Geological Quarterly, 2023, 67: 24
DOI: http://dx.doi.org/10.7306/gq.1694

Does the multi-proxy Eemian record from the Słup site (central Poland) indicate a more humid climate at the beginning of the hornbeam phase?

Kamil KULTYS[1, 2], Dorota BRZOZOWICZ[3], Danuta DRZYMULSKA[4], Marcin SZYMANEK[5], Joanna MIROSŁAW-GRABOWSKA[6], Irena Agnieszka PIDEK[1,] * and Marcin ŻARSKI[7]

[1] Maria Curie-Sklodowska University, Institute of Earth and Environmental Sciences, al. Kraśnicka 2 d, 20-718 Lublin, Poland; ORCID: 0000-0002-2412-0846 [K.K.], 0000-0002-1979-4897 [P.I.A.]

[2] ECOTECH COMPLEX Analytical and Programme Centre for Advanced Environmentally-Friendly Technologies, Głęboka 39, 20-612 Lublin, Poland

[3] Łódź University, Faculty of Geographical Sciences, Narutowicza 88, 90-139 Łódź, Poland; ORCID: 0000-0002-8553-5121

[4] University of Bialystok, Faculty of Biology, K. Ciołkowskiego 1J, 15-245 Białystok, Poland; ORCID: 0000-0001-8383-4374

[5] University of Warsaw, Faculty of Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland; ORCID: 0000-0002-6033-8025

[6] Polish Academy of Sciences, Institute of Geological Sciences, Twarda 51-55 Warszawa, Poland; ORCID: 0000-0003-4270-106x

[7] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland; ORCID: 0000-0002-0699-6561

Kultys, K., Brzozowicz, D., Drzymulska, D., Szymanek, M., Mirosław-Grabowska, J., Pidek I.A., Żarski, M., 2023. Does the multi-proxy Eemian record from the Słup site (central Poland) indicate a more humid climate at the beginning of the hornbeam phase? Geological Quarterly, 2023, 67: 24, doi: 10.7306/gq.1694

Associate Editor: Wojciech Granoszewski

A new site of Eemian organogenic deposits in Słup (central Poland) has revealed an intermittent record of several phases within this interglacial. Pollen based studies of the core Sł-19, drilled at the littoral zone of the palaeolake, indicated the absence of the E2, E3, E6 and an incomplete record of the E4 and E5 zones of the typical pollen succession. Results of other proxies (plant macrofossils, Cladocera, molluscs, NPPs, isotopes) supported the conclusions derived from the pollen diagram regarding the high humidity and lake water level during the E4 (*Corylus*-*Quercus*-*Tilia*) phase and at the beginning of the E5 (*Carpinus*-*Corylus*-*Alnus*) phase, when the fossil lake was most extensive. Thus, the lack of a record of the E3 and E4 RPAZs was associated with water level lowering and a less humid climate. The results stand in agreement with several other Eemian records from central Poland.

Key words: Eemian Interglacial, MIS 5e, multi-proxy approach, Garwolin Plain, central Poland.

INTRODUCTION

Interglacial lake deposits are valuable archives of the state of the natural environment and its changes, both at the local and regional scale. Nonetheless, the Eemian Interglacial, corresponding to the isotope-oxygen stage MIS 5e (Shackleton et al., 2002; Cohen and Gibbard, 2011), remains beyond the reach of radiocarbon dating. Fortunately, its well-known palynostratigraphy makes it possible to establish a relative chronology, conduct detailed palaeoenvironmental reconstructions and correlate these findings with numerous other contemporaneous sites. Poland includes >400 Eemian fossil lakes, 187 of which have served as a base for mapping Eemian isopolles, and thus the migration of trees from glacial refugia. The data have also highlighted their diversity vis-à-vis Weichselian (=Vistulian) refugia (Kupryjanowicz et al., 2016, 2018).

The differences among them reflect climatic conditions of the Eemian, which include a significant degree of climate oceanization and high sea level (Zagwijn, 1983) manifesting itself in Poland as marine transgression (Makowska, 2009). Interest in the palaeoclimate of the Eemian Interglacial has continued since the 1980s (e.g., Velichko et al., 1984; Cheddadi et al., 1998; Seppä et al., 2004; Tarasov et al., 2005; Brewer et al., 2008) and has facilitated intense research into this interval. In particular, the Eemian is emphasised as the last interglacial which saw no human interference in climate phenomena, and

* Corresponding author, e-mail: irena.pidek@mail.umcs.pl
Received: September 22, 2022; accepted: May 19, 2023; first published online: September 26, 2023

therefore an excellent testing ground for modelling natural climate variability and environmental changes.

Within Poland, the palynostratigraphic framework of the Eemian Interglacial was outlined by Mamakowa (1989), and recently refined by Kupryjanowicz and Granoszewski (2018). This presented a new perspective, allowing detailed interpretations and palaeoenvironmental reconstructions. Notably, Mamakowa's palynostratigraphy (1989) fully correlates with the Eemian succession patterns for both western and eastern Europe (Granoszewski et al., 2012).

Not only palynological results, but also Cladocera fossil assemblages have been used for palaeohydrological reconstruction (Niska, 2012; Niska and Roman, 2014; Suchora et al., 2022). Furthermore, findings from other kinds of analysis have been taken into account for palaeoenvironmental reconstruction. These include diatoms (Zalat et al., 2021), plant macroremains (Stachowicz-Rybka and Korzeń, 2014; Bober et al., 2021a, b), mollusc faunas and stable isotopes of nitrogen (N), oxygen (O) and carbon (C) (Mirosław-Grabowska et al., 2015; Roman et al., 2021).

However, the Eemian shows an incomplete record at many sites. Sedimentation breaks can be seen especially at the end of the hornbeam phase; the record is then often reactivated in the pine phase and in some cases can continue for a significant part of the next glaciation (Kupryjanowicz, 2008 and others). There are also many examples of a complete record of the hornbeam zone.

Nevertheless, the multi-proxy approach, adopted by an increasing number of studies, brings us closer to explaining the climatic conditions of the Eemian optimum and accounting for the presence of hiatuses (Roman et al., 2021).

Here, we provide a detailed reconstruction of the environmental changes recorded in the Eemian palaeolake at the Słup site. The site is located on the Garwolin Plain, within the southern border of the vast Eemian Lakeland. The Słup palaeolake is one of many of this age in this region (Bober et al., 2021a, b; Hrynowiecka et al., 2021; Kupryjanowicz et al., 2021; Pidek et al., 2021; Suchora et al., 2022). Among the ~20 Eemian Interglacial sites discovered on the Garwolin Plain during the remapping of the Garwolin sheet of the Detailed Geological Map of Poland, scale 1:50,000, the Słup site (core Sł-19) showed an incomplete record of the interglacial succession, with the changes seemingly captured in the littoral zone of the lake.

Varied research methods (palynology, Cladocera, plant macroremains, carbon and nitrogen stable isotopes, malacofauna) combined with multi-proxy data from other Eemian profiles allow for unambiguous conclusions to be drawn regarding water level fluctuations under the influence of climatic factors and for these to be distinguished from local factors related to the natural evolution of the lake. The multi-proxy record obtained from the Słup site can either confirm, or reject, the hypothesis that the Eemian lakes reached their highest level in the hazel phase and at the beginning of the hornbeam phase (e.g., Kupryjanowicz, 2008; Roman et al., 2021).

STUDY AREA

The Słup palaeolake is located on the eastern part of the Garwolin Plain, which is a part of the Central Mazovian Lowland – itself a part of the vast province of the Central European Lowlands (Solon et al., 2018) in central Poland (Fig. 1A). The site is located on the southern edge of the vast Eemian palaeolake district. New sites with Eemian lake deposits were discovered, including the Słup palaeolake (Fig. 1C), during revision of the Detailed Geological Map of Poland (Garwolin sheet, scale 1:50,000; Żarski, 2020). The following palaeolakes have already been examined on the Garwolin Plain, near the Słup (Sł-19) site: Jagodne (Bober et al., 2021a), Kozłów (Pidek et al., 2021; Suchora et al., 2022), Struga (Zalat et al., 2021), Żabieniec (Pidek et al., 2022), Parysów (Bober et al., 2021b) and Wola Starogrodzka (Kupryjanowicz et al., 2021). They are located in the valleys of the Wilga and Świder, which are left-bank tributaries of the Vistula (Fig. 1B).

GEOLOGICAL AND GEOMORPHOLOGICAL SITUATION

The Słup site, with deposits of the Eemian Interglacial, is located on the postglacial plateau of the Garwolin Plain (Solon et al., 2018), which was formed after the melting of the Late Saalian (MIS 6) ice sheet (Żarski, 2020). The Garwolin Plain mainly consists of postglacial uplands, the surface of which is mostly built of tills up to thirty metres thick. The post-glacial plateau is cut by river valleys, mostly running E–W. The largest is the Wilga Valley, located ~4 km south of the Słup site. To the north of the site, ~1–1.5 km away, there are valleys of un-named watercourses flowing into the Rydnia River. The entire area belongs to the Vistula River basin. The postglacial plateau is variously covered by tills, glacifluvial sands and gravels, silt and lake clays from the Saalian glaciation (Żarski, 2020) as well as aeolian and weathered dust, sands and silts from the Vistula Glaciation.

The areal pattern of the Late Saalian (MIS6) deglaciation significantly influenced the topography of the Garwolin Plain north of the Wilga Valley. The disappearance of the ice sheet resulted in the formation of numerous kames, dead ice moraines, and undrained depressions (Żarski, 2020). Many of the current such depressions that underlie the Holocene and Weichselian (=Vistulian) deposits, including that of the Słup site, contain lake deposits of the Eemian Interglacial (Żarski, 2020). These lakes filled depressions after the dead ice mass of the Late Saalian ice sheet (MIS 6) melted. The Garwolin Plain, at the sites of Żabieniec, Jagodne, Kozłów, Wola Starogrodzka, Struga, Parysów and Słup, is believed to have represented a lake district during the Eemian Interglacial. More than 30 Eemian Interglacial palaeolakes have been documented in this area, filled with lake and peat bog deposits up to ten metres thick, or more (Żarski, 2020). The closest site with deposits of the Eemian Interglacial is Parysów, as documented by palaeobotanical and geological methods (Bober et al., 2021b), which is located ~500 m north of the Słup palaeolake.

The surface of the outflow area of the basin in Słup is located at 150.4–150.8 m a.s.l.; this value is only ~1.5 m lower than the surrounding plateau, which rises to a height of 152–152.5 m a.s.l. in the immediate vicinity of the depression (Fig. 2). The longer axis of the basin (W–E) is ~280 m long, and the shorter axis (N–S) is ~80 m. The area around the basin is made of tills, as at Parysów (Żarski, 2020).

MATERIALS AND METHODS

MATERIALS

The G-Słup borehole (Fig. 2) drilled in 2016 for the Detailed Geological Map of Poland 1:50 000 (Garwolin sheet, published by Żarski, 2020) penetrated peat of a fossil lake basin, the age of which unfortunately could not be reliably determined due to technical difficulties and the inability to reach the bottom of the

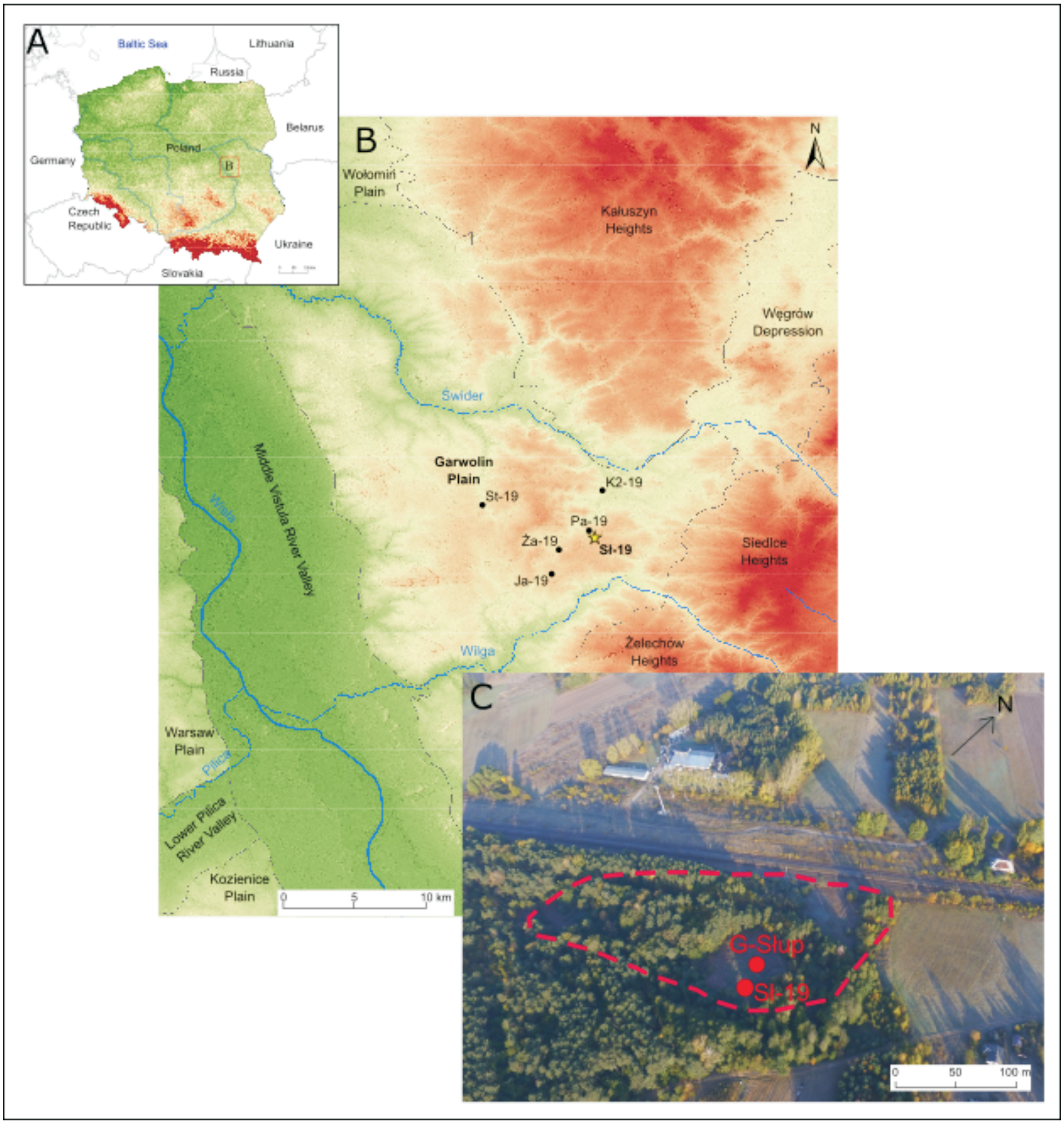

Fig. 1. Location of the area under study

A – location of the Garwolin Plain in Poland; **B** – geomorphological map of the Garwolin Plain with Eemian palaeolake sites; **C** – aerial photo with sites of the G-Słup and Sł-19 boreholes

biogenic succession. The G-Słup core reached 507 cm depth (Table 1) and did not reach the base of the peat layer.

Results of random palynological analysis of the peats at the depth of 360–479 cm (Fig. 3) bear no diagnostic features for a particular interglacial. The pollen diagram (Fig. 3) has been divided into two local pollen assemblage zones: an older one dominated by pine pollen has also much spruce and frequent hornbeam pollen; a younger zone has more abundant birch pollen and more numerous NAP.

It can be suggested that the G-Słup pollen diagram (Fig. 3), by comparison with the preliminary pollen data from the neighbouring Parysów and Żabieniec Eemian palaeolakes (Bober et al., 2021b; Pidek et al., 2022), may represent an Early Weichselian age. This is indicated by a similarity to Early Weichselian pollen spectra from other sites in Poland (e.g., Zgierz-Rudunki by Jastrzębska-Mamełka, 1985, Horoszki Duże by Granoszewski, 2003). Our suggestion is additionally supported by the findings of Caspers and Freund (2001), who made a regional

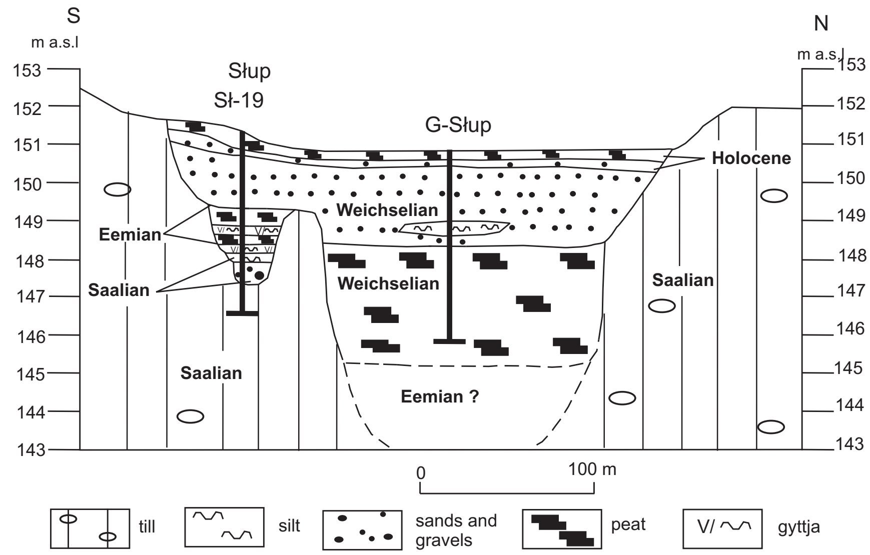

Fig. 2. Geological cross-section of the Słup palaeolake showing the G-Słup and Sł-19 core sites

Table 1

Lithological description of the G-Słup core

Depth [cm]	G-Słup sediment description
0–30	black-brown peat
30–120	fine-grained and medium-grained sands, grey unconsolidated sands
120–170	light grey sand
17–220	grey silt
220–250	silty fine-grained and medium-grained sands
250–370	brown-black peats
370–507	brown peats (undecomposed in the bottom layer)
	507 cm end of the borehole in the undecomposed peats

comparison of vegetation and climate evolution from the beginning of the Early Weichselian glaciation to the Weichselian Pleniglacial by analysing numerous pollen diagrams from north and central Germany and from the adjacent lowlands of the Netherlands, Denmark, Poland and Belarus. They found that the climate was characterized by increasing continentality up to the end of the Oerel Interstadial. However, summer temperatures were sufficiently high to enable boreal forest to grow in the Brörup Interstadial. The Brörup Interstadial is subdivided into two phases (of birch and pine, respectively). Pollen of deciduous trees, e.g., *Quercus, Ulmus, Tilia* and *Carpinus*, is often found only as traces and may be reworked. In the light of these findings and by comparison with Brörup pollen spectra of the Horoszki Duże pollen diagram (Granoszewski, 2003), we consider the pollen spectra of the G-Słup diagram (Fig. 3) to represent this first interstadial of the Weichselian glaciation.

It can be assumed that, similarly to the neighbouring Parysów site (Bober et al., 2021b), there is a layer of Eemian lake gyttja beneath the peat, which is hypothetically shown in Figure 2 with a question mark. The Eemian biogenic succession rests at the depth of 10.20 to 13.00 m in the Parysów palaeolake. Another borehole at the Słup site was drilled in 2019, but as the area was much wetter than in 2016, it was not possible to approach the central part of the fossil lake and drilling was performed ~25 m distant from the G-Słup coring, presumably in the palaeolake's littoral zone (present profile Sł-19). We hoped to capture palaeohydrological changes in the pollen spectra, the record of which in the littoral zone can often be interrupted at lower water levels. This allows for the detection and interpretation of sedimentary breaks of various origins. The Sł-19 core showed a significantly lithological composition very different from the incomplete pilot core of the G-Słup core, containing mainly Weichselian peats, and overlain by Weichselian sands at the top and with thin Holocene peat.

In the Sł-19 core, there are sands at the bottom, and gyttja, peats and Weichselian sands above them. The uppermost 47 cm of deposits consist of Holocene peat (Fig. 4). Both the lithological profile and the subsequent palynological analysis indicate that we are dealing with a small lake basin adjacent to the main one. There is no sedimentary continuity between the two basins, and pollen spectra of the Sł-19 profile unequivocally show Eemian ages, with only minimal representation of the Early Weichselian (Fig. 5).

The lithological profile (Fig. 4) of Sł-19 is 4.80 m thick. The Eemian biogenic deposits are 1.03 m thick and lie under a 1.98 m thick layer of Weichselian sands overlain by 0.47 m of Holocene peats. The local palynostratigraphy, correlating with the regional pollen zones determined by Mamakowa (1989), confirms the presence of Regional Pollen Assemblage Zones (R PAZs) representing the Eemian succession in the profile (Fig. 5). This record includes sedimentary gaps, as detailed in section Pollen analysis.

METHODS

The core was collected using a Powerprobe corer of probe diameter of 4.8 cm in 2019. In laboratory conditions, the core was divided into 1 cm sections.

POLLEN ANALYSIS

Samples were prepared for palynological analysis according to the standard procedure described by Berglund and

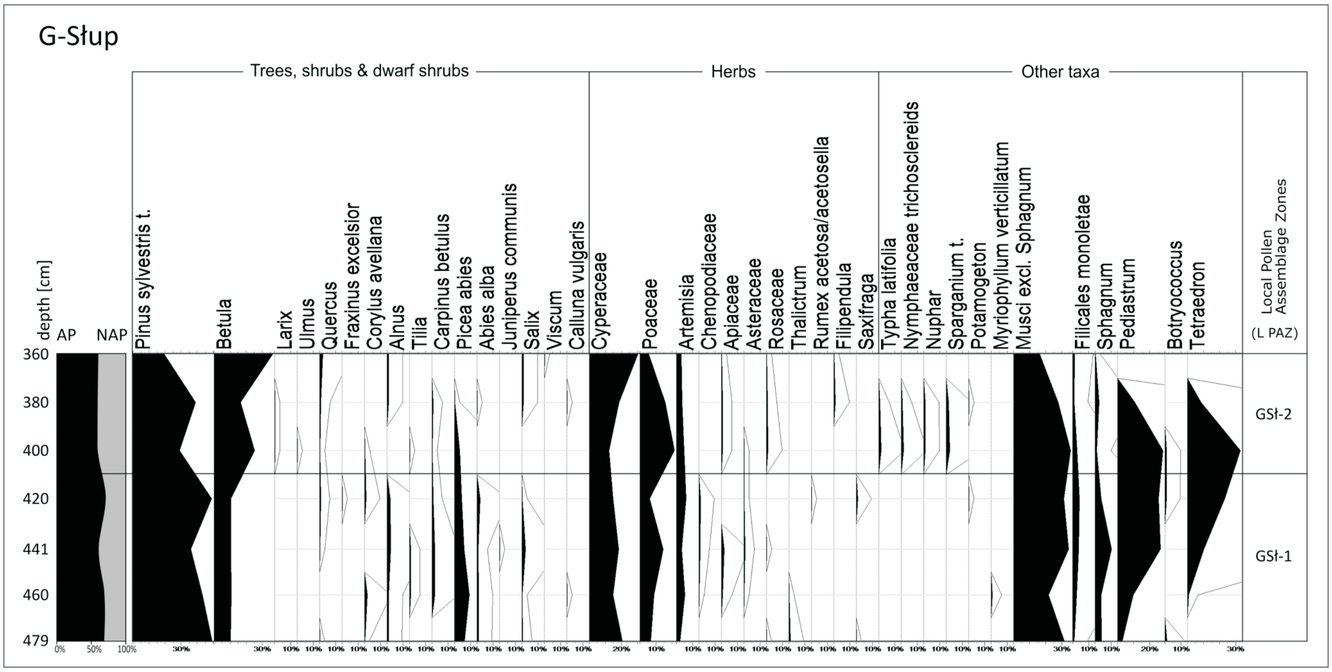

Fig. 3. Percentage pollen diagram of the G-Słup profile

Ralska-Jasiewiczowa (1986). The material was first treated with 10% HCl to remove calcium carbonate and then silicate minerals were removed with 40% HF. The samples were then subjected to Erdtman's acetolysis (Faegri and Iversen, 1975). The pollen samples were analysed using an optical microscope of magnification 400–600x. In general, up to 800 pollen grains of trees, shrubs (AP) and dwarf shrubs, as well as terrestrial herbaceous plants (NAP) were counted in the samples. The exceptions were samples with a lower frequency, in which a sum of at least 500 (AP + NAP) was counted. Spores of Pteridophyta and Bryophyta as well as the remains of aquatic and rush plants and green algae (of the genera *Botryococcus*, *Pediastrum* and *Tetraedron*) were noted. The base sum for percentage calculations was the sum of AP + NAP = 100%. The percentage share of the remaining taxa was calculated in relation to the sum of AP + NAP + given taxon = 100%. Following this, a pollen diagram (Fig. 5) was prepared using *POLPAL* software (Nalepka and Walanus, 2003), and the boundaries of Local Pollen Assemblage Zones (L PAZs) were distinguished and assigned to the Regional Pollen Assemblage Zones (R PAZs) according to Mamakowa (1989).

CLADOCERA ANALYSIS

Cladoceran remains were analysed in 41 samples. The standard treatment (Frey, 1986) was adapted to the varied sediments of the profile. A single sample (1 cm^3 of fresh sediment) was decalcified (with 10% HCl), soaked overnight, and washed with distilled water on a 33 m mesh. Then, it was slowly heated in 10% KOH (60–100°C) while being gently stirred with a glass rod and then subjected to ultrasonic treatment (15 minutes). Next, after repeated warm KOH and distilled water sieving, all residues were transferred to scaled test tubes and topped up to 10 ml volume. All cladoceran remains (shells, headshells, postabdomens, postabdomenal claws and ephippia) were identified under 100–600x magnification by a compound light microscope (type *MBL 800*). For a single slide, 0.1 ml of sample was used. Two to five slides were examined for each sample to exceed the minimum counting sum of 150 (Kurek et al., 2010). Results were presented as a percentage diagram, P/L ratio (relative abundance of planktonic to littoral taxa), total cladoceran abundance, species richness (*n*) and Shannon-Weiner diversity index (*H'*). Cladocera Assemblage Zones (CAZ) were delineated based on CONISS cluster analysis (*Tilia Graph*, 171 – Grimm, 2011). Ecological diversity measures were calculated by means of PAST software (Hammer et al., 2001).

Other microfossils observed during the analysis of cladoceran fossil remains were also counted: *Ceratophyllum* hairs, Nymphaeaceae trichosclereids, remains of Chironomidae spp. (head cases) without specifying species affiliation, Rotifera eggs, *Glomus* sporangia, Turbellaria cocoons. These results were converted into the number of individual microfossils per 1 cm^3 residuum and shown in the diagram.

PLANT MACROFOSSIL ANALYSIS

The section between 330 and 198 cm was also subjected to plant macrofossil analysis. In total, 39 sediment samples were collected. The deposits were flooded with distilled water with the addition of 10% KOH and then washed out on a 0.2 mm sieve. Each sample was analysed for vegetative plant remains using a light microscope of 100–400x magnification. The standard percentage proportion of vegetative remains in total tissue mass was estimated. In the case of *Thelypteris palustris* sporangia, their presence in a sample was marked by "+", "++", or "+++", depending on how often they appeared in the field of view. Generative remains such as seeds and fruits were picked out and then placed in a glycerine-thymol mixture. A stereoscopic microscope of magnification 10–100x was used for recognition. The remains were then counted and identified based on

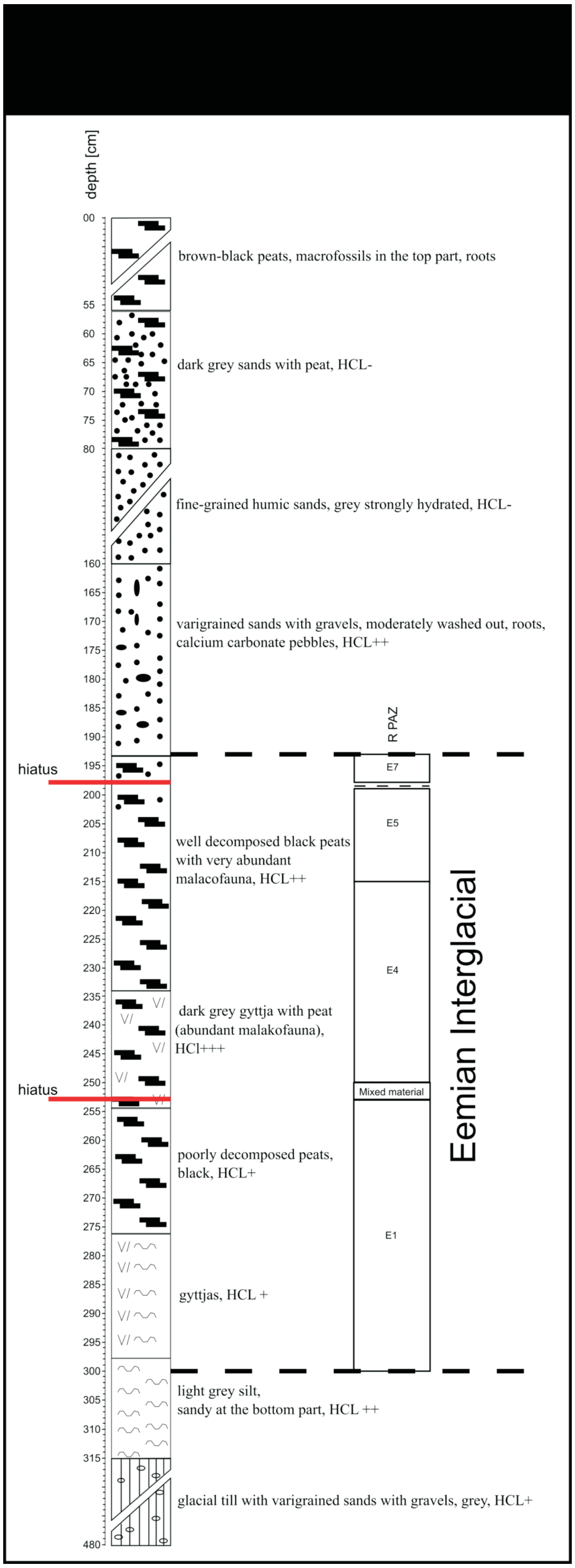

Fig. 4. Lithological profile of the Sł-19 core with Eemian interval marked

Grosse-Brauckamnn (1972, 1974), Katz et al. (1977), Mauquoy and van Geel (2007), and the collection of macroscopic plant remains at the Faculty of Biology, the University of Bialystok.

The results of plant macrofossil analysis were shown on a diagram drawn with *POLPAL* software (Nalepka and Walanus, 2003). Macrofossil assemblage zones were identified based on a taxonomic composition of samples, supported by stratigraphically-constrained cluster analysis (CONISS) (Grimm, 1987).

MALACOLOGICAL ANALYSIS

Molluscan material was subjected to the standard procedure proposed by Ložek (1964), Alexandrowicz (1987) and Alexandrowicz and Alexandrowicz (2011). Pellets were washed through a sieve of 0.5 mm diameter. All complete mollusc shells, the apex (and/or mouth) parts of the shells and fragments suitable for unambiguous identification were counted in the dried residuum. Some incomplete specimens without any characteristic features were identified only to genus level. Identification of molluscan material was carried out using a *Delta Optical IPOS 808* stereoscopic microscope (magnification up to 65x) with the use of keys and atlases for the determination of malacofauna (Piechocki, 1979; Welter-Schultes, 2012; Piechocki and Wawrzyniak-Wydrowska, 2016). Information on the ecological requirements of the species identified was taken from the same publications and assigned to the ecological groups proposed by Alexandrowicz and Alexandrowicz (2011).

STABLE ISOTOPE ANALYSIS

Organic deposits from the Sł-19 core were subjected to analyses of organic carbon and nitrogen concentrations and carbon and nitrogen isotope compositions. Analyses for carbon and nitrogen isotopes were performed on 27 samples (depth 193–300 cm). The samples were dried at 60°C and ground. The carbonate fraction was removed with hydrochloric acid. Carbon and nitrogen isotope compositions were analysed using a *Flash Elemental Analyzer 1112* and a *Thermo MAT 253* mass spectrometer, which were calibrated based on an internal nicotinamide standard and reported as per mill (‰) deviations versus atmospheric N_2 (^{15}N) and Vienna Pee Bee Belemnite (^{13}C). Carbon and nitrogen isotope ratios are shown in the form of curves of variation of ^{13}C and ^{15}N. The analytical errors (l SD) for the ^{13}C and ^{15}N measurements were 0.17 and 0.24‰, respectively. The isotopic analyses were performed in the Stable Isotope Laboratory at the Institute of Geological Sciences of the Polish Academy of Sciences in Warsaw, Poland.

ANALYSIS OF THE SHARE OF ORGANIC, MINERAL MATTER AND CARBONATES

In order to determine the share of organic matter (LOI550) and carbonates (LOI950), ignition loss analysis was performed. In total, 42 sediment samples were selected, dried and homogenized by grinding in a mill. The material prepared in this way was calcined sequentially at temperatures of 550°C for 4.5 hours and 950°C for 2 hours (Myślińska, 2001). Each time the crucibles had cooled down in the desiccators, the material was weighed on a laboratory balance to the nearest milligram. The percentage of organic matter and carbonates were calculated using *MS Excel* spreadsheets.

RESULTS

POLLEN ANALYSIS

In the pollen percentage diagram (Fig. 5), seven Local Pollen Assemblage Zones (L PAZs) were distinguished, which were labelled from Sł-19 1 to Sł-19 7 (from the bottom to the top of the section studied; Table 2). A comparison of L PAZs with the R PAZs by Mamakowa (1989) indicated that the beginning of the succession in Słup Sł-19 coincides with the beginning of the Eemian. The initially weak frequency of palynomorphs (Sł-19 1 L PAZ) gradually improves and the share of brown moss spores decreases. This pollen record reflects a steppe-tundra landscape, with patches of pine, birch and a small admixture of larch, in which a shallow lake began to form. The Sł-19 2 L PAZ is dominated by *Betula* tree birch pollen, with a significant share of NAP, including mainly Cyperaceae and Poaceae. The pollen spectra of this zone illustrate the spread of pioneering birch forests and the entry of *Ulmus* into river valley communities. Oak and ash could appear in these pioneering riparian forests. There were areas of wet herbaceous communities around the lake with *Filipendula* (*F. ulmaria*?), *Mentha* and Apiaceae. A bog formed with the participation of *Sphagnum*, Cyperaceae and Filicales. The E2 R PAZ was not distinguished as no increase in the *Ulmus* was noted, as is characteristic of this zone. There is also no record of the E3 R PAZ, which is characterized by an increase in the share of *Quercus* pollen until it reaches the maximum of ~50%. Only the sample at 251 cm (Sł-19 3 L PAZ) contains some more *Quercus* pollen, but in general it seems to be mixed pollen material after a hiatus observable between the Sł-19 2 L PAZ and Sł-19 4 L PAZ which belongs to E4 R PAZ: the *Quercus* share decreases, the *Corylus* share increases significantly and continuous *Alnus* and *Tilia* curves appear.

It seems that the E4 R PAZ with a maximum value of *Corylus* is well-represented by the Sł-19 4 L PAZ. In addition, *Tilia* and *Alnus* reach their maxima here, and the share of *Carpinus* gradually increases. Such a picture is typical of the older part of the E4 R PAZ and represents the expansion of hazel in forest communities, which at that time were probably oak-lime-hornbeam forests. It has been proposed that patches of warm hazelnut scrubs of *Peucedano cervariae-Coryletum* type formed during this time (*cf.* Matuszkiewicz, 2001, after Mamakowa, 1989). At the same time, two warm climate indicators are present in this zone: *Hedera helix* and *Viscum*. *Taxus*, a tree associated with an oceanic climate, appeared in the communities at that time. The E5 R PAZ (represented by the Sł-19 5 L PAZ) represents the hornbeam phase of the Eemian Interglacial; however, the results seem fragmentary, as there is no younger part in which the expansion of *Carpinus betulus* would culminate (pollen >40%), with a simultaneous significant decrease in the share of *Corylus*, the disappearance of *Taxus* and the beginning of the encroachment of *Abies* and *Picea* into forest communities.

A lack of sediment is also observed in the E6 R PAZ, i.e. the zone characterized by the expansion of fir and spruce and the increasing role of pine in the telocratic interglacial period. The pollen record appears again in E7 R PAZ, which is characterized by a high proportion of *Pinus* and the reappearance of taxa associated with wet habitats. In the Sł-19 7 L PAZ, these include Musci, Filicales monolete and *Sphagnum*. The presence of such pollen spectra indicates a reactivating transitional fen. Presumably, the lake later reverted to a shallow lake again, as

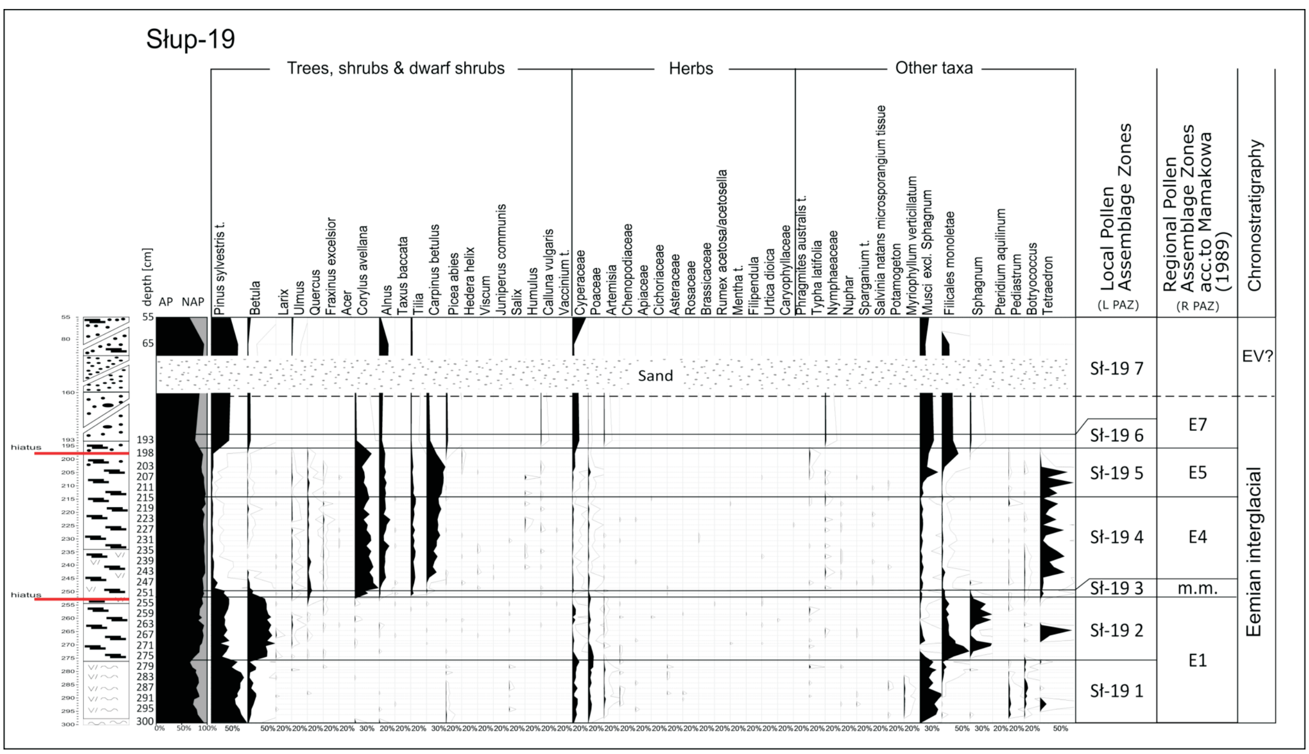

Fig. 5. Pollen percentage diagram from the Słup Sł-19 core

EV? – probably Early Vistulian deposits

Table 2

Descriptions of Local Pollen Assemblage Zones in the Sł-19 profile

Corresponding R PAZs acc. to Mamakowa (1989)	Depth [cm] and number of samples	Characteristic features of pollen spectra
E1	Sł-19 1 277–300 cm (14 samples)	The frequency of palynomorphs at the bottom of the zone is small, increasing significantly at the top. *Pinus sylvestris* t. dominates the pollen spectra throughout, with its share in the range of 50–80%. *Betula* constitutes up to 20%. *Ulmus, Salix, Larix* and *Picea* pollen appear regularly. The pollen of herbaceous plants such as Cyperaceae, Poaceae and *Artemisia* is also significant. *Typha latifolia* and *Sparganium* t. are found among the pollen of aquatic plants and rushes.
	Sł-19 2 253–275 cm (14 samples)	*Betula* increases its share, reaching a value of >50%, while the share of *Pinus sylvestris* t. decreases to ~30%. A continuous *Ulmus* curve is maintained, while *Quercus, Larix, Fraxinus, Alnus, Corylus* and *Salix* appear sporadically. The share of Cyperaceae, Poaceae and *Artemisia* also decreases. *Filipendula, Mentha* t., *Urtica dioica* and representatives of the Apiaceae family are occasionally noted. The number of Musci spores has dropped significantly. Spores of Filicales monolete and *Sphagnum* appear in large numbers. Nymphaeaceae trichosclereids and *Typha latifolia* pollen are present. 263–267 cm shows a very high proportion of *Tetraedron*, with a simultaneous reduced proportion of Filicales monolete spores and the disappearance of *Sphagnum*. *Viscum*, *Taxus baccata* and *Acer* appear individually.
Mixed pollen material	Sł-19 3 251 cm (1 sample)	A reduction of the amount of *Pinus sylvestris* t. pollen (to ~30%) and *Betula* (to ~15%) and an increase in the share of *Quercus, Corylus, Alnus, Tilia*, which is also continued by the adjacent L PAZ. The proportion of pollen of aquatic and rush plants and all spores is reduced. In addition, the beginning of the increase in the *Tetraedron* percentage curve is noticeable.
E4	Sł-19 4 215–249 cm (18 samples)	The share of *Corylus, Alnus* and *Tilia* is at its maximum. The share of *Quercus* falls. *Carpinus betulus* increases from ~2 to >20%, while *Pinus sylvestris* t. and *Betula* appear only in small amounts. Continuous curves of *Ulmus* and *Fraxinus* appear. *Viscum, Hedera helix, Taxus* and *Humulus* are present. Among the taxa of aquatic and rush plants, the frequent presence of *Nuphar* and Nymphaeaeceae trichosclereids, *Salvinia natans* – microsporangium tissue, *Potamogeton*, *Typha latifolia* and *Phragmites australis* was noted. *Tetraedron* achieves a significant increase, up to 60%.
E5	Sł-19 5 198–213 cm (7 samples)	The share of *Carpinus betulus* gradually increases, reaching 40%, with the proportion of *Corylus, Alnus* and *Tilia* remaining high. *Ulmus* and *Quercus* have continuous percentage curves. *Fraxinus, Taxus* and *Acer* are sporadic. Likewise, the share of Cyperaceae increases to >10%. *Humulus lupulus* and *Calluna vulgaris* are sporadic. Musci and *Filicales* increase their share, reaching >30%in the upper part of the zone. Significant amounts of *Tetraedron* were reported.
E7	Sł-19 6 193 cm (1 sample)	The pollen of almost all trees, except for pine, significantly reduces their share. *Betula, Picea* and Cyperaceae are found again more frequently. At the bottom of the zone, the beginning of continuous *Artemisia* and *Typha latifolia* was recorded. The number of Musci spores and Filicales monolete throughout the zone is stable at ~30%. *Sphagnum* spores form a continuous percentage curve.
Early Weichselian	Sł-19 7 55–65 cm (2 samples)	The zone includes two samples above the sand layer. The frequency of palynomorphs is very poor, as is their state of conservation. The share of *Pinus sylvestris* t. pollen is >50%, *Alnus* and Cyperaceae pollen and Musci spores are numerous. *Sphagnum* and Filicales monolete are present. The percentages of *Betula, Ulmus* and *Tilia* are low.

shown by the presence of Nymphaeaeceae trichosclereids. Thus, several sedimentary gaps were found in the succession representing the Eemian Interglacial, the most complete recordbeing obtained for the protocratic period, the hazel phase and the older part of the hornbeam phase of the interglacial climatic optimum.

The two upper samples separated as the Sł-19 7 L PAZ do not show diagnostic features allowing them to be classified as an interglacial sequence, and moreover, they occur above the erosional limit, in the sand layer, or in the sediment. Their pollen spectra may belong to the Early Weichselian.

FOSSIL CLADOCERA ASSEMBLAGES

In total, 24 Cladocera taxa belonging to four families were found in the sediments of the Słup Sł-19 core: Bosminidae, Daphnidae, Sididae, and Chydoridae. Few cladoceran remains were found in the profile studied, but they were well-preserved. Remains which were least well preserved were found at the bottom of the core. The total number was relatively low (in two samples cladoceran remains were absent), but the density varied considerably, reaching a maximum of 8,050 individuals per 1 cm^3. Species richness was also low, ranging from 2 to 21

Table 3

Descriptions of Cladocera assemblage zones in the Sł-19 core

Zone/ subzone	Depth [cm]	Description
1	285–301	Very low total abundance (at the depth of 301 cm only to 850 individuals/cm^3) and low species richness, which increases from 2 to 13 taxa. The littoral species have the largest share: *Chydorus sphaericus* and small *Alona*. In this zone, there are two planktonic taxa represented by *Bosmina longirostris* and *Daphnia pulex*-group.
1A	295–301	Very low total abundance (13–394 specimens/cm^3), which constantly increases. Species richness is also very low (n: 2–10). The most numerous groups are *Ch. sphaericus*, small *Alona*, *Alonella nana*, and *Acroperus harpae*. In this sub-zone, the remains were in a poor state of preservation, reflected in the relatively large share of undetermined remains (up to 15%).
1B	285–295	The sub-zone is distinguished by a lower total number (419–850) than in previous sub-zone 1A. The species richness ranges from 10 to 13 taxa. From the beginning of the zone, new taxa can be identified: *D. pulex*-group, *Sida crystallina*, *Camptocercus rectirostris*, *Eurycercus lamellatus*, *Alona affinis*, *Disparalona rostrata*.
2	273–285	Low total abundance (263–2225 individuals/cm^3) and very low species richness (n: 4–12). The largest share is achieved by *Ch. sphaericus* (66%), small *Alona* (41%) and *Alonella excisa* (32%), which reach their maximum values in this zone. At the end of the zone, *Kurzia latissima* and *Oxiurella tenuicaudis* enter for the first time.
3	245–273	The total number of cladocerans varied greatly (81–8050). The species richness ranges from 4 to 18 taxa. The most numerous was *Chydorus sphaericus*. The share of small *Alona* taxa constantly decreases, and the share of *Sida crystalina, Acroperus harpae,* and *Camptocercus rectirostris* increases. *Alonella exigua* enters and *Camptocercus fennicus* then disappears. At the end of the zone, *Leydigia acanthocercoides* appears and *Oxiurella tenuicaudis* returns.
4	198–245	The highest total number of cladocerans (613–7413 individuals/cm^3). Species richness is also still high (8–21 taxa). The largest share is achieved by *Ch. sphaericus* (max. 61%). *Camptocercus liljeborgi* and *Leydigia leydigi* appear for the first time.
4A	237–245	Low total abundance of cladoceran remains (800–1794). The disappearance of *Alonella excisa* and reappearance of *Alona affinis* and *Alonella exigua*. Maximum values are achieved by *S. crystalina* (up to 19%).
4B	198–237	The total number of cladocerans peaks (max. 7423 individuals/cm^3) and then drops sharply to 613 individuals/cm^3 towards the top of the zone. Species richness also peaks (8–21 taxa) and then declines towards the top of the zone. The dominant taxon is *Ch. sphaericus* (max. share 61%). *Bosmina longirostris* is continuously present and is the only planktonic species. *Graptoleberis testudinaria*, which lives among vegetation, also increases its share. Taxa such as *Peracantha truncata, Kurzia latissima* and *Disparalona rostrata* reappear. *Leydigia leydigi* occurs only in this zone.

taxa. In the studied profile, four Cladocera assemblage zones were determined (CAZ 1-4), with sub-zones (a-b) being designated in two of them (CAZ 1 and CAZ 4) (Table 3 and Fig. 6).

SELECTED NON-POLLEN PALYNOMORPHS (NPPs) ENCOUNTERED DURING CLADOCERA ANALYSIS

Remains of plants (Nymphaeaceae*, Ceratophyllum, Stratoites aloides*), animals (Turbellaria, Chironomidae, Rotifera) and fungi (Microthyriaceae, *Glomus*) were identified during the Cladocera analysis (Fig. 7).

E1

In the early Eemian deposits (depth of 285–295 cm) Nymphaeaceae trichosclereids (max. 500 pcs/cm^3) were found in abundance. The *Ceratophyllum* hairs were sparse and single Turbellaria cocoons and Chironomidae remains, or Rotifera eggs (*Brachionus* type) were encountered. The remains of Microthyriaceae and *Glomus* sporangia were the most numerous (max. at the depth of 283 cm).

Subsequently, the abundance increased, the remains of Turbellaria, Chirionomidae and Rotifera (*Brachionus* type) peaked at the depth of 265–270 cm. At this depth, significant amounts of *Ceratophyllum* hairs were found, while Nymphaeaceae trichosclereids were absent. At this zone, the amount of fungi decreases significantly and Microthyriaceae disappear completely.

At the depth of mixed pollen material, the registered NPPs also show features both below the hiatus and above it. The NPPs spectra are characterized by an increase in the number of plants (Nymphaeaceae and *Ceratophyllum*). The number of Turbellaria cocoons and Rotifera eggs (*Brachionus* type) decreases, but the Chironomidae increase, and reach maximum values of >70 pcs/cm^3. *Glomus* sporangia represent the only fungus to be found.

E4

The E4 zone is associated with abundant vegetation. It can be divided into two subzones. At first, the number of Nymphaeaceae trichosclereids and *Ceratophyllum* hairs increases. *Stratoites aloides* spikes also appear at this level, and their numbers peak later at the end. The number of animals decreases: Turbellaria cocoons, Chironomidae. Incidentally, Rotifera eggs (*Filinia* type) appear (for the first time), and *Brachionus* type is constant. *Glomus* sporangia are also still present.

The second subzone of E4 is associated with the development of vegetation, however, the amount of plant debris decreases towards the end. *Stratoites aloides* spikes (at 220 cm) disappear first. At this subzone, the maximum values are observed for Nymphaeaceae trichosclereids (at 223 cm). Animals are abundant in this subzone. Turbellaria cocoons are constantly

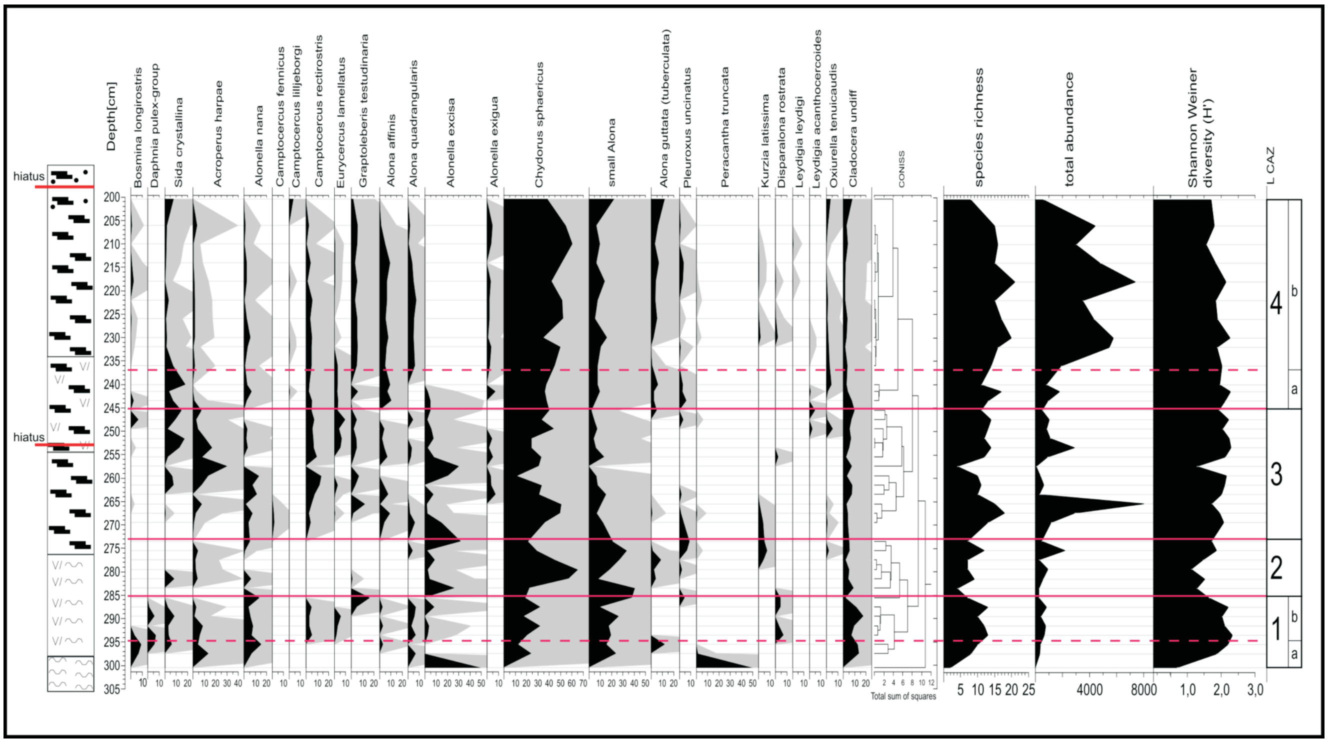

Fig. 6. Diagram of Cladocera of the Słup Sł-19 core

present, reaching their maximum numbers at the depth of 230 cm. Chironomidae remains are also abundant. Rotifera eggs are less abundant, *Filinia* is incidentally found in two samples and *Brachionus* is still present. *Glomus* fungi are also still present.

E5

A considerable drop in Nymphaeaeceae trichosclereids and simultaneous increase in *Ceratophyllum* hairs (at a depth of 210 cm) marks the following zone corresponding to E5 RPAZ.

PLANT MACROFOSSIL ANALYSIS

Vegetative and generative remains (seeds, fruit, fruit scales, oogonia, oospores), of 25 plant taxa of various rank (family, genus, species, section) were identified. Many vegetative fossils were impossible to identify. Remains of animal origin (mollusc shells) were also identified.

Four zones of macroremains (Local Macrofossil Assemblages Zones, L MAZs) were distinguished in the profile (Table 4 and Fig. 8); these are numbered 1–4 from the bottom.

MALACOLOGICAL ANALYSIS

12 taxa were identified in the Słup Sł-19 profile (including eight snail species, one mussel species, and three generic assignations), represented by a total of 339 specimens and 228 shell fragments. Seventy specimens and 59 fragments were unidentifiable. Shell detritus was also abundant (Table 5).

The number of taxa in the samples analysed varies from 1 to 10, and the number of specimens from 2 to 58. A lower frequency of molluscs was recorded in the lower part of the profile (2.39–2.54 m). At the depth of 2.27–2.39 m, the number of recognized taxa and individuals clearly increases (Table 5).

All the mollusc species determined are associated with freshwater, inhabiting both stagnant water bodies (ponds, lakes) and slowly flowing rivers. The group is dominated by snails of permanent water bodies of various sizes (ecological group 11), represented by five species. Three species are typical of small, periodic and heavily overgrown water bodies (group 3), and only 1 is a rheophilic species (group 12), represented by a single specimen (Table 5).

The dominant group of molluscs is *Bithynia tentaculata*, represented by lids and their fragments. It is accompanied by numerous *Valvata cristata*, *Gyraulus crista* and *Gyraulus albus* appearing at the top of the profile. Other taxa include *Acroloxus lacustris* and single shells of *Valvata macrostoma*, *Valvata piscinalis*, *Segmentina nitida* and *Pisidium nitidum*. There are also single specimens and fragments of clams of the genus *Pisidium* (Table 5).

ISOTOPE ANALYSES

The amount of total organic carbon in the deposits studied (TOC) rises from 0.8 to 49.9% and total nitrogen (TN) from 0.01 to 2.7% (Table 6). The TOC/TN_{atomic} ratio varies from 17 to 110, the carbon isotope ratio between –32.4 and –16.1‰, and the nitrogen isotope ratio is between –0.7 and 2.8‰. Four geochemical zones (GZ1–GZ4) can be distinguished based on variations in carbon and nitrogen, and isotopic composition.

The analyses of organic matter (LOI550) indicate a low, but gradually increasing share of up to 50%. This value then increases to ~80% with one incidental decrease of up to 55% at the depth of 260 cm below ground level. The proportion of organic matter remains low (<30%) to the depth of 215 cm, and then gradually increases to 60% at 205 cm below the surface, before decreasing.

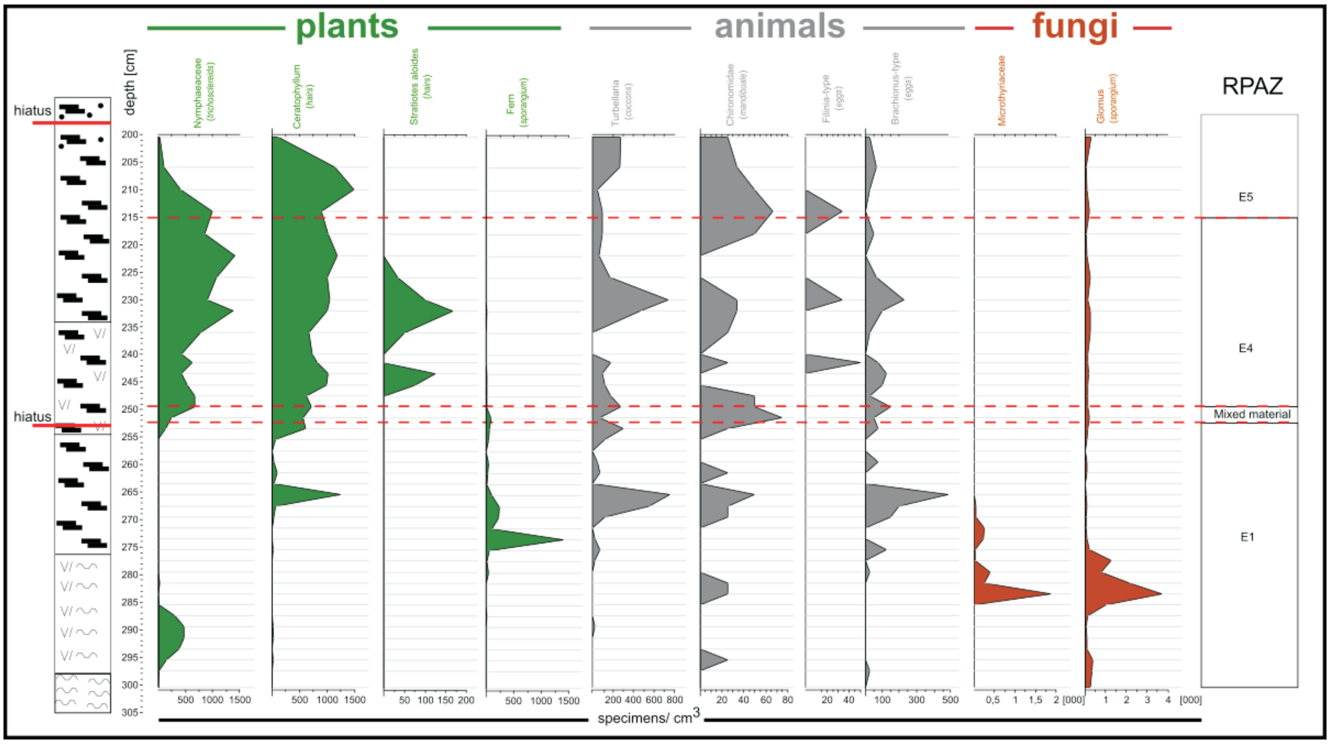

Fig. 7. Diagram of non-pollen palynomorphs (NPPs) in the Słup Sł-19 profile encountered during Cladocera analysis

In a significant part of the profile, the share of carbonates (LOI950) is below detection limits based on the loss on the ignition method. The first increase in the share of carbonates, i.e. to ~15%, is observed at the depth of 260-265 cm below ground level. Following this, the share of carbonates increases at 215–245 cm below ground level, where the share ranges from 13 to 43% (Fig. 9).

DEVELOPMENTAL PHASES OF THE SŁUP FOSSIL LAKE

Based on the results of multi-proxy analyses, the following have been distinguished:

PHASE 1 (INITIAL) UP TO 296 cm

The initial phase of development of the Słup palaeolake occurred in the Early Eemian. The palynological record is modest, indicating the presence of poor steppe-tundra vegetation with patches of birch and pine. This picture is supported by the interpretation of plant macroremains (Sł-19 1 L MAZ), which indicates vegetation dominated by brown mosses in the depression studied. The moss was also home to *Thelypteris palustris* fern, *Sphagnum teres* minerotrophic sphagnum moss (Sł-19 1 L MAZ) and *Carex* spp. sedges. The isotope analyses provide most information about the initial state of development of the water body.

The lowest deposits (depth of 300 cm) are characterized by the lowest concentration of organic carbon, ~1%, as well as nitrogen, i.e. <0.01% (Table 6). The ^{13}C values reach their maximum (–16.1‰) for the whole profile; this is probably connected with the low carbon availability in the water. The geochemical data indicate a very low amount of organic matter (low values of TOC and TN), which was probably derived from land (high values of ^{13}C). This low level of organic matter indicates poor environmental conditions.

Similarly, the results of the Cladocera zone 1 (sub-zone 1a) determinations, i.e. low abundance and low species richness, indicate the initial state of a poor oligotrophic lake. This is corroborated by the very poor non-pollen microfossils at this zone. Remains of Rotifera (*Brachionus* type) and sporangia of *Glomus* fungi were found.

PHASES 2 AND 3 – DEVELOPMENT (275–295 cm)

Plant macroremains indicate that initially the moss gave way to a rush community with sedges, rushes and reeds. This community functioned in a water body where *Potamogeton,* Characeae and *Hippuris vulgaris* grew. In addition, patches of woody vegetation with *Pinus sylvestris* and *Betula* spp. (Sł-19 1 and 2 L MAZ) could be found in its immediate vicinity. Following this, brown mosses, accompanied by *Thelypteris palustris* ferns and *Sphagnum* mosses, re-entered. Birch trees survived. Thus, there appears to be a recurrence of a moss habitat similar to that of the first stage of the development of the deposit, although no *Pinus sylvestris* was recorded in this case. The water body with Characeae still functioned. *Ceratophyllum* (Sł-19 2 L MAZ) was also present.

During this phase, the amounts of organic carbon and nitrogen systematically increased, suggesting an enhancement of primary productivity and the development of macrophytes in the lake (Mirosław-Grabowska et al., 2018). This was caused by an improvement in environmental conditions, mainly higher water

Table 4

Local plant macrofossil zones in the Sł-19 core

L MAZs	Depth [cm]	Characteristics
1	288–303	The sediment consists mainly of remains that are difficult to determine, with dominance of highly fragmented remains of Bryales (share is 90%); *Sphagnum teres* appears rarely; numerous sporangia of *Thelypteris palustris*. Radicles of *Carex* spp. and conifer wood (max. 5%) appear; traces of *Phragmites australis* epidermis, as well as *Pinus sylvestris* and *Betula* spp. periderm. There are generative remains of aquatic plants, such as Characeae, *Potamogeton* spp. and *Hippuris vulgaris*, and rushes – *cf. Schoenoplectus* spp., *Carex* spp.
2	276–287	The amount of undetermined remains is reduced compared to the previous zone; more woody elements, including up to 55% of the *Pinus sylvestris* periderm and 35% of *Betula* spp. periderm as well as coniferous and deciduous wood. A few oogonia and oospores of the Characeae are still present. Remains of Bryales are dominant (up to 85%). These are accompanied by *Sphagnum* spp. (up to 20%) and in traces: wood, periderm *Betula* spp., radicles of *Carex* spp., *Sphagnum* from *Squarrosa* section, remains of *Ceratophyllum* spp. *Thelypteris palustris* sporangia were clearly present. Nuts of *Carex* spp. including *Carex pseudocyperus* and nuts of birch trees (*Betula sec. Albae*) were also identified.
3	250–273	The remains of *Sphagnum* spp. (max. 35%) and Bryales (max. 65%) dominate; *Sphagnum teres* can make up 100 % of samples; only traces of Cyperaceae epidermis, single leafy teeth (spines) of *Ceratophyllum* spp. and sporangia of *Thelypteris palustris*. Single generative remains of *Betula* and Characae are also present.
4	198–253	There is a significant share of undetermined remains; traces of radicles of *Carex* spp., wood, *Sphagnum* and Bryales leaves and leaf spines of *Ceratophyllum* spp. Present are generative remains of aquatic plants (*Najas marina* and *N. flexilis*), *Potamogeton* spp. and Characeae as well as nuts of *Tilia tomentosa* and *Carpinus betulus.*

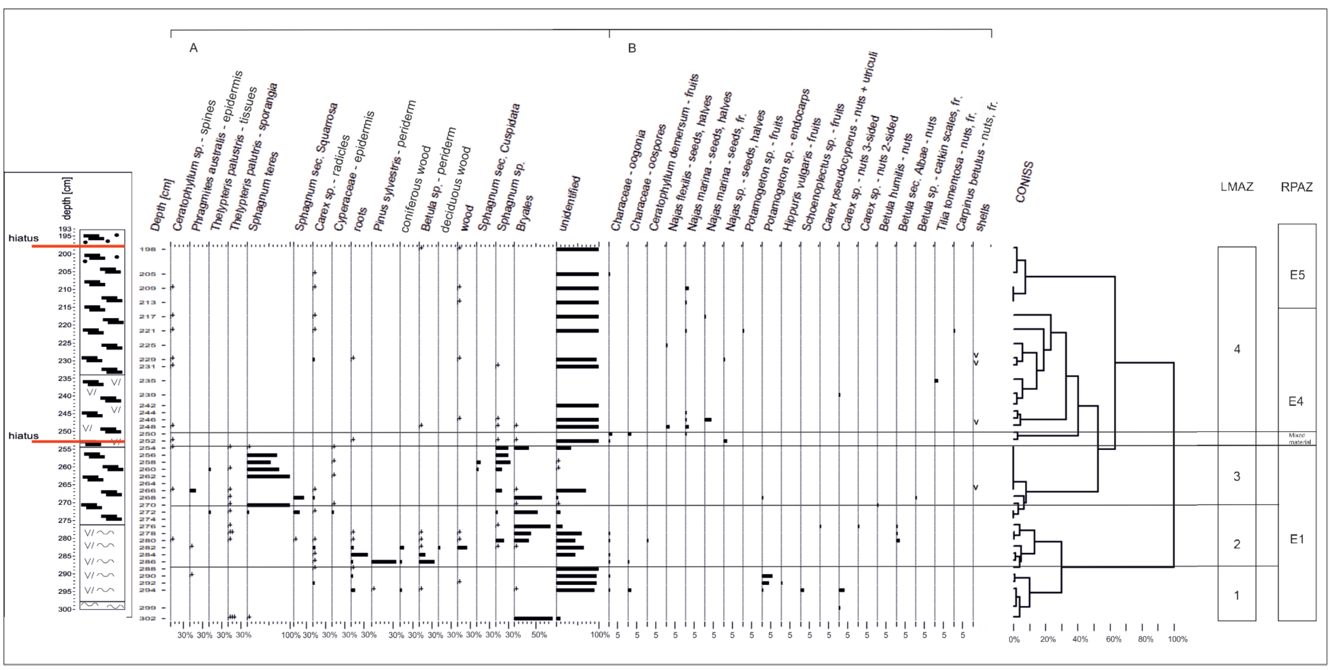

Fig. 8. Diagram of plant macrofossils of the Słup Sł-19 core

A – vegetative remains, **B** – generative remains and others; v – presence in the sample

temperatures. The TOC/TN_{atomic} ratio remains around 24, indicating a mixed source of organic matter, both terrestrial and primary. The decrease in $\delta^{13}C$ values to ~–30‰ indicates a greater share of algae; indeed, $\delta^{13}C$ values <–26‰ are typical of freshwater algae (Leng et al., 2005). The presence of the highest $\delta^{15}N$ values (to 2.8‰) are more indicative of low nitrogen availability than higher trophic levels.

The part of the profile discussed encompasses zone 2 with regard to the development of Cladocera, in which the total number of specimens increased but with very low species richness. Thus, the upper boundary of CAZ 3 in the profile studied coincides with the upper boundary of the GZ1 isotope zone, and the transition between the Sł-19 1 and Sł-19 2 L PAZs. In the pollen diagram, this transition (~275 cm) represents the boundary between the E1a and E1b RPAsZs in the subzonation by Kupryjanowicz and Granoszewski (2018), marking the retreat of steppe-tundra communities due to progressive warming. The water body also appeared to be expanding, as indicated by the presence of non-pollen palynomorphs, the most numerous of which were Microthyriaceae fungi and *Glomus* sporangia.

Table 5

Malacofauna of the Słup Sł-19 profile

E	10	10	10	11	11	11	11	11	12						
Depth [cm]	*Valvata cristata* Müller	*Valvata cf macrostoma* Mörch	*Segmentina nitida* (Müller)	*(Linnaeus) opercula*	*Valvata piscinalis* (Müller)	*Acroloxus lacustris* (Linnaeus)	*Gyraulus albus* (Müller)	*Gyraulus crista* (Linnaeus)	*Pisidium nitidum* Jenyns	*Valvata* sp.	*Gyraulus* sp.	*Pisidium* sp.	N_t	N_s	Unid.
225–227	3			3			2f			2+2f			4	8+6f	1+d
227–229	9			12+3f		2	1+5f	5		4		2f	7	33+8f	8+d
229–231	16			17+6f		1	5	13		1+2f		1f	7	53+9f	5+d
231–233	7			3+4f		2f	1f	5		3			6	18+7f	4+49f
233–235	18			6+5f	1	2f	10	14		5	3	1f	9	57+8f	10+d
235–237	21	1	1	6+8f		1f	7+2f	19+2f	1	1+2f	1		10	58+15f	9+d
237–239	12			12+18f			1+4f	4+1f		2+1f	1	4f	7	32+28f	8+d
239–241				2+11f									1	2+11f	2
242–243	4			1+10f						1			3	6+10f	1+d
243–244	5+2f			2+4f			1f	1			1		5	9+7f	1+d
244–245	2+2f			2+5f						1		1f	4	5+8f	2+d
245–246		1		2+9f				1		3f		1f	5	4+13f	2+d
246–247	1			3+21f				1		1f			4	5+22f	2+d
247–248				9+6f						2+1f			2	11+7f	1+d
248–249				2+8f						1+1f		1f	3	3+10f	3+d
249–250				3+16f			3f			3+1f			3	6+20f	4
250–251				9+13f						1			2	10+13f	d
251–252				5+9f						1+2f		1+1f	3	7+12f	5
252–253				6+10f									1	6+10f	2+9f
253–254				6+4f									1	6+4f	1f
Total	98+4f	2	1	111+170f	1	3+5f	24+18f	63+3f	1	28+16f	6	1+12f		339+228f	70+59f

E – ecological groups, N_t – number of taxa , N_s – number of specimens, f – shell fragments, d – shell detritus, Unid. – unidentifiable

PHASE 4 – STABILIZATION OF CONDITIONS (253–274 cm)

This phase coincides with the E1b RPAsZ of the protocratic period of the Eemian Interglacial, represented by the Sł-2 L PAZ, during which the area around the lake was covered by pioneering birch and pine communities with an admixture of larch and patches of surviving herbaceous vegetation, including in peat bogs. Their presence is indicated by macroremains (Sł-19 3 L MAZ) with a greater share of *Sphagnum* from the *Squarrosa* section, including *Sphagnum teres* and sedges. Brown mosses, *Thelypteris palustris* and birch species, including shrubs, such as *Betula humilis*, were still present. In the protocratical period of the interglacial, the birch and pine dominant in the forest were joined by representatives of more thermally demanding trees, i.e. elm and oak. Granoszewski (2003) associates the entry of elm with an average July temperature of at least 16°C and suggests the presence of elm riparian communities with the participation of *Quercus robur*.

The relatively stable number of cladoceran species in the middle of the phase shows a further increase and stabilization of their total abundance. A significant share of *Alona excisa*, *A. nana* and the appearance of *A. exigua* indicate the development of peat bog vegetation.

This phase was marked by a significant increase in the numbers of other animals (Turbellaria, Chironomidae, Rotifera; Fig. 7). The share of fungi significantly decreased, which may indicate reduced erosion in the catchment area. This may have been caused by the development of vegetation in the littoral and coastal zones of the lake.

This episode also includes the geochemical zone 2 (GZ2) based on the isotope analysis. Initially, the TOC content continues to rise, reaching its maximum values, but TN falls. Simultaneously, the TOC/TN_{atomic} ratio rapidly increases. The $\delta^{13}C$ and ^{15}N values remain at ~4‰ and 0.6‰, respectively. These data reflect a rapidly growing supply of organic matter from the land (Meyers and Lallier-Vergès, 1999), which was connected with the development of a rich fen (Kołaczek et al., 2016).

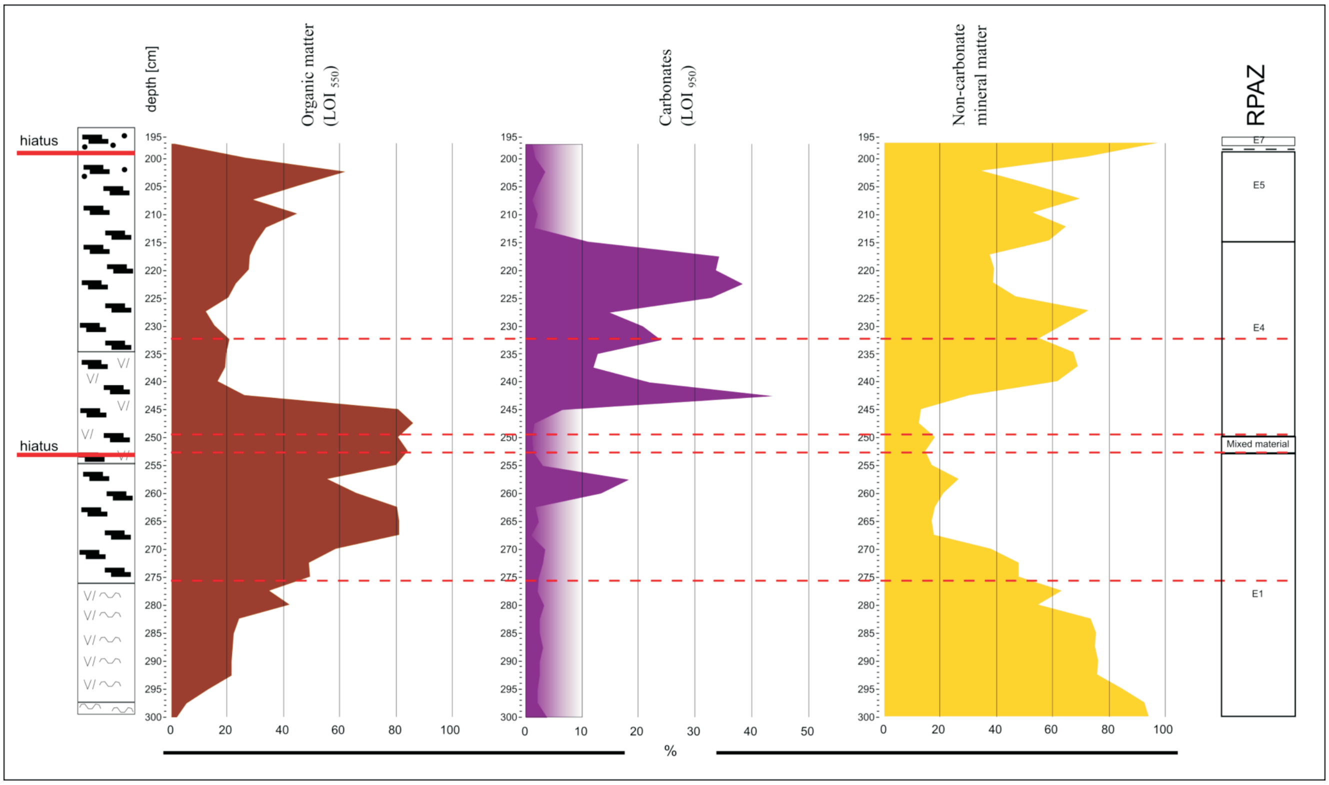

Fig. 9. Diagram of organic matter, mineral matter and carbonate contents in the Słup Sł-19 core

The shading on the carbonate graph indicates those parts of the profile where the $CaCO_3$ content was <10% and therefore the method used has a lower reliability

After the initial dominance of Bryales and *Sphagnum* from the *Squarrosa* section, the *Phragmites australis* reed took a greater share in the surrounding marshland. *Ceratophyllum* was present in the lake. In the next zone, peat moss began to dominate, especially *Sphagnum teres*. This was followed by the reappearance of Bryales brown moss, co-creating moss communities with *Sphagnum*. *Ceratophyllum* was still present in the water body.

In the pollen spectra of the Sł-19-2 L PAZ, there was a sharp increase in the share of *Tetraedron*. This is associated with the presence of thermophilic palynological indicators (*Viscum)* and *Taxus baccata*, which usually appears later in Eemian diagrams, i.e. only in the hazel phase (E4 R PAZ). This is an indication of disturbance by younger sediments, possibly in the course of core collection.

Thus, the interpretation of samples from the depth of 263–267 cm must be approached with great care. The plant macroremains include single fragments of reeds and brown mosses, while peaks in various Cladocera taxa can be seen, including one peak representing their total abundance in the profile; as in the case of pollen, these seem to match the pollen zones seen above 250 cm. This is similar to the obscure fluctuations observed in the isotope curves. It hence appears that approximately 4 cm of the sedimentary section has been removed from the adjacent zone.

A similar interpretation can be applied to the apparent increase in the proportion of carbonates, followed by their peak and subsequent decrease.

Above the 263 cm sample, similar pollen spectra are observed, indicating their formation during the protocratic period of the Eemian Interglacial. This is also suggested by plant macroremains, in the domination of *Sphagnum teres*. In this zone (Sł-19 3 L MAZ), the macroremains do not indicate the presence of a water body, while in the pollen diagram, the few colonies of *Pediastrum* and *Botryococcus* and the species composition of Cladocera indicate that such a body was either very shallow or it was a wetland.

The boundaries of Sł-19 2 L PAZ, and GZ2 coincide quite closely.

PHASE 5 – LIMITATIONS OF THE LAKE FUNCTIONING DURING THE CLIMATE OPTIMUM (203–252 cm)

A rapid change is visible above the depth of 253 cm where a hiatus occurred. The changes are observable both in the pollen and plant macroremain diagrams. Following this, the percentage pollen curves of *Pinus* and *Betula* break, and the high values of *Corylus* begin, accompanied by an increase in the values of *Quercus, Tilia, Alnus, Carpinus betulus* and other taxa characteristic of the Eemian climatic optimum. Macroremains are very few and moss remains are almost absent. In addition, *Najas marina, Najas flexilis* and Characeae appear. This clearly indicates the presence of an eutrophic water body, and the share of *Tetraedron* is similarly very high. The presence of *Tilia tomentosa* and *Carpinus betulus* macroremains (Sł-19 4 L MAZ) indicate the presence of hornbeam and silver linden trees in the vicinity of the lake. Molluscs typical of the littoral zone appear and persist, their species composition and the carbonate content increasing. From a malacofaunal perspective, this reflects a lake with a well-developed littoral zone.

In this phase, a significant decrease in the amount of organic matter and TOC/TN_{atomic} ratio can be seen, which probably re-

Table 6

The characteristics of geochemical zones GZ1-GZ4

Zone	Depth [cm]	TOC, TN and TOC/TN_{atomic}	Isotopic data: $\delta^{13}C$ and $\delta^{15}N$
GZ1	**<275**		
	below 300	TOC – the lowest amount: ~1% TN – the lowest amount: <0.01% (minimum content of this profile)	$\delta^{13}C$ – the highest values: –16‰ $\delta^{15}N$ – no measurement
	300–285	TOC – an increase to ~12% TN – an increase to ~0.6% TOC/TN_{atomic} – oscillations around 25	$\delta^{13}C$ – a drop in values to ~–30‰ $\delta^{15}N$ – an increase in values to ~1‰
	285–275	TOC – a further increase to ~27% TN – a further increase to ~1.2% TOC/TN_{atomic} – fluctuations between 20 and 27	$\delta^{13}C$ – a further drop of values to –32.4‰ (the minimum value) $\delta^{15}N$ – a further increase to 2.8‰ (the maximum value) and next a drop to ~0.3‰
GZ2	**275–255**	TOC – an increase to ~50% and then a drop to ~40% TN – a slight drop to 0.3% and a systematic increase to 0.7% TOC/TN_{atomic} – initially an abrupt increase to 110 (the maximum value) and next a drop to 72–80	$\delta^{13}C$ – initially fluctuations between –28 and –32‰ and then constant values of ~–27.4‰ $\delta^{15}N$ – initially an increase to 0.09‰ and next a drop to –0.7‰ (the minimum value)
GZ3	**255–205**		
	255–240	TOC – a decrease to 15 and then to 9% TN – a drop to 0.5% TOC/TN_{atomic} – a decrease to 20	$\delta^{13}C$ – constant values of ~–29‰ $\delta^{15}N$ – an increase to 0.5‰
	240–233	TOC – an increase to 25 and then a drop to 17% TN – an increase to 1–1.5% TOC/TN_{atomic} – a constant ratio of 19	$\delta^{13}C$ – a drop to –29.8 and then an increase to –28.9‰ $\delta^{15}N$ – a drop to 0‰
	233–220	TOC – an increase to 32 and then a drop to 17% TN – an increase to 1.9 and slight drop to 1% TOC/TN_{atomic} – a constant ratio of 19	$\delta^{13}C$ – a constant value of ~–29.5‰ $\delta^{15}N$ – a slight increase to 0.3‰
	220–205	TOC – an irregular increase to 38% TN – an increase to 2.7% (the maximum of values) TOC/TN_{atomic} – slight fluctuation between 17 and 20	$\delta^{13}C$ – a constant value of ~–29‰ $\delta^{15}N$ – fluctuations from –0.3 to 0.3‰
GZ4	**205–198**	TOC – a decrease to 21 and then to 0.8% TN – a decrease to 1 and then below 0.01% TOC/TN_{atomic} – initially an increase to 22, and subsequently the ratio cannot be calculated	$\delta^{13}C$ – an abrupt increase to –20.4‰ $\delta^{15}N$ – an increase to 1.5‰

flects a limitation of the supply of matter from land (GZ3). The accumulated lacustrine deposits are dominated by organic matter, correlated with a large share of algae and the presence of macrophytes. However, above the depth of ~240 cm, the concentrations of organic carbon and nitrogen both change. TOC and TN values shift in three steps. The isotopic data and the high amount of organic matter reflect climatic conditions appropriate for vegetation development. The TOC/TN_{atomic} ratio remains steady at ~19–20, reflecting a constant share of both higher plants and algae in the composition of the organic matter. The $\delta^{13}C$ values indicate the share of algae (Table 6).

A decrease in the species richness and total abundance of Cladocera is noted from a depth of 205 cm, together with a decrease in the abundance of *Tetraedron* and a renewed increase in the share of brown moss spores and Filicales monolete. This clearly indicates limitations in the lake surface area, renewed peat bogs and the functioning of the fen.

The water level then changed and the bog was flooded, as shown by the increased share of *Bosmina longirostris*, the only planktonic species present at that time, and *Sida crystalina* (233–255 cm), which lives among aquatic vegetation. A slight increase in the water level is also indicated by the results of non-pollen microfossils and the entry of *Stratoites aloides* in this phase.

The TOC and TN values rapidly decrease above the depth of 205 cm (GZ4). However, the opposite trends are observed for $\delta^{13}C$ values and $\delta^{15}N$, suggesting lower nitrogen availability in the surface waters (Talbot and Laerdal, 2000). The more positive $\delta^{13}C$ and very low TOC values reflect a reduction of primary production and input of organic matter from land, probably associated with climatic cooling.

The lack of a record of the younger part of the climatic optimum (the upper part of E5 R PAZ) and spruce-fir phase (E6 R PAZ) suggests that, at that time, the palaeolake could have been very limited and the Sł-19 sampling site did not include the littoral zone.

PHASE 6 – RE-APPEARANCE OF THE SHALLOW LAKE (193–202 cm)

Increased moisture was already noted in the declining – pine – phase of the interglacial (E7 R PAZ), which is well-developed in many Eemian diagrams in Poland. Sometimes it is possible to distinguish a temporary increased share of NAP, reflecting a movement towards a cooler climate (Kupryjanowicz et al., 2016). Unfortunately, in the Sł-19 profile, the pine phase is recorded only in one sample (193 cm), indicating that this may only be part of the pine phase which happens to have high *Pinus* values. The pollen record also suggests the littoral zone of the lake based on *Typha latifolia*, of the Cyperaceae, which was present in large numbers. Spruce trees were also present in the stand next to the pine trees. It can be assumed that the numerous moss and fern spores, as well as the less numerous *Sphagnum* spores, come from the peat bog surrounding the shallow lake. The sediments had a much lower organic matter content (<0.8% of TOC), which would have resulted in higher water clarity. No carbonates were observed here.

The significant sandiness of the material (depth sample 193 cm), resulting from erosion in the catchment area, made it impossible to perform other analyses in these samples.

The erosive boundary, indicated by the layer of sand above the 193 cm sample does not allow any further reconstruction of the rest of the pine phase. It is also unknown whether or not the two upper samples represent Early Weichselian time.

DISCUSSION

A COMPARISON OF THE EEMIAN SITE IN SŁUP WITH OTHER PALAEOLAKES IN THE GARWOLIN PLAIN

Our findings regarding the palaeolake in Słup, despite the fact that the core studied was obtained from its edge, help refine the palaeohydrological, and indirectly, the palaeoclimatic and palaeoenvironmental, interpretation of the Eemian lakeland within the Late Saalian ice sheet range. Some examples of lakes with a complete interglacial record can be found next to the Słup site in a small area of the Garwolin Plain (see Kozłów – Pidek et al., 2021; Suchora et al., 2022). In addition, some lakes lack certain phases, most often the E5/E6 R PAZ transition; Jagodne (Bober et al., 2021a) and Żabieniec (Pidek et al., 2022) are such lakes. However, more modern high-resolution, multi-proxy approaches have provided more detailed palaeoenvironmental interpretations of the these Eemian lakes, including palaeohydrological interpretations. This has been made possible by *inter alia* accurately identifying the traditional phases of the Eemian Interglacial (R PAZs) developed by Mamakowa (1989) into smaller units (sub-zones) according to Kupryjanowicz and Granoszewski (2018). This approach allowed for the comparison of various palynological diagrams of different resolutions and degrees of completeness.

This approach was used in the construction of isopollen maps for the Eemian Interglacial (Kupryjanowicz et al., 2018). The findings also indicate that many sites of Eemian lakes exhibit sedimentation breaks.

The use of a range of study methods for the Słup palaeolake provided a highly-detailed record that could highlight these gaps. These are best revealed by littoral lake cores.

The beginning of the lake is associated with the melting of a block of dead ice, filling a depression in Late Saalian till. At the end of the glacial phase, the block was additionally preserved due to the presence of permafrost in the substrate. At the bottom of the lake, there is a low-permeability glacial till.

The Sł-19 core provides a very good record of the protocratic period of the interglacial, and this is analogous to other profiles identified for the Kozłów, Żabieniec and Jagodne lakes. It seems that this lake may have originated by melting of a dead ice block, as also occurred for many other Eemian lakes, both on the Garwolin Plain (*vide* Suchora et al., 2022) and in central Poland (Roman et al., 2021). This thesis is supported by the poor representation of cladoceran species, low pollen abundance and low organic matter content, accompanied by indicators of the shallowness of the water body in conditions of persistent permafrost.

The existence of the lake in the interglacial period was conditioned by a favourable hydrological context. The overlying layers of this till have sandy interbeds and when the aquifer was cut, it was from these permeable layers that the lake was fed. Probably, the E3 RPAZ period was one when the lake shrank, at least from the littoral zone from which the core was taken, which became dry land, interrupting lacustrine sedimentation. A more humid climate in the E4 RPAZ phase, lasting until the older part of the E5 RPAZ, resulted in reactivation of the lake. This phase is also recorded at other sites as the wettest phase of the Eemian Interglacial. Many reports on water levels in Eemian lakes indicate that these reached their peak in the hazel phase (E4 R PAZ) and at the beginning of the hornbeam phase (cf. Kupryjanowicz, 2008; Roman et al., 2021). Thus, it can be concluded that the Słup lake had its greatest depth and range at that time, as in Eemian lakes in central Poland (Roman et al., 2021). This thesis is consistent with our results from the Sł-19 study site. However, a new complete core in the central part of the palaeolake in Słup is planned to test the hypothesis of the similar development of the Słup and Parysów palaeolakes.

Many authors also point out that some lakes had ceased to function in the earlier part of the E5 R PAZ phase. This was also observed in the case of lakes such as Żabieniec, Jagodne and Parysów on the Garwolin Plain. This may have been related to a significant decrease in climate humidity. During this time, many lakes paludified, ceasing to function as lakes and turning into peat bogs.

The record from lakes such as Żabieniec (Pidek et al., 2022), Jagodne (Bober et al., 2021a), Parysów (Bober et al., 2021b) supports this thesis. The palaeoenvironmental record in biogenic deposits can be seen to reactivate in the next phase, i.e. E6 R PAZ, when a spruce community (locally fir and spruce forest) entered the peaty lake basin, and the humidity of the habitat was high, allowing for the existence of the fen. It has been suggested that this was not so much due to high rainfall, but to reduced evapotranspiration and a reduction in temperature (Kupryjanowicz, 2008). This situation continued in some lakes throughout the telocratic period, and thus also in the pine phase (E7 R PAZ), and sometimes also in the Early Weichselian (Granoszewski, 2003; Kupryjanowicz, 2008). Unfortunately, there is no record of this period in the core analyzed, due to the presence of a very thick layer of poorly sorted sands acting as an erosive boundary: the palynological samples above this boundary lack any characteristic pollen features allowing them to be assigned to a specific period.

CLIMATIC CONDITIONS FOR THE DEVELOPMENT AND DISAPPEARANCE OF EEMIAN PALAEOLAKES

The relatively good representation of the early Eemian in the Sł-19 profile studied, which comprises a moderately thick sedimentary succession, produces a clear picture of two phases in the accumulation of lake gyttja. The first phase corresponding to E1a subphase is associated with a large supply of fine mineral material. The substrate was not fixed by the vegetation cover around the forming lake, and hence was the source of *Glomus* sporangia. The E1b subphase represents birch forest development and stabilisation of the ground.

It is likely that the ice sheet disappeared quickly in response to the change in climate from the beginning of the interglacial (Zagwijn, 1983); this is believed to be related to a marine transgression, the first stage of which occurred at the onset of the Eemian (Makowska, 2009). These data are in line with the broad discussion of climatic conditions at the onset of the Eemian Interglacial by Govin et al. (2015), who stressed a particularly high boreal summer insolation values and an increase in global mean sea level up to 5–10 m above the present-day level.

In the early Eemian, the presence of *Typha latifolia* in lakes indicates that the July mean temperature was ~+14°C (Väliranta et al., 2015). On the other hand, the NAP values were quite high, which may suggest that the climate still possessed continental features. Winters could still be very harsh and the climate was continental at the beginning of the interglacial. Brewer et al. (2008), based on climate reconstructions from 17 sites distributed across the European continent, stressed that large changes in temperature occurred in the mean temperature of the coldest month at the onset of the Eemian, which caused a subsequent change in seasonality with a weakening of seasonal contrasts. In our palaeolake in Słup, the ground was deeply frozen at that time and the flow of groundwater was disturbed. Therefore the lake could not be supplied with water. The same conclusions regarding the low temperature of the coldest month also came from the interpretation of modern pollen analogues (Pidek et al., 2022). The switch from a highly continental pre-Eemian climate to an oceanic climate in the early Eemian was previously noted also by Cheddadi et al. (1998) and Klotz et al. (2003) for west-central Europe. Only a significant increase in the temperature of the coldest month at the end of the E2 RPAZ could be conducive to the gradual activation of the water supply of the Słup palaeolake by groundwater.

The development of the Vistula River valley adjacent to the Garwolin Plain is another aspect of the water level in these lakes. After the Saalian ice sheet had receded, the Vistula River valley was formed in a similar shape as today and its width was ~15 km (Żarski, 2002). Around the Saalian-Eemian boundary, the river cut into the plateau, by up to ~40 m, the ice sheet disappeared and there was no obstacle in the Baltic basin in the north. The cutting of the Vistula bed in the late glacial period was an important factor influencing the lowering of the erosional base, which resulted in the lowering of groundwater level and of the water level in some lakes. The phenomenon of deep incision occurred both at the Late Saalian/Eemian and the Late Weichselian/ Holocene transition (Żarski, 2002; Molewski, 2014). This might explain the lack of organogenic deposition in the Słup palaeolake during the E2 and E3 RPAZ. Although the rise in water level is generally observable from the Late Saalian, during which many Eemian water bodies were created, the rise occurred both in the palaeolakes of the Garwolin Plain and in other Eemian lakes of central Poland (Mirosław-Grabowska and Niska, 2005; Niska, 2012; Roman et al., 2021). Melting of dead ice blocks and the permafrost melting effect both contributed to this.

The wide spread of riparian forests, expansion of oak communities in various habitats, and the occurrence of *Hedera helix* indicate further climate amelioration from the E3 R PAZ. This suggests that winter temperature was not lower than –1.5°C. The indicative value of *Hedera helix* is very high in this respect (Iversen, 1944). Both the presence of *Hedera helix* and the spread of riverine communities with elm and ash indicate that the climate had oceanic features.

Only in the E4 RPAZ did the humid climate cause the formation of the highest water level of the Słup palaeolake and its largest extent. Our record supports these suggestions very well. The maximum water level is in accordance with earlier findings: many lakes, including those at Studzieniec (Mirosław-Grabowska and Niska, 2005) in central Poland, recorded their highest water levels in the hazel phase, and some even in the end of the oak phase (Roman et al., 2021). However, Mirosław-Grabowska and Gąsiorowski (2010) also found examples of lowered water levels during the E2-E3 RPAZs. Data from northern Podlasie, a region farther north than the Garwolin Plain, show that the majority of the Eemian lakes in this region were formed during the hazel phase (Kupryjanowicz, 2008). Kupryjanowicz (2008) attributes this process to both the intensity of the melting of dead ice blocks in the substrate and to the increased oceanization of the climate. This was favoured by a very warm climate. The identification of *Tilia tomentosa*, whose presence indicates that the mean July temperature was not lower than 21°C, was an important observation (Mamakowa, 1989; Kupryjanowicz et al., 2018).

The hazel phase (E4 RPAZ) saw a transgression of the Eemian Tychnowy sea. In the Eemian optimum, the Vistula River already exhibited the accumulation stage after the deep incision at the onset of the interglacial. Water levels were high in most lakes in this phase, as indicated by the presence of *Ceratophyllum* in the Słup palaeolake. This is also detectable in the Struga (Zalat et al., 2021) and Kozłów lakes (Pidek et al., 2021; Suchora et al., 2022) on the Garwolin Plain.

Various aquatic plant taxa with higher climatic requirements can be found in addition to *Tilia tomentosa*. For example, *Salvinia natans* is a water fern that usually grows in warm zones with temperate sub-oceanic climates and in tropical climates (Holm et al., 1979). Its megaspores can only develop when winter months remain above 0°C (Święta-Musznicka et al., 2011). This thermophilic taxon is most commonly found in eutrophic waters of large rivers, oxbow lakes, ditches and canals, and in shallow, slow rivers (Casper and Krausch, 1980).

Another aspect related to water level change during the Eemian Interglacial was considered by Schokker et al. (2004). Their study of Eemian and Early Weichselian biogenic deposits in southeastern Netherlands showed a significant rise in groundwater level at the beginning of the interglacial, whereas already in the E3 oak zone this level dropped below ground level. Thus the lake disappeared. In such a case, the rise of the lake water level did not coincide with the rise of Eemian sea level. The lack of sediments representing the regional E4 and E5 zones was linked by Schokker et al. (2004) to the presumed low groundwater level at this time. In the case of our Słup palaeolake of central Poland, the reasons for the lack of the record in the E2 and E3 RPAZs may be similar, while definitely in the E4 RPAZ the water level was high (Fig. 10). Certainly, one has to keep in mind the asynchronicity of different palaeoenvironmental processes taking place in such distant areas. Schokker et al. (2004) also emphasised that even the delimitation between glacials and interglacials on biostratigraphic grounds is not the same as that between marine isotope substages.

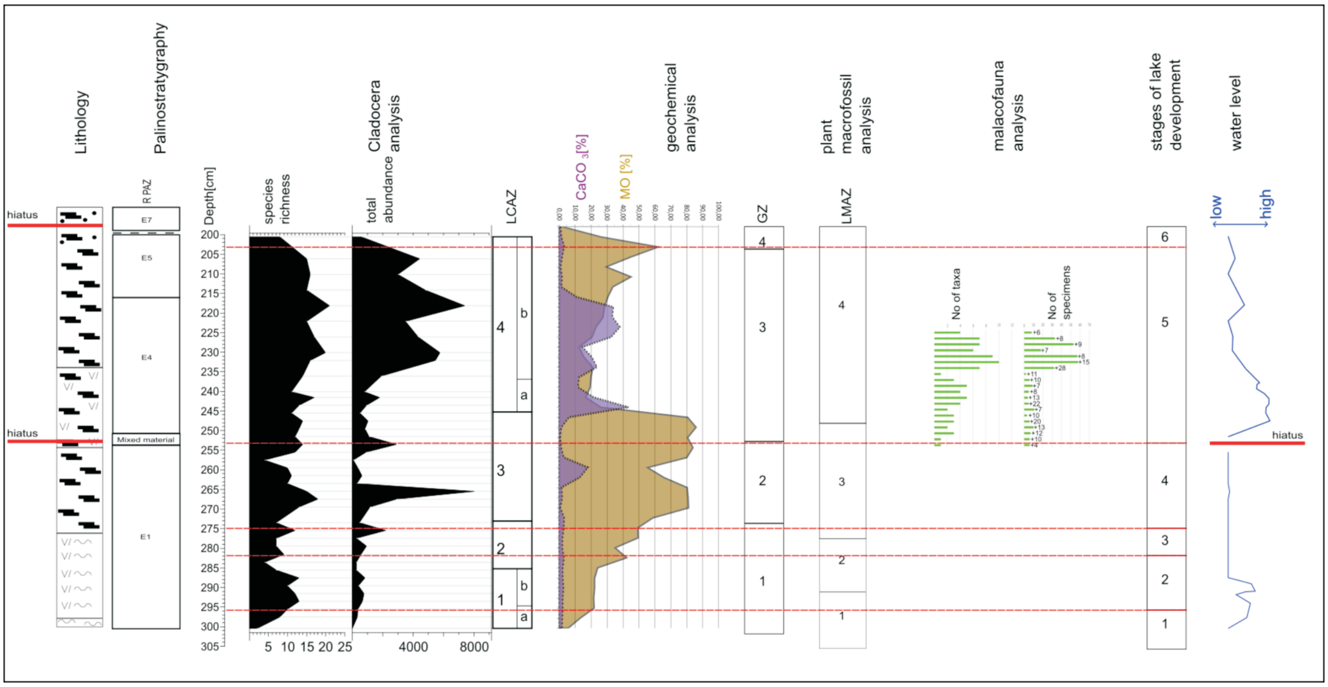

Fig. 10. Developmental phases of the Słup Sł-19 core fossil lake based on multi-proxy data

The reconstructed water level is interrupted in the E2-E3RPAZs for which there is no record in the profile

The second part of the climate optimum of the Eemian Interglacial was characterized by the dominance of hornbeam forests. Based on the presence of *Tilia tomentosa* pollen in the older part of this phase, both Granoszewski (2003) and Kupryjanowicz et al. (2018) considered it the warmest part of the interglacial. This interpretation is consistent with earlier findings (Litt et al., 1996; Zagwijn, 1996; Aalbersberg and Litt, 1998) and with the results of climate reconstruction using modern pollen analogues in the PPP base program (Pidek et al., 2022).

There is no record of the next phase (E6 R PAZ) in the Słup Sł-19 core. A hiatus can be seen here, which probably also covers the younger part of the hornbeam phase (E5 R PAZ). Data on other profiles of the Garwolin Plain show the next phase to be undoubtedly cooler. The disappearance of all thermophilous trees and the expansion of conifers was the most important change in vegetation composition during the late Eemian (E6-E7 R PAZs). These changes indicate lower temperatures and increased precipitation by comparison with the hornbeam phase. The reduction in water level noted in the younger E5 R PAZ very often also covers the older E6 R PAZ; such examples are frequent in NE Poland (cf. Kupryjanowicz, 2008). Nevertheless, Kupryjanowicz et al. (2018) propose that the fall in summer mean temperature could not have been very sharp, even in the region of northern Podlasie, and the presence of *Viscum* at that time indicates that the mean July temperature was not lower than +17°C. Our data support the opinions of the authors who stress that a decrease in winter temperatures greater than that of summer temperatures leads to an overall increase in seasonality, supporting the return to a more continental climate (Cheddadi et al., 1998; Rioul et al., 2001; Klotz et al., 2003; Sánchez-Goñi et al., 2005). These changes seem to be restricted to the north of Europe, with little or no change observed in the south (Brewer et al., 2008). The Lago Grande di Monticchio site can exemplify the process in which the cooling at the termination of the last interglacial occurred nearly 5 thousand years later in the south (Allen et al., 1999).

The problem of lowered water level in the Eemian water bodies and its causes, such as the reduction of annual rainfall, is a key issue concerning the decline of the Eemian Interglacial optimum. Our record seems to corroborate that it was probably this factor that caused another reduction in the surface area of the lake at Słup, or even its disappearance.

Cheddadi et al. (1998), based on pollen data from two profiles from Poland (Imbramowice and Główczyn) and five from other parts of Europe suggest that precipitation dropped by ~200–300 mm/year from the very beginning of the hornbeam phase. In addition, Kupryjanowicz (2008) report lower water levels in lakes and mires in the northern Podlasie region during the E5 R PAZ to E5/E6 R PAZ transition. Data from the Żabieniec site in the Garwolin Plain, where the E6 R PAZ has been well developed (Pidek et al., 2022), suggest a reduction in water level, which resulted in the drying out of smaller water bodies. Such was the fate of the neighbouring small water bodies, e.g. Żabieniec-1 and Żabieniec-2, which would develop into marshlands as the more humid *Picea-Abies* phase followed. These changes are analogous to those associated with the transformation of the Eemian palaeolake into a peatbog at the Hinterste Mühle site in northern Germany, where deposition of lacustrine sediments ceased at the end of the *Carpinus* phase and was soon replaced by peat accumulation (Börner et al., 2016).

SUMMARY AND CONCLUSIONS

Multi-proxy analyses were carried out on a core of organogenic sediments from the fossil Eemian lake at the Słup site on the Garwolin Plain (central Poland). The sediment thickness was 1.03 m. The results of the palynological analyses, which provided the basis for palynostratigraphy and the interpretation of the history of vegetation, were supported by analyses of the lithostratigraphy, plant macrofossils, Cladocera fossil assemblages, mollusc shells and stable isotope composition.

Palaeohydrological changes in the studied palaeolake were also reconstructed. In addition, the results were compared to climate changes identified on the basis of pollen diagrams from other sites of Eemian lakes of the Garwolin Plain. These changes provide an insight into the differences and similarities in vegetation succession resulting from local conditions, thus supporting regional climatic conditions interpreted on the basis of other Eemian profiles from Europe.

Local pollen assemblage zones (L PAZs) from the Słup site and corresponding R PAZs (Mamakowa, 1989) reflect palaeoenvironmental changes from the beginning of the Eemian Interglacial (E1 R PAZ). Regional zones of E4, E5 (without the younger part) and E7 R PAZ are also represented in the deposits.

The lack of the E2, E3, E6 zones and of part of E5 R PAZ, together with our comparisons with other high-resolution pollen diagrams from the same region, suggest the presence of several sedimentation gaps, which are also reflected in previous analyses.

The lack of sediments recording the majority of the E3 R PAZ, the younger part of the E5 R PAZ and the entire E6 R PAZ, and the results of multiproxy analyses seem to confirm that the sequence represents the overgrowth of a shallow, eutrophic palaeolake. The lack of deposits representing the E3 R PAZ is of special interest and have been discussed against the background of the development of the Vistula River valley at the beginning of the interglacial.

Shallowing in the E5 R PAZ led to the formation of a peat bog. The dampness and cooling at the end of the interglacial allowed for the re-creation of a moist wetland. Similar temporary cessations of biogenic accumulation in shallow bodies and their transformation into transitional bogs were recorded in several lakes on the Garwolin Plain and in other regions of Poland during the E5/E6 R PAZs transition. The causes may have been driven by a regional factor, possibly a reduction in the erosional base, combined with the intensification of climate continentality (including less rainfall).

Unfortunately, the upper part of the profile contains a sandy intercalation that may come from the Weichselian period and the uppermost peats may be Holocene. However, the peats lack diagnostic features for any warm interglacial section.

Acknowledgements. The research was financed by the National Science Centre, Poland, project No. 2017/27/B/ST10/01905. We would like to thank S. Terpiłowski for consultations regarding an improved model of the development of the lake. We are also grateful to M. Kupryjanowicz, J. Schokker and an anonymous reviewer for their valuable suggestions and comments, which significantly improved the manuscript.

REFERENCES

Aalbersberg, G., Litt, T., 1998. Multiproxy climate reconstruction from the Eemian and Early Weichselian. Journal of Quaternary Science, **13**: 367–390. https://doi.org/10.1002/(SICI)1099-1417(1998090)13:5%3C367::AID-JQS400%3E3.0.CO

Alexandrowicz, S.W., 1987. Analiza malakologiczna osadów czwartorzędowych (in Polish). Kwartalnik Akademii Górniczo-Hutniczej, Geologia, **12**: 1–240.

Alexandrowicz, S.W., Alexandrowicz W.P., 2011. Analiza malakologiczna. Metody badań i interpretacji (in Polish). Rozprawy Wydziału Przyrodniczego PAU, **3**. Wydawnictwa PAU, Kraków.

Allen, J.R.M., Brandt, U., Brauer, A., Hubberten, H.-W., Huntley, B., Keller, J., Kraml, M., Mackensen, A., Mingram, J., Negendank, J.F.W., Nowaczyk, N.R., Oberhänsli, H., Watts, W.A., Wulf, S., Zolitschka, B., 1999. Rapid environmental changes in southern Europe during the last glacial period. Nature, **400**: 740–743. https://doi.org/10.1038/nature23432

Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Handbook of Holocene Palaeoecology and Palaeohydrology (eds. B.E. Berglund and M. Ralska-Jasiewiczowa): 455–484. J. Wiley and Sons Ltd., Chichester-Toronto.

Bober, A., Brzozowicz, D., Drzymulska, D., Żarski, M., Suchora, M., 2021a. Palaeobotanical record of the Eemian Interglacial succession at the Jagodne sit (Garwolin Plain, central Poland). Geological Quarterly, **65** (2): 34. https://doi.org/10.7306/gq.1602

Bober, A., Stachowicz-Rybka, R., Żarski, M., 2021b. Paleobotaniczny obraz rozwoju roślinności w eemskim stanowisku Parysów na Równinie Garwolińskiej (in Polish). Sympozjum Sekcji Paleobotanicznej Polskiego Towarzystwa Botanicznego. (eds. M. Badura, A., Noryśkiewicz and G. Skrzyński): 21–23. Streszczenia, 4.12.2021, Warszawa.

Börner, A., Hrynowiecka, A., Stachowicz-Rybka, R., Niska, M., Kuznetsov, V., Maksimov, F., Petrov, A., Moskal-del Hoyo, M., 2016. Palaeoecological investigations of the Eemian Interglacial peat sequence Neubrandenburg-Hinterste Mühle (Mecklenburg-Western Pomerania, NE Germany): 63–66. XXIII Konferencja Stratygrafia Plejstocenu Polski, Biała Podlaska/Brest, 5–9.09.2016

Brewer, S., Guiot, J., Sánchez-Goñi, M.F., Klotz, S., 2008. The climate in Europe during the Eemian: a multi-method approach using pollen data. Quaternary Science Reviews, **27**: 2303–2315. https://doi.org/10.1016/j.quascirev.2008.08.029

Casper, S.J., Krausch, H.D., 1980. Pteridophyta und Anthophyta. Lycopodiaceae bis Orchidaceae, Gustav Fischer Verlag, Jena: 72–74.

Caspers, G., **Freund, H., 2001**. Vegetation and climate in the Early- and Pleni-Weichselian in northern central Europe. Journal of Quaternary Science, **16**: 31–48.

Cheddadi, R., Mamakowa, K., Guiot, J., de Beaulieu, J.-L, Reille, M., Andrieu, V., Granoszewski, W., Peyron, O., 1998. Was the climate of the Eemian stable? A quantitative climate reconstruction from seven European pollen records. Palaeogeography, Palaeoclimatology, Palaeoecology, **143**: 73–85. https://doi.org/10.1016/S0031-0182(98)00067-4

Cohen, K.M., Gibbard, P., 2011. Global chronostratigraphical correlation table for the last 2.7 million years. Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy), Cambridge, England. https://doi.org/10.1016/j.quaint.2019.03.009

Faegri, K., Iversen, J., 1975. Text Book of Pollen Analysis. Third edition. Hafner, New York, USA.

Frey, D.G., 1986. Cladocera analysis. In: Handbook of Holocene Palaeoecology and Palaeohydrology (ed. B.E. Berglund): 667–692. John Wiley and Sons Ltd.

Govin, A., Capron, E., Tzedakis, P.C., Verheyden, S., Ghaleb, B., Hillaire-Marcel, C., St-Onge, G., Stoner, J.S., Bassinot, F., Bazin, L., Blunier, T., Combourieu-Nebout, N., El Ouahabi, A., Genty, D., Gersonde, R., Jimenez-Amat, P., Landais, A., Martrat, B., Masson-Delmotte, V., Parrenin, F., Seidenkrantz, M.-S., Veres, D., Waelbroeck, C., Zahn, R., 2015. Sequence of events from the onset to the demise of the Last Interglacial: evaluating strengths and limitations of chronologies used in climatic archives. Quaternary Science Reviews, **129**: 1–36. https://doi.org/10.1016/j.quascirev.2015.09.018

Granoszewski, W., 2003. Late Pleistocene vegetation history and climatic changes at Horoszki Duże, eastern Poland: a palaeobotanical study. Acta Palaeobotanica, **4**: 3–95.

Granoszewski, W., Winter, H., Rylova, T.B., Savćenko, I.E., 2012. The course and correlation of the Late Pleistocene pollen sequences from Poland and Belarus (in Polish with English summary). Przegląd Geologiczny, **60**: 605–614.

Grimm, E.C., 1987. Coniss: a fortran 77 program for stratigraphically constrained cluster analysis by method of incremental sum of squares. Computer Geosciences, **13**: 13–35. http://dx.doi.org/10.1016/0098-3004(87)90022-7

Grimm, E.C., 2011. Tilia Software V. 1.7.16. Illinois State Museum, Springfield.

Grosse-Brauckmann, G., 1972. Über pflanzliche Makrofossilien mitteleuropäischer Torfe I. Gewebereste krautiger Pflanzen und ihre Mekmale. Telma, **2**: 19–55. https://doi.org/10.23689/fidgeo-5276

Grosse-Brauckmann, G., 1974. Über pflanzliche Makrofossilien mitteleuropäischer Torfe. II. Weitere Reste (Früchte und samen, Moose u.a.) und ihre Bestimmungsmöglichkeiten. Telma, **4**: 51–117. https://doi.org/10.23689/fidgeo-5277

Hammer, Ø., Harper, D.A., Ryan, P.D., 2001. PAST: paleontological statistics software package for education and data analysis. Palaeontologia Electronica, **4**: 1–9.

Holm, L., Pancho, J.V., Herberger, J.P., Plucknett, D.L., 1979. A Geographical Atlas of World Weeds. Wiley, New York.

Hrynowiecka, A., Stachowicz-Rybka, R., Niska, M., Moskal-del Hoyo, M., Borner, A., Rother, H., 2021. Eemian (MIS 5e) climate oscillations based on palaeobotanical analysis from the Beckentin profile (NE Germany). Quaternary International, **605–606**: 38–54. https://doi.org/10.1016/j.quaint.2021.01.025

Iversen, J., 1944. *Viscum*, *Hedera* and *Ilex* as climate indicator. Geol. Föreningen i Stockholm Förhandlingar, **66**: 463–483. https://doi.org/10.1080/11035894409445689

Jastrzębska-Mamełka, M., 1985. The Eemian Interglacial and the early Vistulian at Zgierz-Rudunki in the Łódź Plateau. Acta Geographica Lodziensis, **53**: 1–75.

Katz, N.J., Katz, S.W., Skobiejeva, J.I., 1977. Atlas of Plant Remains in Peat (in Russian). Nedra, Moskva.

Klotz, S., Guiot, J., Mosbrugger, V., 2003. Continental European Eemian and early Würmian climate evolution: comparing signals using different quantitative reconstruction approaches based on pollen. Global and Planetary Change, **36**: 277–294.

Kołaczek, P., Niska, M., Mirosław-Grabowska, J., Gałka, M., 2016. Periodic lake-peatland shifts under the Eemian and Early Weichselian climate changes in Central Europe on the basis of multi-proxy studies. Palaeogeography, Palaeoclimatology, Palaeoecology, **461**: 29–43. https://doi.org/10.1016/j.palaeo.2016.08.002

Kühl, N., Litt, T., 2003. Quantitative time series reconstructions of Eemian temperature at three European sites using pollen data. Vegetation History and Archaeobotany, **12:** 205–214. doi:10.1007/s00334-003-0019-2.

Kupryjanowicz, M., 2008. Vegetation and climate of the Eemian and Early Vistulian Lakeland in northern Podlasie. Acta Palaeobotanica, **48** : 3–130

Kupryjanowicz, M., Granoszewski, W., 2018. Detailed palynostratigraphy of the Eemian Interglacial in Poland. In: Eemian History of Vegetation in Poland Based on Isopollen Maps (eds. M. Kupryjanowicz, D. Nalepka, E. Madeyska and Ch. Turner): 17–20. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Kupryjanowicz, M., Granoszewski, W., Nalepka, D., Pidek, I.A., Walanus, A., Balwierz, Z., Fiłoc, M., Kołaczek, P., Majecka, M., Malkiewicz, M., Nita, M., Noryśkiewicz, B., Winter, H., 2016. Instability of the environment at the end of the Eemian Interglacial as illustrated by the isopollen maps for Poland. Geological Quarterly, **60** (1): 225–237. https://doi.org/10.7306/gq.1271

Kupryjanowicz, M., Nalepka, D., Madeyska, E., Turner, Ch. eds., 2018. Eemian history of vegetation in Poland based on isopollen maps. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Kupryjanowicz, M., Fiłoc, M., Drzymulska, D., Poska, A., Suchora, M., Mroczek, P., Żarski, M., 2021. Environmental changes of the stadial/interstadial type during the Late Saalian (MIS-6) – multi-proxy record at the Wola Starogrodzka site, central Poland. Palaeogeography, Palaeoclimatology, Palaeoecology **572:** 110420. https://doi.org/https://doi.org/10.1016/j.palaeo.2021.110420

Kurek, J., Korosi, J.B., Jeziorski, A., Smol, J.P., 2010. Establishing reliable minimum count sizes for cladoceran subfossils sampled from lake sediments. Journal of Paleolimnology, **44**: 603–612. https://doi.org/10.1007/s10933-010-9440-6

Leng, M.J., Lamb, A.L., Marshall, J.D., Wolfe, B.B., Jones, M.D., Holmes, J.A., Arrowsmith, C., 2005. Isotopes in Lake Sediments. In: Isotopes in Palaeonvironmental Research (ed. M.J. Leng): 147–184. Springer, the Netherlands.

Litt, T., Junge, F.W., Böttger, T., 1996. Climate during the Eemian in north central Europe – a critical review of the palaeobotanical and stable isotope data from Central Germany. Vegetation History and Archaeobotany, **5**: 247–256. https://doi.org/10.1007/BF00217502

Ložek, V., 1964. Quartärmollusken der Tschechoslowakei. Rozpravy Ústředního ústavu geologického, **31**: 1–374.

Makowska, A., **2009**. Intermorainic Lower Vistula formation against the background of geological structure of Pleistocene deposits in Vistula Pomerania, and its development during the Younger Pleistocene (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **437**: 59–124.

Mamakowa, K., 1989. Late Middle Polish Glaciation, Eemian and Early Vistulian vegetation at Imbramowice near Wrocław and the pollen stratigraphy of this part of the Pleistocene in Poland. Acta Palaeobotanica, **29**: 11–176.

Mauquoy, D., van Geel, B., 2007. Mire and peat macros. In: Encyclopedia of Quaternary Science, 3 (ed. S.A. Elias): 2315–2336. Elsevier, Heidelberg.

Meyers, P.A., Lallier-Vergčs, E., 1999. Lacustrine sedimentary organic matter records of Late Quaternary paleoclimates. Journal of Paleolimnology, **21**: 345–372.

Mirosław-Grabowska, J., Gąsiorowski, M., 2010. Changes of water level in the Eemian palaeolake at Imbramowice (SW Poland) based on isotopic and cladoceran data. Quaternary Research, **73**: 143–150.

Mirosław-Grabowska, J., Niska, M., 2005. Isotopic and Cladocera records of climate changes of Early Eemian at Besiekierz (Central Poland). Geological Quarterly, **49** (1): 67–74.

Mirosław-Grabowska, J., Niska, M., Kupryjanowicz, M., 2015. Reaction of lake environment on the climatic cooling – transition from the Eemian Interglacial to Early Vistulian on the basis of Solniki palaeolake sediments (NE Poland). Quaternary International, **386**: 158–170. https://doi.org/10.1016/j.quaint.2015.03.056

Mirosław-Grabowska, J., Niska, M., Roman, M., 2018. Long (MIS 5e–3) environmental history of a paleolake in central Poland recorded in the succession from Kubłowo. Quaternary International, **467**: 26–42. https://doi.org/10.1016/j.quaint.2016.06.027

Molewski, P., 2014. Paleogeographical conditions of the outflow from the Warsaw ice-dammed lake through the Bachorza valley and the Warsaw-Berlin pradolina during the main stage of the Weichselian Glaciation. Landform analysis, **25**: 105–114. https://doi.org/10.12657/landfana.025.009

Myślińska, E., 2001. Grunty organiczne i laboratoryjne metody ich badania (in Polish). PWN, Warszawa.

Nalepka, D., Walanus, A., 2003. Data processing in pollen analysis. Acta Palaeobotanica, **43**: 125–134.

Niska, M., 2012. Fossil Cladocera remains in the Eemian sediments – preservation, frequency and dominant species. Studia Quaternaria, **29**: 31–43.

Niska, M., Roman, M., 2014. Development of the Kubłowo palaeolake, central Poland, during the Eemian interglacial as against subfossil Cladocera analysis – preliminary results. Studia Quaternaria, **31**: 31–37. https://www.doi.org/10.2478/squa-2014-0003

Piechocki, A., 1979. Mięczaki (Mollusca). Ślimaki (Gastropoda) (in Polish). Fauna słodkowodna Polski, z. 7. Zakład Biologii Rolnej PAN, Poznań: 7–173.

Piechocki, A., Wawrzyniak-Wydrowska, B., 2016. Guide to Freshwater and Marine Mollusca of Poland. Bogucki Wydawnictwo Naukowe, Poznań.

Pidek, I.A., Zalat, A.A., Hrynowiecka, A., Żarski, M., 2021. A high-resolution pollen and diatom record of mid- to late-Eemian at Kozłów (Central Poland) reveals no drastic climate changes in the hornbeam phase of this interglacial. Quaternary International, **583**: 14–30. https://doi.org/10.1016/j.quaint.2021.02.032

Pidek, I.A., Poska, A., Hrynowiecka, A., Brzozowicz, D., Żarski, M., 2022. Two pollen-based methods of Eemian climate reconstruction employed in the study of the Żabieniec-Jagodne palaeolakes in central Poland. Quaternary International, **362**: 21–35. https://doi.org/10.1016/j.quaint.2021.09.014

Rioul, P., Andrieu-Ponel, V., Rietti-Shati, M., Batterbee, R.W., de Beaulieu, J.-L., Cheddadi, R., Reille, M., Svobodova, H., Shemesh, A., 2001. High resolution record of climate stability in France during the last interglacial period. Nature, **413:** 293–296.

Roman, M., Mirosław-Grabowska, J., Niska, M., 2021. The Eemian Lakeland of the central Polish Plain: environmental changes and palaeogeography. Palaegeography, Palaeoclimatology, Palaeoecology, **561**: 110087. https://doi.org/10.1016/j.palaeo.2020.110087

Sánchez-Goñi, M.-F., Loutre, M.F., Crucifix, M., Peyron, O., Santos, L., Duprat, J., Malaizé, B., Turon, J.L., Peypouquet, J.-P., 2005. Increasing vegetation and climate gradient in Western Europe over the Last Glacial Inception (122–110 ka): data-model comparison. Earth and Planetary Science Letters, **231:** 111–130. https://doi.org/10.1016/j.epsl.2004.12.010

Schokker, J., Cleveringa, P., Murray, A., 2004. Palaeoenvironmental reconstruction and OSL dating of terrestrial eemian deposits in the southeastern Netherlands. Journal of Quaternary Science, **19**: 193–202.

Seppä, H., Birks, H.J.B., Odland, A., Poska, A., Veski, S., 2004. A modern pollen–climate calibration set from northern Europe: developing and testing a tool for palaeoclimatological reconstructions. Journal of Biogeography, **31**: 251–267.

Shackleton, N.J., Chapman, M., Sánchez-Goñi, M.-F., Pailler, D., Lancelot, Y., 2002. The classic marine isotope substage 5e. Quaternary Research, **58**: 14–16. https://doi.org/10.1006/qres.2001.2312

Solon, J., Borzyszkowski, J., Bidłasik, M., Richling, A., Badora, K., Balon, J., Brzezińska-Wójcik, T., Chabudziński, Ł., Dobrowolski, R., Grzegorczyk, I., Jodłowski, M., Kistowski, M., Kot, R., Krąz, P., Lechnio, J., Macias, A., Majchrowska, A., Malinowska, E., Migoń, P., Myga-Piątek, U., Nita, J., Papińska, E., Rodzik, J., Strzyż, M., Terpiłowski, S., Ziaja, W., 2018. Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica, **91**: 143–170. https://doi:10.7163/GPol.0115

Stachowicz-Rybka, R., Korzeń, K., 2014. Rozwój roślinności w późnym vistulianie oraz funkcjonowanie i zanik ekosystemu leśnego w stanowisku Koźmin Las (in Polish). Acta Geographica Lodziensia, **102**: 53–63.

Suchora, M., Kultys, K., Stachowicz-Rybka, R., Pidek, I.A., Hrynowiecka, A., Terpiłowski, S., Łabęcka K., Żarski, M., 2022. Palaeoecological record of long Eemian series from Kozłów (Central Poland) with reference to palaeoclimatic and palaeohydrological interpretation. Quaternary International, **632**: 36–50. https://doi.org/10.1016/j.quaint.2022.02.022

Święta-Musznicka, J., Latałowa, M., Szmeja, J., Badura, M., 2011. *Salvinia natans* in medieval wetland deposits in Gdańsk, northern Poland: evidence for the early medieval climate warming. Journal of Paleolimnology, **45**: 369–383. https://doi.org/10.1007/s10933-011-9505-1

Talbot, M.R., Laerdal, T., 2000. The Late Pleistocene–Holocene paleolimnology of Lake Victoria, East Africa, based upon elemental and isotopic analyses of sedimentary organic matter. Journal of Paleolimnology **23:** 141–164.

Tarasov, P., Granoszewski, W., Bezrukova, E., Brewer, S., Nita, M., Abzaeva, A., Oberhänsli, H., 2005. Quantitative reconstruction of the Last Interglacial vegetation and climate based on the pollen record from Lake Baikal, Russia. Climate Dynamics, **25**: 625–637.

Väliranta, M., Salonen, J., Heikkilä, M., Amon, L., Helmens, K., Klimaschewski, A., Kuhry, P., Kultti, S., Poska, A., Shala, S., Veski, S., Birks, H.H., 2015. Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe. Nature Communications, **6**: 6809. https://doi.org/10.1038/ncomms7809

Velichko, A.A., Bogucki, A.B., Morozova, T.D., Udartsev, V.P., Khalcheva, T.A., Tsatskin, A.I., 1984. Periglacial landscapes of the East European Plain. In: Late Quaternary Environments of the Soviet Union (eds. A.A. Velichko, H.E. Wright Jr. and C.W. Barnosky): 94–118. University of Minnesota Press, Minneapolis.

Welter-Schultes, F., 2012. European non-marine molluscs, a guide for species identification. Planet Poster Editions, Goettingen.

Zagwijn, W.H., 1983. Sea-level changes in the Netherlands during the Eemian. Geologie en Mijnbouw, **62**: 437–450.

Zagwijn, W.H., 1996. An analysis of Eemian climate in western and central Europe. Quaternary Science Reviews, **15**: 451–469.https://doi.org/10.1016/0277-3791(96)00011-X

Zalat, A.A., Bober, A., Pidek, I.A., Żarski, M., 2021. Environmental and climate change during the Late Saalian–Eemian Interglacial at the Struga site (Central Poland): a diatom record against the background of palynostratigraphy. Review of Palaeobotany and Palynology, **288**: 104386. https://doi.org/10.1016/j.revpalbo.2021.104386

Żarski, M., 2002. Pleistocene river valleys and ice sheet limits in the Southern Mazovian Lowland, central Poland. Geological Quarterly, **46** (2): 147–163.

Żarski, M., 2020. Szczegółowa Mapa Geologiczna Polski w skali 1: 50 000, ark. Garwolin (566) (in Polish). Państwowy Instytut Geologiczny – PIB, Warszawa.