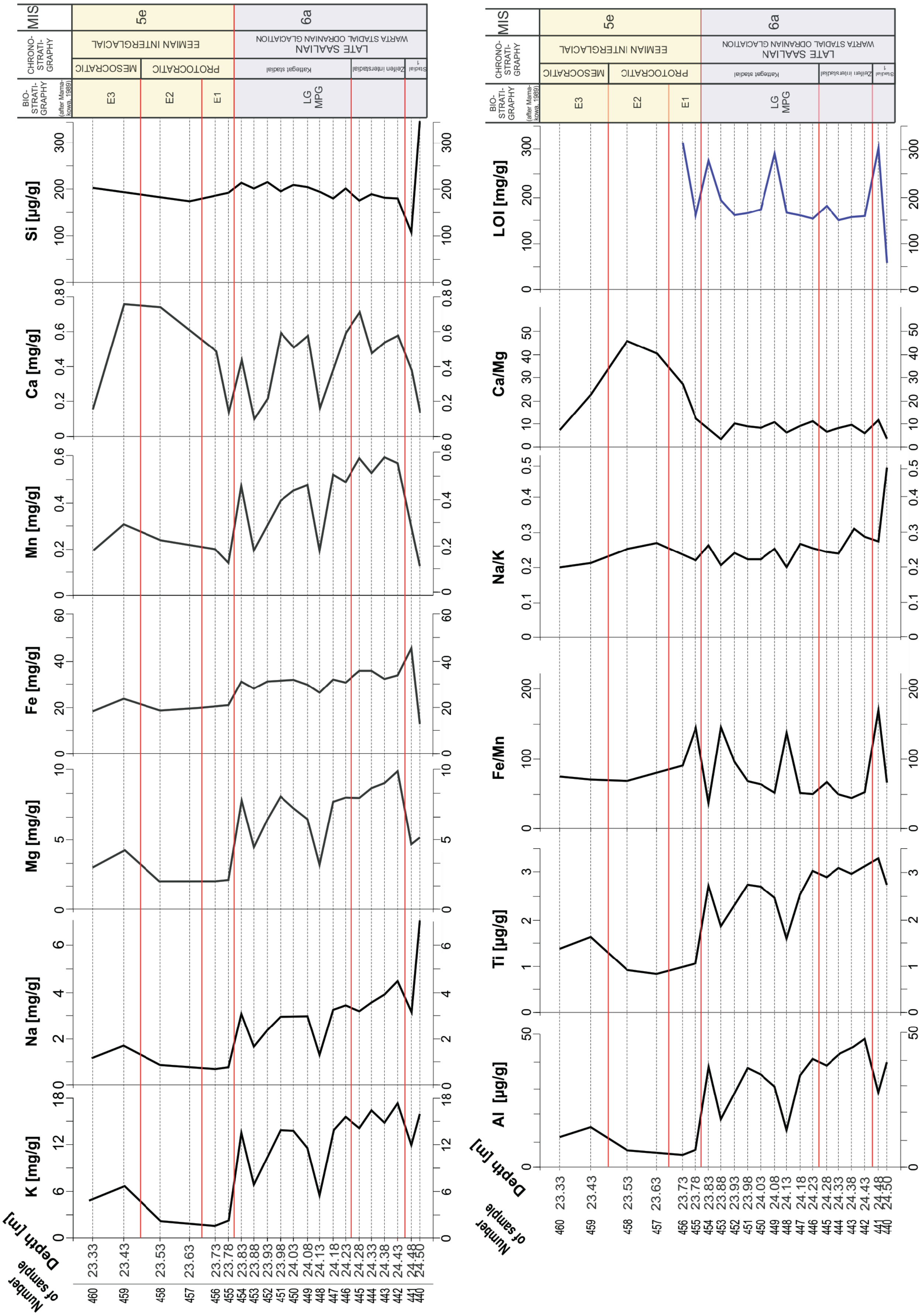


Fig. 9. Geochemical composition of the Parchliny 2016 profile

fauna is the high demand for available calcium (for building shells and carapaces) dissolved in the lake waters, and the lack of available carbonate may explain this absence.

GEOCHEMICAL AND ISOTOPIC DATA

ELEMENTAL STUDIES

The elemental composition of the sediment was dominated by silica (208–371 mg/g) and organic matter (>300 mg/g), which demonstrated its mineral-organic character (Fig. 9). The higher average LOI values in samples 441 (depth 24.48 m), 449 (depth 24.08 m), 454 (depth 24.83 m) and 456 (depth 23.78 m) at the expense of other components may indicate stronger plant cover development in the lake during climate fluctuations. From the bottom to the top of the profile, the contents of lithophilic elements such as K, Na, Mg, Si, Al decrease and the contents of the biogenic elements Ca, Fe and Mn remain at a variable level. The trends of Ca and Mn show increase from the depth of 23.78 m and decrease below 24.08 m.

GEOCHEMICAL AND ISOTOPIC ANALYSIS

The amounts of total organic carbon (TOC) and total nitrogen (TN) increased upwards in the 21 samples taken from the profile, from 2.6 to ~20% and from 0.1 to 1.2%, respectively (Fig. 10). The deposits from depths below 23.93 m are characterized by very low concentrations of organic carbon (~7%) and nitrogen (~0.5%). In the overlying deposits, the contents of both TOC and TN rapidly increased to 19 and 1.2%, respectively. The TOC/TN atomic ratio was ~18 and increased to 28–30 only in the two bottom samples.

The carbon isotope ratio (^{13}C) varied between –27.4 and –31.4‰, while the nitrogen isotope ratio (^{15}N) ranged from –1.4 to +1.7‰. The highest values of ^{13}C were found in the lowest sample from the basement of the palaeolake (24.50 m). In the samples from depths of 23.83–24.48–m, the ^{13}C values slightly increased to –29‰, and the ^{15}N values fluctuated around 1.5‰ (Fig. 10). Above 23.83 m depth, the ^{13}C values decreased below –31‰ and then rapidly increased to ~–28‰. The ^{15}N values initially dropped below –1.4‰ and then fluctuated around –1‰. The lake deposits that accumulated during the glacial period are isotopically differently from the basement deposits, which are characterized by the highest ^{13}C values and high ^{15}N values (Fig. 11). The sediments deposited under cool conditions have high values of carbon and nitrogen isotopes, caused by insufficient amounts of these elements in the water. The small amount of organic matter in these sediments was of terrestrial origin. The deposits correlated with the Eemian interglacial are characterized by much lower ^{13}C values (below –30‰), probably associated with an increase in primary production due to the improvement of environmental conditions (Fig. 11).

DISCUSSION

BIOSTRATIGRAPHY AND CHARACTER OF ENVIRONMENTAL CHANGES RECORDED IN SEDIMENTS

The pollen analysis results were integrated with the results of the other biological and geochemical analyses and used to interpret the Parchliny 2016 profile (Fig. 12). Our study could approximate the palaeoclimate conditions recorded in the lacustrine sediments deposited in the palaeolake after the ice sheet decay of the Warta Stadial of the Odranian Glaciation (Fig. 12). Pollen analysis allowed distinction of six local pollen assemblage zones (L PAZ; see Fig. 6). The lower three represent the beginning of vegetation development during the Late Saalian (MIS 6a). The three upper zones indicate the evolution of the interglacial vegetation associated with the onset of the Eemian interglacial (MIS 5e). The profile investigated does not fully document the Eemian succession, however the Eemian age is indicated by typical features of the protocratic phase, i.e. succession of trees in the order *Betula, Pinus*, *Ulmus*, followed by particular features of the mesocratic stage with a marked increase in *Quercus* and *Fraxinus excelsior*, and the appearance of *Corylus avellana*. The Parchliny 2016 profile together with the Parchliny 2012 and Parchliny 2014 profiles (Wachecka-Kotkowska et al., 2018) provide a picture of the succession of the Eemian interglacial vegetation (zones E-1 to E-7) registered in the sediments of one palaeolake (Tables 1, 2 and 5).

The data from Polish sites e.g. Imbramowice (Mamakowa, 1989), Warszawa-Wawrzyszew XV (Krupiński and Morawski, 1993), Zgierz-Rudunki (Jastrzębska-Mamełka, 1985), Horoszki (Granoszewski, 2003), and also from eastern Germany (Menke and Tynni 1984; Strahl, 2000) show that initially the end of the Late Saalian is marked by various herbaceous plant communities. The high proportion of NAP indicates that grass and sedge communities prevailed, in which heliophytes played a dominant role. Shrub communities were also of great importance, mainly *Juniperus communis*, *Salix, Betula nana*, and *Hippophaë rhamnoides*. The record of the vegetation from the bottom three pollen zones (P-1–P-3 L PAZ) from the Parchliny 2016 profile indicates instability of the climate in the Late Saalian which might reflect stadial/interstadial oscillations. The P-1 *Poaceae-Pinus-Betula* L PAZ (depth 24.48 m) indicates the coolest climate conditions with a high, nearly 35%, share of NAP, dominated by Poaceae (25%) and the 38% share of *Pinus sylvestris*. The P-1 L PAZ my correspond to Stadial 1, distinguished at the end of the Late Saalian in Western Europe (Menke and Tynni, 1984) at e.g. the Klinge site (Strahl, 2000; Velichko et al., 2005) or Neubrandenburg-Hinterste Mühle (Börner et al., 2018). The geographically nearest profiles where levels with significant NAP domination have been distinguished are Zgierz-Rudunki (Jastrzębska-Mamełka, 1985), Żabieniec Południowy (Majecka, 2014) and Wola Starogrodzka (Kupryjanowicz et al., 2021). As at our study site, and in neighbouring ones, this stage can be considered as the initial stage of any vegetation development, as shown in being always expressed in single samples.

In the next, P-2 *Pinus-Betula* L PAZ (depth 24.28–24.43 m), the proportions of AP and NAP clearly change, there is a decrease in NAP values to 15% (mainly Poaceae), and an increase in the proportion of *Pinus sylvestris* pollen to 61.5%. Previous palynological data show that the importance of trees in plant communities of the Late Saalian was relatively low, and the pine and birch pollen present may be associated with long-distance transport (Kuszell, 1998; Kołaczek et al., 2012; Malkiewicz, 2018a, b). In our opinion, such tree pollen values might testify to the local presence of this tree as a component of patchy communities in the landscape already in Late Saalian. High values of such pollen are also present in the profiles from Zgierz-Rudunki (Jastrzębska-Mamełka, 1985) and Żabieniec Południowy (Majecka, 2014). Warming, expressed by the spreading of shrub communities, followed by an initial birch forest, was also recorded to the east in the Warszawa-Wawrzyszew XV profile (Krupiński and Morawski, 1993), while open pine forests with birch and a small admixture of spruce have been reported from the Babin profile (Żarski et al., 2018; Table 5).

In the Parchliny 2016 profile, spruce presence is negligible (0.8%). Its presence below the Late Saalian/Eemian boundary has been shown mainly in profiles from Eastern Poland, e.g. at Dziewule (Bińka and Nitychoruk, 2001), Szwajcaria 1 (Borówko-Dłużakowa and Halicki, 1957) and also in Wola

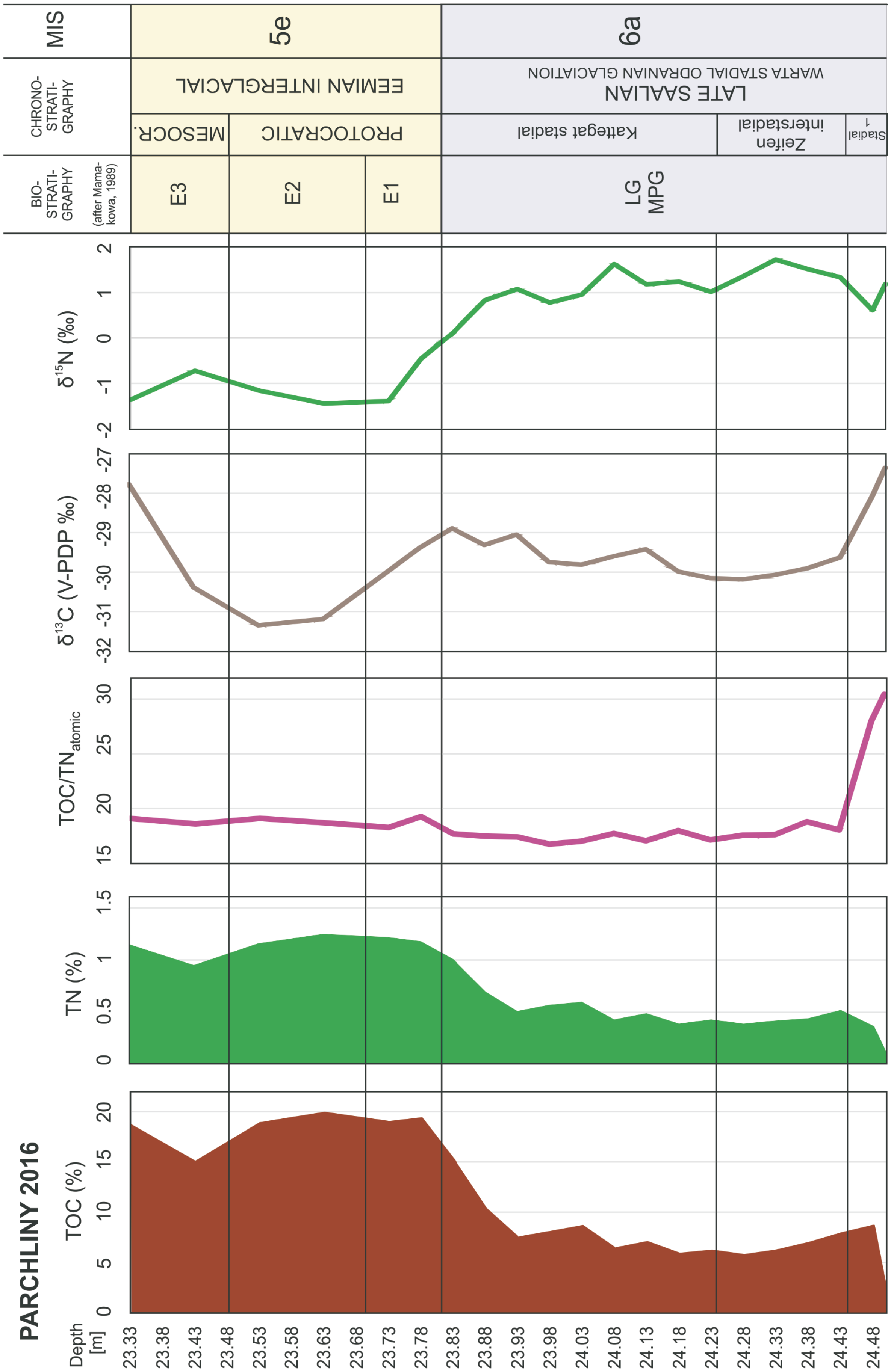


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Fig. 10. Results of selected geochemical and isotopic analyses of the deposits of the Parchliny 2016 profile

TOC – total organic carbon content; TN – total nitrogen content; TOC/TN$_{atomic}$ – atomic ratio of TOC to TN; ^{13}C, ^{15}N – isotopic data

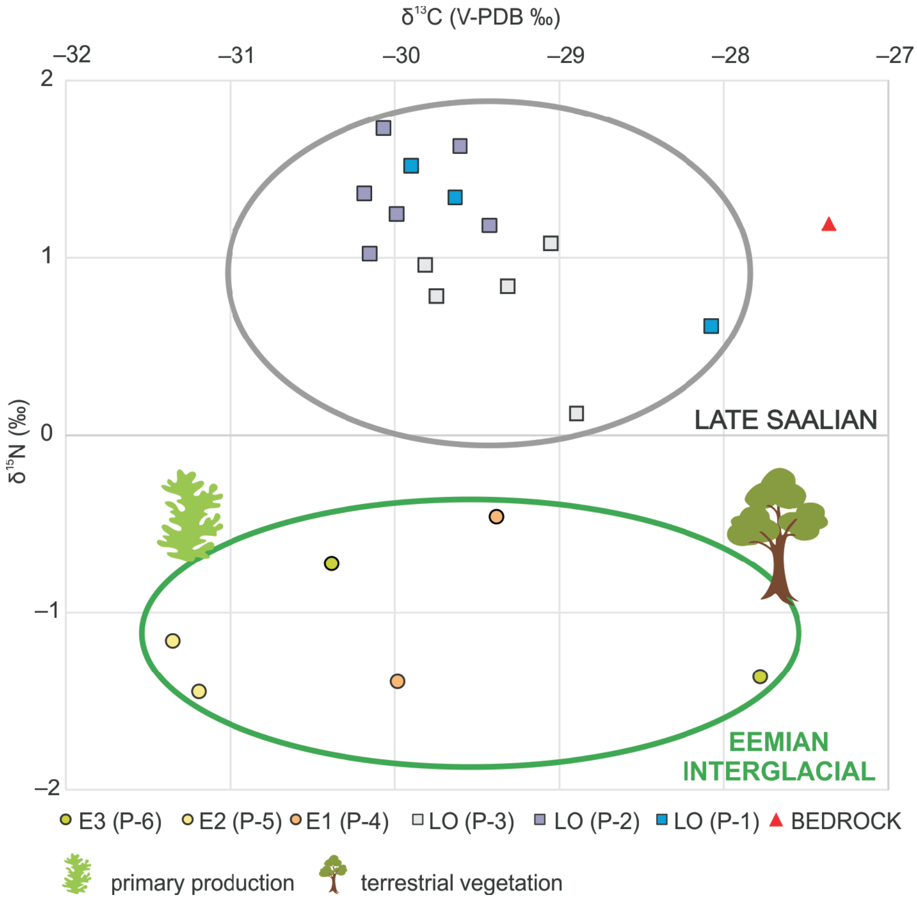

Fig. 11. Variations in the isotopic data of the deposits of the Parchliny 2016 profile

^{13}C, ^{15}N – isotopic data; P-1–P-6 – local pollen assemblage zones; LO – Late Saalian; E1–E3 – Eemian regional pollen assemblage zones

Starogrodzka in central Poland (Kupryjanowicz et al., 2021). The level with spruce, called the „lower spruce” zone (e.g., Grichuk, 1961; Mamakowa, 1989) corresponds to the Zeifen interstadial. The spruce probably appears as a supplement to the high proportions of pine and birch, indicating the existence of sparse forest communities and, consequently, amelioration of climate conditions, but its presence is not constant nor due to habitat control. For example, in Wola Starogrodzka, it appears in only one of the two sedimentary profiles palynologicaly analysed. (~28% in profile G-122; in profile WH-122 this subzone is not represented; Kupryjanowicz et al., 2021). Most likely it was *Picea obovata* (Mamakowa, 1989) sometimes accompanied by fir, probably *Abies sibirica*. These types of communities correspond to the modern Siberian taiga communities (Kupryjanowicz et al., 2021). In the Parchliny 2016 profile, no fir was recorded in this zone, and the low levels of spruce does not prove that this type of communities was present here. The increase in the share of AP, including *Pinus* sylvestris in particular, to the detriment of *Betula* undiff. and the increase in biodiversity, including of cladocerans (I-B CAZ) indicates that in central Poland, the air temperature probably increased at that time, as well as annual precipitation (cf. Rotnicki, 1996), while permafrost began to disappear (cf. Mojski, 2005).

The third section, 0.40 m long, (depth 23.83–24.23 m), associated with the P-3 L PAZ (*Pinus-Betula*-NAP) represents a record of slightly marked cooling (stadial) at the very end of the Late Saalian (MIS 6a). The pollen assemblage of this episode is distinguished by a reduction in the sparse pine-birch forest communities and slight increase in cold steppe communities with *Artemisia, Helianthemum* and Chenopodiaceae, Asteraceae, Rosaceae. NAP values reach 16–23%, including the Poaceae maximum of 10%. The *Artemisia* value increases to a maximum of 7% (5% maximum in P-2 L PAZ), but then drops to 4%. A similar slight change in the pollen record compared to the earlier zone was recorded in the profile from Wola Starogrodzka, where the authors believe that the decrease in the percentage of AP is a result of slight reduction of forest community area or that the pollen production of the trees forming them decreased. It is inferred that climatic conditions may have been generally similar as during the earlier zone, corresponding to the Zeifen interstadial (Kupryjanowicz, et al., 2021). Nevertheless, this zone is classified as likely corresponding to the Kattegat stadial. The Parchliny 2016 profile P-3 L PAZ, in our opinion, may also correspond to the Kattegat stadial.

The pollen data obtained allow the conclusion that the Parchliny 2016 profile reveals the slight climate oscillations of the Late Saalian (MIS 6a). Changes in climatic conditions are corroborated by the sedimentary geochemistry. The curves, especially of the peaks most of elements, align with the zones distinguished in other analyses. This is particularly visible in the sample at 23.78 m, which marks the beginning of the Eemian interglacial. In general, there is a relative lack of variability of element ratios in warmer periods (Zeifen stadial, as well as the Eemian interglacial) and significant variability of its proportions

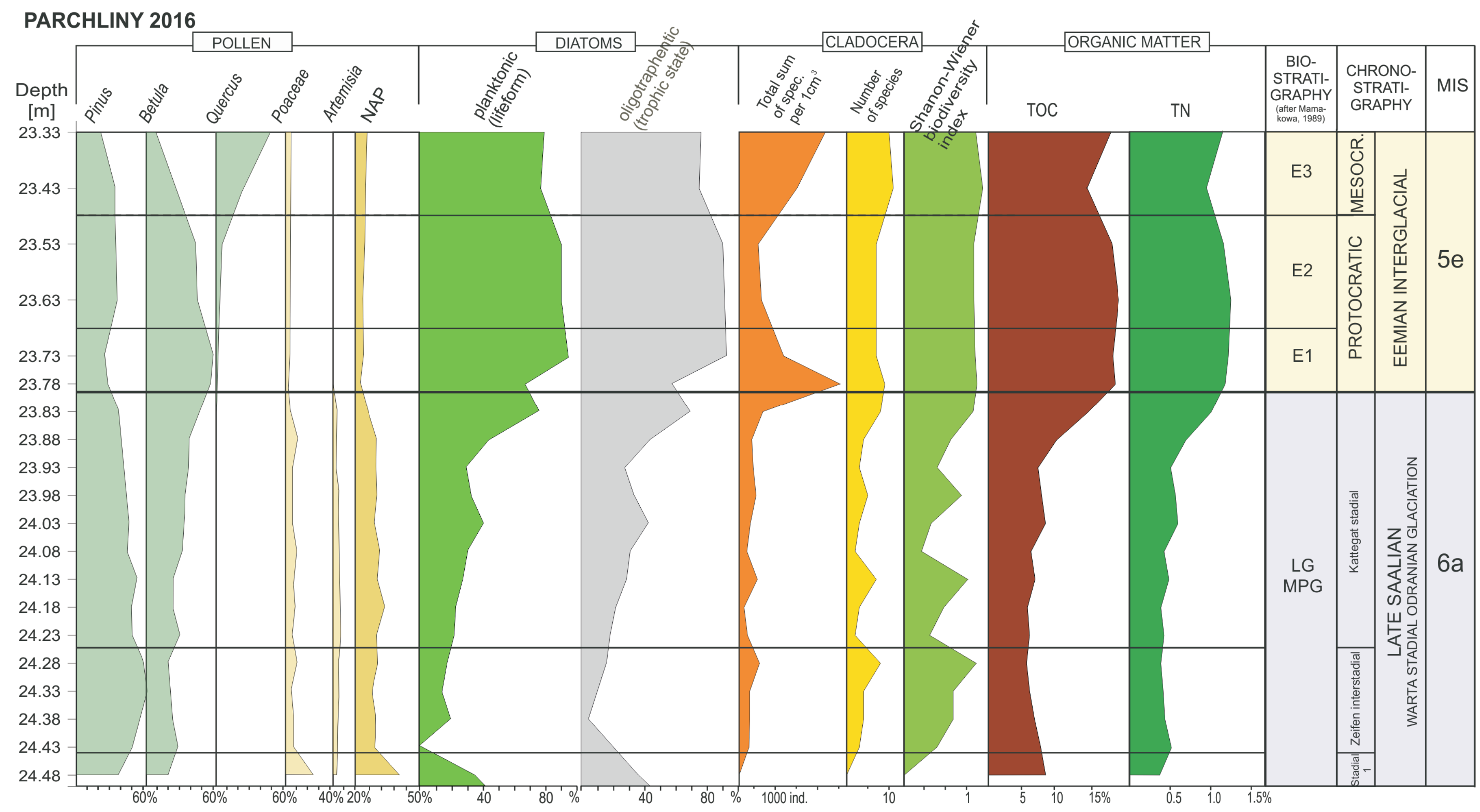

Fig. 12. Correlation of selected proxies from the Parchliny 2016 profile

Table 5

Correlation of the local pollen assemblage zones L PAZ distinguished for the Late Saalian and Eemian interglacial in selected sections from the Szczerców Basin and central Poland with the regional pollen assemblage zones R PAZ (Mamakowa, 1989)

Parchliny 2012	**Parchliny 2014**	**Parchliny 2016**	**Kuców IIc**	**Zgierz-Rudunki**	**Żabieniec Południowy**	**Warszawa-Wawrzyszew XV**	**Babin**	**Wola Starogrodzka G-122**	**R PAZ (Mamakowa, 1989)**	**Stratigraphy**
	PA-5 *Pinus*		*Pinus*	ZRII 9b *Betula-Pinus-Picea*-NAP ZRII 9a *Pinus-Picea-Betula*	Ż.Pd-7 *Pinus-Picea-Betula*-NAP	WW 10 *Pinus-Picea-(Carpinus)*	Ba 13 *Pinus*-NAP Ba 12 *Betula-Pinus-Picea* Ba 11 *Pinus-Picea*		E7 *Pinus*	Eemian interglacial
	PA-4 *Abies-Picea*		*Picea-Abies-Alnus*	ZRII 8 *Picea-Abies-Carpinus-Alnus*	Ż.Pd-6 *Alnus-Picea-Abies*	WW 9 *Picea-Abies-Carpinus-Pinus*	Ba 10 *Picea-Abies-Carpinus*	9 *Picea-Pinus-(Abies)*	E6 *Picea-Abies-Alnus*	
	PA-3 *Carpinus-Alnus*		*Carpinus-Tilia-Alnus*	ZRII 7b *Carpinus-Picea* ZRII 7a *Carpinus-Tilia-Corylus-Alnus*	Ż.Pd-5 *Carpinus-Corylus-Alnus-Picea*	WW 8 *Carpinus-Corylus-Picea*	Ba 9 *Carpinus-Picea-Abies* Ba 8 *Carpinus-Corylus-Tilia*	8 *Carpinus-Picea-Alnus*	E5 *Carpinus-Corylus-Alnus*	
P5 *Corylus-Tilia*	PA-2 *Corylus-Tilia*		*Corylus*	ZRII 6 *Corylus-Tilia-Acer*	Ż.Pd-4 *Corylus-Quercus-Tilia-Alnus*	WW 7 *Corylus-Tilia-Carpinus*	Ba 7 *Corylus-Quercus-Tilia*	7 *Corylus-Tilia-Alnus-Carpinus*	E4 *Corylus-Quercus-Tilia*	
P4 *Quercus-Corylus* P3 *Quercus-Fraxinus-Ulmus*	PA-1 *Quercus-Corylus*	P-6 *Quercus*	*Quercus-Ulmus*	ZRII 5 *Quercus-Corylus*		WW 6 *Quercus-Pinus-Fraxinus-Corylus*	Ba 6 *Quercus-Ulmus-Fraxinus*	6 *Quercus-Pinus*	E3 *Quercus-Fraxinus-Ulmus*	
P2 *Pinus-Betula-Ulmus*		P-5 *Pinus-Betula-Ulmus-Quercus*	*Pinus-Betula*	ZRII 4 *Pinus-Betula*		WW 5 *Pinus-Betula-Ulmus-Quercus*	Ba 5 *Pinus-Quercus-Ulmus*	5 *Pinus-Betula-Quercus-(Picea)*	E2 *Pinus-Betula-Ulmus*	
P1 *Betula-Pinus-Ulmus*		P4 *Betula* - *Ulmus*	*Betula-Juniperus*	ZRII 3 *Betula-Pinus*	Ż.Pd-3 *Betula-Pinus*	WW 4 *Betula-Pinus*-NAP-(*Ulmus*)	Ba 4 *Pinus-Betula*	4 *Betula-Pinus-Picea*	E1 *Pinus-Betula*	
		P-3 *Pinus-Betula- NAP*		ZRII 2 *Pinus-Betula*	Ż.Pd-2 *Pinus-Betula*	WW 3 *Pinus-Juniperus-(Artemisi-Hippophae)*	Ba 3 *Betula Artemisia*	3 NAP-*Betula-Pinus-Picea*	*Cyperaceae-Artemisia-Betula nana* LG MPG	Late Saalian
		P2 *Pinus-Betula*				WW 2 *Betula-Hippophae-Artemisia*	Ba 2 NAP-*Betula-Salix*	2 *Pinus*-NAP-*Picea*		
		P-1 *Poaceae-Pinus-Betula*		ZRII 1 NAP-*shrubs*	Ż.Pd-1 NAP	WW 1 *Hippophae-Salix*-NAP	Ba 1 *Pinus*-NAP-*Cyperaceae*	1 NAP-*Betula*-reb.		

in cool periods (Stadial 1 and Kattegat stadial). In addition, in warm periods, the content of mineral elements (e.g., K, Na, Mg) decreases, which indicates a smaller supply of mineral sediments from the lake catchment area. The increasing content of Mn and Ca indicates an increase in the proportion of organic matter. High values of the Fe/Mn index in cool periods indicate changes in the water level. The Fe/Mn values are lower and more homogeneous in the warm periods. There is also a significant increase in the Ca/Mg ratio during the development of the Eemian interglacial, which can be related to the dynamic development of the lake fauna (Fig. 9).

The Late Saalian/Eemian boundary (MIS 6a/MIS 5e) in the Parchliny 2016 profile is marked in a decrease in values of herbs (NAP) and shrubs and an increase in the share of tree taxa. The Eemian interglacial begins with the development of pioneering forests of birch and birch-pine (P-4 L PAZ). The value of *Betula* reaches 60.5%. The pollen zones that began the Eemian interglacial, attesting to a dense boreal forest, have also been recorded at other nearby sites (see Table 5). Subsequently, forest communities of the study area became enriched in deciduous trees and shrubs - elm, ash, oak, alder and hazel (P-5/P-6 L PAZ).

No cladoceran remains from the open water zone have been recorded in the lacustrine deposits, which may indicate that the lake was shallow or that the samples were taken from its shallow-water area. The relatively high frequency of cladocerans in the Late Saalian as well as the presence of a species with higher thermal requirements (*Pleuroxus uncinatus*) were characteristic of the profile studied. The transition to a warmer period, the Eemian interglacial, was distinctly reflected in an increase in cladocerans and in a species arrival (*Monospilus dispar*). A similar situation occurred at another site in the Bełchatów Mine – Kuców IIc (Niska, 2008) and in the nearby Besiekierz palaeolake (Mirosław-Grabowska and Niska, 2005). In these reservoirs, at the beginning of the Eemian interglacial (E1), the frequency of cladoceran species and individuals increased, and in the next period (E2) it decreased again, which may be related to cooling, as shown by, for example, the withdrawal during this period of two species with higher thermal requirements, *Camptocercus rectirostris* and *Monospilus dispar*, from the Parchliny 2016 palaeolake).

RECONSTRUCTION OF THE PALAEOLAKE DEVELOPMENT DURING THE TRANSITION FROM MIS 6a to MIS 5e

On the basis of the proxies obtained proxies (lithological, palaeobotanical, palaeozoological and geochemical) from the Parchliny 2016 profile investigated, we have reconstructed the palaeoenvironment between the Late Saalian and Eemian interglacial in the Szczerców Basin and determined the evolutionary phases of the palaeolake (Fig.13).

Ist PHASE: DECAY OF THE WARTA STADIAL OF THE ODRANIAN ICE SHEET

The basement of the Parchliny 2016 profile is composed of disturbed glacial tills that were observed locally at the bottom of subglacial channels or melt-out kettles. The lithological-petrographic examination of the tills suggests that it is lithotype T4, which corresponds to the Ławki Formation (Wachecka-Kotkowska et al., 2021). However, in a typical sequence, we would expect one of the younger lithotypes, such as lithotype T7 (cf. Allen and Krzyszkowski, 2008). Our findings confirm the existence of glaciotectonic deformation structures, which, *nota bene*, were also observed on the left side of a wall: large-scale, and over a long section of the excavation wall (Fig. 2). Thus, the situation was that a dead-ice block, buried within the disturbed tills melted out in the Late Saalian (MIS 6a). The pavement at the top of the tills represents a washed-out till surface. The ventifact, on the other hand, indicates a longer period when the boulders were exposed to wind after the ice sheet decayed. Similar periglacial traces at the top of the Odranian deposits in the Polish Lowland (Mazovia), 250 km north of the investigated area, have been recorded (Dąbski et al., 2017). The general geological picture (Fig. 2) and surface mapping (prior to the quarrying excavation) show that glacial tills occurred locally at the bottoms of subglacial channels or melt-out kettles (Baraniecka, 1971).

After formation, the glacial tills were preserved for some time with included blocks of ice that melted out rapidly. After the decay of the ice sheet, dead ice blocks melted out in the kettle-holes and post-glacial channels, as outflow valleys of initially glacial and subsequently extraglacial waters, that were very clearly marked in the topographic relief at that time (Fig. 13). However, they were not filled with mineral sediments, because no such deposits have been found (Wachecka-Kotkowska et al., 2021). Hence, we conclude that the deposits must have been incorporated into the drainage system quite quickly. In the bottom of these landforms, some boulders were exposed to aeolian processes (Dąbski et al., 2017). A ventifact was found at the top of the till (Fig. 4C). The aeolian reworking was probably very intense but did not last long. There was no dense vegetation at that time.

IInd PHASE: FORMATION OF A LAKE SYSTEM FOLLOWING DEGLACIATION (LATE SAALIAN)

The river water outflow must have been blocked, possibly because of a landslide or other kind of damming in the postglacial channel system, somewhere north of the study area. The damming was so effective that it allowed the formation of a lake system in which prolonged lacustrine accumulation occurred. The sharp boundary between visible gravel and boulder pavement between tills and peat and gyttja indicates the inflow of terrigenous material, possibly caused by the greater erosive activity of watercourses feeding the lakes at that time.

The dominant content of silica and other mineral elements in the profile may be related to the inflow of water with suspended sediment into the lake. This is supported by the fine grain size of the sediment: silt and clay (Fig. 9). During the Late Saalian, organic carbon (TOC) levels increased in the sediments (Fig. 10). At the time, the highest values of the TOC/TN atomic ratio occurred, suggesting the presence of organic matter of terrestrial origin (Meyers and Lallier-Vergès, 1999).

Initially, even before these kettle holes were filled with water, a thin peat layer was deposited (Figs. 3 and 13), which subsequently became compacted to be ~2 cm thick. Plant macroremains and tree branch fragments were preserved (Fig. 4D). Above the peat, deposits that indicate accumulation in a lake were found (Fig. 3). This period corresponds to the P-1 *Poaceae-Pinus-Betula* L PAZ, which shows the dominance of cold steppe communities, dominated by grasses (Poaceae) and other heliophytes including *Artemisi*a, Chenopodiaceae, *Helianthemum*, Caryophyllaceae and *Rumex*. *Juniperus communis* and *Ephedra* were also present in this community. In wet habitats, there were patches of shrub communities with *Betula nana*, willows, and herbaceous plants including Asteraceae, *Galium*, Ranunculaceae and Rosaceae. The presence of *Betula nana* in the shrub communities of this section was demonstrated by numerous macroremains (Pa-1 L MAZ). Pine and birch were not prominent in the landscape of that time, but their presence was confirmed by macroremains of pine bark, fruit, and birch wood. *Pinus sylvestris* and *Betula* undiff.

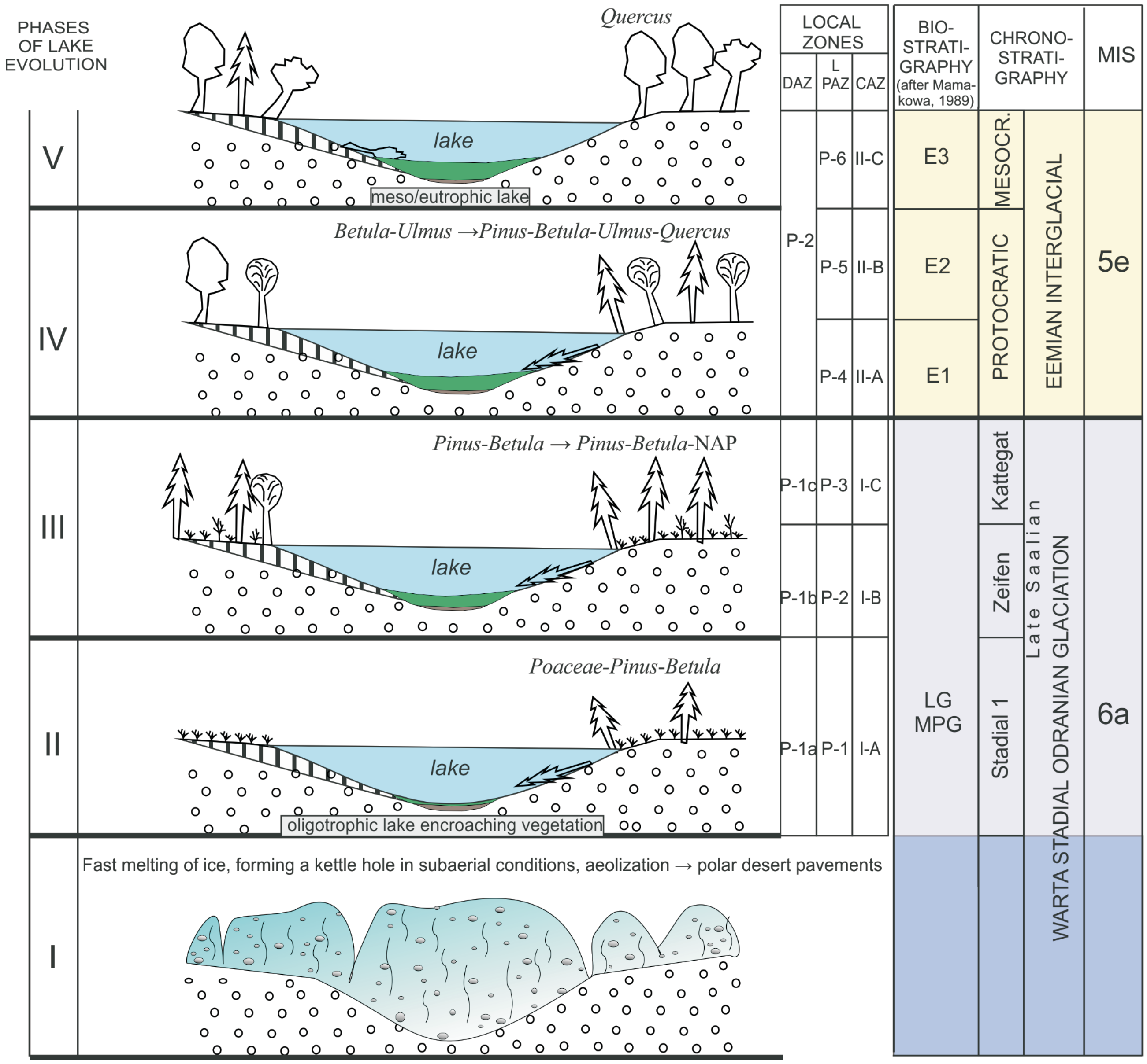

Fig. 13. Reconstruction of the palaeolake development during the transition from MIS 6a to MIS 5e based on the Parchliny 2016 profile

Local zones: DAZ – Diatom assemblage zones; L PAZ – Local pollen assemblage zones; CAZ – Cladocera assemblage zones

May have occurred in the tundra communities. *Carex rostrata* dominated the Cyperaceae, the fruit of which was found in large amounts in this zone. In the presence of *Polytrichum* sp. and *Climacium dendroides* (Pa-1 L MAZ), *Sphagnum* formed a moss layer on the peat bog present at that time. The presence of *Juniperus communis* and the nature of the plant communities with clear participation of *Betula nana* in tundra communities indicate moderately cold climate conditions, with the MTWM ranging from +8 to +10°C (Iversen, 1954; Mamakowa, 1989; Isarin and Bohncke, 1999; Granoszewski, 2003), corresponding to the conditions of arctic or subarctic climates. The mean temperature of the coldest month (MTCM) did not exceed –5°C (Zagwijn, 1996). At the time a shallow water body with low fertility existed and was dominated by littoral (periphyton and benthic) diatoms (Fig. 5). Small planktonic *Cyclotella sensu lato* species, which are commonly observed in higher abundances in oligotrophic-mesotrophic lakes, i.e., low nutrient levels, were also present (Rühland et al., 2003; Zalat et al., 2018; Pidek et al., 2021).

The beginning of the lake's existence coincides also with the low frequency of cladocerans (I-A CAZ, Fig. 8). The lake hosted species resistant to lower temperatures: *Alona affinis, Eurycercys lamellatus* and *Acroperus harpae* (Whiteside, 1970; Korhola, 1990). Moreover, these species are undemanding as regards the abundance of nutrients in water, and they live in aquatic plants. This suggests the existence of a relatively shallow and cool lake with a macrophyte zone (Bledzki and Rybak, 2016).

IIIrd PHASE: DEVELOPMENT OF THE LAKE DURING THE EXPANSION OF VEGETATION (LATE SAALIAN)

The increase in pine and birch indicated a greater importance of trees in plant communities during the beginning of this phase. Open forests in a type of boreal forest probably appeared in the study area, at first pine and pine-birch (zone P-2 *Pinus-Betula* L PAZ). Afterwards, the share of pine decreased in favour of an increasing percentage of birch pollen with a slight increase in the importance of herbaceous plants (zone P-3 *Pinus-Betula*-NAP L PAZ). The presence of forest communities was supported by the fruit of *Betula* sp. and *Betula pendula*, and fragments of bark of *Pinus sylvestris* found in Pa-2 L MAZ and Pa-3 L MAZ (Table 2).

Shrub communities were still present, in which *Dryas octopetala* appeared next to *Betula nana* and *Salix*. The role of steppe communities had increased slightly, with domination by *Artemisia* and Chenopodiaceae. The presence of Asteraceae, Rosaceae, *Potentilla*, *Galium*, *Thalictrum*, Ranunculaceae and Apiaceae corroborates the continuously significant role of open communities. *Juniperus communis* continued to occur in drier habitats, while alder and willows occupied wet habitats, the proportions of which increased, indicating an increase in humidity. The continued presence of *Pediastrum* and *Botryococcus* algae emphasizes that it was a eutrophic and shallow lake surrounded by *Equisetum*, *Sparganium*, *Typha latifolia* and Cyperaceae. The existence of a shallow lake was demonstrated by sparse fruit of the aquatic plants *Typha* sp. and *Potamogeton* sp. (Oberdorfer, 2001). The constant presence of *Juniperus communis* during P-2 and P-3 L PAZ indicates an average July temperature of +8 to +10°C (Isarin and Bohncke, 1999); however, the general nature of the changing vegetation, i.e. a slightly increased share of herbaceous plants and a clear withdrawal of pine, testifies to the cooling of the climatic conditions at the very end of Late Saalian.

Diatom analysis also revealed a change in the environmental conditions of phase III of the lake. At the beginning (P-1b DAZ), we observed an improvement in the availability of nutrients. This is indicated by the dominance of mesoeutrophic species accompanied by eutrophic and hypereutrophic species. The dominant diatom species were the benthic *Amphora pediculus, Pseudostaurosira brevistriata, Stauroneis construens* and *S. lapponica*. *Fragilaria sensu lato* species are known to predominate in oligo-mesotrophic, cold-water lakes or in shallow moats of partially frozen ponds and are hence characteristic of reduced growing seasons (Douglas and Smol, 1999; Lotter and Bigler, 2000; Schmidt et al., 2004).

In the P-1c subzone, there is a change in diatom composition. This subzone was characterised by increased oligotrophic species (nutrient-deficient) waters. Also, increasing abundance of planktonic species, e.g. *Pantocsekinella comesis*, is seen at the top of P-1c DAZ, and the occurrence of some benthic taxa may indicate a deepening of the water level and slow transition to the interglacial period. The clear increase in the abundance of planktonic taxa, in particular *Cyclotella sensu lato* spp., with concurrent relative decrease in benthic taxa including fragilarioid species, suggest a warming climate, longer ice-free periods and enhanced thermal stratification (Rühland et al., 2008, 2015; Zalat et al., 2018).

The third phase of the lake's evolution brought an improvement in the living conditions for cladocerans, as shown by the increase in the number of cladoceran species and individuals, with more favourable conditions for a larger assemblage of species. The presence of *Alona affinis* may indicate a slightly higher water level (depth 24.43 m; I-B CAZ). The share of *Eurycercus lamellatus* and *Chydorus sphaericus* increases, among the pioneering species (Hofmann, 2000), which corroborates the improvement of conditions and the availability of macrophyte habitat. An increase in water temperature and fertility may also be suggested by the appearance of *Pleuroxus uncinatus* (Hofmann, 2000). In the I-C CAZ sub-zone, the cladoceran frequency decreases, which is associated with the deterioration of living conditions, probably related to cooling (Kattegat stadial).

We observed the lower content of organic matter (TOC and TN) in the deposits, which reflects low primary production as well as lesser delivery of organic matter from land (Fig. 10). The higher ^{15}N values in the deposits below 23.88 m suggest lower nitrogen availability in the surface waters (Talbot and Laerdal, 2000).The transition from glacial to interglacial conditions was recorded in the geochemical data above 23.88 m by an increase in organic matter content (TOC of ~10% and TN of 0.7%). This phenomenon, occurring at the end of the P-3 L PAZ, was caused by the earlier reaction of lake water to climate warming. The content of mineral elements, e.g. K, Na, Mg, decreases and the content of Mn and Ca increases.

IVth PHASE: THE DEVELOPMENT OF LAKE DURING THE EEMIAN INTERGLACIAL – PROTOCRATIC PHASE (E1-E2 R PAZ)

The transition between the Late Saalian and Eemian Interglacial caused an increase in the mean temperature of the warmest month (MTWM) from +10 to +16°C. Similarly, the mean temperature of the coldest month (MTCM) increased from –5°C to 0°C at the beginning of the interglacial (Mamakowa, 1989; Litt et al., 1996; Zagwijn, 1996; Aalbersberg and Litt, 1998; Granoszewski, 2003; Kupryjanowicz, 2008), which triggered the expansion of forest communities. The change in plant communities was caused by the spread of boreal birch and pine forests. Initially, these forests were dominated by birch (P-4 *Betula-Ulmus* L PAZ), followed by a greater share of pine (P-5 *Pinus-Betula-Ulmus-Quercus* L PAZ) and an increasing admixture of oak (*Quercus*). Riparian forests with elm (*Ulmus*), ash (*Fraxinus excelsior*), alder (*Alnu*s), and willow (*Salix*) developed in wet habitats and depressions. The importance of steppe communities with herbaceous vegetation and *Betula nana* became insignificant. *Nymphea alba, Sparganium t.* appeared in the lake, confirming the improvement in thermal conditions and indicating an average temperature of the warmest month (MTWM) of +13–+14°C (Iversen, 1954; Kolstrup, 1980; Mamakowa, 1989). The presence of much denser forests was shown by the higher number of *Betula pendula* fruit, bark beetles, and *Pinus sylvestris* scales.

Diatom analysis revealed a clear dominance of circumneutral species. There was an increase in mesotrophic and oligotrophic diatom trophic preferences (P-2 DAZ). We also observed the occurrence of planktonic species and benthic species, indicating a slight increase in water depth, but generally it was a shallow lake.

During this phase, the frequency of cladoceran individuals and the number of species increased significantly (II-A CAZ; Fig. 8 and Table 4). The frequency of the specimens reached ~2,000 ind./cm^3 of sediment, indicating a significant improvement in living conditions. The increase in the number of species such as *Pleuroxus uncinatus* and small *Alona* may indicate an increase in trophic state (mesotrophy) and water temperature (e.g., *Monospilus dispar* and *Pleuroxus uncinatus*, Hofmann, 2000). The lake was shallow (lack of cladoceran species from the open water zone but the appearance of *Alona affinis* probably indicates a slightly higher water level (Nevalainen, 2012; Fig. 13). Next (II-B CAZ), a decrease in the frequency of cladoceran species to eight occurred. The number of cladoceran specimens also decreased, showing the deterioration in living conditions. The species *Monospilus dispar* withdrew from the lake, which may be related to the periodic drop in water temperature in the lake.

During the protocratic phase of the Eemian interglacial, a two-fold increase in TOC and TN suggests an increase in primary production caused by climate warming and also the development of vegetation. Similar results were observed in Ustków (Kołaczek et al., 2016), Rzecino and Kubłowo sites (Niska and Mirosław-Grabowska, 2015; Mirosław-Grabowska et al., 2018). The ^{13}C values dropped below –30‰ reflecting a greater proportion of freshwater algae in organic matter (Leng et al., 2005) and suggesting enhanced primary production (Fig. 11).

Vth PHASE: EXISTENCE OF THE LAKE DURING THE EEMIAN INTERGLACIAL – MESOCRATIC PHASE (E3 R PAZ)

The change in the forest communities began the mesocratic phase of the Eemian interglacial (P-6 *Quercus* L PAZ). Boreal pine-birch forests gave way to much warmer mixed forests with a significant share of oak (*Quercus*) and hazel (*Corylus avellana*) appearing in the undergrowth of these forests. Riparian forests dominated by elm (*Ulmus*) and ash (*Fraxinus excelsior*), and with the presence of alder (*Alnus undiff.*) and willow (*Salix.*) also gained importance. The appearance of ivy (*Hedera helix*) indicates moderately high summer temperatures, with the coldest months no colder than –1.5°C (Iversen, 1954).

The presence of the planktonic diatom *Pantocsekiella comensis*, which indicates well-stratified lake water in summer (Hausmann and Lotter, 2001; Rühland et al., 2008, 2015; Saros and Anderson, 2015), corroborates the warming trend in the lake development (P-2 DAZ).

The frequency of cladoceran species and individuals increased significantly in the lake (II-C CAZ). The increase in frequency and the appearance of the species *Camptocercus rectirostris, Monospilus dispar* and *Pleuroxus uncinatus*, preferring higher water temperatures (Frey, 1962), indicate an improvement in thermal and living conditions in the lake. The presence of the species *Pleuroxus, Monospilus* and *Leydigia leydigi* also suggests an increase in trophic state to the meso/eutrophic level (Adamska and Mikulski, 1969). The species found in the lake live among aquatic plants, which indicates that a macrophyte zone developed in the basin. The increase in the frequency of *Alona quadrangularis* may also suggest a slight increase in lake water level.

During this phase, a rapid increase in the ^{13}C value above –28‰ may indicate either a shallowing of this basin or intensified photosynthesis (the beginning of P-6 L PAZ), with the latter being more likely.

CONCLUSIONS

Our research on the Parchliny 2016 profile within Szczerców Basin has allowed comprehensive reconstruction of the palaeoenvironmental changes taking place in the terrestrial and aquatic environment during the Late Saalian (MIS 6a) and the beginning of the Eemian interglacial (MIS 5e) in central Poland. Three phases of changes have been distinguished within the Late Saalian. The first phase was related to the rapid melting of a block of dead ice buried in the tills and the formation of a lake with no traces of vegetation cover. The second phase was gradual, with a mosaic of tundra and cold steppe communities (P-1 *Poaceae-Pinus-Betula* L PAZ), indicating relatively low temperatures in both warm and cold months, correlated with Stadial 1. The third phase indicates climatic amelioration, with sparse pine-birch boreal forest communities (P-2 *Pinus-Betula* L PAZ), correlated with the Zeifen interstadial and subsequently Kattegat stadial, expressed by the coexistence of forest and open park tundra communities (P-3 *Pinus-Betula*-NAP L PAZ). In general, the plant cover in the Late Saalian did not change radically. The changes recorded resulted from the variability in the proportion of the area occupied by the forest and non-forest plant communities.

The fourth phase of lake development covered the beginning of the Eemian interglacial (protocratic phase), expressed in the development of pioneering birch-pine and pure birch forests (P-4 *Betula-Ulmus* L PAZ), followed by a transitional period (P-5 *Pinus-Betula-Ulmus-Quercus* L PAZ) to the fifth phase with the beginning deciduous forest development (mesocratic phase) with oak dominant (P-6 *Quercus* L PAZ).

The transition from glacial to interglacial conditions is reflected in the increasing proportion of organic matter. Low carbon isotope values (^{13}C) probably reflect an increase in primary production and in oxygenation of the lake water. The number of cladoceran species in the lake increased significantly at the beginning of the interglacial, including those indicating higher trophic conditions and water temperatures (*Pleuroxus uncinatus, Monospilus dispar* – II-A CAZ). Throughout its existence, the reservoir was shallow, with slight, periodic increases in water level. It was a eutrophic lake, as evidenced by numerous species of diatoms from the meso- and hypereutrophic group, and a significant amount of *Pediastrum* and *Botryococcus* algae, surrounded by Cyperaceae. Only in the initial phase (II), was the lake of low fertility with the dominance of coastal diatoms (periphytonous and benthic) (P-1a DAZ) and the presence of *Alona affinis, Eurycercys lamellatus* and *Acroperus harpae* (I-A CAZ).

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