Late Glacial and Early Holocene palaeoenvironmental changes in the Kuyavian Lakeland, Smólsk site, central Poland

Renata STACHOWICZ-RYBKA[1, *], Piotr KITTEL[2], Dorota NALEPKA[1], Mateusz PŁÓCIENNIK[3],
Witold P. ALEXANDROWICZ[4], Dominik PAWŁOWSKI[5], Monika RZODKIEWICZ[6], Daniel OKUPNY[7],
Agnieszka GRUSZCZYŃSKA[8, 9], Krzysztof STACHOWICZ[1], Katarzyna KORZEŃ[10],
Błażej MUZOLF[11], Bartosz KOTRYS[12], Tomi P. LUOTO[13] and Piotr PAPIERNIK[11, 14]

[1] Polish Academy of Science, W. Szafer Institute of Botany, Lubicz 46, 31-512, Kraków, Poland; ORCID: 0000-0002-0802-0570 [R.S.-R.], 0000-0002-5624-3488 [D.N.], 0000-0002-8170-8240 [K.S.]

[2] University of Lodz, Faculty of Geographical of Sciences, Department of Geology and Geomorphology, Narutowicza 88, 90-139 Łódź, Poland; ORCID: 0000-0001-6987-7968

[3] University of Lodz, Department of Invertebrate Zoology and Hydrobiology, Banacha 12/16, 90-237 Łódź, Poland; ORCID: 0000-0003-1487-6698

[4] AGH University of Krakow, Al. A. Mickiewicza 30, 30-059, Kraków, Poland; ORCID: 0000-0002-5403-6696

[5] Adam Mickiewicz University in Poznań, Institute of Geology, B. Krygowskiego 12, 61-680 Poznań, Poland; ORCID: 0000-0003-4616-6666

[6] Adam Mickiewicz University in Poznań, Institute of Geoecology and Geoinformation, B. Krygowskiego 10, 61-680 Poznań, Poland; ORCID: 0000-0002-6672-2183

[7] University of Szczecin, Institute of Marine and Environmental Sciences, Adama Mickiewicza 18, 70-383 Szczecin, Poland; ORCID: 0000-0002-8836-6044

[8] Polish Academy of Sciences, Institute of Geography and Spatial Organization, Twarda 51/55, 00-818 Warszawa, Poland; ORCID: 0000-0002-3534-7843

[9] Leipzig University, Institute of Geography, Johannisallee 19a, Leipzig, 04103, Germany

[10] Kazimierza Wielkiego 110/2-3, 30-074 Kraków, Poland

[11] Museum of Archaeology and Ethnography in Lodz, Plac Wolności 14, 91-415 Łódź, Poland; ORCID: 0000-0002-0970-5627 [P.P.]

[12] Polish Geological Institute – National Research Institute, Pomeranian Branch, Wieniawskiego St. 20, 71-130, Szczecin, Poland; ORCID: 0000-0002-2732-6970

[13] Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland; ORCID: 0000-0001-6925-3688

[14] The Professor Konrad Jażdżewski Foundation for Archeological Research, Plac Wolności 14, 91-415 Łódź, Poland

High-resolution biological proxies (pollen, plant macrofossils, Cladocera, Chironomidae, malacological analysis and diatoms), geochemical analyses, and AMS radiocarbon dating were employed to reconstruct the responses of the Smólsk palaeolake (Kuyavian Lakeland, central Poland) to rapid climatic and other environmental changes during the Late Glacial-Early Holocene transition. The integration of palaeoecological and geochemical data enabled detailed insights into the dynamics of short-term shifts in terrestrial and aquatic ecosystems triggered by abrupt climate events. Precise age control and high-resolution sampling allowed the identification of temporal leads and lags between proxy responses to climatic shifts during this transitional period. Key findings include: (1) the coolest lake development phase, corresponding to the Late Glacial (9.050–5.400 m; 13,835–12,800 cal[14]C BP); (2) evidence of an open landscape and decreased water levels in the Late Glacial, resulting in

intensified catchment erosion; (3) a change in sediment deposition at a depth of 5.35 m (~11,000 cal ^{14}C BP), marked by a transition from silt to calcareous gyttja and peat, indicating a lowering of groundwater levels and improved climatic conditions at the beginning of the Holocene; (4) a hiatus between the Late Glacial and Early Holocene recorded across all proxies; and (5) progressive eutrophication during the Holocene, characterized by reed belt development, reduced sedimentation, and the cessation of terrigenous sediment input. These findings highlight the lake system's sensitivity to rapid climatic and environmental changes during this critical period.

Key words: Late Glacial, Holocene, palaeoenvironment, palaeoclimate, multiproxy, central Poland

INTRODUCTION

The Kuyavian Lakeland is characterized by numerous palaeolakes that serve as vital archives of past environmental changes, offering insights into climate dynamics, vegetation shifts, and geomorphological processes over various temporal and spatial scales. Subfossil plant and animal remains, along with the geochemical character of the lake and bog deposits, reflect these past changes, as demonstrated in prior studies (Ralska-Jasiewiczowa et al., 1998; Pawłowski et al., 2015; Makohonienko et al., 2023). Similar palaeoenvironmental studies across central Europe have provided comprehensive documentation of climatic and anthropogenic impacts on peatland ecosystems using a variety of palaeobotanical, palaeozoological and geochemical proxies.

The Smólsk palaeolake, situated in the eastern Kuyavian Lakeland in the immediate vicinity of the Vistula ice-marginal valley, offers a unique opportunity to investigate the interactions between climate and other environmental change. Initial research, conducted during archaeological rescue excavations between 2006 and 2011, revealed extensive evidence of human activity, particularly from the Neolithic period, in a settlement complex spanning several hectares. The site is located on a flat moraine plateau, surrounded by a diverse landscape of landforms, surface geological structures, vegetation, and soils. Alongside archaeological studies, preliminary interdisciplinary investigations addressed palaeoecological and environmental archaeology questions concerning pre-settlement conditions (Kittel et al., 2015).

A notable feature of the Smólsk site is a kettle hole at its southeastern edge, filled with organic deposits up to 10 m depth. This depression lies within a narrow tunnel valley through which a small watercourse (a modern drainage canal) currently flows. Sediment cores from the site reveal a sequence of silts, sands, peats and gyttja, documenting the basin's evolution during archaeological and geomorphological surveys (Muzolf et al., 2012; Kittel 2015; Kittel et al., 2015). Previous palaeoecological studies on the uppermost 3.5 m of the deposit confirmed the presence of a small mesotrophic lake, active from the Late Glacial through to the Middle Ages, though pollen preservation was insufficient for detailed vegetation reconstructions.

In this study, we present new high-resolution multiproxy data from the Smólsk palaeolake, focusing on lake ecosystem, local vegetation, and catchment area responses to abrupt climate changes between 13,835 and 9,200 cal ^{14}C BP. This interval encompasses the critical transition from the Late Glacial to the Early Holocene, a period marked by rapid climate oscillations (Goslar et al., 1993; von Grafenstein et al., 1999, 2013; Wang et al., 2001; Litt et al., 2001; Schaub et al., 2008; Feurdean et al., 2014; Rasmussen et al., 2014; Muschitiello et al., 2015; Müller et al., 2021; Płóciennik et al., 2022; Zander et al., 2024). Previous research has documented time lags between lake and ice-core proxies in western Germany, southern Norway, and Greenland during the Younger Dryas cooling (Lane et al., 2013; Rach et al., 2014), underscoring the need for synchronized proxy records to understand regional climate change mechanisms better. By investigating the proxy responses at Smólsk, this study contributes to a broader understanding of the timing, dynamics, and drivers of climatic and environmental changes during this critical transitional period.

STUDY AREA, SITE DESCRIPTION

Physico-geographically, the study area is located in the eastern part of the Kuyavian Lakeland on the border with the Płock Basin (Kondracki, 1994, 2002; Solon et al., 2018).

In the area surrounding the Smólsk site, the moraine plateau of the Kuyavian Lakeland rises to a maximum of 84–85 m a.s.l. and represents a part of the extensive exaration depression of the Kuyavian Plateau (Molewski, 2007). The site is located in the immediate vicinity of the edge of the Płock Basin within the Vistula ice-marginal valley (Fig. 1C).

The surrounding area of the site is a flat moraine plateau, composed of glacial till of the Vistulian Glaciation (Brzeziński, 2001, 2003; Wysota, 2002; Mojski, 2005; Molewski, 2007; Przegiętka et al., 2008; Nowaczyk, 2008; Roman, 2010). South of Brześć Kujawski, two clay units of the Vistulian Glaciation were recognized (Brzeziński, 2003). The younger, upper clay, 6 m thick, correlates with the Poznań Phase, which forms a uniform upland surface in this area. The older, lower clay, 3 m thick, correlates with the Leszno Phase or with the Świecie Stage, and is separated from the upper clay by a layer of glaciofluvial sands or glacial till and stagnant-facies silts. The lower clay has been distinguished only in the Kazań area. The succession of lake clays and silts analysed at the Guźlin site were related to the main stage of the Vistulian Glaciation (Roman, 2010).

The surface of the upland in the Smólsk area includes a few depressions left by dead ice, and in the vicinity of the site a moderately narrow subglacial tunnel valley, mostly filled with biogenic accumulation deposits (Fig. 1B). This relief form extends on the northern side of the village of Smólsk and farther west towards Brześć. To the west of the Zgłowiączka River valley, this form may continue to the NW, and is preserved in the form of a sequence of oval drainless depressions, including in the Osłonki area (Nowaczyk, 2008). South and west of the Smólsk site, there are four small (<1 ha in area) drainless depressions occupied by biogenic accumulation plains. The largest and most prominent in the morphology of the site is the Smólsk (SMO2) palaeochannel. It forms part of an east-west subglacial tunnel valley, which is better defined in the relief a little farther west of
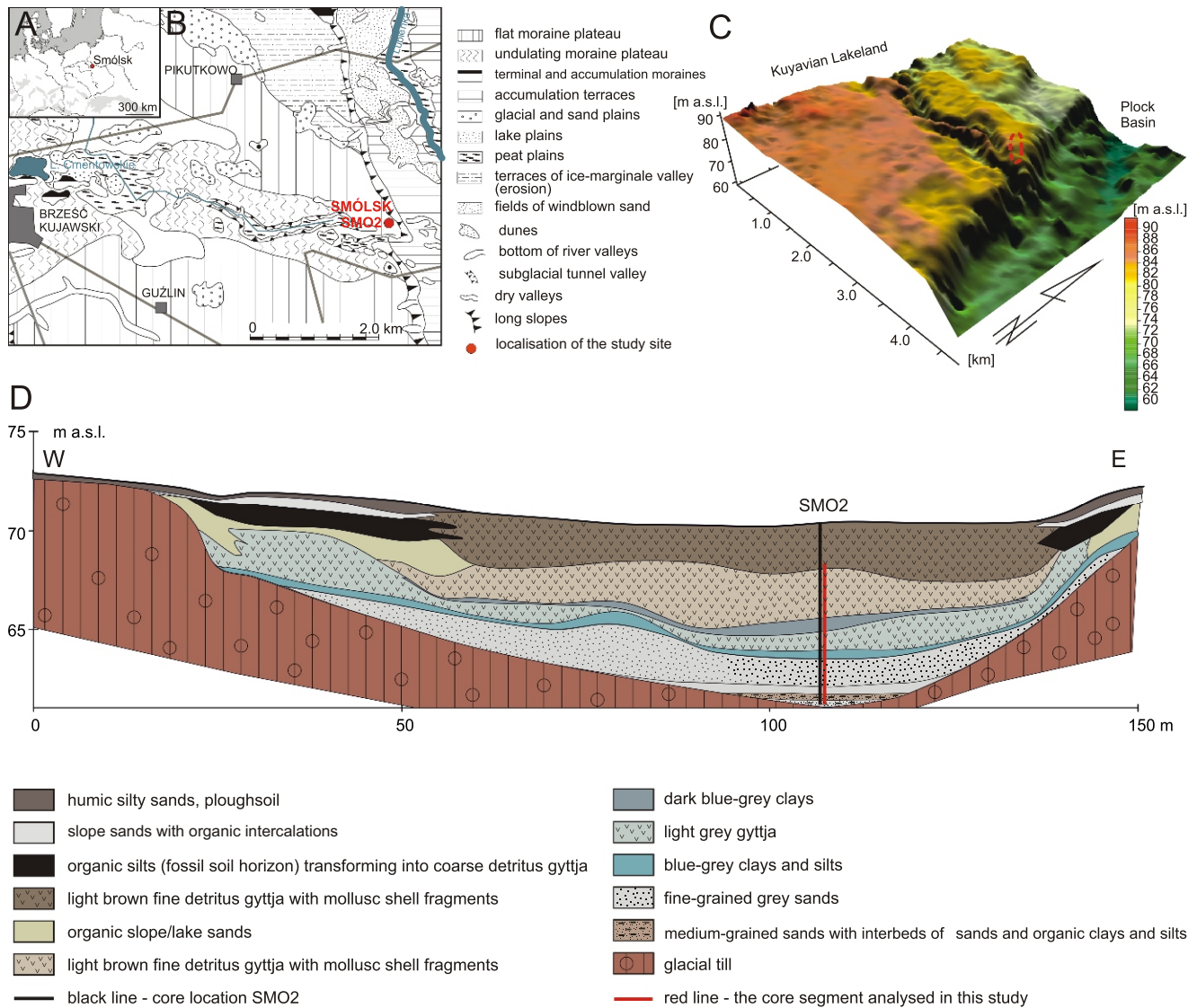
Fig. 1A – location of the Smólsk site on a map of Central Europe; B – location of the Smólsk site on a geomorphological
map of Poland at 1:100 000 scale, Brześć Kujawski Sheet (441) according to Brzeziński (2003); C – location
of the Smólsk palaeolake (purple circle); D – cross-section through the deposits of the Smólsk palaeolake

the site. The upper part of the succession in this basin has already been studied (Kittel, 2007, 2008). These basins are most likely a continuation of the subglacial channel noted towards the SSE.

The distinct morphological edge of the proglacial valley reaches ~10 m in height. Subglacial depressions and channels with an organic sedimentary infill make the relief of the area clearly differentiated (Fig. 1B–D). Preliminary results of palaeoenvironmental studies based on analysis of the upper part of 3.5 m of the organic deposits, covering ~6,000 years, confirm the existence of a small (~1 ha) relatively mesotrophic lake from the Late Glacial and Holocene transition to the Middle Ages. Periodic fluctuations in water level, changes in pH and low water levels since the Neolithic have also been observed for this time interval (Kittel, 2015).

MATERIALS AND METHODS

The main core for study, with the identification code SMO2, spanning 5.500 m (9.050–3.550 m from present surface level),

was retrieved from a palaeobasin (52°36´02,5"N–18°59´17,5"E; 70 m a.s.l.) using a Więckowski piston corer with diameters of 5 cm and lengths of 100 cm. Three parallel cores of the deposits were collected for multi-proxy analyses. Samples were taken from the cores at intervals of 2.5 cm and prepared for the following analyses: pollen, plant macroremains, lithological, geochemical, diatoms, Cladocera, Chironomidae and malacological. Fourteen radiocarbon (^{14}C) dates were obtained for the sediment profile (Table 1).

SEDIMENT DESCRIPTION

3.550–3.850 m light brown fine detritus gyttja with fragments of mollusc shells
3.850–4.900 m gyttja light brown fine detritus gyttja with fragments of mollusc shells
4.900–5.300 m fine detritus gyttja, grey-green to brown, slightly laminated
5.300–5.750 m blue-grey mineral gyttja
5.750–6.050 m dark blue-grey clays

6.050–6.350 m light grey gyttja
6.350–7.075 m dark blue-grey clay
7.075–7.500 m light blue-grey clay
7.500–7.600 m blue-grey clays and silts
7.600–7.700 m fine-grained grey sands
7.700–7.850 m dark grey muds with single mollusc shells
7.850–8.550 m fine-grained grey sands
8.550–8.750 m grey silts
8.750–8.875 m compact brown peat
8.875–8.950 m sands with organic admixtures
8.950–9.050 m medium-grained sands with interbeds of sand and organic mud

RADIOCARBON DATING

A total of 14 radiocarbon dates were obtained from a depth interval of 3.550–8.775 m of the core SMO2. Taxonomically identified plant macro-remains were selected for AMS radiocarbon dating undertaken in the Radiocarbon Laboratory in Poznań (see Goslar et al., 2004 for details). The ^{14}C age BP was further calibrated using the *OxCal v. 4.4* software (Bronk Ramsey, 2009) and the IntCal20 calibration curve (Reimer et al., 2020; Fig. 2 and Table 1).
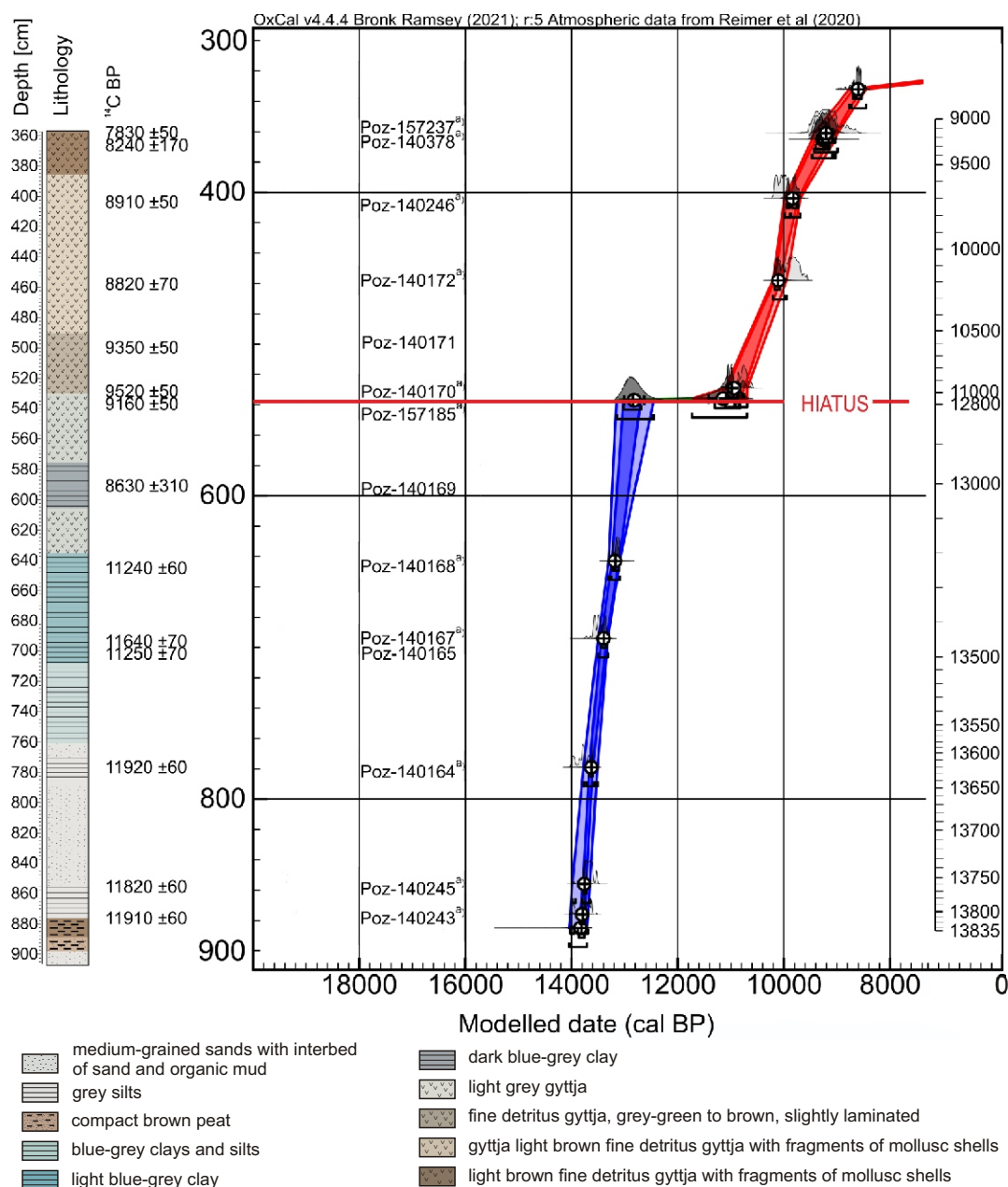

Fig. 2. Model age-depth of the Smólsk SMO2 core

a) – samples that were used in the age-depth model

Table 1

The results of radiocarbon dating of plant macroremains from the SMO2 core

Depth [cm b.s.l.]	Laboratory code	Age^{14}C [yr BP]	Age cal^{14}C prob. 68.3%	Age cal^{14}C prob. 95.4%	Dated macrofossils
Smólsk 3.30–3.35	Poz-157237	7,830 ±50 BP[a]	8,752–8,545 BP	8,855–8,455 BP	*Pinus sylvestris* – 4 bud scales *Carex rostrata* – 3 fruits *Urtica dioica* – 9 fruits
Smólsk 3.600–3.625	Poz-140378	8,240 ±170 BP[a]	9,325–9,108 BP	9,441–9,006 BP	*Carex* sp. 2 sided – 1 fruit *Typha* sp. – 6 fruits *Pinus sylvestris* – 1 bud scale, 1 seed scale
Smólsk 4.025–4.050	Poz-140246	8,910 ±50 BP[a]	9,939–9,739 BP	9,999–9,695 BP	*Pinus sylvestris* – 1 dwarf, 2 seed scale
Smólsk 4.575–4.600	Poz-140172	8,820 ±70 BP[a]	10,172–10,071 BP	10,204–9,948 BP	*Betula* sect. *albae* – 11 fruits, 1/2 fruit scale *Pinus sylvestris* – 1 seed scale
Smólsk 4.925–4.950	Poz-140171	9,350 ±50 BP	10,645–10,347 BP	10,824–10,232 BP	*Betula* sect. *albae* – 6 fruits, 4 fruit scales *Pinus sylvestris* – 2 seed scales
Smólsk 5.275–5.300	Poz-140170	9,520 ±50 BP[a]	11,071–10745 BP	11,104–10672 BP	*Betula* sect. *albae* – 10 fruit scales *Pinus sylvestris* – 6 seed scales, 2 needles, 2 dwarfs, 3 fr. of male cone
Smólsk 5.775–5.800	Poz-157185	9,160 ±50 BP	13,111–12858 BP	13,217–12679 BP	*Carex* 3-sided – 1 fruit *Betula* sect. *albae* – 1 fruit scales *Betula* sect. *albae* – 2 fruits
Smólsk 5.875–5.900	Poz-140169	8,630 ±310 BP	13,128–12,903 BP	13,231–12,744 BP	*Pinus sylvestris* – 1 seed scale, 2 bud scale
Smólsk 6.425–6.450	Poz-140168	11,240 ±60 BP[a]	13,236–13,113 BP	13,300–13,099 BP	*Pinus sylvestris* – 4 bud scales, 6 needles, 2 dwarfs
Smólsk 6.925–6.950	Poz-140167	11,640 ±70 BP[a]	13,437–13,341 BP	13,500–13,315 BP	*Betula* sect. *albae* – 1 frut; *Pinus sylvestris* – 2 bud scales, 6 fr. of needles brown mosses – 1 stem
Smólsk 7.025–7.050	Poz-140165	11,250 ±70 BP	13,469–13,368 BP	13,522–13,330 BP	*Eleocharis palustris* – 1 fruits *Ranunculus sceleratus* – 1 fruits *Betula* sect. *albae* – 1 fruit scale *Pinus sylvestris* – 2 bud scales, 1 fr. of leaf
Smólsk 7.775–7.800	Poz-140164	11,920 ±60 BP[a]	13,656–13,602 BP	13,775–13,515 BP	*Pinus sylvestris* – 2 bud scales; 3 fr. of needles *Cirsium palustre* – 2 fruits *Betula* sect. *albae* – 1 fruits *B. nana* – 2 fr. of leaves
Smólsk 8.550–8.575	Poz-140245	11,820 ±60 BP[a]	13,785–13,724 BP	13,987–13,657 BP	*Pinus sylvestris* – 3 bud scales; 1 seed scale; 6 fr. of needles *Betula* sp. – 1 frut scale
Smólsk 8.750–8.775	Poz-140243	11,910 ±60 BP[a]	13,819–13,750 BP	14,020–14,028 BP	*Carex rostrata* – 2 fruits, 16 epicarps

a) – samples that were used in the age-depth model

GEOCHEMICAL ANALYSIS

For geochemical analyses, sediment samples were frieze-dried and homogenized in a laboratory agate mill. Organic matter (LOI) and carbonate contents (CaCO$_3$) were determined by combustion of the samples at 550°C for 4 h and subsequently at 925°C for 2 h. Carbonate content was calculated as CaCO$_3$ = 1.36 × LOI$_{925}$, as defined by Heiri et al. (2001). To determine the contents of terrigenous (SiO$_{2ter}$) and biogenic (SiO$_{2biog}$) silica in the samples, powdered samples were combusted at 550°C for 4 h and subsequently digested in aqua regia at 100°C for 2 h. The residue after acid treatment was assumed to represent total SiO$_2$ (SiO$_{2tot}$). SiO$_{2ter}$ and SiO$_{2biog}$ were separated by extraction of biogenic opal (SiO$_{2biog}$) with 0.5 n NaOH on a water bath at 100°C for 2 h (Bechtel et al., 2007). The content of SiO$_{2biog}$ was calculated as SiO$_{2biog}$ [%] = SiO$_{2tot}$-SiO$_{2ter}$ (Woszczyk et al., 2011). The procedure described is commonly used for palaeo-

environmental analyses of lakes in the Polish Lowland (e.g., Tylmann et al., 2009; Apolinarska et al., 2012; Makohonienko et al., 2023).

PALYNOLOGICAL ANALYSIS

One hundred and ten samples were used for palynological analysis, 1 cm^3 in volume, were subjected to standard Erdtman acetolysis (Faegri et al., 1989), boiled in HF (Berglund, Ralska-Jasiewiczowa, 1986) and tablets with *Lycopodium* spores were added (Stockmarr, 1971). Palynological samples were analysed under a transmitted light microscope, at 400× or 1000× magnification, using immersion (anisole). In several late-glacial samples, <100 sporomorphs were counted (total sum) and these samples were omitted from the analysis of the diagram. In the Holocene samples, up to ~600 sporomorphs of trees and
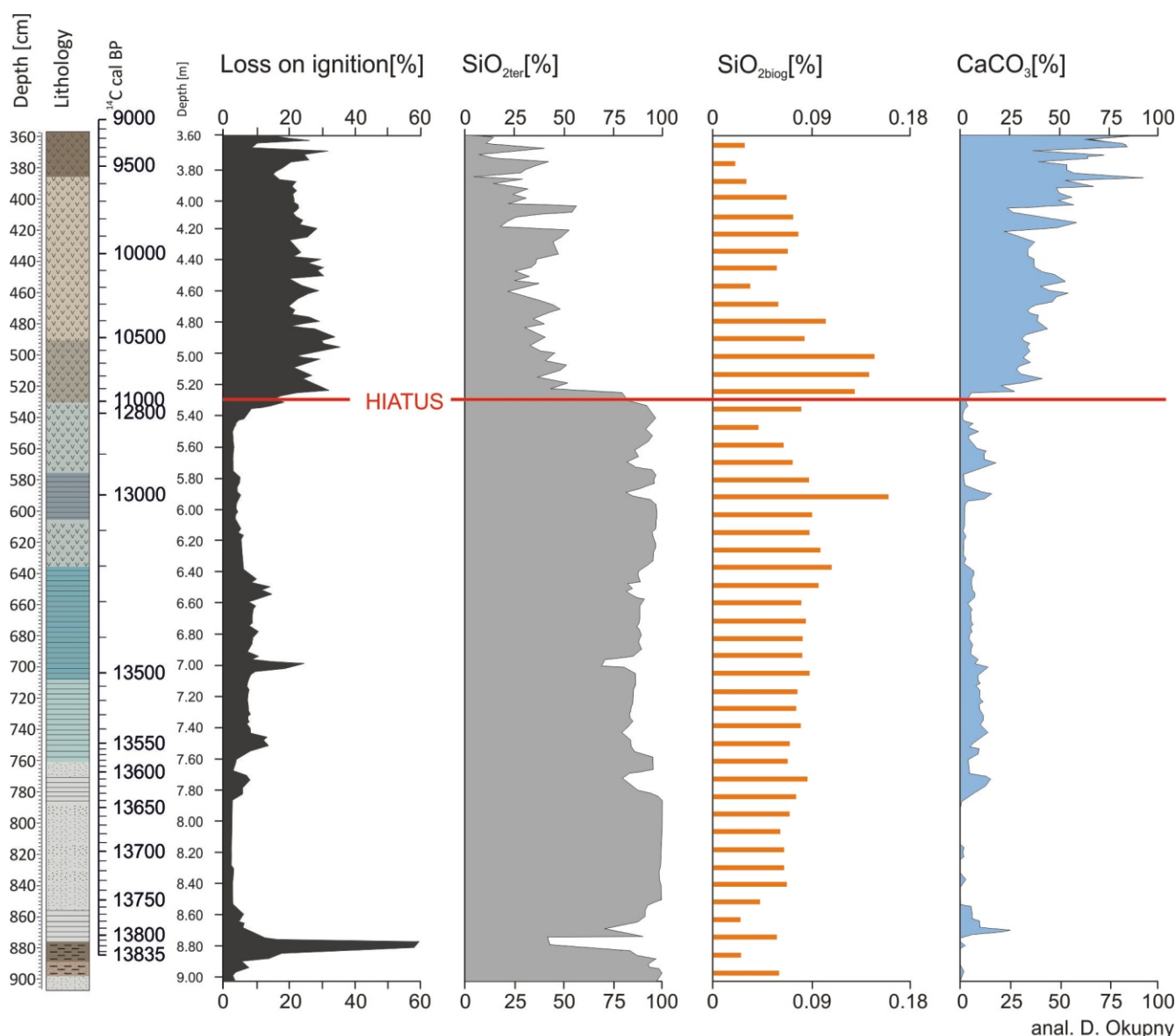
Fig. 3. Stratigraphical content of mainly lithogeochemical components from the Smólsk SMO2 core

Characterization of organic matter, SiO_{2ter}, SiO_{2biog} and $CaCO_3$ content

shrubs (AP) and terrestrial herbaceous plants (NAP) were counted. The identification was made using handbooks and keys for pollen grain identification (Moore et al., 1991; Beug, 2004), and comparative preparations from the KRAM P collection of the Palaeobotany Department (currently known as the Palaeobotany and Palaeoenvironment Research Group) of the W. Szafer Institute of Botany, Polish Academy of Sciences. The state of preservation of the sporomorphs was generally not good, which made their identification and counting difficult.

The results of palynological analysis are shown in the form of a classic percentage diagram. When calculating the percentage share of sporomorphs, the total amount was tree and shrub pollen (AP) and terrestrial herbaceous plants (NAP), excluding pollen grains of aquatic and red-swamps, and fern spores. At the end of the diagram, summary concentration curves for trees, shrubs and herbs are shown. The diagram was created using *Polpal* software (Nalepka and Walanus, 2003; www.polpal). The basic palynological diagram includes all spe-

ctra counted. Then, in the diagram, interruptions are marked (in purple) where fewer than 100 sporomorphs were counted, or where some taxon was overrepresented (*Pinus*, *Selaginella helvetica*). In the part of the spectra where single taxa occurred, they are shown not as percentage silhouettes, but were introduced as plus signs. The following estimates were adopted: one plus (+) indicates a single occurrence of the taxon, two pluses (++) several occurrences, and three pluses (+++) a more numerous occurrence (Fig. 4).

PLANT MACROREMAINS ANALYSIS

Plant macroremains were analysed in 220 samples (3–22 cm³ – the precise volume is given in the diagram; Fig. 5). They were boiled with the addition of KOH and detergent to reduce the amount of sediment and remove humic matter. The sediment was then subjected to wet sieving on a 0.2 mm mesh
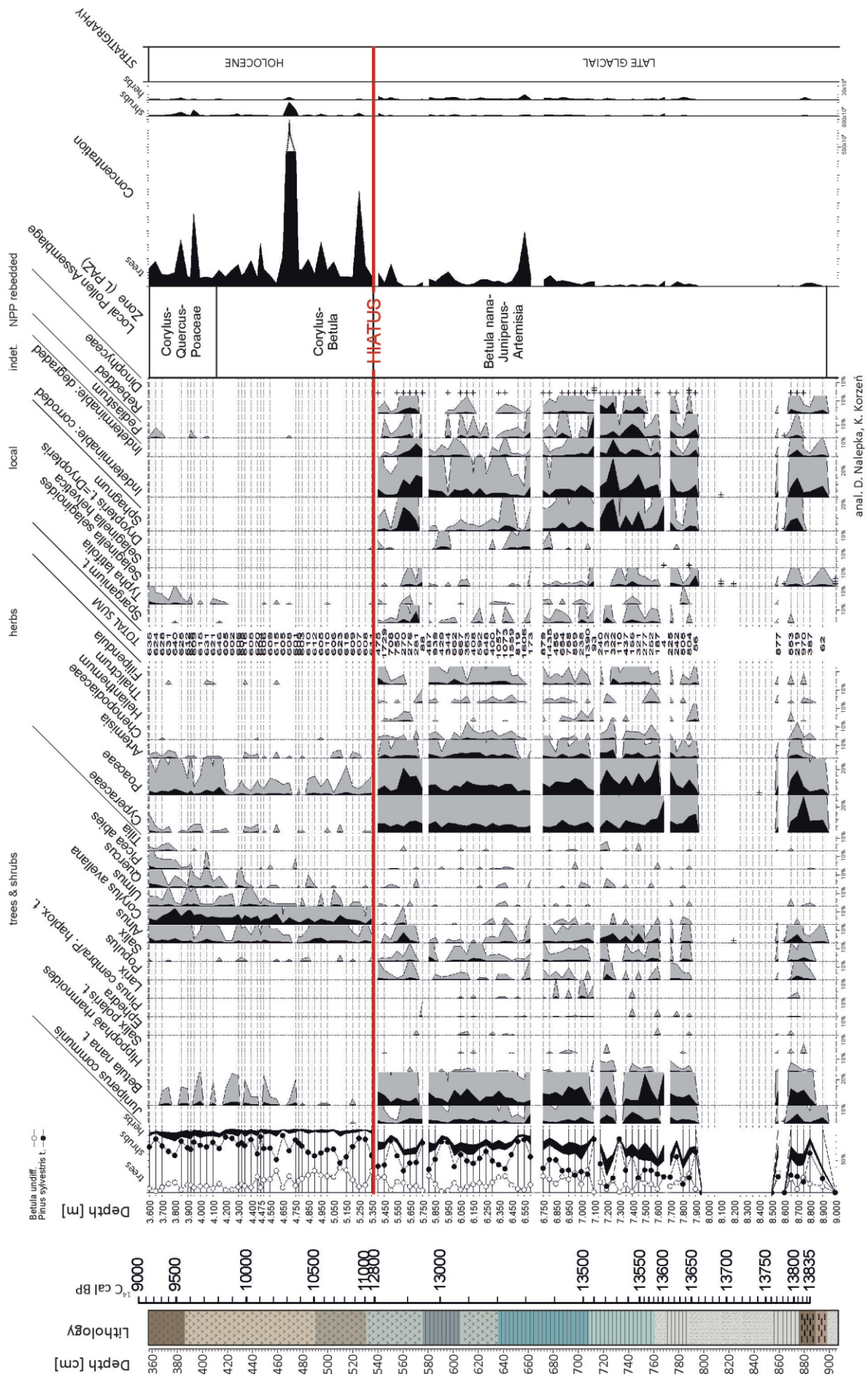
Fig. 4. Palynological diagram from the Smólsk SMO2 core

sieve. The material received was examined with a stereo microscope. The conservation of plant remains was treated with a standard mixture of alcohol, water and glycerin in 1:1:1 proportion, with the addition of thymol. Then the plant fragments were dried with 50% ethyl alcohol. Macrofossils were identified with the use of plant keys, atlases (Kats et al., 1965, Berggren, 1969; Cappers et al., 2006; Velichkevich and Zastawniak, 2006, 2008), other scientific descriptions and publications, and compared with a reference collection of modern diasporas, as well as fossil flora specimens from the National Biodiversity Collection of Recent and Fossil Organisms at the W. Szafer Institute of Botany, Polish Academy of Sciences, in Kraków (herbarium KRAM) (https://www.rcin.org.pl/dlibra/collectiondescription/548). Qualitative and quantitative results are shown on a diagram drawn with the use of the *Polpal* software (Nalepka and Walanus, 2003).

DIATOM ANALYSIS

For diatom analysis, 220 samples of 1 cm^3 volume size were selected. Sample processing and analyses followed Battarbee (1986). At least 300 diatom valves per sample were analysed with a light microscope using oil immersion at 1000×. For identification keys (Lange-Bertalot and Krammer, 1987; Lange-Bertalot and Metzeltin, 1996; Krammer and Lange-Bertalot, 2008a, b, 2010, 2011; Lange-Bertalot et al., 2011) and AlgaeBase (Guiry and Guiry, 2023) were used. Diatom ecological groups were determined using the *Omnidia* software (Version 4.2; Lecointe et al., 1993). Next, the ecological groups were distinguished according to Denys (1991) and Van Dam et al. (1994). We considered the following indicator parameters: habitat category (Denys, 1991), preference for pH, trophic state and moisture (Van Dam et al., 1994) and dominant taxa (abundance over 2%). A stratigraphic diagram was plotted using *C2* software (Juggins, 2007; Fig. 6A, B).

CLADOCERA ANALYSIS

Analysis of subfossil Cladocera took place at 2.5 cm intervals (depth 9.050–3.575 m). One hundred sixteen samples of 1 cm^3 each were processed according to the standard procedure (Frey, 1986). Each sample of 1 cm^3 of deposit was processed according to the standard procedure (Frey, 1986). All Cladocera remains (i.e. the head shield, shell, postabdomen, claw, ephippium) were counted. For each taxon, the most abundant body part was taken to represent the number of individuals, and percentages were calculated from the sum of individuals. The results of these calculations are shown in a diagram (Fig. 7), drawn with the use of *Polpal* software (Nalepka and Walanus, 2003). The taxonomy of cladoceran remains in this paper follows those of Szeroczyńska and Sarmaja-Korjonen (2007), Van Damme and Dumont (2008), Van Damme et al. (2010) and Faustova et al. (2011). Classification of Cladocera habitat preferences followed Flössner (1972, 2000), Bjerring et al. (2009), and Błędzki and Rybak (2016).

CHIRONOMIDAE

Chironomidae subfossils were collected from 162 samples within core depths 8.275–3.575 m mostly with 2.5 cm resolution. Larval head capsule (hc) preparation methods follow Brooks et al. (2007). The samples were passed through a 90 μm sieve. Identification of Chironomidae hc follows mainly keys by Brooks et al. (2007) and Andersen et al. (2013). Ecological preferences of the taxa identified were based on Vallenduuk and Moller Pillot (2007), Brooks et al. (2007) and Moller Pillot (2009, 2013). The reference collection is deposited and available at the Department of Invertebrate Zoology and Hydrobiology, University of Lodz. Chironomid assemblage zones were determined in *R* software (R Core Team, 2020) using detrended hierarchical clustering (with Coniss algorithm and Euclidean distance) from the rioja package (Juggins, 2017). The zones were tested for statistical significance with the broken-stick model using the *R* package 'Vegan'. The Detrended Correspondance Analysis (DCA) was also calculated with the *R* package 'Vegan' using percentage data and downweighting rare species (Oksanen et al., 2019). A stratigraphic diagram was plotted using *C2* software (Juggins, 2007; Figs. 8 and 9).

The Chironomidae inferred (CH–I) mean July air temperature reconstruction is based on Swiss-Norwegian-Polish TS (SNP TS) and East European TS (EE TS) (Luoto et al., 2019; Kotrys et al., 2020). Samples that contained <50 head capsules (hc) according to Quinlan and Smol (2001) were merged or deleted. The SNP TS includes 357 lakes, 134 taxa and the 3.5–20.1°C temperature range. The EE TS includes 212 lakes, 142 taxa and covers the 11.3–20.1°C temperature range. The SNP TS Root Mean Squared Error of Prediction (RMSEP) and R_2jack for the WA-PLS (Weighted Averaging-Partial Least Squares transfer function) component 3 are 1.39°C and 0.91, respectively, and the EE TS RMSEP and R^2jack for the WA-PLS component 2 are 0.88°C and 0.88, respectively (Luoto et al., 2019; Kotrys et al., 2020).

MALACOLOGICAL ANALYSIS

Sixty-two sediment samples were subjected to malacological analysis. Due to the small volume of individual samples and the not very abundant molluscan shells, it was necessary to combine them within the lithological layers distinguished in the profile. Ultimately, 12 samples were the basis for analysis. The identification was made using keys (Welter-Schultes, 2012; Piechocki and Wawrzyniak-Wydrowska, 2016). The species were classified into ecological groups according to the scheme described by Alexandrowicz and Alexandrowicz (2011). The percentages of ecological groups and individual taxa in each sample were calculated. On this basis, a malacological diagram was constructed as a basis for palaeoenvironmental interpretations (Fig. 10). Based on the similarity dendrogram [UPGMA clustering and Morisita's algorithm (Morisita, 1959)], two faunal assemblages were distinguished (Fig. 11). The *PAST* program was used for statistical analyses (Hammer et al., 2001).

RESULTS

RADIOCARBON DATING

The absolute chronology of the Smólsk SMO2 sediment sequence was derived by constructing a Bayesian age-depth model based on 10 ^{14}C AMS dates and includes only the organic-rich section. The dates are given as cal BP age (with 95.4% probability; Table 1). The stratigraphic discontinuity, which depending on the resolution of the samples is located at a depth between 3.50 and 3.55 m, was initially recognized by palaeoecological methods. To recognize the age of this interval in detail, samples just above and below the hiatus were selected (Fig. 2).
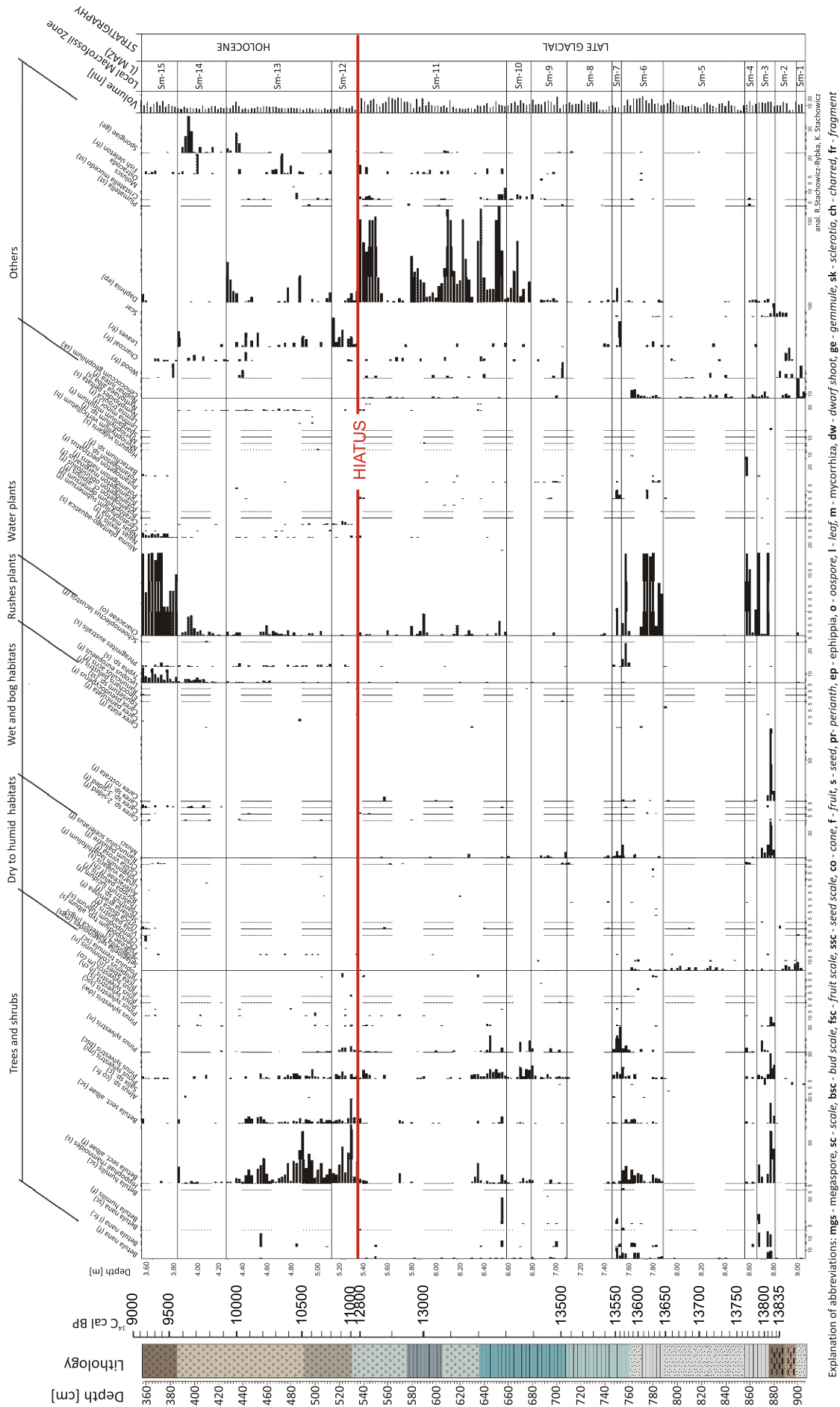
Fig. 5. Plant macroremains diagram from the Smólsk SMO2 core

Explanation of abbreviations: **mgs** - megaspore, **sc** - scale, **bsc** - bud scale, **fsc** - fruit scale, **ssc** - seed scale, **co** - cone, **f** - fruit, **s** - seed, **pr** - perianth, **ep** - ephippia, **o** - oospore, **l** - leaf, **m** - mycorrhiza, **dw** - dwarf shoot, **ge** - gemmule, **sk** - sclerotia, **ch** - charred, **fr** - fragment
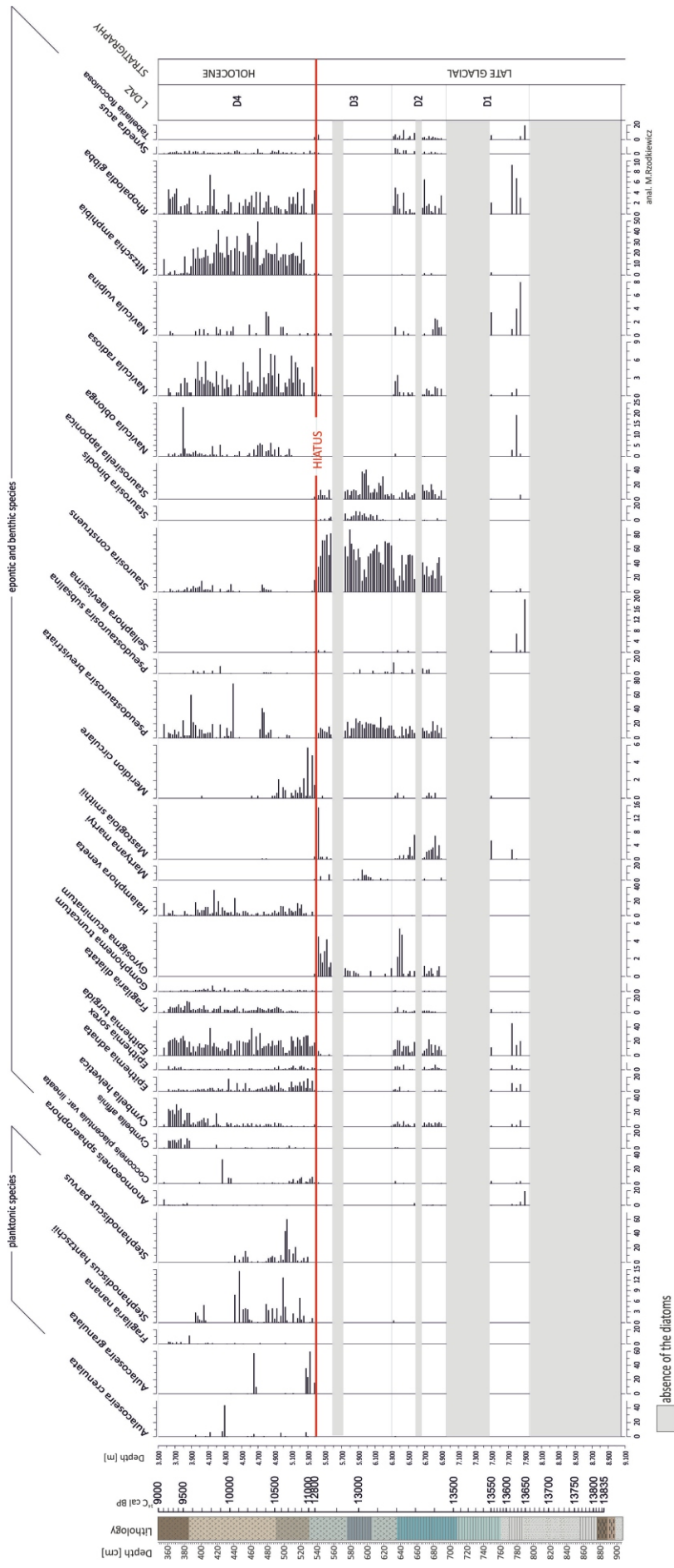
anal. R.Stachowicz-Rybka, K. Stachowicz

Fig. 6A. Diatom percentage diagram of the Smólsk SMO2 – dominant species
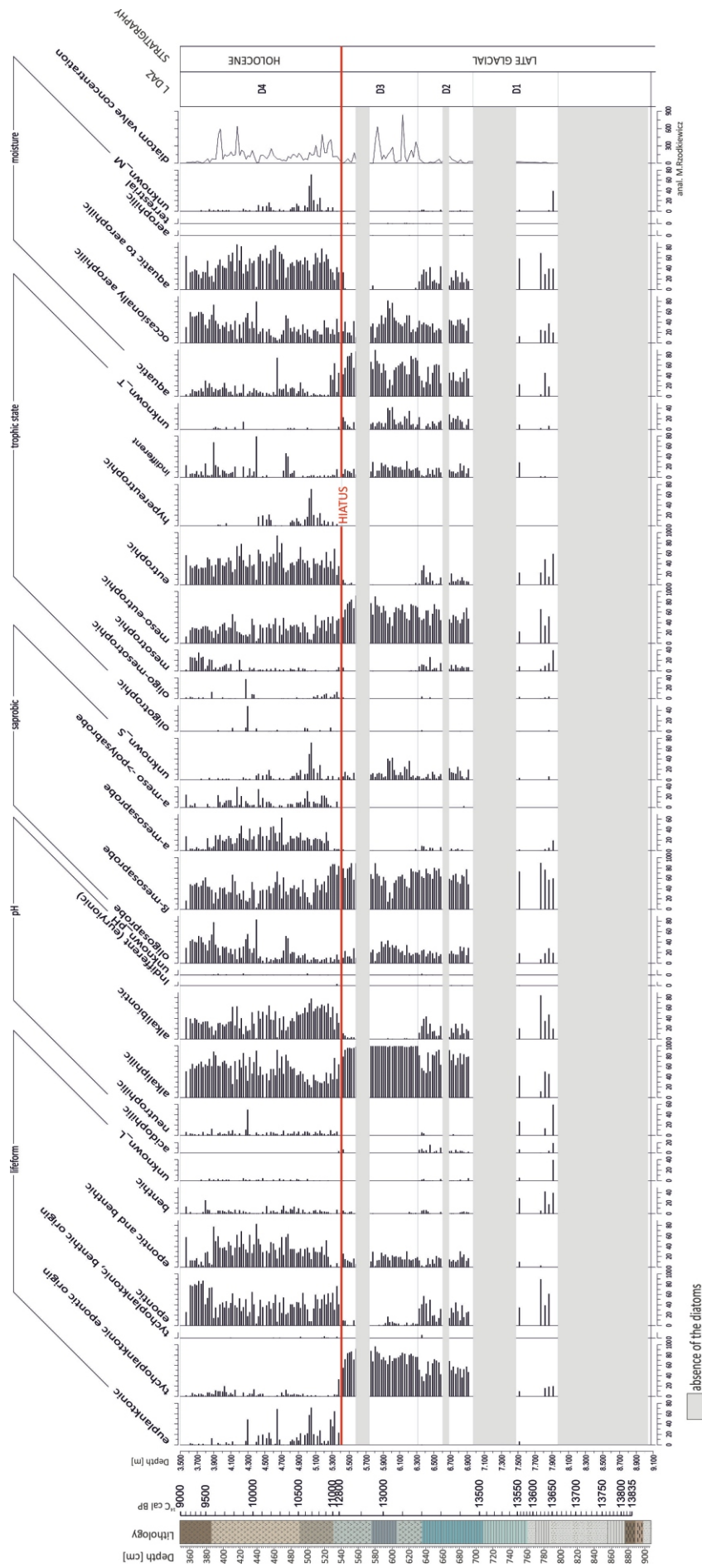
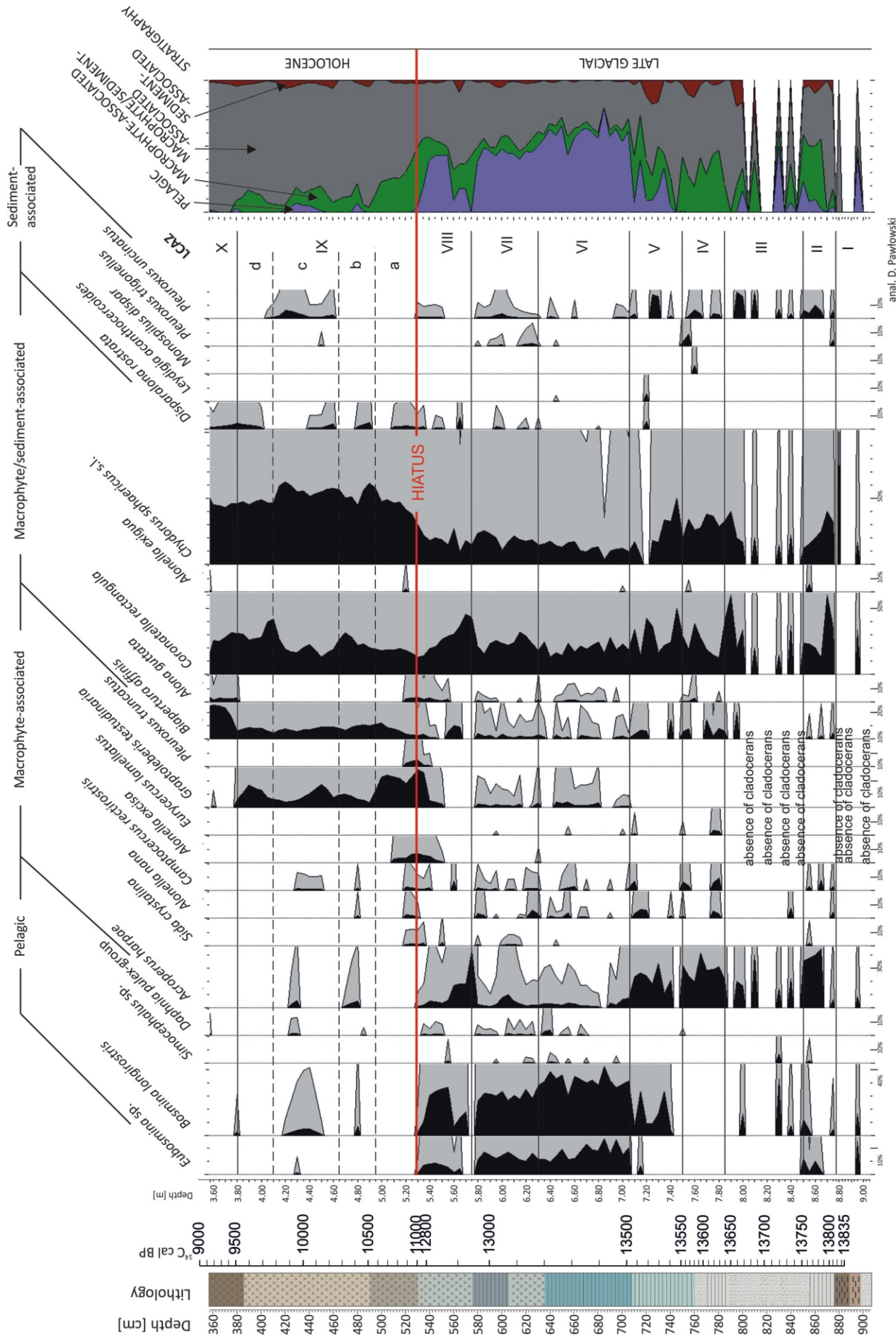**Fig. 6B – Diatom ecological group of the Smólsk SMO2 core**

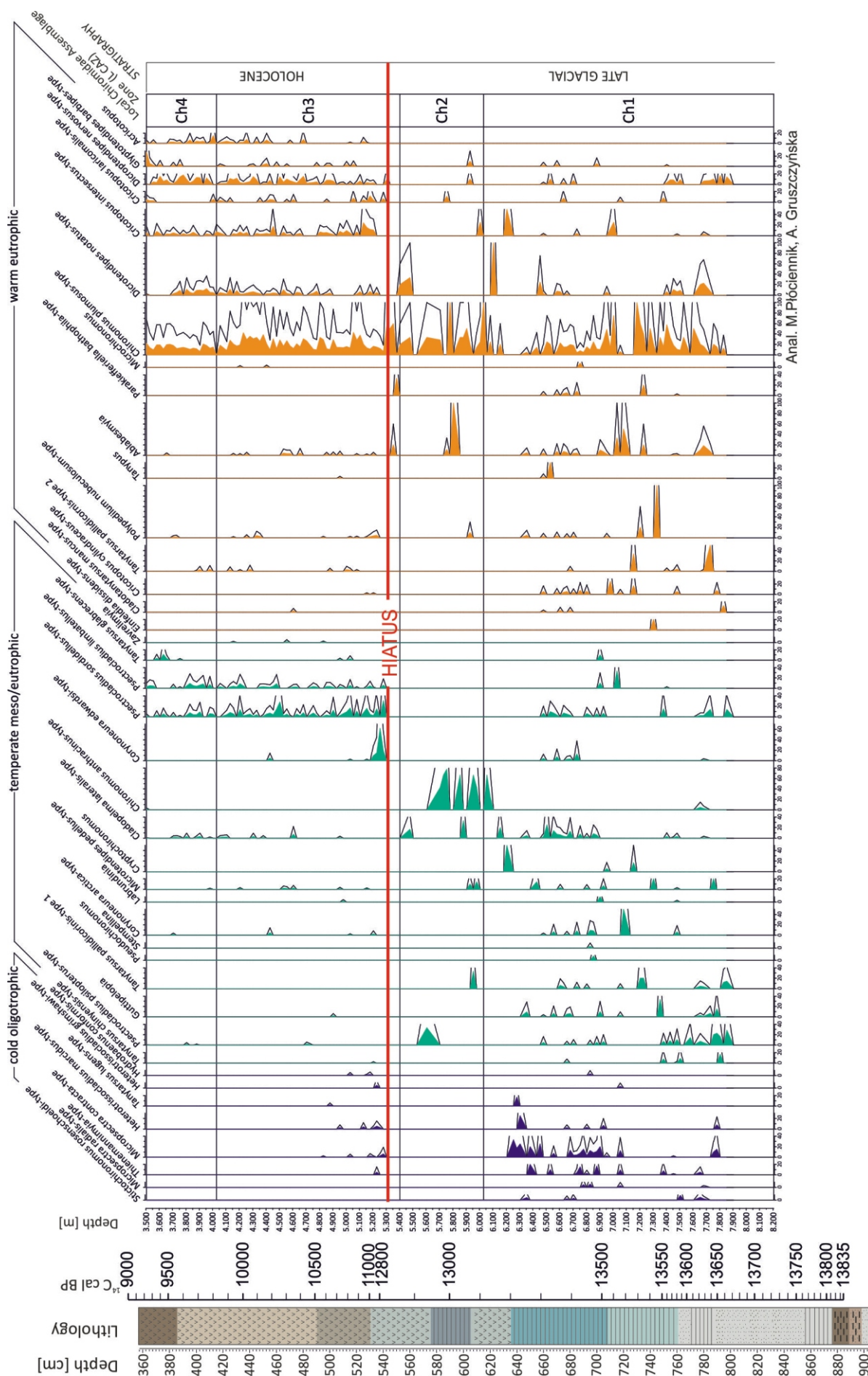**Fig. 7. Cladocera percentage diagram of the Smólsk SMO2 core**

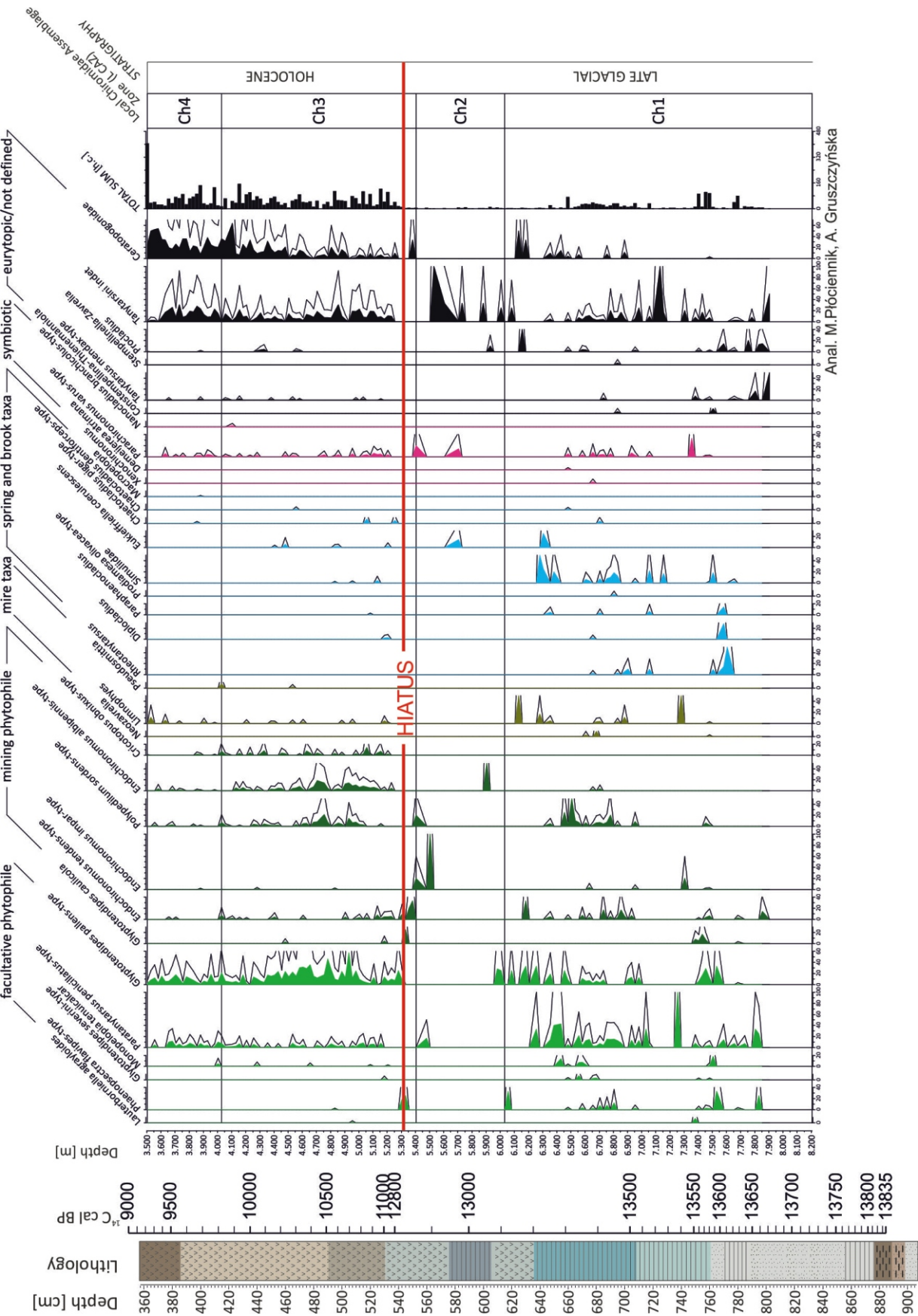Fig. 8A, B – Chironomidae percentage diagram from the Smólsk SMO2 core
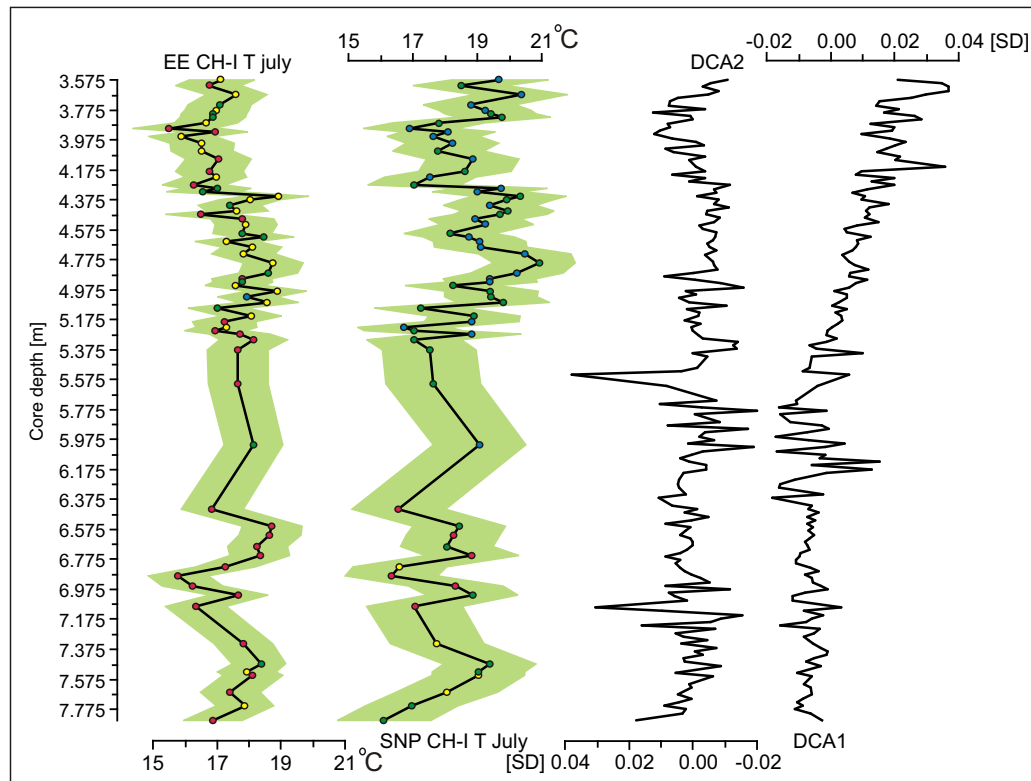
Fig. 8B

Fig. 9. Chironomiadae-inferred mean July air temperature and Chironomidae DCA

RMSEP is denoted by green shading at the reconstruction curves; modern analogues of reconstructed temperatures are represented by dots (blue – very good, green – good, yellow – moderate, red – poor modern analogues; EE CH-I T july – East–European Chironomidae-inferred mean July air temperature model; SNP CH-I T july – Swiss-Norwegian-Polish Chironomidae-inferred mean July air temperature model; SD – standard deviation

GEOCHEMICAL ANALYSIS

Geochemical changes in the succession investigated reflect two stages in the palaeolake evolution (Fig. 3). The first stage represent Late Glacial deposits (9.00–5.30 m; older than 13,853 to 12,800 cal ^{14}C BP). These deposits mainly comprise terrigenous silica (SiO_{2ter}; 75–100%) with an admixture of organic matter (LOI, average 10–20%, with the peak at depth 8.80 m) and $CaCO_3$ (1–23%). The biogenic silica content was very low, just 0.03–0.18%. The second stage, of Holocene deposits (5.30–3.60 m; 12,800–9,350 cal ^{14}C BP), shows an increase in LOI, $CaCO_3$ and SiO_{2biog} concentration. The terrigenous silica concentration decreases to the top of the core.

PALYNOLOGICAL ANALYSIS

In the pollen diagram from the SMO2 profile (Fig. 4), three Local Pollen Assemblage Zones (LPAZ) were distinguished and the deepest sample was distinguished separately, without assigning it the rank of a pollen zone. Only 62 sporomorphs were identified and counted in this sample. Local pollen zones were distinguished despite the interruptions in the course of the curves in the pollen diagram, indicating the presence of clear sedimentary disturbances. Hiatuses are located at those depths where in the samples analysed there were no sporomorphs, their number was too low, or almost all sporomorphs belonged to one taxon (e.g., *Pinus sylvestris*), which prevents percentage calculations and the obtaining of reliable results in the statistical analysis. Also due to the presence of hiatuses in

the succession, local pollen subzones were not distinguished in the diagram. The interval between the depths of 6.700 to 8.800 m, despite containing hiatuses, was included in one pollen zone SMO2 1 LPAZ (Table 2), because the pollen curves of diagnostic taxa are similar. However, when characterizing this zone, four sections were described, without formalization, separated by hiatuses, in which individual pollen taxa are distinguished in some way.

PLANT MACROREMAINS ANALYSIS

In the diagram of plant macroremains plotted for the Smólsk profile, 15 Local Macrofossil Assemblage Zones (LMAZ) were distinguished (Fig. 5 and Table 3). This division was based on the presence of one or several of the most abundant or characteristic and diagnostic taxa in the zone. Boundaries of the zones were determined based on occurrence, increase, or decrease, in the number of taxa, of a significant quantitative or indicative value. The subdivision of LMAZ and a correlation to LPAZ are compiled in Figure 12.

DIATOM ANALYSIS

Diatom analysis of the succession reveals moderate to deplorable conditions of the diatom frustule, as shown by many traces of destruction or dissolution. The habitat structure of diatoms was also not diverse. No diatoms were detected at depths of 9.050–7.950, 7.450–6.900, 6.675–6.575 and 5.750–5.575
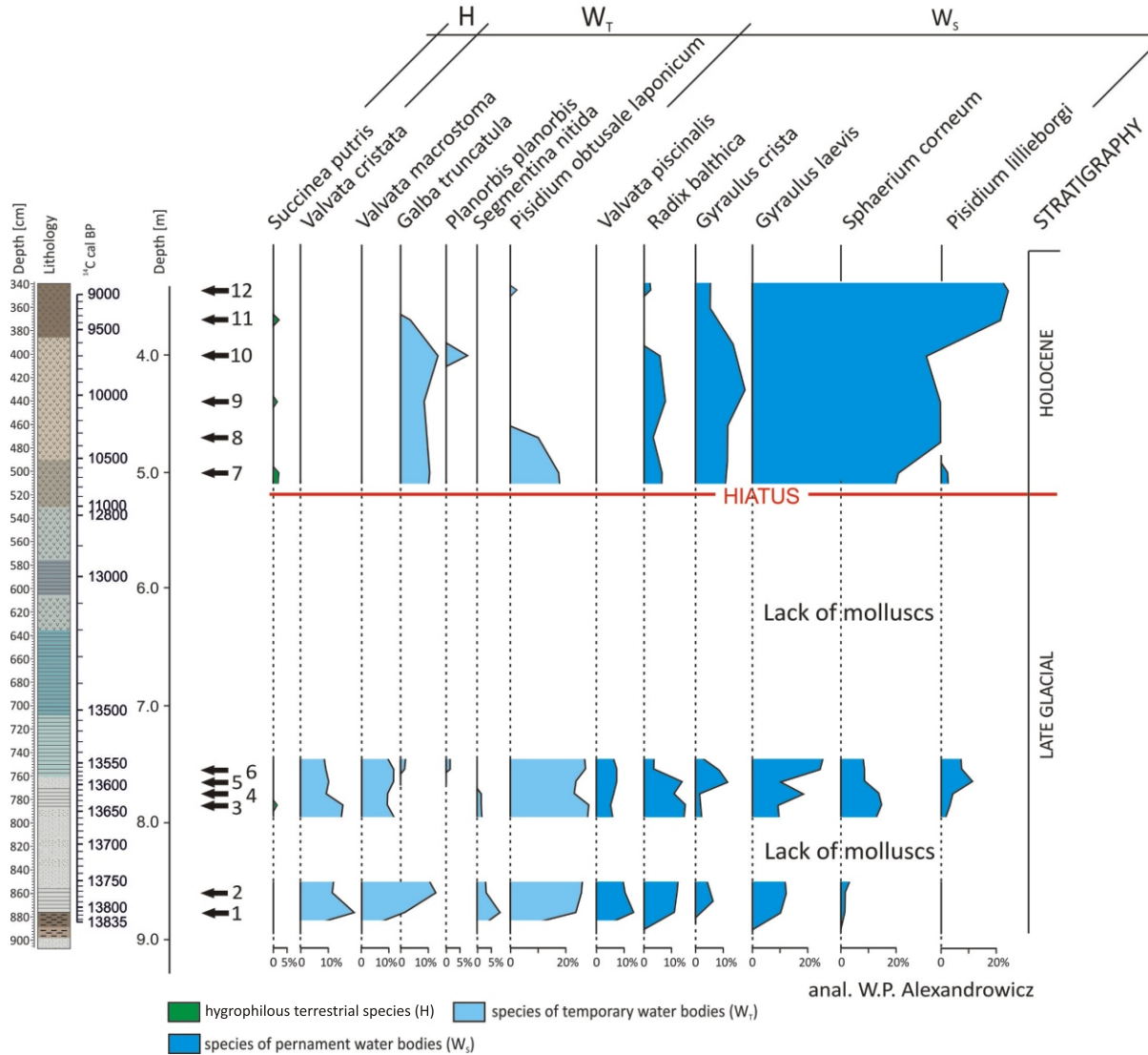
Fig. 10. Ecological structure of the mollusc community from the Smólsk SM02 core

Mollusc ecological groups after Ložek (1964), Alexandrowicz and Alexandrowicz (2011)

m. A total of 155 diatom species were identified in the core examined. The dominant taxa account for >5% of the relative abundance and represent 32 species. The predominant species were tycho-planktonic species, i.e. random plankton (D1, D2, D3 phase; Fig. 6). This abundance of tycho-plankton in lakes is influenced by waves and vertical mixing of the water, causing benthic diatoms to detach from the substrate and float in the water. According to the classification of Denys (1991), benthic diatoms that have been resuspended are classified as tychoplankton (Fig. 6A). Phase D4 characterized a high relative abundance of epontic and benthic species with the occurrence of euplanktonic taxa. Forty-seven species were rare (occurring only once). In comparison, 32 species were dominant (i.e., occurring in more than ten samples with a proportion >5% of the community), while five species were most abundant (i.e., ≥50% of the community). The most abundant species were *Staurosira construens, Pseudostaurosira brevistriata, Stephanodiscus parvus, Aulacoseira*
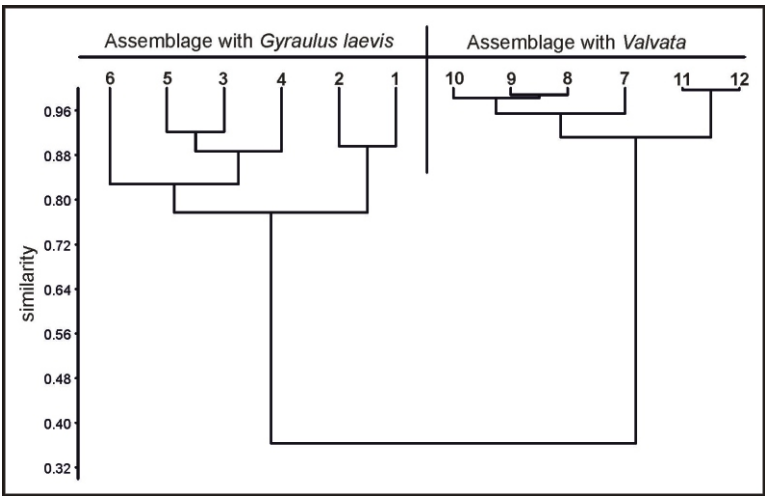

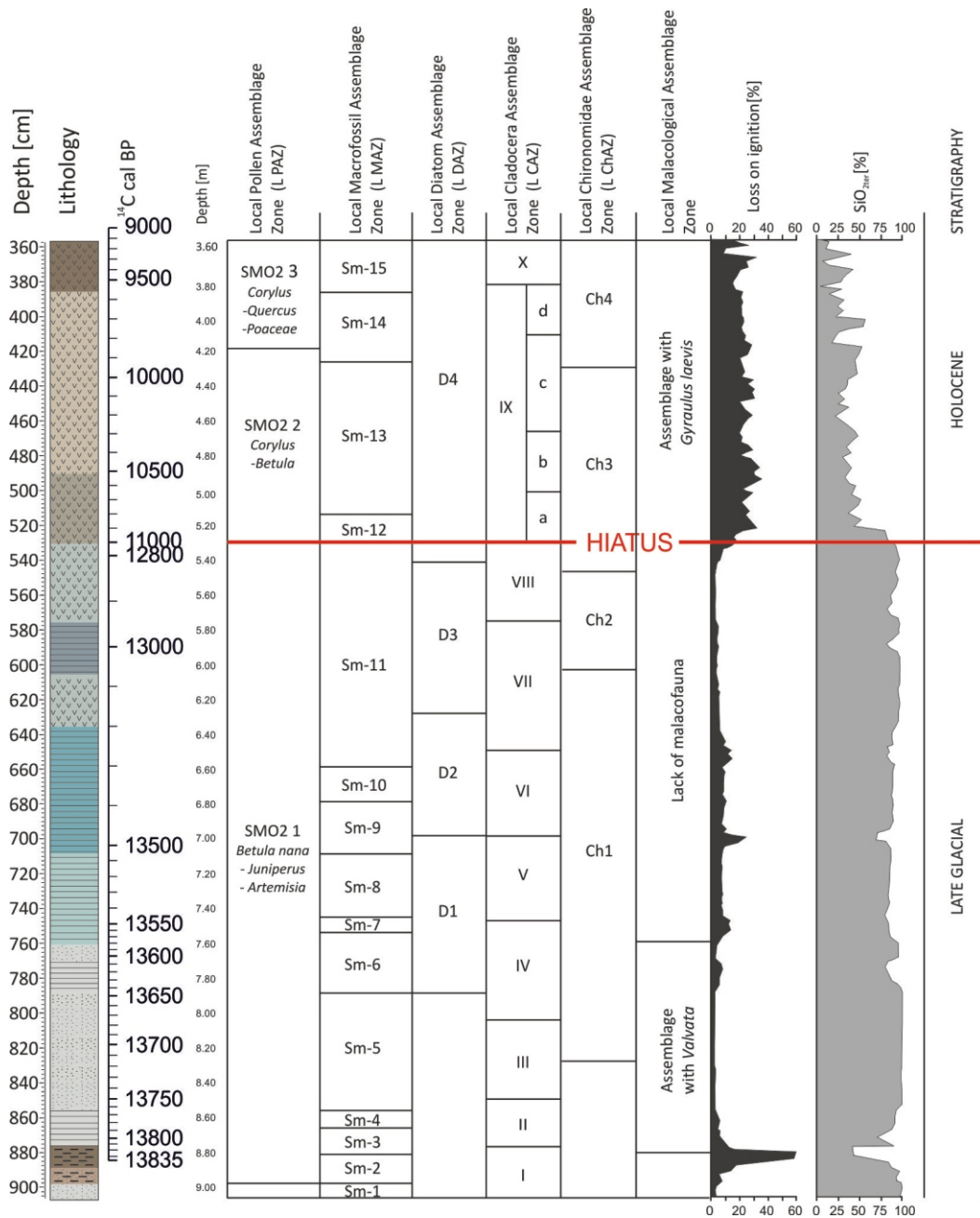**Fig. 11. Dendrogram of similarities and mollusc assemblages from the Smólsk SMO2 core**

**Fig. 12. Correlation of local palaeoenvironmental changes recorded
in the Smólsk SMO2 core**

granulata and *Nitzschia amphibia. Staurosirtra construens* was identified in 98 samples with 88.1% of the maximum relative abundance, *Pseudostaurosira brevistriata* occurred in 104 samples (max. 76.9%), *S. parvus* in 34 samples (max. 60.5%).

Changes in species composition and, thus, differences in the proportions of certain ecological diatom groups, divided the core into four local diatom assemblage zones (D1–D4). Indicators such as habitat category, pH preference, saprobic and trophic state and moisture were considered (Fig. 6 and Table 4).

CLADOCERA ANALYSIS

The sediments from Smólsk core contain 23 Cladocera species, belonging to 4 families: Bosminidae, Daphniidae, Si-

didae and Chydoridae. The number of Cladocera specimens fluctuated between 13,600 and 300, and the number of species between 3 and 17 per cm^3. Ten Local Cladocera Assemblage Zones (L CAZ's) have been distinguished (Fig. 7 and Table 5). At depths: 9.050–9.000; 8.925–8.800; 8.475–8.425; 8.350–8.325; 8.275–8.125; 8.075–8.025; 7.875 m, no Cladocera remains occur.

CHIRONOMIDAE STRATIGRAPHY

Five thousand three hundred forty-three head capsule (hc) of 72 Chironomidae morphotypes, Tanytarsini indet., Ceratopogonidae and Simuliidae were collected (Fig. 8). Four statistically

T a b l e   2

Description of local pollen assemblages zones (LPAZ) at Smólsk SMO2

Depth [m]	Name LPAZ	Description	
4.150–3.600	SMO2 3 *Corylus-Quercus--Poaceae*	high amount of *Corylus avellana* pollen grains, continuous curve of *Quercus* and *Ulmus* taxa	
5.350–4.200	SMO2 2 *Corylus-Betula*	continuous percentage curve of *Corylus avellana*; high amount of *Betula* undiff., decreasing upwards; upper limit: the beginning of the continuous *Quercus* curve, increase of Poaceae; concentration of sporomorphs slightly lower	
8.800–5.400	SMO2 1 *Betula nana-Juniperus--Artemisia*	course most of the curves is relatively similar from the bottom to the top of the zone (despite the clear hiatuses in the succession); almost continuous curves of *Betula* t. *nana*, *Juniperus* and *Artemisia*; discontinuous *Populus* curve. Upper limit: a sharp decline or disappearance of most curves; concentration of sporomorphs from very low in the bottom, slightly increased to the top; upper limit of L PAZ is not described because of hiatuses	5400–5700 mm; higher amount of *Populus*, *Alnus* and Poaceae pollen grains, as well as *Sphagnum*, indeterminable and rebedded; concentration of sporomorphs slightly higher
			5750–6550 mm; high amount of *Artemisia* pollen grains, as well as *Filipendula;* a lower percentage of local, rebedded and corroded degraded taxa; concentration of sporomorphs low
			6700–7100 mm; percentage, but discontinuous curve of *Larix;* high amount of *Betula* t. *nana*; the curves of *Pinus sylvestris* and *Betula* undiff. amounts similar; single grain of *Pinus cembra*/*Pinus haplox*; concentration of sporomorphs low
			7150–8800 mm; percentage, discontinuous, *Hippophaë rhamnoides* and *Selaginella selaginoides* curves; high amount of indeterminable: corroded and rebedded sporomorphs; concentration of sporomorphs very low
8.900	one spectrum only; total sum including sporomorphs of trees, shrubs, dwarf-shrubs and terrestrial herbaceous plants = 62 is insufficient for statistical calculations and interpretation of vegetation		

significant zones were identified. The Local Chironomidae Assemblage Zones (L ChAZ) are compiled in Table 6 and Figure 8.

MALACOLOGICAL ANALYSIS

The material analysed yielded a relatively poor malacofauna. Thirteen species of molluscs were recognized, 1 terrestrial species, 9 species of aquatic snails and 3 species of bivalves represented by a total of almost 1600 specimens. The terrestrial malacofauna is represented only by single shells of a hygrophilous species – *Succinea putris* (Fig. 10 and Table 7).

Aquatic molluscs typical of intermittent lakes (ecogroup$_{WT}$) appear in large numbers especially in the lower part of the sequence. *Pisidium obtusale laponicum* is notably present; this form is characteristic of small, often intermittent water bodies in cold climate conditions. It is a common component of malacocenoses found in postglacial and Early Holocene deposits filling palaeochannels (Alexandrowicz, 1989, 1999, 2013; Wojciechowski, 1999; Apolinarska and Ciszewska, 2006; Georgopoulou et al., 2016) and indicative of this period (Alexandrowicz, 2009; Fig. 10 and Table 7).

Permanent water body taxa appear throughout the sequence analysed. Particularly noteworthy is the common occurrence (especially in the higher interval of the profile) of *Gyraulus laevis*. This is a pioneer, cold-tolerant species inhabiting shallow water bodies with moderately rich vegetation (Welter-Schultes, 2012; Piechocki and Wawrzyniak-Wydrowska, 2016). The form described here is one of the most characteristic components found in lake sequences of the Late Glacial and Early Holocene and can be regarded as indicative of this period (Alexandrowicz, 2009). Another important species is *Pisidium*

lillieborgi. It is a cold-tolerant bivalve inhabiting shallow water bodies with moderate vegetation and sandy bottoms (Welter-Schultes, 2012; Piechocki and Wawrzyniak-Wydrowska, 2016; Fig. 10 and Table 7).

PALAEOLAKE TRANSFORMATION DURING THE LATE GLACIAL AND EARLY HOLOCENE

LATE GLACIAL
(BEFORE ~13,835 cal[14]C BP)

With the beginning of the functioning of the palaeolake in Smólsk studied, the environmental conditions were not sufficient for the deposition of organic matter on the lake bottom, such as the sporomorphs of plants that could already be growing in the vicinity of the site or even in the lake itself. This is shown by the analysis of the lowest pollen spectrum from a sample of sand with organic matter from a depth of 9.000 m (<13,835 cal[14]C BP) in which only numerous (+++) *Selaginella selaginoides* spores were recorded (Fig. 4). The plant macroremains also document a significant amount of *Selaginella selaginoides* megaspores, as well as vegetation typical of wet or periodically flooded areas such as *Viola palustris* or *Typha* sp. The relatively large share of *Cenococcum geophilum* indicates that the soils around the basin were not stabilized by vegetation. Despite the lack of pollen grains from trees, shrubs and dwarf shrubs, it seems that they were present around the lake. This is indicated by the few fruits of *Betula nana* and mycorrhiza of *Pinus sylvestris*. In the cool and probably calcium carbonate-rich waters, there were few representatives of Characeae.

T a b l e 3

Description of local macrofossil assemblages zones (LMAZ) of the Smólsk SMO2 core

LMAZ Depth [m]	Description of LMAZ Smólsk SMO2 core
Sm-1 9.050–8.975 3 samples	*Betula nana* fruits and mycorrhiza of *Pinus sylvestris* represented the terrestrial plants. Among the dry to humid habitats, numerous *Selaginella selaginoides* megaspores and single *Viola palustris* seeds were identified. There were no plant macroremains from the peatbog group. Reedswamp vegetation was represented only by *Typha* sp. seeds. A few Characeae oospores appeared among the aquatic vegetation at the top. In addition, *Cenococcum geophilum* sclerotia, wood fragments, were marked. The upper boundary of this zone was determined on the basis of a decrease in *Cenococcum geophilum* remains.
Sm-2 8.975–8.800 7 samples	*Betula nana* fruits and *B.* sect. *albae* fruits and fruit scales were among the trees and shrubs at the top of the zone. Mycorrhizas and bud scales of *Pinus sylvestris* were also present. *Selaginella selaginoides* and *S. helvetica* megaspores were still abundant in addition to *Viola palustris* and *Urtica dioica* seeds appearing. Peatbog plants were represented only by a single *Carex* sp. *biconvex* fruit. There were no plant macroremains from the reedswamp and aquatic plants group. The scars and fragments of wood and charcoal as well as *Cenococcum geophilum* sclerotia were marked. The boundary of the zone was based on the increase in the share of trees, shrubs and plants from peatbog habitats.
Sm-3 8.800–8.650 6 samples	In this zone, the number of plant macroremains was higher in all ecological groups. Among the trees, the remains of *Betula nana*, *B. humilis*, *B.* sect. *albae* and *Pinus sylvestris* were marked. Among the plant groups preferring dry habitats to humid ones, taxa such as *Selaginella selaginoides* megaspores, *Stellaria graminea* fruit and undefined Poaceae seeds were present. The peatbog plants group included stems of brown mosses and *Carex* sp., *Carex* sp. *biconvex*, *C. rostrata*, *C. pseudocyperus* fruits. The remains of reedswamp plants such as *Phragmites australis* were very few. Aquatic plants were represented by numerous Characeae oospores, and fruits of *Najas flexilis*, *Batrachium* sp., *Lemna minor* as well as *Potamogeton natans* and *P.* cf. *alpinus* endocarps. Among the remains of animals, *Cristatella mucedo* statoblasts and ephippia of *Daphnia* sp. were found. There were also numerous scars and fragments of wood. The boundary of the zone was based on a decrease in the share of trees, shrubs and plants from peatbog habitats.
SM-4 8.650–8.550 4 samples	The number of *Betula nana* leaf fragments, *Betula* sect. *albae* fruit and fruit scales and *Pinus sylvestris* bud scales, mycorrhiza, needles, dwarfs and seed scales were clearly decreasing. In the group of plants preferring dry habitats to humid ones, nitrophilous taxa such as *Ranunculus sceletratus* and *Rorippa palustris* appeared. *Selaginella selaginoides* megaspores were still present. The remains of peatbog plants almost completely disappeared. Only single stems of brown mosses and *Carex rostrata* fruits were noted. The reedswamp vegetation was represented by a single *Phragmites australis* and *Typha* sp. seeds. The aquatic plants were represented by *Batrachuim* sp. fruit and Characeae oospores whose share was very high. There were statoblasts of the bryozoans *Cristatella mucedo* and *Plumatela* sp., and *Daphnia* sp. ephippia, as well as *Cenococcum geophilum*, leaves and wood fragments.The boundary of the zone was based on a decline in the proportion of aquatic plant macroremains.
Sm-5 8.550–7.875 27 samples	In the group of trees and shrubs, *Betula nana* fruit and fruit scales and *Salix* sp. capsules were marked. Dry habitats to humid ones were represented by a single *Urtica dioica* and Poaceae fruits. Moreover, *Selaginella selaginoides* and *S. helvetica* megasospores were still moderately numerous and present throughout the zone. The share of taxa representing boggy habitats was still low and was represented only by both *Carex rostrata* and *Equisetum* sp. Reedswamp vegetation was represented by a single fruit of *Phragmites australis*. The remains of aquatic plants almost completely disappeared. Only single *Potamogeton natans* endocarps and Characeae oospores were marked at the top of the zone. Ephippia of *Daphnia* sp., sclerotia of *Cenococcum geophilum*, as well as scars, fragments of charcoal, wood and leaves were determined. The boundary was based on a slight increase in the proportion of aquatic plant remains in all ecological groups.
Sm-6 7.875–7.525 14 samples	The abundance of trees and shrubs plant remains was significantly increasing, especially *Betula nana* fruit and leaf fragments, *B.* sect. *albae* fruit, fruit scales, remains of *Pinus sylvestris* and *Picea abies*. There were *Alnus* sp. cone fragments, *Hippophae rhamnoides* seeds and *Populus tremula* scales. *Selaginella selaginoides* and *S. helvetica* megasospores were still moderately numerous and present throughout the zone.The fruits of *Diathus* sp., *Thalictrum lucidum*, *Cicuta virosa*, *Rorippa palustris* and *Cirsium palustre* were representatives of the dry to humid group. Only single stems of brown mosses were noted. The share of Cyperaceae fruit increased significantly. *Carex rostrata*, *C. elata* and *C.* sp. div. trigonous, appeared. Reedswamp vegetation was represented by large number of seeds: *Phragmites australis*, *Typha* sp. and single *Schoenoplectus lacustris* fruit. Among aquatic plants, the endocarps of *Potamogeton natans*, *P. obtusifolius*, *P.* sp. dominated, as well as *Bartachium* sp. fruit reappeared in a single example. The share of Characeae oospores was the highest in the entire profile. Only single *Potamogeton natans* endocarps were marked in the top of the zone. The statoblasts of the bryophytes *Cristatella mucedo* and *Plumatela* sp. as well as Spongiae gemmule, remains of a fish skeleton, Ostracoda, *Daphnia* sp. and *Cenococcum geophilum* were determined. The boundary was based on a slight increase in the proportion of *Pinus sylvestris* remains
Sm-7 7.525–7.450 3 samples	Trees and shrubs were represented by a *Betula nana*, *B. humilis* and *B.* sect. *albae* and *B.* sp. fruit, fruit scales and leaves. *Pinus sylvestris* seeds, bud scales, and needles were present. Cone fragments of *Alnus glutinosa* appeared. In the dry to humid habitats group, Poaceae fruit reappeared. Peatbog plants, represented by stem moss fragments, were relatively numerous while individual fruits of *Carex elata* and *Eleocharis palustris* appeared. Among the remains of reedswamp plants, seeds of *Phragmites australis* were found in an individual example. Endocarps of *Potamogeton natans*, *P.* sp. and Characeae oospore were present in the aquatic plants group. Ephippia of *Daphnia* sp. as well as fragments of leaves and scars were determined. The boundary was based on a significant decrease in the proportion of plant remains in all ecological groups.
Sm-8 7.450–7.075 15 samples	In the bottom of this zone only a few fruits and fruits scales of *Betula* sect. *albae* among trees and shrubs were observed. In the group of plants preferring dry habitats to humid ones, nitrophilous taxa such as *Urtica dioica* and *Rorippa palustris* and *Thalictrum lucidum* individuals reappeared. The remains of peatbog plants almost completely disappeared. Only single stems of brown mosses were noted. There were no remains of the reedswamp and plants group. Aquatic plants was represented only by Characeae oospores. Statoblasts of *Plumatela* sp., ephippia of *Daphnia* sp., gemmule of Spongiae as well as fragments of leaves and scars were determined.The boundary was based on an increase in the proportion of plant remains in all ecological groups.
Sm-9 7.075–6.775 12 samples	Leaves and fruit of *Betula nana* reappeared in the group of trees and shrubs. There were also fruit and fruit scales of *Betula* sect. *albae*, *B. humilis* and seeds, bud scales and needles of *Pinus sylvestris* and *Juniperus communis* needles. *Selaginella selaginoides* and *S. helvetica* megaspores were abundant, in addition *Ranunculus sceleratus* fruit appeared. The abundance of peatbog plant remains was slightly increasing, especially the stems of brown mosses, *Carex* sp. fruit, *C. fusca*, and *Eleocharis palustris*. Reedswamp vegetation was represented by a single *Typha* sp. and *Phragmites australis* fruit. Compared to the previous zone, the number of aquatic plants remains increased, including Characeae oospores, *Batrachium* sp. fruit and *Potamogeton natans* and *P.* sp. endocarps. Individual *Cenococcum geophilum* sclerotia, charcoal and leaf fragments were also marked. Among animal remains, *Cristatella mucedo* and *Plumatela* sp. statoblasts, *Daphnia* sp. ephippia, Spongiae gemmule, ostracoda and fish skeleton fragments were found in low numbers. The upper boundary of this zone was based on the increase in the share of *Daphnia* sp. ephippia, and the *Pinus sylvestris* remains.

Tab. 3 cont.

LMAZ Depth [m]	Description of LMAZ Smólsk
Sm-10 6.775–6.575 8 samples	As in the previous zone, there were tree and shrub taxa such as *Betula nana* leaves and fruit, *Betula* sect. *albae* fruit and fruit scales, and more abundant *Pinus sylvestris* bud scales and needles. There were no remains of the dry to humid plants group. Among the peatbog plants, a few *Lycopus europaeus* fruit and single stems of brown mosses were identified. There were no remains of reedsswamp and aquatic vegetatation except for an individual Characeae oospore. *Daphnia* sp. ephippia as well as *Cristatella mucedo*, *Plumatella* sp. statoblasts, fish skeleton fragments, wood and charcoal were also marked. There were also numerous scars and fragments of leaves. The boundary of the zone was based on an increase in the share of tree and shrub remains.
Sm-11 6.575–5.350 46 samples	At the bottom in this zone, the number of plant macroremains increased in all ecological groups, especially trees and shrubs. The remains of *Betula nana*, *B. humilis*, *Betula* sect. *albae*, *Pinus sylvestris* and *Populus tremula* were marked. The presence of *Betula humilis* fruit was highest in the whole profile. In the group of plants preferring moist habitats, nitrophilous taxa such as remains of *Ranunculus sceletratus*, *Urtica dioica*, Poaceae and Asteraceae were observed. The share of taxa representing boggy habitats was still low and was represented by *Carex elata*, *C. rostrata*, *C.* sp. div. *biconvex*, and *Carex* sp. fruit and single stems of brown mosses. Reedsswamp vegetation was represented only by *Phragmites australis* and *Typha* sp. seeds. Aquatic plants were represented by the less numerous fruit of *Alisma plantago aquatica*, *Najas marina*, *Nymphaea alba*, *Nuphar lutea*, endocarps of *Potamogeton natans*, *P. marginatus*, *Potamogeton* sp., *Myriophyllum* sp., *Sparganium minimum* and oospores of Characeae. Numerous ephippia of *Daphnia* sp., statoblasts of *Cristatella mucedo*, and less numerous wood, charcoal, scars and fragments of leaves were marked. Individual *Cenococcum geophilum* sclerotia were also present. The boundary of the zone was marked on the basis of an increase in *Pinus sylvestris* and *Betula* sect. *albae* remains.
Sm-12 5.350–5.125 11 samples	This zone was characterized by a significant increase in the existence of *Betula* sect. *albae* remains which is the highest in the entire profile. Bud scales, needles, dwarfs of *Pinus sylvestris* and bud scales of *Populus tremula* were also numerous. There were still *Betula nana* remains. The share of taxa from the dry habitat group to the humid one was still low and was represented by a few *Selaginella selaginoides* megaspores and Poaceae seeds. The peatbog plants included *Carex* sp. trigonous, *Carex* sp. *biconvex*, *C. elata*, *C. pseudocyperus*, and *Lycopus europaeus*. Reedsswamp plants were represented by *Phragmites australis* and *Typha* sp. Compared with the previous zone, the number of aquatic plants remains including Characeae, *Najas marina*, *Ceratophyllum demersum*, *Potamogeton natans*, *Nymphaea alba* and *Nuphar lutea* increased. In this zone the presence of leaf fragments was higher. Meanwhile the share of *Daphnia* sp. ephippia decreased significantly. Statoblasts of *Plumatella* sp., *Cristatella mucedo*, and less numerous wood, charcoal and fish skeleton fragments were marked. Individual *Cenococcum geophilum* sclerotia were also present. The boundary of the zone was placed on the basis of a decrease in *Daphnia* sp. ephippia.
Sm-13 5.125–4.250 35 samples	This zone was constantly characterized by a high proportion of tree and shrub remains, especially *Betula* sect. *albae*, *B. nana* and *Pinus sylvestris*. Poaceae seeds were still abundant. In addition, *Urtica dioica*, *Cicuta virosa* and Asteraceae seeds reappeared. Only single stems of brown mosses were noted. The share of Cyperaceae such as *Carex rostrata*, *C. paniculata*, *C.* sp. div. *biconvex* and, *C.* sp. div. trigonous were present. Reedsswamp vegetation was represented by numerous *Phragmites australis* and *Typha* sp. fruit. The proportion of aquatic plants also increased significantly, represented by also a great number of Characeae, *Najas marina*, *Ceratophyllum demersum*, *C. submersum*, *Nymphaea alba*, *Nymphoides peltata*, *Lemna trisulca* and *Myriophyllum verticilllatum* remains as well as *Potamogeton pectinatus*, *P. natans* and *Potamogeton* sp. endocarps. Among the animal remains, *Cristatella mucedo* and *Plumatella* sp. statoblasts, fish skeleton fragments, molluscs and ephippia of *Daphnia* sp. were found. There were also numerous fragments of leaves, wood and charcoal. The boundary was based on a significant decrease in the proportion of plant remains in the terrestrial plants groups.
Sm-14 4.250–3.850 16 samples	The abundance of trees and shrubs plant remains was increasing, especially the fruit and fruit scales of *Betula* sect. *albae*, *Alnus* sp. cone fragments and remains of *Pinus sylvestris*. Among the plant groups preferring dry habitats to humid ones, only *Polygonum lapathifolium* fruit was present. Only the share of Cyperaceae fruit increased slightly. The fruit of *Carex elata* and, *C.* sp. div. *biconvex* and *Carex* sp. were found. Among the remains of reedsswamp plants, the seeds of *Phragmites australis*, fruit of *Schoenoplectus lacustris* and numerous seeds of *Typha* sp. were present. A few *Ceratophyllum demersum*, *C. submersum* fruit, *Nymphaea albe* seeds and Characeae oospores were among the aquatic vegetation. Spongiae gemmule, fish skeleton remains, as well as *Daphnia* sp. ephippia were determined. The boundary of the zone was based on the increase in the share of aquatic plants, especially Characeae oospores.
Sm-15 3.850–3.550 12 samples	In this zone, the number of plant macroremains increased in all ecological groups. As in the previous one, the presence of both *Betula* sect. *albae* and *Pinus sylvestris* remains were similar. In the group of plants preferring moist habitats, nitrophilous taxa such as fruit of *Urtica dioica*, *Ranunculus sceleratus* reappeared. There were also *Chanopodium* t. *album*, *Ch. rubrum*, *Linaria vilgaris* and Poaceae remains. The share of taxa representing boggy habitats, including a few *Carex* sp., *C.* sp. *biconvex*, *Carex* sp. trigonous, *C. rostrata*, *C. paniculata* fruits and single stems of brown mosses were still low. Reedsswamp plants, of which the presence was the highest in the entire profile, were represented by the *Typha* sp. seeds. Also the proportion of *Phragmites australis* seeds is relatively high. The aquatic plants group was dominated by the remains of Characeae, *Najas marina* and *Batrachium* sp. Fruit of *Ceratophyllum demersum* and *C. submersum* were still present, although only in a single example. Numerous wood, charcoal fragments were marked. A few *Daphnia* sp. ephippia and fish skeleton fragments were also present.

In the spectrum of pollen deposited above 8.900 m, in muds with organic matter, very few (total sum = 62) sporomorphs were identified. Among these, the presence of juniper pollen and *Selaginella selaginoides* spores indicates an open environment, not demanding in terms of soil richness, but requiring access to sunlight. However, this is still an insufficient number of sporomorphs to characterize the vegetation at that time, because the presence of *Pinus sylvestris* t. and *Betula* undiff. pollen grains, which may come from outside the site studied, as well as pollen of Cyperaceae, Poaceae and individual ecologically unspecified herbaceous plants does not provide a basis for this. At that time, *Selaginella helvetica* and birch trees (*Betula* sect. *albae*) are also present in the set of plant macroremains. Terrestrial herbaceous vegetation is represented by *Viola palustris*, *Urtica dioica* and *Carex* sp., which, together with the decrease in the amount of *Cenococcum geophilum* sclerotia, shows that the vegetation became more dense on the gradually developing soil.

The samples above, in which about 500 sporomorphs were counted, provide a basis for a very general interpretation, indicating that the substrate was stabilizing and creating the conditions for the development of vegetation and the deposition of their remains in the sediment in the form of very strongly decomposed organic matter. In such conditions, sporomorphs could have already been preserved. However, the concentration of sporomorphs in the spectra described is very low. In addition, most of them are unidentifiable, and have been classified as corroded sporomorphs (indet. corroded) and degraded

Main phases of diatom development recorded in the Smólsk SMO2 profile

Zone	Depth [m]	Main results of diatom analysis
	9.050–7.950	No diatoms in this part of core
D1	7.900–6.950	The composition of diatom species reflected the improvement of environmental conditions. In samples 7.900, 7.850, 7.750, and 7.500, a diatom flora occurred, dominated by aquatic to aerophilic species (69.8–30.1%). Major groups were epontic (90.7–35.7%) and benthic species (43.3–5.8%). A predominance of pH alkaliphilous (50.6–12.8%). -mesosaprobous species also occurred (90.7–57.3%), with a slightly higher proportion of meso-eutraphentic species (66.3–22.6%). At the beginning of the zone, the diatom valve concentration increased from 3.2 10^6/cm^3 to 16.1 10^6/cm^3, and later, at the top of the D1, it increased to 24.1 10^6/cm^3. From the depth of 7.500 to the top of the D1 phase, diatoms disappear. The most abundant were *Epithemia turgida*, *Sellaphora laevissima*, *Navicula vulpina* and *Rhopalodia gibba*.
D2	6.900–6.325	Diatoms reappear from at the depth of 6.900 to 6.325 m and present between 6.675–6.575 m. Aquatic habitats (62.8–18.1%) dominated and were favourable for tychoplanktonic taxa (72.4–30.1%): e.g., *Staurosira construens*, *Pseudostaurosira brevistriata*, *Epithemia turgida*, *Mastogloia smithii* and *Rhopalodia gibba*. Occasionally aerophilic and aquatic to aerophilic taxa also occurred. The most frequent were alkaliphilous taxa (93.0–47.7%). Dissolved organic matter concentration was favourable for -mesosaprobous taxa (48.6–80.5%). Meso-eutraphentic species (75.9–34.5%) were also most abundant in this zone. The highest diatom concentration was at 6.675 m, with 116.7 10^6/cm^3, then decreasing to 2.8 10^6/cm^3 toward the upper part of the core.
D3	6.300–5.425	In D3 most abundant were aquatic species (89.8–15.5%), with a predominance of pH alkaliphilous (100.0–79.8%) and -mesosaprobous (89.8–15.5%) taxa. Oligosaprobous species also occurred. A slightly higher proportion of meso-eutraphentic taxa than in the previous zone (92.6–34.0%). The most abundant species were: *Staurosira construens*, *Staurosira lapponica*, *Staurosira binodis*, *Pseudostaurosira brevistriata*. High diatom valve concentration (average 164.0 x 10^6/cm^3) with peaks at depth 6.125 m (834.1 10^6/cm^3) and 5.825 m (633.6 10^6/cm^3). No diatoms at the depth 5.75–5.575 m
D4	5.400–3.575	The diatom species composition reflected the changes in environmental conditions. Diatoms occurred in a wide range of life forms: euplanktonic, tychoplanktonic, epontic and benthic species. The diatoms were also dominated by occasionally aerophilic (80.0–5.7%, average 32.3%) and aquatic to aerophilic species (average 48.4%). Decrease in aquatic species. Predominance of pH alkaliphilous (93.2–20.5%) and alkalibiontic (78.3–2.1%). -mesosaprobous species also occurred (87.9–3.2%). Decrease in meso-eutraphentic, and increase in eutraphentic taxa from 20.0 to 56.8% (average 43.6%). The diatom valve concentration increased from 7.3 10^6/cm^3 to 639.6 10^6/cm^3

sporomorphs (indet. degraded). All this indicates an unstable sedimentary environment and the possibility of much redeposition of sporomorphs. The amount of plant macroremains in all ecological groups, and especially among trees, shrubs and dwarf shrubs, increased significantly. Both pollen grains and macroremains of *Pinus sylvestris* and *Betula* sect. *Albae* trees dominated, although the share of *Juniperus communis* and *Betula humilis* shrubs and *B. nana* dwarf shrubs is also very high. The basin analysed became shallower and in its place there was a brief development of peat bog with the domination of stems of brown mosses: *Carex* sp., *C. rostrata* and *C. pseudocyperus.* Other herbaceous plants such as Poaceae and *Stellaria graminea* grew in drier areas around the basin. Also noteworthy are the very numerous Characeae oospores, as well as diaspores of *Najas flexilis*, *Batrachium* sp., *Lemna minor*, *Potamogeton natans* and *P*. cf. *alpinus*. Both the presence of Characeae and *Potamogeton alpinus* show that the palaeolake/basin waters were rich in calcium carbonate.

SMO2 1 *BETULA NANA-JUNIPERUS-ARTEMISIA* LPAZ
(13,835–12,800 cal^{14}C BP)

At that time, an open landscape still dominated, mainly the light-demanding herbaceous plants *Artemisia*, Chenopodiaceae and *Helianthemum*. Similarly *Juniperus* and *Hippophaë rhamnoides* shrubs grew in dry and open areas. *Ephedra* dwarf-shrubs also grew in dry and open areas. Similarly, in unshaded habitats, single trees of *Populus*, *Larix*, *Pinus cembra* grew. Pine (*Pinus*) and birch (*Betula*) formed small clusters, but probably some of their pollen blew in from farther away. In open, moist habitats, the herbaceous plants *Filipendula*, *Thalictrum* and *Selaginella selaginoides* grew, as well as *Betula nana* and *Salix polaris* shrubs, forming tundra thickets. In the lower part of the level (depth 8.800–7.150 m; 13,800–13,450 cal^{14}C BP) the diagram documents a part of the vegetation where sea buckthorn shrubs (*Hippophaë rhamnoides*) grew in unshaded, dry areas. This local zone is interrupted by hiatuses, the presence of which indicates unstable soils (Krupiński et al., 2004a).

In the Sm-4 LMAZ zone (8.550–8.650 m; 13,790–13,765 cal^{14}C BP) the type of sediment transformed from peat to grey mud, the share of plant macroremains decreases, and the nature of the vegetation around the basin only slightly changed its character. The amount of Cyperaceae and other peatland plants decreased rapidly, while the amount of plants from wet and open habitats such as *Betula nana*, *Ranunculus sceleratus* and *Rorippa palustris* and *Selaginella selaginoides* increased. Reedswamp vegetation was represented by *Phragmites australis* and *Typha* sp. The high amounts of *Batrachium* sp. and Characeae oospores indicate that the waters were still cool, clear and rich in calcium carbonate. Such conditions are also indicated by statoblasts of the bryozoans *Cristatella mucedo* and *Plumatela* sp. However, in zones I LCAZ to III LCAZ (depth: 9.000–7.825 m; 13,865–13,650 cal^{14}C BP) conditions were unfavourable for cladoceran colonization. The Cladocera pioneer assemblages are dominated by a brief appearance of pelagic forms (from the Bosminidae and Daphniidae families), together with an increase in the number of benthic Cladocera species, especially macrophyte/sediment-associated taxa such as *Chydorus sphaericus* s.l., *Biapertura affinis*, *Acroperus harpae* and the sediment-associated taxon *Pleuroxus uncinatus.* The-

T a b l e 5

Description of local Cladocera assemblage zones (LCAZ) in the Smólsk SMO2 profile

LCAZ Depth [m]	Description of LCAZ
I (9.050–8.775)	Only four species occur, two planktonic (*Eubosmina* sp. and *Bosmina longirostris*) and 2 littoral, macrophyte/sediment-associated forms (*Chydorus sphaericus* and *Coronatella rectangulata*) are observed. The frequency of cladocerans does not exceed 500 specimens per cm^3.
II (8.775–8.500)	Littoral, mainly macrophyte/sediment-associated taxa dominated, especially *Chydorus sphaericus* and *Biapertura affinis*, and macrophyte-associated taxa such as *Acroperus harpae*. Sediment-associated taxa such as *Pleuroxus uncinatus* were also noted. Pelagic forms, *Eubosmina* sp., *Bosmina longirostris* and *Simocephalus* sp., also occur. For the first time appear *Sida crystalina, Coronatella rectangulata, Alonella nana, A. exigua, Camptocercus rectirostris, Pleuroxus trigonellus*. The numbers of Cladocera were higher than in previous zone, with over 2,700 specimens and 10 species per cm^3.
III (8.500–7.850)	Cladocera occur sporadically, and frequency of cladocerans do not exceed 500 specimens per cm^3 and 6 species. Pelagic taxa, *Bosmina longirostris,* macrophyte-associated taxa such as *Acroperus harpae, Alonella nana,* and macrophyte/sediment-associated species such as *Chydorus sphaericus, Coronatella rectangula*, as well as sediment-associated taxa, *Pleuroxus uncinatus*, were observed in this zone.
IV (7.850–7.500)	The most dominant species were *Acroperus harpae, Chydorus sphaericus, Biapertura affinis* and *Pleuroxus uncinatus*. For the first time appear *Eurycercus lamellatus, Alona guttata, Monospilus dispar.* Macrophyte/sediment-associated taxa such *Coronatella rectangulata, Alonella exigua,* macrophyte-associated taxa, *Alonella nana* and *Camptocercus rectirostris* and sediment-associated taxa, *Pleuroxus trigonellus* occur occasionally. The numbers of Cladocera increased, with over 4,300 specimens and 9 species per cm^3.
V (7.500–7.075)	Littoral, mainly macrophyte/sediment-associated taxa dominated, with *Chydorus sphaericus* and *Coronatella rectangula*, as well as sediment-associated taxa such as *Pleuroxus uncinatus*. Pelagic forms are represented by *Bosmina longirostris* and *Eubosmina* sp. For the first time appear sediment-associated taxa such as *Disparalona rostrata* and *Leydigia acanthocercoides*. Macrophyte-associated taxa such as *Alonella nana, Camptocercus rectirostris, Eurycercus lamellatus* and macrophyte/sediment-associated taxa, such as *Biapertura affinis* were observed occasionally. Cladocera numbers decreased, not exceeding 2000 specimens and 7 species per cm^3.
VI (7.075–6.300)	Pelagic forms, *Eubosmina* sp. and especially, *Bosmina longirostris*, dominated. Other pelagic taxa (*Daphnia pulex, Simocephalus* sp.) occur occasionally. Macrophyte/sediment-associated taxa such as *Chydorus sphaericus* and *Coronatella rectangula* were also very abundant. Macrophyte-associated taxa such as *Sida crystalina, Alonella nana, Camptocercus rectirostris, Eurycercus lamellatus* and macrophyte/sediment-associated taxa such as *Biapertura affinis, Alona guttata, Alonella exigua* as well as *Disparalona rostrata, Leydigia acanthocercoides, Pleuroxus uncinatus* and *Pleuroxus trigonellus* were also noted, though occasionally. *Graptoleberis testudinaria* appears for the first time. The numbers of Cladocera increased significantly, with over 12,000 specimens and 14 species per cm^3.
VII (6.300–5.775)	*Bosmina longirostris, Chydorus sphaericus* and *Coronatella rectangula* dominated. The frequency of *Acroperus harpae, Alona affinis* and *Pleuroxus uncinatus* also increased. Pelagic taxa such as *Eubosmina* sp., *Daphnia pulex, Simocephalus* sp., macrophyte-associated taxa such as *Sida crystalina, Alonella nana, Alonella excisa, Camptocercus rectirostris, Eurycercus lamellatus, Graptoleberis testudinaria* and macrophyte/sediment-associated taxa, such as *Biapertura affinis, Alona guttata* and sediment-associated taxa such as *Disparalona rostrata* and *Pleuroxus trigonellus* were observed occasionally. The numbers of Cladocera were the highest in whole section but fluctuated, from over 13,600 to 4600 specimens and from 17 to 10 species per cm^3.
VIII (5.775–5.300)	At the beginning only three species, such as *Acroperus harpae, Chydorus sphaericus* and *Coronatella rectangulata* appear. Pelagic taxa such as *Eubosmina* sp., *Bosmina longirostris* and *Simocephalus* sp. occur later. Similarly, the macrophyte-associated taxa, such as *Sida crystalina, Alonella excisa, Camptocercus rectirostris, Graptoleberis testudinaria*, macrophyte/sediment-associated taxa such as *Biapertura affinis, Alona guttata* and sediment-associated taxa such as *Disparalona rostrata* and *Pleuroxus trigonellus* and *Pleuroxus uncinatus* were observed in the second part of this zone. The numbers of Cladocera fluctuated but systematically increased, from over 300 to 4000 specimens and from 3 to 12 species per cm^3 at the end of this zone.
IX (5.300–3.800)	The frequency of Cladocera taxa fluctuated from 4600 to 2400 specimens and 12 to 5 taxa per cm^3, and therefore four subzones were distinguished.
IXa (5.300–4.950)	The numbers of Cladocera was relatively high, exceeding 4600 specimens and 12 species per cm^3. The littoral, macrophyte-associated taxon (*Graptoleberis testudinaria*) and macrophyte/sediment-associated forms (*Coronatella rectangula* and *Chydorus sphaericus*) were abundant. At the end, the frequency of Cladocera taxa decreases.
IXb (4.950–4.650)	The frequency of Cladocera increased to 4040 specimens and 9 taxa. The pelagic form, *Bosmina longirostris* occurs occasionally, similarly the sediment-associated taxon, *Disparalona rostrata*. Littoral, macrophyte-, and macrophyte/sediment-associated taxa, especially *Acroperus harpae, Graptoleberis testudinaria, Biapertura affinis, Chydorus sphaericus* and *Coronatella rectangula* dominated.
IXc (4.650–4.100)	The frequency of Cladocera taxa was relatively high, exceeding 3800 specimens and 9 species per cm^3. Sediment-associated taxa such *Disparalona rostrata, Pleuroxus uncinatus, and Pleuroxus trigonellus* are relatively frequent. Pelagic forms occur occasionally once more.
IXd (4.100–3.800)	The frequency of Cladocera taxa decreased to 2440 specimens and 5 taxa per cm^3. Littoral, mainly macrophyte and macrophyte/sediment-associated taxa dominated, especially *Graptoleberis testudinaria, Biapertura affinis, Chydorus sphaericus* and *Coronatella rectangula*.
X (3.800–3.575)	The numbers of Cladocera were similar to those of the previous zone (2400 specimens and 5 taxa per cm^3). However, pelagic and macrophyte-associated taxa were negligible. In turn, the macrophyte/sediment associated taxa such as *Biapertura affinis, Chydorus sphaericus* and *Coronatella rectangula* were significant.

se taxa are cosmopolitan species, which have very high adaptive abilities and thus can live in water bodies of various depths, and trophic and thermal conditions. Most of them are cold-tolerant and are early immigrants following the retreat of the ice and may indicate cold, turbulent water conditions, or influx of siliciclastic matter to the lake (Hrynowiecka et al., 2018).

Another sedimentary change at a depth of 8.500–7.900 m (13,750–13,650 cal ^{14}C BP) to fine-grained grey sands is a break that is almost completely barren of pollen grains, but also severely restricted in plant macrofossils. The only plant taxa present in this interval (Sm-5 LMAZ) are megaspores of *Selaginella selaginoides* and *S. helvetica*, as well as *Potamogeton natans* and Characeae. Another characteristic feature of this period, whose range can be extended to a depth interval of 9.000–7.900 m, is the absence of whole diatom frustules, which may be related to the nature of the sediments accumulating in

Table 6

Description of local Chironomidae assemblage zones (LChAZ) in the Smólsk SMO2 profile

Depth [m]	Name LChAZ	Description
8.275–6.100	Ch1	The zone reveals a substantial share of cold oligotrophic taxa (i.e. *Micropsectra contracta*-type) and taxa typical to springs and flowing waters (i.e. Simuliidae, *Rheotanytarsus*, *Paraphaenocladius*-type). The total number of hc/sample ranges from 0 to 104 hc/sample (mean 17 hc/sample) but the accumulation of subfossils is generally low and has high values only in samples 7.750, 7.550–7.475, and 6.550 m.
6.100–5.475	Ch2	There is a thin layer with very low subfossil accumulation (mean 3hc/sample) reaching 10 hc only in one (6.000 m) sample. *Chironomus* spp. dominate.
5.475–4.100	Ch3	This zone reveals a domination of warm-stenothermic eutrophic (*Chironomus* spp., *Dicrotendipes* spp., *Cricotopus* spp.) and phytophile taxa (*Glyptotendipes* spp., *Endochironomus* spp., *Paratanytarsus penicillatus*-type). There are also abundant mesotrophic *Psectrocladius* spp. The accumulation of hc is high, ranging from 3 hc/sample to 123 hc/sample (mean 48 hc/sample). Cold oligotrophic taxa appear briefly between 5.350 and 4.900 m.
4.100–3.575	Ch4	This zone has a similar taxonomic composition to Ch3, but many chironomid phytophile taxa decline, being replaced by Ceratopogonidae. The share of Tanytarsini increases. The accumulation of subfossils is high, ranging from 14 hc/sample to 405 hc/sample (mean 70 hc/sample).

the lake. Traces of diatom appearance comprise sparse, crushed parts of diatom frustules that could not be identified. Indications of the nature of the sediments is also seen in the absence of biogenic silica and a high terrigenous silica concentration (Fig. 3). Amon et al. (2010) attributed the lack of diatoms to factors including a considerable dispersion of these microalgae caused by high rates of sedimentary accumulation. Besides, processes such as removal in the outflow of lakes, resuspension and reworking of older sediments, and dissolution, may negatively influence diatom presence in sediments (Battarbee, 1986; Jones, 2007). During this time, we also observe a low frequency of Cladocera and the appearance of molluscs characteristic of temporary water bodies (Figs. 7 and 10). All this indicates an unstable sedimentary environment and the possibility of rapid changes in water level, sedimentary redeposition, and inflow of water from the catchment with substantial amounts of terrigenous silica.

The composition of the local vegetation did not change significantly in the Sm-6 LMAZ (7.875–7.525 m; 13,650–13,550 cal[14]C BP) zone, compared to that recorded in the Sm-3–4 LMAZ zone (8.800–8.550 m), except for the sandy Sm-5 LMAZ zone (7.875–8.550 m). The terrestrial vegetation was dominated by the *Betula* sect. *albae* trees, though also also by *Pinus sylvestris*, *Alnus* sp., and *Populus tremula*, which grew in loose clusters. However, dry open areas were still present, where terrestrial herbaceous plants grew, and in the humid and marshy areas and in the waters, plants characteristic of a cool climate grew, such as *Betula nana*, *Selaginella selaginoides*, *Hippuris vulgaris* and *Batrachium* sp. Initially, in the Sm-6 level, the cool, clear, calcium carbonate-rich waters of the lake were again occupied by charophyte meadows with Characeae, *Batrachium* sp., and *Potamogeton natans*. Intense autochthonous precipitation of CaCO$_3$ by Characeae indicates that the waters of the Smólsk basin at that time were alkaline (Pełechaty et al., 2013). Calcium carbonate is also an important component of snail shells, and their occurrence in the sedimentary record of this interval correlates with the high amounts of Characeae oospores (Figs. 5, 10 and Tables 3, 6). Although conditions were still not very favourable for zooplankton during the IV LCAZ phase (depth: 7.825–7.500 m; 13,650–13,550 cal[14]C BP), the constant presence of benthic, mainly macrophyte and macrophyte-sediment cladoceran taxa is evident.

The composition of diatom species reflected the amelioration of environmental conditions. Samples 7.900, 7.850, 7.750 and 7.500 m yielded diatoms. Most were aquatic and some had periodically wet associations. However, the frequency was still low. In the upper part of this zone, from the depth of 7.500 m to

the top of the D1 phase (6.950 m), diatoms disappear again. A sudden fluctuation in lake water level caused by cool water inflowing from the catchment may explain the temporary disappearance of diatoms (Kołaczek et al., 2015). Diatoms reappear from at a depth of 6.900 to 6.325 m with low abundance between 6.675–6.575 m. Aquatic diatoms dominated. That may indicate an increase in the water level in the lake. The abundance of tychoplanktonic taxa, e.g., *Stauroneis construens*, *Pseudostaurosira brevistriata, Epithemia adnata, Epithemia turgida* and *Navicula vulpina* that is a random plankton, may indicate wave action and vertical mixing of the water, which causes benthic diatoms to break away from the substrate and float in the water (Denys, 1991). The occurrence of this taxa indicated meso- to eutrophic conditions. Occasional aerophilic and aquatic to aerophilic taxa also occurred.

In the Sm-7 LMAZ zone (7.525–7.450 m; ~13,550 cal[14]C BP), the share of *Betula nana* and tree birch remains decreases. *Pinus sylvestris* began to dominate on the shores of the basin. Patches of herbaceous vegetation and the occurrence of *Betula nana* and *Hippophaë rhamnoides* shrubs suggest the boreal climate continued. There was probably a shallowing of the lake and spread of peat bog together with deciduous mosses, *Carex elata*, *C. rostrata* and *Eleocharis palustris*, which were also included in the area of the reed bed with *Phragmites australis*. The next, Sm-8 and Sm-9, LMAZs (7.455–6.775 m; 13,550–13,350 cal[14]C BP) document further development of vegetation. Both in the plant macroremains as in palynological samples at depths of 7.730 and 7.100 m, pollen grain particles are rare with a large share of redeposited sporomorphs (rebedded) and Dinophyceae cysts. The presence of plant remains such as *Urtica dioica*, *Rorippa palustris* and *Thalictrum lucidum* may also indicate a supply of material from the shores of the basin. Then, in the part of the level at a depth of 7.100–6.700 m (13,450–13,300 cal[14]C BP), the diagram shows a still-open landscape, where single pines, birch, larch (*Larix*) and poplars (*Populus*) grew. In the prevailing open, very sunny areas, grasslands with *Helianthemum* developed. Tundra thickets with *Betula nana*, *Selaginella selaginoides*, *S. helvetica* and *Ranunculus sceleratus* also developed in moist habitats.

A similar ecological expression is seen in the malacological analysis results. In the lower part of the profile at depths <7.500 m, the malacofaunal remains examined within the six samples were classified into a *Valvata* assemblage (Figs. 10 and 11), characterized by significant species diversity. Cold-loving aquatic taxa (*Pisidium obtusale laponicum* and *Pisidium lillieborgi*) have a dominant role here. They are accompanied by

T a b l e 7

Composition of malacofauna at the Smólsk SMO2 site

Ecological groups of molluscs	Taxon	Group of samples											
		1	2	3	4	5	6	7	8	9	10	11	12
		Depth [m]											
		8.800–8.750	8.750–8.550	7.900–7.800	7.800–7.700	7.700–7.600	7.600–7.500	5.100–4.900	4.900–4.500	4.900–4.250	4.250–3.800	3.800–3.500	3.500–3.400
H	*Succinea putris*			1				2		1		2	
W$_T$	*Valvata cristata*	19	11	15	9	10	9						
W$_T$	*Valvata macrostoma*	15	26	9	9	11	11						
W$_T$	*Galba truncatula*						1	10	9	8	13	5	
W$_T$	*Planorbis planorbis*						1				7		
W$_T$	*Segmentina nitida*	8	3	1	1								
W$_T$	*Pisidium obtusale laponicum*	18	22	25	19	22	27	19	10				2
W$_S$	*Valvata piscinalis*	13	10	5	6	7	7						
W$_S$	*Radix balthica*	10	11	14	10	13	3	6	3	7	5		2
W$_S$	*Gyraulus crista*	6	4	1	11	8	2	11	11	17	13	5	5
W$_S$	*Gyraulus laevis*	10	12	9	18	10	24	52	67	67	62	88	91
W$_S$	*Sphaerium corneum*	1	1	14	13	8	12						
W$_S$	*Pisidium lillieborgi*			6	4	11	7	2					
Total species		10	10	12	11	10	12	8	6	5	5	4	4
Total specimens		122	119	191	155	156	130	113	109	103	109	115	160

For explanations see Figure 10

species with high ecological tolerance, both habitat-related and thermal (*Valvata cristata*, *V. macrostoma*, *Radix balthica*). This assemblage reflects a shallow water body, probably with a sandy bottom and not very lush vegetation. The relatively abundant occurrence of temporary water body species may indicate brief episodes of drainage. The species composition and age determinations of the deposits containing the fauna in question indicate its association with the Late Glacial period. Similar malacocoenoses, of similar age, have been described from many palaeolake sites in the European Lowlands (Alexandrowicz, 1989, 1999, 2013; Griffiths et al., 1994; Wojciechowski, 1999; Apolinarska and Ciszewska, 2006; Sanko et al., 2010; Georgopoulou et al., 2016).

The plant macroremain analysis also shows that pine was an important element in the landscape, and played a large role in shaping the composition of vegetation in the studied area in terrestrial habitats. This is seen from the large share of pine needles and bud scales, especially in the Sm-10 LMAZ zone (6.775–6.575 m; 13,350–13,250 cal ^{14}C BP). Around the basin there persisted peat bogs with brown mosses, *Carex fusca*, *Eleocharis palustris*, *Lycopus europaeus* and reed beds, which included *Typha* sp. and *Phragmites australis*. Among the macrophytes there were still *Batrachium* sp. and *Potamogeton natans*. In the Sm-11 LMAZ (6.575–5.350 m; 13,250–12,850 cal ^{14}C BP) horizon the share of ephippia of *Daphnia* sp. also increases. The Characeae almost completely withdrew from the basin waters, which may have been associated with both increased shading and decreased water pH caused by the presence of *Pinus sylvestris*. In the younger part, at a depth of 6.500–5.750 m (13,200–12,950 cal ^{14}C BP), vegetation developed similarly as in the earlier period; among the herbaceous plants, ferns (*Dryopteris*) were locally developed. Tundra habitats were still present. In open and dry areas, light-demanding

Artemisia and Chenopodiaceae grew, and in wet locations *Filipendula*. Reed and aquatic plants found less space to develop. Perhaps the environmental conditions were calmer, as indicated by fewer destroyed (indeterminable: corroded and indeterminable: degraded) and redeposited (rebedded) sporomorphs and dinocysts (Dinoflagellatae). Initially, at this depth range, there were no distinct changes in the record of plant macroremains. *Betula nana* and *B. humilis* were still present in wet habitats, and the herbaceous vegetation included *Urtica dioica*. However, a change occurred in the composition of aquatic vegetation, where herbaceous plants with higher thermal requirements appeared, such as *Najas marina*, *Nymphaea alba* and *Nuphar lutea*. This is also indicated by an increase in the share of Characeae oospores and macrophytes such as *Potamogeton natans*, *P. marginatus*, *Potamogeton* sp., *Myriophyllum* sp. and *Sparganium minimum*. At the top of the zone, the share of plant remains clearly decreased in all ecological groups, and the dominant species were ephippia of cladocerans, *Daphnia* sp. High *Daphnia* values may indicate cool, stressful environmental conditions, but also waters rich in calcium carbonate.

In zones V LCAZ–VIII LCAZ (depth 7.500–5.300 m; 13,550–12,800 cal ^{14}C BP; Fig. 7), the frequency and diversity of Cladocera includes large numbers of benthic taxa, of which a few are important indicators of eutrophic water (*Coronatella rectangula, Chydorus sphaericus* s.l. and *Bosmina longirostris*) and rich vegetation in this part of lake (*Biapertura affinis, Alona guttata, Graptoleberis testudinaria, Pleuroxus* sp.). The occurrence of these taxa indicates relatively warm and meso-/eutrophic conditions. However, most of these taxa disappear at the end of this phase, which suggests a decrease in water level, an increase in macrovegetation and relatively shallow conditions and/or inwash of sediment to the lake. The presence of taxa of

the Bosminidae (*Eubosmina* sp.) and Daphniidae (*Simocephalus* sp. and *Daphnia pulex*-group) suggests development of open-water conditions. However*, D. pulex* occurs in a wide range of aquatic habitats, especially in small, shaded pools rich in macrovegetation and nutrients.

From the depth interval of 5.700–5.400 m (12,950–12,850 cal^{14}C BP), the vegetation record changes gradually. Among the vegetation there were more hazel bushes (*Corylus avellana*). There was continually an open landscape where light-demanding poplars (*Populus*) found favourable, suitable conditions for development. In damp habitats there grew foregrip (*Selaginella selaginoides*), porcupines and cattails (*Sparganium* t. and *Typha latifolia*), while alder (*Alnus*) increased its area. In the waters, *Pediastrum* algae once again found good conditions for development. The environmental conditions were less stable, as the studied part of the core again contained significantly more destroyed (indeterminable: corroded, degraded) sporomorphs, redeposited species included in one category rebedded, as well as *Taxus baccata* from redeposition (Krupiński et al., 2004b; Noryśkiewicz, 2006), as well as *Ilex*, *Vitis* and *Lonicera periclymenum*. At the top of the Sm-11 LMAZ zone (6.575–5.350 m; 1325–12850 cal^{14}C BP), plant macroremains were scarce, especially in the group of trees and shrubs. Birch and pine almost completely disappeared from the reservoir catchment, while the remains of *Betula nana* and *Juniperus communis* show that vegetation typical of a boreal climate still grew on the banks. The rapid increase in the share of plant remains at the boundary with the Sm-12 LMAZ zone shows the discontinuity of sedimentation.

Most diatoms were typically aquatic species, e.g., *Staurosira construens, Geisslera schoenfeldii, Navicula vulpina*. The occurrence of these taxa also indicates meso-eutraphentic conditions and vertical mixing in the water column. The frequency of diatoms also increases, which may indicate an improvement in environmental conditions. There were also epontic and benthic taxa, e.g., *Staurosira brevistriata, Staurosirella pinnata, Mastogloia smithii.* These occur in low-water-level lakes. Another lack of diatoms was observed at a depth of 5.7550–5.570 m (~12,950 cal^{14}C BP). With the disappearance of diatoms at that level, CaCO$_3$ and terrigenous silica concentration increased (Fig. 3).

In summary, both the pollen level SMO2 1 *Betula nana-Juniperus-Artemisia* LPAZ and the regional vegetation character recorded in it, as well as the local vegetation record with the continuous presence of cool climate indicators such as *Betula nana*, *Selaginella selaginoides* and *Potamogeton alpinus* describe the vegetation associated with the Younger Dryas stadial. The nature of the vegetation during this period in Smólsk corresponds to the B*etula nana-Juiperus-Artemisia* LPAZ horizons isolated south-west of the site studied in Kujawy, in the area of Osłonki (Nalepka, 2005, 2008). At the Smólsk site, sedimentation was discontinuous and, due to the hiatus, there is no record of a transition from the Late Glacial to the Holocene. At this level in the lithological profile there is a sharp change from blue-grey gyttja to fine detritus gyttja, grey-green to brown, slightly laminated.

HOLOCENE

SMO2 2 *CORYLUS-BETULA* LPAZ
(11,100–9,900 cal^{14}C BP)

There were clear changes in the vegetation pattern. Sunlit pine forests (*Pinus sylvestris*) developed, with the participation

of birch trees (*Betula* undiff.) as a component. Hazel bushes developed in unshadowed places, on the edges of overexposed forests and in clearings. In the area studied, a few elms (*Ulmus*) appeared, or their pollen blew in with the pollen rain from the nearby area, where elms could already find suitable conditions for development. Small areas were still occupied by damp tundra thickets with *Betula nana*. Probably there were worse conditions than before for sedges and reed swamps. Alders (*Alnus*) grew more and more distinctly in damp habitats. In the younger part of the level, spruce (*Picea abies*) and deciduous trees with higher thermal requirements, including oak (*Quercus*) and lime (*Tilia*), appeared as forest components. In summary, open pine and birch forests with hazel were expanding. The area where herbaceous plants grew was decreasing. In the Sm-12 LMAZ zone (5.350–5.125 m; between 11,100 and 10,700 cal^{14}C BP), the record of local vegetation development changed substantially in relation to the previous zone. Birch-pine forests dominated directly around the basin, as indicated by high values of *Pinus sylvestris* and *Betula* sect. *albae* remains with the presence of *Populus tremula* and sparse *Betula nana* remains. The latter indicate that at the beginning of the Holocene, in the pre-Boreal phase, patches of tundra vegetation still remained. Significant changes began to occur in the composition of aquatic and reed vegetation, where communities of *Najas marina*, *Ceratophyllum demersum*, *Potamogeton natans* and *Nymphaea alba* gained increasing importance. At the bottom of the Sm-13 LMAZ zone (5.125–4.250 m; 10,750–9950 cal^{14}C BP), a clear improvement in climatic conditions is indicated by the appearance of *Ceratophyllum submersum*, and *Nymphoides peltata*, which occurs most frequently in eutrophic waters at a depth of 1.0–1.5 m (Van der Velder et al., 1979). The area occupied by rush vegetation, mainly *Phragmites australis* and *Typha* sp., probably increased. This was likely associated with a decrease in the water level in the basin and progressing eutrophication in it. At the end of this phase, the basin probably deepened at the top of the Sm-13 zone and the forest communities moved away from the basin shores. Such conditions are also indicated by a brief increase in the share of *Daphnia* in this zone.

SMO2 3 *CORYLUS-QUERCUS*-POACEAE LPAZ
(9,900–9,000 cal^{14}C BP)

The developing pine forests with the participation of oak (*Quercus*), elm (*Ulmus*), lime (*Tilia*) and spruce (*Picea abies*) and the appearance of lime (*Tilia*) and hazel (*Corylus avellana*) occupied increasingly larger areas. The share of tree birches gradually decreased. Dry, open grassland habitats remained in decreasing areas, where grasses (Poaceae) and mugworts (*Artemisia*) grew, among others. The record of plant macroremains in the Sm-14 LMAZ zone (4.250–3.850 m; 9950–9500 cal^{14}C BP) signals another change in local environmental conditions, which indicates a gradual decrease in water level and an increase in the share of rush and boggy habitats. The dominance of Characeae oospores and a higher share of nitrophilous taxa such as *Urtica dioica* and *Ranunculus sceleratus* from wet habitats on the shores of the basin, recorded in the Sm-15 LMAZ zone (3.850–3.550 m; 9500–9100 cal^{14}C BP), indicate that the environment became more eutrophic.

There are visible changes in benthic cladoceran taxa frequency (and the frequency of their fluctuations) in the IX LCAZ (depth 5.300–3.800 m; 11,000–9,500 cal^{14}C BP) and X LCAZ (depth: 3.800–3.600 m; 9,500–9,000 cal^{14}C BP) phases. Four taxa, *Graptoleberis testudinaria*, *Biapertura affinis*, *Chydorus sphaericus* s.l. and *Coronatella rectangula*, were dominant. Although most of these taxa have very high adaptive abilities, they

mostly inhabit shallow lakes with warm waters containing humic substances (e.g., after terrestralisation) as well as increasing macrovegetation. Additionally, repeated colonisation of pelagic Cladocera assemblages in the time represented by this part of the core studied may indicate periodic rises in water level in the lake. Also, the diatom species composition reflects changes in environmental conditions. Planktonic diatoms increased during the Preboreal/Boreal transition and the Boreal. This indicates changes in environmental variables (e.g., rise of temperature) and a slight increase in water level (Gałka et al., 2015). However, the diatoms occurred in a wide range of life forms: euplanktonic, tychoplanktonic, epontic and benthic species. The diatoms were also dominated by occasionally aerophilic and aquatic to aerophilic species with decreases in aquatic species. The occurrence of species such as *Aulacoseira granulata*, *Halamphora veneta*, *Cymbella affinis*, *Epithemia sorex*, *Nitzschia amphibia*, *Rhopalodia gibba* and *Stephanodiscus hantzschii* may indicate progressing eutrophication of the lake. The second mollusc assemblage recognized, with *Gyraulus laevis*, occurs in the interval 5.100–3.400 m (Figs. 10 and 11) and comprises 6 specimens, with low species diversity and abundant *Gyraulus laevis* (this form accounts for all specimens recognized in the upper interval of the profile). It is supplemented by taxa with high ecological tolerance, and the sparse occurrence of molluscs typical of periodic water bodies. The fauna describe characterizes a small, shallow body of permanent water. The results of radiocarbon dating indicate that the assemblage in question is related to the Early Holocene. Mollusc assemblages of similar composition and age have been described from numerous palaeochannel fills in the European Lowlands (Alexandrowicz, 1989, 1999, 2013; Griffiths et al., 1994; Wojciechowski, 1999; Apolinarska and Ciszewska, 2006; Sanko et al., 2010; Georgopoulou et al., 2016; Gałka et al., 2019).

In the section of the SMO2 profile analysed in Smólsk, which includes an interval of 5.350–3.550 m (11,100–9,100 cal¹⁴C BP), palaeoenvironmental changes representing the transition from the Preboreal to the Boreal phase of the Early Holocene were recorded. The improvement of both thermal conditions and the progressive eutrophication of the palaeolake are documented by the changes recorded in the *Corylus--Quercus*-Poaceae phase (SMO2 3 LPAZ) and the corresponding zones of plant macrofossils (Sm-12–Sm-15 LMAZ), diatom (D4 zone), Cladocera (IX LCAZ and X LCAZ zones), Chironomidae (Ch 3 and Ch 4 zones) and the mollusc assemblage with *Gyraulus laevis* (Fig. 12).

CHIRONOMIDAE MEAN JULY AIR TEMPERATURE RECONSTRUCTION

The Chironomidae mean July air temperature East European TS reconstruction values range from 15.5 (3.900 m) to 18.9°C (4.985 m, 4.350 m) (Fig. 9). The Swiss-Norwegian-Polish TS reconstruction values vary from 16.1 (7.850 m) to 20.9°C (4.800 m). Generally, the SNP TS reconstruction gives higher values for the early Greenlandian then the Late Glacial and the EE TS gives similar values for both periods. In the Late Glacial (7.850–5.315 m) section the EE TS temperature varies between 15.8 and 18.7°C and SNP TS temperature varies between 16.1 and 19.4°C. Both reconstructions give, in the Late Glacial, lower summer temperatures at 7.850–7.665 m (13,650–13,600 cal¹⁴C BP), 7.335–6.825 m (13,500–13,350 cal¹⁴C BP), and 5.435 m (13,100 cal¹⁴C BP). In the Greenlandian (5.275–3.575 m) EE TS temperature varies between 15.5 and 18.9°C and SNP TS temperature varies between 16.7 and 20.9°C. Both TSs reconstructions show a cool

oscillation at 4.275–3.865 m (10,100–9,600 cal¹⁴C BP) when temperature dropped to 15.5 (EE TS)/16.9°C (SNP TS).

The EE TS reconstruction reveals a common trend with that of the the DCA Ax2 values. The SNP TS also has similar trend to the DCA Ax2 variation but the similarity is less clear then between the Ax 2 and EE TS reconstructions (Fig. 9). On the other hand, the SNP TS reconstruction has closer modern analogues, especially in the Greenlandian section, than the EE TS reconstruction. Both reconstructions have weaker modern analogues in the Late Glacial section then in the Greenlandian section. The EE TS reconstruction reveals very good modern analogues (minDC <2 percentile; minDC <7.24578) for one sample and good modern analogues (2 percentile<minDC<5 percentile; 7.24578<minDC<8.50537) for 13 samples mostly distributed in the Greenlandian section. The EE TS modern analogues are moderate (5 percentile<minDC<10 percentile; 8.50537<minDC<9.75318) for 23 samples and poor modern analogues (10 percentile< minDC; 9.75318< minDC) are recorded for 29 samples, mostly distributed in the Late Glacial section. The SNP TS reconstruction reveals very good modern analogues (minDC <2 percentile; minDC <6.98983) for 26 samples and good modern analogues (2 percentile<minDC<5 percentile; 6.98983<minDC<8.57757) for 30 samples, all from the Greenlandian section and several from the Late Glacial section. The SNP TS modern analogues are moderate (5 percentile <minDC<10 percentile; 8.57757<minDC<10.0564) for 4 samples and poor (10 percentile< minDC; 10.0564< minDC) for 6 samples, only in the Late Glacial section.

CLIMATE CHANGES

The Chironomidae inferred mean July air temperatures have a similar range in both reconstructions (using EE TS and SNP TS). The SNP TS gives higher values for the Greenlandian, but generally, both reconstructions reveal high summer temperatures, comparable with the present values from the 20th and 21st century. The DCA Ax2 also does not show any distinct change in the community composition from the Holocene onset. The only difference is a higher share of reophile taxa in the Late Glacial. This suggests a spring- or stream-water supply to the lake, though these taxa also prefer lower temperatures and the colder climate might favour their presence in the lake basin and catchment (Antczak-Orlewska et al., 2021, 2023). Even though the reconstructed temperatures and community compositions in the Greenlandian are not much different from those of the Late Glacial, the chironomid abundance strongly increases from the Holocene onset as also reflected by DCA Ax1. This indicates that during the Late Glacial local conditions were unfavourable for chironomids. This might come from colder climate manifested as lower winter temperatures, winter-summer thermal contrast and lower precipitation, but not only the mean July air temperature (Engels et al., 2014; Schenk et al., 2020; Płóciennik et al., 2022). Also, local conditions in the lake (rapid sedimentation) negatively influenced Chironomidae populations in the Late Glacial.

The Chironomidae-inferred reconstructions do not indicate a strong summer temperature difference between the Late Glacial and Early Holocene intervals but clearly show two cool oscillations at 13,500–13,350 cal¹⁴C BP and 10,100–9,60 cal¹⁴C BP. The first coincides with the 2GI-1c cool oscillation according to Lowe et al. (2008) and Ammann et al. (2013). The Smólsk temperature decreased by 2°C (EE TS)/3°C (SNP TS) which is consistent with other records in Europe (Van Asch et al., 2012; Brooks et al., 2012; Pauly, 2022). The early GI-1c in Smólsk is also manifested by low Chironomidae abundances. This can

come from climate cooling but also water level decrease in the lake as inferred for this time in west European lakes (Magny, 2001; Kaiser et al., 2012).

The DCA Ax1 illustrates an increase in Chironomidae and Ceratopogonidae abundance since the beginning of the Holocene. This is a reaction of these communities to improving conditions in the lake and in regional climate. The period of 10,500–9,000 cal^{14}C BP was a time of pronounced temperature increase in northern latitudes (Van der Bilt et al., 2019) though there was a succession of cold Boreal oscillations during that time in Europe (~10,200–9,300 cal^{14}C BP) (Joannin et al., 2013). The Smólsk palaeorecord reveals 10,100–9,600 cal^{14}C BP summer temperature cooling in a series of 10 Chironomidae samples, which are rich in hc and represented by diverse communities. This is also reflected in the DCA Ax2 shift. SNP TS temperature records have, for this event, only very good and good modern analogues. This event correlates with Lake Agassiz outburst phase (Lewis and Anderson, 1989; Fisher and Smith, 1994; Teller, 2001; Young et al., 2021). Whereas the earlier Preboreal Oscillation was reported from the nearby Pomeranian Lakeland (Kramkowski et al., 2023), the Boreal Oscillation was not previously reported from Poland with quantitative temperature reconstructions, mostly due to the low resolution of the earlier palaeorecords (Kaufman et al., 2020). The stronger Preboreal Oscillation is not seen in the Smólsk Chironomidae palaeotemperature reconstructions in contrast to the weaker Boreal Oscillation, due to the hiatus in sedimentation at 11,700–11,000 cal^{14}C BP in the Smólsk record.

CONCLUSIONS

Palynological analysis has revealed the vegetation succession of the Late Glacial (oldest spectra from the depths of 9.00 and 8.900 m) and the Younger Dryas stage (*Betula nana-Juniperus-Artemisia* LPAZ) and the Early Holocene parts of the Preboreal and Boreal phases (*Corylus-Ulmus* LPAZ). Due to the presence of gaps in the geoarchive analysed, the pollen zones distinguished are only broadly representative. The description of the vegetation is generalized, but it is consistent with those from neighbouring regions (Nalepka, 2005 and earlier literature therein; and the syntheses of Ralska-Jasiewiczowa and Latałowa, 1996; Ralska-Jasiewiczowa et al., 2004).

The vegetation described transformed from the Late Glacial open landscape, where light-demanding herbaceous plants grew in moist and dry habitats. In moist areas, tundra thickets developed. Single pioneer trees, also undemanding in terms of soil richness (pine, birch, larch, poplar), gradually entered dry areas. Then, at the beginning of the Holocene, sparse forests with pine and birch developed. In this last interval, representing the transition from the Preboreal to the Boreal phase, terrestrial vegetation in the vicinity of the basin was dominated by trees; in the areas around the basin, pine-birch forests developed, with increasing amounts of deciduous trees (*Ulmus*, *Quercus*, *Tilia*) and shrubs (*Corylus*) with higher thermal requirements.

The local vegetation of the palaeolake underwent numerous cyclical changes. During the Younger Dryas, the sparse vegetation on the shores of the lake failed to inhibit the supply of terrigenous material from the slopes, so the development of fen meadows, Potamion-type communities and sedges developing on the banks of the threshers was interrupted several times (Matuszkiewicz, 2008). During the Younger Dryas, *Selaginella selaginoides* and *Betaula nana* were commonly found in wetlands throughout the Younger Dryas. In the Holocene, there was a gradual eutrophication of the lake waters, and the development of a reed belt. Sedimentation became quiescent, and episodes of terrigenous material delivery ceased.

The cladoceran and diatom assemblages show three apparent phases in the development of the Smólsk Lake. The first phase, dated to 13,850–13,500 cal^{14}C BP, is characterized by the presence of pioneering, cold-tolerant crustacean taxa and may indicate the development of cold, turbulent water conditions or an influx of siliciclastic sediment into the lake. The second phase of the Smólsk lake's development, in the period 13,500–12,800 cal^{14}C BP, was characterized by the development of meso-/eutrophic conditions in the lake with a well-developed littoral zone and rich macrophyte vegetation. The third phase, associated with the Early Holocene, records the presence of shallow lakes with warm water, containing humic substances (e.g., after terrestralisation), as well as increasing macrovegetation, with periodic fluctuations in water level.

The DCA Ax1 illustrates the increase of Chironomidae and Ceratopogonidae abundance since the beginning of the Holocene. The Smólsk palaeorecord reveals 10,100–9,600 cal^{14}C BP summer temperature cooling in a series of 10 Chironomidae samples, which are reach in hc and represented by diverse communities. This is also reflected in the DCA Ax2 shift. The SNP TS temperature records have for this event only very good and good modern analogues. This event correlates with the Agassiz Lake outburst phase.

The mollusc fauna analysed represents the Late Glacial and Early Holocene. However, the sequence is not continuous. Associated with the Late Glacial is the presence of an assemblage of *Valvata*, which indicates a shallow water body. Its functioning may have been interrupted by short periods of drying out. The abundance of species with low thermal requirements indicates a cold climate. In the higher interval, an assemblage characterized by the dominance of *Gyraulus laevis* appears. At the same time, cold-loving species typical of the Late Glacial disappear. This fauna inhabited a shallow, permanent body of water and represents the Early Holocene.

REFERENCES

Alexandrowicz, S.W., 1989. Molluscs associations in Late Quaternary lake deposits of northern Poland (in Polish with English summary). Studia i Materiały Oceanologiczne, **56:** 267–276.

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

Alexandrowicz, W.P., 1999. Evolution of the malacological assemblages in North Poland during the Late Glacial and Early Holocene. Folia Quaternaria, **70:** 39–69.

Alexandrowicz, W.P., 2009. Malacostratigraphy of Vistulian and Holocene in Poland. Studia Quaternaria, **26:** 55–63.

Alexandrowicz, W.P., 2013. Late Glacial and Holocene molluscan assemblages in deposits filling palaeolakes in Northern Poland. Studia Quaternaria, **30:** 5–17.

Ammann, B., van Leeuwen, J.F.N., van der Knaap, W.O., Lischke, H., Heiri, O., Tinner, W., 2013. Vegetation responses to rapid warming and to minor climatic fluctuations during the Late-Glacial Interstadial (GI-1) at Gerzensee (Switzerland), Palaeogeography, Palaeoclimatology, Palaeoecology, **391:** 40–59; https://doi.org/10.1016/j.palaeo.2012.07.010

Amon, L., Heinsalu, A., Veski, S., 2010. Late glacial multiproxy evidence of vegetation development and environmental change at Solova, southeastern Estonia. Estonian Journal of Earth Sciences, **59:** 151–163.

Andersen, T., Cranston, P., Epler, J., 2013. Chironomidae of the Holarctic Region: Keys and Diagnoses: Larvae. Scandinavian Society of Entomology.

Antczak-Orlewska, O., Płóciennik, M., Sobczyk, R., Okupny, D., Stachowicz-Rybka, R., Rzodkiewicz, M., Siciński, J., Mroczkowska, A., Krąpiec, M., Słowiński, M., Kittel, P., 2021. Chironomidae morphological types and functional feeding groups as a habitat complexity vestige. Frontiers in Ecology and Evolution, section Paleoecology, **8,** 583831; https://doi.org/10.3389/fevo.2020.583831

Antczak-Orlewska, O., Okupny, D., Pawłowski, D., Kotrys, B., Krąpiec, M., Luoto, T.P., Peyron, O., Płóciennik, M., Stachowicz-Rybka, R., Wacnik, A., Szmańda, J.B., Szychowska-Krąpiec, E., Kittel, P., 2023. The environmental history of the oxbow in the Luciąża River valley – study on the specific microclimate during Allerød and Younger Dryas in central Poland. Quaternary International, **644–645:** 178–195; https://doi.org/10.1016/j. quaint.2021.08.011

Apolinarska, K., Ciszewska, M., 2006. Late Glacial and Holocene lacustrine molluscs from Wielkopolska (central Poland) and their environmental significance. Acta Geologica Polonica, **56:** 51–66.

Apolinarska, K., Woszczyk, M., Obremska, M., 2012. Late Weichselian and Holocene palaeoenvironmental changes in northern Poland based on the Lake Skrzynka record. Boreas, **41:** 292–307; https://doi.org/10.1111/j.1502-3885.2011.00235.x

Battarbee, R.W., 1986. Diatom analysis. In: Handbook of Holocene Paleoecology and Paleohydrology (ed. B.E. Berglund): 527–570. Wiley and Sons, London.

Bechtel, A., Woszczyk, M., Reischenbacher, D., Sachsenhofer, R.F., Gratzer, R., Püttmann, W., Spychalski, W., 2007. Biomarkers and geochemical indicators of Holocene environmental changes in coastal Lake Sarbsko (Poland). Organic Geochemistry, **38:** 1112–1131; https://doi.org/10.1016/j.orggeochem.2007.02.009

Berggren, G., 1969. Atlas of Seeds and Small fruits of Northwest-European Plant Species with Morphological Descriptions. Part 2. Cyperaceae. Swedish Natural Science Research Council, Stockholm.

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. Wiley & Sons, Chichester, New York.

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

Bjerring, R., Becares, E., Declerck, S., Gross, E.M., Hansson, L.-A., Kairesalo, T., Nykänen, M., Halkiewicz, A., Kornijów, R., Conde-Porcuna, J.M., Seferlis, M., Noges, T., Moss, B., Amsinck, S.L., Odgaard, B.V., Jeppesen, E., 2009. Subfossil Cladocera in relation to contemporary environmental variables in 54 Pan-European lakes. Freshwater Biology, **54:** 2401–2417; https://doi.org/10.1111/j.1365-2427.2009.02252.x

Błędzki, L.A., Rybak, J.I., 2016. Freshwater Crustacean Zooplankton of Europe: Cladocera & Copepoda (Calanoida, Cyclopoida); Key to Species Identification. Springer.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, **51:** 337–360.

Bronk Ramsey, C., 2021. OxCal version 4.4. Available at: https://c14.arch.ox.ac.uk/oxcal/OxCal.html# (accessed 19 December 2022).

Brooks, S.J., Heiri, O., Langdon, P.G., 2007. The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology. Quaternary Research Association, London.

Brooks, S.J., Axford, Y., Heiri, O., Langdon, P.G., Larocque-Tobler, I., 2012. Chironomids can be reliable proxies for Holocene temperatures. A comment on Velle et al., 2010. The Holocene, **22:** 1482–1494; https://doi.org/10.1177/0959683612449757

Brzeziński, W., 2001. Szczegółowa mapa geologiczna Polski 1:50 000, arkusz Brześć (441) (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Brzeziński, W., 2003. Objaśnienia do Szczegółowej mapy geologicznej Polski 1:50 000, arkusz Brześć (441) (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Cappers, R.T.J., Bekker, R.M., Jans, J.E.A., 2006. Digital seed atlas of the Netherlands. Groningen, Barkhuis/Groningen University Library.

Denys, L., 1991. A check-list of the diatoms in the Holocene deposits of the Western Belgian coastal plain with a survey of their apparent ecological requirements. I. Introduction, ecological code and complete list. Belgische Geologische Dienst, Professional Paper, **246:** 1–41.

Engels, S., Self, A.E., Luoto, T.P., Brooks, S.J., Helmens, K.F., 2014. A comparison of three Eurasian chironomid – climate calibration datasets on a W-E continentality gradient and the implications for quantitative temperature reconstructions. Journal of Paleolimnology, **51:** 529–547; https://doi.org/10.1007/s10933-014-9772-8

Faegri, K., Kaland, P.E., Krzywinski, K., 1989. Textbook of Pollen Analysis. Wiley & Sons Ltd, Chichester-Singapore.

Feurdean, A., Perşoiu, A., Tanţău, I., Stevens, T., Magyari, E.K., Onac, B.P., Marković, S., Andrič, M., Connor, S., Fărcaş, S., Gałka, M., Gaudeny, T., Hoek, W., Kołaczek, P., Kuneš, P., Lamentowicz, M., Marinova, E., Michczyńska, D.J., Perşoiu, I., Płóciennik, M., Słowiński, M., Stancikaite, M., Sumegi, P., Svensson, A., Tămaş, T., Timar, A., Tonkov, S., Toth, M., Veski, S., Willis, K.J., Zernitskaya, V., 2014. Climate variability and associated vegetation response throughout Central and Eastern Europe (CEE) between 60 and 8 ka. Quaternary Science Reviews, **106:** 206–224; https://doi.org/10.1016/j.quascirev.2014.06.003

Faustova, M., Sacherova, V., Svensson, J.E., Taylor, D.J., 2011. Radiation of European *Eubosmina* (Cladocera) from *Bosmina* (E.) *longispina* — concordance of multipopulation molecular data with paleolimnology. Limnology and Oceanography, **56:** 440–450; https://doi.org/10.4319/lo.2011.56.2.0440

Fisher, T.G., Smith, D.G., 1994. Glacial Lake Agassiz: its northwest maximum extent and outlet in Saskatchewan (Emerson Phase). Quaternary Science Reviews, **13:** 845–858; https://doi.org/10.1016/0277-3791(94)90005-1

Flössner, D., 1972. Kiemen-und Blattfüßer, Branchiopoda-Fischläuse, Branchiura: Krebstiere. Die Tierwelt Deutschlands 60. Veb Gustav Fischer Verlag, Jena.

Flössner, D., 2000. The Haplopoda and Cladocera (without Bosminidae) in Central Europe. Backhuys, Leiden.

Frey, D.G., 1986. Cladocera analysis. In: Handbook of Holocene Paleoecology and Paleohydrology (ed. B.E. Berglund): 667–692. Wiley & Sons, New York.

Gałka, M., Tobolski, K., Bubak, I., 2015. Late Glacial and Early Holocene lake level fluctuations in NE Poland tracked by macrofollis, pollen and diatom records. Quaternary International, **388**: 23–38; https://doi.org/10.1016/j.quaint.2014.03.009

Gałka, M., Sypniewski, J., Apolinarska, K., 2019. Early Holocene succession of vegetation and molluscs in Lake Jaczno, East-Central Europe. Quaternary International, **524:** 31–39; https://doi.org/10.1016/j.quaint.2019.07.010

Georgopoulou, E., Neubauer, T.A., Strona, G., Kroh, A., Mandic, O., Harzhauser, M., 2016. Beginning of a new age: how did freshwater gastropods respond to the Quaternary climate change in Europe? Quaternary Science Reviews, **149:** 269–278; https://doi.org/10.1016/j.quascirev.2016.07.034

Goslar, T., Kuc, T., Ralska-Jasiewiczowa, M., Rozanski, K., Arnold, M., Bard, E., Vangeel, B., Pazdur, M.F., Szeroczynska, K., Wicik, B., Wieckowski, K., Walanus, A., 1993. High-resolution lacustrine record of the late-glacial Holocene transition in central-Europe. Quaternary Sciences Review, **12**: 287–294; https://doi.org/10.1016/0277-3791(93)90037-M

Goslar, T., Czernik, J., Goslar, E., 2004. Low-energy ^{14}C AMS in Poznan Radiocarbon Laboratory, Poland. Nuclear Instruments and Methods in Physics Research B, **223-224**: 5–11.

Griffiths, H.J., Ringwood, V., Evans, J.G., 1994. Weichselian, Late-glacial and early Holocene molluscan and ostracod sequences from lake sediments at Stellmoor, north Germany. Hydrobiologia, **3:** 357–380.

Guiry, M.D., Guiry, G.M., 2023. AlgaeBase. World-wide electronic publication, University of Galway; https://www.algaebase.org

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

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology, **25**: 101–110; https://doi.org/10.1023/A:1008119611481

Hrynowiecka, A., Żarski, M., Jakubowski, G., Nadachowski, A., Pawłowska, K., Pawłowski, D., Szymanek, M., Nast, D., 2018. Eemian and Vistulian (Weichselian) paleoenvironmental changes: a multi-proxy study of sediments and mammal remains from the Ławy paleolake (Eastern Poland). Quaternary International, **467A:** 131–146; https://doi.org/10.1016/j.quaint.2016.10.033

Joannin, S., Vannichre, B., Galop, D., Peyron, O., Haas J.N., Gilli A., Chapron, E., Wirth, S.B., Anselmetti, F., Desmet, M., Magny, M., 2013. Climate and vegetation changes during the Lateglacial and early-middle Holocene at Lake Ledro (southern Alps, Italy). Climate of the Past, **9:** 913–933; https://doi.org/10.5194/cp-9-913-2013

Jones, V., 2007. Diatom introduction. In: Encyclopedia of Quaternary Science (ed. S.A. Elias): 476–484. Elsevier, Amsterdam, Boston.

Juggins, S., 2007. C2 version 1.5 user guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation. Newcastle University, Newcastle: 1–73.

Juggins, S., 2017. "rioja: Analysis of Quaternary Science Data, R package version 0.9-21. http://cran.r-project.org/package=rioja

Kaiser, K., Lorenz, S., Germer, S., Juschus, O., Küster, M., Libra, J., Bens, O., Hüttl, R.F., 2012. Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact – an overview. E&G Quaternary Science Journal, **61** (2): 103–132.

Kats, N.Ya., Kats, S.V., Kipiani, M.G., 1965. Atlas and keys of fruits and seeds occuring in the Quaternary deposits of the USSR (in Russian). Nauka, Moskva.

Kaufman, D.S., McKay, N.P., Routson, C.C., Erb, M.P., Davis, B.A., Heiri, O., Jaccard, S.L., Tierney, J.E., Dätwyler, C., Axford, Y., Brussel, T.V., Cartapanis, O., Chase, B.M., Dawson, A., de Vernal, A., Engels, S., Jonkers, L., Marsicek, J.P., Moffa-Sánchez, P., Morrill, C., Orsi, A.J., Rehfeld, K., Saunders, K.M., Sommer, P.S., Thomas, E.K., Tonello, M.S., Toth, M., Vachula, R.S., Andreev, A.A., Bertrand, S., Biskaborn, B.K., Bringuè, M., Brooks, S.J., Caniupàn, M., Chevalier, M., Cwynar, L.C., Emile-Geay, J., Fegyveresi, J.M., Feurdean, A., Finsinger, W., Fortin, M.C., Foster, L.C., Fox, M.L., Gajewski, K., Grosjean, M., Hausmann, S., Heinrichs, M.L., Holmes, N., Ilyashuk, B.P., Ilyashuk, E.A., Juggins, S., Khider, D., Koinig, K.A., Langdon, P.G., Larocque-Tobler, I., Li, J., Lotter, A.F., Luoto, T.P., Mackay, A.W., Magyari, E.K., Malevich, S.B., Mark, B.G., Massaferro, J., Montade, V., Nazarova, L.B., Novenko, E.Y., Pařil, P., Pearson, E.J., Peros, M.C., Pienitz, R., Płóciennik, M., Porinchu, D.F., Potito, A., Rees, A., Reinemann, S.A., Roberts, S.J., Rolland, N., Salonen, S., Self, A., Seppä, H., Shala, S., St-Jacques, J., Stenni, B., Syrykh, L.S., Tarrats, P., Taylor, K.J., van den Bos, V., Velle, G., Wahl, E.R., Walker, I., Wilmshurst, J.M., Zhang, E., Zhilich, S., 2020. A global database of Holocene paleotemperature records. Scientific Data, **7:** 1–34; https://doi.org/10.1038/s41597-020-0445-3

Kittel, P., 2007. Środowiskowe uwarunkowania lokalizacji wczesno-średniowiecznego grodziska w Mchówku na Kujawach (in Polish). In: Zapis działalności człowieka w środowisku przyrodniczym (eds. E. Smolska and P. Szwarczewski): 55–63. Bogucki Wydaw. Nauk., Poznań.

Kittel, P., 2008. Geomorfologiczne cechy lokalizacji osadnictwa pradziejowego w mikroregionie leśnieńskim (in Polish). In: Leśno i mikroregion w późnej epoce brązu i wczesnej epoce żelaza (ed. K. Walenta): 197–224. Zakład Archeologii Pomorza Instytutu Archeologii Uniwersytetu Łódzkiego, Muzeum Historyczno-Etnograficzne w Chojnicach, Chojnice.

Kittel, P., 2015. The prehistoric human impact on slope development at the archaeological site in Smólsk (Kuyavian Lakeland). Bulletin of Geography, Physical Geography Series, **8:** 107–122; https://doi.org/10.2478/7035

Kittel, P., Muzolf, B., Alexandrowicz, W.P., Nalepka, D., Okupny, D., Stachowicz-Rybka, R., 2015. Stanowisko Smólsk. Badania paleoekologiczne w Smólsku na Kujawach obejmujące okres od starszego neolitu (in Polish). VII Konferencja Paleobotaniki Czwartorzędu „Dynamika zmian roślinności Niżu Polskiego w dobie późnoglacjalnych zmian klimatu i narastania antropopresji w holocenie" (eds. D. Dzieduszyńska and M. Roman): 80–89, Łódź.

Kondracki, J., 1994. Geografia fizyczna Polski (in Polish). Wydaw. Nauk. PWN, Warszawa.

Kondracki, J., 2002. Geografia regionalna Polski (in Polish). Wydaw. Nauk. PWN, Warszawa.

Kołaczek, P., Gałka, M., Karpińska-Kołaczek, M., Lutyńska, M., 2015. Late Pleniglacial and Late Glacial lake-mire transformations in south-eastern Poland reflected in aquatic and wetland vegetation changes. Quaternary International, **388:** 39–50; https://doi.org/10.1016/j.quaint.2014.04.042

Kotrys, B., Płóciennik, M., Sydor, P., Brooks, S.J., 2020. Expanding the Swiss-Norwegian chironomid training set with Polish data. Boreas, **49**: 89–107; https://doi.org/10.1111/bor.12406

Kramkowski, M., Filbrand-Czaja, A., Zawisza, E., Rzodkiewicz, M., Kotrys, B., Mirosław-Grabowska, J., Błaszkiewicz, M., Szewczyk, K., Słowiński, M., 2023. Preboreal oscillation in the light of multiproxy analyses – Early Holocene in Lake Jelonek (North Poland). Holocene, **33:** 998–1011; https://doi.org/10.1177/09596836231169993

Krammer, K., Lange-Bertalot, H., 2008a. Bacillariophyceae 2, Ephitemiaceae, Bacillariaceae, Surirellaceae. In: Süsswasserflora von Mitteleuropa (eds. H. Ettl, J. Gerloff, H. Heyning and D. Mollenhauer). Spektrum.

Krammer, K., Lange-Bertalot, H., 2008b. Bacillariophyceae 3, Centrales, Fragilariaceae, Eunotiaceae. In: Süsswasserflora von Mitteleuropa (eds. H. Ettl, J. Gerloff, H. Heyning and D. Mollenhauer). Spektrumt.

Krammer, K., Lange-Bertalot, H., 2010. Bacillariophyceae 1. Naviculaceae. In: Süsswasserflora von Mitteleuropa (eds. H. Ettl, J. Gerloff, H. Heyning and D. Mollenhauer). Spektrum.

Krammer, K., Lange-Bertalot, H., 2011. Bacillariophyceae 4, Achnanthaceae. In: Süsswasserflora von Mitteleuropa (eds. H. Ettl, J. Gerloff, H. Heyning and D. Mollenhauer). Spektrum.

Krupiński, K.M., Tobolski, K., Ralska-Jasiewiczowa, M., Nalepka, D., 2004a. *Hippophaë rhamnoides* L. – sea-buckthorn. In: Late Glacial and Holocene history of vegetation in Poland based on isopollen maps (eds. M. Ralska-Jasiewiczowa, M. Latałowa K. Wasylikowa, K. Tobolski, E. Madeyska, H.E. Wright and Ch. Turner). W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Krupiński, K., Noryśkiewicz, A.M., Nalepka, D., 2004b. *Taxus baccata* L. – Yew. In: Late Glacial and Holocene history of vegetation in Poland based on isopollen maps (eds. M. Ralska-Jasiewiczowa, M. Latałowa K. Wasylikowa, K. Tobolski, E. Madeyska, H.E. Wright and Ch. Turner). W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Lane, C.S., Brauer, A., Blockley, S.P.E., Dulski, P., 2013. Volcanic ash reveals time-transgressive abrupt climate change during the Younger Dryas. Geology, **41**: 1251–1254; https://doi.org/10.1130/G34867.1

Lange-Bertalot, H., Krammer, K., 1987. Bacillariaceae, Epithemiaceae, Surirellaceae. Königstein.

Lange-Bertalot, H., Metzeltin, D., 1996. Indicators of oligotrophy – 800 taxa representative of three ecologically distinct lake types, Carbonate buffered – Oligodystrophic – Weakly buffered soft water. In: Iconographia Diatomologica (ed. H. Lange-Bertalot). Annotated Diatom Micrographs. Vol. 2. Ecology, Diversity, Taxonomy.

Lange-Bertalot, H., Bąk, M., Witkowski, A., Tagliaventi, N., 2011. Eunotia and related genera. Diatoms of Europe, **6**: 1–747.

Lecointe, C., Coste, M., Prygiel, J., 1993. OMNIDIA: software for taxonomy, calculation of diatom indices and inventories management. Hydrobiologia, **269/270**: 509–513.

Lewis, C.F.M., Anderson, T.W., 1989. Oscillations of levels and cool phases of the Laurentide Great Lakes caused by inflows from Lake Agassiz and Barlow-Ojibway. Journal of Paleolimnology, **2**: 99–146.

Litt, T., Brauer, A., Goslar, T., Merkt, J., Bałaga, K., Müller, H., Ralska-Jasiewiczowa, M., Stebich, M., Nagendank, J.F.W., 2001. Correlation and synchronisation of Lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments. Quaternary Science Review, **20**: 1233–1249; https://doi.org/10.1016/S0277-3791(00)00149-9

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C., 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. Quaternary Science Reviews, **27**: 6–17; https://doi.org/10.1016/j.quascirev.2007.09.016

Luoto, T.P., Kotrys, B., Płóciennik, M., 2019. East European chironomid-based calibration model for past summer temperature reconstructions. Climate Research, **77**: 63–76; https://doi.org/10.3354/cr01543

Magny, M., 2001. Palaeohydrological changes as reflected by lake-level fluctuations in the Swiss Plateau, the Jura Mountains and the northern French Pre-Alps during the Last Glacial–Holocene transition: a regional synthesis. Global and Planetary Change, **30**: 85–101; https://doi.org/10.1016/S0921-8181(01)00080-7

Makohonienko, M., Płóciennik, M., Papiernik, P., Kittel, P., Gałka, M., Mroczkowska, M., Apolinarska, K., Okupny, D., Panfil, M., Kotrys, B., Luoto, T.P., Krąpiec, M., Tyszkowski, S., 2023. Environmental changes during Mesolithic-Neolithic transition in Kuyavia Lakeland, Central Poland. Quaternary International, **644–645:** 196-221; https://doi.org/10.1016/j.quaint.2021.11.020

Matuszkiewicz, J., 2008. Potencjalna roślinność naturalna Polski (in Polish). IGiPZ PAN, Warszawa.

Mojski, J., 2005. Ziemie polskie w czwartorzędzie. Zarys morfogenezy (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Molewski, P., 2007. Neotektoniczne i glacjodynamiczne uwarunkowania wykształcenia plejstocenu Wysoczyzny Kujawskiej (in Polish). Wydaw. UMK, Toruń.

Moller Pillot, H.K.M., 2009. Chironomidae Larvae of the Netherlands and Adjacent Lowlands. Biology and Ecology of the Chironomini. KNNV Publishing, Zeist.

Moller Pillot, H., 2013. Chironomidae Larvae of the Netherlands and Adjacent Lowlands, Biology and Ecology of the Aquatic Orthocladiinae. KNNV Publishing, Zeist.

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

Morisita, M., 1959. Measuring of interspecific association and similarity between communities. Memories of the Faculty of Sciences, Kyushu University, E, **3**: 65–80.

Müller, D., Tjallingii, R., Płóciennik, M., Luoto, T.P., Kotrys, B., Plessen, B., Ramisch, A., Schwab, M.J., Błaszkiewicz, M., Słowineski, M., Brauer, A., 2021. New insights into lake responses to rapid climate change: the Younger Dryas in Lake Gościąż, central Poland. Boreas, **50**: 535–555; https://doi.org/10.1111/bor.12499

Muschitiello, F., Andersson, A., Wohlfarth, B., Smittenberg, R.H., 2015. The C20 highly branched isoprenoid biomarker – a new diatom-sourced proxy for summer trophic conditions? Organic Geochemistry, **81**: 27–33; https://doi.org/10.1016/j.orggeochem.2015.01.007

Muzolf, B., Kittel, P., Muzolf, P., 2012. Sprawozdanie z prac badawczych na wielokulturowym kompleksie osadniczym w miejscowości Smólsk, stanowisko 2/10, gm. Włocławek, woj. kujawsko-pomorskie (in Polish). Raport I, 2007–2008, 43–64; https://nid.pl/up-load/iblock/d40/d40e6c30eb7a5a8023a496ff1ca67fb9.pdf

Nalepka, D., 2005. Late glacial and Holocene palaeoecological conditions and changes of vegetation cover under early farming activity in the south Kujawy region (central Poland). Acta Palaeobotanica Supplement, **6**: 3–90.

Nalepka, D., 2008. Late Glacial and Holocene history of vegetation at Osłonki (Kujawy, Central Poland). Folia Quaternaria, **78**: 33–44.

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

Noryśkiewicz, A.M., 2006. Historia cisa w okolicy Wierzchlasu w świetle analizy pyłkowej (in Polish). Instytut Archeologii UMK w Toruniu, Towarzystwo Przyjaciół Dolnej Wisły, Toruń.

Nowaczyk, B., 2008. Changes in the natural environment in the vicinity of Osłonki (Kujawy, Central Poland) in light of geological and geomorphological investigations. Folia Quaternaria, **78**: 7–31.

Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E., Wagner, H., 2019. Vegan: Community Ecology Package. R package version 2.5-6; https://cran.r-project.org/package=vegan

Pauly, M., 2022. Dendroclimatology using stable isotopes from subfossil tree-rings. Refubium – Freie Universität Berlin Repository.

Pawłowski, D., Milecka, K., Kittel, P., Woszczyk, M., Spychalski, W., 2015. Palaeoecological record of natural changes and human impact in a small river valley in Central Poland. Quaternary International, **370**: 12–28; https://doi.org/10.1016/j.quaint.2014.06.033

Pełechaty, M., Pukacz, A., Apolinarska, K., Pełechata, A., Siepak, M., 2013. The significance of *Chara* vegetation in the precipitation of lacustrine calcium carbonate. Sedimentology, **60**: 1017–1035; https://doi.org/10.1111/sed.12020

Piechocki, A., Wawrzyniak-Wydrowska, B., 2016. Guide to freshwater and marine molluscs of Poland. Bogucki Wydawnictwo Naukowe, Poznań.

Płóciennik, M., Zawiska, I., Rzodkiewicz, M., Noryśkiewicz, A.M., Słowiński, M., Müller, D., Brauer, A., Antczak-Orle-wska, O., Kramkowski, M., Peyron, O., Nevalainen, L., Luoto, T.P., Kotrys, B., Seppä, H., J.C. Bidaurreta, Rudna, M., Mielczarek, M., Zawisza, E., Janowska, E., Błaszkiewicz, M., 2022. Climatic and hydrological variability as a driver of the Lake Gościąż biota during the Younger Dryas. Catena, **212,** 106049.

Przegiętka, K., Chruścicka, A., Oczkowski, H., Molewski, P., 2008. Chronostratigraphy of the Vistulian Glaciation the Kujawy Moraine Plateau (central Poland) based on lithostratigraphic research and OSL dating. Geochronometria, **32:** 69–77; https://doi.org/10.2478/v10003-008-0024-7

Quinlan, R., Smol, J.P., 2001. Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. Journal of Paleolimnology, **26:** 327–342; https://doi.org/10.1023/A:1017562703986

Rach, O., Brauer, A., Wilkes, H., Sachse, D., 2014. Delayed hydrological response to Greenland cooling at the onset of the Younger Dryas in western Europe. Nature Geoscience, **7:** 109–112; https://doi.org/10.1038/ngeo2053.

Ralska-Jasiewiczowa, M., Latałowa, M., 1996. Poland. In: Regional Syntheses of Palaeoecological Studies in Lakes and Mires in Europe (eds. B.E. Berglund, J.H.B. Birks, M. Ralska-Jasiewiczowa and H.E. Wright Jr.): 403–472. Wiley & Sons, Chichester.

Ralska-Jasiewiczowa, M., Goslar, T., Madeyska, T., Starkel, L., 1998. Lake Gościąż, Central Poland: a monographic study. Part 1. W. Szafer Institute of Botany, Polish Academy of Sciences Kraków.

Ralska-Jasiewiczowa, M., Latałowa, M., Wasylikowa, K., Tobolski, K., Madeyska, E., Wright, H.E., Turner, Ch. (eds.), 2004. Late Glacial and Holocene history of vegetation in Poland based on isopollen maps. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

R Core Team, 2020. R: A language and environment for statistical computing. Austria: R Foundation for Statistical Computing.

Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B.M., Walker, M.J., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quaternary Science Reviews, **106:** 14–28; https://doi.org/10.1016/j.quascirev.2014.09.007

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). Radiocarbon, **62:** 725–757; https://doi.org/10.1017/RDC.2020.41

Roman, M., 2010. Rekonstrukcja lobu płockiego w czasie ostatniego zlodowacenia (in Polish). Acta Geographica Lodziensia, **96:** 1–171.

Sanko, A., Vainorius, J., Melešytė, M., 2010. Malacofauna of Holocene freshwater calcareous deposits in Lithuania. Geologija, **52:** 69–72.

Schaub, M., Kaiser, K.F., Frank, D.C., Büntgen, U., Kromer, B., Talamo, S., 2008. Environmental change during the Allerød and Younger Dryas reconstructed from Swiss tree-ring data. Boreas, **37:** 74–86; https://doi.org/10.1111/j.1502-3885.2007.00004

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. Physicogeographical mesoregions of Poland: verification

and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica, **91:** 143–170; https://doi.org/10.7163/gpol.0115

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

Szeroczyńska, K., Sarmaja-Korjonen, K., 2007. Atlas of subfossil Cladocera from Central and Northern Europe. Friends of the Lower Vistula Society.

Teller, J.T., 2001. Formation of large beaches in an area of rapid differential isostatic rebound: the three-outlet control of Lake Agassiz. Quaternary Science Reviews, **20:** 1649–1659; https://doi.org/10.1016/S0277-3791(01)00007-5

Tylmann, W., Turczyński, M., Kinder, M., 2009. Sedimentation rates and erosion changes recorded in recent sediments of Lake Piaseczno, south-eastern Poland. Geologia, **51**: 125–120; https://doi.org/10.2478/v10056-009-0013-1

Vallenduuk, H.J., Moller Pillot, H.K.M., 2007. Chironomidae Larvae. In: Tanypodinae: General Ecology and Tanypodinae, **1**. KNNV Publishing, Zeist.

Van Asch, N., Lutz, A.F., Duijkers, M.C.H., Heiri, O., Brooks, S.J., Hoek, W.Z., 2012. Rapid climate change during the Weichselian Lateglacial in Ireland: Chironomid-inferred summer temperatures from Fiddaun, Co. Galway. Palaeogeography, Palaeoclimatology, Palaeoecology, **315–316:** 1–11; https://doi.org/10.1016/j.palaeo.2011.11.003

Van Dam, H., van Mertens, A., Sinkeldam, J., 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. Netherlands Journal of Aquatic Ecology, **28:** 117–133; https://doi.org/10.1007/BF02334251

Van Damme, K., Dumont, H.J., 2008. Further division of *Alona* Baird, 1843: separation and position of *Coronatella* Dybowski & Grochowski and *Ovalona* gen. n. (Crustacea: Cladocera). Zootaxa, **1960**: 1–44; https://doi.org/10.11646/zootaxa.1960.1.1

Van Damme, K., Kotov, A.A., Dumont, H.J., 2010. A checklist of names in *Alona* Baird 1843 (Crustacea: Cladocera: Chydoridae) and their current status: an analysis of the taxonomy of a lump genus. Zootaxa, **2330**: 1–63.

Van der Bilt, W.G.M., D'Andrea, W.J., Werner, J.P., Bakke, J., 2019. Early Holocene temperature oscillations exceed amplitude of observed and projected warming in Svalbard lakes. Geophysical Research Letters, **46:** 14732–14741; https://doi.org/10.1029/ 2019GL084384

Van der Velder, G., Giesen, T.G., Van der Heijden, L., 1979. Structure, biomass and seasonal changes in biomass of *Nymphoides peltata* (Gmel.) O. Kuntze (Menyanthaceae), a preliminary study. Aquatic Botany, **7:** 279–399; https://doi.org/10.1016/0304-3770(79)90029-9

von Grafenstein, U., Erlenkeuser, H., Brauer, A., Jouzel, J., Johnsen, S.J., 1999. A mid-European decadal isotope-climate record from 15,500 to 5000 years B.P. Science, **284**: 1654; https://doi.org/10.1126/science.284.5420.1654

von Grafenstein, U., Belmecheri, S., Eicher, U., van Raden, U.J., Erlenkeuser, H., Andersen, N., Ammann, B., 2013. The oxygen and carbon isotopic signatures of biogenic carbonates in Gerzensee, Switzerland, during the rapid warming around 14,685 years BP and the following interstadial. Palaeogeography, Palaeoclimatology. Palaeoecology, **391**: 25–32; https://doi.org/10.1016/j.palaeo.2013.08.018

Velichkevich, F.Yu., Zastawniak, E., 2006. Atlas of Pleistocene vascular plant macroremains of Central and Eastern Europe, Part I – Pteridophytes and monocotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Velichkevich, F.Yu., Zastawniak, E., 2008. Atlas of vascular plant macroremains from the Pleistocene of central and eastern Europe, Part II – Herbaceous dicotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.

Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., Dorale, J.A., 2001. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu cave, China. Science, **294**: 2345–2348; https://doi.org/10.1126/science.1064618

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

Wojciechowski, A., 1999. Late Glacial and Holocene lake-level fluctuations in the Kórnik-Zaniemyśl lakes area, Great Poland Lowland. Quaternary Studies in Poland, **16:** 81–101.

Woszczyk, M., Bechtel, A., Cieśliński, R., 2011. Interactions between microbial degradation of sedimentary organic matter and lake hydrodynamics in shallow water bodies: insights from Lake Sarbsko (northern Poland). Journal of Limnology, **70**: 293–304; https://doi.org/10.3274/JL11-70-2-09

Wysota, W., 2002. Stratygrafia i środowiska sedymentacyjne zlodowacenia wisły w południowej części dolnego Powiśla (in Polish). Wydaw. UMK. Toruń: 1–144.

Young, N.E., Briner, J.P., Miller, G.H., Lesnek, A.J., Crump, S.E., Pendleton, S.L., Schwartz, R., Schaefer, J.M., 2021. Pulse-beat of early Holocene glaciation in Baffin Bay from high-resolution beryllium-10 moraine chronologies. Quaternary Science Reviews, **270:** 107179; https://doi.org/10.1016/j.quascirev.2021.107179

Zander, P.D., Żarczyński, M., Tylmann, W., Vogel, H., Grosjean, M., 2024. Subdecadal Holocene warm-season temperature variability in central Europe recorded by biochemical varves. Geophysical Research Letters, **51**, e2024GL110871; https://doi.org/10.1029/2024GL110871

https://www.rcin.org.pl/dlibra/collectiondescription/548   National Biodiversity Collection of Recent and Fossil Organisms at the W. Szafer Institute of Botany, Polish Academy of Sciences, in Kraków (herbarium KRAM).