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The natural environment in the vicinity of Lake Sporovskoye in the Late Glacial and Holocene

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ABSTRACT. Due to the relatively small number of lakes in the southern part of Belarus, in the Polesie region, each lake and its bottom sediments are of great scientific interest for palaeoecological reconstructions. Lake Sporovskoye is one of the largest lakes in Belarusian Polesie, previously studied in the field of palaeoecology by a number of researchers. The discovery in 2018 of the Kakoryca-4 archaeological site near Lake Sporovskoye inspired the beginning of this study, during which new palaeoecological data were obtained. The purpose of the article was to build palaeoecological reconstructions based on spore-pollen, macroremains, sedimentological, and radiocarbon analyses of the Sporovo II core. As a result, it was proven that Lake Sporovskoye was formed in the Late Glacial. Water level changes in the lake, as well as a period of increased activity of the Yaselda River, were detected in the Holocene. The author proposed the reconstructions of regional and local vegetation and corrected some previous views on the development of the study area in the Late Glacial and Holocene.

KEYWORDS: Lake Sporovskoye, the Yaselda River, Sporovo II core, spore-pollen analysis, calcareous and organic gyttja, telmatic and fen peat

INTRODUCTION

Lacustrine and wetland geological deposits are a kind of natural chronicles in which information about the past state of the natural environment is recorded. Through the use of palaeoecological research methods, some of which are presented in this article, we can decipher these natural records and tell a lot not only about natural changes in the past, but also trace the anthropogenic influence and the relationship between man and nature in the distant past. An attempt to decipher the lacustrine and wetland deposits of the Sporovo II core near Lake Sporovskoye is presented in this article. The reasons for writing this article also include a small number of palaeoecological studies on the territory of Belarus, as well as the problem of distinguishing between peat and organic gyttja in lithological interpretations. Therefore, among other things, this article corrects previous lithological interpretations of Belarusian scientists, using a methodological approach in accordance with Tobolski (2021).

Lake Sporovskoye is located in Southern Belarus, on the territory of Belarusian Polesie (Fig. 1). The present-day area of the lake is 11.1 km^2, the maximum depth is 1.5 m, the average depth is 0.9 m (Vlasov et al., 2004) (Fig. 2). A tributary of the Pripyat River – Yaselda River – flows through the described reservoir, which is situated in its valley. At the mouth of the Yaselda River a large delta is formed. The studied environs of the lake are under state protection and belong to the Sporovsky Biological Reserve.

Vast surroundings of the lake are occupied by grass wetlands with small rounded sandy

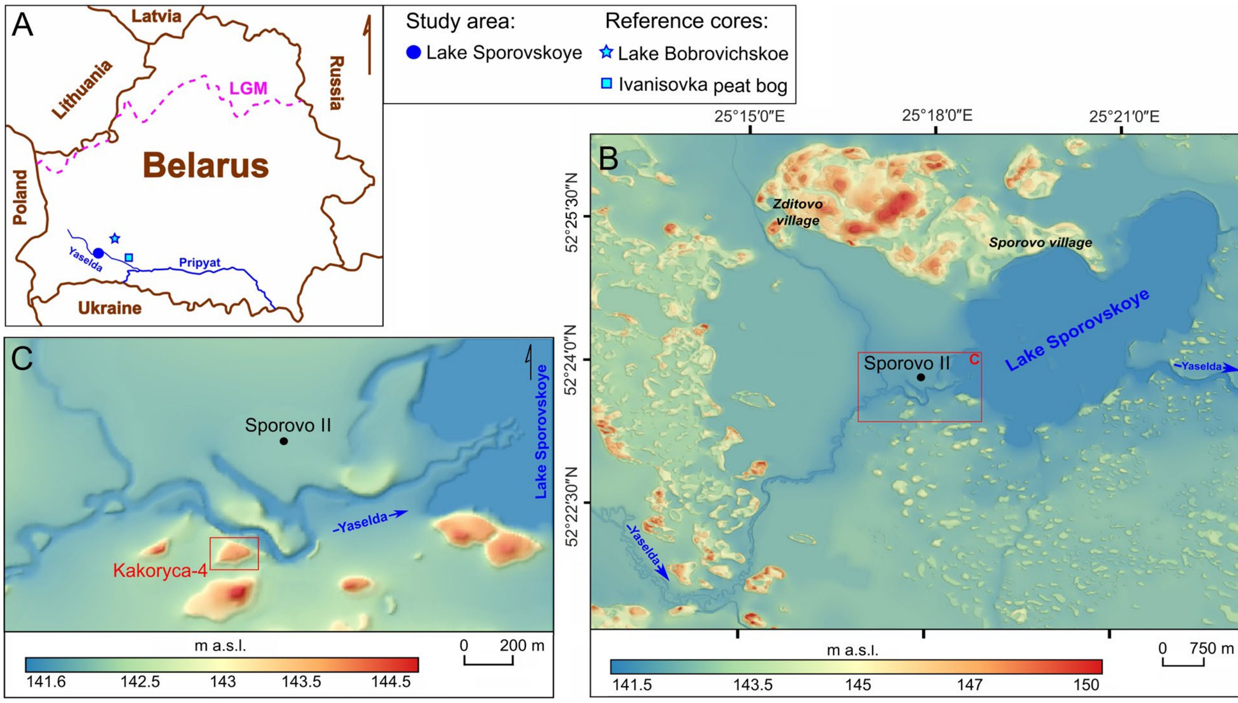

Figure 1. Location of the studied Sporovo II core in the basin of the Yaselda River and Lake Sporovskoye (**B**, **C**), beyond the border of the last glaciation (**A**), together with the location of reference spore-pollen cores of Lake Bobrovichskoe and the Ivanisovka peat bog (Trifonov, 2021; Tsvirko et al., 2021b; Tsvirko and Kittel, 2022a)

elevations. Modern regional vegetation to the west and south of Lake Sporovskoye is characterized by a significant transformation as a result of modern agricultural activities. In turn, to the northeast (toward Lake Bobrovichskoe), large areas are covered by fens and poor fens with primary birch, pine-birch and alder forests (Fig. 3).

Archaeological research carried out on one of the sandy elevations near Lake Sporovskoye has revealed an archaeological layer rich in artifacts, mainly from the Neolithic and Bronze Age (from fifth to second millennium BC) (Tsvirko et al., 2021b). This exciting archaeological site Kakoryca-4 (52°23′36.657″N, 25°17′34.355″E) provoked

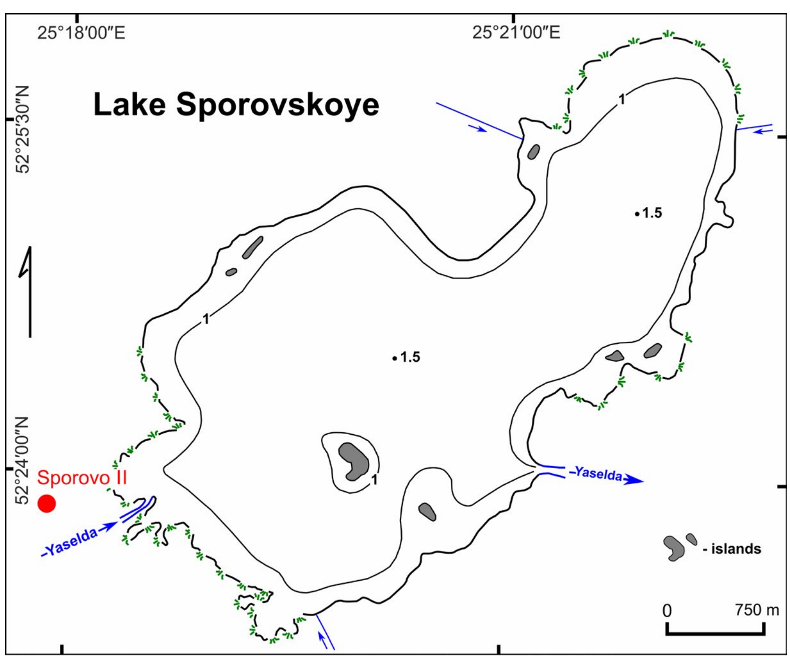

Figure 2. Bathymetric survey of Lake Sporovskoye, depths are given in meters (modified by the author based on Vlasov et al., 2004)

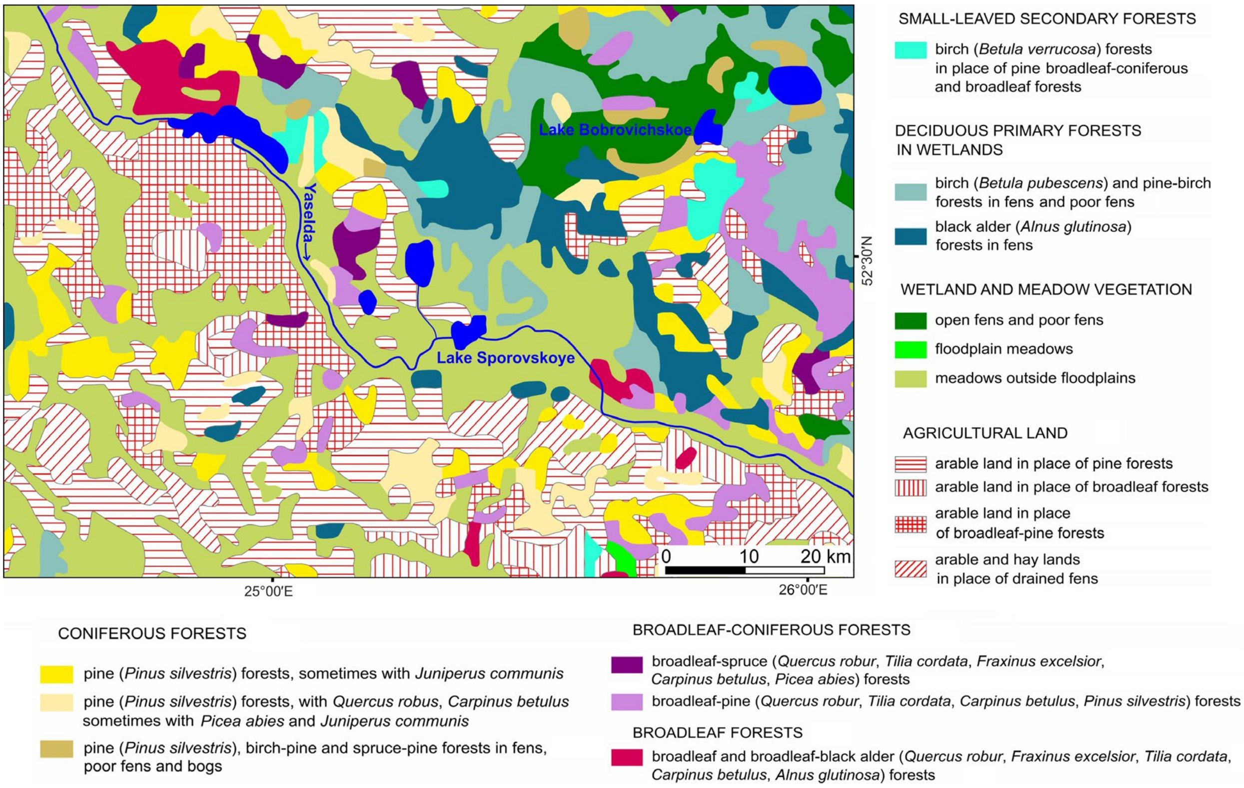

Figure 3. Map of modern vegetation in the vicinity of Lake Sporovskoye (modified by the author based on Natsionalnyiy atlas Belarusi, 2002)

new palaeoecological studies focusing on the area around the lake.

Previously V. Zernitskaya (1985) studied 195 cm of bottom sediments of Lake Sporovskoye using spore-pollen analysis. The borehole was situated 1.1 km SE of the eastern outskirts of Sporovo village. The age of the studied sediments was determined exclusively from pollen data, radiocarbon dating was not carried out.

The spore-pollen data presented by V. Zernitskaya should be considered in close connection with the results of carpological analysis made by E. Krutous (1990). She examined a 190 cm long sediment core (Fig. 13) and compared the results with Zernitskaya's palynological data. It was not shown in the text of the publication whether the carpological analysis was performed from the same core as the pollen analysis or from two adjacent profiles, however, their lithology was similar.

Northwest of Lake Sporovskoye, the spore-pollen study was made also for fen deposits near the village of Zditovo (Zernitskaya and Daineko, 1986). The age of these deposits was determined using spore-pollen data and a single radiocarbon date 7020 ± 70 BP (Tln-588).

Preliminary results of palaeoecological studies for Kakoryca-4 archaeological site and surrounding area were presented recently by Tsvirko et al. (2019, 2021a, b), Trifonov et al. (2020), and Tsvirko and Kittel (2022a, b). In this paper, some of the ideas and interpretations expressed then are corrected and specified based on new data.

In connection with the discovery of the Kakoryca-4 archaeological site, and also due to insufficient amount of palaeoecological information, it seems promising to continue palaeoecological investigations of the area of Lake Sporovskoye.

The aim of this paper is to present the palaeoecological reconstructions for Lake Sporovskoye and its surroundings, based on palaeodata obtained from the new Sporovo II core.

MATERIALS AND METHODS

In 2019 a field expedition was carried out in the vicinity of Lake Sporovskoye, aimed to collect the deposit cores for spore-pollen, sedimentological, geochemical, radiocarbon and other palaeoecological analyses. The 270 cm long Sporovo II core (52°23′52.797″N 25°17′44.802″E) was collected from the Lozy fen, to the west of Lake Sporovskoye, not far from the delta of the Yaselda River and the archaeological site Kakoryca-4 (Fig. 1). The close location of the Sporovo II core to the Yaselda channel made it possible to record the influence of the river on sediment accumulation.

RADIOCARBON ANALYSIS

Radiocarbon dating of organic deposits (bulks) from the Sporovo II core was carried out in the "Laboratorium Datowań Bezwzględnych" in Cracow using the liquid scintillation technique (LSC). The results of radiocarbon dating of three samples were published earlier by Tsvirko et al. (2021b). In the paper, when interpreting the results, calibrated dates (cal BP) were given with a 68.3% probability.

SPORE-POLLEN ANALYSIS

Preliminary palynological results from the Sporovo II core were published earlier by Tsvirko et al. (2021b). Laboratory processing included the chemical treatment of geological sediment samples using HCl and KOH to extract pollen and spores of plants. The processing was carried out according to the standard technique of Faegri and Iversen (1989), with the exception of acetolysis and HF treatments. Sieving of samples was also carried out to separate pollen and spores from large macroremains of plants. The remaining material was preserved in glycerol. The samples were processed in the laboratory of the Institute for Nature Management of the National Academy of Sciences of Belarus.

During microscopic analysis, more than 500 pollen grains of trees and shrubs (AP) were counted in each sample. A number of pollen atlases and Internet resources were used in the identification of taxa (Kupriyanova and Aleshina, 1972, 1978; Bobrov et al., 1983; Faegri and Iversen, 1989; Moore et al., 1991; Reille, 1992; PalDat, 2000; Firnin, 2010; Wieckowska-Lüth et al., 2020).

The percentages of trees, shrubs and upland herbs were calculated from the total sum of trees and shrubs (AP) and upland herbs (AP + UPHE = 100%), excluding Cyperaceae pollen. The pollen percentage of Cyperaceae was calculated separately from the sum of AP + UPHE + Cyperaceae. The percentages of aquatic vascular plants, spore vegetation, and non-pollen palynomorphs were calculated from AP + UPHE + the sum of aquatic plants, or spore plants, or NPP. The percentages of Undeterminable (damaged, indistinguishable pollen and spores) and Undetermined (pollen and spores that were not identified) were calculated from the total sum of all pollen grains and spores. For constructing spore-pollen and macroremains diagrams, the Tilia program (Grimm, 1992) was used. The CONISS cluster diagram (Grimm, 1987) was built on the basis of AP and UPHE (without Cyperaceae) data.

The proposed chronology of events was largely based on palynostratigraphy. The pollen spectra of the Sporovo II core were correlated with reference palynological diagrams of Lake Bobrovichskoe and the Ivanisovka peat bog (Zernitskaya and Mikhailov, 2009; Zernitskaya et al., 2010; Zernitskaya, 2022) (Fig. 1).

PLANT MACROREMAINS ANALYSIS

The identification of the found macroremains was carried out by M. Słowiński for 19 samples of the Sporovo II core. It should be clarified that the presented data reflected single macroremains found occasionally during the preparation of the samples for other analyses. A detailed analysis of the sediments for the content of macroremains was not carried out.

When constructing the carpological diagram of E. Krutous (1990), the value "100" was used for the category called "many" by Krutous, since in her data the maximum numerical values were less than 100: 98, 88, 77.

SEDIMENTOLOGICAL ANALYSIS

Preliminary sedimentological results for the Sporovo II core were previously published by Tsvirko et al. (2021b). To construct a loss on ignition (LOI) diagram of the Sporovo II core, samples containing organic matter were dried at 50°C, grinded in a porcelain mortar, and then ignited at 550°C for 8 hours in a muffle furnace. Before ignition, some highly organic

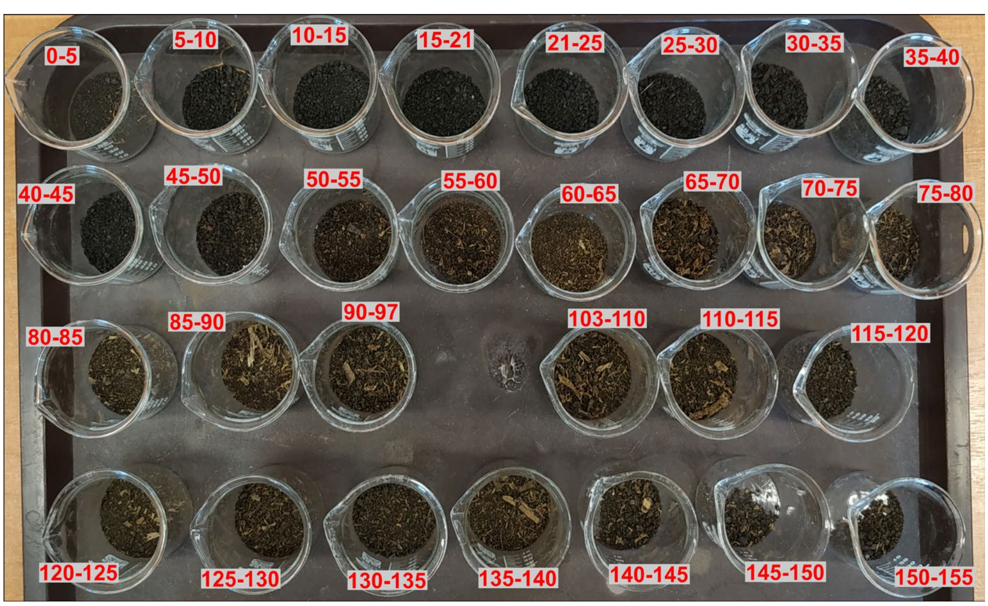

Figure 4. Organic samples from the Sporovo II core after drying at 50°C and grinding in a porcelain mortar; the upper peat samples (~0–50 cm) are darker in colour (photo by D. Tsvirko)

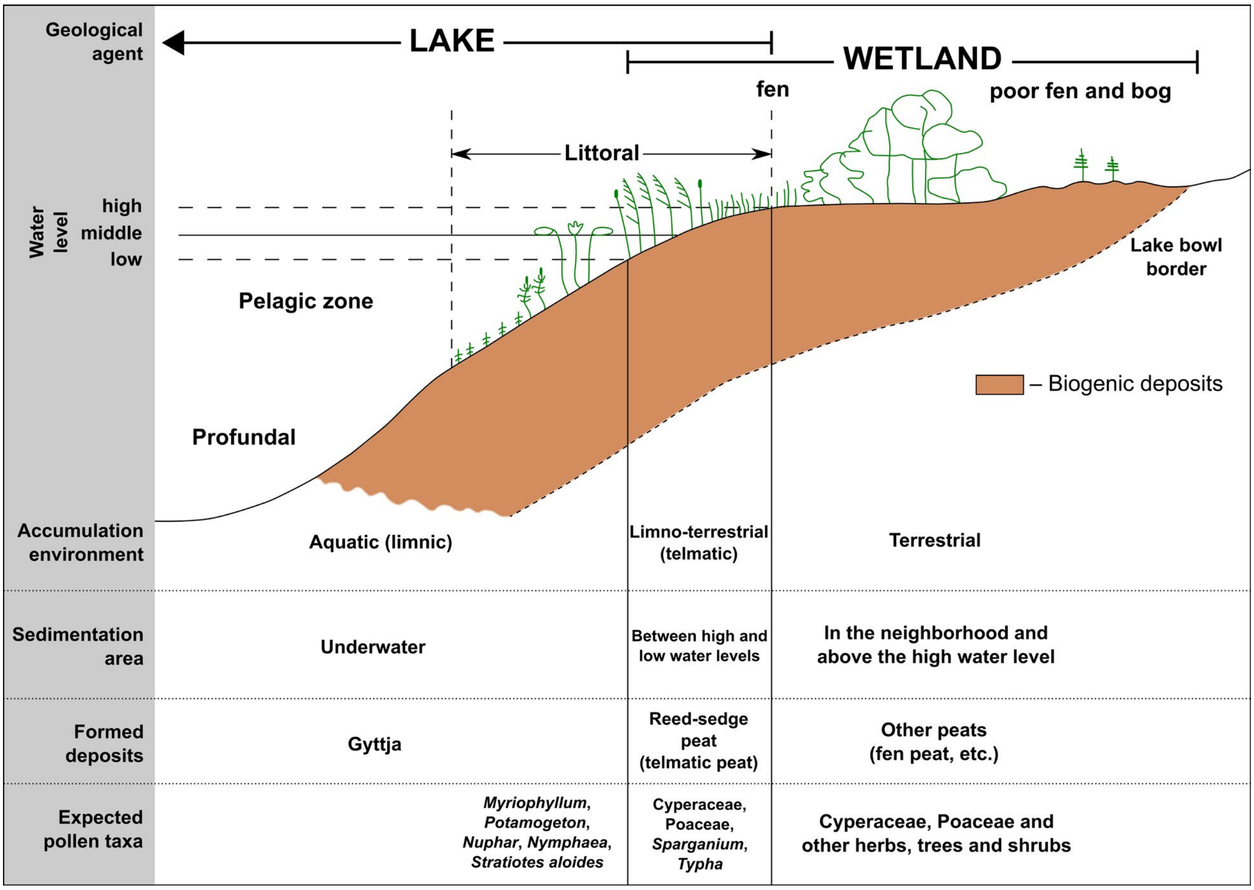

Figure 5. Biogenic accumulation in the lake reservoir and its peaty shore (according to Tobolski, 2021; modified and supplemented by D. Tsvirko)

samples were separated by colour. Samples from 0–45 cm were black and contained a small number of organic pieces. The sample from 45–50 cm was identified as transitional with a black-brown colour. In contrast, samples from 50–97 cm and 103–155 cm were predominantly brown in colour and contained many large organic pieces (Fig. 4).

Textural analysis of highly organic deposits (depth interval 0–183 cm) was carried out on the basis of the study of granulometric composition of the ash purified from metal oxides and carbonates according to the technique (the HCl cleaning procedure) previously proposed by Tsvirko et al. (2022a, b). The analysed ash was obtained by ignition of organic deposits in a muffle furnace at a temperature of 550°C for 8 hours. Then, in the laboratory at the Faculty of Geographical Sciences of the University of Lodz, the ash underwent chemical treatment using the HCl cleaning procedure. After purification from metal oxides and carbonates, the ash was analysed with a Laser Mastersizer 3000 at the Institute of Geography, Pedagogical University of Krakow. Thus, the textural analysis of the purified ash is given for the depth interval of 0–183 cm. In turn, the deposits from depths of 189–270 cm were analysed by the Laser directly after grinding in a porcelain mortar and were not subjected to temperature (ignition in the muffle furnace) or chemical (the HCl cleaning procedure) treatment due to the lack of significant organic admixtures.

For textural analysis, the Gradistat Version 9.1 software was used (Blott and Pye, 2001), in which textural groups and sample statistics (mean M_z, standard deviation δ_I, skewness Sk_I, kurtosis K_G) were calculated.

$CaCO_3$ content was determined with a Scheibler calcimeter (Korabiewski, 2011).

LITHOLOGICAL INTERPRETATION

The identification of lithological units in the Sporovo II core was based on LOI values, textural data, geochemical analysis ($CaCO_3$ %), as well as pollen, macroremains data and a visual description of the deposits.

The determination of genesis (lacustrine or wetland) of the deposits was based on dividing the littoral zone into two ecological zones (Tobolski, 2021). The first littoral ecological zone is characterized by the accumulation of gyttja in permanently underwater (limnic) conditions. This zone corresponds to the distribution range of fully submerged plants (e.g. *Myriophyllum*, *Potamogeton*) and plants with floating leaves (e.g. *Nuphar*, *Nymphaea*, *Stratiotes aloides*). In the case of Sporovo II core, the sediments that permanently contained the pollen of these plants (as well as found macroremains) were interpreted as gyttja accumulated in the underwater conditions of the lake (Fig. 5).

The second littoral ecological zone is characterized by the accumulation of peat in limno-terrestrial (telmatic) conditions between the high and low water levels of the reservoir. This zone corresponds to the area of semi-submerged and wetland vegetation, such as Cyperaceae, Poaceae, *Sparganium*-type, *Typha*. Thus, in the Sporovo II core, a large amount of pollen from these plants indicated a peat-accumulative environment, with telmatic (nearshore) peat.

Sediments contained a large amount of pollen from Cyperaceae and other upland herbs were interpreted as fen peat accumulated above the littoral zone (Fig. 5).

The gyttja identification was carried out according to three main types from the classification of Markowski (1980): organic gyttja, calcareous gyttja and non-calcareous mineral gyttja.

RESULTS

RADIOCARBON DATA

The calibration of the obtained dates is shown in Table 1. The calibration was made with the OxCal 4.4 online (Bronk Ramsey, 2021), using the "IntCal 20" curve (Reimer et al., 2020).

SPORE-POLLEN DATA.

Based on the results obtained, using visual evaluation, as well as cluster analysis (CONISS), eight local pollen assemblage zones (LPAZ) were identified (Table 2, Fig. 6).

LPAZ SPII-1 and SPII-2. One of the main features of the SPII-1 and SPII-2 pollen zones was the largest number of *Artemisia* and Chenopodiaceae pollen grains throughout the entire section, as well as the presence of *Juniperus*, *Hippophaë* and *Betula nana*-type pollen. In addition, *Helianthemum* pollen was found in the SPII-1 zone. The presence of *Myriophyllum* and *Potamogeton* pollen grains in both described zones, as well as *Nymphaea* in SPII-1 and *Nuphar* in SPII-2, was recorded.

Table 1. Radiocarbon dating of organic deposits from the Sporovo II core and calibration of the obtained results (based on Tsvirko et al., 2021b; supplemented by D. Tsvirko)

No.	Depth b.g.l. (cm)	Age ^{14}C yr BP	Laboratory No.	Age cal yr BP prob. 68.3%	Age cal yr BP prob. 95.4%	Mean age	Dated deposits
1	97–103	5600 ± 70	MKL-4786	6441–6305	6555–6281	6392 calBP (4443 calBC)	organic gyttja
2	155–161	5190 ± 110	MKL-4785	6176–5757	6272–5663	5964 calBP (4015 calBC)	organic gyttja
3	183–189	8190 ± 90	MKL-4784	9275–9019	9449–8812	9166 calBP (7217 calBC)	organic gyttja

Table 2. Local pollen assemblage zones (LPAZ) in the Sporovo II core

LPAZ	Depth (cm)	The distinctive features of the zone
SPII-5	0–25	The zone included 5 samples. *Pinus* (70.0–56.1%), *Betula* (9.1–3.9%), *Corylus* (2.0–0.2%), *Quercus* (4.1–1.8%), *Ulmus* (1.0–0.1%), *Tilia* (0.7–0.1%), *Fraxinus* (0.5–0.1%), *Acer* (0.2–0.1%), *Carpinus* (0.5–0.2%), *Fagus* (0.4–0.1%), *Picea* (3.3–1.0%), *Abies* (0.3–0.2%), *Salix* (3.7–1.5%), Poaceae (13.1–4.5%), *Galium*-type (8.8–1.1%), *Artemisia* (1.9–0.2%), Boraginaceae (1.2–0.2%), Cyperaceae (36.1–25.0%), *Nymphaea* (0.2%), Undeterminable (5.2–1.2%), HdV-128A (4.4–2.6%)
SPII-4b	25–45	The zone included 4 samples. *Pinus* (67.4–57.8%), *Betula* (6.1–3.7%), *Corylus* (3.5–2.0%), *Ulmus* (1.7–1.0%), *Quercus* (5.6–2.3%), *Tilia* (1.3–0.7%), *Fraxinus* (0.3–0.1%), *Carpinus* (0.2–0.1%), *Picea* (1.3–0.3%), *Hedera* (0.2%), Cerealia (0.1%), Cyperaceae (28.7–16.1%), *Sparganium*-type (10.2–4.8%), *Myriophyllum* (0.2%), *Potamogeton* (0.1%), Undeterminable (4.3–2.2%), HdV-128A (2.8–0.7%)
SPII-4a	45–65	The zone included 4 samples. *Pinus* (47.3–42.4%), *Corylus* (4.6–3.2%), *Ulmus* (4.1–2.6%), *Quercus* (6.7–3.6%), *Tilia* (1.3–0.7%), *Fraxinus* (1.5–0.7%), *Carpinus* (0.1%), *Fagus* (0.1%), *Picea* (1.3–0.4%), Poaceae (16.2–10.0%), *Galium*-type (4.3–0.3%), Cyperaceae (29.2–4.2%), *Sparganium*-type (9.5–2.9%), *Stratiotes aloides* (0.1%), *Nuphar* (0.1%), *Myriophyllum* (0.1%), *Potamogeton* (0.1%), *Riccia* (0.1%), Undeterminable (6.2–2.9%)
SPII-3b	65–95	The zone included 6 samples. *Pinus* (45.8–33.0%), *Betula* (16.2–9.4%), *Alnus* (19.5–14.0%), *Corylus* (8.9–5.3%), *Ulmus* (5.2–3.1%), *Fraxinus* (1.9–0.5%), *Tilia* (2.2–0.5%), *Quercus* (4.3–2.0%), *Acer* (0.2%), *Hedera* (0.2%), *Viscum* (0.2%), *Salix* (4.2–1.2%), *Artemisia* (1.3–0.6%), *Sparganium*-type (7.2–1.5%), Polypodiaceae (32.6–9.6%), *Stratiotes aloides* (0.5–0.1%), *Nymphaea* (0.2–0.1%), *Nuphar* (0.2%), *Riccia* (0.1%)
SPII-3a	95–175	The zone included 17 samples. *Pinus* (51.0–30.1%), *Betula* (24.6–12.1%), *Alnus* (20.2–6.7%), *Corylus* (9.0–4.5%), *Ulmus* (6.1–2.0%), *Fraxinus* (2.6–0.2%), *Tilia* (1.6–0.3%), *Quercus* (4.8–1.9%), *Carpinus* (0.2–0.1%), *Fagus* (0.2–0.1%), *Hedera* (0.2%), *Viscum* (0.2–0.1%), *Urtica* (0.9–0.1%), *Cannabis-Humulus* (0.4–0.1%), *Stratiotes aloides* (0.5–0.1%), *Nymphaea* (0.6–0.1%), *Nuphar* (0.3–0.1%), *Potamogeton* (0.5–0.1%), *Myriophyllum* (0.2–0.1%), *Riccia* (0.2–0.1%)
SPII-2/3	175–189	The zone included 3 samples. *Pinus* (42.4–37.6%), *Betula* (34.3–28.9%), *Corylus* (4.1–2.2%), *Ulmus* (2.0–1.5%), *Fraxinus* (0.7–0.3%), *Tilia* (0.6–0.1%), *Quercus* (1.3–0.4%), *Alnus* (3.4–0.6%), *Salix* (2.7–0.7%), Poaceae (11.7–11.5%), *Urtica* (0.8–0.3%), *Cannabis-Humulus* (0.6–0.2%), Polypodiaceae (4.4–3.4%), *Stratiotes aloides* (0.1%), *Nuphar* (0.4–0.1%), *Nymphaea* (0.5–0.1%), *Myriophyllum* (0.1%)
SPII-2	189–220	The zone included 7 samples. *Pinus* (60.4–53.3%), *Betula* (28.5–18.6%), *Betula nana*-type (1.1–0.2%), *Salix* (3.5–1.4%), *Juniperus* (0.9–0.1%), *Hippophaë* (0.1%), *Ephedra* (0.3–0.1%), *Artemisia* (9.9–3.5%), Chenopodiaceae (2.5–0.7%), *Myriophyllum* (0.8–0.2%), *Nuphar* (0.2–0.1%), *Potamogeton* (0.2–0.1%)
SPII-1	220–250	The zone included 6 samples. *Pinus* (50.7–30.3%), *Betula* (33.6–29.1%), *Betula nana*-type (1.0–0.2%), *Salix* (17.6–4.7%), *Juniperus* (0.9–0.1%), *Hippophaë* (0.6–0.1%), *Artemisia* (10.0–2.5%), Chenopodiaceae (1.9–0.7%), *Helianthemum* (0.2%), *Myriophyllum* (1.5–0.5%), *Nymphaea* (0.2%), *Potamogeton* (0.4%)

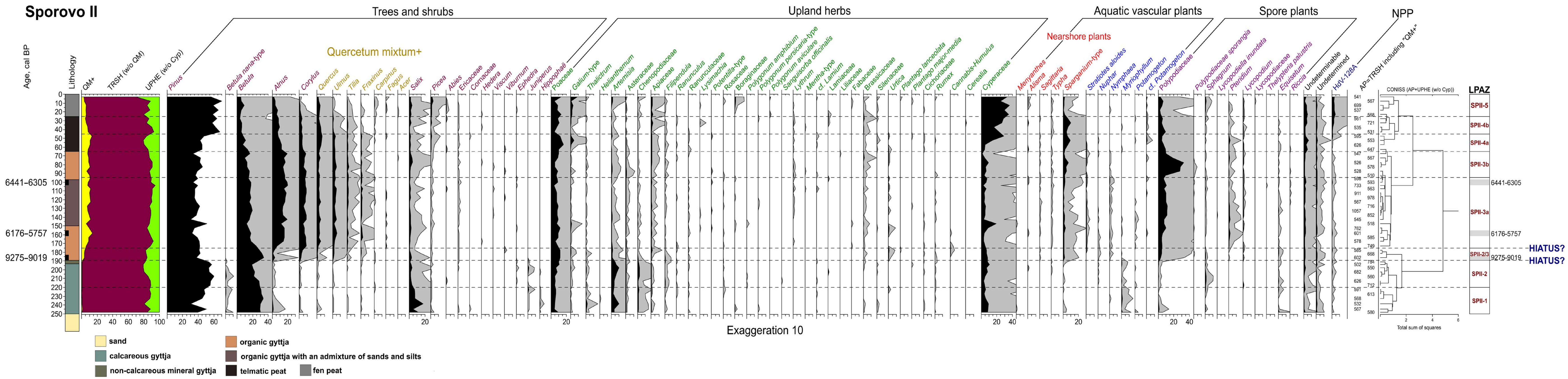

Figure 6. Spore-pollen diagram (percentage) from the Sporovo II core (analysed by D. Tsvirko). QM+ – *Quercus* + *Ulmus* + *Tilia* + *Fraxinus* + *Carpinus* + *Fagus* + *Acer*; TRSH (w/o QM) – trees and shrubs without QM+; UPHE (w/o Cyp) – upland herbs without Cyperaceae

Among others, SPII-1 was distinguished by an increased content of *Betula* and *Salix* pollen, as well as a relatively lower content of *Pinus*. In contrast, SPII-2 showed high values of *Pinus* and a decrease in the amount of *Betula* and *Salix* pollen.

LPAZ SPII-2/3. The selected zone was marked by the maximum of *Betula* pollen and a decrease in *Pinus*, along with a significant number of *Corylus* and *Ulmus* pollen. Among aquatic plants, pollen grains of *Nymphaea*, *Nuphar*, *Myriophyllum* and *Stratiotes aloides* were present.

LPAZ SPII-3a and SPII-3b. Zones SPII-3a and SPII-3b were characterized by the highest values of *Corylus*, *Ulmus*, *Tilia*, *Fraxinus* and *Alnus* throughout the section, as well as the smallest values of *Pinus*. There were also single pollen grains of *Hedera*, *Viscum* and *Fagus*. Pollen of *Nymphaea* and *Stratiotes aloides* were constantly present, together with the periodic finds of *Nuphar*, *Potamogeton* and *Myriophyllum* grains.

The local zone SPII-3b was distinguished mainly due to the large number of Polypodiaceae spores, as well as a noticeable increase in the number of *Salix*, *Artemisia* and *Sparganium*-type pollen grains.

LPAZ SPII-4a and SPII-4b. Pollen zones SPII-4a and SPII-4b were marked mainly by the first significant drop of the *Corylus* pollen curve, the rise of the *Quercus* and *Picea* curves and also by a relatively constant presence of *Carpinus* pollen. Both identified zones were characterized by a decrease in the amount of *Alnus* and *Betula* pollen. The disappearance of *Nymphaea* pollen, occasional presence of single pollen grains of *Myriophyllum*, *Nuphar*, *Stratiotes aloides* and *Potamogeton*, together with the high values of *Sparganium*-type and Cyperaceae, as well as the presence of a large amount of damaged/hard-to-identify pollen (Undeterminable) were recorded here.

The SPII-4a zone was defined mainly based on the high values of *Ulmus* and UPHE (w/o Cyp) curves, as well as low values of *Pinus*. The SPII-4b zone was characterized by a significant drop in the *Ulmus* and *Fraxinus* curves, along with an increase in the amount of *Pinus*.

LPAZ SPII-5. The identification of the SPII-5 zone was based on the second significant drop in the *Corylus* curve, the marked increase in the *Picea* and *Carpinus* curves, the frequent presence of *Fagus* and *Abies* grains and the large amounts of *Pinus* pollen. In addition, SPII-5 was characterized by a slight increase in the amount of *Salix*, *Betula* and *Quercus* pollen, as well as a decrease in the amount of *Ulmus*, *Tilia* and *Fraxinus*. A surface sample (0–5 cm) showed a growth in the UPHE (w/o Cyp) pollen curve. The maximum amount of Cyperaceae pollen, together with the disappearance of aquatic plant pollen (*Stratiotes aloides*, *Nuphar*, *Nymphaea*, *Myriophyllum* and *Potamogeton*) were recorded in the SPII-5 local pollen zone.

MACROREMAINS DATA

The results of a partial analysis of macroremains are presented in Table 3 and Figure 7.

SEDIMENTOLOGICAL AND LITHOLOGICAL DATA

The results of textural analysis of the ash purified from metal oxides and carbonates using the HCl cleaning procedure, as well as some corrections of the previous sedimentological data for the Sporovo II core, are shown in Figure 8.

Table 3. Macroremains data from the Sporovo II core (analysed by M. Słowiński)

Depth (cm)	Macroremains
50–55	1 *Ranunculus* sp., seed fragment
60–65	1 *Carex* sp., seed fragment
70–75	1 *Carex lasiocarpa*, seed
85–90	4 *Carex rostrata*, seeds
90–97	1 *Carex rostrata*, seed; 1 *Stratiotes aloides*, seed
103–110	2 *Potamogeton* sp., seeds; 1 *Carex rostrata*, seed
110–115	1 *Potamogeton lucens*, seed
120–125	1 *Potamogeton lucens*, seed
125–130	1 *Stratiotes aloides*, seed; 1 *Potamogeton* sp., seed
130–135	Fish scale
135–140	1 *Carex lasiocarpa*, seed; 1 *Carex rostrata*, seed; 1 *Stratiotes aloides*, seed
140–145	1 *Potamogeton* sp., seed; 1 *Potamogeton natans*, seed; 1 *Stratiotes aloides*, seed
145–150	1 Nymphaeaceae sp., seed fragment; 1 *Potamogeton* sp., seed fragment
150–155	2 *Potamogeton* cf. *lucens*, seeds; 1 *Carex rostrata*, seed
175–180	1 *Potamogeton* sp., seed fragment
195–200	1 *Potamogeton* cf. *compressus*, seed
230–235	1 *Potamogeton* cf. *rutilus*, seed
235–242	1 *Potamogeton* sp., seed fragment
242–247	1 *Potamogeton* cf. *rutilus*, seed

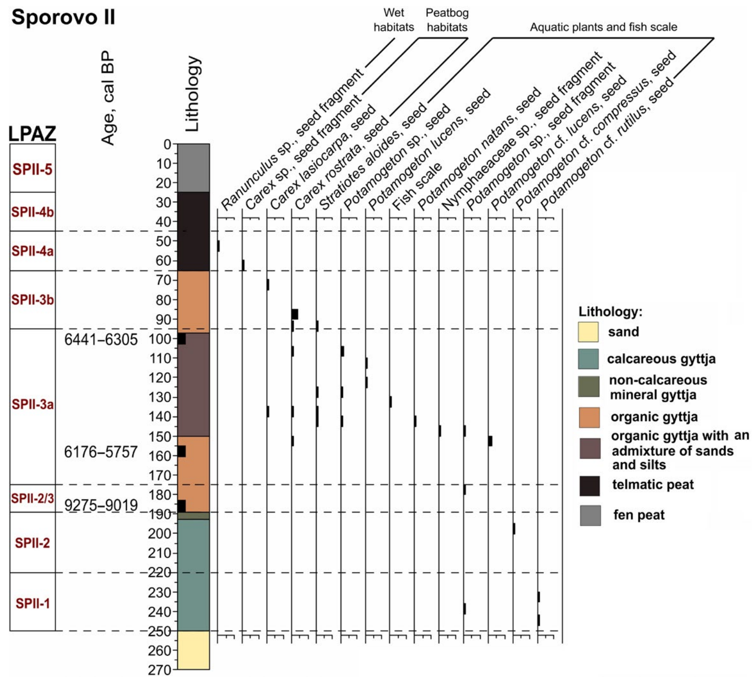

Figure 7. Single macroremains from the Sporovo II core (analysed by M. Słowiński, construction and interpretation by D. Tsvirko)

Based on previously published data (Tsvirko et al., 2021b) and new sedimentological (LOI, textural and geochemical, visual description) and palaeobotanical (spore-pollen and macroremains) data, seven lithological units were identified in the Sporovo II core (Table 4).

RECONSTRUCTIONS AND INTERPRETATIONS

Despite the lack of a sufficient number of radiocarbon dates, the new data obtained from the Sporovo II core made it possible to make several interpretations and reconstruct the chronology of palaeogeographic events (Fig. 9).

Fine- and medium-grained sands from a depth of 270–250 cm were recognised not as lacustrine deposits, since they did not contain organic matter, were relatively coarse in size and, from a textural point of view, were similar to the sands forming the elevation of the Kakoryca-4 site (Tsvirko et al., 2021b). Thus, sands from a depth of 270–250 cm were recognised as fluvial deposits accumulated before the formation of Lake Sporovskoye. Apparently, the accumulation of these relatively coarse-grained sands occurred as a result of channel alluvia deposition of a braided river. Later, finer lacustrine calcareous deposits of Lake Sporovskoye (from a depth of 250 cm) formed.

Based on the spore-pollen data obtained from the Sporovo II core, it can be argued that Lake Sporovskoye began its existence in the Late Weichselian (apparently in the Younger Dryas), as a result of the development of thermokarst processes. Lake Sporovskoye could have formed initially as an alas lake due to the intense thawing of permafrost (Tsvirko and Kittel, 2022a, b).

In the newly formed lake, the accumulation of calcareous gyttja (250–193 cm) began, with the amount of $CaCO_3$ ranging from 31.98 to 72.58%. $CaCO_3$ disappeared only at the depth of 193–189 cm together with an increase in LOI up to 27.54%. The granulometric composition of the mineral fraction of calcareous gyttja and non-calcareous mineral gyttja (250–189 cm) showed the predominance of very fine sand, sometimes fine sand, but with a significant admixture of silts.

The units of calcareous gyttja and non-calcareous mineral gyttja (silty sands) at a depth of 250–189 cm corresponded to the local pollen zones SPII-1 and SPII-2, which contain pollen spectra of periglacial plant assemblages: *Pinus*, *Betula*, *Betula nana*-type, *Salix*, *Juniperus*, *Hippophaë*, *Ephedra*, *Helianthemum*, *Artemisia*, Chenopodiaceae (Fig. 10). In general, a large number of *Artemisia* and Chenopodiaceae testified to the existence of cold and open steppelike landscapes. Light *Pinus* forests could grow on the sandy soils of the

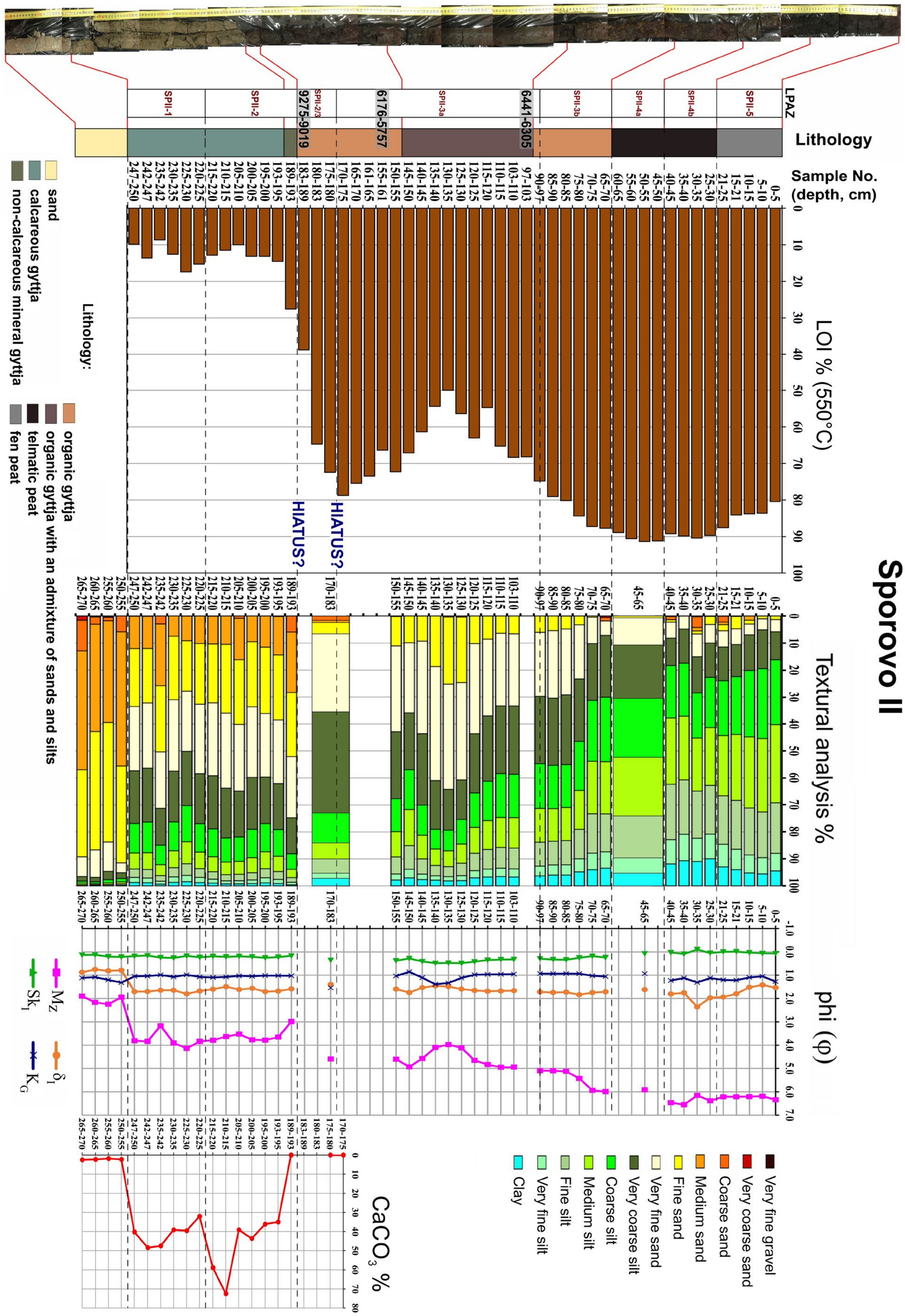

Figure 8. Sedimentological diagram of the Sporovo II core with identified lithological units (based on Tsvirko et al., 2021b; modified and supplemented by D. Tsvirko; photos by D. Tsvirko)

Table 4. Lithology of the Sporovo II core

Depth (cm)	Lithological unit	LOI, %	Dominant size of mineral particles	Corresponding LPAZ (cm)	Palaeobotanical data
0–25	Fen peat	80.41–87.59	Medium silt (Mz: 6.19–6.34 φ)	SPII-5 (0–25)	Pollen of Cyperaceae, Poaceae, *Galium*-type, Undeterminable. Absence or single finds of *Pediastrum*.
25–45	Telmatic peat	89.26–90.45	Medium silt (Mz: 6.15–6.55 φ)	SPII-4b (25–45)	Pollen of Cyperaceae, *Sparganium*-type, Undeterminable. Absence or single finds of *Pediastrum*.
45–65		88.94–91.34	Coarse silt (Mz: 5.91 φ)	SPII-4a (45–65)	Pollen of Cyperaceae, Poaceae, *Galium*-type, *Sparganium*-type, Undeterminable, single grains of *Stratiotes aloides*, *Nuphar*, *Myriophyllum* and *Potamogeton*. Absence or single finds of *Pediastrum* (45–60 cm); many finds of *Pediastrum* (60–65 cm). Seeds of *Ranunculus* and *Carex*.
65–97	Organic gyttja	74.87–87.77	Coarse silt (65–75 cm), Very coarse silt (75–85 cm, 90–97 cm), Very fine sand (85–90 cm) (Mz: 5.09–5.99 φ)	SPII-3b (65–95), SPII-3a (95–97)	Pollen of *Sparganium*-type, Polypodiaceae, *Stratiotes aloides*, *Nymphaea*, *Nuphar*. Medium or many finds of *Pediastrum*. Seeds of *Carex* and *Stratiotes aloides*.
97–150	Organic gyttja with an admixture of sands and silts	50.00–68.29	Very fine sand (103–150 cm) (Mz: 3.97–4.95 φ)	SPII-3a (97–150)	Pollen of *Stratiotes aloides*, *Nymphaea*, *Nuphar*, *Potamogeton*, *Myriophyllum*. Many finds of *Pediastrum*. Seeds of *Potamogeton*, *Stratiotes aloides*, Nymphaeaceae and *Carex*, as well as fish scale.
150–189	Organic gyttja	38.82–78.87	Very fine sand (150–155 cm), very coarse silt (170–183 cm) (Mz: 4.59–4.60 φ)	SPII-3a (150–175), SPII-2/3 (175–189)	Pollen of *Stratiotes aloides*, *Nymphaea*, *Nuphar*, *Potamogeton*, *Myriophyllum*. Many finds of *Pediastrum*. Seeds of *Potamogeton* and *Carex*.
189–193	Non-calcareous mineral gyttja	27.54	Fine sand (Mz: 2.98 φ)	SPII-2 (189–193)	Pollen of *Myriophyllum*. Many finds of *Pediastrum*.
193–250	Calcareous gyttja	8.59–17.41	Very fine sand (200–235 cm, 242–250 cm), fine sand (193–200 cm, 235–242 cm) (Mz: 3.17–4.13 φ)	SPII-2 (193–220), SPII-1 (220–250)	Pollen of *Myriophyllum*, single grains of *Nymphaea*, *Nuphar* and *Potamogeton*. Many finds of *Pediastrum*. Seeds of *Potamogeton*.
250–270	Sand	–	Fine sand (255–265 cm), medium sand (250–255 cm, 265–270 cm) (Mz: 1.89–2.24 φ)	–	–

surrounding elevations. Dense pine forests in the Younger Dryas also grew in the river valleys, which were a refuge for the woods during the expansion of open habitats and the general reduction in forest cover (Dzieduszyńska et al., 2013). *Betula* and *Salix* spread over low and humid places between elevations. Among aquatic plants, *Myriophyllum* grew in the palaeolake, which indicated a water depth of at least 2–3 m (Zernitskaya, 2022). The existence of relatively deep water conditions was also indicated by single finds of *Potamogeton*, *Nymphaea* and *Nuphar* pollen grains, as well as *Potamogeton* seeds.

The fall of the *Betula* and *Salix* curves, along with the growth of the *Pinus* curve during the transition from SPII-1 to SPII-2 could indicate a gradual drying of the surrounding area, when the size of wet areas around Lake Sporovskoye occupied by *Salix* and *Betula* decreased. The decrease in wet areas, apparently, was associated with the gradual degradation of permafrost and the removal of meltwater by braided (or multi-channel) rivers. The dried up territories were occupied by sparse *Pinus* forests.

A depositional hiatus, representing a break in sedimentation, was recognised at a depth of 189 cm. The existence of the depositional hiatus was confirmed by the presence of Late Glacial pollen assemblages in calcareous gyttja and non-calcareous mineral gyttja (250–189 cm), which were overlain by late Boreal organic gyttja (~9275–9019 cal BP). The change in lithological units at a depth of 189 cm (Table 4) also indicated the existence of the hiatus. Accordingly, the beginning of the Holocene (PB and BO-1) could be associated with the first significant reduction in the size of Lake Sporovskoye, lowering of groundwater table and thus the depositional hiatus. The available data from the Sporovo II core indicated that the Preboreal period was dry, the lake was significantly reduced in size (or disappeared), and even fen processes of peat sedentation did not develop in the vicinity of the Sporovo II.

The resumption of sediment accumulation, and hence the transgression of Lake Sporovskoye as a result of climate humidification, occurred at the very end of the Boreal period, as indicated by radiocarbon dating ~9275–9019 cal BP (Table 1). Humid climatic conditions in the late Boreal were evidenced by the rise of aquatic vascular plant curves, the rise in the curves of Polypodiaceae, *Equisetum*, *Betula* and *Alnus* (Fig. 6), as well as the sedimentation of organic gyttja at the Sporovo II site (Table 4). The SPII-2/3 thin layer of late Boreal deposits (189–175 cm) was formed in aquatic conditions, as evidenced by the presence of *Stratiotes aloides*, *Nuphar*, *Nymphaea* and *Myriophyllum* pollen, as well as *Potamogeton* seeds. In the sediments of the described pollen zone, the amount of organic matter significantly increased upwards in the section (LOI from 38.82% to 72.45%), which could indicate the fast development of littoral vegetation and increasing climate warming. The pollen spectra of the SPII-2/3 zone recorded a significant transformation of the surrounding vegetation with an increasing role of broadleaf species over time. Thermophilic species of trees and shrubs appeared: *Ulmus*, *Fraxinus*, *Tilia*, *Quercus*, *Corylus*. The rise of *Betula* and *Alnus* curves, among others, was associated with the expansion of wet areas as a result of climate humidification and the transgression of Lake Sporovskoye. The sharp changes of some pollen curves at a depth of 189 cm could also indicate the existence of a depositional hiatus.

In all likelihood, the accumulation of lacustrine sediments, which began at the end of the Boreal period, continued throughout the entire Atlantic period. However, the obtained radiocarbon dates show that the late Boreal deposits were overlain by the deposits of late Atlantic (AT-3): ~6176–5757 cal BP at 155–161 cm and ~6441–6305 cal BP at 97–103 cm (Table 1).

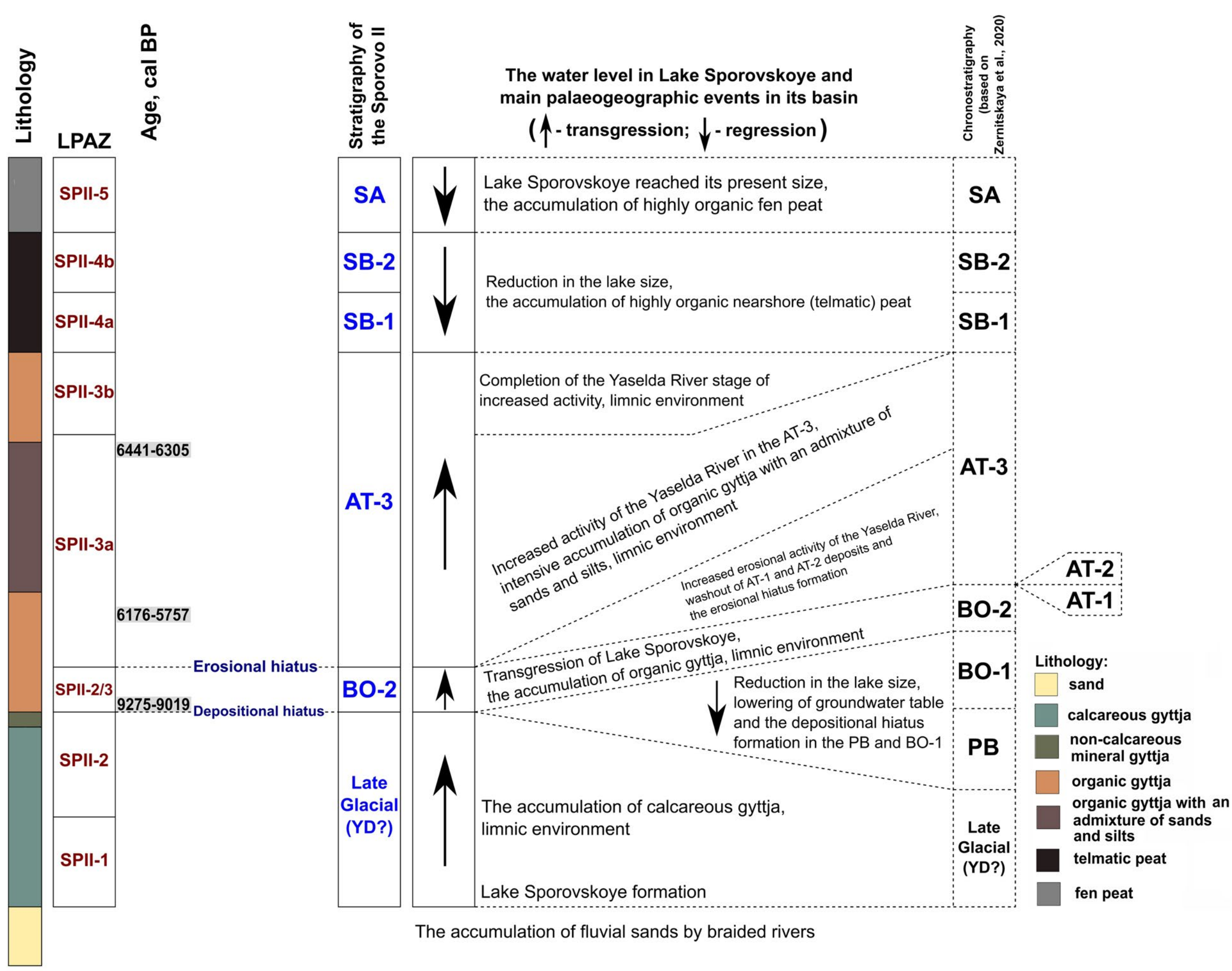

Figure 9. Reconstruction of the chronology of the main palaeogeographic events in the vicinity of Lake Sporovskoye in the Late Glacial and Holocene (according to D. Tsvirko)

Figure 10. Pollen grains from the calcareous gyttja and non-calcareous mineral gyttja (250–189 cm) of the Sporovo II core (photos by D. Tsvirko). **A**, **B**. *Artemisia* (the same grain in different positions; sample depth: 189–193 cm); **C**, **D**. Chenopodiaceae (two different grains; sample depth: 189–193 cm); **E**. *Ephedra* (sample depth: 195–200 cm); **F**, **G**. *Ephedra* (the same grain in different positions; sample depth: 210–215 cm); **H–K**. *Helianthemum* (the same grain in different positions; sample depth: 230–235 cm; the photos without scale bars); **L–O**. *Hippophaë* (the same grain in different positions; sample depth: 200–205 cm); **P–T**. *Hippophaë* (the same grain in different positions; sample depth: 247–250 cm); **U**. *Juniperus* (sample depth: 189–193 cm); **V**. *Juniperus* (sample depth: 193–195 cm); **W**. *Juniperus* (sample depth: 195–200 cm); **X**. *Juniperus* (sample depth: 200–205 cm); **Y**. *Juniperus* (sample depth: 215–220 cm). Scale bars = 10 μm for all specimens

The inversion could be explained by the reservoir effect, or by the erosional activity of the Yaselda River. Thus, there could be another hiatus, caused by increased erosional activity of the Yaselda River at the end of the Atlantic period, when the previously accumulated early

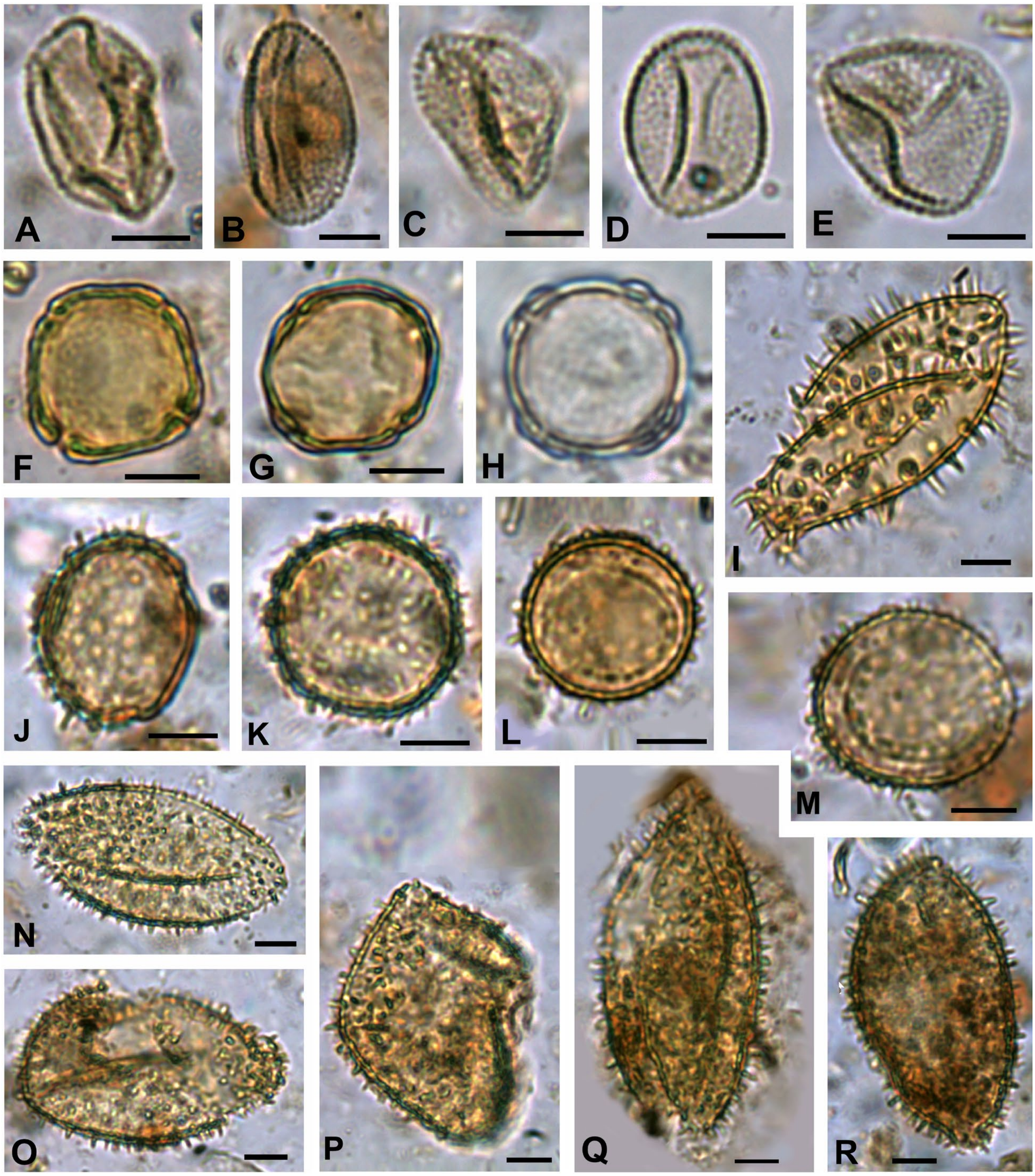

Figure 11. Selected pollen grains of aquatic plants from the Sporovo II core (photos by D. Tsvirko). **A.** *Potamogeton* (sample depth: 25–30 cm); **B**. *Potamogeton* (sample depth: 135–140 cm); C. *Potamogeton* (sample depth: 140–145 cm); **D**. *Potamogeton* (sample depth: 140–145 cm); **E**. *Potamogeton* (sample depth: 161–165 cm); **F**. *Myriophyllum* (sample depth: 35–40 cm); **G**. *Myriophyllum* (sample depth: 60–65 cm); **H**. *Myriophyllum* (sample depth: 220–225 cm; the photo without a scale bar); **I**. *Nuphar* (sample depth: 50–55 cm); **J**, **K**. *Nymphaea* (the same grain in different positions; sample depth: 110–115 cm); **L**. *Nymphaea* (sample depth: 110–115 cm); **M**. *Nymphaea* (sample depth: 125–130 cm); **N**. *Stratiotes aloides* (sample depth: 75–80 cm); **O**. *S. aloides* (sample depth: 55–60 cm); **P**. *S. aloides* (sample depth: 65–70 cm); **Q**. *S. aloides* (sample depth: 70–75 cm); **R**. *S. aloides* (sample depth: 140–145 cm). Scale bars = 10 µm for all specimens

and middle Atlantic sediments were washed out. At the level of eroded deposits, there was an intensive accumulation of late Atlantic sediments. It should be noted that the Sporovo II core is situated near the Yaselda River channel, in the zone of active river influences. The active influence of the Yaselda River on the sedimentation processes at the end of the Atlantic could be evidenced by the lithology of the palynozone SPII-3a, which contained less organic matter (LOI from 78.87% to 50.00%) due to the inwash of fluvial sands and silts in the period of ~6176–5757 cal BP or ~6441–6305 cal BP (Fig. 8).

The SPII-3a palynozone (175–95 cm), formed in the late Atlantic, is characterized by the greatest distribution of broadleaf forests on elevations in the vicinity of Lake Sporovskoye. The warm conditions of the late Atlantic favoured the spreading of *Ulmus*, *Tilia*, *Fraxinus*, *Quercus* and *Corylus*. *Viscum* and *Hedera* growing on trees were also common. Significant areas of wetlands were covered with *Alnus* and *Betula*. SPII-3a sediments accumulated in aquatic conditions, which was confirmed by the constant presence of *Nymphaea* pollen indicating a water depth of ~2 meters. The warm and humid conditions of the late Atlantic contributed to the intensive overgrowth of the reservoir by aquatic vegetation. In addition to *Nymphaea*, in Lake Sporovskoye, *Stratiotes aloides*, *Nuphar*, *Potamogeton* and *Myriophyllum* grew, as seen from the pollen and macroremains data. A fish scale was also found in these deposits. The existence of exceptionally warm conditions in the late Atlantic was evidenced by the found *Stratiotes aloides* seeds and pollen.

The SPII-3b palynozone (95–65 cm) was formed also at the end of the Atlantic period and was represented by gyttja with a high content of organic matter (LOI from 74.87% to 87.77%). The regional vegetation of the SPII-3b zone was identical to that of the SPII-3a zone. Here, broadleaf trees also reached their greatest distribution in the surrounding forests: *Ulmus*, *Tilia*, *Fraxinus*, *Quercus* and *Corylus*. The main distinguishing feature of the SPII-3b zone was the peak of the Polypodiaceae curve, as well as a noticeable increase in the amount of *Salix*, *Artemisia* and *Sparganium*-type, which could indicate a slight drying of the surrounding area and, apparently, the end of the Yaselda River stage of increased activity (which was also expressed in high LOI values). Thus, the SPII-3b zone recorded local hydrological changes that took place in the study area. The Sporovo II site was still in freshwater conditions, which was expressed by the constant presence of *Nymphaea* and *Stratiotes aloides* pollen (Fig. 11), but closer to the shoreline of the lake, which was confirmed by the presence of *Sparganium*-type, Polypodiaceae, *Artemisia* and *Salix* pollen and spores, as well as the found *Carex* seeds.

Significant climatic and hydrological changes in the study area were associated with the SPII-4a palynozone (65–45 cm), which corresponded to the first half of the Subboreal period. Mainly, there was a significant shallowing of Lake Sporovskoye at that time. Highly organic nearshore peat (LOI from 88.94 to 91.34%) accumulated in this palynozone. The constant presence of typically aquatic plant pollen ceased: *Nymphaea* disappeared; sometimes single pollen grains of *Stratiotes aloides*, *Nuphar* and *Myriophyllum* appeared. The number of shore plants (*Sparganium*-type pollen), plants of wetlands (Cyperaceae pollen, *Carex* seed) and moist to dry habitats (*Ranunculus* seed; Poaceae, *Galium*-type and Silenaceae pollen) increased. The amount of damaged Undeterminable pollen increased sharply, which could also indicate the periodic (or seasonal) drying of the area and the penetration of oxygen into the sediments. Some palynomorphs from the Sporovo II core resembled *Potamogeton* pollen, but due to the poor preservation of the pollen (especially in palynozones SPII-4a, SPII-4b and SPII-5) and significant doubts, they were assigned to cf. *Potamogeton* (probably it was NPP, not pollen). Thus, with the beginning of the Subboreal, the second significant reduction in the size of Lake Sporovskoye occurred, and the Sporovo II point was in limno-terrestrial (telmatic) conditions at the boundary of the littoral and wetland zones (Fig. 12).

The beginning of the Subboreal period was associated with the first substantial decrease in the amount of *Corylus* in the regional forests and an increase in the presence of *Quercus*. In addition to the *Quercus* succession, *Picea* gradually entered the surrounding forests. In the first half of the Subboreal period, *Ulmus* was still often present in regional forests. Local changes were expressed in a decrease in the number of areas occupied by *Alnus* and *Betula*.

In the second half of the Subboreal period, corresponding to the SPII-4b palynozone (45–25 cm), the sedentation of highly organic nearshore peat (LOI from 89.26 to 90.45%) continued. The area was still in telmatic conditions, as evidenced by single pollen grains of *Myriophyllum* and *Potamogeton*, as well as a large amount of *Sparganium*-type, Cyperaceae and damaged Undeterminable pollen. The increased amount of HdV-128A palynomorph (or Volvocaceae according to Wieckowska-Lüth et al., 2020) was probably associated with stagnant shore conditions, or floods, or their development in wet soil.

Noticeable changes took place in the composition of regional forests in the second half of the Subboreal period. Mainly, the amount of *Ulmus* visibly decreased. The participation of *Fraxinus* in the forests also declined. At the same time, the described broadleaf trees were replaced by *Pinus* succession. *Quercus* (whose trunks were covered with *Hedera*) and *Corylus* still played an important role in the structure of forests. *Carpinus* and *Picea* were constantly present. Wet areas were occupied by *Alnus* and *Betula*.

In the SPII-4b palynozone, Cerealia pollen grain was found at a depth of 35–30 cm, which could indicate agricultural activity at higher elevations among the surrounding wetlands.

With the beginning of the Subatlantic period, a second significant decrease in the amount of *Corylus* in regional forests occurred, as could be seen from the SPII-5 palynozone (25–0 cm). The presence of *Ulmus*, *Tilia* and *Fraxinus* in the forests also significantly decreased. As before, an important share in the composition of forests belonged to *Quercus*. *Picea* and *Carpinus* continued to enter the regional forests. The distant elevations were covered with forests with an admixture of *Fagus* and *Abies*. However, the dominant species in the woods was *Pinus*. In the surrounding wetlands, the areas covered by *Salix* expanded, probably due to a certain rise in humidity. The increase in the amount of *Artemisia* and Chenopodiaceae, the constant presence of Silenaceae, the growth of herb curves (Poaceae, *Galium*-type, Apiaceae, Boraginaceae) were apparently associated not only with climatic changes, but also with agricultural activities.

Most likely, in the Subatlantic period, the area around the Sporovo II core was more distant from the shoreline of Lake Sporovskoye. This was indicated by the maximum amount of Cyperaceae, a fall of *Sparganium*-type curve, a large amount of damaged Undeterminable pollen and the lack of typically aquatic plant pollen, except for the find of a single *Nymphaea* grain. Thus, in the Subatlantic period, the sedentation of highly organic fen peat took place, the amount of organic matter in which slightly decreased upwards in the section (LOI from 87.59 to 80.41%). A large amount of HdV-128A (or Volvocaceae) in the sediments of the SPII-5 palynozone could probably be explained by their development in small puddles on the floodplain or in the fen soil.

Figure 12. The current littoral zone of Lake Sporovskoye with semi-submerged vegetation, near the Yaselda River delta, view from a boat in 2019 (photo by M. Kryvaltsevich)

DISCUSSION

PALYNOLOGICAL CORRELATIONS

The pollen data from the Sporovo II core were compared with the nearest well-dated cores of Lake Bobrovichskoe and the Ivanisovka peat bog (Zernitskaya and Mikhailov, 2009; Zernitskaya et al., 2010; Zernitskaya, 2022). The diagrams were correlated based on the *Corylus*, *Ulmus*, *Quercus*, *Picea*, *Artemisia* and several other curves. Due to the specifics of the ecological environment around Lake Sporovskoye, it was not possible to use the *Carpinus* and *Fagus* curves for correlation due to the poor representation of their pollen in the Sporovo II core. The *Betula* pollen curve also had a low correlation potential, since the presence of a large amount of its pollen in the Sporovo II indicated that this taxon always occupied a significant part of the study area.

The radiocarbon-dated pollen assemblages from the Ivanisovka peat bog, which contained a large amount of *Artemisia* and *Salix*, as well as a significant amount of Chenopodiaceae, together with the findings of *Hippophaë* and *Juniperus*, made it possible to attribute the SPII-1 and SPII-2 palynozones to the Late Glacial period.

The SPII-2/3 palynozone from the Sporovo II, dated to the late Boreal, corresponded to the Boreal pollen assemblages from Lake Bobrovichskoe and the Ivanisovka peat bog, which are characterized by the rise of the *Corylus*, *Ulmus*, *Quercus*, *Fraxinus*, *Tilia* and *Alnus* curves.

The late Atlantic time, expressed primarily by the largest amount of *Ulmus* and *Corylus* on both reference diagrams, was reflected in the SPII-3a and SPII-3b palynozones. In the late Atlantic, the Sporovo II and the reference diagrams were characterized by a reduced amount of *Pinus*, maximum values of *Fraxinus* and *Tilia*, and a large amount of *Quercus* and *Alnus*. The appearance of *Fagus* and *Acer* pollen in the SPII-3a and SPII-3b zones can also indicate the late Atlantic period, as it is observed in the diagrams of Lake Bobrovichskoe and the Ivanisovka peat bog.

The correlation reference point for the beginning of the Subboreal period was the first significant drop of the *Corylus* curve, noted in the SPII-4a palynozone. Such a decrease in the amount of *Corylus* pollen marks the beginning of the Subboreal period in the cores of Lake Bobrovichskoe and Ivanisovka peat bog. Also, the correlation taxon for the Subboreal was the *Quercus* curve, since for the pollen diagram of Lake Bobrovichskoe the maximum amount of *Quercus* is characteristic of the Subboreal period. In the case of the Sporovo II, this was observed in the SPII-4a and SPII-4b zones. An increase in *Picea* values, which is typical for the Subboreal deposits of reference profiles, was also observed in the SPII-4a and SPII-4b. In the first half of the Subboreal period, *Ulmus* still played an important role in the regional forests, as can be seen from the pollen assemblages of Lake Bobrovichskoe and the SPII-4a zone.

The beginning of the Subatlantic period was dated by the second significant drop in the *Corylus* curve, observed in the pollen spectra of the reference sections and in the SPII-5 zone. During the correlation, attention was paid to the maximum *Picea* values in the Subatlantic in the compared cores, as well as to the high values of *Pinus*, and the fall of the *Ulmus*, *Fraxinus* and *Tilia* curves.

HYDROLOGICAL CORRELATIONS

The hydrological changes recorded in the Sporovo II core were correlated with other geological profiles.

The data from the Sporovo II core clearly showed that in the Late Weichselian (apparently in the Younger Dryas) the size of Lake Sporovskoye was much larger than today. Increased humidity during the Younger Dryas contributed to the formation of a wide and shallow lake in the study area. High environmental humidity in the Younger Dryas is also evidenced by the results of stable carbon and oxygen isotope study of carbonate sediments of Lake Sergeyevskoye from central Belarus (Makhnach et al., 2009; Zernitskaya, 2022). Other data show that during the first half of the Younger Dryas, the water level in many Belarusian lakes rose (Novik et al., 2010).

The first significant regression of Lake Sporovskoye in the Preboreal-Boreal, identified from the Sporovo II core, was correlated with regressions in other lakes. Palynological data from the bottom sediments of Lake Bobrovichskoe (Zernitskaya, 2022) indicate that, most likely, in the Preboreal and Boreal, the area of the lake was much smaller than

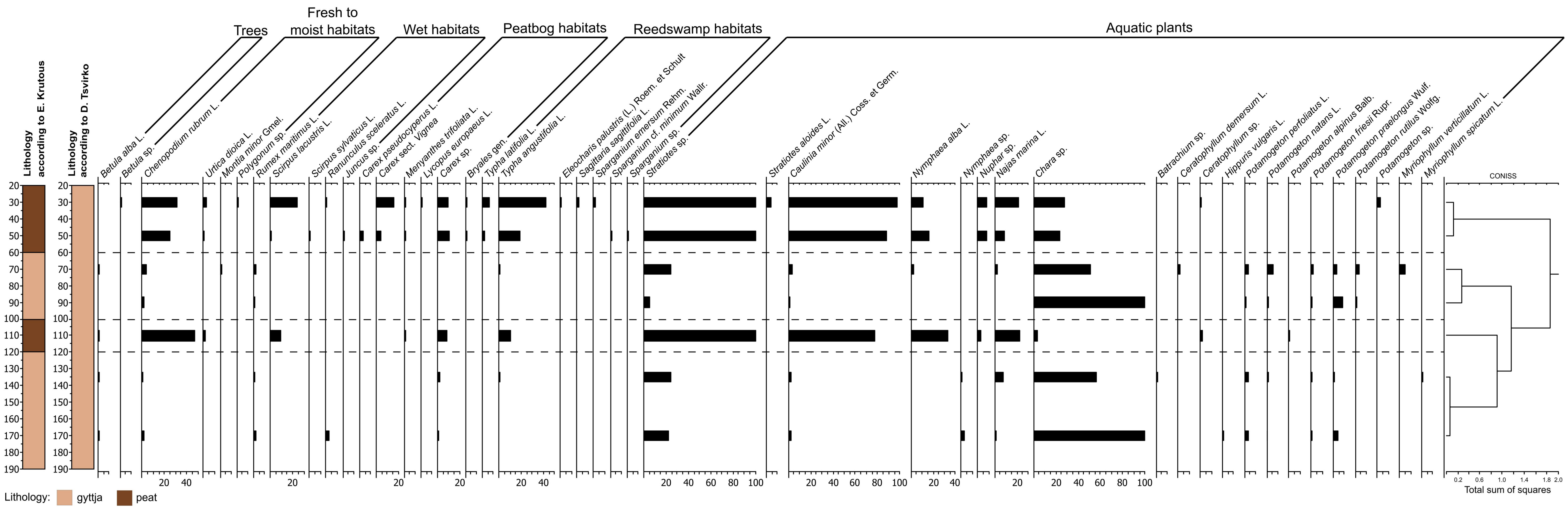

Figure 13. Carpological diagram from the bottom sediments of Lake Sporovskoye (analysed by E. Krutous (1990), construction and interpretation by D. Tsvirko)

that in modern times. This is evidenced by the high values or constant presence of pollen from wetland and nearshore vegetation (Cyperaceae, Poaceae, *Typha latifolia*, *Alisma*, *Equisetum*), as well as the frequent presence of pollen from fully submerged plants and plants with floating leaves in the Preboreal and Boreal spectra. The number of microfossils of the described plants decreases significantly upwards in the core of Lake Bobrovichskoe (Zernitskaya, 2022). Dry conditions during the Preboreal period are confirmed by isotopic studies from Lake Sergeyevskoye (Makhnach et al., 2009). A drop in the water level at the beginning of the Preboreal is also recorded in Lake Kuz'michskoe and Lake Staroje (Zernitskaya et al., 2015; Zernitskaya, 2022).

The late Boreal transgression of Lake Sporovskoye (SPII-2/3, ~9275–9019 cal BP) can be correlated with the water level rise in Lake Bobrovichskoe at that time (Zernitskaya, 2022). In the deposits of Lake Bobrovichskoe, this transgression is expressed in pollen assemblages and geochemistry. An increase in humidity and a rise in the water level in the second half of the Boreal are also observed in isotope and pollen data from the sediments of Lake Sergeyevskoye (Makhnach et al., 2009; Zernitskaya, 2022). A distinct transgression ~9500–8500 cal BP is also recorded in the annually laminated sediments of Lake Gościąż from Central Poland (Ralska-Jasiewiczowa et al., 1998; Starkel et al., 2013).

The pollen and macroremains data obtained from the Sporovo II core indicated that in the late Atlantic (SPII-3a and SPII-3b, ~6176–5757 cal BP, ~6441–6305 cal BP) the water level of Lake Sporovskoye was higher than in present times. Evidence of a high water level in the late Atlantic has also been found in the bottom sediments of Lake Bobrovichskoe (Zernitskaya, 2022).

In addition to the transgression of Lake Sporovskoye in the late Atlantic, the Sporovo II core recorded a period of increased fluvial activity of the Yaselda River, which was initially expressed in the erosion of sediments (erosional hiatus), and later in the inwash of fluvial sands and silts into organic gyttja (~6176–5757 cal BP, ~6441–6305 cal BP). It is worth noting that the presented data could be correlated with the phase of increased fluvial activity identified for Polish rivers ~6400–5600 cal BP, during which many paleochannels were abandoned (Starkel et al., 2013). Thus, the oxbow lakes to the north of the modern Yaselda River channel were most likely formed at that time, during the transition from the Atlantic to the Subboreal period (Fig. 1). The data could be correlated also with the period of increased fluvial activity 5700–5050 BP (conventional radiocarbon age), identified by Kalicki (2006) for some Belarusian rivers.

The second significant regression of Lake Sporovskoye was associated with the beginning of the Subboreal period and continued throughout the Subboreal and later the Subatlantic periods, when telmatic and then fen peat accumulated at the Sporovo II. However, in the bottom sediments of Lake Bobrovichskoe, there are no signs of such a decrease in the water level with the beginning of the Subboreal (Zernitskaya, 2022). Apparently, such a decrease in the size of Lake Sporovskoye was associated with its gradual overgrowth and transformation into a wetland. That is why the Sporovo II core showed a gradual transition from the nearshore (telmatic) peat in the Subboreal to fen peat in the Subatlantic. A similar situation is observed in Lake Lozoviki core, in which, starting from the Subboreal, peat began to accumulate due to the gradual overgrowth of the reservoir (Novik et al., 2010; Zernitskaya, 2022).

REINTERPRETATION OF PREVIOUS DATA

In this paper reinterpretations of the results of previous studies of bottom sediments of Lake Sporovskoye are proposed, in particular regarding the lithology identified by V. Zernitskaya (1985) and E. Krutous (1990).

The first disputed lithological unit was identified as "peat" (depth 120–100 cm on both diagrams) and palynologically related to the Atlantic period (Fig. 13). As shown by carpological analysis, these deposits contained a large number of remains of aquatic plants such as *Stratiotes* sp., *Nymphaea alba*, *Caulinia minor*, *Najas marina*. This demonstrates that the deposits were accumulated in aquatic conditions and, in fact, can be interpreted as organic gyttja. The accumulation was associated with intense overgrowth of Lake Sporovskoye during the warm Atlantic period, but not with a decrease of the reservoir. Even today, the western part of Lake Sporovskoye is heavily overgrown with floating-leaf plants

Figure 14. The current state of the western part of Lake Sporovskoye, heavily overgrown with floating-leaf vegetation, view from a boat in 2019 (photos by M. Kryvaltsevich)

(Fig. 14). Similar conditions existed in the Atlantic near the drilling sites presented by E. Krutous (1990) and V. Zernitskaya (1985). The same can be said about the deposits in the depth interval of 60–20 cm identified by E. Krutous (1990) as peat (Fig. 13).

The second discussed lithological unit is represented by the lacustrine deposits at the depth interval of 100–60 cm and correlated with the Subboreal period (Zernitskaya, 1985). Here, the pollen spectra with very low frequency of *Quercus*, *Ulmus*, *Tilia*, *Typha* and *Sparganium* are the most interesting. The amount of *Alnus* and *Corylus* significantly decreased. At the same time, the number of *Artemisia* and Chenopodiaceae pollen grains increased. Such significant changes in the pollen spectra were most likely associated with the processes of erosion and redeposition of older sediments (from Younger Dryas?), and did not reflect regional changes in vegetation. Despite the absence of radiocarbon dates, it can be suggested that the redeposition of sediments occurred at the Atlantic-Subboreal boundary, as a result of a decrease in lake size and a phase of increased fluvial activity recorded in the deposits of the Sporovo II core.

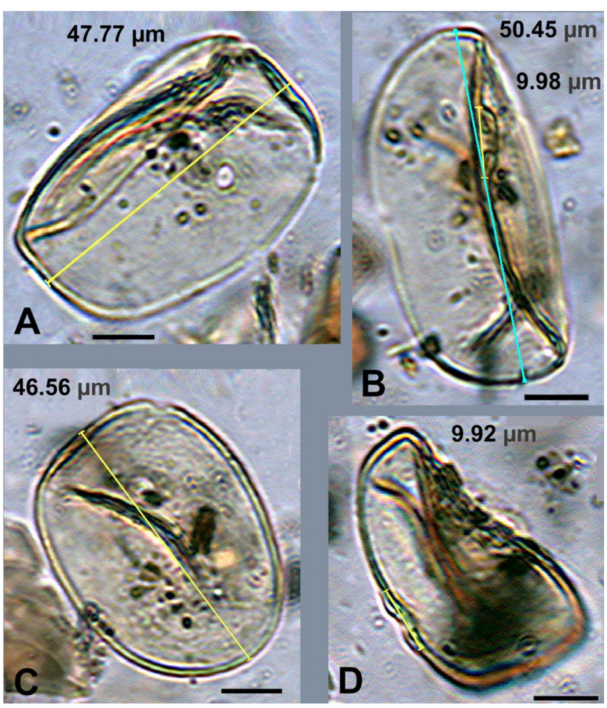

Figure 15. Examples of Poaceae pollen grains with an indistinct annulus from the Sporovo II core, which were previously misinterpreted as Cerealia (photos from Tsvirko et al., 2021a). **A**, **B.** Poaceae with the longest axis size of 47.77–50.45 µm and the annulus size of 9.98 µm (the same grain in different positions; sample depth: 145–150 cm); **C**, **D**. Poaceae with the longest axis size of 46.56 µm and the annulus size of 9.92 µm (the same grain in different positions; sample depth: 0–5 cm). Scale bars = 10 µm for all specimens

In addition to the studies mentioned above, this research allowed the correction of the previously proposed interpretations, as well as making some changes to earlier published data on the Sporovo II core (Trifonov et al., 2020; Tsvirko et al., 2021a, b). The chronology of events was corrected, changes were made to the pollen curves of Cerealia, cf. *Plantago* and others. Previously, HdV-128A (or Volvocaceae) palynomorphs were mistaken for *Lemna* pollen. The situation is similar with erroneously identified cf. *Plantago* grains, which were actually non-pollen palynomorphs.

It is important to note that the pollen identified as Cerealia in previous publications (Trifonov et al., 2020; Tsvirko et al., 2021a, b) were actually wild-growing Poaceae species, the pollen grains of which were large (the longest axis was more than 40 µm) but had an indistinct annulus (Fig. 15). In the mentioned publications, the main criterion for identifying pollen as Cerealia was a polar diameter of more than 40 µm, proposed by Simakova (2003). It is quite probable that such large pollen grains of

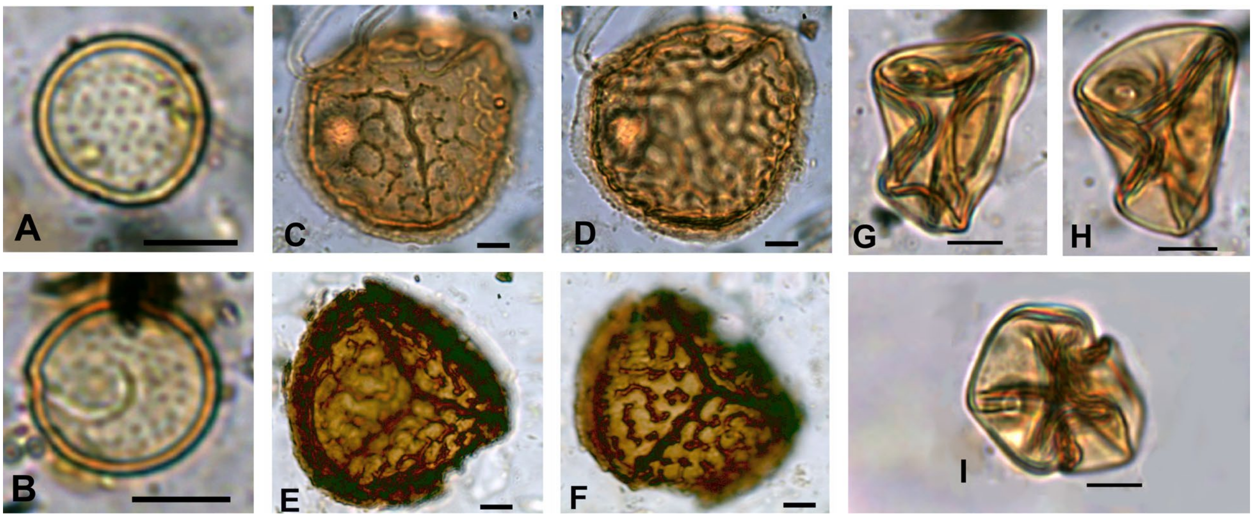

Figure 16. Selected NPPs, spores and Cerealia pollen from the Sporovo II core (photos by D. Tsvirko). **A**. HdV-128A or Volvocaceae (sample depth: 0–5 cm); **B**. HdV-128A or Volvocaceae (sample depth: 35–40 cm); **C**, **D**. *Riccia* (the same grain; sample depth: 97–103 cm); **E**, **F**. *Riccia* (the same grain; sample depth: 110–115 cm); **G**–**I**. Cerealia (sample depth: 30–35 cm). Scale bars = 10 µm for all specimens

wild-growing Poaceae could be present in the cores of Lake Sporovskoye and "Zditovo" made by V. Zernitskaya (Zernitskaya, 1985; Zernitskaya and Daineko, 1986).

In the current publication, the identification of pollen as Cerealia (single grain in the sample from the depth of 30–35 cm), was based mainly on the size of the annulus (9–10 µm in diameter) and on the sharpness of the annulus boundaries. At the same time, the longest axis size of the entire Cerealia grain was relatively small (~35 µm), but it should be taken into account that the grain was dented (Fig. 16).

ECONOMIC ACTIVITY OF PREHISTORIC COMMUNITIES

The record of human activity in the Sporovo II profile was poor: a single Cerealia pollen grain from the second half of the Subboreal period (depth 35–30 cm), and a rise in the *Artemisia*, Chenopodiaceae, Poaceae and other herb curves in the upper Subatlantic part of the profile.

However, the obtained hydrological reconstructions made it possible to build an assumption regarding the influence of the Atlantic-Subboreal regression of Lake Sporovskoye on the appearance of Early Neolithic communities at the Kakoryca-4 site. It should be noted that the specificity of the study area today is the high geodiversity of the landscape: a lot of small rounded sandy hills to the south of Lake Sporovskoye, rising among the wetland spaces. Some of these hills during the Atlantic period were apparently surrounded by the waters of Lake Sporovskoye, which was much larger. Only at the very end of the Atlantic and the beginning of the Subboreal, after a significant reduction in the size of the lake, these elevations became available for active economic use by prehistoric communities. Thus, the appearance of Early Neolithic communities on the sandy elevation of the Kakoryca-4 site could be explained by a decrease in the size of the lake at the AT-SB boundary.

CONCLUSIONS

Palaeodata obtained from the Sporovo II core allowed the palaeoecological reconstructions for the area surrounding Lake Sporovskoye. Reconstructions of changes in regional and local vegetation, fluctuations in the size of Lake Sporovskoye, the stage of increased fluvial activity of the Yaselda River, sedimentation changes in the Late Glacial and Holocene were proposed.

– The entire Sporovo II core could be divided into two large parts. The first part was predominantly mineral and correlated with the Late Weichselian (represented by: sands, calcareous gyttja and non-calcareous mineral gyttja). The second part consisted of Holocene organic deposits (gyttja and peat with different content of organic matter and microfossils of aquatic plants).

– Basal fine- and medium-grained sands were formed as a result of accumulation by braided (or multi-channel) rivers.

– Lake Sporovskoye was formed in the Late Weichselian, most likely in the Younger Dryas, as a result of thermokarst processes and alas lake formation. Moreover, the data indicated that the Younger Dryas was a wet period, since the level of the lake was high.

– During lake transgressions in the Holocene, organic gyttja was accumulated with the frequent presence of typically aquatic plant pollen *Stratiotes aloides*, *Nymphaea*, *Nuphar*, *Myriophyllum* and *Potamogeton* (in the BO-2 and AT-3), as well as with macroremains indicating limnic accumulation. During the regressions of Lake Sporovskoye, a break in sedimentation occurred (PB depositional hiatus), or there was an accumulation of telmatic (in the SB) or fen (in the SA) peats with the predominance of pollen from semi-submerged and wetland plants (Cyperaceae, Poaceae, *Sparganium*-type). These Subboreal and Subatlantic peats were also characterized by the absence or single finds of typically aquatic plant pollen and a large amount of damaged Undeterminable pollen.

– The period of increased activity of the Yaselda River (dated to ~6441–6305 and ~6176–5757 cal BP) was recorded. During this phase, the Yaselda River influenced the lake sediments by eroding the AT-1 and AT-2 deposits (erosional hiatus), as well as by introducing sandy and silty mineral material into the AT-3 deposits.

– Traces of human economic activity were found in the Sporovo II core. The regression of Lake Sporovskoye at the AT-SB boundary could have contributed to the emergence of Early Neolithic cultures at the Kakoryca-4 site.

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