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Organic shales in some Polish Eemian deposits: the case study of the Srebrna palaeolake

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Lacustrine Eemian Interglacial deposits are widely preserved in Poland, mainly beyond the maximum extent of the Vistula Glaciation. In some profiles, specific deposits are present, characterized by a black colour, a very high amount of organic matter and very hard shale-like texture. We describe these organic shales from a newly located occurrence, the Srebrna site (N Mazovia). The presence of fossil aquatic plants including algae suggests that these shales formed in shallow, eutrophic lakes that were gradually overgrown and/or transforming into peat bogs. The organic-rich sediments were subjected to repeated drying and compaction, leading to the formation of these hard, shale-like layers. No clear correlation was found between the occurrence of these deposits and the lithology of the overburden and underlying strata. The formation of these shales is also not dependent on the thickness of, and hence compactional pressure exerted by, the deposits overlying them. This particular lithology is not restricted to one time interval, but global factors occurring in the E5 zone of the Eemian Interglacial may have contributed to water level fluctuations at many locations. This suggests that factors such as short-term drainage and flooding cycles may have influenced the formation of these organic shales.

Key words: Eemian Interglacial (MIS 5e), Płońsk Upland, organic shale, water level changes, pollen analysis, geochemical analysis.

INTRODUCTION

The lake sediments that accumulated during the Eemian Interglacial (MIS 5e) are very important for environmental studies. Eemian data allow the tracking of climate changes influenced solely by natural factors, devoid of human impacts. The resulting lake-peat bog deposits have been crucial to investigations of the entire cycle of the formation, development and disappearance of postglacial lakes. The formation of lakes and subsequent accumulation of lacustrine sediments on the Polish Plain as well as the European Plain were associated with the retreat of the ice sheet of the Warta Glaciation (Saalian) (Mamakowa, 1988; Roman et al., 2021). As a consequence of deglaciation, lake districts developed, in which sediments accumulated in postglacial lakes. Therefore, sequences with palynologically documented deposits from the Eemian Interglacial are found in the area between the maximum extents of the Warta and the last – Vistula Glaciation (Bruj and Roman, 2007; Roman et al., 2021).

Typically, the lake sedimentary profile begins with mineral deposits (sands and silts) at the bottom, followed by calcareous-detritus (in varying proportions) gyttja and organic silts, overlain by peat. Locally, this lithological sequence is interbedded with lake marl, or interrupted by erosional sandy layers. In some Eemian profiles, a specific additional organic layer is noted, sometimes called “organic shales”. These deposits are characterized by a black colour, a very high amount of organic matter and very high hardness like that observed in lithified shales. They are often associated with a palynologically documented hiatus. Organic shales from the Eemian Interglacial have been identified in numerous sites across Poland, including, Horoszki Duże, Nadolnik, Solniki, Choroszczewo, Kubłowo, Ustków, Kozłów (Fig. 1; Granoszewski, 2003; Krupiński, 2005; Kupryjanowicz, 2008; Roman and Balwierz, 2010; Kołaczek et al., 2016; Pidek et al., 2021; Suchora et al., 2022) and Gołków (Gadomska, 1966). The authors of more recent studies described these deposits as organic shales or bituminous shales (Gadomska, 1966; Granoszewski, 2003; Kupryjanowicz, 2008; Kołaczek et al., 2012), peaty shales, slate gyttja (Krupiński, 2005) or gyttja-shales (Pidek et al., 2021; Suchora

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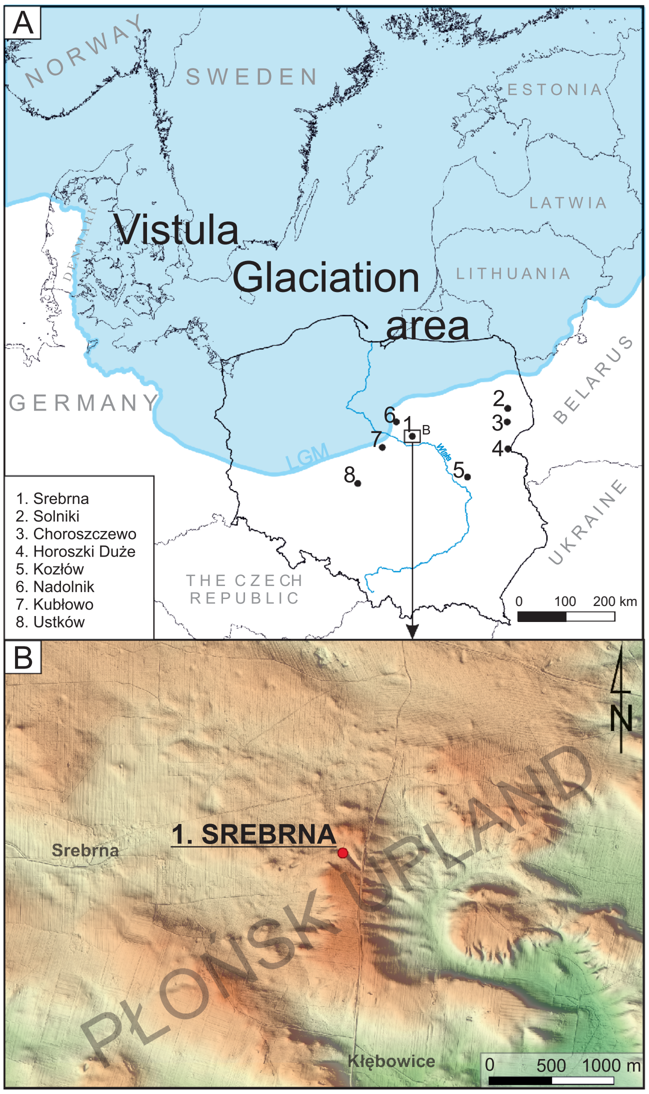


Fig. 1. Location of the research area on A – on the map of Europe with the Last Glacial Maximum (LGM) indicated (Marks et al., 2016); B – Digital Terrain Model (NMT) at 1:20,000 scale (source: Geoportal)

et al., 2022) and refered to them as *substantia humosa* according to the Troels-Smith description (Granoszewski, 2003; Kupryjanowicz, 2008). Apart from the Gołków site, no information regarding the bitumen content has been obtained from these locations.

Among the many scientific studies on the Eemian Interglacial in other countries, we have found one description of similar deposits. Only Müller et al. (2003) described the lithology of one layer from the Füramoos site as "dark brown foliated, strongly compacted fine detritus mud", which is probably similar to organic shales. The many studies of the Eemian terrestrial deposits usually focus on the evolution of the vegetation and reconstructions of climatic parameters (e.g., Klotz et al., 2004; Borisova et al., 2007; Helmens et al., 2015). Geological/lithological aspects of the Eemian deposits are often neglected.

The newest locality of Eemian Interglacial deposits containing organic shales was found at the Srebrna site in northern Mazovia (Sieradz and Rychel, 2023; Fig. 1). Here, we describe results of palynological and geochemical analyses of these deposits, with particular attention to the occurrence of organic shales. Our main questions were: are Eemian profiles with organic shales associated with a common sedimentary sequence? Were they created at the same time or in different periods? What conditions favoured the formation of these deposits? For comparison, we analysed other sites with such shales to determine whether such deposits are a common or a unique phenomenon. To constrain their origin, we examined the lithological conditions and palynological zones in which these shales occur.

GEOLOGICAL SETTING AND STUDY AREA

The Srebrna palaeolake (52°29'29.7''N 20°12'11.6''E) is situated on the Płońsk Upland (Kondracki, 2009; Solon et al., 2018), ~2 km east of the village of Srebrna and ~11 km north of the city Czerwińsk nad Wisłą in central Poland, at an elevation of 146.5 m a.s.l. (Fig. 1).

The deposits studied were identified in an elongated depression with an east-west orientation, situated within kame hills on the moraine plateau of the Warta Glaciation (Saalian) (Fig. 1; Krawczyk and Pochocka-Szwarc, 2021). During the updating of the Detailed Geological Map of Poland (SMGP) sheet in Czerwińsk nad Wisłą, organic deposits were discovered at this location (Krawczyk and Pochocka-Szwarc, 2021). Several samples were collected for palynological analysis, which confirmed their age as belonging to the Eemian Interglacial (Winter, 2016).

The study area was not affected by the Vistula Glaciation (MIS 5d-a, MIS 4-3). The front of the maximum range (LGM) of the last glacial (Vistula Glaciation) is situated ~40 km west and 105 km north of the site (Marks et al., 2016). Two other recently identified sites with Eemian Interglacial (MIS 5e) deposits are located ~46 km north-northwest: Stara Maryśka II (Rychel et al., 2022) and Białe Błota (Sieradz et al., 2024). However, no occurrences of organic shale were observed at these locations.

REFERENCE SITES

A number of peat bog sediment sites in Poland have been analysed lithologically, revealing the presence of organic shales, as published (see below) and illustrated here in Figure 1. Organic shales have been identified at sites including:

– Solniki (Kupryjanowicz, 2008; Mirosław-Grabowska et al., 2015; Niska, 2015, 2016);
– Choroszczewo (Kupryjanowicz, 2008; Kupryjanowicz et al., 2015);
– Otapy 1 and Otapy 2 (Bitner, 1956; Kupryjanowicz, 2008);
– Horoszki Duże (Bitner, 1954; Granoszewski, 2003);
– Kubłowo (Roman and Balwierz, 2010; Mirosław-Grabowska et al., 2018; Roman et al., 2021);
– Nadolnik (Krupiński, 2005);
– Ustków (Kołaczek, et al., 2012, 2016);
– Besiekierz (Janczyk-Kopikowa, 1991; Mirosław-Grabowska and Niska, 2005);
– Warszawa-Wawrzyszew (Krupiński and Morawski, 1993);
– Kuców IIc (Niska, 2012, 2015; Balwierz, 2017);
– Jagodne (Bober et al., 2021);
– Kozłów (Pidek et al., 2021; Suchora et al., 2022);
– Mikorzyn (Stankowski and Nita, 2004);
– Sławno I and Sławno II (Tołpa, 1961);
– Gołków (Gadomska, 1966; Jańczyk-Kopikowa, 1966);
– Moczydło II, Rogów, Faustynów (Mamakowa, 1989);
– Białynin (Borówko-Dłużakowa, 1973);

The sites marked in Figure 1 were chosen based on lithological descriptions made during palynological studies. The intervals of accumulation of the organic deposits, according to RPAZ, in conjunction with the location of the shale layers within the lithological successions of the sites, is illustrated schematically in Figure 2. The sites selected were those with recent and detailed palynological analyses. The remaining sites were analysed many years ago and it is challenging to correlate them with modern data, as they commonly lack sufficiently detailed palynological information.

The Solniki palaeolake is located ~18 km south of Białystok in NE Poland (no. 2, Fig. 1), and has an 11 metre thick lake sedimentary sequence that has been analysed for pollen, Cladocera, diatoms, and geochemistry (Kupryjanowicz et al., 2005; Kupryjanowicz, 2008; Niska, 2015, 2016; Mirosław-Grabowska et al., 2015). The original lithological profile is based on the work of Kupryjanowicz (2008) and begins with black organic silt (11.00–11.10 m) covered by black clayey peat (10.60–11.00 m). Overlying these are black organic silt (10.00–10.60 m), brown and brown-black organic clayey silt (5.60–10.00 m) and organic silt with sand (3.90–5.60 m). This is followed by dark grey peaty silt (3.00–3.90 m) and dark grey silt (2.00–3.00 m) overlain by yellow fine and medium sand and grey soil (0.00–2.00 m). In some other publications (Kupryjanowicz et al., 2005; Niska, 2015; Mirosław-Grabowska et al., 2015), the description of the core has been modified and shale layers are unambiguously present. In the present study, the part of the lithological profile from the Solniki site included in the Mirosław-Grabowska et al. (2015) papers was used to compare the profiles, to obtain the following succession: gyttja (8.10–9.90 m) overlain by laminated silt with shale (7.45–8.10 m), shale (7.00–7.45 m), laminated silt (6.65–7.00 m), shale (6.40–6.65 m) and laminated silt (5.70–6.40 m) (Fig. 2).

The Choroszczewo palaeolake is situated ~25 km SW of Bielsk Podlaski in eastern Poland (no. 3, Fig. 1). A 9 metre thick profile was analysed palynologically (Kupryjanowicz, 2008; Kupryjanowicz et al., 2015); part of the core description was reconstructed after Kupryjanowicz (2008). At a depth of 7.20–7.90 m lies grey-green organic silt overlain by black-brown *substantia humosa* (6.20–7.20 m). Above this is grey organic silt with *substantia humosa* (5.35–6.20 m), weakly decomposed brown-black peat (5.30–5.35 m), and grey-brown organic silt with *substantia humosa* (5.00–5.30 m). The next layer is fine sand, light grey with organic matter (4.85–5.00 m). Another layer with *substantia humosa* is at a depth of 3.80–4.85 m (organic silt, black, grey-brown, dark grey) and is covered by yellow sand (3.75–3.80 m). Another layer of organic silt with *substantia humosa* is found at a depth of 2.70–3.75 m. The last

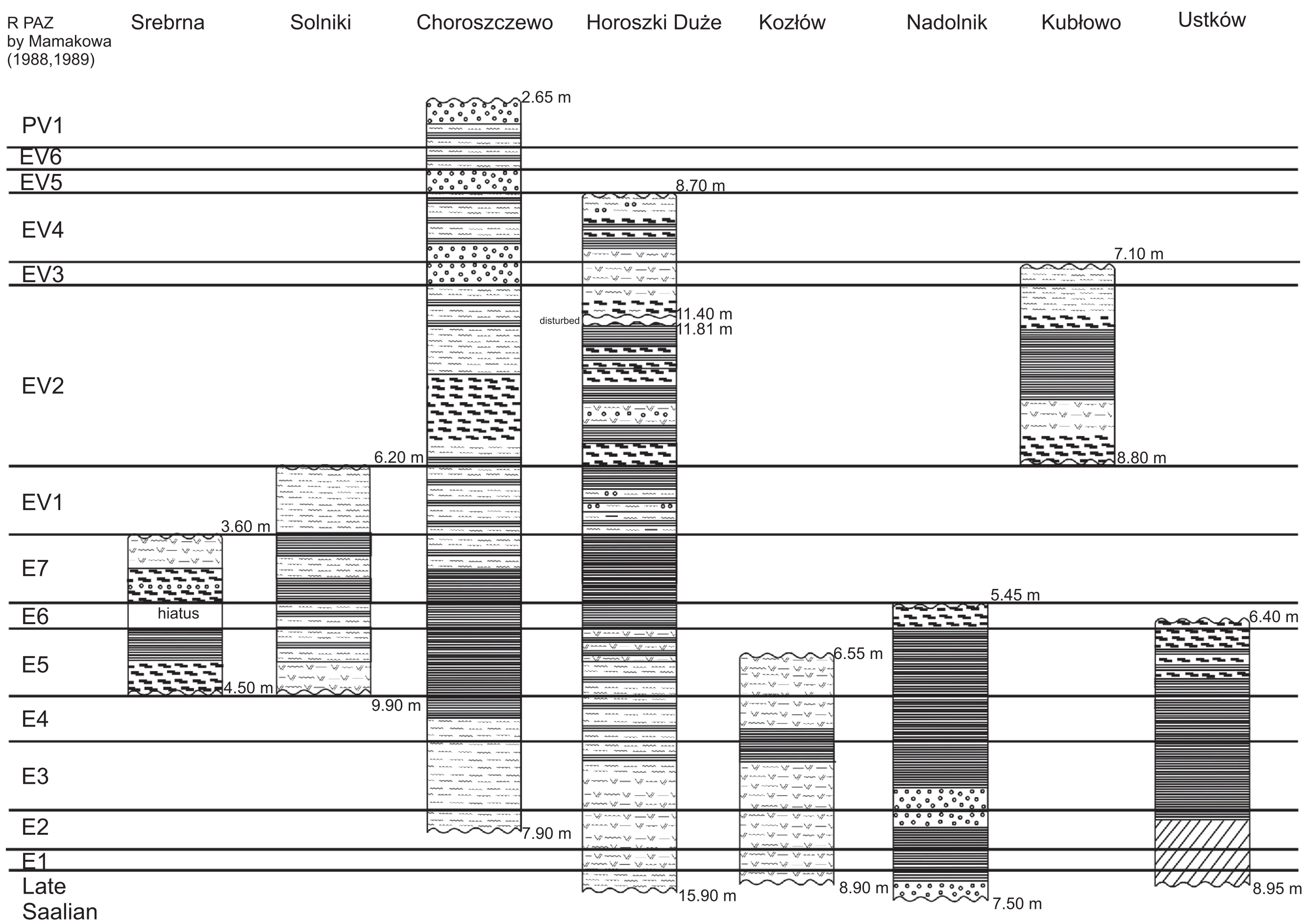


Fig. 2. The occurrence of organic shales shown in relation to the stratigraphic division distinguished by Mamakowa (1988, 1989) on parts of the lithological profiles of selected sites

The thickness of the layers and the elevation of each profile are not to a common scale; the thickness of the palynological zones varies, reflecting the lithological variability observed in individual profiles; gyttja-shale has been described as a shale; the lithological description is shown in Figure 3 layer of organic silt with *substantia humosa* is covered by fine medium yellow sand (2.65–2.70 m) (Fig. 2).

The Horoszki Duże palaeolake is located ~25 km NNW of Biała Podlaska in eastern Poland (no. 4, Fig. 1). An almost 16-metre long core of lake deposits was drilled and palynologically analysed by Granoszewski (2003). The lowest part (depths of 15.33–15.90 m) consists of olive-grey calcareous silt with gyttja overlain by silty calcareous gyttja. Another layer is organic dark grey and black silts with *substantia humosa* at depths of 14.30–15.33 m. At depths of 14.02–14.30 m there is grey silty calcareous gyttja with *substantia humosa* and at depths 13.48–14.02 m there is a layer of *substantia humosa*. Above this (12.98–13.48 m) there are dark grey and black clayey silts and sandy silts. In a section at a depth of 12.84–12.98 there is sandy silt with *substantia humosa*. At 11.81–12.84 m, the layers of *substantia humosa* are separated by layers of dark brown peat (12.60–12.63 m), black sandy silty gyttja (12.20–12.50 m), brownish-yellow peat (11.93–12.02 m) and black peat with *substantia humosa* (11.86–11.93 m). At a depth of 11.40–11.81 m, the deposits were disturbed during drilling. Black silty peat (10.40–11.40 m) and dark grey clayey gyttja (9.60–10.40 m) overlie the discontinuity. The last layer of *substantia humosa* is at the depth 9.50–9.60 m and it is overlain by black peat with *substantia humosa* (9.10–9.50 m) and black organic silt (8.70–9.10 m) (Fig. 2).

Bitner (1954) published the findings from the Horoszki profile, detailing levels of bituminous shale that occur at depths similar to the *substantia humosa* described by Granoszewski (2003) in a new profile from the same site. Consequently, in this article the authors treat the *substantia humosa* in Choroszczewo (Kupryjanowicz, 2008; Kupryjanowicz et al., 2015) and Horoszki Duże (Granoszewski, 2003) as a shale layer. Moreover, in these profiles, where the description indicated *substantia humosa* (Sh) exceeding 1, it was suggested that these deposits might exhibit shale-like characteristics or contain minor shale layers.

The Kozłów palaeolake is located in central Poland, ~14 km NE from Garwolin Plain (no. 5, Fig. 1). An almost 11 metre long profile was analysed for palynology, diatoms and macrofossils (Pidek et al., 2021; Suchora et al., 2022). Dark olive grey gyttja-shales appear at a depth of 7.80–8.55 m above the layer of gyttja in the bottom part, which is brown and clayey. Above this layer brown peaty gyttja occurs (7.55–7.80 m), which is overlain by olive grey gyttja, with visible lamination (6.55–7.55 m) (Fig. 2).

The Nadolnik palaeolake is located ~6 km NE of Sierpc in central Poland (no. 6, Fig. 1). An >8 metre-long profile was analysed palynologically by Krupiński (2005). Below organic shale, grey fine and medium-grained sands with organic matter occur (6.70–6.78 m). Organic shales (grey, grey-brown, brown) appear at a depth of 6.10–6.70 m. They are overlain by well-decomposed grey-brown peat (5.45–6.10 m) and well-decomposed grey-brown and grey peat with an admixture of sand in its upper part (4.90–5.45 m) (Fig. 2).

The Kubłowo palaeolake is located ~23 km from Kutno in central Poland (no. 5, Fig. 1). A 14.5 metre-long profile was analysed for palynology, Cladocera and geochemistry (Roman and Balwierz, 2010; Mirosław-Grabowska et al., 2018). Brownish-black peat, loamy at the bottom (8.20–8.75 m) is overlain by greyish-brown silty gyttja from depth 8.00–8.20 m. This is succeeded by brownish-black organic shales (7.45–8.00 m) overlain by strongly decomposed dark brown peat (7.37–7.45 m) and silt (7.10–7.37) (Fig. 2).

The Ustków palaeolake is located in central Poland ~55 km W from Łódź (no. 7, Fig. 1). An 11 metre-long profile was analysed for palynology, macrofossils and geochemistry (Kołaczek et al., 2016). Organic shales appear at a depth of 7.25–8.20 m above a layer of bluish-grey mineral loam and brownish-black organic loam (8.20–8.95 m). Above this occurs moss peat compacted into shale (7.18–7.25 m) overlain by reddish-brown moss peat (5.35–7.18 m) (Fig. 2).

MATERIAL AND METHODS

FIELDWORK

Drilling at the Srebrna site was conducted using a GEOPROBE geotechnical rig to obtain a core with an intact structure. The drilling was carried out in the centre of the depression (Fig. 1). The total length of the obtained core was 6.0 m. Unfortunately, due to technical problems, it was not possible to drill through the full sequence of lacustrine deposits. The lithological profile is described in Figure 3.

LITHOLOGICAL ANALYSIS

The characteristics of the sediments were identified and their sedimentary environments and post-sedimentary transformations were reconstructed. The thickness and types of contact between the units, as well as texture and structure of deposits, were analysed, to include macroscopic recognition of sedimentary structures and structural features, using the lithofacies code proposed by Miall (1977, 1985) and modified by Zieliński and Pisarska-Jamroży (2012).

POLLEN ANALYSIS

Samples for pollen analysis were taken every 3–10 cm from the 1.6–6.0 m depth interval. Sampling resolution was determined based on the lithology. A total of 3 cm^3 was extracted from 38 samples (1.645–4.05 m depth), while 1 cm^3 was extracted from 38 samples (4.10–5.98 m depth) for chemical preparation. The material selected for palynological analysis included silt, gyttja and peat. The samples were prepared in the laboratory according to the standard palynological preparation procedure, which includes treatment with 7% hydrochloric acid (HCl), 10% potassium hydroxide (KOH), density separation methods to separate the mineral and organic fractions, and the modified Erdtman's acetolysis (Faegri et al., 1989). The heavy liquid used in the process was zinc chloride ($ZnCl_2$, density 2.1 g/cm^3). The macerates were secured by addition of a single drop of anhydrous glycerine. A pellet of *Lycopodium* spores was added to all samples (Stockmarr, 1971). For samples with a volume of 3 cm^3, the number of spores was multiplied by three.

Microscopic preparations were analysed using a *Zeiss Axioscope* microscope at 40x magnification. Palynological slides were prepared from each sample using glycerine. A total of 500 pollen grains of tree, shrub and herbaceous plants were counted in all samples. All pollen and spores were identified by using taxonomic keys (e.g., Moore et al., 1991; Reille, 1992; Beug, 2004). In addition, the number of algae belonging to the genera *Pediastrum*, *Tetraedron,* and spores were also recorded for each sample.

GEOCHEMICAL ANALYSIS

Geochemical analyses of 92 samples from depths of 0.25–5.98 m included determination of total organic carbon (TOC), selected metals (Al, K, Ca, Mg, Fe, Mn, Cu, Zn) and P content determinations. All the geochemical analyses of the samples were carried out at the Regional Research Centre for Environment, Agricultural and Innovative Technologies, John Paul II University of Applied Sciences in Biała Podlaska. Samples for geochemical analysis were mineralized in a closed microwave reaction system using *Anton Paar Multiwave PRO* with concentrated HCl and HNO_3 (3:1). Mineralized samples were analysed using an ICP OES spectrometer (*SPECTROBlue*). Operating parameters for the ICP OES instrument were: coolant flow: 12 l/min; auxiliary flow: 0.90 l/min; nebulizer flow: 0.78 l/min.; pump speed: 30 rpm; number of measurements: 3. Standards used: *Bernd Kraft Der Standard Spectro Genesis* ICAL *Solutions* and VHG *SM68-1-500 Element Multi Standard 1* in 5% HNO_3.

RESULTS

LITHOLOGICAL DATA

Two depositional units were identified in the 6 m profile studied (Fig. 3).

Unit S-1 (2.93 m thick) occurs in the lower part of the sequence and comprises alternating layers of sandy gyttja, sandy gyttja and sandy with gravel (ST(G)/Gy), organic gyttja (Gy), peaty gyttja (GyP), peat (P), sandy silt (STm) with organic matter and gyttja again. Peat/organic shale, occurs at depths: 5.95–6.0 m and 4.35–4.45 m (Fig. 3). Pollen analysis showed that this-section was disturbed during drilling, these intervals originating from the higher part of the profile. The first undisturbed sedimentary layer (depth 4.55–5.55 m) consists of highly compressed organic gyttja (HCl-), followed by 5 cm of peaty gyttja, 5 cm of peat, and a 10 cm layer of organic shale. Above these lies peat (depth 3.60–4.35) with a 10 cm layer of fine sands with organic material at a depth of 4.00–4.10 m. The next layer comprises organic gyttja (HCl-) (depth 3.07–3.60 m).

Unit S-2 (3.07 m thick) begins with massive sandy silt (TSm) at a depth of 1.65–3.07 m. At a depth of 1.50–1.65 m medium sands with gravel S(G)m appear, followed by massive clayey sands (FSm) (depth 1.00–1.50 m). The unit concludes with a 1.00 m layer of silty sands (ST) (Fig. 3).

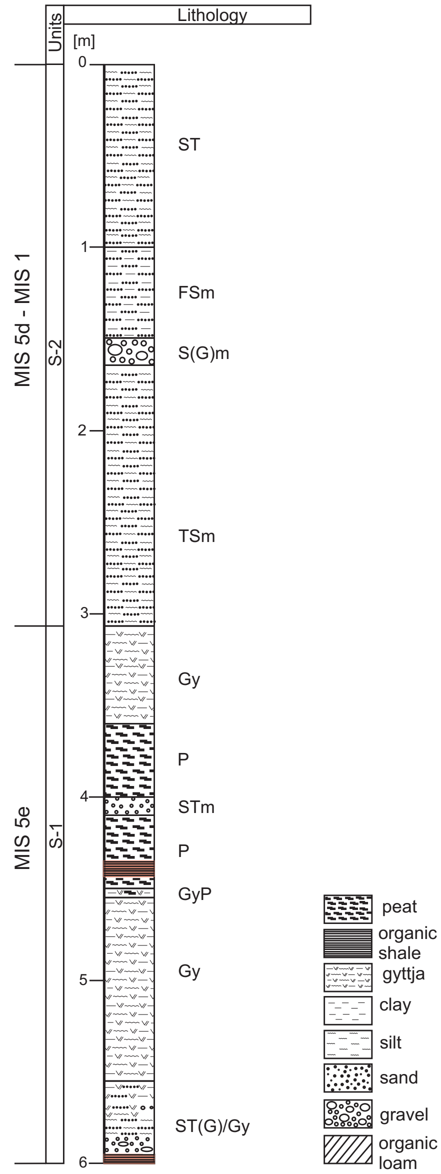


Fig 3. Lithological log from Srebrna site

The red shading indicates the presence of shales in the profile

POLLEN DATA

The palaeolake deposits at Srebrna site were dated by means of pollen analysis. Six Local Pollen Assemblage Zones (LPAZ) were distinguished in the profile (Sr-1 LPAZ–Sr-6 LPAZ).

The results of the palynological analysis are shown in Table 1 and as a percentage pollen diagram in Figure 4. The diagram was generated using the *POLPAL* software (Nalepka and Walanus, 2003). The basis for the percentage calculation includes pollen grains of trees and shrubs (AP) and terrestrial herbaceous plants and dwarf shrubs (NAP) (Nalepka and Walanus, 2003). In addition to the pollen grains, other microfossils were counted in the samples, including aquatic plants, colonies of *Pediastrum* algae, and spores of Filicales monolete. These were then calculated in relation to the basic sum. The percentage pollen diagram was divided into six Local Pollen Assemblage Zones (LPAZs). The zonation was created on the basis of changes in the pattern of the curves. The division criteria were based on the principles defined by West (1970), Birks (1973) and Jańczyk-Kopikowa (1987). Each level is identified by the first two letters of the position name and its name is based on the names of the taxa that are quantitatively dominant or that are specific to a given level. Local zones were assigned to Regional Pollen Assemblage Zones according to the methodology described by Mamakowa (1988, 1989) and detailed by Kupryjanowicz and Granoszewski (2018).

GEOCHEMICAL DATA

Based on the variations in the chemical composition of sediments five main geochemical zones (GZ-1–GZ-5) were distinguished (Table 2 and Fig. 5).

Table 1

Description of Local Pollen Assemblage Zones (LPAZs) distinguished in the Srebrna profile

Regional Pollen Assemblage Zone according to Mamakowa (1989)		Local pollen Assemblage Zones	Depth [m]	Main features of Local Pollen Assemblage Zones
EV2		Sr-6 *Betula-Artemisia*	1.65–1.78	In this zone the *Betula* pollen reaches maximum values of 60%. The curves of *Betula nana* t., *Artemisia* and Asteraceae also show small peaks. The Poaceae curve drops sharply to 5%. *Pediastrum* and *Tetraedron* disappear from the record, but *Botryococcus* appears more frequently and reaches maximum values of 33%.
EV1		Sr-5 Poaceae-Cyperaceae-*Artemisia*	1.78–3.05	Absolute dominance of NAP values up to 75% is observed. Poaceae and *Artemisia* pollen values constantly grow. In the middle of the zone, the share of Cyperaceae starts to decrease. Pollen grains of *Thalictrum, Ranunculus arctis t.,* Asteraceae, Rubiaceae are recorded throughout the zone. At the beginning the curve of *Pediastrum* rises rapidly and reaches maximum values of 80% in the middle of the zone, and the curve of *Tetraedron* behaves similarly. From the aquatic plants *Myriophyllum spicatum* appears in the middle of the zone. *Sphagnum* spores disappear almost completely at the beginning of the zone. A constant curve is observed for *Botryococcus*.
E7	E7c	Sr-4 *Pinus*-NAP	3.05–3.85	*Pinus* values decrease gradually, while Poaceae, Cyperaceae increase faster. The *Salix, Betula nana, Juniperus* and *Calluna* curves are almost continuous. *Artemisia* and Chenopodiaceae appear together with a number of other herbaceous plants such as *Saxifraga*, *Potentilla* or Caryophyllaceae. For the first time *Pediastrum* and *Tetraedron* appear more frequently, forming a constant curve. *Sphagnum* spores are also noted. The NAP values increase constantly and reach 45% at the end of the zone.
	E7b	Sr-3 *Pinus*	3.85–4.34	After a rapid increase in the previous zone, *Pinus* pollen becomes a dominant taxon. *Betula* values also increase and reach 4–5%. Thermophilic taxa such as *Carpinus, Corylus* have almost completely disappeared from the record. *Alnus* has two peaks, the second of which reaches 30%. The NAP values start to increase gradually. The curves of Poaceae and Cyperaceae start to increase. *Betula nana t.* and *Juniperus* appear more frequently.
E5	E5c	Sr-2 *Carpinus*	4.34–5.31	Through almost the entire zone, *Carpinus* values remain constant at ~55%. Only at the beginning is there a small peak of up to 70% and at the end of the zone its values drop sharply to ~1%. *Corylus* values continue to decrease. At the beginning of the zone, a small peak of *Tilia cordata* and *Fraxinus* is recorded. The *Betula, Quercus, Alnus* and *Abies* curves are continuous and remain at a constant level. At the end of the zone, *Pinus* values increase rapidly up to 80%. *Picea* reaches maximum values of 6%. *Taxus baccata* and *Ulmus* curves are almost continuous. Pollen of *Viscum* and *Hedera helix* are recorded. Among the aquatic plants pollen of *Potamogeton, Nuphar lutea* and *Myriophyllum spicatum* appear.
	E5b	Sr-1 *Carpinus-Corylus*	5.31–5.53	In this zone *Carpinus* pollen dominates, reaching maximum values of 65%. At the beginning of the zone *Corylus* reaches values up to 24%, the highest recorded in the profile. After that its curve starts to decrease rapidly. Pollen of *Picea, Abies, Fraxinus, Ulmus, Tilia cordata, Tilia platyphyllos, Acer* and *Taxus boccata* are present. The NAP values are the lowest in the whole profile (2–5%).
			5.53–6.00	Disturbed sediments

DISCUSSION

CHANGES IN LITHOLOGY IN THE SREBRNA PROFILE

The core from the Srebrna site shows a late part of the Eemian Interglacial biogenic succession (S-1), beneath the clastic deposits of the Vistula Glaciation (S-2). The lithology of the succession analysed is shown in Figure 3.

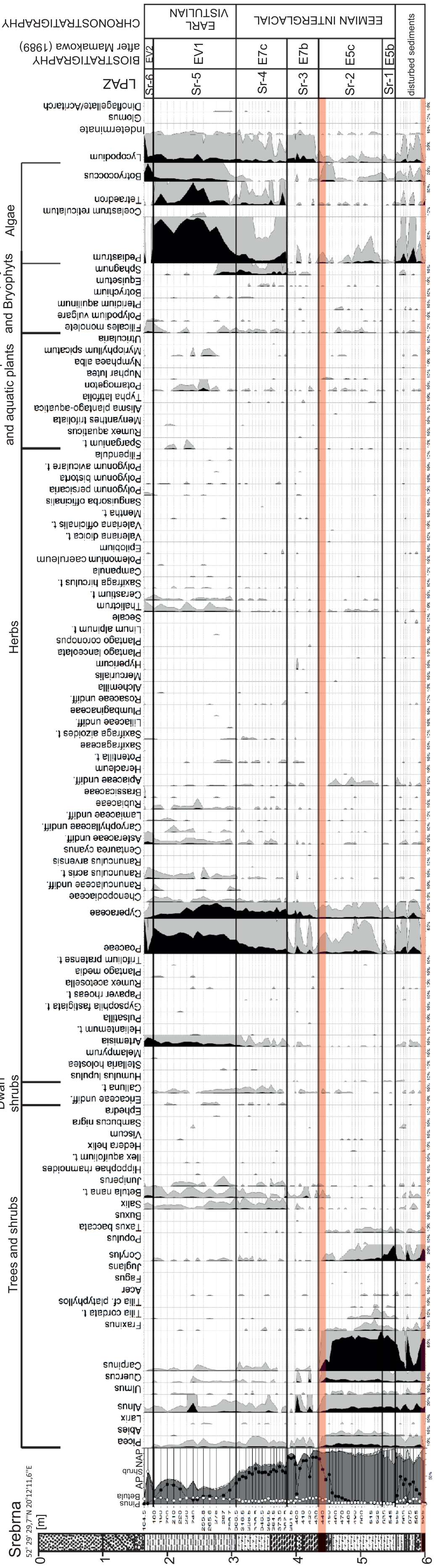
Unit S-1 begins with sands containing gravel and silts at the bottom, representing disturbed sediments. These deposits are overlain by non-calcareous gyttja (corresponding to pollen zone E5). Subsequently, the gyttja is replaced by peat, followed by very hard, compact, organic shales, marking the end of pollen zone E5. This is followed by peat with a thin layer of humic sand (in pollen zone E7). Above this, non-calcareous gyttja reappears, representing the upper gyttja and corresponding to pollen zone E7. In the upper part of the sequence, deposition of this unit concludes with sandy silts and sands, corresponding to pollen zones EV1–EV2.

Unit S-2 begins with sandy silt, which marks the sediments from the onset of the glaciation, deposited in an aquatic environment. Palynological analysis shows that it represents an early stage of the Vistula Glaciation. The appearance of sands with gravel and clayey sands probably reflects slope processes during the Vistula Glaciation (MIS 4–MIS 2). Unit S-2 concludes with silty sands, likely the result of transport and deposition of fine material from the surrounding kame hills in periglacial climate conditions, as also indicated by quartz grain surface textures (Krawczyk and Pochocka-Szwarc, 2021).

BIOSTRATIGRAPHY AND EVOLUTION OF VEGETATION RECORDED IN THE SREBRNA PROFILE

Palynological analysis confirms representation of the Eemian Interglacial and early Vistulian at the Srebrna site.

The pollen succession begins in the Middle Eemian (LPAZ Sr-1 *Carpinus-Corylus*, Fig. 4), though sedimentation in the Srebrna palaeolake began earlier (the profile is incomplete). In the first documented zone *Carpinus* dominates, forming a diverse broadleaved forest alongside with *Tilia, Acer, Picea, Abies* and *Taxus. Corylus* remains an important component of the forest, but gradually gives way to hornbeam towards the end of the zone. A small proportion of herbaceous plant pollen indicates the dominance of forest communities in the landscape around the Srebrna palaeolake. *Alnus*, together with *Fraxinus* and *Ulmus*, may have formed ash-alder riverine forests in less boggy areas, although their low pollen values suggest that these communities may have been rare or at a distance from the Srebrna palaeolake. The climate during the Middle Eemian was very warm and humid, with a strong oceanic influence and



high winter and summer temperatures (Kupryjanowicz, 2008). The presence of *Ilex* and *Hedera* indicates mean January temperatures above 0 and –2°C, and mean July temperatures >+15 and +16°C, respectively (Iversen, 1944; Kupryjanowicz, 2008).

Further changes in the mixed deciduous forest resulted in the absolute dominance of hornbeam (LPAZ Sr-2 *Carpinus*, Fig. 4). *Carpinus* formed almost pure hornbeam stands and successfully displaced hazel from the understorey. The proportion of lime and ash is reduced or even disappears, while there is a slight increase in the presence of oak, spruce, fir, and, towards the end of the zone, pine and birch. The presence of spruce and fir in the tree stands may indicate an increase in precipitation (Granoszewski, 2003). The presence of *Taxus baccata* (Sr-1 to Sr-2 LPAZ) indicates that the mean temperature of the coldest month was not lower than –2°C (Iversen, 1944; Kupryjanowicz, 2008). However, the northern range limit of *Tilia platyphyllos* lies close to the +17°C isotherm of the warmest month (Granoszewski, 2003; Kupryjanowicz, 2008).

Sedges and cattails grew along the edges of the reservoir. The presence of *Nuphar lutea* indicates a rather shallow basin, filled by organic sediments (Podbielkowski and Tomaszewski, 1979; Mamakowa, 1989) corresponding to organic gyttja and peat in the profile.

Towards the end of this zone, a 10 cm layer of organic shale is present, similar to shales found in other Eemian Interglacial profiles from Poland (e.g., Jańczyk-Kopikowa, 1966, 1991; Krupiński and Morawski, 1993; Granoszewski, 2003; Krupiński, 2005; Kupryjanowicz, 2008; Niska, 2012, 2015; Kołaczek et al., 2016; Balwierz, 2017; Roman et al., 2021).

No deposits have been identified in the Srebrna profile that correlate with the E6 zone of the Mamakowa (1988) regional division, this gap possibly reflecting fluctuations in water level that resulted in the formation of the organic shales at the end of the E5 zone and gaps in the palynological record (Sieradz and Rychel, 2023). Kupryjanowicz (2008) proposed that the absence of the E6 *Picea* zone in the profile from northern Podlasie may be correlated with lowered water levels or even the complete drying of some water bodies at the end of the E5 zone. The palynological data from other profiles in Poland, including Główczyn (Niklewski, 1968), Besiekierz (Janczyk-Kopikowa, 1991), and Dziewule (Bińka and Nitychoruk, 2003), also indicate a lowering of the water table in this zone (Kupryjanowicz, 2007). This suggests a general drying tendency at this time. Water level appears to increase once more during the E7 *Pinus* zone (Kupryjanowicz, 2007). The palynological and lithological data from the Srebrna site are consistent with the overall pattern identified by Kupryjanowicz (2005, 2007).

Following an evident hiatus, sedimentation in the basin resumed. The accumulation of peat and the appearance of *Sphagnum* spores indicate peat bog formation. In the pollen spectra, there is a notable reduction in the presence of pollen from all thermophilous trees. *Pinus* is the dominant species, with a minor admixture of *Picea*, forming a boreal pine forest. The record also shows the complete absence of *Abies* in this zone (LPAZ Sr-3 *Pinus,* Fig. 4). The proportion of NAP gradually increases due to the rising share of herbaceous plants. Additionally, there is an increase in the proportion of shrub com-

Fig. 4. Percentage pollen diagram for the Srebrna site

LPAZ 1-6 – Local Pollen Assemblage Zone; AP – arboreal pollen; NAP – non-arboreal pollen; the red shading indicates the presence of organic shales in the profile; for lithology see Figure 3

Table 2

The characteristics of geochemical zones GZ-1–GZ-5 – geochemical content

Zone	Depth [m]	Concentrations of chemical elements
GZ 5b	0.25–0.73	Decrease in Al content to ~7 mg/g; low K content <1 mg/g; very low Ca content of 0.3–0.7 mg/g; constant Mg content of ~0.6 mg/g; low Fe content of ~4 mg/g; very low Mn content <0.1 mg/g; very low Cu content to 5 mg/g (in separate samples); varying Zn content from 4 to 18 mg/g; low constant P content of ~0.3 mg/g; further decrease in TOC to <0.2%
GZ-5 GZ 5a	**0.25–1.20** 0.73–1.20	Firstly decreasing Al amount to 8 mg/g and then increase to 21 mg/g; firstly decrease in K content to 0.9 mg/g and then increase to 2.2 mg/g; low Ca content of 0.4–2.4 mg/g; increasing Mg content from 0.6 to 1.1 mg/g; increasing Fe content to 13 mg/g; increasing Mn content to 0.3 mg/g; Cu content from 0.5 to 12 mg/g (in separate samples); varying Zn content from 5 to 32 mg/g; decreasing P content to 0.4–0.7 mg/g; further decrease in TOC to <0.4%.
GZ-4	**1.20–2.60**	Varying Al content from 7 to 44 mg/g; irregular K content – 0.7–7.4 mg/g; low constant Ca content of <1 mg/g; irregular increase in Mg to <4 mg/g; firstly increase in Fe content to 24 mg/g, then drop to 3 mg/g; varying Mn content to 0.2 mg/g; changing Cu content from 0.5 to 16 mg/g (in separate samples); increasing Zu content to 49 mg/g; increasing P content to 1.7 mg/g; further decrease in TOC to <1%
GZ 3b	2.60–3.85	Increase in Al amount to max. 39 mg/g; increasing K content to 7.4 mg/g; decreasing Ca content to 1.3 mg/g; increasing Mg content to 4.4 mg/g; constant Fe amount of ~16 mg/g; low Mn amount of 0.07–0.16 mg/g; low Cu content to 9 mg/g (in separate samples); increasing Zn content to 64 mg/g; drop in P content to 0.1 mg/g; systematic decrease of TOC from 23 to 1%.
GZ-3 GZ 3a	**2.60–4.27** 3.85–4.27	Firstly decreasing Al amount to 2 mg/g and then increase to 17 mg/g, and again drop to 5 mg/g; firstly decreasing K content to 0.3 mg/g and then increase to 2 mg/g; increasing Ca content to 10 mg/g; decreasing Mg content to 1 mg/g; decreasing Fe content to 7 mg/g and next increase to 13 mg/g; decreasing Mn amount <0.1 mg/g; very low Cu content to 6 mg/g (in separate samples); increasing Zn content to 28 mg/g; a slight increase in P content to 0.5 mg/g; varying TOC from 1 to 53%
GZ-2	**4.27–5.55**	High, constant Al amount of ~37 mg/g; increasing K content to 10 mg/g; quite even Ca content of ~4 mg/g; decreasing Mg content from 6 to 2 mg/g; drop of Fe content from 26 to 10 mg/g; decreasing Mn amount from 0.2 to 0.07 mg/g; varying low Cu content – 3–10 mg/g; increase in Zn content to 70 mg/g; a quite even P content of ~0.3 mg/g; increasing TOC to 38%
GZ-1	**<5.55** sediment disturbed	Al concentration between 17–39 mg/g, varying K content from 2 to 10 mg/g; low Ca content – 1–4 mg/g; high, varying Mg content of 1–6 mg/g; high, varying Fe content – 9–25 mg/g; Mn content of ~1.1 mg/g; Cu content to 8 mg/g; Zn content – 23–71 mg/g; P content of ~0.4 mg/g; decreasing TOC from 40 to 4%

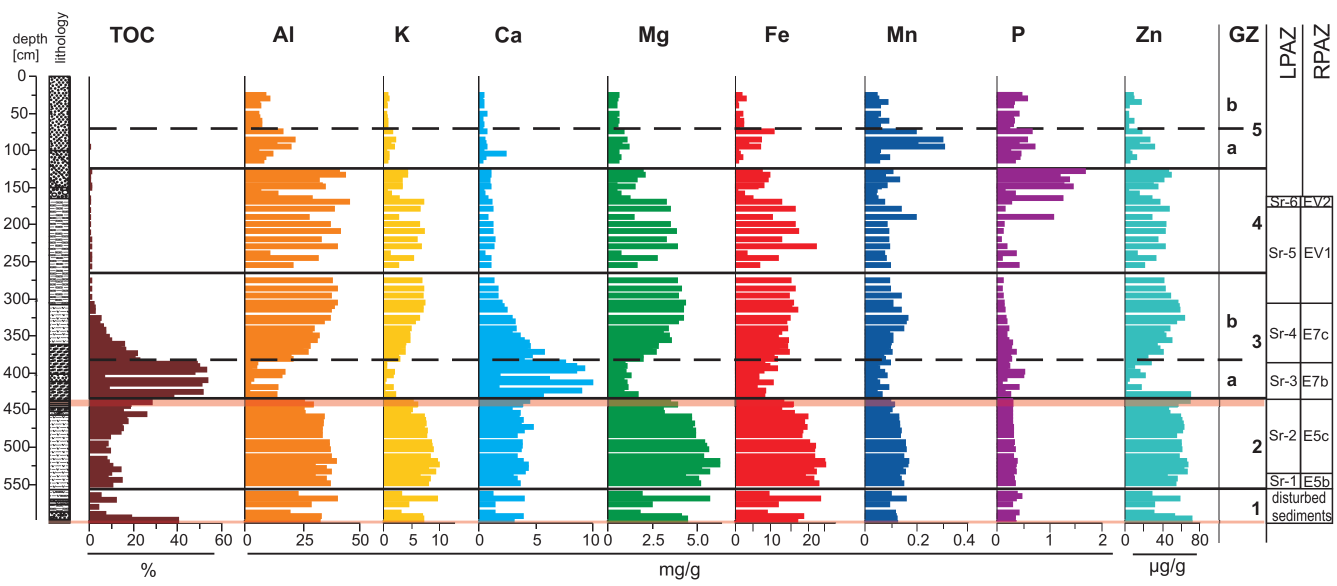


Fig. 5. Results of geochemical analysis of the deposits from the Srebrna site

GZ – geochemical zones, the red shading indicates the presence of shales in the profile; for lithology see Figure 3

munities, reflected in the growing abundance of *Betula nana, Juniperus and Salix* pollen. A rise in water levels and the onset of biogenic sedimentation is indicated at numerous sites representing the Late Eemian (regional zone E7), as documented by Kupryjanowicz (2007, 2008). A similar pattern is observed in Srebrna, where peat accumulations initiated. This change is likely due to an increase in precipitation and a decrease in evaporation, combined with a significant decrease in winter and summer temperatures, indicating a cooling and wetting trend in the climate (Kupryjanowicz, 2008).

A further deterioration in climatic conditions led to a gradual expansion of open habitats and a decline in the abundance of *Pinus* (LPAZ Sr-4 *Pinus*-NAP; Fig. 4). The thinning of the forest areas resulted in improved light conditions and the gradual spread of herbaceous plants, mainly Poaceae, Cyperaceae and *Artemisia*. Wet habitats were occupied by willow thickets, rushes, and sedges, while steppe communities developed, and patches of heathland appeared. At this time the water level in the reservoir rose, as indicated by the appearance of peat followed by gyttja and the appearance of algae of the genera *Pediastrum* and *Tetraedron*.

The trends observed in the sequence of vegetation succession at the end of the Late Eemian suggest a continuous climatic deterioration, shown by a significant decrease in the abundance of *Pinus* and the dominance of NAP values in the Early Vistula Glaciation (LPAZ Sr-5 *Poaceae-Cyperaceae-Artemisia*; Fig 4). Gyttja is replaced by sandy silt, and this change is associated with the disappearance of forest cover and an increasing supply of clastic material. There was a slight increase in *Betula* and *Betula nana* t., but open communities of herbaceous vegetation dominated the landscape.

The vegetation of this period was characterized by the dominance of Poaceae, Cyperaceae, and various species of *Artemisia* and Chenopodiaceae. The diversity of taxa recorded at this time indicates the prevalence of open habitats. The abundant occurrence of *Pediastrum* in the reservoir may indicate eutrophic conditions in the lake at that time, while the presence of *Myriophyllum spicatum* suggests water up to 6 m deep (Podbielkowski and Tomaszewicz, 1979).

The spread of birch in the area represents the final stage documented in the palynological succession (LPAZ Sr-6 *Betula-Artemisia*; Fig. 4). This spread is a phenomenon that has also been documented in other sites across Poland (e.g., Mamakowa, 1989; Tobolski, 1991; Granoszewski, 2003; Krupiński, 2005). The regional expansion of birch may indicate an improvement in climatic conditions. *Betula nana* and *Salix* pollen indicates the presence of dwarf shrub tundra patches. The high NAP values are probably related to the birch forests in this area being not particularly dense. Instead, they formed loose tree stands, interspersed with areas of herbaceous vegetation consisting mainly of *Artemisia* and Asteraceae.

CHANGES IN GEOCHEMICAL COMPOSITION IN THE SREBRNA PROFILE

The lithology had a significant influence on the chemical composition. The bottom deposits, likely disturbed, show irregular contents of each chemical element as well as organic carbon (geochemical zone GZ-1; Fig. 5). The initial lacustrine deposits, composed of gyttja, are characterized by the constantly highest content of lithophile elements (Al, K, Mg) in the profile (geochemical zone GZ-2; Fig. 5). This is probably linked to a relatively high water level (possibly due to increased precipitation) increasing mineral supply from the catchment area (as indicated by a low Ca/Mg index). The shallowing of the lake led to overgrowth and peat sedimentation in the upper part of GZ-2. In these deposits, a decrease in the concentration of lithophile elements (Al, K, Mg) and an increase in the share of organic carbon (TOC) are observed, likely indicative of vegetation preventing erosion along the lake shores.

Towards the end of GZ-2, organic shales appear, characterized by lower content of all chemical elements except zinc, and an increasing amount of organic carbon (up to 38%). The highest zinc concentration in the entire profile may be related to the higher presence of organic matter (Kittel et al., 2016). The overlying peat layer (GZ-3a; Fig. 5) displays lower concentrations of lithophile elements (Al, K, Mg) and the maximum organic carbon content. The maximum Ca content probably indicates groundwater supply, suggesting a short-term increase in water levels (Kittel et al., 2016). The Fe/Mn ratio shows strong variations, reflecting redox changes. A thin sandy layer follows, with very low organic carbon content and slightly higher shares of lithophile elements, suggesting slight erosion and sand transport from the banks.

The subsequent layer of gyttja (GZ-3b; Fig. 5) has a very similar chemical composition to the lower gyttja, with the Fe/Mn ratio dropping <100, indicating more oxidized conditions (Mirosław-Grabowska et al., 2022). Then sandy silts and sands were deposited (GZ-4; Fig. 5), characterized by high amounts of lithophile elements (Al, K, Mg) and very low organic carbon, reflecting the mineral deposition. Higher copper and zinc concentrations correlate with an increase in the erosion index (K + Mg + Al/Ca), suggesting that these elements are linked to the intensity of mechanical denudation (Mirosław-Grabowska et al., 2022), particularly with the supply of clay material. Elevated zinc concentrations may also be associated with the bioaccumulation of zinc by certain tundra plant taxa, including *Betula nana* (Kittel et al., 2016). The Fe/Mn ratio again shows significant variations, indicating redox changes. The presence of phosphorus is highest in this layer, likely due to secondary concentration in the clayey sands.

The upper sandy layers (GZ-5a-b; Fig. 5) are characterized by the lowest total organic carbon (TOC) and low concentrations of lithophile elements. The Fe/Mn ratio drops <100, indicating more oxidized conditions. The highest manganese content suggests river water supply in this section.

PHENOMENA OF THE ORGANIC SHALES

Various factors contributed to the formation of organic shales in the lakes. The occurrence of this very hard layer with its shale-like structure is usually associated with organic deposits. Similar lithologies have been identified at various Eemian Interglacial sites, including Srebrna. The thickness of these shale layers varies among the sites, ranging from 10 centimetres to 1.05 metres. They occur at a different depths, from 14.02 to 2.70 metres below ground level. Consequently, the thickness of overlying deposits also varies, ranging from 13.48 to 2.70 metres. This variation suggests that the pressure of the overlying layers, while causing sedimentary compaction, was not the determining factor for the shale formation. Thus, the shale formation did not require an overburden of glacial sediments deposited during the Vistula Glaciation. The data suggest an individual scenario for each lake. Neither lake size nor adjacent lithology were the main determining factors. The organic shales are present in profiles with a high organic content, particularly of peat, high-organic silt or gyttja. However, there is no clear correlation with a specific sediment type that consistently leads to the appearance of shale layers.

During the Eemian Interglacial, many small, disconnected water bodies with various sediments were formed, which influenced the chemical composition of the water and the vegetation that developed there. The organic shales did not form in one specific time period, but are known from different regional pollen zones of the Eemian Interglacial, from zone E1 to E7. However, in many of the sites analysed, these shales most often appeared in the E5 zone, which coincides with the palynological signal of reduced water levels. Palynological data from organic shale layers reveal the presence of aquatic plants, including taxa such as *Potamogeton* and *Nuphar lutea* and the algae *Pediastrum* and *Tetraedron.* These findings suggest the presence of water during shale formation. *Sphagnum* spores, indicating the development of a peat bog, also occurred in each profile analysed, but not necessarily in the organic shale layers.

The geochemical data from Srebrna were compared with data from Ustków and Kubłowo (Kołaczek et al., 2016; Mirosław-Grabowska et al., 2018). At these three sites, the average total organic content (TOC) increased from 12 to 50%, with an average of 28–33%. Additionally, in Ustków and Kubłowo, the average nitrogen content (TN) was 2% and the TOC/TN parameter was 18–19. It appears that the shale formation was associated with an increase in the concentration of organic carbon and a decrease in the content of other chemical elements (Fig. 5). The increase in TOC was probably due to the organic origin of these sediments, while the increase in the Ca/Fe ratio suggests a drop in water level. Lowering water level could limit the supply of terrigenous material from the lake's catchment area.

Comparing the results from Srebrna with data from other sites, water level fluctuations are proposed as the most likely scenario for the formation of the organic shales. Lowering water levels causes organic sediments, such as peat or organic mud/gyttja, to dry out, compact and harden, and ends with formation of a layer of shale. This scenario also coincides with the occurrence of sedimentary gaps in some profiles, visible as hiatuses in palynological diagrams during periods of low water levels, which inhibited sediment accumulation in the lakes. Therefore, the shale layer most often occurred in the E5 zone, where the palynological data (*Sparganium*, *Typha latifolia, Nymphea alba, Nuphar, Myriophyllum* sp.) suggests a low water level. Additionally, the organic shales are not always characterized by a high content of algae such as *Pediastrum* or *Tetraedron.* For typical bituminous shales, i.e. deposits containing bitumens, of various ages, such as occur in Gołków, Łyczewska (1966) proposed a different origin. These deposits were characterized by different amounts and distribution of petroleum components, e.g., benzine, heavy oils, resins, asphalt. According to Łyczewska (1966), the formation of these shales was not caused by bituminization of the deposits, but it was related to the migration of petroleum along fault (tectonic) zones from older rocks of the subsurface and their subsequent deposition within sedimentary material.

CONCLUSIONS

Organic shale distribution was analysed in several palynologically documented Eemian profiles in Poland. Organic shales have always been associated with organic-rich sediments. They characterized by a high organic carbon content (up to 50% in some cases) and the presence of aquatic plants and algae; these shales likely formed in shallow, eutrophic water bodies that were gradually overgrown and/or transformed into peat bogs. The initial organic sediments, such as organic/detritus gyttja and partially peat, were subjected to repeated drying and compaction, leading to the formation of these hard, shale-like layers.

The depth and thickness of these shales vary significantly depending on location, indicating that their formation was influenced by numerous local factors. After examining Eemian profiles from various regions of Poland, no clear correlation was found between the occurrence of these shales and the lithology of the overburden and underlying deposits. The depth of occurrence of these shales, i.e. the thickness of the overburden, also varies, indicating that their formation is not depth-related. Nevertheless, these organic shales always occur beneath an overburden, which could cause additional compaction. The organic shales are not confined to one region but were noted in many Eemian profiles in Poland.

During the Eemian Interglacial, many small, disconnected water bodies with various sediments were formed, influencing the chemical composition of the water and the vegetation that developed there. Aquatic plant fossils identified in the shales indicate a shallowing and then overgrowth, possibly due to sediment infill or water level fluctuations. The shales were not formed in single period/zone, but global factors occurring in the E5 zone (hornbeam zone) of the Eemian Interglacial may have contributed to water level fluctuations in many locations. It is better to consider each reservoir individually. Lower water levels can be attributed to natural overgrowth or lowering of groundwater levels at specific sites. Factors such as short-term drainage and flood cycles may have influenced the formation of the organic shales. However, the available data do not provide a comprehensive explanation for the selective occurrence of organic shales in some reservoirs and not in others.

Organic shales also appear in other interglacial periods e.g., the Ferdynandovian Interglacial: Ferdynandów (Ber, 2005, Stachowicz-Rybka et al., 2017), Łuków (Stachowicz-Rybka, 2015) and the Mazovian Interglacial: Lipnica (Bińka et al., 1997; Nitychoruk et al., 2005), Pawłów Nowy, Biała Podlaska, Komarno (Nitychoruk, 2000), Wylezin (Rühle, 1968), Barkowice Mokre (Łyczewska, 1966; Ber, 2005), Zakrucze near Małogoszcz (Lindner and Rzętkowska-Orowiecka, 1998).

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REFERENCE

Balwierz, Z., 2017. Palynological studies in the Łódź region (in Polish with English summary). Acta Geographica Lodziensia, **106**: 129–138. https://doi.org/10.26485/AGL/2017/106/10

Ber, A., 2005. Polish Pleistocene stratigraphy – a review of interglacial stratotypes. Netherlands Journal of Geosciences, **84**: 61–76. https://doi.org/10.1017/S0016774600022964

Beug, H.J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Varlag Dr. Friedrich Pfeil, München.

Bińka, K., Nitychoruk, J., 2003. The Late Saalian, Eemian and Early Vistulian pollen sequence at Dziewule, eastern Poland. Geological Quarterly, **47** (2): 155–168.

Bińka, K., Lindner, L., Nitychoruk, J., 1997. Geologic-floristic setting of the Mazovian Interglacial sites in Wilczyn and Lipnica in southern Podlasie (eastern Poland) and their palaeogeographic connections. Geological Quarterly, **41** (3): 381–394.

Birks, H.J.B., 1973. Past and Present Vegetation of the Isle of Skye. A Palaeobotanical Study. Cambridge University Press.

Bitner, K., 1954. The palaeobotanic characteristic of the interglacial deposits at Horoszki near Mielnik in Podlasie (in Polish with English summary). Biuletyn Instytutu Geologicznego, **69**: 79–91.

Bitner K., 1956. Interglacial flora in Otapy/District Białystok (In Polish with English summary). Biuletyn Instytutu Geologicznego, **100**: 61–142.

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

Borisova, O.K., Novenko, E.Yu., Velichko, A.A., Kremenetski, K.V., Junge, F.W., Boettger, T., 2007. Vegetation and climate changes during the Eemian and Early Weichselian in the Upper Volga region (Russia). Quaternary Science Reviews, **26**: 2574–2585. https://doi.org/10.1016/j.quascirev.2007.07.001

Borówko-Dłużakowa, Z., 1973. Pollen analysis of the Eemian Interglacial at Skierniewice, Białynin and Wyszków (in Polish with English summary). Przegląd Geograficzny, **45**: 771–779.

Bruj, M., Roman, M., 2007. The Eemian lakeland extent in Poland versus stratigraphical position of the middle polish glaciations (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **425**: 27–34.

Faegri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis. John Wiley and Sons Ltd.

Gadomska, S., 1966. Geological situation of the Eemian Interglacial deposits at Gołków, near Warsaw (in Polish with English summary). Geological Quarterly, **10** (2): 442–452.

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

Helmens, K.F., Salonen, J.S., Plikk, A., Engels, S., Väliranta, M., Kylander, M., Brendryen, J., Renssen, H., 2015. Major cooling intersecting peak Eemian Interglacial warmth in northern Europe. Quaternary Science Reviews, **122**: 293–299. https://doi.org/10.1016/j.quascirev.2015.05.018

Iversen, J., 1944. *Viscum*, *Hedera* and *Ilex* as climate indicators. A contribution to the study of the Post-Glacial temperature climate. Geologiska Föreningen i Stockholm Förhandlingar, **66**: 463–483. https://doi.org/10.1080/11035894409445689

Janczyk-Kopikowa, Z., 1966. Eemian interglacial at Gołków near Warsaw (in Polish with English summary). Kwartalnik Geologiczny, **10** (2): 453–461.

Janczyk-Kopikowa, Z., 1987. Remarks on palynostratigraphy of the Quaternary (in Polish with English summary). Kwartalnik Geologiczny, **31** (1): 155—162.

Janczyk-Kopikowa, Z., 1991. Palynostratigraphy of the Pleistocene in Poland and the problem of the age of deposits from Besiekierz (Central Poland). Annales Universitatis Mariae Curie-Skłodowska. Sectio B. Geographia, Geologia, Mineralogia et Petrographia, **46**: 111–128.

Kittel, P., Płóciennik, M., Borówka, R.K., Okupny, D., Pawłowski, D., Peyron, O., Stachowicz-Rybka, R., Obremska, M., Cywa, K., 2016. Early Holocene hydrology and environments of the Ner River (Poland). Quaternary Research **85**: 187–203. https://doi.org/10.1016/j.yqres.2015.12.006

Klotz, S., Muller, U., Mosbrugger, V., de Beaulieu, J.-L., Reille, M., 2004. Eemian to early Würmian climate dynamics: history and pattern of changes in Central Europe. Palaeogeography, Palaeoclimatology, Palaeoecology, **211**: 107–126. https://doi.org/10.1016/j.palaeo.2004.04.009

Kołaczek, P., Karpińska-Kołaczek, M., Petera-Zganiacz, J., 2012. Vegetation patterns under climate changes of the Eemian and Early Weichselian in Central Europe inferred from palynological sequence from Ustków (central Poland). Quaternary International, **268**: 9–20. https://doi:10.1016/j.quaint.2012.05.004

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

Kondracki, J., 2009. Geografia Regionalna Polski (in Polish). PWN, Warszawa.

Krawczyk, M., Pochocka-Szwarc, K., 2021. Objaśnienia do Szczegółowej Mapy Geologicznej Polski, ark. Czerwińsk n. Wisłą 1:50 000 (in Polish). Wyd. Geol., Warszawa.

Krupiński, K.M., 2005. The investigations of the Younger Pleistocene lacustrine sediments of the Płock Upland (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **184**: 3–58.

Krupiński, K.M., Morawski, W., 1993. Geological position and pollen analysis of Eemian Interglacial sediments of Warsaw-Wawrzyszew. Acta Palaeobotanica, **33**: 309–346.

Kupryjanowicz, M., 2005. Vegetation and climate at north Podlasie during the Eemian interglacial and Early and Middle Vistulian (in Polish with English summary). Prace Komisji Paleogeografii Czwartorzędu PAU, **3**: 73–80.

Kupryjanowicz, M., 2007. Water level changes in the Eemian lakes and peat-bogs in the north Podlasie (in Polish with English summary). Przegląd Geologiczny, **55**: 336–342.

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. Szafer Institute of Botany Polish Academy of Sciences : 17–20.

Kupryjanowicz, M., Ciszek, D., Morosław-Grabowska, J., Marciniak, B., Niska, M., 2005. Two climatic oscillations during the Eemian interglacial: preliminary results of multi-proxy researches of palaeolake at Solniki, NE Poland. Polish Geological Institute Special Papers, **16:** 53–57.

Kupryjanowicz, M., Drzymulska, D., Fiłoc, M., 2015. Eemian and early Weichselian Lobelia lakes in northeastern Poland. Review of Palaeobotany and Palynology, **219**: 28–38. https://doi.org/10.1016/j.revpalbo.2015.03.006

Lindner, L., Rzętkowska-Orowiecka, A., 1998. New data on interglacial sediments at Zakrucze near Małogoszcz, the Holy Cross Region. Geological Quarterly, **42** (2): 201–208.

Łyczewska, J., 1966. Interglacial bituminous shales in Poland as a symptom of migration of bitumens (in Polish with English summary). Annales Societatis Geologorum Poloniae, **36**: 369–379 .

Mamakowa, K., 1988. Pollen stratigraphy of Eemian and adjoining glacial deposits based on continuous sequences in Poland. Bulletin of the Polish Academy of Sciences, Earth Sciences, **36**: 299–307.

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.

Marks, L., Gałązka, D., Woronko, B., 2016. Climate, environment and stratigraphy of the last Pleistocene glacial stage in Poland. Quaternary International, **420**: 259–271. https://doi.org/10.1016/j.quaint.2015.07.047

Miall, A.D., 1977. A review of the braided river environment. Earth--Science Reviews, **13**: 1–62.

Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth-Science Reviews, **22**: 261–308.

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

Mirosław-Grabowska, J., Borówka, R.K., Radzikowska, M., Sławińska, J., Hrynowiecka, A., Sobczyk, A., Stachowicz-Rybka, R., Stefaniak, K., 2022. Environmental changes recorded in the sequence of lake-peat bogs in the Eemian Interglacial and Vistulian on the basis of multi-proxy data. Quaternary International, **632**: 51–64. https://doi.org/10.1016/j.quaint.2021.11.023

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell, Oxford.

Müller, U.C., Pross, J., Bibus, E., 2003. Vegetation response to rapid climate change in Central Europe during the past 140,000 yr based on evidence from the Füramoos pollen record. Quaternary Research, **59**: 235–245. https://doi:10.1016/S0033-5894(03)0005-X

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

Niklewski, J., 1968. The Eemian Interglacial at Główczyn near Wyszogród (Central Poland) (in Polish with English summary). Monographiae Botanicae, **27**: 125–192.

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

Niska, M., 2015. History of the development of Eemian Interglacial lakes on the basis of Cladocera subfossil analysis (Central and Eastern Poland). Limnological Review, **15**: 85–93. https://doi.org/10.2478/limre-2015-0010

Niska, M., 2016. The Eemian/Early Vistulian development of the Solniki paleolake (north-eastern Poland) as shown by subfossil Cladocera. Advances in Oceanography and Limnology, **7**: 206–219. https://doi.org/10.4081/aiol.2016.6217

Nitychoruk, J., 2000. Climate reconstruction from stable-isotope composition of the Mazovian Interglacial (Holsteinian) lake sediments in eastern Poland. Acta Geologica Polonica, **50**: 247–294.

Nitychoruk, J., Bińka, K., Hoefs, J., Ruppert, H., Schneider, J., 2005. Climate reconstruction for the Holsteinian Interglacial in eastern Poland and its comparison with isotopic data from Marine Isotope Stage 11. Quaternary Science Reviews, **24**: 631–644. https://doi.org/10.1016/j.quascirev.2004.07.023.

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

Podbielkowski, Z., Tomaszewicz, H., 1979. Zarys hydrobotaniki (in Polish). Państwowe Wydawnictwo Naukowe, Warszawa.

Reille, M., 1992. Pollen et spores d'europe et d'afrique du nord. Laboratoire de Botanique historique et Palynologie, Marseille.

Roman, M., Balwierz, Z., 2010. Eemian and Vistulian pollen sequence at Kubłowo (Central Poland): implications for the limit of the Last Glacial Maximum. Geological Quarterly, **54** (1): 55–68.

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

Rühle, E., 1968. The profile of Quaternary sediments at Wylezin, North of Dęblin (in Polish with English summary). Rocznik Polskiego Towarzystwa Geologicznego, **38**: 531–543 .

Rychel, J., Sieradz, D., Massalska, B., Standzikowski, K., Wasiluk, R., Woronko, B., Nawrocki, J., 2022. Paleoenvironmental changes reconstruction in the Eemian kettle holes of the last ice sheet glaciation foregrounds on the example of the Stara Maryśka II site (Northern Mazovia, Central Poland) (in Polish with English summary). Landform Analysis, **41**: 53–68. https://doi.org/10.12657/landfana-041-004

Sieradz, D., Rychel, J., 2023. Vegetation change at the turn of the Eemian Interglacial and Early Vistulian at the Srebrna site (central Poland) (in Polish with English summary). Przegląd Geologiczny, **71**: 523–526. http://dx.doi.org/10.7306/2023.40

Sieradz, D., Mirosław-Grabowska, J., Rychel, J., Massalska, B., Zbucki, Ł., 2024. Evolution of a kettle hole from the Late Saalian to the Holocene: A case study from Białe Błota, northern Masovia, central Poland. Catena, **245**, 108299. https://doi.org/10.1016/j.catena.2024.108299

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., Krąż, 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. http://dx.doi.org/10.7163/GPol.0115

Stachowicz-Rybka, R., 2015. Record of environmental and climatic changes in middle Pleistocene sediments from Łuków (eastern Poland) on the basis of plant macroremains analysis. Acta Palaeobotanica, **55**: 67–91. https://doi.org/10.1515/acpa-2015-0006

Stachowicz-Rybka, R., Pidek, I.A., Żarski, M., 2017. New palaeoclimate reconstructions based on multidisciplinary investigation in the Ferdynandów 2011 stratotype site (eastern Poland). Geological Quarterly, **61** (2): 276–290. http://dx.doi.org/gq.10.7306/gq.1353

Stankowski, W., Nita, M., 2004. Stratigraphy of Late Quaternary deposits and their neotectonic record in the Konin area, Central Poland. Geological Quarterly, **48** (1): 23–34.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores, **13**: 615–621.

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

Tobolski, K., 1991. Biostratygraphy and paleoecology of the Eemian Interglacial and the Vistulian glaciation of the Konin region (in Polish with English summary). Przemiany środowiska geograficznego obszaru Konin-Turek. UAM, Poznań: 45–87.

Tołpa, S., 1961. Interglacial flora from Sławno near Radom, Central Poland (in Polish with English summary). Biuletyn Instytutu Geologicznego, **169**: 15–56.

West, R.G., 1970. Pollen zones in the Pleistocene of Great Britain and their correlation. New Phytologist, **69**: 1179–1183.

Winter, H., 2016. Orzeczenie dotyczące wyników analizy pyłkowej próbek wiercenia Srebrna i sond 617, 619 na arkuszu Czerwińsk n. Wisłą SMGP w skali 1:50 000 (in Polish). Narodowe Archiwum Geologiczne PIG-PIB, Warszawa.

Zieliński, T., Pisarska-Jamroży, M., 2012. Which features of deposits should be included in a code and which not? (in Polish with English summary). Przegląd Geologiczny, **60**: 387–397.