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**PALAEOENVIRONMENTAL CONDITIONS
AND HUMAN-ENVIRONMENT
RELATIONSHIPS IN THE STONE AGE AND
THE BRONZE AGE IN SOUTHERN BELARUS**

Warunki paleośrodowiskowe oraz relacje człowiek-środowisko w
epoce kamienia i epoce brązu w południowej Białorusi

Doctoral dissertation prepared
under the direction of supervisor
prof. dr. hab. Piotr Kittel
in Department of Geology and Geomorphology
Faculty of Geographical Sciences

DEDICATION

To my parents, Iosif and Natallia Tsvirka, with deepest gratitude and love

ПОСВЯЩЕНИЕ

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INTRODUCTION

Several factors motivated the author to undertake the study presented in this dissertation. The most important among them is the deficit of multidisciplinary and geoarchaeological research on archaeological sites in Belarus. Archaeological investigations were frequently carried out independently of palaeogeographical studies (Kryvaltsevich, 1999; Kalechits, 2018; Vashanau and Tkachova, 2025). Only a limited number of archaeological sites were examined with the involvement of methods from palaeogeography and palaeoecology. However, almost all of these palaeoecological studies were limited to pollen analysis of sediment cores collected near archaeological sites (Zernitskaya et al., 2001; Kryvaltsevich and Simakova, 2004; Simakova, 2007; Zernitskaya, 2022), for example, pollen analysis of deposits from Lake Kuz'michskoe in the vicinity of the Neolithic–Bronze Age site (Kryvaltsevich, 2014; Zernitskaya and Kryvaltsevich, 2014). In some cases, the pollen interpretations were not supported by radiocarbon dating, for example at the Neolithic sites of Fedotkina Griva and Mishurova Griva (Simakova, 1996). In other cases, pollen diagrams were supported by only one or two radiocarbon dates, for example at the Neolithic site of Zatsenie (Yelovicheva et al., 2002), at the Krivina Mire close to the Neolithic–Early Bronze Age site (Simakova, 2000; Zernitskaya et al., 2001), and at Lake Viachera near the Mesolithic–Iron Age site (Kryvaltsevich and Simakova, 2004).

The majority of palaeogeographical studies in Belarus were also conducted independently of archaeological research. In most cases, the pollen data were presented without correlation to archaeological chronology and without references to archaeological excavation materials, even when human indicators were recorded in pollen assemblages. This reflects the fact that most pollen studies in Belarus were not designed as environmental archaeology investigations, and that the findings of pollen indicators of human activity were incidental. Such situations are characteristic of numerous lacustrine and wetland cores, for example those from: Lake Bobrovichskoe (Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022), the palaeolake Ivanisovka (Zernitskaya and Mikhailov, 2009; Zernitskaya et al., 2010; Zernitskaya, 2022), Lake Neropla (Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022), Lake Mezhuhol (Zernitskaya and Mikhailov, 2009; Zernitskaya and Novenko, 2016), Lake Sergeyevskoye (Makhnach et al., 2009), the palaeomeander Ogorodniki (Tsvirko and Zernitskaya, 2019), Tserkovnoe 2 wetland (Zernitskaya, 2022),

and many others. For many of these cores, pollen data were not supported by radiocarbon dates, for example in the case of Lake Peschanoe 2 (Zernitskaya et al., 2001), Lake Okono (Simakova, 2002), as well as Lake Sporovskoye, which is particularly important for this study (Zernitskaya, 1985; Zernitskaya and Daineko, 1986). In some instances, pollen diagrams were based on only one radiocarbon date, for example at the Zditovo wetland (Zernitskaya and Daineko, 1986; Zernitskaya et al., 2001), Tserkovnoe 1 wetland (Zernitskaya et al., 2001; Zernitskaya, 2022), Osveya wetland (Zernitskaya and Mikhailov, 2009), and Lake Teklits (Simakova, 2002). For a more detailed description of the main pollen diagrams from the territory of Belarus, see Tsvirko (2018) and Zernitskaya (2022).

The absence of correlation between pollen records and archaeological data has led some authors to suggest the possible presence of settlements of the Early Neolithic Linear Pottery culture on the territory of Belarusian Polesie (Zernitskaya and Mikhailov, 2009). This culture is commonly associated with the spread of early agriculture in Central Europe (Cofta-Broniewska and Koško, 1982, 2002; Czerniak, 1994; Czekaj-Zastawny, 2017). However, no archaeological evidence of the presence of Linear Pottery culture communities has been discovered in Belarus (Kalechits, 2018). It is likely that such assumptions were made by Zernitskaya and Mikhailov (2009) due to the misidentification of *Cerealia* pollen and its confusion with wild-growing *Poaceae* found in the deposits dated to 7,900–7,000 cal BP. Apparently, in identifying *Cerealia* pollen, Zernitskaya and Mikhailov (2009) relied primarily on its large size ($>40\text{ }\mu\text{m}$, following Simakova, 2003), which may have led to incorrect identification.

In the study of archaeological sites in Belarus, archaeozoological analysis has been widely applied (Kryvaltsevich et al., 2008; Kryvaltsevich, 2014). It should be noted, however, that methods such as plant macrofossil analysis, sedimentological analysis, and geochemical analysis have rarely been applied at Belarusian archaeological sites (Kalechits, 2018; Loshenkov, 2021). As a result, radiocarbon dating of geological layers at archaeological sites was frequently performed on bulk sediment material rather than on identifiable plant macrofossils (Vashanau and Tkachova, 2025).

I would like to comment separately on the study of the Ogorodniki palaeomeander from the Bug River valley floor in Belarus, conducted by the author of this dissertation in 2019 using the research capacities of Belarusian scientific institutions (Tsvirko and Zernitskaya, 2019; Tsvirko, 2019a, 2019b). This study represents an example of palaeogeographical research carried out independently of archaeological investigations. A high proportion of *Cerealia* pollen was recorded in the Ogorodniki profiles; however, these

pollen data were not correlated with the activities of particular historical or prehistoric communities. The author currently expresses doubts regarding the correct identification of *Cerealia* pollen grains in the Ogorodniki cores, as some of them may have been misidentified and could represent wild-growing *Poaceae*. The age-depth model, constructed on the basis of a small number of radiocarbon dates, also raises numerous doubts. Moreover, in Tsvirko (2019b), the positions of the radiocarbon dates within the palaeomeander deposits were presented incorrectly; the corrected version is provided in Tsvirko and Zernitskaya (2019) and Tsvirko (2019a). Further doubts relate to the proposed lithological interpretation. During the investigation, neither plant macrofossil analysis nor sedimentological analysis was conducted, and lithological units were identified based on the visual macroscopic evaluation of the deposits (Tsvirko and Zernitskaya, 2019). These and other shortcomings of the Ogorodniki palaeomeander study revealed to the author of this dissertation the limited research capacity of Belarusian scientific institutions. Consequently, the author decided to undertake comprehensive geoarchaeological research using the scientific facilities of the University of Lodz in Poland.

Another reason that motivated the author to undertake this dissertation was the relatively large number of archaeological investigations conducted in Southern Belarus and in neighbouring countries (Kalechits, 2018), including those involving radiocarbon dating. The oldest archaeological site in Belarus was discovered in the southern part of the country (the Upper Palaeolithic Yurovichi site, 26,470±420 BP; Arslanov et al., 1972; Kalechits, 2018, 2023). A series of radiocarbon dates has been obtained from archaeological sites in Belarus and neighbouring countries (for instance, through the dating of charcoal fragments or bulk sediments) for the Swiderian culture (Stupak, 2006; Gudaitienė et al., 2019), the Kudlaevka culture (Zaliznyak, 2009; Vashanau and Tkachova, 2025), and the Janisławice culture (Asheichyk, 2017; Kalechyts and Kolasau, 2023).

A significant number of radiocarbon dates have been obtained for Neolithic and Bronze Age artefacts from Southern Belarus and adjacent territories (for instance, through the dating of charred food crust on pottery or organic temper), which has made it possible to establish the chronology of archaeological cultures (see Table S3 in Chapter 1). For example, radiocarbon dates have been obtained for the Pripyat-Neman culture (Charniauski, 2011; Tkachou, 2017, 2018, and 2019; Jóźwiak, 2018; Tkachev and Tkacheva, 2024) and the Neman culture (Piličiauskas, G., 2002; Charniauski, 2011; Jóźwiak, 2018), attributed to the so-called “forest Neolithic” cultures (Czebreszuk and Szmyt, 2003; Jóźwiak, 2018; Tkachou, 2018; Wieckowska-Lüth et al., 2021;

Dolbunova and Mazurkevich, 2025). Radiocarbon dates were also obtained for the Globular Amphora culture (Czebreszuk and Szmyt, 2003; Zuyeva, 2009; Szmyt, 2010; Vaitovich, 2016, 2019, 2020; Kryvaltsevich, 2016a), the Corded Ware culture circle (Czebreszuk and Szmyt, 2003; Kryvaltsevich, 2004a, 2006ab and 2011; Piličiauskas et al., 2018), the Middle Dnieper culture (Czebreszuk and Szmyt, 2003; Kryvaltsevich, 2006a), the Trzciniec Cultural Circle (Kryvaltsevich, 2006b, 2016b; Makarowicz, 2010) and other archaeological cultural groups. Thus, the relatively well-developed prehistoric chronology has enabled the dating of geological layers at the Kakoryca-4 site based on the artefacts contained within them (see Chapter 1).

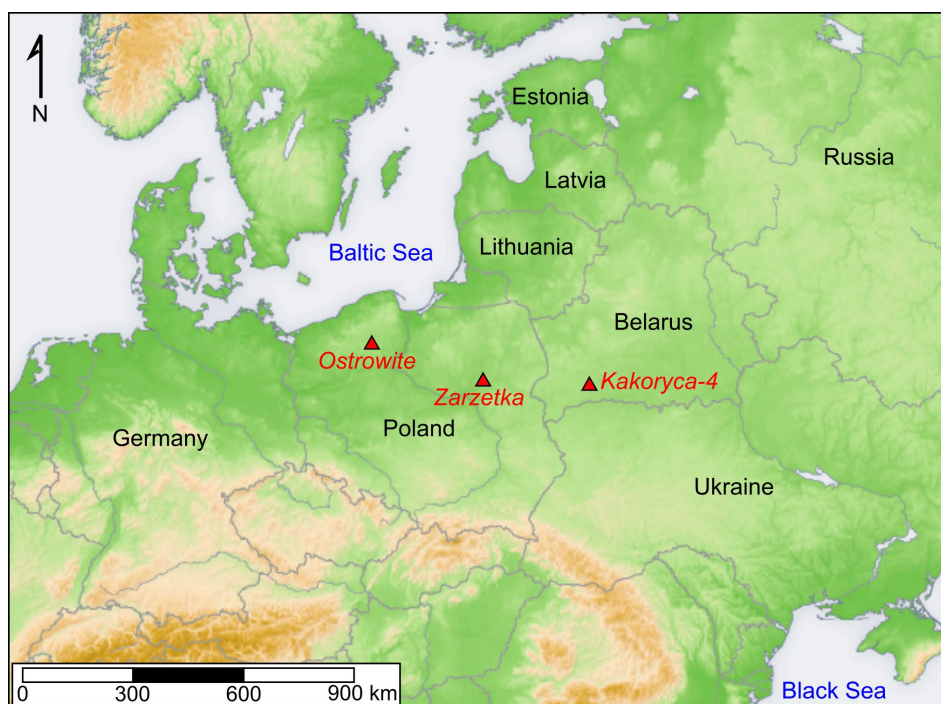
The final motivating factor for undertaking this dissertation was the intense development of multidisciplinary and geoarchaeological research (or, more broadly, environmental archaeology) in Europe over the past 20–30 years. The author aimed to conduct similar research in Belarus, where such integrated studies have not yet been carried out. Particular inspiration was drawn from the geoarchaeological investigations conducted at the Mesolithic–Middle Ages Serteya archaeological complex in Western Russia (Piech et al., 2018, 2024; Tarasov et al., 2019; Kittel et al., 2020a, 2020b, 2023; Mroczkowska et al., 2021; Wieckowska-Lüth et al., 2021; Gauthier et al., 2025).

At Serteya, an extensive range of palaeoenvironmental and archaeological methods was employed, including pollen, plant macrofossil, and macrocharcoal analyses; palaeozoological studies (Cladocera and Chironomidae); and geochemical, sedimentological, and micromorphological analyses. This comprehensive methodological framework allowed researchers to reconstruct regional and local vegetation dynamics (Tarasov et al., 2019; Wieckowska-Lüth et al., 2021; Gauthier et al., 2025), determine the origin of geological deposits and document changes in depositional processes in the palaeolake nearshore zone (Kittel et al., 2020a), describe the development of slope processes (Piech et al., 2018, 2024), reconstruct lake-level fluctuations (Kittel et al., 2020b; Wieckowska-Lüth et al., 2021), and produce climatic (Mroczkowska et al., 2021) and other palaeoenvironmental reconstructions. Crucially, the researchers were able to correlate palaeoecological interpretations with archaeological data and to develop palaeoeconomic reconstructions (Kittel et al., 2020b; Wieckowska-Lüth et al., 2021).

The author of the dissertation was also inspired by multi-proxy investigations conducted at the Lutomiersk-Koziówki site (Kittel et al., 2014, 2016), the Wietrzychowice Cultural Park (Makohonienko et al., 2023), the Koźmin Las site (Dzieduszyńska, 2014; Dzieduszyńska and Twardy, 2014; Stachowicz-Rybka and Korzeń, 2014), and other

studies. The author also gained personal experience in multidisciplinary and geoarchaeological research at the Ostrowite archaeological complex (see Chapter 3) and became a co-author of a publication presenting the results of these investigations (see Kittel et al., 2025).

In summary, multidisciplinary and geoarchaeological research at archaeological sites in Belarus remains an important and relevant task. Accordingly, the Kakoryca-4 archaeological site was selected as the case study for multidisciplinary research. The site is located in the basin of the Yaselda River and Lake Sporovskoye (Belarusian Polesie), on a small rounded elevation formed by fluvial deposits. Currently, the site is situated on the border of several geosystems: terrestrial, alluvial (floodplain and river channel), and wetland.



Location of the sites studied in this dissertation (source: <http://pl.wikipedia.org>, author: San Jose; modified), including the Kakoryca-4 archaeological site (Belarus), the Zarzetka oxbow lake (Poland), and the Ostrowite archaeological site with palaeolake OST2B (Poland)

The Kakoryca-4 archaeological site was selected for investigation for several reasons. First, it is a relatively recently discovered site (found in 2018, Kryvaltsevich et al., 2023), which provided an opportunity to conduct joint archaeological and geological research and to study sediments from excavation contexts. Second, the Kakoryca-4 site is exceptionally

rich in artefacts (more than 60,000 artefacts have already been found). The elevation on which the Kakoryca-4 site is located contains far more artefacts than the surrounding hills. In the course of the dissertation research, the author sought to explain why such a high concentration of artefacts was deposited at this location and what made this location attractive to prehistoric communities. Third, the sandy elevation on which the Kakoryca-4 site is situated borders the Iržave wetland, whose biogenic deposits of diverse origins contain artefacts from different periods. This provided an opportunity to link specific palaeoenvironmental conditions with distinct prehistorical chronological phases. Fourth, the Kakoryca-4 site is located within the Belarusian Polesie region, an area that has several research problems highlighted in the literature. The author attempted to address the following problems: (1) the origin of so-called “lacustrine-alluvial” deposits (Gosudarstvennaya geologicheskaya karta SSSR, 1982; Velichkevich et al., 2001; Kalechits, 2018; Vezhnovets and Shkurganov, 2019; Gusev et al., 2023), (2) the emergence of agriculture in Polesie (with literature reporting pollen evidence of farming dating back to 7,900–7,000 cal BP; Zernitskaya and Daineko, 1986; Zernitskaya et al., 2001; Kryvaltsevich and Simakova, 2004; Simakova, 2007; Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022), and (3) the transgressions and regressions of Lake Sporovskoye and the correct interpretation of the origin of biogenic and mineral-organic sediments (Zernitskaya, 1985; Krutous, 1990; Tsvirko, 2023).

It should also be noted that the dissertation focuses on the Kakoryca-4 archaeological site partly because the author had previously conducted research at this site, as evidenced by numerous publications presenting preliminary results of these investigations (cf. Trifonov et al., 2020; Tsvirko et al., 2021a, 2021b).

The main objective of the dissertation was to reconstruct landscape evolution, palaeoenvironmental conditions, and human-environment interactions during the Stone Age and the Bronze Age in the area of the Kakoryca-4 archaeological site in Southern Belarus.

Our study of the Kakoryca-4 archaeological site is unique and represents the first multidisciplinary investigation in Belarus using a wide range of analytical methods. Our research relied mainly on radiocarbon dating, pollen and plant macrofossil analyses, geochemical and sedimentological analyses, and the use of cartographic and archaeological materials (see Chapter 1). The general methodological framework of our study involved detailed analyses of geoarchives associated with the Kakoryca-4 archaeological site. These included archaeological layers, bioarchives preserved in biogenic and organo-mineral

deposits, and evidence of fluvial activity recorded in mineral and organo-mineral sediments. This strategy allowed for comprehensive reconstructions integrating palaeoecological and archaeological datasets.

Further details regarding the Kakoryca-4 archaeological site are presented in Chapter 1 of this manuscript, which is fully dedicated to the investigation of the site. Chapter 1 has been written in the form of an article that is currently under second stage of peer review. Part of the results from the Kakoryca-4 archaeological site have already been published in a single-authored article written in the course of the doctoral research (Appendix 1; Tsvirko, 2023).

In addition to the investigation of the Kakoryca-4 archaeological site, the author conducted several supplementary studies aimed at resolving specific methodological problems. These included the study of bottom sediments from the Zarzetka oxbow lake (Chapter 2) and the palaeolake marked with the symbol “OST2B” (Chapter 3), both situated in Poland. The Zarzetka oxbow is located in the Bug River valley floor, approximately 50 km NE of Warsaw. The palaeolake OST2B is located in Northern Poland in the immediate vicinity of the Ostrowite archaeological complex, approximately 60 km N of Bydgoszcz.

In my dissertation, Chapter 2 focuses on pollen indicators of human economic activity. Since one of the principal methods applied in the investigation of the Kakoryca-4 site was pollen analysis, it was necessary to determine how human economic activities – such as cultivation, grazing, and the formation of trampled and ruderal environments – are expressed in pollen assemblages, that is, which taxa serve as indicators.

The review of the literature presented in Chapter 2 reveals considerable variation in the interpretation of anthropogenic indicators. For instance, Behre (1981, 1988) regarded Brassicaceae pollen as indicative of cultivated fields, while Poska et al. (2004) assigned this taxon to ruderal communities, and Związek et al. (2024) considered it characteristic of meadow vegetation. Comparable inconsistencies are observed in the ecological interpretation of several other taxa (cf. Behre, 1981 and 1988; Simakova, 1996; Yelovicheva et al., 2002; Poska et al., 2004; Kołaczek, 2010; Zernitskaya, 2011; Święta-Musznicka et al., 2013; Tsvirko, 2017; Brown et al., 2019; Związek et al., 2024).

Based on the published results, the author of the dissertation proposed groups of taxa indicative of human economic activity (see the Zarzetka pollen diagram in Chapter 2). To test the proposed ecological groups of human indicators, additional pollen studies were conducted on modern bottom sediments (40 or 60 years old, according to ^{14}C dating) from

the Zarzetka oxbow lake. The Zarzetka oxbow is located in a region characterised by intense modern agricultural activity (Fig. 12B in Chapter 2). This allowed for an assessment of whether the proposed human indicator groups are indeed strongly represented in modern pollen assemblages from the Zarzetka core.

The author of the dissertation also prepared a photographic comparative dataset of Cerealia pollen grains from the Zarzetka core (see Fig. 16 in Chapter 2), including measurements of their size and documentation of their visual characteristics. The use of this comparative material made it possible to establish that the pollen previously identified as Cerealia in the sediments of the Lake Sporovskoye basin (Trifonov et al., 2020; Tsvirko et al., 2021a and 2021b) was, in fact, pollen of wild-growing Poaceae (see the presence of Poaceae with an axis $>40\text{ }\mu\text{m}$ in Fig. 10 in Chapter 1; Tsvirko, 2023).

Accurate identification of Cerealia pollen is crucial, since confusion with wild-growing Poaceae may result in incorrect palaeoecological conclusions. The reports by Zernitskaya et al. (2001), Velichkevich et al. (2002), Kryvaltsevich and Simakova (2004), Zernitskaya and Mikhailov (2009), and Zernitskaya (2022) of Cerealia pollen dated to 7,900–7,000 cal BP in the deposits of lakes and wetlands in Belarusian Polesie likely represent cases of such misidentification, involving confusion with wild-growing Poaceae (see Chapter 1). Therefore, the photographic material from the Zarzetka core was used as reference material throughout the dissertation research for the identification of Cerealia pollen grains.

Chapter 3 was written by the author of the dissertation to address a number of problematic issues that emerged during the investigation of the Kakoryca-4 archaeological site. During the analysis of deposits in the Lake Sporovskoye basin, I faced the issue of differentiating peat from detritus gyttja (see Chapter 1). This issue is of considerable importance, since misidentification of sediment origin may result in incorrect palaeoecological interpretations (Tobolski, 2021), particularly erroneous reconstructions of lake regressions and transgressions. It appears that different methodological approaches exist in the classification of biogenic deposits. In Belarusian literature, lake bottom sediments rich in macrofossils of nearshore and wetland vegetation, even when accompanied by abundant aquatic taxa, are often classified as peat (Tsvirko, 2023). Based on this approach, thick peat layers are often distinguished within the sedimentary sequences of Belarusian lakes (Tsvirko, 2023). For instance, multiple peat layers were reported in the bottom sediments of Lake Sporovskoye by Zernitskaya (1985), Zernitskaya and Daineko (1986), Krutous (1990), and Velichkevich et al. (2002). Moreover, Krutous (1990)

classified the uppermost part of the bottom sediments of Lake Sporovskoye, situated beneath approximately a 1.8 m water column, as peat (see Fig. 13 in Tsvirko, 2023). Apparently, in determining the origin of sediments, the above-mentioned researchers also relied strongly on the visual characteristics of the deposits, particularly on the resemblance of some bottom sediments of Lake Sporovskoye to peat.

In many cases, Belarusian authors determine the type of bottom sediments primarily based on the organic matter content (Zhukhovitskaya et al., 1998; Novik et al., 2010). For example, Novik et al. (2010) defined detritus gyttja as deposits containing more than 50% organic matter. The author of this dissertation argues that, when determining the lacustrine or wetland origin of lake bottom sediments, primary attention should be paid to the abundance of aquatic or wetland plant micro- and macrofossils in the deposits. A substantial admixture of aquatic plant remains in the sediments should not be ignored.

A different methodological approach is presented in Polish literature. According to Tobolski (2021), the origin of sediments should not be determined on the basis of visual assessment alone, as detritus gyttja may visually resemble peat. Following Tobolski (2021), deposits containing a large proportion of aquatic plant remains should be interpreted as gyttja. Additionally, Polish researchers employ the term telmatic zone of a lake (Słowiński et al., 2018, 2022; Tobolski, 2021; Mirosław-Grabowska et al., 2023), which does not occur in Belarusian literature. The telmatic (or limno-terrestrial) zone refers to the transitional zone existing between high and low water levels in a lacustrine environment (Tobolski, 2021). This zone is dominated by nearshore semi-submerged vegetation, and it is characterised by the accumulation of telmatic peat, which may contain an admixture of aquatic plant remains (Tobolski, 2021). It is plausible that the deposits described in Belarusian literature as “peat with gyttja” (Zhukhovitskaya et al., 1998; Novik et al., 2010) correspond to telmatic peat in the sense proposed by Tobolski (2021).

Thus, since we found a record of the gradual regression of Lake Sporovskoye and, consequently, changes in the accumulation environment (see Chapter 1; Tsvirko, 2023), additional studies were conducted using diverse deposits (basal and telmatic peats, as well as gyttja) from the small palaeolake OST2B in Northern Poland (Tsvirko et al., 2023; Leszczyk et al., 2025) to examine how the transition from lacustrine to wetland conditions (or vice versa) is reflected in pollen and plant macrofossil assemblages. This additional study made it possible to identify pollen and macrofossil indicators of peat and gyttja deposits, thereby broadening the knowledge obtained from the investigation of deposits from the Lake Sporovskoye basin.

Additionally, given that no reliable pollen evidence of agriculture was found in the Sporovo II core from the Lake Sporovskoye basin (see Chapter 1), the author conducted an additional study using the OST2B core from Northern Poland (Chapter 3; Tsvirko et al., 2023; Leszczyk et al., 2025) to evaluate whether the groups of human indicators identified in Chapter 2 (see the pollen diagram of the Zarzetka core) could be effectively used to interpret past human economic activities, particularly agriculture. The OST2B core was selected as a case study to test the identified ecological groups of pollen indicators of human activity, although the original intention had been to use the Sporovo II core, which, however, contained no clear evidence of agricultural activity (see Chapter 1).

During the investigation of biogenic deposits in the vicinity of the Kakoryca-4 site, overbank organic muds were identified, often containing less than 30% organic matter (see Fig. 6B in Chapter 1). Some of these organic muds exhibited a substantial admixture of sand (see unit a₄ in Fig. 6B in Chapter 1), which was interpreted as evidence of strong flooding events of the Yaselda River. In addition, a significant sand admixture was detected in coarse detritus gyttja (see unit l₆ in Fig. 6A in Chapter 1), suggesting fluvial influence on sediment accumulation in Lake Sporovskoye. To identify these sandy admixtures in the biogenic deposits and to elaborate such palaeoecological interpretations, the mineral fraction had to be separated from the coarse detritus gyttja and organic muds and subjected to textural analysis. Therefore, it was proposed to use the ash remaining after ignition of biogenic sediments for textural analysis (Tsvirko et al., 2024). The ash, however, required prior purification from secondary impurities (metal oxides and carbonates) formed during ignition in the muffle furnace at 550°C. Therefore, we developed a procedure for purifying the ash from secondary metal oxides and carbonates, referred to as the Ash Purification Procedure (APP; Tsvirko et al., 2024). The APP was actively used throughout this study. The textural characteristics of the mineral component of the coarse detritus gyttja and organic muds were employed to determine lithological boundaries and to support palaeoecological reconstructions of Yaselda River activity (see Chapter 1). For a more detailed discussion of the Ash Purification Procedure, see our published paper attached to this dissertation (Appendix 2; Tsvirko et al., 2024).

To sum up, the presented manuscript includes two published papers (Appendices 1 and 2), one article currently under peer review (Chapter 1), as well as three original chapters prepared by the author (Chapters 2–4). Chapter 4 presents brief remarks and discusses the main challenges encountered during the doctoral research.

For the preparation of Chapter 1, the author personally conducted pollen analysis (52 samples), sedimentological analysis (231 samples), and geochemical analysis (361 samples). The author also personally carried out the laboratory processing of 23 samples for plant macrofossil analysis and participated in archaeological excavations in 2019–2021 at the Kakoryca-4 site. As a result of the author's efforts, the UŁ IDUB grant no. 7/ODW/DGB/2022 was obtained to support research at the Kakoryca-4 archaeological site, which enabled the acquisition of a large number of radiocarbon dates. The author participated in numerous conferences, research internships, consultations with specialists, and other academic activities. The author prepared the text of Chapter 1 and developed the majority of the interpretations included in it.

The author personally conducted the pollen analysis for Chapter 2 (28 samples) and Chapter 3 (66 samples). Chapters 2 and 3 were written entirely by the author, who also developed the majority of the interpretations presented in these chapters. Chapter 2 was prepared with financial support from the NCN OPUS-22 grant (UMO/2021/43/B/HS3/02636, "Biskupie drzewa. Historia środowiskowa Puszczy Białej"), under which the author held a scholarship position. Through the author's efforts, financial support was obtained from the Doctoral School of Exact and Natural Sciences UŁ to conduct plant macrofossil analysis, the results of which are presented in Chapter 3.

In total, 761 samples of geological deposits were processed and analysed by the author for the preparation of this dissertation.

It should also be noted that the author of the dissertation usually publishes under the name Dmitry Tsvirko.

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CHAPTER I

PALAEOECOLOGICAL AND CULTURAL CHANGES IN THE STONE AGE AND THE BRONZE AGE IN THE YASELDA RIVER VALLEY AND ON THE SHORE OF LAKE SPOROVSKOYE (BELARUSIAN POLESIE)

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Abstract: The Kakoryca-4 terrace remnant is a unique archaeological site exceptionally rich in artefacts and ecofacts, spanning from the Final Palaeolithic to the Modern and Contemporary eras, with the largest number of finds from the Neolithic and Early Bronze Age. Our aim was to reconstruct the palaeoecological conditions under which human communities occupied the Kakoryca-4 site during different periods, with a particular focus on the Stone Age and the Bronze Age. We applied a wide range of palaeogeographical methods (pollen, plant macrofossil, sedimentological analyses, radiocarbon dating, etc.) together with archaeological data. Our results show that the deposits traditionally described in Belarusian literature as “lacustrine-alluvial” in fact represent sediments of a sand-bed braided river. Lake Sporovskoye was formed during the Bølling-Allerød warming and for most of its history was considerably larger than it is today. Transgressions and regressions of the lake influenced the functioning of prehistoric communities. A clear record of lake transgression is identified for the Early and Middle

Atlantic. The regression of Lake Sporovskoye that began in the Late Atlantic was most likely the main factor driving the intense occupation of the Kakoryca-4 terrace remnant by Neolithic and Early Bronze Age communities. These communities were adapted to phases of increased Yaselda River activity, when strong floods led to the accumulation of black overbank organic mud north of the Kakoryca-4 terrace remnant. We present a critical review of palynological studies concerning the onset of agriculture in the Belarusian Polesie. Our findings provide direct evidence of agricultural activity at the Kakoryca-4 site during the Late Middle Ages.

Keywords: Kakoryca-4 archaeological site, Sporovsky Biological Reserve, lacustrine-alluvial deposits, “forest” Neolithic, backswamp organic mud

INTRODUCTION

1.1 Research issues

Polesie is a key region for studying prehistoric communities in Belarus. It was the initial settlement area and the territory from which many socio-economic phenomena began to spread across the country. In Polesie lies the oldest known prehistoric site in Belarus, Yurovichi site ($26,470 \pm 420$ BP, JIY-125), dated to the Upper Palaeolithic (Arslanov et al., 1972; Kalechits, 2018 and 2023). The process of Neolithization in Belarusian Polesie, which marks the transition from hunting-gathering to food-producing subsistence, is of particular interest to researchers. Traditionally, the Neolithization is associated with the appearance of agriculture, cattle-breeding, pottery, polished stone tools, and other advancements (Zernitskaya and Mikhailov, 2009). Radiocarbon evidence suggests that the first pottery in Belarusian Polesie appeared around the mid-6th millennium BC: Vostrau 3 site, pottery of the Pripyat-Neman culture dated to 5,766–5,559 cal BC with prob. 68.3% (^{14}C : $6,764 \pm 110$, SPb-3036; Tkachev and Tkacheva, 2024). The emergence of agriculture and cattle-breeding in Polesie remains, however, a subject of debate. It seems that Neolithic groups of people who adopted pottery, including the Pripyat-Neman and Neman cultures, continued to follow the traditional, millennia-old and successful subsistence strategy of hunting and gathering. This type of Neolithization, known as the “forest Neolithic” was widespread across vast areas of the Eastern European forest zone, including on the territory of Belarus (Czebreszuk and Szmyt, 2003; Jóźwiak, 2018; Tkachou, 2018; Wieckowska-Lüth et al., 2021; Dolbunova and Mazurkevich, 2025).

Currently, researchers are attempting to find evidence of food-producing economy within the “forest Neolithic” cultures of Polesie. Archaeological investigations are primarily focused on searching for domestic animal bones and imprints of cultivated plant seeds on pottery (Kryvaltsevich, 2004b; Kryvaltsevich et al., 2008; Grikpēdis et al., 2018; Loshenkov, 2021). Palynological analysis of wetland and lacustrine deposits is also used to search for signs of early agriculture (Tsvirko, 2018). Some researchers suggest that the earliest *Cerealia* pollen grains in Polesie region are as old as 7,900–7,000 cal BP (7,020±70 BP from Zditovo core, Tln-588; 6,630±125 BP from Ozernoe core, IGSB-826; 6,230±80 BP from Bobrovichskoe core, IGSB-810), which corresponds to the Mesolithic-Neolithic transition (Zernitskaya and Daineko, 1986; Zernitskaya et al., 2001; Kryvaltsevich and Simakova, 2004; Simakova, 2007; Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022). However, we express doubts regarding this pollen data and the existence of agriculture in the “forest Neolithic” Polesie, which will be addressed in the Discussion section.

Reliable scientific data undoubtedly suggest that the earliest forms of agriculture and cattle-breeding in Belarusian Polesie were associated with the spread of the Globular Amphora culture, the Corded Ware culture circle (CWC), and the Middle Dnieper culture in the 3rd millennium BC (Late Neolithic–Early Bronze Age). This is evidenced by botanical studies (imprints of cultivated plant seeds on pottery), osteological data (bones of domestic animal), finds of artefacts traditionally associated with agriculture (axes, sickles, hoes, etc.), stable isotope analysis of human bone collagen from CWC grave in Krasnasielski, and organic residue analysis of two CWC beakers from the graves Dakudava-5 and Drazdy-12 (Kryvaltsevich, 2004b; Vaitovich, 2016; Grikpēdis et al., 2018; Piličiauskas et al., 2018; Loshenkov, 2021).

The settlement patterns and economic strategies in prehistoric Polesie seem to have been significantly influenced by local environmental factors, such as: main landscape features resulted from geological structure and palaeogeographical evolution, lake transgressions and regressions, wetland processes, plant cover evolution, and others. To address the questions of the environmental impact on prehistoric communities and human-environment relationships in prehistoric Polesie, it is essential to perform palaeoecological research at archaeological sites and its closest vicinity. For this purpose, we selected the Kakoryca-4 site for a comprehensive palaeoecological and archaeological studies. The Kakoryca-4 site stands out for its relatively well-preserved stratigraphy, organic cultural and ecological remains, compared to other sites in Polesie. Located in the very centre of

Western Belarusian Polesie and within the Lake Sporovskoye basin, the site is mainly represented by artefacts from the Stone Age and Bronze Age. Detailed interdisciplinary research of this basin may reveal how Neolithic communities utilised the landscape features of Polesie and provide insights into some aspects of the Neolithic economy in Southern Belarus.

In our research, in addition to palaeoecological and archaeological reconstructions, we focus also on three important issues present in Belarusian literature, and for each, we have collected relevant data. The first issue is distinguishing between peat and coarse detritus gyttja. As previously shown by Tsvirko (2023), in Belarusian literature, lacustrine coarse detritus gyttja are often referred to as peat. This problem is crucial since, according to Tobolski (2021), misinterpretation of these deposits leads to incorrect palaeoecological conclusions. Probably for this reason, Kalechits (2018) previously noted, that it is difficult to find in Belarusian literature convincing evidence for the dynamics (transgression/regression) of paleolakes. The fluctuations of Lake Sporovskoye size had a direct influence on the functioning of prehistoric societies, which highlights the importance of the described issue. In our paper, when distinguishing peat from coarse detritus gyttja, we use the approach proposed by Tobolski (2021).

The second problem is distinguishing *Cerealia* pollen grains from wild-growing *Poaceae* pollen. This is a highly significant issue, since the presence of *Cerealia* pollen is used as an indicator of agricultural activity in Polesie. In Belarusian academic publications, large pollen grains of wild *Poaceae* have apparently been frequently misidentified as *Cerealia* pollen, as previously noted by Tsvirko (2023). Such misinterpretations could arise from focusing exclusively on the diameter of pollen grain of more than 40 μm , proposed by Simakova (2003). Consequently, some publications report the presence of *Cerealia* pollen in the sediments dated to the Early Neolithic (Zernitskaya and Mikhailov, 2009) and even Mesolithic (Velichkevich et al., 2002; Zernitskaya, 2022), which we doubt. The lessons learned from studying deposits around the Kakoryca-4 site show that the sharpness of the annulus contours is as important criterion as grain size or other parameters.

The third issue addressed in the study is the genesis of the so-called “lacustrine-alluvial” deposits identified in the Yaselda River basin (Gosudarstvennaya geologicheskaya karta SSSR, 1982; Velichkevich et al., 2001; Kalechits, 2018; Vezhnovets and Shkurganov, 2019; Gusev et al., 2023). We have obtained new sedimentological data that will shed light on their origin. We consider this issue important

because, according to the traditional interpretation, the Kakoryca-4 site is located on a “lacustrine-alluvial” elevation (Gosudarstvennaya geologicheskaya karta SSSR, 1982).

In our study, the following hypotheses are tested.

Tested Hypothesis 1: currently, there are no reliable pollen data indicating the existence of agriculture in Belarusian Polesie during the Late Mesolithic, the Early Neolithic, or throughout the so-called “forest” Neolithic. Pollen grains interpreted by some authors as *Cerealia* and dated to 7,900–7,000 cal BP were produced by wild-growing *Poaceae*. Evidence of prehistoric and historic agricultural activities can be found in the organic deposits near the Kakoryca-4 site.

Tested Hypothesis 2: the deposits referred to as “lacustrine-alluvial” in Belarusian literature, which form the elevation on which the Kakoryca-4 site is located, actually represent sediments of a sand-bed braided river. The braided river formed the Kakoryca-4 mid-channel bar in a favourable location and with suitable dimensions for the intense occupation by Neolithic and Early Bronze Age communities.

Tested Hypothesis 3: Lake Sporovskoye was much larger than at present for most of its history. The present-day wetlands adjacent to the lake are therefore largely composed of coarse detritus gyttja, often mistakenly identified as peat in the Belarusian literature. Transgressions and regressions of Lake Sporovskoye influenced the intensity of use of the Kakoryca-4 elevation by prehistoric communities during the Mesolithic, Neolithic, and Early Bronze Age.

Tested Hypothesis 4: the communities that occupied the Kakoryca-4 elevation in the Neolithic and the Early Bronze Age were adapted to phases of increased Yaselda River activity, during which strong floods occurred. Despite these conditions, they maintained an active use of the Kakoryca-4 elevation, which is indicated by the large number of artefacts preserved in a black overbank organic mud layer. The large number of artefacts of different ages accumulated within this relatively thin black overbank organic mud layer partly as a result of breaks in sedimentation (hiatuses).

1.2 State of the art

A number of palaeogeographical and palaeoecological studies have already been carried out on the territory of the Kakoryca-4 site and in the surrounding area of the Yaselda River basin and Lake Sporovskoye. Among the published materials, one can highlight the works of Zernitskaya (1985), Zernitskaya and Daineko (1986), Krutous (1990), Matveev et al. (1993), Trifonov et al. (2019), Tsvirko et al. (2021ab, 2023ab, 2024),

Trifonov (2021), Frączek and Kalicki (2021), Tsvirko and Kittel (2022), Tsvirko (2022ab, 2023), as well as data from the Gosudarstvennaya geologicheskaya karta SSSR (1982). We have obtained new palaeogeographical and palaeoecological data that allow for an important correction and complementation of previous results. Some archaeological data on the Kakoryca-4 site were previously published by Kryvaltsevich et al. (2023), as well as by Trifonov et al. (2020). When studying the Early Neolithic pottery at the Kakoryca-4 site, we relied on the works of Tkachou (2017, 2018, 2019).

1.3 Objective

The purpose of the study was to reconstruct palaeoecological conditions of the functioning of human communities at the Kakoryca-4 archaeological site during the Poozerian (Weichselian, Vistulian, Valdai) glaciation and Holocene, with a particular focus on the Stone Age and the Bronze Age. The presented here reconstructions are based on the results of geological survey both at the area and around the Kakoryca-4 site, using the methods of palaeogeography and archaeology, as well as on a comparison with other well-studied sites.

STUDY AREA

2.1 Location

The archaeological site Kakoryca-4 is located in Southern Belarus, in the western part of Belarusian Polesie, beyond the border of the last glaciation. In close proximity to the site lies the shallow Lake Sporovskoye (or Sporovskoe; the present-day maximum depth is 1.5 m according to Vlasov et al., 2004), through which the Yaselda River flows. The closest present-day settlements to the study area are the villages of Kakoryca, Khomsk, Bezdezh, Zditovo and Sporovo (Fig. 1; Figs. S1 and S2 in the online supplementary material (OSM)).

Vast areas in the basin of the Yaselda River and Lake Sporovskoye are occupied today by grass wetlands. To the south of Lake Sporovskoye, a large number of small (about 150–200 m in diameter) rounded or elongated sandy “lacustrine-alluvial” elevations rise slightly above the wetlands, creating a mosaic image of the landscape (Fig. 1B; Figs. S1 and S2B). Higher “lacustrine-alluvial” elevations (1–2 meters above the surrounding wetlands) are located mainly SW of Lake Sporovskoye (Figs. S1 and S3). The Kakoryca-4 site is located on the surface of one of these elevations, that is the closest to the modern Yaselda River channel and rising approximately 1.5 meters above the Lozy and Iržave

wetlands (Figs. 1–3; Fig. S4). Lower “lacustrine-alluvial” elevations (about 0.5 meters above the surrounding wetlands) are located mainly NE, E and SE of Lake Sporovskoye, some of them have a depression in the central part. These lower elevations do not interfere with present-day agricultural activities and are therefore ploughed along with the surrounding artificially drained wetlands (Figs. S5–S7). Between these lower elevations, the traces of flow (paths of a braided river in our interpretation) are clearly visible on the satellite images (Figs. S7–S8).

2.2 Geological situation

The study area was formed under the influence of the Pripyat’ glaciation (= Saale glaciation in W Europe, Odranian glaciation in Poland, Dnieper glaciation in Russia, MIS 6, 195–130 ka BP), consisting of the Dnieper and Sozh stages (Lindner et al., 2004; Karabanov and Matveyev, 2011; Velichko et al., 2011; Lindner and Marks, 2012; Marks and Karabanov, 2017). Glacial and fluvioglacial deposits of the Dnieper stage (= Drenthe stage, Odranian main stage, Dnieper stage) adjoin the study area from S and E, while the same deposits of the Sozh stage (= Warthe stage, Wartanian stage, Moscow stage) adjoin from N and W (Fig. 4). The territory is located in close proximity to the boundary of the maximum distribution of the Sozh ice sheet (Gosudarstvennaya geologicheskaya karta SSSR, 1982; Tsvirko and Kittel, 2022). Terminal moraine deposits of the Dnieper stage had a particularly significant influence on the functioning of prehistoric communities, since it was a relatively easy source of raw flint material. Our field observations showed that today large amounts of raw flint can be found on agricultural lands on moraine deposits to the west of Bezdezh village, near the Struve Geodetic Arc Monument (Fig. 4 – Area rich in raw flint; Fig. S9).

During the last Poozerian glaciation (= Weichselian, Vistulian, Valdai, from MIS 5d to the beginning of MIS 1, 115–10 ka BP) this territory was under periglacial conditions, in which the accumulation of so-called “lacustrine-alluvial” deposits (braided river deposits in our interpretation) occurred. In the Holocene, the study area was mainly characterized by the accumulation of biogenic sediments. According to our observations, the studied area around the Kakoryca-4 site exhibit a typical structure for Belarusian Polesie, with Weichselian fluvial sands and/or calcareous gyttja overlain by Holocene organic gyttja, peat and muds. The maximum thickness of organic deposits near the Kakoryca-4 site was 189 cm.

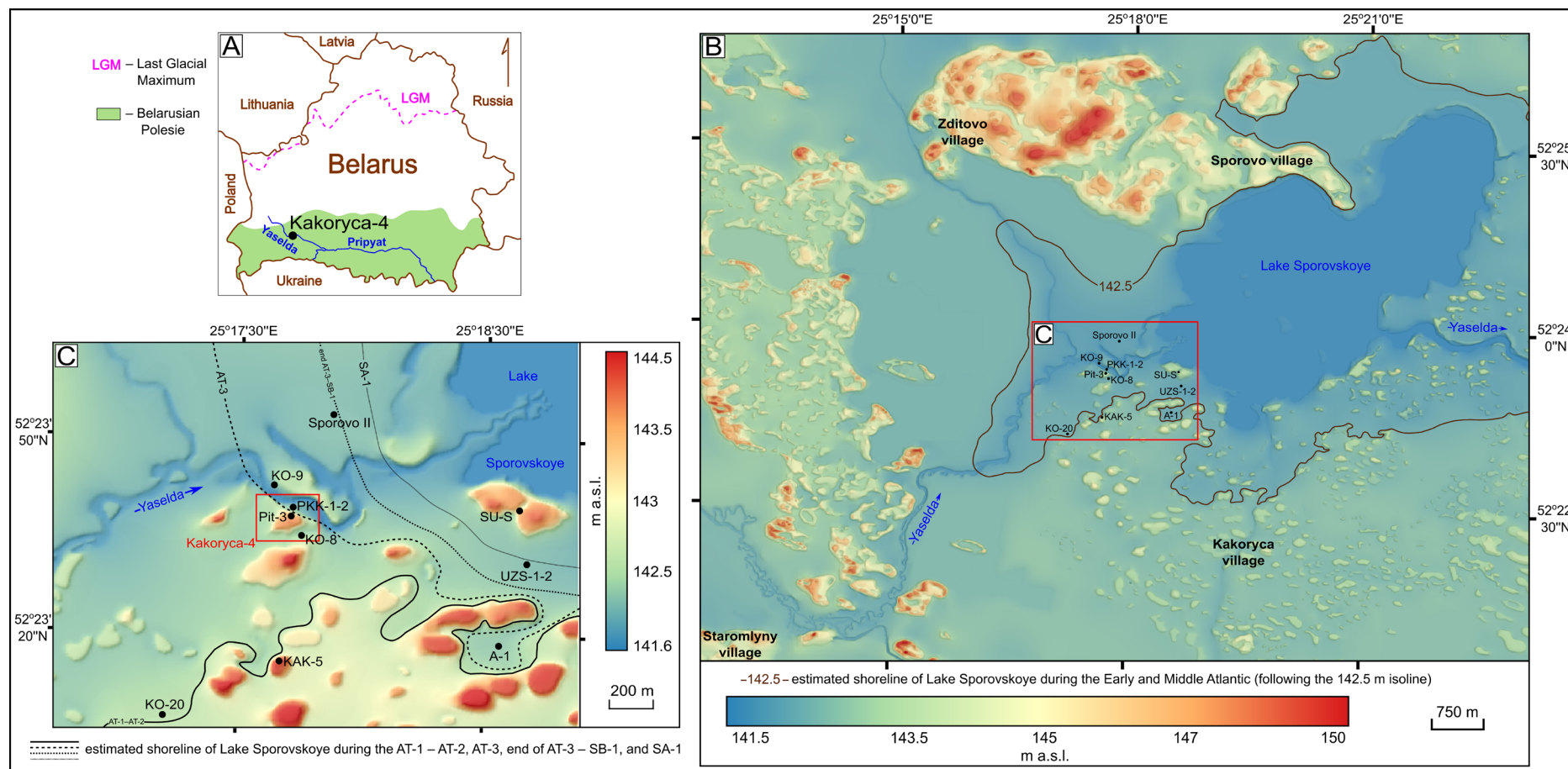


Fig. 1. Location of the Kakoryca-4 archaeological site on the territory of Belarussian Polesie (A) in the basin of the Yaselda River and Lake Sporovskoye (B–C). B and C – fragments of a digital elevation model (DEM) with reference boreholes (see also Trifonov, 2021; Tsvirko et al., 2021a; Tsvirko, 2023)

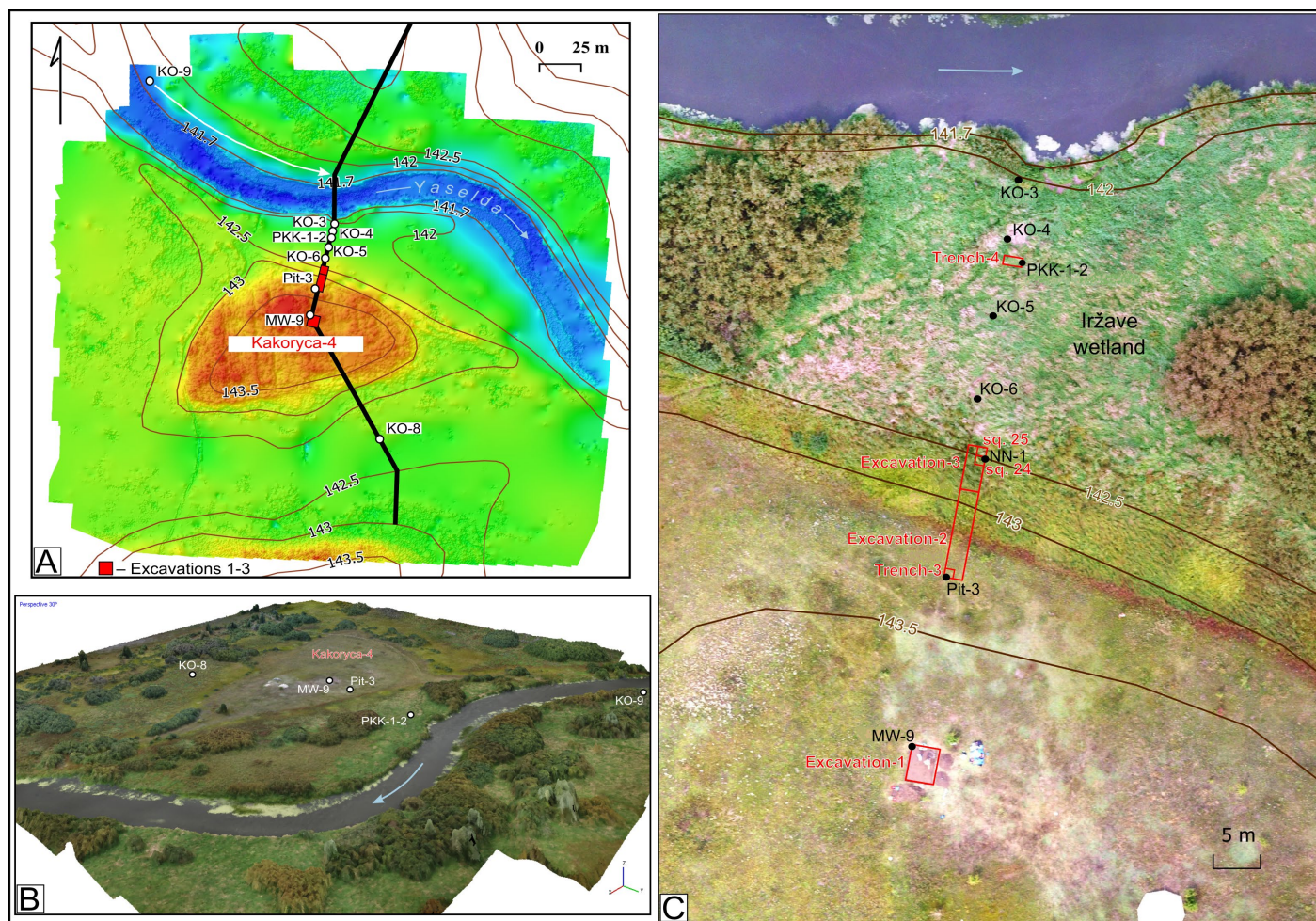


Fig. 2. Aerial photography materials obtained using a DJI Mavic Pro quadcopter during the expedition in August 2019 on the archaeological site Kakoryca-4; with cross-section line (A), reference boreholes, outcrops, trenches and excavations. A – 2d DEM; B – 3d digital terrain model (DTM); C – Orthophotomap (cf. Tsvirko et al., 2021b; Trifonov, 2021)

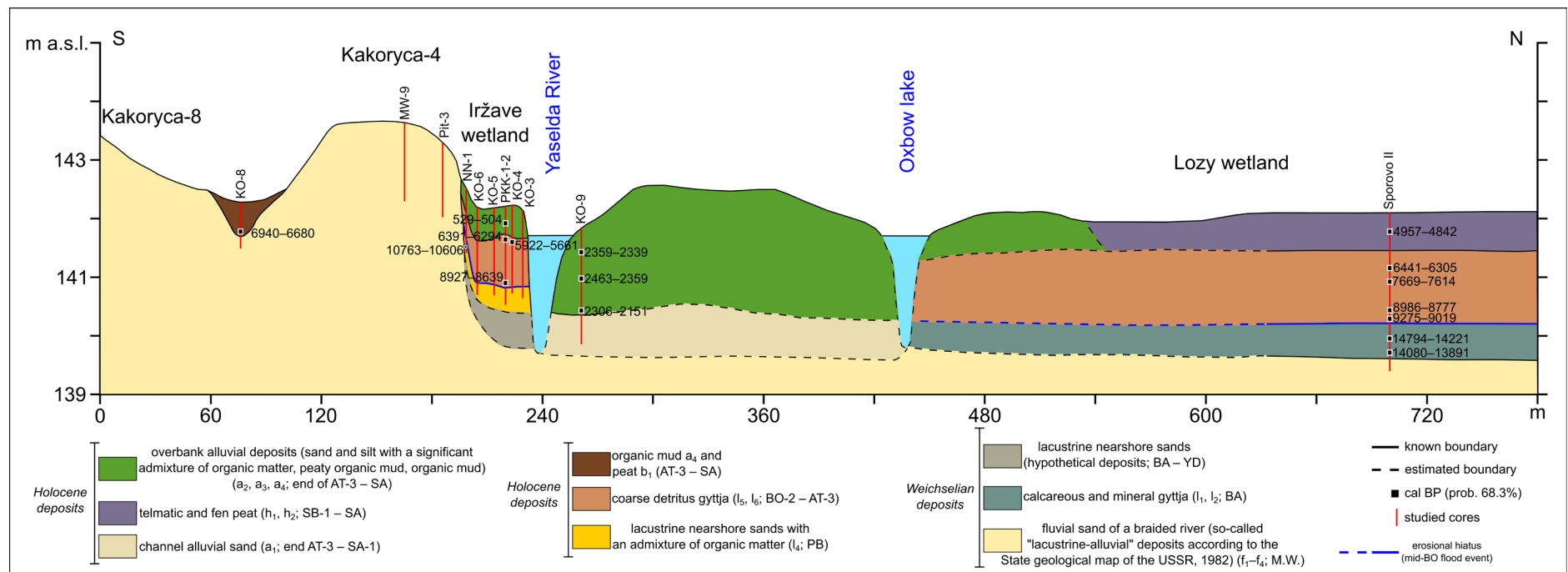


Fig. 3. Geological cross-section for the area near the Kakoryca-4 archaeological site (supplemented mainly based on Tsvirko et al., 2021b, and also Frączek and Kalicki, 2021)

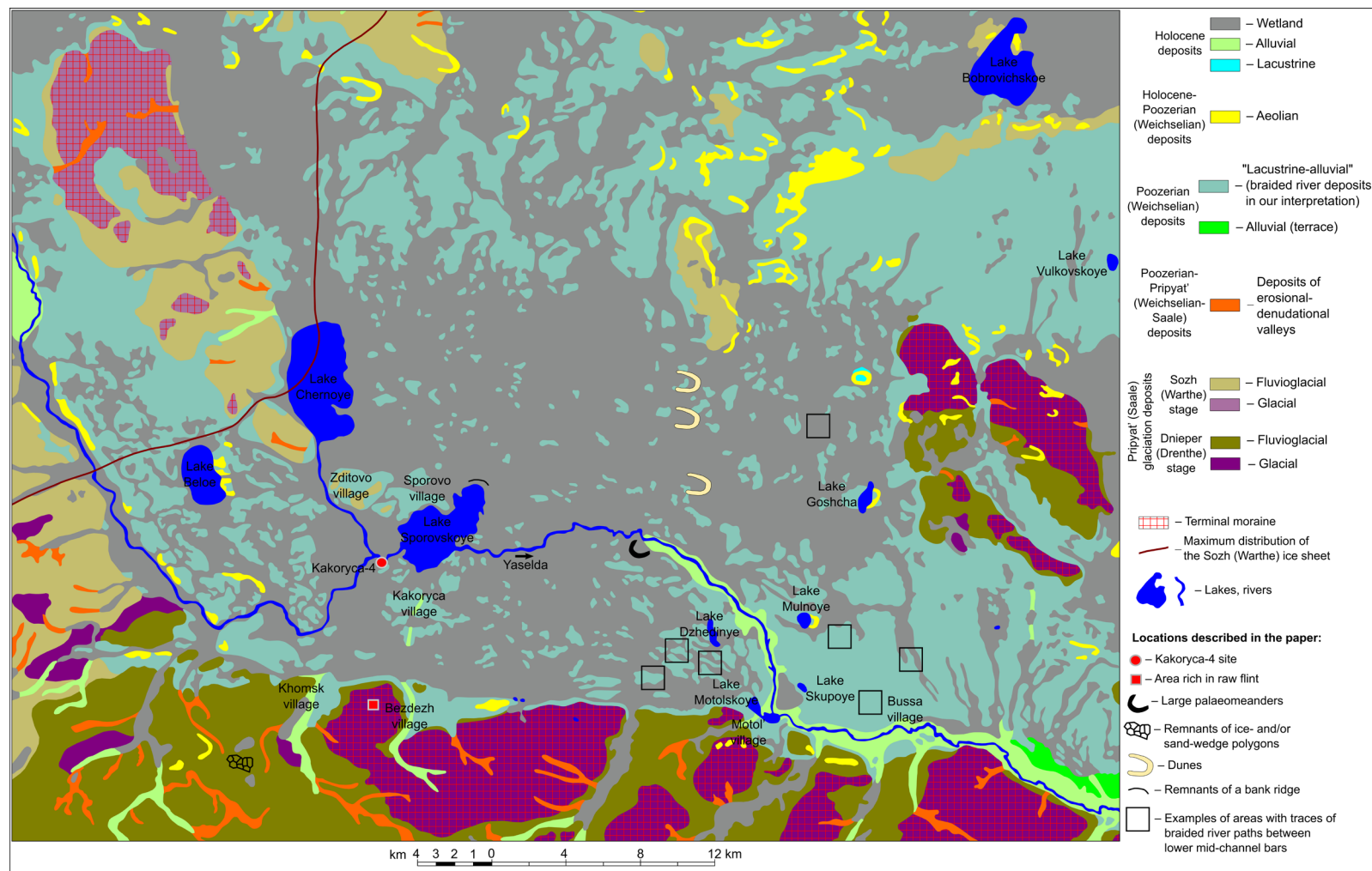


Fig. 4. Geological map of the study area (based on the Gosudarstvennaya geologicheskaya karta SSSR, 1982; modified by the authors)

2.3 Modern vegetation cover at the Kakoryca-4 site

Our field observations showed that at the Kakoryca-4 site, the composition of the modern vegetation depends on the microrelief of the Yaselda River valley, where four distinct groups of phytocenoses are clearly differentiated (Fig. 2C; Fig. S10A).

The surface of the sandy elevation is overgrown with dry meadow vegetation, occupying approximately 80–90% of its area. Among the low-growing (up to 10 cm) plants, *Pilosella officinarum* occurs, which in some places forms a continuous cover. It is accompanied by low-growing Poaceae, *Helichrysum arenarium*, sometimes moss. The higher tier is formed by *Hypericum perforatum*, *Artemisia vulgaris*, *Artemisia absinthium*, Poaceae. Additionally, there are 16 solitary *Prunus spinosa* shrubs growing here.

On the gentle slopes of the elevation, young shoots of *Betula* are noticed, on the eastern slope – *Betula* up to 10 m high. In some places, the slopes are marked with bushes of various *Salix* taxa. The grass cover of the slopes consists of a more diverse variety of herbs: *Achillea*, *Galium*, *Artemisia absinthium*, *Centaurea phrygia*, *Trifolium arvense*, *Hypericum perforatum*, *Potentilla anserina*, *Potentilla erecta*, *Ranunculus sceleratus*, *Rumex*, *Chenopodium*, Caryophyllaceae, Poaceae (e.g. *Poa*) and Juncaceae (e.g. *Juncus*). Apiaceae dominate in some parts of the slope. The presence of *Trifolium arvense* and *Poa* in the modern vegetation cover indicates agricultural activity on the Kakoryca-4 elevation in the recent past. The striped pattern of the elevation surface in the DEM (Fig. 2A – furrows from ploughing), oral testimonies of senior residents of Kakoryca village, as well as the agricultural land clearly visible in the older satellite image (Fig. S10B), also supports this. The ploughing of the surface of Kakoryca-4 elevation has resulted in the fragmentation and damage of artefacts and ecofacts (pottery, flint, bones) on the sandy hill, in comparison with the well-preserved artefacts and ecofacts found in the organic deposits of the adjacent wetland.

Vegetation of the wetland surrounding Kakoryca-4 is relatively monotonous, mainly Cyperaceae. Here *Carex* forms high tussocks-columns (about 40–50 cm high), which makes it difficult to move along the floodplain. Wetland phytocenosis is also represented by *Typha latifolia*, *Glyceria arundinacea* and *Urtica dioica* (Fig. S10A). In the surrounding wetlands we also found *Oenanthe aquatica*, *Symphytum officinale*, *Stachys palustris*, *Pedicularis palustris*, *Sonchus palustris*, *Rumex maritimus*, *Veronica longifolia*, *Persicaria hydropiper*, *Comarum palustre*, *Ranunculus sceleratus*, *Potentilla anserina*, *Potentilla erecta*, *Plantago major* and other species.

The banks of the Yaselda River near the water are bordered by *Salix* bushes and thickets of *Phragmites*. *Nuphar lutea*, *Stratiotes aloides*, *Alisma plantago-aquatica* and numerous of *Lemna minor* grow near the banks in the slow brown waters of the Yaselda River.

2.4 General archaeological characteristics of the Kakoryca-4 site

The archaeological site Kakoryca-4 was discovered in 2018 (Kryvaltsevich et al., 2023). During field archaeological expeditions in 2018–2021, the site was explored through four test pits (termed “trenches” in this paper) and three excavations (Fig. 2). In addition, archaeological surficial survey was carried out over the entire territory of the site. As of 2021, during the period of mentioned expeditions, more than 60,000 artefacts had been found at the site (Table S1). Further excavations in 2022 and 2023 brought the total number of artefacts to nearly 92,228. The artefact collection consists of pottery fragments, flint tools and raw materials, osteological remains, bone and horn products (tools, ornaments), as well as stones and stone tools. The discovered osteological materials include not only animal bone remains but also occasional pieces of human skulls and teeth. The ecofacts discovered in archaeological excavations include: nuts, acorns, cones, tree branch fragments, woody remains, shells, and more.

The archaeological investigations concentrated on fieldwork and the primary processing of materials, including the cultural and chronological classification of finds and their stratigraphic identification. The reconstruction of pottery forms, the typological study of pottery, flint, stone, and bone artefacts, archaeozoological, archaeobotanical, and anthropological analyses, the development of a radiocarbon-based chronology, and the use-wear analysis of bone and flint tools are still at an early stage.

Among the artefacts found at the site, a few have been attributed to the Final Palaeolithic Swiderian culture, making them the oldest discoveries there. A relatively small part of the artefacts is associated with the activities of Early and Late Mesolithic communities (Kudlaevka and Janisławice cultures). However, the vast majority of cultural remains at the site belongs to the Neolithic and Bronze Age populations (Kryvaltsevich et al., 2023). A small number of finds are classified as artefacts from the Iron Age, the Middle Ages, and the Modern and Contemporary eras.

Archaeological reconnaissance carried out in the vicinity of Kakoryca-4 site has shown that almost all relatively high “lacustrine-alluvial” elevations SW of Lake Sporovskoye contain cultural deposits. To date, about 30 new archaeological sites have

been discovered near the Kakoryca-4 site on these rounded sandy “lacustrine-alluvial” elevations (Fig. S11). Among all the sites, the archaeological layers of the Kakoryca-4 are distinguished by a high concentration of artefacts.

MATERIAL AND METHODS

3.1 Geological field works

During field expeditions in 2019–2021, a number of reference (primary in our study) and survey (providing additional information) cores and outcrop of biogenic and mineral deposits were collected and described. Following the field reconnaissance, we selected the locations of cores and outcrops using three main criteria: (i) preference was given to sites with the thickest organic deposits (Sporovo II, UZS-1-2, KO-20, A-1; Fig. 1C); (ii) locations suitable for easy excavation and coring were selected (KAK-5, SU-S, C-1, KO-9; Fig. 1C; Fig. S3); (iii) sampling sites were located along the geological cross-section line (KO-8, MW-9, Pit-3, NN-1, KO-6, KO-5, PKK-1-2, KO-4, KO-3; Figs. 2 and 3).

The most comprehensive analysis of deposits, utilizing a wide array of methods, was conducted for the reference cores PKK-1-2 and Sporovo II (Fig. 1C). Accordingly, these profiles were used as reference points for constructing the lithological characteristics of other, less studied cores and outcrops. The survey biogenic cores and outcrops consisted of KO-3, KO-4, KO-5, KO-6, KO-8, KO-9, KO-20, UZS-1-2, A-1 and NN-1 (Figs. 1C and 2). The profiles of mineral deposits were also collected for analyses and descriptions: KAK-5, SU-S, MW-9, Pit-3 and C-1 outcrops (Figs. 1C and 2; Fig. S3; Tsvirko et al., 2021ab, 2023 and 2024; Frączek and Kalicki, 2021; Tsvirko, 2022ab, 2023). The sampling strategy for laboratory analyses is presented in Table S2.

Some of the sediment samples were collected from the walls of outcrops. For example, geological profiles MW-9, Pit-3 and NN-1 were selected from the walls of Excavation-1, Trench-3, and Excavation-3, respectively (Fig. 2C). In many cases, an Instorf hand drill with a 50 cm long spoon was used to sample biogenic sediments (for example, Sporovo II core). Sometimes, due to groundwater, part of the samples was taken from the outcrop wall, and the remaining part was taken using an Instorf sampler (Table S2). In particular, part of the PKK-1-2 profile was selected from the wall of archaeological Trench-4 (Fig. 2C; Fig. S4). The remaining part of the PKK-1-2 profile was extracted using a hand drill from the bottom of Trench-4, yielding two cores: one for sedimentological (sed core, depth interval of 70–150 cm b.g.l.), the second for plant macrofossil (macro core,

depth interval of 60–165 cm b.g.l.) analyses, which were then correlated by radiocarbon dating (Fig. S12D; Figs. 6B and 7).

Our study particularly focused on examining the deposits between the Kakoryca-4 elevation and the present-day channel of the Yaselda River. This area represents a remnant of lake deposits, consisting of lacustrine sand and organic gyttja (KO-3, KO-4, PKK-1-2, KO-5, KO-6, and NN-1 profiles). Today, this remnant is gradually being eroded by the Yaselda River waters (Fig. 3). Throughout the entire remnant, the lithology of the sediments is similar, allowing us to correlate deposits from different profiles based on macroscopic description, loss on ignition (LOI) and textural analysis data.

3.2 Radiocarbon analysis

Radiocarbon dating of bulk organic matter, plant macrofossils and pollen concentrate samples was carried out in three laboratories using the liquid scintillation technique (LSC) and the accelerator mass spectrometry (AMS): “Laboratorium Datowań Bezwzględnych” in Krakow (Poland), “Poznańskie Laboratorium Radiowęglowe” in Poznan (Poland) and Beta Analytic testing laboratory in Miami (USA). Preparation of pollen concentrate samples for dating took place at the Institute of Geological Sciences PAS in Warsaw (Poland), where the samples were purified of glycerol with distilled water and then treated with KOH, HF and HCl.

The construction of the age-depth models and the calibration of radiocarbon dates were performed using the OxCal 4.4 online program (Bronk Ramsey, 2024), with the “IntCal 20” curve (Reimer et al., 2020). In the interpretation and discussion sections, the calibrated age (cal BP or cal AD/BC) is given with a 68.3% probability. In our paper, we use the chronology of the Weichselian glaciation and Holocene according to Dzieduszyńska et al. (2020), Zernitskaya et al. (2020), Zernitskaya (2022) and Naughton et al. (2023) (Table S8).

3.3 Pollen analysis

Pollen studies were conducted on the Sporovo II core, with continuous 5 cm sediment slices sampled. The pollen diagram and description of the analysis performed were published earlier by Tsvirko (2023). In the current publication, with the acquisition of new radiocarbon dates, the chronology of paleogeographic events is revised and the results of palynological studies are reinterpreted.

The percentages of arboreal pollen (AP) and nonarboreal pollen (NAP) were calculated based on the total sum $AP + NAP = 100\%$. Pollen grains of local aquatic and telmatic/wetland plants, as well as spores, were excluded from this total sum. The percentages of Cyperaceae (Cyp), aquatic vascular plants (AQVP), spore plants (F), and nonpollen palynomorphs (NPP) were calculated separately based on the sums $AP + NAP + Cyp$ (or $AQVP$ / or F / or NPP) = 100%. The taxa included in these calculation groups are indicated in colour in Figs. 10 and S20. The percentages of undeterminable (heavily damaged or deformed; Unable) and undetermined (was not identified; Uned) pollen and spores were calculated from the sums $AP + NAP + Cyp + AQVP + F + Unable$ (or $Uned$) = 100%.

3.4 Plant macrofossil analysis

The paper presents new results of plant macrofossils study for the PKK-1-2 core (eastern wall of Trench-4). For this analysis, 5-cm slices of deposits with an approximate volume of 3 litres were collected from a depth interval of 0–60 cm of the outcrop wall (Fig. S12D). The remaining 10-cm slices of deposits with an approximate volume of 100 ml were taken from the borehole at a depth interval of 60–165 cm (Fig. S12D – macro core). However, in some cases, the sampling step was changed to account for lithological boundaries (Fig. S12D). Selected samples from the PKK-1-2 were processed according to the known technique after Nikitin (1969). In constructing the PKK-1-2 plant macrofossil diagram, the taxa were divided into ecological groups based on their habitats. Within the ecological group, the position of a taxon was determined stratigraphically – from taxa mainly present in the lower part of the section to those occurring more frequently in the upper part of the profile (for a similar approach to constructing diagrams, see also Stachowicz-Rybka, 2011). Macrofossils in all diagrams are given in absolute values. The macrofossil diagram was constructed using the Tilia software (Grimm, 1992).

In this publication we have placed on some sedimentological diagrams the findings of individual plant macrofossils, discovered incidentally during sample preparation for other analyses (for example, Sporovo II, KO-9 diagrams, etc.). The data on plant macrofossils findings from Sporovo II core were published earlier by Tsvirko (2023).

3.5 Malacological analysis

Malacological studies were performed only for the sample 0–7 cm of the PKK-1-2 core. While processing samples for plant macrofossil analysis, we found at a depth of 0–

7 cm individual, well-preserved and undamaged mollusc shells, which were then analysed by A. Sanko (on keys to identification see Sanko, 2007).

3.6 Geochemical analysis

The study primarily involved loss on ignition (LOI) analysis of biogenic samples using a muffle furnace. For this analysis, wet samples were dried at 50°C (24 hours), and then carefully ground in a porcelain mortar. Before combustion, the biogenic samples were dried again at a temperature of 105°C (1 hour), and the empty crucibles at 550°C (1 hour). The ignition of the studied samples in a muffle furnace was carried out at 550°C for 8 hours, following the procedure after Dean (1974) and Heiri et al. (2001).

CaCO₃ content was determined using a Scheibler calcimeter after Korabiewski (2011).

3.7 Sedimentological analysis

In our study, we used laser analysis with the Malvern Panalytical Mastersizer 3000 to obtain grain size distribution data of mineral deposits. Before laser textural analysis, samples were sieved through a 2 mm sieve to ensure that only material less than 2 mm was used for the laser. This sieve grain size distribution data were then combined with the initial laser data. Before laser analysis, samples were thoroughly homogenized in a porcelain mortar and sonicated. The grain size distribution results, as well as sample statistics (mean M_z , standard deviation σ_1 , skewness Sk_1 and kurtosis K_G values after Folk and Ward (1957)) were obtained by statistical processing the initial laser data using Gradistat Version 9.1 software (Blott and Pye, 2001). The textural fractions were defined after Udden (1914) and Wentworth (1922).

Some samples were boiled in hydrogen peroxide H₂O₂ (Mikutta et al., 2005) to remove organic matter before laser textural analysis. Ignition in a muffle furnace was also used to remove organic matter from samples, especially highly organic ones. The ash obtained in this way was purified from secondary metal oxides and carbonates using the ash purification procedure (APP) after Tsvirko et al. (2024) and then analysed for its textural features.

For the mineral deposits of the KAK-5, SU-S, MW-9, and Pit-3 outcrops, we calculated the average velocities at which these sediments were accumulated using the Koster (1978) formula:

$$v = 49D^{0.381} \quad (1)$$

$$D = \frac{\varphi_{16} + \varphi_{50} + \varphi_{84}}{3} \quad (2)$$

where: v – deposition velocities after Koster (1978) [cm/s]; D – average grain size [cm]; φ_{16} – grain diameter, which together with smaller ones constitutes 10% of the sediment volume [cm]; φ_{50} – grain diameter, which together with smaller ones constitutes 50% of the sediment volume [cm]; φ_{84} – grain diameter, which together with smaller ones constitutes 84% of the sediment volume [cm]

According to Szymańska (2011), Koster's formula (1978) is the most reliable because the results are the most consistent with the grain immobilization velocities at the bottom determined by Sundborg's formula (1967).

Some sedimentological data presented in the article were published earlier by Tsvirko et al. (2021b) and Tsvirko (2023). In the current publication, we modify, supplement and reinterpret previously published results. On some sedimentological diagrams, the estimated age of the deposits is shown in red (e.g., AT, SA-1, SA-2, and so on).

3.8 Lithology

The identification of lithological units was based on: visual macroscopic description of the deposits, textural analysis results, geochemical (mostly LOI, CaCO_3) data, as well as plant macrofossil and pollen analyses data.

Plant macrofossil and pollen analyses played a key role in identifying lacustrine or wetland genesis of organic or mineral-organic deposits, as described by Tobolski (2021). In our study, we applied an approach whereby the constant presence and/or dominance of macrofossils and pollen grains of fully submerged and floating-leaved plants in deposits (e.g., *Chara*, *Potamogeton*, *Nuphar*, *Nymphaea*, *Stratiotes aloides*) indicates their lacustrine origin.

Telmatic peat (in the Sporovo II core) was distinguished by its high organic matter content and the predominance of telmatic and wetland vegetation pollen (Cyperaceae and *Sparganium*-type), accompanied by a minor admixture of aquatic plant pollen. Fen peat was identified by a high organic matter content and the dominance of Cyperaceae pollen (in the Sporovo II core).

The high mineral content of the sediments, combined with a significant admixture of macrofossils from telmatic, wetland, and aquatic plants, served as an indicator of floodplain backswamp environments characterized by the accumulation of organic mud. In our study, organic muds were classified according to their organic matter content: >30% organic matter – peaty organic mud; <30% organic matter – organic mud (in the PKK-1-2 and KO-9 cores).

The proposed classification of geological deposits in the vicinity of the Kakoryca-4 site is presented in Fig. 5. Identification of gyttja types was done according to Markowski (1980).

3.9 Archaeological characteristics of layers

In our study, we mainly rely on the archaeological data obtained from two squares of Excavation-3 (each 1 m²): squares 24 and 25 (Figs. 2C and 9). The focus on these squares is based on the fact that they provide a clear stratigraphic pattern of deposits, which can be correlated with other well-dated biogenic profiles north of the Excavation-3. We created a stratigraphic diagram showing the distribution of artefacts across geological layers in the squares 24 and 25. The archaeological methodology in these squares of Excavation-3 involved documenting finds according to arbitrary excavation layer depths: 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, 90–100 and 100–110 cm below ground level (b.g.l.). Square-by-square recording of archaeological finds for the 0–30 cm excavation layer was not conducted throughout Excavation-3, as this layer contained a large number of Cyperaceae roots and its high tussocks, which complicated field work. The 0–30 cm layer, collected from the entire Excavation-3, was sieved for artefacts, but without associating found artefacts with specific squares.

It is also important to note that the conclusions about the cultural history of the Kakoryca-4 site were based not only on data from Excavation-3, but also on the primary analysis of the entire volume of archaeological material collected during the excavations from 2018 to 2023. All cultures identified at the Kakoryca-4 site and their time frames are presented in Table S3

Braided river, or so-called "lacustrine-alluvial", deposits (f) 1 – fine and medium sands with coarse sand and sometimes gravel (thread deposits) 2 – mid-channel bar fine and medium sands 3 – mid-channel bar humic fine and medium sands 4 – overbank fine and medium sands with a slight admixture of organic matter Alluvial, Yaselda River, deposits (a) 1 – channel fine and medium sands 2 – overbank fine and medium sands and silt with a significant admixture of organic matter 3 – backswamp peaty organic mud 4 – backswamp organic mud – undifferentiated a_3 & a_4 Lacustrine deposits (l) 1 – sandy and silty calcareous gyttja 2 – sandy and silty non-calcareous mineral gyttja 3 – medium detritus gyttja 4 – lacustrine nearshore fine and medium sands and silt, often with a significant admixture of organic matter 5 – coarse detritus gyttja 6 – coarse detritus gyttja with a significant admixture of silt and sand Wetland deposits (h) 1 – telmatic peat 2 – fen peat Biogenic deposits (b) 1 – detritus gyttja and/or peat	Textural fractions after Udden (1914) and Wentworth (1922) - Very fine gravel - Very coarse sand - Coarse sand - Medium sand - Fine sand - Very fine sand - Very coarse silt - Coarse silt - Medium silt - Fine silt - Very fine silt - Clay	Folk and Ward (1957) parameters M_z – mean diameter σ_1 – standard deviation Sk_1 – skewness K_G – kurtosis Other parameters – organic matter content, LOI_{550} [%] – $CaCO_3$ content [%] – Deposition velocities after Koster (1978) [cm/s]
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Fig. 5. Proposed classification of the geological deposits studied around the Kakoryca-4 site

3.10 Cartographic data

Our study employed various types of cartographic data, such as satellite images, images obtained from a UAV, digital elevation models, and a 3d digital terrain model, all of which were previously published and described in detail (cf. Trifonov et al., 2019; Tsvirko et al., 2021b; Trifonov, 2021). This study also incorporates a set of Google Earth satellite images.

RESULTS

4.1 Area with organic deposits

4.1.1 PKK-1-2 core (in Trench-4)

Macroscopic description, geochemistry, sedimentology and ^{14}C chronology of the PKK-1-2 core

From the geochemical and sedimentological point of view, the studied PKK-1-2 core can be divided into four main units: the lower unit (l_4), middle unit (l_5), and the upper units (a_4 and a_3) (Fig. 6B, see symbols in Fig. 5). Based on this division, we correlated the PKK-1-2 core with other nearby profiles of geological deposits (Figs. 6AC, 9 and 10; Fig. S16). The age-depth model for the PKK-1-2 core are shown in Fig. S13.

The bottommost unit of the PKK-1-2 core is grey lacustrine fine and medium sands and silt with a mean grain size M_z of 2.13–2.31 phi, and an organic matter content of 4–6% (unit l_4 , depth from 165 to 133 cm b.g.l. in Fig. 7, and from 150 to 142 cm b.g.l. in Fig. 6B). The occurrence of *Stratiotes aloides* seeds in this layer l_4 (Fig. 7) points to warm climatic conditions in the summer (Gałka, 2010), and therefore allowed us to attribute the organic-rich sands of layer l_4 to the warm Holocene period. Lithological correlation of the PKK-1-2 core with the radiocarbon-dated NN-1 outcrop made it possible to determine the age of layer l_4 as Middle Preboreal (mid-PB; 10,763–10,606 cal BP; Fig. 9AB; Fig. S16).

Above, at a depth between 142 (133) and 45 cm b.g.l., brown highly organic coarse detritus gyttja l_5 was identified, reaching more than 80% for the amount of organic matter (Fig. 6B; Table S4). The accumulation of gyttja l_5 began in the Early Atlantic: 8,927–8,639 cal BP (6,978–6,690 cal BC) and 8,640–8,406 cal BP (6,691–6,457 cal BC) (Table 1; Figs. 6B and 7). The deposition of gyttja ended in the Late Atlantic: 6,391–6,294 cal BP (4,442–4,345 cal BC) and 6,276–6,015 cal BP (4,327–4,066 cal BC) (Figs. 6B and 7).

At a depth of 45 to 28 cm b.g.l. is a layer of black organic mud a_4 (Fig. 6B). This organic mud layer is characterized by a low content of organic matter (LOI often below 30%) and a significant admixture of sand (M_z reaching 5.03 phi). Most likely, this

layer of sediments accumulated in backswamp conditions. A high content of mineral matter in the deposits serves as the primary indicator of backswamp conditions. It is possible to establish only an approximate age for unit a₄. This age was estimated using the artefacts it contained (AT-3–SB-2; Fig. 9B; Table S3), radiocarbon dates from the underlying l₅ unit (6,391–6,294 and 6,276–6,015 cal BP; end of AT-3; Fig. 6B), a radiocarbon date from the upper part of layer l₅ in the KO-4 core (5,922–5,661 cal BP; end of AT-3; Fig. S16), and correlation with the Sporovo II core, which, similar to PKK-1-2, records the regression of Lake Sporovskoye (1st half of SB-1; LPAZ SPII-4a and SPII-4b; Fig. 10). Thus, we assume that layer a₄ most likely accumulated during the end of AT-3–SB-2, approximately between 5,900 and 3,700 cal BP (Fig. 6B).

Above in the core is backswamp brown peaty organic mud a₃ (depth from 28 to 0 cm b.g.l.; Fig. 6B). This sediment layer is characterized by a higher organic matter content (LOI >30%) and a substantial admixture of silt (M_z reaching 6.26 phi). The accumulation of these deposits a₃ took place during the 2nd half of the Late Subatlantic, as indicated by radiocarbon dates of 529–504 cal BP (1,421–1,446 cal AD) and also 456–319 cal BP (1,494–1,631 cal AD) (Figs. 6B, 7 and 8E–G). A radiocarbon age of 456–319 cal BP, obtained from *Oenanthe aquatica* and *Carex* sp. div. macrofossils (Table 1), most likely reflects partial sediment mixing between units a₃ and a₄, as these taxa are more abundant in unit a₃ and at the a₃/a₄ boundary than in unit a₄ (Fig. 7). This mixing is also indicated by the diffuse and indistinct boundary between units a₄ and a₃ (Fig. 6B).

The radiocarbon date of 3,826–3,583 cal BP (1,877–1,634 cal BC) was obtained from a bulk sample collected near an indistinct and diffuse boundary between units a₄ and a₃ (Table 1; Figs. 6B and 7). Although this date is in good agreement with other data, it was not taken into account, for reasons of stratigraphic uncertainty, when determining the ages of the geological units.

Plant macrofossils of the PKK-1-2 core

Six local plant macrofossil assemblage zones (LMAZ) were identified in the PKK-1-2 core based on visual evaluation and cluster analysis (CONISS) of the obtained data (Fig. 7; Table S5).

Plant macrofossils extracted from the core PKK-1-2 mainly consist of taxa that still inhabit the surrounding wetlands, Lake Sporovskoye, the Yaselda River channel and its banks. The exception was some telmatic and aquatic species – *Elatine hydropiper*, *Caulinia minor* and *Salvinia natans* (Fig. S14), which do not occur in the modern flora of the Yaselda

River basin according to Parfenov (1999). It is also worth noting that in the PKK-1-2, we found a large number of *Stratiotes aloides* seeds, which may indicate very warm climatic conditions in the summer, when the seeds were formed (Gałka, 2010).

LMAZ KK-1 (165–133 cm b.g.l.; unit l₄ from the borehole). The zone is dated to the Middle Preboreal. A large number of macrofossils of fully submerged (*Chara*, *Potamogeton pectinatus*) and floating-leaved (*Stratiotes aloides* (including seeds), *Nuphar lutea*, *Nymphaea alba*) plants (Fig. 7). The dominance of macrofossils of these aquatic plants allowed us to classify the organic-rich sands of layer l₄ as lacustrine. The lacustrine genesis of the sand with organic matter layer l₄ is also evidenced by the fish remains, Ostracoda and mollusc shells found within this unit (Table S4).

The telmatic and wetland vegetation is represented by the remains of Cyperaceae, *Cyperus fuscus*, *Schoenoplectus lacustris*, *Typha latifolia*, *Alisma plantago-aquatica*, and *Oenanthe aquatica*. The fresh-to-moist habitats are indicated by *Eupatorium cannabinum* and *Cirsium palustre* macrofossils. Among the ruderal species, *Chenopodium glaucum* and *Urtica* were discovered. A macrofossil of *Alnus glutinosa* was found.

LMAZ KK-2 (133–70 cm; unit l₅ from the borehole). The zone is dated to the Early and Middle Atlantic. A very large number of macrofossils of aquatic vegetation was found, including *Sparganium minimum*, *Sparganium emersum*, *Hippuris vulgaris*, *Stratiotes aloides*, *Nuphar lutea*, *Nymphaea alba*, *Lemna trisulca*, *Lemna minor*, *Salvinia natans*, *Potamogeton trichoides*, *Potamogeton pusillus*, *Potamogeton* sp. div., *Ceratophyllum submersum*, *Caulinia minor*, *Najas marina*, and *Chara*. This allow us to classify the sediments of the KK-2 zone as gyttja. The presence of fish remains, Ostracoda and mollusc shells in the deposits of layer l₅ also indicates the lacustrine genesis of this unit (Table S4).

The telmatic and wetland areas are indicated by macrofossils of *Schoenoplectus lacustris*, *Cyperus fuscus*, *Carex*, *Typha angustifolia*, *Eleocharis palustris* and others. The wet habitats are represented by *Mentha longifolia*. The ruderal taxa included *Chenopodium glaucum*, *Urtica* cf. *dioica*, and *Persicaria lapathifolia*. Tree vegetation is represented by macrofossils of *Betula alba* and *Betula* sp.

LMAZ KK-3 (70–45 cm; unit l₅ from the borehole and trench wall). The zone is dated to the Late Atlantic. A clear decrease in the number of *Stratiotes aloides* (seeds were found) and *Nuphar lutea* macrofossils, as well as the disappearance of *Chara*, *Caulinia minor*, *Najas marina*, *Ceratophyllum submersum* and *Potamogeton* macrofossils. Increase in the number of *Salvinia natans*, *Lemna minor*, and *Nymphaea alba* (Fig. 7). The expansion of telmatic and wetland vegetation, mainly *Schoenoplectus lacustris* and *Typha angustifolia*.

The presence of a large number of *Typha latifolia* and *Alisma plantago-aquatica* macrofossils in LMAZ KK-3 is apparently related to their redeposition into KK-3 from KK-4, as indicated by the high abundance of these taxa in LMAZ KK-4 (Fig. 7; Table S5).

It should be noted that the samples from LMAZ KK-3 contained a significant number of *Salvinia natans* and *Typha latifolia* macrofossils. The total macrofossil count was 56–1,208 per sample, but without *Salvinia natans* and *Typha latifolia* – 36–157 per sample (Fig. 7).

LMAZ KK-4 (45–28 cm; unit a₄ from the trench wall). The zone is most likely dated to the end of AT-3–SB-2. Macrofossils of telmatic and wetland vegetation dominated, including *Alisma plantago-aquatica*, *Sagittaria sagittifolia*, *Typha angustifolia*, and *Typha latifolia*. An admixture of aquatic plant remains was also found. In particular, numerous remains of the small floating-leaved plant *Salvinia natans* were identified, along with a few seeds of *Stratiotes aloides*. This mixture of aquatic and telmatic/wetland plant remains indicates limno-terrestrial conditions that existed in the backswamp.

The occurrence of a considerable number of ruderal plant seeds *Atriplex* and *Chenopodium album* in LMAZ KK-4 is apparently associated with their redeposition from KK-5 into KK-4 during the formation of LMAZ KK-5 (Fig. 7). The large number of *Juncus* and *Carex* remains in KK-4 is also probably associated with redeposition during the formation of the KK-5 LMAZ (Fig. 7).

The total number of macrofossils in LMAZ KK-4 ranged from 1,323 to 7,515 per sample; however, excluding *Salvinia natans* and *Typha latifolia*, it amounted to 783–1,038 per sample (Fig. 7; Table S5).

LMAZ KK-5 (28–7 cm; unit a₃ from the trench wall). The zone is dated to the 2nd half of the SA-3. A large number of telmatic and wetland plant remains were found, including *Oenanthe aquatica*, *Eleocharis palustris*, *Sparganium erectum*, *Lycopus europaeus*, *Stachys palustris*, *Alisma plantago-aquatica*, *Sagittaria sagittifolia*, *Schoenoplectus lacustris*, *Carex*, *Cyperus fuscus*, and *Menyanthes trifoliata*.

The vegetation of wet and fresh-to-moist habitats reached its highest diversity and was represented by macrofossils of *Juncus*, *Viola*, *Mentha longifolia*, *Potentilla anserina*, *Glyceria fluitans*, and others (Fig. 7; Table S5).

At the same time, a high content of aquatic plant macrofossils was noted, including *Salvinia natans*, *Stratiotes aloides* (spines), *Lemna minor*, *Lemna trisulca*, *Potamogeton*, *Chara*, *Nitella*, *Batrachium*, and *Myriophyllum* cf. *verticillatum*. This mixture of telmatic/wetland and aquatic plant remains indicates limno-terrestrial conditions in the

backswamp. The influence of a lacustrine environment is also suggested by the presence of Ostracoda shells within LMAZ KK-5 (Table S4).

A large number of human indicators were noted, including remains of *Panicum miliaceum*, *Rumex acetosella*, *Scleranthus annuus*, *Atriplex*, *Chenopodium album*, high values of Poaceae and others (Fig. 7).

LMAZ KK-6 (7–0 cm; unit a₃ from the trench wall). The zone is dated to the final part of the SA-3. The KK-6 LMAZ included only one sample. It should be noted that for the two uppermost samples (depth 13–0 cm b.g.l.), some macroremains were lost during laboratory processing, as well as due to seed germination during about 10-day transportation and storage. Therefore, the data from the 7–0 cm surface sample represent only a partial record of landscape changes.

Compared with LMAZ KK-5, the abundance of aquatic plant macrofossils was markedly reduced. Only a small admixture of aquatic plant remains was noted, including *Lemna minor*, *Salvinia natans*, and *Batrachium*, indicating limno-terrestrial conditions in the backswamp.

The amount of telmatic and wetland plant remains was also notably reduced, and was represented only by small amounts of *Oenanthe aquatica*, *Typha latifolia*, *Sparganium erectum*, and other taxa. The number of *Carex* fruits slightly increased.

Among the macrofossils of wet habitats, remains of *Bidens tripartita*, *Iris pseudacorus*, and *Mentha longifolia* were identified. The main distinctive feature of LMAZ KK-6 was the dominance of Poaceae remains, which can serve as an indicator of human activity (Fig. 7; Table S5).

Malacology of the PKK-1-2 core

Mollusc shells found in the PKK-1-2 core (sample 7–0 cm b.g.l.) were represented by species of two ecological groups (Table 2).

Ecological group 10 comprises species found in small, intermittent, and heavily overgrown water bodies (Alexandrowicz, 1987): *Segmentina nitida* and *Planorbis planorbis*. *Segmentina nitida* is adapted to remaining out of water for extended periods (Fig. S15CD). This species is tolerant of a wide range of pH changes – from 4.9 to 7.3. *Segmentina nitida* inhabits small water bodies with fluctuating water levels, including various types of meadow and wetland water bodies. Less frequently, this species is found among thickets of aquatic plants in shallow lake waters or in overgrown river oxbows and meanders.

Ecological group 11 comprises aquatic species typical of permanent water bodies, primarily lakes (Alexandrowicz, 1987): *Anisus vortex* and *Bathyomphalus contortus*. In the sample, shells of the adult *Anisus vortex* species are more commonly found (Fig. S15AB). Due to the fact that the resistance of this species to desiccation is low (lower than that of any other species in the genus *Anisus*), it prefers permanent water bodies. In most cases, temporary water bodies are colonized by *Anisus vortex* accidentally. This species inhabits various water bodies, including lakes, rivers, and others, with a pH range of 6.6 to 8.55. Inhabiting small, vegetation-rich stagnant water bodies, it attaches to macrophytes, but more often freely floats on the water surface. *Anisus vortex* is more closely associated with aquatic vegetation than with bottom sediments.

Archaeology and archaeological chronology of the PKK-1-2 core

A single artefact and one ecofact were found in the PKK-1-2 core. A fragment of the Early Neolithic Pripyat-Neman culture pottery of the Dubičiai-type was discovered at a depth of 50 cm in the coarse detritus gyttja I₅ (Fig. 8AB). An absolute chronology has been estimated for this pottery fragment through radiocarbon dating of the gyttja I₅ deposits in the direct contact with the pottery (6,391–6,294 cal BP or 4,442–4,345 cal BC). According to the LOI data, the gyttja I₅ surrounding this pottery fragment contained about 80% organic matter. Therefore, the upper part of the gyttja layer I₅ (at a depth of about 50 cm) accumulated during the Early Neolithic (Fig. 6B; Fig. S12D).

Direct evidence of agricultural activity at the Kakoryca-4 site dates to the Late Middle Ages. Specifically, a charred seed of *Panicum miliaceum*, dated to 529–504 cal BP (1,421–1,446 cal AD), was found in a sample from a depth of 28–23 cm b.g.l. (Figs. 7, 8E–G).

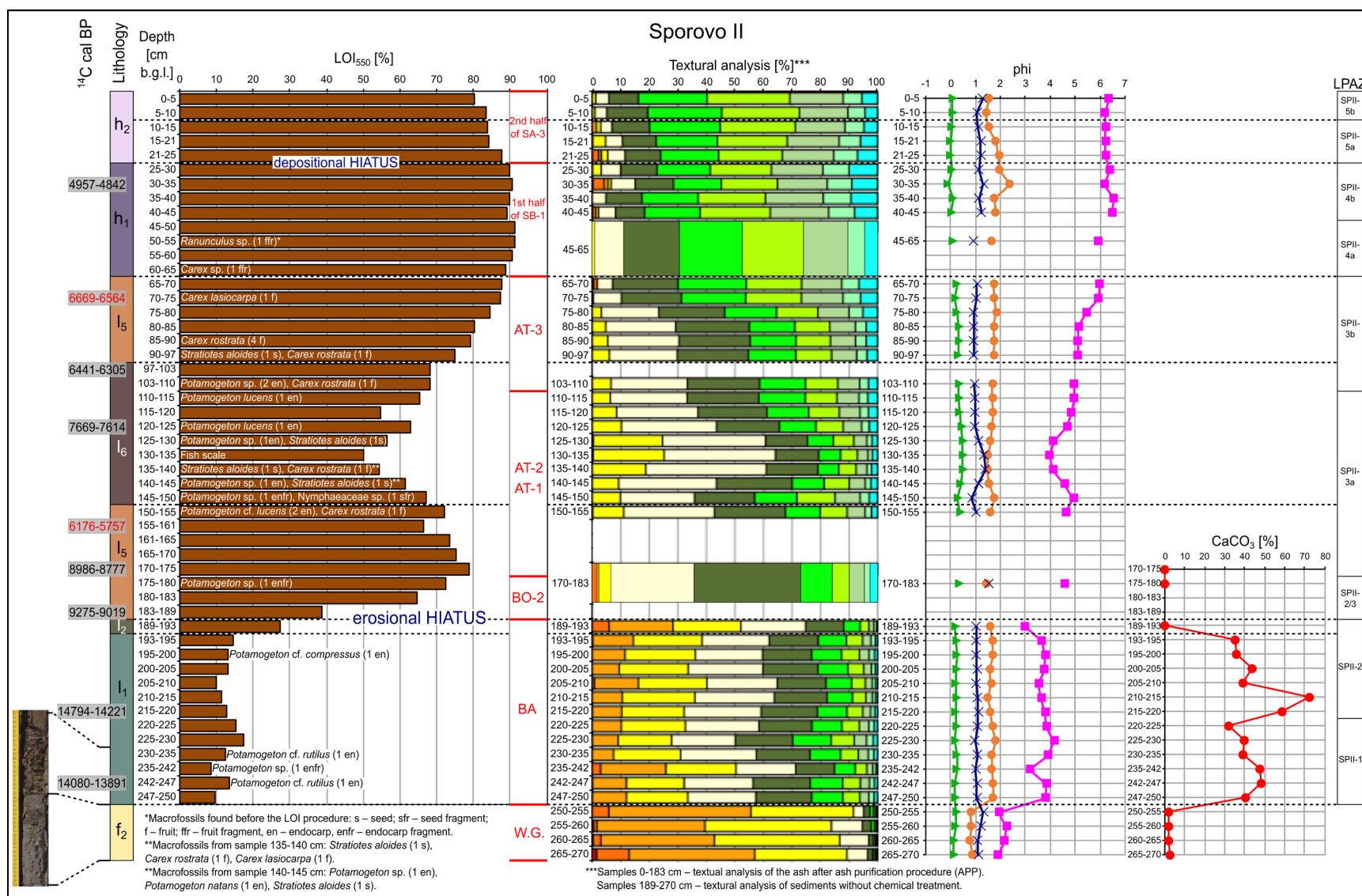


Fig. 6A. Sedimentological diagram of the Sporovo II core with identified lithological units

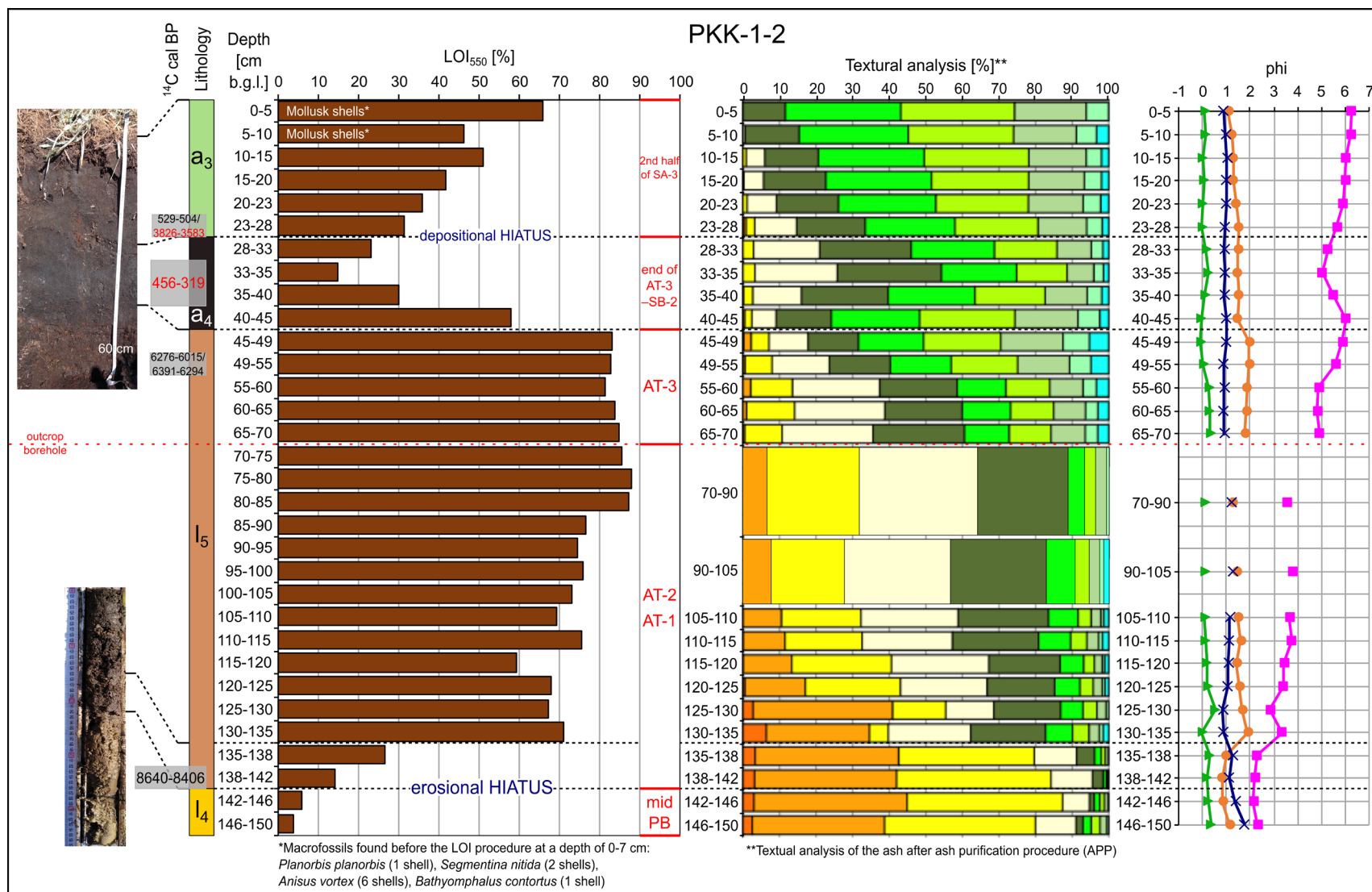
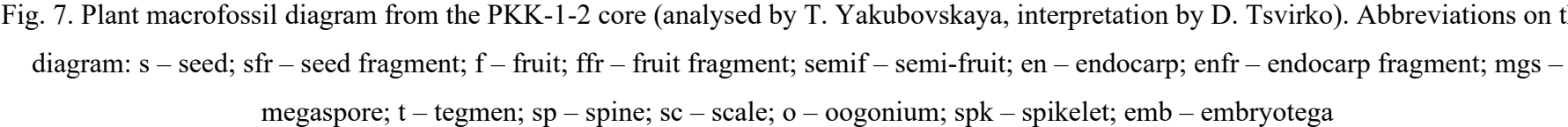


Fig. 6B. Sedimentological diagram of the PKK-1-2 core with identified lithological units



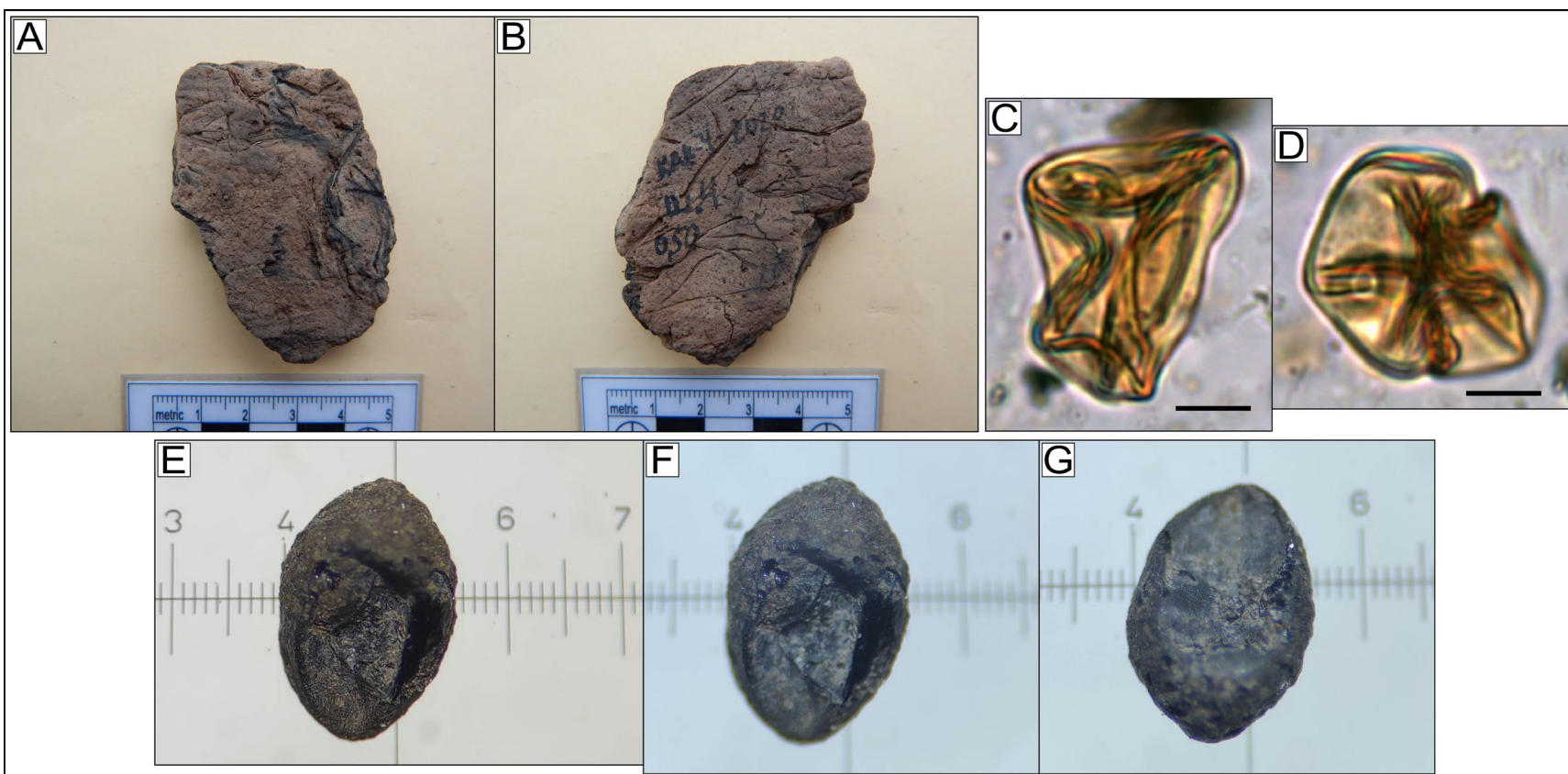


Fig. 8. Artefacts and ecofacts from the Kakoryca-4 site dated using AMS technique. A and B – outer (A) and inner (B) surfaces of the Early Neolithic Pripyat-Neman culture pottery fragment of the Dubičiai-type from a depth of 50 cm of the PKK-1-2 core, age of the surrounding coarse detritus gyttja 6,391–6,294 cal BP (4,442–4,345 cal BC) (photos by M. Kryvaltsevich); C and D – cf. *Cerealia* pollen grain from a depth of 30–35 cm of the Sporovo II core, age of the pollen concentrate sample 4,957–4,842 cal BP (3,008–2,893 cal BC) (scale bars = 10 μ m, photos by D. Tsvirko); E–G – charred *Panicum miliaceum* seed in different positions from a depth of 23–28 cm of the PKK-1-2 core, seed age 529–504 cal BP (1,421–1,446 cal AD) (photos by M. Majorek-Lipowicz)

Table 1. Radiocarbon dating of pollen concentrate, plant macrofossils and bulk organic matter samples from the geological profiles in the vicinity of the Kakoryca-4 site. The dates used in constructing the age-depth models are shown in **bold**

No.	Depth [cm b.g.l.]	Age conv BP	Laboratory No.	Age cal BP prob. 68.3%	Age cal AD/BC prob. 68.3%	Dated material	Notes and references
PKK-1-2							
1.	23–28	480±30	Poz- 155567	529–504	1,421–1,446 cal AD	<i>Panicum miliaceum</i> (1 charred seed)	AMS technique. Outcrop wall. Beginning of the peaty organic mud a ₃ accumulation. Used to build the age-depth model
2.	23–28	3440±70	MKL-5417	3,826–3,583	1,877–1,634 cal BC	bulk of peaty organic mud	LSC technique. Outcrop wall. The date is considered unreliable, as it likely represents the age of mixed deposits from layers a ₄ and a ₃
3.	33–40	340±30	Beta- 678648	456–319	1,494–1,631 cal AD	<i>Oenanthe aquatica</i> (6 semi-fruits), <i>Carex</i> sp. div. (2 fruits)	AMS technique. Outcrop wall. The dated macrofossils were redeposited from layer a ₃ into layer a ₄
4.	49–55	5370±60	MKL-5416	6,276–6,015	4,327–4,066 cal BC	bulk of coarse detritus gyttja	LSC technique. Outcrop wall. End of coarse detritus gyttja accumulation
5.	50	5538±26	MKL- A5436	6,391–6,294	4,442–4,345 cal BC		AMS technique. Outcrop wall. End of coarse detritus gyttja accumulation. Gytja sample directly covering a fragment of Early Neolithic Pripyat-Neman (Dubičiai-type) pottery. Used to build the age-depth model
6.	126–133	7920±30	Beta- 683372	8,927–8,639	6,978–6,690 cal BC	<i>Schoenoplectus lacustris</i> (3 fruits)	AMS technique. Borehole for plant macrofossils analysis. Onset of coarse detritus gyttja accumulation. Used to build the age-depth model
7.	138–142	7750±110	MKL-5418	8,640–8,406	6,691–6,457 cal BC	bulk of coarse detritus gyttja	LSC technique. Borehole for sedimentological analysis. Onset of coarse detritus gyttja accumulation

Table 1 (continued)

No.	Depth [cm b.g.l.]	Age conv BP	Laboratory No.	Age cal BP prob. 68.3%	Age cal AD/BC prob. 68.3%	Dated material	Notes and references
Sporovo II							
8.	30–35	4320±30	Beta-688946	4,957–4,842	3,008–2,893 cal BC	pollen concentrate sample from telmatic peat	AMS technique. After treatment with distilled water, KOH, HF and HCl. Sample with cf. Cerealia pollen grain. Used to build the age-depth model
9.	70–75	5820±30	Beta-688008	6,669–6,564	4,720–4,615 cal BC	pollen concentrate sample from coarse detritus gyttja	AMS technique. After treatment with distilled water, KOH, HF and HCl. The date is considered to be anomalously old
10.	97–103	5600±70	MKL-4786	6,441–6,305	4,492–4,356 cal BC	bulk of coarse detritus gyttja with a significant admixture of silt and sand	LSC technique. See Tsvirko et al., 2021b. Used to build the age-depth model
11.	120–125	6800±30	Beta-680215	7,669–7,614	5,720–5,665 cal BC	pollen concentrate sample from coarse detritus gyttja with a significant admixture of silt and sand	AMS technique. After treatment with distilled water, KOH, HF and HCl. Phase of silt and sand influx. Used to build the age-depth model
12.	155–161	5190±110	MKL-4785	6,176–5,757	4,227–3,808 cal BC	bulk of coarse detritus gyttja	LSC technique. Most likely contaminated by younger sediments. See Tsvirko et al., 2021b
13.	170–175	7980±30	Beta-688947	8,986–8,777	7,037–6,828 cal BC	pollen concentrate sample from coarse detritus gyttja	AMS technique. After treatment with distilled water, KOH, HF and HCl. Used to build the age-depth model
14.	183–189	8190±90	MKL-4784	9,275–9,019	7,326–7,070 cal BC	bulk of coarse detritus gyttja	LSC technique. Onset of coarse detritus gyttja accumulation. Used to build the age-depth model. See Tsvirko et al., 2021b
15.	215–220	12360±40	Beta-688948	14,794–14,221	12,845–12,272 cal BC	pollen concentrate sample from sandy and silty calcareous gyttja	AMS technique. After treatment with distilled water, KOH, HF and HCl. The emergence of the lake. Used to build the age-depth model
16.	242–247	12130±30	Beta-678650	14,080–13,891	12,131–11,942 cal BC		AMS technique. After treatment with distilled water, KOH, HF and HCl. The emergence of the lake. Used to build the age-depth model (but with poor agreement; A = 5.7%)

Table 1 (continued)

No.	Depth [cm b.g.l.]	Age conv BP	Laboratory No.	Age cal BP prob. 68.3%	Age cal AD/BC prob. 68.3%	Dated material	Notes and references
KO-4							
17.	58–63	5070±110	MKL-5181	5,922–5,661	3,973–3,712 cal BC	bulk of coarse detritus gyttja	LSC technique. End of coarse detritus gyttja accumulation. See Frączek and Kalicki, 2021
18.	132–137	6280±120	MKL-5182	7,320–7,010	5,371–5,061 cal BC		LSC technique. Most likely contaminated by younger sediments. See Frączek and Kalicki, 2021
KO-8							
19.	53–58	5980±90	MKL-5183	6,940–6,680	4,991–4,731 cal BC	bulk of organic deposits	LSC technique. Onset of biogenic deposits accumulation. See Frączek and Kalicki, 2021
KO-9							
20.	36–42	2344±25	MKL-A6304	2,359–2,339	410–390 cal BC	bulk of organic deposits	AMS technique. Phase of increased activity of the Yaselda River
21.	84.5–89	2409±21	MKL-A6305	2,463–2,359	514–410 cal BC		
22.	144–149	2205±21	MKL-A6306	2,306–2,151	357–202 cal BC		
KO-20							
23.	11–16	50±70	MKL-6269	256–34	1,694–1,917 cal AD	bulk of organic deposits	LSC technique
24.	75–81	6900±70	MKL-6270	7,830–7,669	5,881–5,720 cal BC		LSC technique. Onset of biogenic deposits accumulation
25.	140–144	8780±110	MKL-6271	10,115–9,558	8,166–7,609 cal BC		

Table 1 (continued)

No.	Depth [cm b.g.l.]	Age conv BP	Laboratory No.	Age cal BP prob. 68.3%	Age cal AD/BC prob. 68.3%	Dated material	Notes and references
UZS-1-2							
26.	45–47	2749±24	MKL- A7138	2,863–2,784	914–835 cal BC	<i>Phragmites australis</i> (about 20 stem fragments)	AMS technique. End of coarse detritus gyttja accumulation
27.	102–104	10507±47	MKL- A7137	12,616–12,479	10,667–10,530 cal BC	<i>Betula nana</i> (1 fruit scale and 3 fruits), <i>Betula</i> sect. <i>Albae</i> (1 fruit scale and 4 fruits)	AMS technique. Onset of medium detritus gyttja accumulation
A-1							
28.	47–50	5422±25	MKL- A7139	6,281–6,205	4,332–4,256 cal BC	<i>Carex panicea</i> (1 fruit), Pinaceae (5 bud scales), <i>Typha</i> sp. (1 tegmen)	AMS technique. Onset of biogenic deposits accumulation
29.	63–67	7839±41	MKL- A7141	8,688–8,548	6,739–6,599 cal BC	<i>Phragmites australis</i> (1 stem fragment), <i>Typha</i> sp. (1 tegmen), Charcoal (1 piece)	AMS technique. Onset of nearshore and lacustrine silt and sand accumulation
NN-1							
30.	87–93	9475±30	MKL- A7140	10,763–10,606	8,814–8,657 cal BC	<i>Schoenoplectus lacustris</i> (10 fruits), <i>Carex panicea</i> (1 fruit)	AMS technique. Nearshore sand accumulation

Table 2. Mollusc shells from the sample 7–0 cm of the PKK-1-2 core (analysed by A. Sanko)

Ecological groups according to Alexandrowicz, 1987	Taxa	Number of finds
10	<i>Planorbis planorbis</i> (Linnaeus)	1
10	<i>Segmentina nitida</i> (Müller)	2
11	<i>Anisus vortex</i> (Linnaeus)	6
11	<i>Bathyomphalus contortus</i> (Linnaeus)	1

4.1.2 KO-3, KO-4, KO-5, and KO-6 cores

Macroscopic description, geochemistry, sedimentology and ¹⁴C chronology of the KO-3, KO-4, KO-5, and KO-6 cores

The geological cores KO-3, KO-4, KO-5, and KO-6 share the identical lithological composition as the PKK-1-2 core and NN-1 outcrop, which provided the basis for their correlation (Fig. S16). In the cores KO-3, KO-4, KO-5, and KO-6, three main geochemical and sedimentological units were distinguished through analyses and field macroscopic description.

The lower unit is primarily composed of nearshore and lacustrine medium and fine sands l_4 with a mean grain size M_z of 1.66–2.25 phi and an organic matter content of about 1–8% (cores KO-3 and KO-4; age Middle Preboreal). The middle unit consists of highly organic coarse detritus gyttja l_5 , with organic matter content often exceeding 80% (Fig. S16). The LOI values higher than 10% served as the basis for marking the boundary between the sand layer l_4 and the gyttja layer l_5 (cores KO-3, KO-4, as well as PKK-1-2; Fig. S16). The upper unit is composed of undifferentiated backswamp organic muds a_4 and a_3 with a reduced organic matter content (sometimes below 30% as in the KO-4 core).

Through profiles correlation, the chronology of palaeogeographical events was supplemented with radiocarbon data from the KO-4 core. In particular, it confirmed that the accumulation of coarse detritus gyttja layer l_5 stopped at the end of the Late Atlantic period, 5,922–5,661 cal BP (3,973–3,712 cal BC). The onset age of gyttja l_5 accumulation in the KO-4 core (7,320–7,010 cal BP or 5,371–5,061 cal BC) was somewhat younger than that indicated by the data from core PKK-1-2, likely due to contamination with younger deposits (Table 1; Fig. S16).

4.1.3 Squares 24 and 25 in the Excavation-3 (with NN-1 outcrop)

Macroscopic description, geochemistry, plant macrofossils, and ^{14}C chronology of sq. 24 and 25

The geological deposits from squares 24 and 25 of Excavation-3 (Fig. 9AB) were correlated with PKK-1-2, as well as KO-3, KO-4, KO-5, and KO-6 cores due to their parallel lithology (Fig. S16). Macroscopic description and geochemical analysis of outcrop NN-1 in Excavation-3 revealed five lithological units.

The bottommost unit consists of nearshore grey-yellow medium and fine sands with only up to 8% organic matter (layer l₄, 110–79.5 cm b.g.l. in the NN-1 outcrop). Abundant macrofossils of *Phragmites australis*, *Schoenoplectus lacustris*, and *Carex panicea* in layer l₄ of the NN-1 outcrop suggest that the deposits were likely formed in a nearshore lacustrine environment (Fig. 9AB). The radiocarbon date of 10,763–10,606 cal BP indicates that the accumulation of unit l₄ deposits took place during the Middle Preboreal period (Fig. 9AB).

Above, there is a thin layer of white fine-grained sand (79.5–79 cm b.g.l. in the NN-1 outcrop), signalling river erosion during a significant flood event that took place between the Middle Preboreal and Early Atlantic (the mid-BO flood event in our interpretation). This thin layer forms a very sharp boundary between the sand l₄ and the gyttja l₅, pointing to a break in sedimentation (erosional hiatus; Fig. 9A).

Above, a brown coarse detritus gyttja l₅ was documented in the core with an organic matter content of 83–25% (79–45 cm b.g.l. in the NN-1 outcrop). Based on ^{14}C correlation with well-dated cores, the accumulation of this unit l₅ deposits occurred between 8,927–8,639 cal BP (6,978–6,690 cal BC) and 5,922–5,661 cal BP (3,973–3,712 cal BC) (Fig. 7; Fig. S16). At that time, squares 24 and 25 were located under the waters of Lake Sporovskoye, but in the shore area. The high admixture of mineral matter within gyttja l₅ indicates an accumulation in the proximity to the shore and the resulting influx of mineral matter from shoreline and/or slope processes (in cores to the N such high mineral matter content in gyttja l₅ was not observed; Fig. S16). The boundary between gyttja unit l₅ and the upper unit a₄ was diffuse and unclear (Fig. 9A).

The uppermost units consist of overbank deposits: backswamp black organic mud a₄ with approximately 36% of organic matter (45–28 cm b.g.l. in the NN-1 outcrop), and above that, backswamp brown peaty organic mud a₃ with around 40% of organic matter (28–0 cm b.g.l. in the NN-1 outcrop). The boundary between units a₄ and a₃ was also diffuse and unclear (Fig. 9A). Accumulation of the organic mud layer a₄ took place during the end of AT-3–SB-2, as evidenced by artefacts recovered from this layer (Fig. 9B) and by its

correlation with the KO-4 (Fig. S16), PKK-1-2 (Fig. 6B), and Sporovo II (Fig. 6A) cores. The accumulation of the peaty organic mud layer a_3 occurred in the 2nd half of SA-3, as indicated by the correlation with the radiocarbon date of 529–504 cal BP (1,421–1,446 cal AD) from the PKK-1-2 core (Figs. 6B, 9).

Archaeology and archaeological chronology of sq. 24 and 25

The chronology of the archaeological cultures identified, following the framework commonly accepted for Belarusian Polesie, is provided in Table S3.

LAZ-1 (local artefact zone 1; excavation layers 110–80 cm). The zone corresponds to the layer of nearshore sand with an admixture of organic matter l_4 dated to the Middle Preboreal (8,814–8,657 cal BC; Fig. 9B). The flint adze with Mesolithic cultural affiliation was found *in situ* in this zone (Fig. 9B). A stone and numerous flint artefacts without certain cultural affiliation were also discovered here. Most likely, all these finds are associated with the Early Mesolithic Kudlaevka culture, since they are located in the sand with organic matter layer dated to the Middle Preboreal (Fig. 9B; Tables S3 and S6).

The flint core fragment of Neman culture–Corded Ware culture circle found in zone 1 (depth 90–80 cm b.g.l.) is considered to be redeposited. The presence of this artefact almost on the surface of the sand layer l_4 is probably the result of its vertical displacement under pressure (perhaps artificial) through the soft coarse detritus gyttja layer l_5 (Fig. 9B).

LAZ-2 (excavation layers 80–50 cm). The zone mainly corresponds to the layer of coarse detritus gyttja l_5 dated to the Early and Middle Atlantic (approximately between 6,978–6,690 and 4,442–4,345 cal BC; Fig. 9B). The flint core of Late Mesolithic Janisławice culture was found *in situ* in zone 2 (Fig. 9B). Apart from this, many bones without traces of processing and flint artefacts without certain cultural affiliation were found in the described zone. The flint burin on truncation of Swiderian–Kudlaevka (?) culture was also discovered in the local zone 2 (Fig. 9B; Table S6). Unfortunately, it is impossible to identify with certainty the cultural affiliation of this find. If this artefact belongs to the Swiderian culture, it dates to the Younger Dryas–Early Preboreal; if it belongs to the Kudlaevka culture, it dates to the Preboreal–Early Atlantic (Table S3). Nevertheless, the presence of this archaic artefact in the coarse detritus gyttja layer l_5 most likely indicates that it was redeposited from the surface of Kakoryca-4 elevation into the gyttja probably as a result of slope and/or shoreline processes.

LAZ-3a (excavation layer 50–40 cm). The zone mainly corresponds to the uppermost part of the coarse detritus gyttja l₅ dated to the Late Atlantic (approximately between 4,442–4,345 and 3,973–3,712 cal BC; Fig. 9B).

The pottery first appeared in the local zone 3a. In the 50–40 cm excavation layer, out of all the pottery fragments from different time periods, the majority belonged to the Early Neolithic Pripyat-Neman culture of the Dubičiai-type (in total 9 fragments). We assume that these Pripyat-Neman culture pottery fragments are preserved *in situ* in the uppermost part of gyttja l₅. The predominance of Pripyat-Neman pottery in the 50–40 cm layer may indicate two things. First, it suggests that these were the first Neolithic groups to appear on the Kakoryca-4 site. Second, the appearance of these communities occurred at the time when the Kakoryca-4 site was surrounded by heavily overgrown shallow Lake Sporovskoye, as evidenced by the presence of gyttja l₅ in the 50–40 cm layer. The last statement is also supported by data from the PKK-1-2 core, where the fragment of Pripyat-Neman pottery was found specifically in these gyttjas l₅ (Figs. 8AB, 6B; Fig. S12D).

The Kudlaevka culture flint core found in the 50–40 cm layer (Fig. 9B) is dated to the Preboreal–Early Atlantic and represents redeposited item mixed with pottery fragments (Fig. 9B; Tables S3 and S6).

LAZ-3b (excavation layer 40–30 cm). The zone mainly corresponds to the layer of backswamp black organic mud a₄ dated to the end of AT-3–SB-2 interval. This zone was the richest in artefacts. The LAZ-3b zone is characterized by the highest amounts of pottery fragments belonging to the “forest” Neolithic Pripyat-Neman culture and Neman culture of the Dobry Bor-type, as well as the Late Neolithic–Early Bronze Age Corded Ware culture circle (including with elements of the Globular Amphora culture; Fig. 9B; Table S6). Moreover, this zone contained the highest number of flint artefacts (including flint products), as well as bones and their fragments without traces of processing (Fig. 9B). We consider that the majority of artefacts recovered from this zone occur *in situ* in the organic mud unit a₄. The high concentration of artefacts from these cultures within the 40–30 cm layer is most likely associated with extremely slow organic mud a₄ accumulation in a backswamp environment (Fig. 9B).

All Kudlaevka culture flint artefacts found in the 40–30 cm layer (trapeze, backed bladelets; Fig. 9B) are dated to the Preboreal–Early Atlantic and represent redeposited items mixed with pottery fragments (Fig. 9B; Tables S3 and S6). These artefacts were originally left by Kudlaevka communities on the surface of the Kakoryca-4 elevation and later redeposited into younger sediments. It is also worth noting that the appearance of a

Kudlaevka culture flint trapeze in the collection (Fig. 9B) suggests that the Kudlaevka people may have been present at the Kakoryca-4 site at the beginning of the Early Atlantic period (cf. Kalechyts and Kolasau (2021, 2023)).

Artefacts from the excavation layer 30–0 cm of the entire Excavation-3. This layer corresponds to the uppermost part of organic mud a₄, as well as to peaty organic mud a₃. The deposits of unit a₃ began to accumulate around 1,421–1,446 cal AD (Fig. 9B). The analysis of archaeological material from the 30–0 cm b.g.l. layer of the entire Excavation-3 (10 m²) revealed artefacts from the Pripyat-Neman (Dubičiai-type), Neman (Dobry Bor-type) cultures, as well as from the Corded Ware culture circle (Table S6). The presence of artefacts from these cultures in the 30–0 cm b.g.l. layer may indicate the mixing of deposits of a₃ and a₄ units. Fragments of fired clay, probably brick, were also found in this 30–0 cm layer (Table S6).

General overview of squares 24 and 25 in Excavation-3. Based on the discovered archaeological materials in squares 24 and 25, it can be concluded that the Kakoryca-4 elevation was most intensively occupied and utilized by communities of the Pripyat-Neman culture (Dubičiai-type), the Neman culture (Dobry Bor-type), and the Corded Ware culture circle during the Neolithic and Early Bronze Age (from the mid-6th/early-5th to the early-2nd millennium BC). Most of the artefacts were buried in the black organic mud layer a₄ and the uppermost part of the brown gyttja l₅, within excavation layers 50–40 cm (15% of the total number of all artefacts found in squares 24 and 25) and 40–30 cm (71.8%). Almost all pottery artefacts, with the exception of some fragments at the 30–0 cm level, were found exclusively within the 50–30 cm layer. Most of the flint artefacts were also concentrated in the upper layers 50–40 cm (22% of all flint artefacts found) and 40–30 cm (55%), and therefore, apart from some redeposited items, correlate with the Neolithic and Early Bronze Age. Almost all discovered stones (30 items) and bones (272 items) were also concentrated in the upper layers, ranging from 50 to 30 cm b.g.l. (Fig. 9B; Table S6). Interestingly, the 50–30 cm layer in squares 24 and 25 contained almost the same number of artefacts (724 items) as the 30–0 cm layer from the entire Excavation-3 area of 10 m² (820 items).

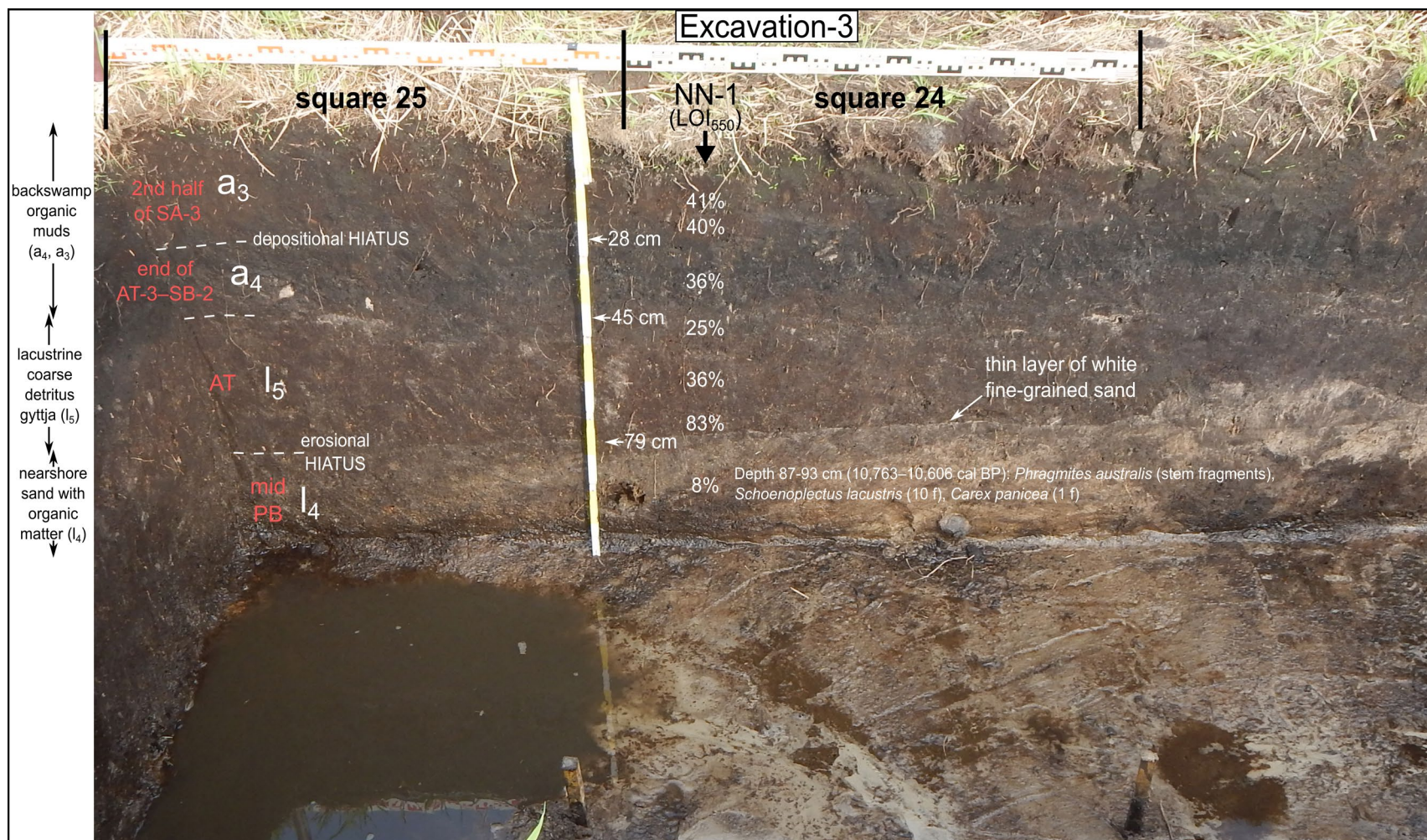


Fig. 9A. Squares 24 and 25 (each 1 m²) of Excavation-3, Kakoryca-4 archaeological site. Photo profile with identified lithological units.

Depth is given in cm below ground level [cm b.g.l.]

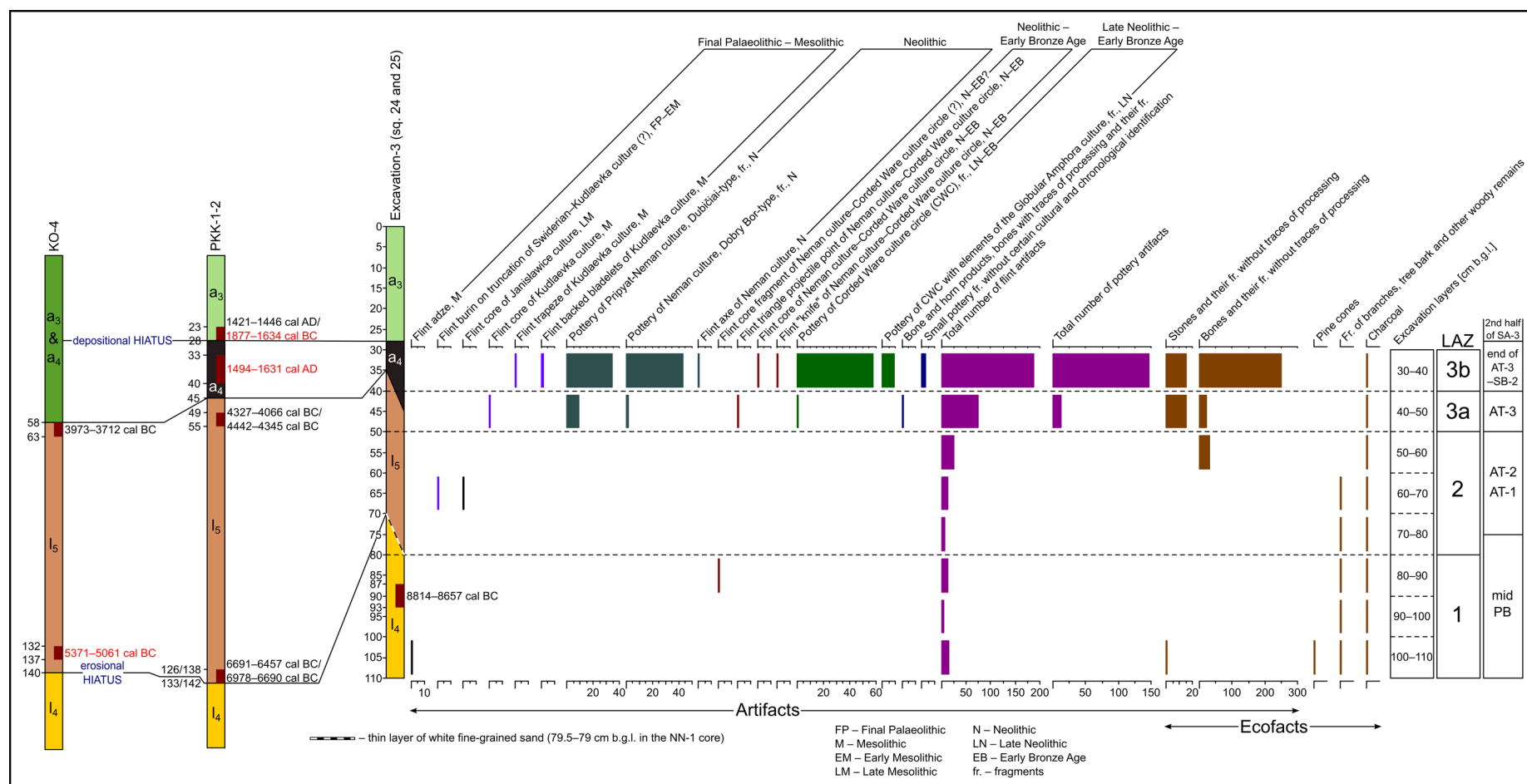


Fig. 9B. Squares 24 and 25 (each 1 m²) of Excavation-3, Kakoryca-4 archaeological site. Distribution of artefacts and ecofacts by depth, and correlation of squares 24 and 25 deposits with PKK-1-2 and KO-4 cores. Depth is given in cm below ground level [cm b.g.l.]

4.1.4 Sporovo II core

Macroscopic description, geochemistry, sedimentology and ^{14}C chronology of the Sporovo II core

The age-depth model for the Sporovo II core is shown in Fig. S19.

The bottommost sediments in the Sporovo II core are white-grey inorganic fluvial sands f_2 , mainly medium and fine-grained, with a mean grain size M_z of 1.90–2.24 phi (depth 270–250 cm b.g.l.; Fig. 6A; Table S7). These sands f_2 were accumulated during the Weichselian glaciation (W.G.), before the Bølling-Allerød, as a result of deposition by a braided river.

Above, at a depth between 250 and 193 cm b.g.l., there is olive sandy and silty calcareous gyttja l_1 , with CaCO_3 content of 31.98–72.58%, a mean grain size M_z of 3.17–4.14 phi and about 10% of organic matter. The gyttja layer l_1 indicates that Lake Sporovskoye was formed and experienced its first major transgression during the Bølling-Allerød: 14,794–14,221 cal BP (12,845–12,272 cal BC) and 14,080–13,891 cal BP (12,131–11,942 cal BC) (Table 1). The gyttja l_1 passes gradually upward into a thin layer of sandy and silty non-calcareous mineral gyttja l_2 , with a mean grain size M_z of 2.99 phi and an organic matter content of 27.54% (depth 193–189 cm b.g.l.).

Above, at a depth from 189 to 65 cm b.g.l., coarse detritus gyttja layers l_5 and l_6 were documented, marking another major transgression of Lake Sporovskoye. The beginning of the coarse detritus gyttja l_5 accumulation and the lake transgression are dated to the Late Boreal, 9,275–9,019 cal BP (7,326–7,070 cal BC). The end of the coarse detritus gyttja l_5 and l_6 accumulation occurred at the very end of the Late Atlantic period, as can be indicated by pollen assemblages and radiocarbon date of 6,441–6,305 cal BP (4,492–4,356 cal BC). The radiocarbon age of 6,669–6,564 cal BP (4,720–4,615 cal BC) is considered to be anomalously old.

Most of the deposits in the Sporovo II core were formed during the Atlantic transgression of the lake, which began 8,986–8,777 cal BP (7,037–6,828 cal BC). Coarse detritus gyttja l_6 (depth 150–97 cm b.g.l.) was distinguished as a separate unit due to a significant admixture of mineral matter (fine and very fine sands, and silt, M_z = 3.98–4.95 phi), resulting in lower organic matter content (LOI 50.00–68.29%). This mineral admixture in gyttja l_6 was most likely introduced by the Yaselda River during the Middle Atlantic 7,669–7,614 cal BP (5,720–5,665 cal BC), indicating the flow-through nature of Lake Sporovskoye at that time (Fig. 6A). The radiocarbon date of 6,176–5,757 cal BP (4,227–3,808 cal BC) is considered to be contaminated by younger deposits (Fig. 6A).

Above in the core, at a depth of 65–25 cm b.g.l., is a layer of highly organic telmatic peat h₁, with an organic matter content of about 90% (Fig. 6A). This telmatic peat unit was accumulated during the 1st half of SB-1, as indicated by the radiocarbon date of 4,957–4,842 cal BP (3,008–2,893 cal BC), and by pollen assemblages SPII-4a and SPII-4b (Fig. 10). We classified peat h₁ as telmatic, as it was rich in organic matter (Fig. 6A) and contained high proportions of Cyperaceae pollen, *Sparganium*-type pollen, and undeterminable pollen and spores, along with a significant admixture of pollen from aquatic plants (*Stratiotes aloides*, *Nuphar*, *Myriophyllum*, and *Potamogeton*; Fig. 10).

The uppermost layer of deposits, at a depth of 25–0 cm b.g.l., is represented by fen peat h₂. This unit h₂ was most likely accumulated in a fen that was periodically flooded by the Yaselda River and Lake Sporovskoye, which led to the formation of temporary water bodies on the fen surface. This is indicated by a higher admixture of silt (lower LOI of 80–90%; Fig. 6A; Table S7) compared to unit h₁, as well as by the presence of *Nymphaea* pollen (Fig. 10). It is possible to establish only an approximate age for unit h₂. We assume that unit h₂ was most likely accumulated during the 2nd half of the SA-3. This age was established on the basis of pollen assemblages SPII-5a and SPII-5b (Fig. 10) and through correlation with the radiocarbon date of 529–504 cal BP from the PKK-1-2 core (Fig. 6B).

Pollen and plant macrofossils of the Sporovo II core

The simplified pollen diagram for the Sporovo II core is shown in Fig. 10. A detailed description of the pollen diagram of Sporovo II core was published earlier by Tsvirko (2023). The extended pollen diagram with new radiocarbon dates and some modifications can be found in the online supplementary material (Fig. S20).

Throughout the entire Sporovo II core, pollen grains of wild-growing Poaceae with a long axis size of more than 40 µm and a large annulus of about 9 µm were frequently found (Fig. 10 – presence of Poaceae with an axis >40 µm). At the same time, the annulus of these Poaceae grains was indistinct, without sharp contours, which did not allow us to classify this pollen as *Cerealia* (Fig. S21).

LPAZ SPII-1 (250–220 cm b.g.l.; unit I₁). The zone is dated to the Bølling-Allerød. The SPII-1 zone was characterized by very high amounts of *Betula* (33.6–29.1%), an absolute maximum of *Salix* (17.6%), high AP values (88.8–80.7%), the presence of *Juniperus* (0.9–0.1%), *Betula nana*-type (1.0–0.2%) and *Hippophaë* (0.6–0.1%). The number of *Pinus* was significantly reduced (50.7–30.3%). Among herbaceous taxa, an absolute maximum of *Artemisia* (10.0%), high values of *Chenopodiaceae* (1.9–0.7%), and

the presence of *Helianthemum* (0.2%), were observed. Pollen from aquatic plants was also recorded, including an absolute maximum of *Myriophyllum* (1.5%), and the presence of *Nymphaea* (0.2%) and *Potamogeton* (0.4%) (Fig. 10; Table S7). Among the macrofossils, remains of *Potamogeton* cf. *utilus* and *Potamogeton* sp. were found (Fig. 6A).

LPAZ SPII-2 (220–189 cm; units l₁ and l₂). The zone is dated to the Bølling-Allerød. The SPII-2 zone was characterized by the dominance of *Pinus* (60.4–53.3%), and the presence of *Juniperus* (0.9–0.1%), *Ephedra* (0.3–0.1%), *Hippophaë* (0.1%), and *Betula nana*-type (1.1–0.2%). The abundances of *Betula* (28.5–18.6%) and *Salix* (3.5–1.4%) decreased, while herbaceous taxa (NAP) increased, showing an absolute maximum of Chenopodiaceae (2.5%) and high values of *Artemisia* (9.9–3.5%). Among aquatic plants, *Myriophyllum* was abundant (0.8–0.2%), with the presence of *Potamogeton* (0.2–0.1%) and *Nuphar* (0.2–0.1%) (Fig. 10; Table S7). In the SPII-2 zone, a single macrofossil of *Potamogeton* cf. *compressus* was found (Fig. 6A).

LPAZ SPII-2/3 (189–175 cm; unit l₅). The zone is dated to the Late Boreal. This zone showed an absolute maximum of *Betula* (34.3%), and relatively high values of *Ulmus* (2.0–1.5%), *Quercus* (1.3–0.4%), *Tilia* (0.6–0.1%), *Fraxinus* (0.7–0.3%), and *Corylus* (4.1–2.2%). The abundance of *Alnus* increased (3.4–0.6%), while *Pinus* declined (42.4–37.6%). Among aquatic taxa, pollen of *Stratiotes aloides* (0.1%), *Nuphar* (0.4–0.1%), *Nymphaea* (0.5–0.1%), and *Myriophyllum* (0.1%) was recorded (Fig. 10). In the SPII-2/3 zone, a single macrofossil of *Potamogeton* sp. was found (Fig. 6A).

LPAZ SPII-3a (175–110 cm; units l₅ and l₆) and LPAZ SPII-3b (110–65 cm; units l₅ and l₆). The SPII-3a zone is dated to the Early and Middle Atlantic, while the SPII-3b zone is dated to the Late Atlantic. The arboreal pollen assemblages of these zones were very similar. The SPII-3a and SPII-3b zones were characterized by absolute maxima of *Corylus* (9%), *Ulmus* (6.1%), *Tilia* (2.2%), *Fraxinus* (2.6%), and *Alnus* (20.2%), together with absolute minima of *Pinus* (30.1%) and NAP (5.8%). *Quercus* (4.8–1.9%) and *Betula* (24.6–9.4%) pollen were present in considerable amounts. The zones also contained high proportions of aquatic plant pollen, including *Stratiotes aloides* (0.5–0.1%), *Nuphar* (0.3–0.1%), *Nymphaea* (0.6–0.1%), *Myriophyllum* (0.2–0.1%), and *Potamogeton* (0.5–0.1%) (Fig. 10).

The SPII-3b zone was distinguished by significant changes in local vegetation. In particular, increased values of *Sparganium*-type (up to 7.2%), Polypodiaceae (absolute maximum of 32.6%), *Salix* (up to 4.2%), and *Artemisia* (up to 1.3%) were recorded, together with the disappearance of *Potamogeton* and *Myriophyllum* pollen (Fig. 10).

In addition, zones SPII-3a and SPII-3b contained numerous macrofossils, including *Potamogeton* sp., *Potamogeton lucens*, *Potamogeton natans*, *Stratiotes aloides* (seeds), Nymphaeaceae, as well as *Carex rostrata* and *Carex lasiocarpa*. A piece of fish scale found at a depth of 135–130 cm b.g.l. also indicated that the unit l₆ was formed in a lacustrine environment (Fig. 6A).

LPAZ SPII-4a (65–45 cm; unit h₁) and LPAZ SPII-4b (45–25 cm; unit h₁). The SPII-4a and SPII-4b zones are dated to the 1st half of SB-1. Zones SPII-4a and SPII-4b were characterized by reduced values of *Corylus* (4.6–2.0%), *Alnus* (12.2–7.3%), and *Betula* (13.5–3.7), together with relatively high values of *Tilia* (1.3–0.7%) and *Picea* (1.3–0.3%). Very high proportions of *Sparganium*-type were recorded (10.2–2.9%), accompanied by a significant decline in aquatic pollen. Only single pollen grains of *Stratiotes aloides* (0.1%), *Nuphar* (0.1%), *Myriophyllum* (0.2–0.1%), and *Potamogeton* (0.1%) were present. Both zones were characterized by very high amounts of undeterminable pollen and spores (6.2–2.2%).

The SPII-4a zone was distinguished by an absolute maximum of *Quercus* (6.7%), high values of *Ulmus* (4.1–2.6%), *Fraxinus* (1.5–0.7%), and NAP (20.8–14.5), and relatively low values of *Pinus* (47.3–42.4%). A gradual increase in Cyperaceae was also observed (4.2–29.2%). In addition, two macrofossils, including *Ranunculus* sp. and *Carex* sp., were found in zone SPII-4a.

In contrast, zone SPII-4b showed a decline in the *Quercus* curve (to 2.3%), low values of *Ulmus* (1.7–1.0%), *Fraxinus* (0.3–0.1%), and NAP (16.5–7.5), and very high values of *Pinus* (67.4–57.8%). A continuous *Carpinus* curve (0.2–0.1%) began in this zone. Also in zone SPII-4b, very high values of Cyperaceae were observed (28.7–16.1%) (Fig. 10).

In zone SPII-4b, we recorded a single pollen grain marked in the diagram as cf. *Cerealia* (Fig. 10), which raised significant doubts as to whether it belongs to cultivated *Cerealia* crops or to wild-growing Poaceae species. The grain was heavily deformed (long axis about 35 µm), preventing reliable measurement of its true size (Fig. 8CD). At the same time, it exhibited a large annulus (9–10 µm in diameter) and sharp annulus boundaries. We assume that this pollen grain most likely derives from wild Poaceae grasses; however, owing to remaining uncertainty, it is kept under the designation cf. *Cerealia*. The age of the five-centimeter pollen concentrate sample containing the cf. *Cerealia* pollen was 4,957–4,842 cal BP (3,008–2,893 cal BC; Fig. 10).

LPAZ SPII-5a (25–10 cm; unit h₂) and LPAZ SPII-5b (10–0 cm; unit h₂). These zones are dated to the 2nd half of SA-3. Zones SPII-5a and SPII-5b were characterized by very high values of *Pinus* (absolute maximum of 70%) and relatively high proportions of *Quercus* (4.1–1.8%) and *Carpinus* (0.5–0.2%). Very low values of *Corylus* (2.0–0.2%), *Ulmus* (1.0–0.1%), *Tilia* (0.7–0.1%), and *Fraxinus* (0.5–0.1%) were recorded in these zones. Very high values of Cyperaceae (absolute maximum of 36.1 %), a substantial amount of *Sphagnum* (0.9–0.1%), and high proportions of undeterminable pollen and spores (5.2–1.2%) were also observed in these zones. In zone SPII-5a, pollen of *Nymphaea* (0.2%) was recorded.

The distinguishing features of zone SPII-5b included absolute maxima of NAP (30.3%) and *Picea* (3.3%), as well as a decline in the curves of *Corylus* (to 0.2%), *Quercus* (to 1.8%), and *Tilia* (to 0.1%) and disappearance of *Fraxinus*. An important characteristic of the SPII-5b zone was the increase in *Artemisia* (to 1.9 %), Chenopodiaceae (to 1%), and Poaceae (to 13.1%), as well as the appearance of *Rumex* (0.3%), *Plantago lanceolata* (0.3%), and *Polygonum aviculare* (0.1%). These features indicate that zone SPII-5b contains a clear signal of human activity (Fig. 10).

4.1.5 KO-9 core

Macroscopic description, geochemistry, sedimentology, plant macrofossils, and ¹⁴C chronology of the KO-9 core

The basal deposits of core KO-9 are channel inorganic primarily medium- and fine-grained sands a₁, with a mean grain size M_z of 1.56–2.11 phi (depth 198–149 cm b.g.l.) (Fig. 6C). The accumulation of this sand layer a₁ most likely took place during the Early Subatlantic (SA-1).

At a depth of 149–141.5 cm b.g.l., is peaty organic mud a₃ with a significant admixture of sand, aged 2,306–2,151 cal BP (357–202 cal BC), and with organic matter content of 41.5–55%. Most likely, this layer of peaty organic mud a₃ was accumulated in the stagnant water conditions of backswamp.

At a depth between 141.5 and 89 cm b.g.l., are overbank rhythmite mostly fine and medium sands a₂, with a mean grain size M_z of 2.22–3.48 phi, and a significant admixture of organic matter (up to 7.6%). These deposits were characterized by alternating layers of inorganic sand and sand with organic mud admixture (rhythmite structure). The described unit a₂ was formed during a period of strong flooding, when the Yaselda River valley experienced several years of large-scale floods, leading to the development of flood

rhythmite structure within unit a₂ (Fig. 6C). One rhythm (a pair of layers with and without organic matter) corresponds to a single flood; at least ten clearly defined rhythmites were identified (Fig. 6C).

At a depth of 89–36 cm b.g.l., there is a backswamp organic mud layer a₄ with a significant admixture of sand and an organic matter content of 13.4–41.1%. This organic mud layer a₄ does not contain light-coloured inorganic layers, which may indicate a decrease in the frequency of severe floods or removing of the river channel further from the core position. Single macrofossils of telmatic/wetland plants such as *Carex* and *Oenanthe aquatica* were found in this layer a₄. Two radiocarbon dates of 2,463–2,359 cal BP (514–410 cal BC) and 2,359–2,339 cal BP (410–390 cal BC) obtained from the described a₄ unit were slightly older than the date from the underlying a₃ layer (depth 149–144 cm; 2,306–2,151 cal BP), which may indicate redeposition of older plant detritus into unit a₄. Nevertheless, we estimate that the organic mud unit a₄ was most likely accumulated during the Early Subatlantic (Fig. 6C; Table 1).

Above this, between 36 and 26 cm b.g.l., lies a layer of overbank silt and sand a₂ with an organic matter content of 5.3–11.7% (Fig. 6C). The reappearance of the layer a₂ suggests an increase in the number of severe floods in the Yaselda River valley.

The uppermost units of backswamp organic mud a₄ and peaty organic mud a₃ (26–0 cm b.g.l.) most likely were accumulated during the second half of the Late Subatlantic, according to the correlation with the PKK-1-2 and Sporovo II cores (Fig. 6ABC; 529–504 cal BP). These units a₄ and a₃, which show an upward increase in organic matter content, were probably formed during a period when backswamp and periodically flooded fen environments with temporary surface water bodies developed over wide areas of Lake Sporovskoye vicinity.

To sum up, floods – including strong ones – that were active after 2,306–2,151 cal BP (357–202 cal BC) during the Early Subatlantic led to fast accumulation of units a₃, a₂ and a₄ (149–26 cm b.g.l.) in the KO-9 core area, most likely due to its close proximity to the river channel (Figs. 2AB, 3 and 6C). Based on the correlation with cores PKK-1-2 and Sporovo II, a depositional hiatus was identified, which ended approximately 529–504 cal BP (Fig. 6BC), after which the accumulation of organic muds a₄ and a₃ (26–0 cm b.g.l.) began.

4.1.6 KO-8 core

Macroscopic description, geochemistry, sedimentology, and ^{14}C chronology of the KO-8 core

The basal sediments of the KO-8 core (depth 80–58 cm b.g.l.) are fluvial fine and medium sands f_2 , with a mean grain size M_z of 2.12–2.59 phi (Fig. S22A). The accumulation of this sand layer f_2 most likely occurred during the Weichselian glaciation (W.G.), as a result of the braided river activity. Above in the core, between 58 and 40 cm b.g.l., is a layer of organic mud a_4 , with an organic matter content of 14–26%. Most likely, these a_4 sediments were deposited in backswamp conditions. The accumulation of this unit a_4 began in the Late Atlantic, as confirmed by a ^{14}C date of 6,940–6,680 cal BP (4,991–4,731 cal BC; Fig. S22A). The uppermost unit (depth 40–0 cm b.g.l.) consists of biogenic deposits b_1 , with an organic matter content of 58–85%. These biogenic deposits are most likely composed of fen peat (Fig. S22A).

4.1.7 KO-20 core

Macroscopic description, geochemistry, sedimentology, plant macrofossils, and ^{14}C chronology of the KO-20 core

The bottommost sediments in the KO-20 core (depth 185–165 cm b.g.l.) consist of fluvial inorganic fine and medium sands f_2 with a mean grain size M_z of 2.62–2.93 phi (Fig. S22B). The deposition of this sand layer f_2 likely occurred as a result of accumulation by a braided river during the Weichselian glaciation (W.G.).

According to our interpretation, at a depth of 165–144 cm b.g.l. lies a layer l_4 of lacustrine nearshore fine and medium sands with a significant admixture of silt and clay (M_z of 3.24–4.39 phi), and in the upper part also with a significant proportion of organic matter (LOI of 10–38%). Macrofossils of *Menyanthes trifoliata* and *Carex* sp. were recorded in the described unit l_4 . This layer l_4 was formed before 10,115–9,558 cal BP (8,166–7,609 cal BC), probably as a result of the Preboreal–Early Boreal transgression of Lake Sporovskoye (Fig. S22B).

Between 144 and 0 cm b.g.l., the sequence consists of highly organic biogenic deposits b_1 , with organic matter contents frequently exceeding 80%. Most of the lower part of unit b_1 (approximately 144–50 cm) most likely consists of highly organic gyttja. This unit b_1 was accumulated during the Early Boreal (BO-1), as shown by a ^{14}C date of 10,115–9,558 cal BP (8,166–7,609 cal BC), and is associated with lacustrine sedimentation, as evidenced by macrofossils of *Potamogeton* and *Hippuris vulgaris* at a depth of 144–140 cm

b.g.l. It seems that a significant part of the KO-20 core deposits was formed during Lake Sporovskoye transgression throughout the Early and Middle Atlantic, as suggested by a sample from the central part of the core dated to 7,830–7,669 cal BP (5,881–5,720 cal BC). The upper part of the core (approximately above 50 cm) was probably formed first under telmatic and later under fen conditions. The discovery of *Potamogeton* macrofossils in the uppermost layer (depth 16–11 cm b.g.l.) indicates that, in the recent past (256–34 cal BP or 1,694–1,917 cal AD), the ecosystem was affected by flooding from the Yaselda River and Lake Sporovskoye, which led to the formation of temporary water bodies with aquatic vegetation on the fen surface (Fig. S22B).

4.1.8 A-1 outcrop

Macroscopic description, geochemistry, sedimentology, plant macrofossils, and ^{14}C chronology of the A-1 outcrop

The basal deposits of the A-1 outcrop (depth 72–67 cm b.g.l.) are fluvial mainly fine and medium sands f_2 , with low admixture of silt, a mean grain size M_z of 2.52–2.58 phi, and organic matter content around 2% (Fig. S23A). This layer f_2 was likely formed by a braided river during the Weichselian glaciation (W.G.).

Above, between 67 and 50 cm b.g.l., are lacustrine nearshore silt and sand deposits l_4 , with a mean grain size M_z of 4.30–5.01 phi, and a significant admixture of organic matter (7.6–25.7%). The presence of *Alisma plantago-aquatica*, *Phragmites australis* and *Typha* macrofossils in the layer l_4 (sample 63–67 cm b.g.l.) may indicate a nearshore aquatic depositional environment (Fig. S23A). The accumulation of the l_4 layer occurred between 8,688–8,548 and 6,281–6,205 cal BP (during the whole Atlantic), when Lake Sporovskoye experienced a major transgression (Fig. 1B).

The uppermost sediments are highly organic biogenic deposits b_1 (depth 50–0 cm b.g.l.), with organic matter content frequently exceeding 80%. These biogenic deposits b_1 apparently consist of organic gyttja in the lower part (approximately 50–43 cm), and telmatic and fen peats forming the upper part of the unit (approximately above 43 cm). The lower part of layer b_1 , dated to 6,281–6,205 cal BP, was accumulated in lacustrine conditions during the Late Atlantic transgression of Lake Sporovskoye, as indicated primarily by the presence of Characeae macrofossils (sample 47–50 cm b.g.l.; Fig. S23A). The presence of *Potamogeton* macrofossils in the uppermost layer of unit b_1 (14–4 cm b.g.l.; Fig. S23A) most likely indicates that, in the recent past, the fen ecosystem was affected by flooding from the Yaselda River and Lake Sporovskoye, leading to the

formation of temporary water bodies with aquatic vegetation on the fen surface (a macrofossil/pollen pattern similar to that observed in the upper deposits of the KO-20 and Sporovo II cores; Fig. S22B; Fig. 10).

4.1.9 UZS-1-2 core

Macroscopic description, geochemistry, sedimentology, plant macrofossils, archaeology, and ^{14}C chronology of the UZS-1-2 core

The bottommost deposits of the UZS-1-2 core (depth 116–106 cm b.g.l.) are grey-yellow lacustrine poorly sorted sand with silt l_4 , with a mean grain size M_z of 2.32–2.57 ϕ , and a significant admixture of organic matter (around 2%) (Fig. S23B). The accumulation of unit l_4 occurred before 12,616–12,479 cal BP, most likely during the older part of Younger Dryas (YD-1; Naughton et al., 2023), though it may also date to the Bølling-Allerød (BA). In the upper part of layer l_4 , at a depth of 109.5–106 cm, a flint flake about 3 cm long was discovered. Considering its stratigraphic position within the BA/YD-1-period layer l_4 , the artefact is presumably associated with the Final Palaeolithic Swiderian culture (Fig. S23B).

Above, between 106 and 45 cm b.g.l., are brown medium l_3 and coarse l_5 detritus gyttja (LOI often over 70%), sometimes with a significant admixture of silt and sand l_6 (LOI 34–49%). Macrofossils of Characeae, *Potamogeton*, *Myriophyllum*, *Cristatella mucedo*, *Daphnia* (sample 101–106 cm b.g.l.), and *Nymphaea* (sample 45–47 cm b.g.l.) indicate that the sediments of l_3 , l_5 and l_6 units were formed under aquatic conditions. The accumulation of these medium and coarse detritus gyttja l_3 , l_5 and l_6 layers began in the older part of Younger Dryas (YD-1; 12,616–12,479 cal BP) and ended by the onset of the Subatlantic (2,863–2,784 cal BP). A significant admixture of silt and sand, with a mean grain size M_z of 4.93–5.69 ϕ , in the coarse detritus gyttja l_6 (depth 75–56 cm b.g.l.; Fig. S23B) indicates that Lake Sporovskoye was a flow-through lake, with the Yaselda River flowing through it (a similar admixture of mineral matter was found in the Sporovo II core layer l_6 – evidence of a flow-through lake; Fig. 6A).

The uppermost deposits (depth 45–0 cm b.g.l.) most likely consist of black telmatic peat h_1 (LOI of 83–88%) and brown fen peat h_2 (LOI of 77–83%). The fen peat h_2 was characterized by a slightly lower content of organic matter compared with the underlying telmatic peat h_1 , which may indicate frequent flooding from the Yaselda River and Lake Sporovskoye and, consequently, a greater input of mineral matter into the fen peat h_2 . Single macrofossils of *Carex* and Poaceae were discovered in the layer of fen peat h_2

(Fig. S23B). The described peat layers h_1 and h_2 were accumulated during the Subatlantic, after 2,863–2,784 cal BP (Fig. S23B).

4.2 Sandy elevations

4.2.1 KAK-5 outcrop

Macroscopic description, sedimentology, geochemistry, and chronology of the KAK-5 core

The deposits documented in the KAK-5 outcrop are primarily composed of fine and medium sands (units f_2 and f_3), with interlamination of coarse sand and gravel (units f_1) (Fig. 11A). The mean grain size M_z for f_2 and f_3 layers is 1.88–2.88 phi, while for f_1 layers it is 0.87–1.67 phi. Units f_2 and f_3 show standard deviation values (σ_1) of 0.60–1.27 phi, in contrast to units f_1 , which exhibit higher σ_1 values ranging from 0.96 to 1.40 phi. The skewness parameter (Sk_1) for layers f_2 and f_3 ranges from -0.041 to 0.317 phi, whereas for layers f_1 it ranges from -0.146 to 0.118. The kurtosis (K_G) for units f_2 and f_3 ranges from 0.97 to 1.69 phi, whereas K_G values for units f_1 range from 0.85 to 1.15 phi. According to our calculations, the highest deposition velocities were found in the coarse sand and gravel layers f_1 , ranging from 31.5 to 38.9 cm/s (Fig. 11A).

The KAK-5 outcrop clearly shows a sub-horizontal layering of the sediments (Fig. 11A; Fig. S24A), which may indicate a slight incline of the terrain and low flow velocities during deposition of these sediments. Besides the thick sub-horizontal layers, numerous very thin layers can also be distinguished. For instance, at a depth of about 130–115 cm, a large number of very thin sub-horizontal layers are clearly observed, indicating that these deposits were formed under flowing water conditions (Area with traces of flow – Fig. S24).

These textural and structural characteristics of deposits indicates the fluvial, most likely braided river, origin of the elevation with the KAK-5 outcrop. This hill was formed as a mid-channel bar of sandy braided river during the Weichselian glaciation. The layers of coarse-grained sand with gravel (unit f_1) can be interpreted as deposits of a shallow path of a braided river or shallow braided stream facies (Zieliński, 2014). The fine and medium sand layers (units f_2 and f_3) represent mid-channel bar deposits. The sub-horizontal layering of these deposits (Fig. 11A; Fig. S24A) also indicated that this elevation was a large mid-channel bar of sandy braided river (Zieliński, 2014).

It is important to emphasize that the deposits from other higher elevations (SU-S, MW-9, and Pit-3 outcrops) are very similar to the deposits of the KAK-5 outcrop.

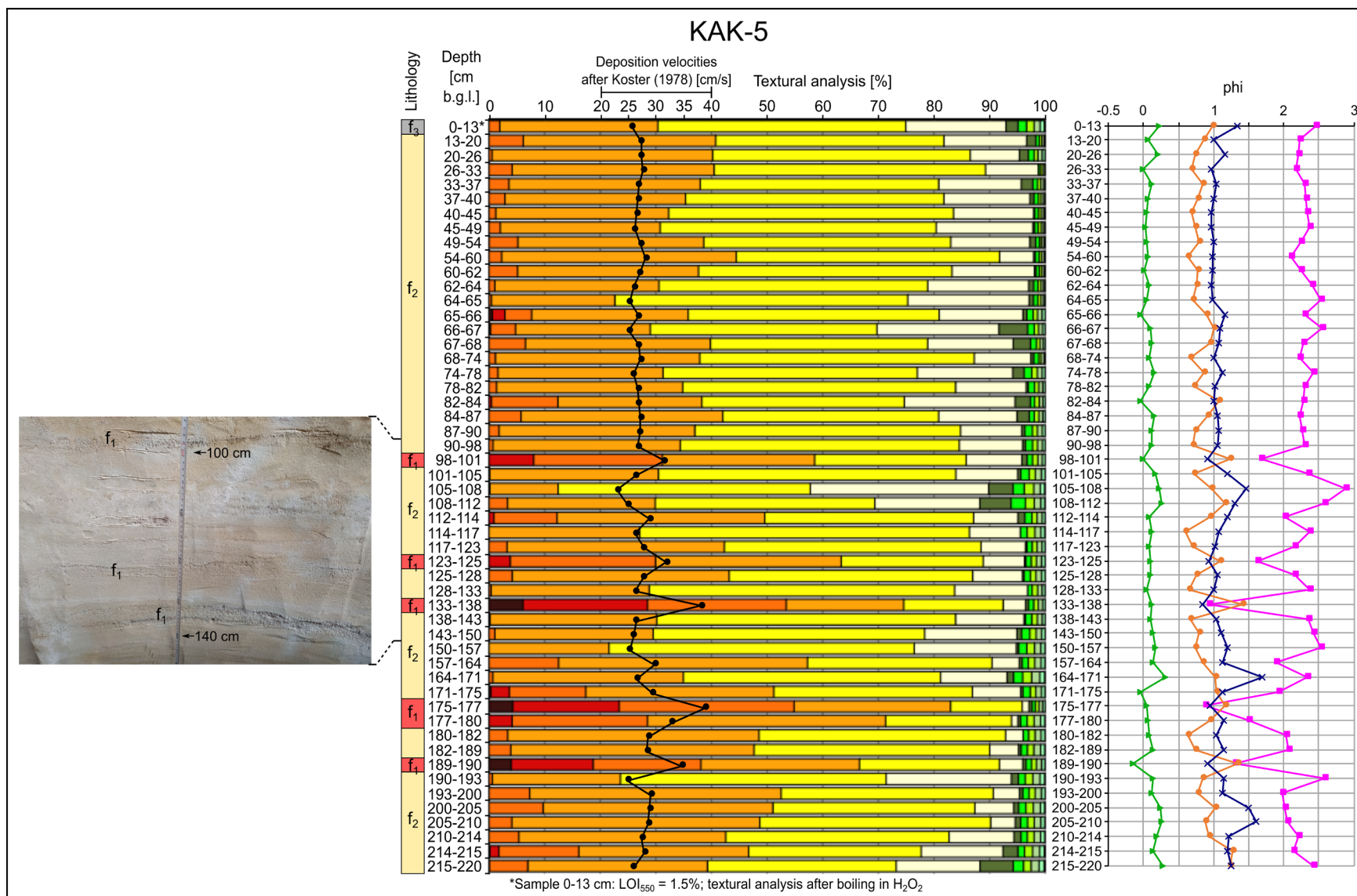


Fig. 11A. Sedimentological diagram of the KAK-5 outcrop with identified lithological units

4.2.2 SU-S outcrop

Macroscopic description, sedimentology, geochemistry, and chronology of the SU-S core

The SU-S outcrop is located on the sandy elevation with a depression in the central part. The outcrop was situated on the slope of this central depression (Fig. 1C; Fig. S3). The documented deposits mainly consist of fine and medium sands (units f_2), fine and medium sands with a significant admixture of silt and organic matter (unit f_3), sub-horizontal layers of coarse sand and gravel (units f_1), as well as fine and medium sands with a slight admixture of organic matter (units f_4) (Fig. 11B; Fig. S24B). The lowest mean grain size (M_z) values are observed in f_1 layers (1.05–1.78 phi). In f_2 layers, M_z values are 1.87–2.59 phi, in the f_3 layer 2.88–3.12 phi, and in f_4 layers 2.08–2.74 phi. The highest standard deviation values (σ_1) are observed in unit f_3 (1.43–1.73 phi), whereas f_1 layers show values of 1.04–1.49 phi, f_2 layers 0.85–1.29 phi, and f_4 layers 0.78–1.35 phi. The lowest skewness (Sk_1) values are characteristic of units f_1 (-0.095 to 0.041 phi), whereas skewness Sk_1 values for units f_2 range from -0.002 to 0.325 phi, for unit f_3 from 0.42 to 0.50 phi, and for unit f_4 from 0.13 to 0.44 phi. The highest kurtosis (K_G) values are observed in f_4 layers (1.11–2.08 phi), with lower values recorded in f_3 (1.46–1.63 phi), f_2 (1.03–1.49 phi), and f_1 (0.85–1.15 phi) layers. The highest deposition velocities were estimated for the coarse sand and gravel layers f_1 , ranging from 30.7 to 37.2 cm/s (Fig. 11B).

According to our interpretation, this texture of sediments suggests that the elevation with the SU-S outcrop was formed as a mid-channel bar of sandy braided river during the Weichselian glaciation. Mid-channel bar deposits are represented by layers of fine and medium sands f_2 and f_3 . The coarse sand and gravel layers f_1 represented deposits of a shallow path of a braided river. According to our assumption, the accumulation of the bottommost deposits of the SU-S outcrop (depth 126–92 cm b.g.l.) occurred in a small chute channel that existed between mid-channel bars Kakoryca-10A and Kakoryca-10B (Fig. S11). The deposits of this chute channel consist of overbank (units f_4 , depth 126–114 and 110–92 cm b.g.l.) and channel (unit f_1 , depth 114–110 cm b.g.l.) alluvia of a braided river. The layers of overbank fine and medium sands f_4 had a slight admixture of organic matter (0.6–0.2%). The deposition velocities for layers f_4 ranged between 23.8 and 28.3 cm/s (Fig. 11B).

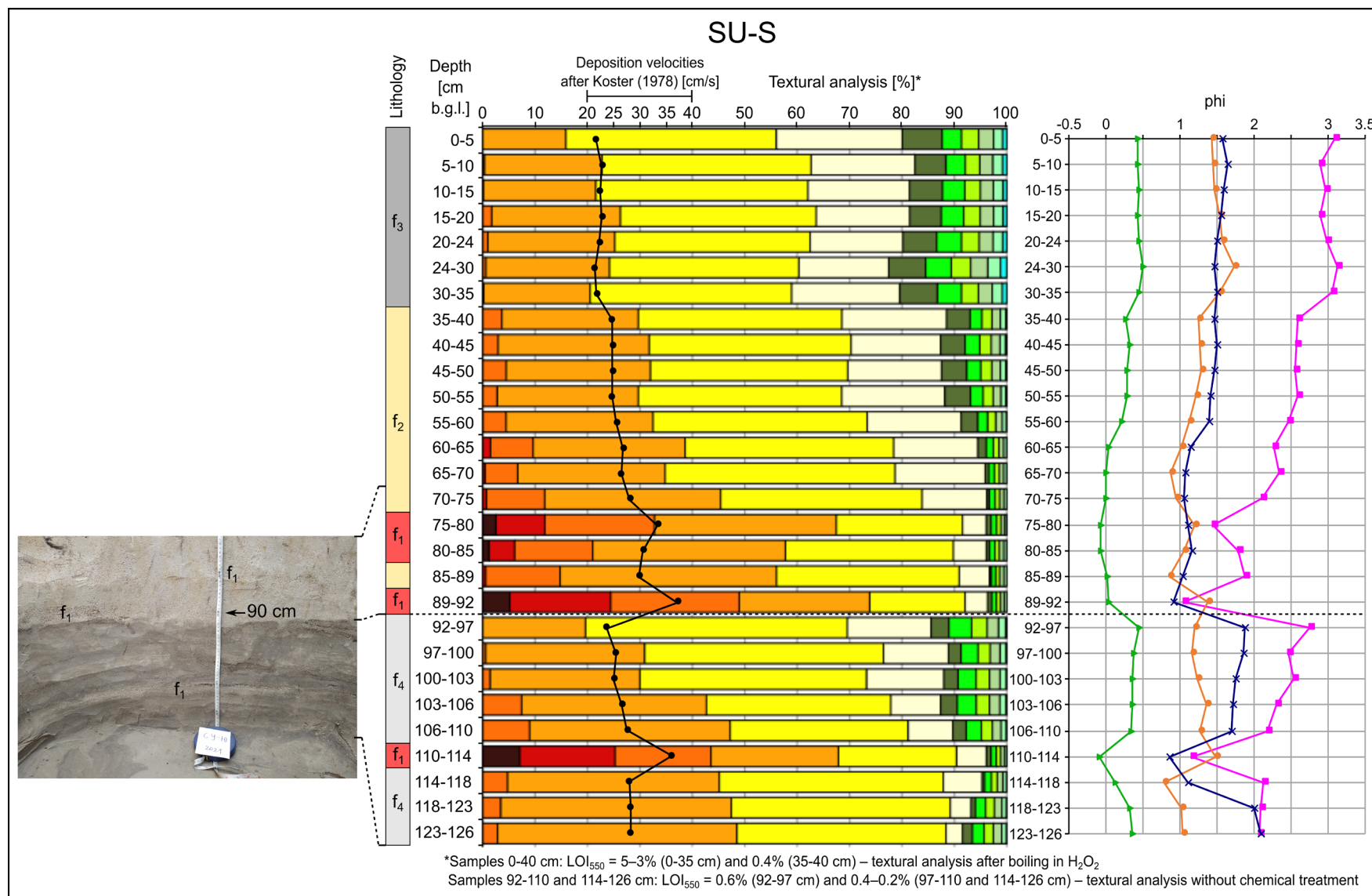


Fig. 11B. Sedimentological diagram of the SU-S outcrop with identified lithological units

4.2.3 C-1 outcrop

Macroscopic description and chronology of the C-1 core

The C-1 core is located in the very centre of a chute channel that existed between mid-channel bars Kakoryca-10A and Kakoryca-10B (Figs. S3 and S11). The deposits of the C-1 core consist of fine and medium sands of braided river overbank (f_4) and channel (f_1) facies, accumulated during the Weichselian glaciation. The subhorizontal layers of overbank deposits f_4 contained a slight admixture of organic matter (Fig. S24C).

4.2.4 MW-9 outcrop (in Excavation-1)

Macroscopic description, sedimentology, geochemistry, archaeology, and chronology of the MW-9 core

The MW-9 outcrop is located in the central part of the Kakoryca-4 elevation, in archaeological Excavation-1 (Figs. 2 and 3). The outcrop predominantly consists of fine and medium sands (units f_2 and f_3), sometimes with admixture of coarse and very coarse sands (unit f_1) (Fig. S25A). The mean grain size M_z for f_2 and f_3 layers is 1.89–2.24 phi, for f_1 layer is 1.71 phi. The highest standard deviation value (σ_1) is observed in the f_1 layer (1 phi), whereas f_2 and f_3 layers are characterized by σ_1 values ranging from 0.60 to 0.87 phi. For the f_1 layer, the skewness (Sk_1) parameter is 0.061 phi, whereas for f_2 and f_3 layers it ranges from 0.045 to 0.157 phi. The f_1 layer exhibits a kurtosis (K_G) value of 1.07 phi, whereas f_2 and f_3 layers show K_G values ranging from 0.95 to 1.16 phi. The deposition velocities range from 27.1 to 29.8 cm/s for f_2 and f_3 units, and 31.2 cm/s for f_1 unit.

The resulting sediment texture allows us to assume that the Kakoryca-4 elevation has a fluvial origin and was formed as a mid-channel bar of a sandy braided river during the Weichselian glaciation.

The uppermost layer of humic sand f_3 (depth 0–30 cm b.g.l.), containing 1–2% organic matter, was saturated with a relatively large number of archaeological artefacts. Below, at a depth of 30–50 cm b.g.l., the number of archaeological finds sharply decreased (on these archaeological studies see Kryvaltsevich et al., 2023).

4.2.5 Pit-3 outcrop (in Trench-3)

Macroscopic description, sedimentology, geochemistry, archaeology, and chronology of the Pit-3 core

The Pit-3 outcrop is situated on the northern slope of the Kakoryca-4 elevation, in Trench-3 (Figs. 2 and 3). It primarily consists of fine and medium sands (units f_2 and f_3),

sometimes with admixture of coarse sand (unit f_1) and silt (in the f_3 unit) (Fig. S25B). The mean grain size M_z for the f_2 and f_3 layers is 1.9–2.66 phi, with the deposition velocities ranging from 24.3 to 29.6 cm/s. The layer f_1 is distinguished by the mean grain size M_z of 1.73–1.77 phi, and the deposition velocities from 30.7 to 31.1 cm/s. The lowest standard deviation values (σ_1) are characteristic of unit f_1 (0.75–0.98 phi), whereas σ_1 values for units f_2 and f_3 range from 0.99 to 1.51 phi. Unit f_1 shows the lowest skewness (Sk_1) values (0.015–0.221 phi), while units f_2 and f_3 are characterized by higher Sk_1 values of 0.221–0.475 phi. Kurtosis (K_G) is lower in f_1 (0.99–1.2 phi) compared with f_2 and f_3 units, which are characterized by values of 1.16–1.49 phi (Fig. S25B).

The sediment layer at a depth of 100–40 cm b.g.l. was rich in iron oxides. These iron oxides cemented sand grains, forming orthstein, and also cemented sand grains together with artefacts, producing orthstein crusts observed on flint fragments (Fig. S25B) and on pottery of the Corded Ware culture circle, the Neman culture, and the Pripyat-Neman culture. The high iron content in the Pit-3 outcrop (unlike in the MW-9) may indicate periods of significantly higher groundwater levels (cf. Tsvirko et al., 2024). We assume that the sediments of the Pit-3 outcrop were formed by a braided river during the Weichselian glaciation, similar to the previously mentioned deposits of the KAK-5, SU-S, C-1 and MW-9 outcrops.

The uppermost layer of humic sand f_3 (depth 50–0 cm b.g.l.), containing 4–6% of organic matter, was rich in artefacts. Below (from 50 cm b.g.l. and deeper), the number of archaeological finds significantly decreased (Fig. S25B; on these archaeological studies see Kryvaltsevich et al., 2023).

4.3 General overview of the studied basin with the Kakoryca-4 archaeological site

Based on sedimentological and geochemical data, a geological cross-section of the Kakoryca-4 site and its surrounding area was constructed (Fig. 3). Bringing together findings from various cores and outcrops, along with some cartographic data, provides a general overview of the studied basin.

Weichselian glaciation phase. According to data from the Gosudarstvennaya geologicheskaya karta SSSR (1982), the deposits of mid-channel bars of a braided river, identified in the KAK-5, SU-S, C-1, MW-9, and Pit-3 outcrops (Fig. 11AB; Figs. S24 and S25), dated to the Weichselian, are marked on this map as “lacustrine-alluvial” elevations (Fig. 4). Traces of the braided river paths are clearly visible on satellite images between

mid-channel bars (Figs. S7 and S8), bearing some resemblance to the present-day sand-bed braided river Yarlung Tsangpo in China (cf. Han et al., 2023; Fig. S26).

Evidence of permafrost from the Weichselian period in the study area – specifically, remnants of ice- and/or sand-wedge polygons – can be observed on satellite images of the fluvioglacial plain (Dnieper stage) south of Khomsk village (Fig. S27; Fig. 4).

Numerous aeolian dunes are visible in the study area on the satellite images (Fig. S28). According to the Gosudarstvennaya geologicheskaya karta SSSR (1982), these dunes are younger than the braided river (“lacustrine-alluvial”) deposits, as they overlie those deposits. Satellite images also convincingly indicate the presence of large palaeomeanders in the Yaselda River valley (Fig. S29; Fig. 4).

Bølling-Allerød phase. For this timeframe, two radiocarbon dates were obtained from calcareous gyttja I₁ of Sporovo II core: 14,794–14,221 cal BP (12,845–12,272 cal BC) and 14,080–13,891 cal BP (12,131–11,942 cal BC) (Fig. 6A).

On the geological cross-section, near the Kakoryca-4 elevation, we designated a layer of hypothetical Late Weichselian lacustrine nearshore sands (i.e., BA–YD; Fig. 3), which will be discussed below.

Younger Dryas phase. For this time interval, only one radiocarbon date was obtained, namely 12,616–12,479 cal BP (10,667–10,530 cal BC; YD-1; cf. Naughton et al., 2023), from the medium detritus gyttja I₃ of the UZS-1-2 core (Fig. S23B).

As for the archaeological results (besides the data from squares 24 and 25 of Excavation-3), our expeditions to the Kakoryca-4 site uncovered a flint straight dihedral burin of the Final Palaeolithic Swiderian culture, which existed in Polesie region during the Younger Dryas and the Early Preboreal (Table S3) (cf. Kryvaltsevich et al., 2023).

Preboreal phase. For the Preboreal, we obtained one radiocarbon date, which places the lacustrine nearshore sand with an admixture of organic matter I₄ at 10,763–10,606 cal BP (8,814–8,657 cal BC; mid-PB; outcrop NN-1 from Excavation-3; Fig. 9AB).

Regarding other archaeological discoveries not yet mentioned, two flint burins on retouched truncation with uncertain cultural affiliation (Swiderian–Kudlaevka culture?) were found in the 80–100 cm b.g.l. layer of Excavation-3 (outside squares 24 and 25), corresponding to the Middle Preboreal period. These two flint items most likely pertain to the Kudlaevka culture. In Excavation-3, layers at depths of 110–30 cm b.g.l. (referring only to those outside squares 24 and 25) contained Early Mesolithic flint artefacts, including those typical of the Kudlaevka culture. The Kudlaevka-type flint artefacts found in the

upper layers of Excavation-3 are likely redeposited or require a typological and chronological reassessment, potentially extending their period of use.

Boreal phase. Two radiocarbon dates were obtained for this period: 10,115–9,558 cal BP (8,166–7,609 cal BC; BO-1) from biogenic deposits b_1 of KO-20 core (most likely from gyttja; Fig. S22B), and 9,275–9,019 cal BP (7,326–7,070 cal BC; BO-2) from coarse detritus gyttja l_5 of Sporovo II core (Fig. 6A).

Satellite images show that the Kakoryca-4 and Kakoryca-6 elevations have erosional remnants of levees extending from their northern slopes, which will be discussed below (Figs. 1C and 2A; Figs. S3, S4 and S11).

Atlantic phase. About half of all obtained in the study ^{14}C dates belong to the Atlantic (Table 1). Three radiocarbon dates from coarse detritus gyttja l_5 and one from lacustrine nearshore silt and sand with a significant admixture of organic matter l_4 have been obtained for the Early Atlantic, pointing to the onset of Lake Sporovskoye transgression: 8,986–8,777 cal BP (7,037–6,828 cal BC) from Sporovo II core (Fig. 6A), 8,927–8,639 cal BP (6,978–6,690 cal BC) and 8,640–8,406 cal BP (6,691–6,457 cal BC) from PKK-1-2 core (Figs. 6B and 7), as well as 8,688–8,548 cal BP (6,739–6,599 cal BC) from A-1 outcrop (Fig. S23).

Two dates were obtained for the Middle Atlantic from coarse detritus gyttjas l_5 and l_6 of Sporovo II and KO-4 cores (Fig. 6A; Fig. S16): 7,669–7,614 cal BP (5,720–5,665 cal BC) and 7,320–7,010 cal BP (5,371–5,061 cal BC). One date was also obtained for the Middle Atlantic from biogenic deposits b_1 of core KO-20 (most likely from gyttja; Fig. S22B): 7,830–7,669 cal BP (5,881–5,720 cal BC).

A significant number of ^{14}C dates were obtained for the Late Atlantic from coarse detritus gyttjas l_5 and l_6 of the Sporovo II, PKK-1-2 and KO-4 cores (Fig. 6AB; Fig. S16), as well as from biogenic deposits b_1 of the A-1 outcrop (most likely from gyttja; Fig. S23A), indicating that the transgression of Lake Sporovskoye was continued during AT-3: 6,669–6,564 cal BP (4,720–4,615 cal BC), 6,441–6,305 cal BP (4,492–4,356 cal BC), 6,391–6,294 cal BP (4,442–4,345 cal BC), 6,281–6,205 cal BP (4,332–4,256 cal BC), 6,276–6,015 cal BP (4,327–4,066 cal BC), and 5,922–5,661 cal BP (3,973–3,712 cal BC). One date was obtained for the Late Atlantic from organic mud layer a_4 of the KO-8 core (Fig. S22A): 6,940–6,680 cal BP (4,991–4,731 cal BC) (Table 1).

Remnants of a bank ridge were identified on satellite images in the area north of Lake Sporovskoye (Fig. S30), which are discussed below.

Subboreal and Subatlantic phases. Two radiocarbon dates were obtained for the Subboreal period from telmatic peat h₁ and peaty organic mud a₃ in the Sporovo II and PKK-1-2 cores (Fig. 6AB): 4,957–4,842 cal BP (3,008–2,893 cal BC) and 3,826–3,583 cal BP (1,877–1,634 cal BC).

The beginning of the Subatlantic (SA) is documented by a radiocarbon date of 2,863–2,784 cal BP (914–835 cal BC) obtained from coarse detritus gyttja l₅ in the UZS-1-2 core (Fig. S23B). The following ¹⁴C dates were obtained for the Early Subatlantic from overbank peaty organic mud a₃ and organic mud a₄ in the KO-9 core (Fig. 6C): 2,463–2,359 cal BP (514–410 cal BC), 2,359–2,339 cal BP (410–390 cal BC) and 2,306–2,151 cal BP (357–202 cal BC). The dates refer to the Late Subatlantic from overbank organic muds a₄ and a₃, and biogenic deposits b₁ in the PKK-1-2 and KO-20 cores (Fig. 6B; Fig. S22B): 529–504 cal BP (1,421–1,446 cal AD), 456–319 cal BP (1,494–1,631 cal AD), and 256–34 cal BP (1,694–1,917 cal AD).

The archaeological discoveries made outside squares 24 and 25 of Excavation-3 have broadened the cultural spectrum of the Corded Ware culture circle at the Kakoryca-4 site. The findings include not only pottery characteristic of the Corded Ware culture circle itself but also its variants incorporating elements from the Neman culture, the Globular Amphora culture, Epi-Corded Ware cultures, and other traditions. We also discovered pottery fragments of the Middle Dnieper culture from the Late Neolithic–Early Bronze Age (Table S3). Our archaeological excavations in 2022 revealed pottery fragments of the Trzciniec Cultural Circle (Middle Bronze Age, Late Subboreal) in the uppermost layer of deposits of the Irżawe wetland, corresponding to the peaty organic mud layer a₃ in Excavation-3 (Fig. 9AB, Table S3). Also, the analysis of the artefact collection showed a small number of finds from the Iron Age, the Middle Ages, and the Modern and Contemporary eras, corresponding to the Subatlantic period (cf. Kryvaltsevich et al., 2023).

INTERPRETATION AND DISCUSSION

The landscape of the Kakoryca-4 site acquired its modern appearance relatively recently. Our reconstructions allow to establish changes in the environment that took place in the vicinity of the Kakoryca-4 site during the Poozerian (Weichselian) glaciation and Holocene, and which undoubtedly influenced the functioning of human communities starting from the Final Palaeolithic.

5.1 Weichselian (primarily before 14,700 cal BP)

Important geomorphological processes shaping the landscape features of the study area occurred during the Weichselian glaciation, when the study area was under periglacial conditions and situated at least 160–190 km S from LGM (Fig. 1A). This period was associated with the expansion of permafrost into the study area, as evidenced by the remnants of ice- and/or sand-wedge polygons found on the surfaces formed from Saale fluvioglacial deposits south of the Khomsk village (Fig. S27). In this study, we were not focused on detailed studies of permafrost in the area of the Kakoryca-4 site. However, we made some correlations and assumptions based on the data from well-studied sites in Central Poland, where periglacial cryogenic structures (such as syngenetic and epigenetic ice-wedge pseudomorphs, sand-wedges, post-pingo remnants, congelifluction involutions) were discovered (Peters-Zganiacz, 2011, 2013; Dzieduszyńska et al., 2020). In Central Poland, the main period of permafrost activity was the Plenivistulian (MIS 4, 3, 2), when a continuous permafrost was established. Most of ice-wedges and sand-wedges were developed during the Middle (~60–30 ka BP, MIS 3) and Upper (~30–15 ka BP, MIS 2) Plenivistulian. The Upper Plenivistulian, with its extreme climate cooling and dryness combined with the maximum extent of the Weichselian ice sheet, was the main stage of the formation of sand-wedges filled with aeolian sand (Peters-Zganiacz, 2011, 2013; Dzieduszyńska et al., 2020). Thus, it is most likely that the remnants of ice- and/or sand-wedge polygons discovered in the vicinity of the Kakoryca-4 site (Fig. S27) were formed during the Plenivistulian.

We consider the braided river activity to be the most significant geological process on the study area during the last glaciation. Our research was not focused on the OSL dating of sediments, however, we assume that the Weichselian glaciation was the time when the deposits forming the Kakoryca-4 elevation and all other higher and lower elevations in the area neighbouring Lake Sporovskoye from E and S were accumulated as mid-channel bars in a sand-bed braided river channel (Fig. 1B; Fig. S3–S8). Evidence from Central Poland shows that in the Middle and Upper Plenivistulian, a large volume of fluvial deposits was accumulated in river valleys (10–30 m of deposits between ~40 ka and 22 ka ¹⁴C BP), as a result of the activity of braided rivers. In Central Poland, the Plenivistulian is generally associated with the most significant aggradation phase in river valleys (Turkowska, 1988; Turkowska and Dzieduszyńska, 2011; Dzieduszyńska et al., 2020). Therefore, by analogy, it is plausible that braided river deposits of the Kakoryca-4 elevation and its surroundings were accumulated mainly in the Middle and/or Upper Plenivistulian. During these

periods, numerous braided rivers created vast plains with mid-channel bars, such as the Kakoryca-4 bar, primarily composed of fine and medium sands that accumulated in a low-energy fluvial environment. During the formation of these mid-channel bars in the Middle and Upper Plenivistulian, small chute channels existed between some bars, where overbank sand with a slight admixture of organic matter was accumulated (f₄; Fig. 11B; Figs. S3 and S24BC). The environment at that time was characterized by high water saturation caused by numerous paths of braided rivers (Figs. S7 and S8). The Plenivistulian landscape around the Kakoryca-4 site (Figs. S7 and S8) could to some extent resemble, for instance, the present-day sand-bed braided river Yarlung Tsangpo in China, with its numerous paths, chute channels and mid-channel bars (Fig. S26; on the topic see Han et al., 2023).

In Belarusian literature, the Plenivistulian braided river deposits of studied elevations (Kakoryca-4, Kakoryca-5, Kakoryca-10A/10B) are described as “lacustrine-alluvial” (Gosudarstvennaya geologicheskaya karta SSSR, 1982; Fig. 4). However, based on our sedimentological analysis data obtained for these “lacustrine-alluvial” elevations (Fig. 11AB; Figs. S24 and S25), we consider their deposits to be the sediments of a sand-bed braided river. These elevations, along with other higher and lower rounded elevations (Fig. 1BC; Figs. S3–S8), which we assume to be of the same origin, are composed of braided river paths and mid-channel bar sediments, with occasional overbank deposits accumulated in small chute channels between some mid-channel bars (Fig. 11B; Fig. S24BC).

The following stage in the geomorphological evolution of the study area is associated with a shift in the Yaselda River channel pattern from braided into meandering river with large meanders (Fig. S29). This transformation of the channel pattern likely occurred as a result of a reduction in sediment load, an expansion of forest vegetation, and a decrease in the frequency of floods within the braided river system (cf. Szumański, 1983; Starkel, 1997; Starkel et al., 2007; Dzieduszyńska et al., 2020). During the transitional phase, the abandonment of numerous paths of the braided river was accompanied by an increase in erosional activity. The intensification of erosion led to the deep incision of the Yaselda River channel into the valley floor and the morphological emergence of a terrace formed with braided river deposits, including mid-channel bar deposits (the terrace is presumably of Middle-Upper Plenivistulian age). Consequently, the Kakoryca-4 mid-channel bar became a fragment of this Vistulian terrace. Following this phase, conditions stabilized, resulting in the formation of a wide meandering channel of the Yaselda River. The evidence of these processes is provided by large palaeomeanders that cut through the plain of braided

stream deposits (Fig. S29). The Yaselda River had a very wide meandering channel, significantly larger than the current one. We did not conduct geochronometric analysis of the described Yaselda R. channel transformation, but assumptions can be made based on the findings from the well-studied river valleys in Central Poland that remained under similar palaeoenvironmental conditions. Evidence from Central Poland suggests that the time of channel pattern transformation – from braided into meandering with large meanders – varied within the Late Weichselian. In some valleys, the channel pattern changed ~14 ka ¹⁴C BP, while in others, the braided pattern persisted up to the Holocene (Turkowska and Dzieduszyńska, 2011; Dzieduszyńska et al., 2020; Antczak-Orlewska et al., 2023). Accordingly, we can infer that in the Late Weichselian the Yaselda R. channel transformed into a meandering form with large meanders.

The open landscape during the last glaciation, characterized by an absence of continuous vegetation cover, is suggested by numerous aeolian dunes visible on satellite images (Fig. S28). Based on comparison with other well-studied sites, we assume that the formation of numerous dunes discovered in the study area most likely occurred during the cold periods of the Late Weichselian (Fig. S28). We did not perform sedimentological or OSL analyses of these dunes, however, evidence from Central Poland suggests that the development of aeolian landforms (aeolian cover and dunes) took place during three cold phases of the Late Weichselian (classic scheme): the Oldest Dryas, the Older Dryas, and the Younger Dryas. Moreover, the Older Dryas was the main phase of formation of distinct aeolian dunes several meters in height (Dylikowa, 1967; Manikowska, 1985; Dzieduszyńska, 2011; Dzieduszyńska et al., 2020; Dzieduszyńska and Petera-Zganiacz, 2024).

5.2 Bølling-Allerød (14,700 to 12,800 cal BP; 12,700 to 10,800 cal BC)

This period marked significant environmental transformations. The climate warming of the Bølling-Allerød interstadial (Rasmussen et al., 2006; Druzhinina et al., 2023; Nogarotto et al., 2023) led to the intense melting of permafrost in the study area. Data from Central Poland indicate that permafrost has completely disappeared in the Allerød (Goździk, 1996; Klatkova, 1996; Dzieduszyńska et al., 2020). Permafrost degradation in the study area most likely resulted in the formation of shallow lakes on the alluvial (braided river) plain. Lake Sporovskoye was one of these lakes, emerged during the Bølling-Allerød probably due to thermokarst processes. At that time, calcareous and mineral gyttja, mixed with organic matter, were accumulated in Lake Sporovskoye (Fig. 6A). The lake was

significantly larger than today (Figs. 1 and 6A), indicating high water levels and a water-saturated environment in the study area. During its Bølling-Allerød transgression, which took place according to the age-depth model (prob. 95.4%) between 14,417–14,057 and 14,310–13,638 cal BP (Fig. S19), Lake Sporovskoye likely approached the Kakoryca-4 elevation from the north, or even surrounded it (see hypothetical lacustrine nearshore sands in Fig. 3).

It is likely that the above-described transformation of the Yaselda River channel pattern took place during the Bølling-Allerød interstadial (cf. Vandenberghe, 1994), partly as a result of the expansion of forest vegetation (cf. Starkel et al., 2007; Fig. S29). Thus, it is likely that the morphological emergence of the Plenivistulian fragmented terrace – consisting of elevations such as Kakoryca-4, Kakoryca-6, Kakoryca-10A, Kakoryca-10B (Figs. S3 and S11), as well as other nearby higher and lower rounded elevations (Fig. 1C) – occurred during the Bølling-Allerød.

The warmer conditions of the Bølling-Allerød led to the expansion of open-canopy pine-birch forests into the study region (LPAZs SPII-1 and SPII-2; Fig. 10). A high abundance of *Pinus* and *Betula* pollen is interpreted as an indicator of a relatively warm and humid environment (cf. Wang et al., 2022). At the same time, the occurrence of a small amount of *Betula nana*-type pollen, a cold-adapted species (cf. Zarzycki et al., 2002), may indicate local depressions characterized by a colder microclimate. A significant part of the landscape was open and treeless, as indicated by the presence of a considerable amount of pollen from light-demanding taxa, including *Juniperus*, *Hippophaë*, *Artemisia*, *Chenopodiaceae*, and *Helianthemum* (Fig. 10; cf. Zarzycki et al., 2002; Pawłowski et al., 2015). The occurrence of pollen from drought-tolerant taxa, such as *Ephedra*, *Chenopodiaceae*, and *Artemisia*, may indicate the presence of locally dry areas within the studied landscape (Fig. 10; cf. Wang et al., 2022).

During the described period, *Myriophyllum-Potamogeton* communities of fully submerged plants prevailed in the littoral zone of Lake Sporovskoye (including *Potamogeton* cf. *utilus*; Figs. 6A and 10).

Bølling-Allerød deposits were identified in a reference core from the nearby palaeolake Ivanisovka (~50 km SE of Lake Sporovskoye; 52°15'20.86"N 26°3'13.39"E; Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022). The Bølling-Allerød interval in the Ivanisovka core is defined based on a single radiocarbon date of 11,470±200 BP (13,573–13,165 cal BP), which corresponds to the *Pinus-Betula* LPAZ (Zernitskaya, 2022). Similarly to the data from the Sporovo II core, pollen assemblages from the Ivanisovka

core indicate the expansion of open-canopy pine-birch forests during the Bølling-Allerød in the Yaselda River basin, together with widespread open, treeless areas, as reflected by high proportions of *Artemisia*, *Chenopodiaceae*, and NAP, as well as the presence of *Juniperus* pollen (Zernitskaya, 2022).

Overall, climate warming, degradation of permafrost, succession of forest-steppe vegetation, and formation of thermokarst shallow lakes, with the large food-abundant Lake Sporovskoye, could potentially contribute to the expansion of Final Palaeolithic communities into the study area. The Kakoryca-4 terrace remnant, being a natural elevation above Lake Sporovskoye, might have been utilized by these societies. However, we did not find any artefacts from this period; therefore, there is no evidence that the Kakoryca-4 territory was used by prehistoric people during the Bølling-Allerød.

5.3 Younger Dryas (12,800 to 11,700 cal BP; 10,800 to 9,700 cal BC; Swiderian culture)

During the older part of the Younger Dryas (YD-1; Table S8; Naughton et al., 2023), medium detritus gyttja started to be accumulated in Lake Sporovskoye (Fig. S23B). At that time, *Myriophyllum-Potamogeton* communities (including *Potamogeton rutilus*) of fully submerged plants thrived in the lake waters. The spread of Characeae algae on the lake bottom (Fig. S23B) indicates hard-water conditions associated with carbonate leaching from the catchment area (cf. Pełechaty et al., 2013; Pukacz et al., 2014; Kittel et al., 2025), as well as with the dissolution of Bølling-Allerød calcareous gyttja (Fig. 6A; cf. Müller et al., 2006; Woszczyk, 2016). The fauna of Lake Sporovskoye during the older part of the Younger Dryas included i.a. *Cristatella mucedo* and *Daphnia*. On the surface of the Kakoryca-4 elevation and adjacent hills, *Betula nana* was present among other plants (Fig. S23B).

It is entirely possible that in the Younger Dryas, the climate cooling could have led to a reappearance of permafrost in certain areas of the study territory. Evidence from Central Poland, for instance Koźmin Las site, suggests the local sporadic presence of frozen ground in the Younger Dryas (Dzieduszyńska, 2014; Dzieduszyńska et al., 2020).

Palaeogeographic data for the Younger Dryas are limited due to a mid-BO flood event that caused an erosion of YD–BO-1 deposits north of the Kakoryca-4 elevation (erosional hiatus – Figs. 3 and 6AB, Fig. S16). Consequently, the history of transgressions and regressions of Lake Sporovskoye from the onset of the Younger Dryas (YD-1) to the Late Boreal (BO-2) remains poorly understood, as only fragmentary data are available.

High-resolution studies in areas unaffected by erosion from the Yaselda River, i.e., located farther from the Kakoryca-4 site, are required to clarify lake dynamics during this period; such studies were not undertaken in the present work. However, we cautiously suggest that in the Younger Dryas, the Kakoryca-4 terrace was probably located on the shore of Lake Sporovskoye, which reached it from the north (YD transgression) (Fig. 3).

In the reference Ivanisovka core, the Younger Dryas is represented by the *Betula-Salix-Artemisia* LPAZ, for which no radiocarbon dates were obtained (Zernitskaya, 2022). Based on the data from Zernitskaya (2022), the Younger Dryas in the Yaselda River basin was characterized by a pronounced expansion of open, treeless areas, as evidenced by a decline in *Pinus* and an increase in *Artemisia* and NAP. Colder climatic conditions during the Younger Dryas are additionally suggested by the occurrence of *Selaginella selaginoides* spores (Zernitskaya, 2022; cf. Zarzycki et al., 2002).

The first human groups at the Kakoryca-4 terrace remnant appeared during the Younger Dryas (Table S3). These pioneer groups of people belonged to the hunter-gatherer Final Palaeolithic Swiderian culture (Kryvaltsevich et al., 2023). Among the artefacts attributed to the Swiderian culture (Kryvaltsevich et al., 2023; Fig. S23B), only a single specimen was recovered from the Younger Dryas deposits: a flint flake found in lacustrine nearshore sand dated to the YD-1/BA period (depth 106–109.5 cm; Fig. S23B). This *in situ* artefact provides evidence that Swiderian communities occupied the Kakoryca-4 terrace remnant, along with the surrounding area, during the older part of the Younger Dryas.

5.4 Preboreal (11,700 to 10,200 cal BP; 9,700 to 8,200 cal BC; Swiderian culture (?), Kudlaevka culture)

Most likely, Lake Sporovskoye experienced a transgression throughout the Preboreal, as evidenced by the presence of a lacustrine nearshore sand layer with a significant silt admixture in the KO-20 core (layer l₄; Fig. S22B), which is interpreted to have accumulated during the Preboreal and Early Boreal (before 10,115–9,558 cal BP; Fig. S22B).

The mid-BO flood event, which caused erosion of the YD–BO-1 deposits in the Sporovo II core area (Fig. 6A), did not affect the mid-Preboreal lacustrine nearshore sands (dated to 10,763–10,606 cal BP) in the PKK-1-2 core area (Figs. 3, 6B and 9). Therefore, we are able to draw certain palaeogeographic conclusions about the mid-Preboreal based on the data obtained from these deposits.

In the Middle Preboreal, Lake Sporovskoye was larger than present time. The Kakoryca-4 terrace remnant was located on the shore of the lake, which approached it from

the north (the mid-PB transgression) (Figs. 3 and 7; Fig. S16). In the littoral zone of the lake near Kakoryca-4, sands with an admixture of macrofossils of typically aquatic plants were accumulated (Figs. 6B and 7). Under the warm mid-PB climate (Pawłowski et al., 2015; Zernitskaya, 2022), the shallow and warm Lake Sporovskoye was dominated by floating-leaved plant communities with *Nuphar*, *Nymphaea*, and *Stratiotes aloides* (Fig. 7). A high abundance of *Stratiotes aloides* seeds provides additional evidence for warm climatic conditions in the summer in the Middle Preboreal (cf. Gałka, 2010). The deeper parts of the lake littoral were overgrown with *Chara* algae (Fig. 7), indicating hard-water conditions at that time (cf. Pukacz et al., 2014; Kittel et al., 2025), which were caused by carbonate leaching from the catchment area (cf. Pełechaty et al., 2013) and, likely, the dissolution of Bølling-Allerød calcareous gyttja (Fig. 6A; cf. Müller et al., 2006; Woszczyk, 2016). It is likely that the Yaselda River, by eroding Bølling-Allerød calcareous gyttja upstream, could have been another source of dissolved carbonates to the lake ecosystem. Among the semi-submerged and nearshore vegetation at the Kakoryca-4 terrace remnant, *Phragmites australis* and members of the Cyperaceae family were dominant (Figs. 7 and 9).

The occurrence of ruderal plants on the Kakoryca-4 terrace remnant, such as *Chenopodium glaucum* and *Urtica*, may indicate the presence of prehistoric human communities at the site in the mid-PB (Fig. 7). Data clearly indicate that alder trees were common on the terrace during this period (Fig. 7). The Kakoryca-4 terrace remnant was densely forested in the mid-PB, mainly with pine and alder (Figs. 7 and 9B), and prehistoric communities of that time lived beneath the canopy of these trees along the lakeshore.

The narrowing of the Yaselda River channel to approximately its current size likely occurred in the Preboreal (Fig. S29). Research results from river valleys in Central Poland have shown that such a transformation of river channel, from large meanders to small ones, occurred in the Early Holocene (Turkowska, 1988; Vandenberghe, 1994; Turkowska and Dzieduszyńska, 2011; Antczak-Orlewska et al., 2023). Consequently, it can be concluded that the present-day Yaselda River is an example of an “underfit” stream after Dury (1970).

In the Ivanisovka reference core (Zernitskaya, 2022), the Preboreal corresponds to the *Betula-Salix-Ulmus* LPAZ, which is dated by a single radiocarbon date of 9,470±300 BP (11,191–10,381 cal BP). Pollen assemblages from the Ivanisovka core indicate that open-canopy birch forests with a minor admixture of *Pinus* dominated the Yaselda River basin during the Preboreal. The data also suggest the appearance of *Ulmus* in the Yaselda River basin during this period (Zernitskaya, 2022).

Preboreal deposits were also identified in the reference core from the nearby Lake Bobrovichskoe (~35 km NE of Lake Sporovskoye; 52°37'35.78"N 25°46'14.67"E; Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022). In the Bobrovichskoe core, the Preboreal corresponds to the *Betula-Ulmus-Poaceae* LPAZ, which is dated by a single radiocarbon date of 9,380±180 BP (11,065–10,297 cal BP; Zernitskaya, 2022). Pollen assemblages from the Bobrovichskoe core are very similar to those from the Ivanisovka core and confirm that open-canopy birch forests with a minor admixture of *Pinus* and a small amount of *Ulmus* dominated the Yaselda River basin during the Preboreal.

It is possible that Swiderian communities continued to use the Kakoryca-4 terrace during the first half of the Preboreal period (Table S3). Nevertheless, we consider the Preboreal to have been mainly a period of activity of the Early Mesolithic Kudlaevka culture people, whose communities first appeared at the Kakoryca-4 terrace during this time. Among all the finds, only a flint adze with Mesolithic affiliation, most likely belonging to the Kudlaevka culture, was found *in situ* in the mid-PB sands (Fig. 9B). Many other artefacts of the Kudlaevka culture were redeposited (Fig. 9B), and some, although located *in situ* in the mid-PB sands, showed uncertain Swiderian–Kudlaevka affiliation (finds outside squares 24 and 25). This uncertainty prevents a definitive identification of which cultural communities occupied the Kakoryca-4 terrace at that time, since both cultures correspond to the Middle Preboreal according to conventional interpretations (Table S3).

The subsistence strategy of the relatively small groups of the Kudlaevka culture were focused on hunting, fishing, and gathering. Some flint artefacts found at the Kakoryca-4 site, along with accompanying bone remains and products, likely support this interpretation.

Communities of both the Swiderian and Kudlaevka cultures may have found the Kakoryca-4 terrace remnant particularly convenient due to its access to Lake Sporovskoye and its ecosystem.

5.5 Boreal (10,200 to 9,000 cal BP; 8,200 to 7,000 cal BC; Kudlaevka culture, Janislawice culture (??))

Limited data were obtained for the Early Boreal (BO-1). Nevertheless, these data point to a transgression of Lake Sporovskoye during BO-1, which was expressed in the accumulation of lacustrine deposits (nearshore sands l_4 and biogenic deposits b_1) at a considerable distance from the present-day lake boundaries (core KO-20 – Fig. 1BC,

Fig. S22B). The results clearly show that in the Early Boreal, *Potamogeton* was present in the deeper parts of Lake Sporovskoye, while *Hippuris vulgaris* occupied the shallow-water areas. The wetland areas adjacent to the lake were covered with mosses, *Carex*, and *Betula* cf. *humilis* (Fig. S22B).

Most likely, in the Middle Boreal, a substantial regression of Lake Sporovskoye took place prior to the mid-BO flood event.

An important palaeogeographic event occurred in the Middle Boreal (mid-BO): a strong flood episode in the Yaselda River valley, that was recorded as a thin layer of white fine-grained sand in Excavation-3 (79.5–79 cm b.g.l. in the NN-1 outcrop; Fig. 9A; Fig. S16). This mid-BO flood event occurred approximately 9,500–9,300 cal BP (calculated based on the difference in ^{14}C in the KO-20 and Sporovo II cores; Fig. S22B and Fig. 6A). The mid-BO flood event caused an erosion of Early Boreal and Late Preboreal deposits in Excavation-3 and in area north of the Kakoryca-4 terrace (KO-3, KO-4, PKK-1-2, KO-5, KO-6, and NN-1 profiles; Fig. 9A; Fig. S16), as well as Early Boreal, Preboreal and Younger Dryas sediments in the Sporovo II core (Fig. 6A). Thus, the mid-BO flood event affected wide floodplain area north of the Kakoryca-4 terrace, extending to the location of the Sporovo II core (erosional hiatus in the Sporovo II, KO-3, KO-4, PKK-1-2, KO-5, KO-6, and NN-1 profiles; Figs. 3, 6A and 9A; Fig. S16). During this strong mid-BO flood event, the waters of the meandering Yaselda River cut the Kakoryca-4 and Kakoryca-6 terrace remnants, which led to the formation of erosional remnants of levees extending from the northern slopes of the hills (Figs. 1C and 2A; Figs. S3, S4 and S11). As a result of the flood, in Excavation-3 we observe a very sharp erosional boundary between geological layers (a thin layer of white fine-grained sand between layers l_4 and l_5 ; Fig. 9A). This flood event correlates well with the distinct phase of increased fluvial activity documented for Polish rivers between 9,600 and 8,400 cal BP (Starkel et al., 2013).

Since the mid-BO flood event did not cause an erosion of mid-PB lacustrine sand layer l_4 north of the Kakoryca-4 elevation (Figs. 6B and 9; Fig. S16), deposits of the Younger Dryas and the Bølling-Allerød (most likely lacustrine nearshore sands) may be preserved beneath this layer (hypothetical deposits – Fig. 3).

This mid-BO flood event also indicates that Lake Sporovskoye was a flow-through lake during the Middle Boreal, with the Yaselda River flowing through it.

In the Late Boreal (BO-2), Lake Sporovskoye underwent a prominent transgression that persisted throughout the Early and Middle Atlantic (Fig. 6A). During the BO-2

transgression, which occurred according to the age-depth model (prob. 95.4%) between 9,778–8,898 and 9,127–8,657 cal BP (Fig. S19), the waters of Lake Sporovskoye were extensively overgrown with aquatic vegetation, including *Stratiotes aloides*, *Nuphar*, *Nymphaea*, *Potamogeton*, and *Myriophyllum* (Figs. 6A and 10).

Pollen assemblages from the Late Boreal (SPII-2/3 LPAZ; Fig. 10) indicate a substantial transformation of the regional forest cover. During this period, closed-canopy pine-broadleaf forests (composed of pine, elm, oak, ash, linden, and hazel) became dominant in the Yaselda River basin. The development of a closed forest canopy is primarily indicated by the expansion of *Corylus* (Fig. 10), a shade-tolerant understorey shrub capable of regeneration under shaded conditions (cf. Catoni et al., 2015; Franzén et al., 2025). The exceptionally high *Betula* pollen values (Fig. 10) probably reflect not only the regional spread of birch but also a pronounced local contribution.

In the reference Ivanisovka core, the Boreal is represented by the *Pinus-Betula-Ulmus-Corylus* LPAZ, for which no radiocarbon dates were obtained (Zernitskaya, 2022). The pollen assemblages from the Ivanisovka core correspond well with those from the Sporovo II core (Fig. 10), confirming that closed-canopy pine-broadleaf forests (*Pinus*, *Ulmus*, *Quercus*, *Fraxinus*, *Tilia*, and *Corylus*) were present in the Yaselda River basin during the Late Boreal. According to the Ivanisovka record, the Early Boreal was characterized by the appearance and gradual expansion of *Corylus*, *Quercus*, *Fraxinus*, and *Tilia* in the Yaselda River basin, accompanied by increasing proportions of *Pinus* and *Ulmus* (Zernitskaya, 2022). Thus, during the Boreal, open-canopy pine-birch forests with an admixture of elm were transformed into closed-canopy pine-broadleaf forests.

In the Bobrovichskoe reference core, the Boreal corresponds to the *Pinus-Ulmus-Corylus* LPAZ, for which no radiocarbon dates were obtained (Zernitskaya, 2022). The Bobrovichskoe record is in good agreement with the data from the Ivanisovka and Sporovo II cores (Zernitskaya, 2022; Fig. 10). It provides further evidence that closed-canopy pine-broadleaf forests developed in the Yaselda River basin during the Boreal, as shown by the appearance and gradual expansion of *Corylus*, *Quercus*, *Fraxinus*, and *Tilia*, together with increasing proportions of *Pinus* and *Ulmus* (Zernitskaya, 2022).

No archaeological artefacts were found in the Boreal-dated deposits. However, redeposited finds (e.g., Fig. 9B) may indicate that Kudlaevka culture communities continued to occupy the Kakoryca-4 terrace during the Boreal (Fig. 9B). According to the conventional chronology of prehistoric cultures (Table S3), communities of the Late

Mesolithic Janisławice culture may have also appeared at the Kakoryca-4 site in the Late Boreal.

The functioning of prehistoric communities – most likely only those of the Kudlaevka culture – was undoubtedly affected by the mid-BO flood event. The increased activity of the Yaselda River at that time likely forced prehistoric people to abandon the Kakoryca-4 terrace remnant and move south to higher-elevated areas.

5.6 Early and Middle Atlantic (9,000 to 6,800 cal BP; 7,000 to 4,800 cal BC; Kudlaevka culture (?), Janisławice culture)

A distinct record of Lake Sporovskoye transgression is associated with the Early and Middle Atlantic (Figs. 1BC and 6AB). According to the age-depth model (prob. 95.4%), this transgression occurred between 9,127–8,657 and 7,571–6,401 cal BP (Fig. S19).

The transgression of Lake Sporovskoye, which began in the Late Boreal (Fig. 6A), intensified significantly in the Early Atlantic. During this AT-1 transgression, the lake covered a much larger area than in the Late Boreal. The intensification of the AT-1 transgression is evidenced by the onset of AT-1 coarse detritus gyttja accumulation near the Kakoryca-4 terrace remnant, along with the absence of BO-2 deposits in this area (Figs. 6B and 9; Fig. S16). This transgression continued in the Middle Atlantic (Figs. 6AB and 1BC).

During the Early and Middle Atlantic, Lake Sporovskoye was at least twice as large as it is today. Its boundaries roughly followed along the present-day isoline of 142.5 m a.s.l. (probably even higher), as evidenced by the discovery of a coarse detritus gyttja layer l_5 in the NN-1 outcrop, which is situated on this isoline (Figs. 1BC, 2C and 9A; Fig. S1). We estimate that the AT-1 and AT-2 water level of Lake Sporovskoye was approximately one meter higher than its current level. The Kakoryca-4 terrace remnant was likely entirely surrounded by the waters of Lake Sporovskoye, turning into an island (Fig. 1C). During the Early and Middle Atlantic transgression, the lake expanded into the areas between the mid-channel bars of a Weichselian braided river, forming there shallow reservoirs where the silty material with a significant admixture of organic matter l_4 was accumulated (A-1 outcrop; Fig. 1BC; Fig. S23A).

During the Early and Middle Atlantic transgression, nearshore processes led to the formation of the lake bank ridge (Fig. S30). Due to the dense overgrowth, the main type of accumulating sediment during the AT-1 and AT-2 lake was coarse detritus gyttja (Fig. 6AB; Fig. S16). The overgrowth was so intense that highly organic coarse detritus

gyttjas l₅ and l₆ accumulated in both the nearshore (PKK-1-2 core) and relatively deep (Sporovo II core) areas of the lake (Fig. 6AB).

During the Middle Atlantic, the Yaselda River flowed through Lake Sporovskoye, introducing sand and silt into the coarse detritus gyttja (Sporovo II core, unit l₆ in Fig. 6A). The high proportion of mineral matter observed in the AT-2 deposits of the Sporovo II core (unit l₆, ¹⁴C age of 7,669–7,614 cal BP) and in the KO-20 core (unit b₁, ¹⁴C age of 7,830–7,669 cal BP) was most likely related to increased activity of the Yaselda River, expressed as a period of intense flooding around 7,800–7,600 cal BP. These data from the Yaselda River valley are in good agreement with data from Polish river valleys, where a peak in fluvial activity was recorded at around 7,700 cal BP (Starkel et al., 2013).

On the slopes of the Kakoryca-4 terrace remnant, slope and shoreline erosion processes were activated, leading to the influx of mineral matter into the coarse detritus gyttja north of the Kakoryca-4 (evidenced by a decrease in LOI values from 83 to 36%; Fig. 9A). These processes may also have led to the redeposition of certain artefacts from the slopes or surface of the Kakoryca-4 terrace into younger gyttja sediments. For instance, the flint burin on truncation attributed to the Swiderian–Kudlaevka culture may represent a redeposited find, particularly if it in fact belongs to the Swiderian culture, since the Kudlaevka culture may have still persisted at the Kakoryca-4 site in the AT-1 (Fig. 9B; Table S3). The activation of erosion processes and the redeposition of sediments and artefacts may have been partly driven by human impact, including vegetation suppression at the Kakoryca-4 site area. The presence of a large number of macrofossils of ruderal plants, including *Chenopodium glaucum* and *Urtica* may indicate anthropogenic impact on the Kakoryca-4 terrace remnant (KK-2 LMAZ; Fig. 7).

The warm and humid climate during the Early and Middle Atlantic (Davis et al., 2003; Kulesza et al., 2012; Zernitskaya, 2022; Herzsuh et al., 2023) led to an increase in the biodiversity of aquatic vegetation in Lake Sporovskoye. Areas covered by floating-leaved plants (*Stratiotes aloides*, *Nuphar*, *Nymphaea*) expanded (Figs. 7 and 10). The warm climatic conditions in the summer during this period are also indicated by a large number of *Stratiotes aloides* seeds found (Fig. 7; cf. Gałka, 2010). Communities of fully submerged vegetation reached the highest biodiversity, with notable expansion of *Ceratophyllum submersum*, *Caulinia minor*, and *Najas marina* (Figs. 7 and 10). The spread of *Chara* algae (Fig. 7) indicates hard-water conditions (cf. Pukacz et al., 2014; Kittel et al., 2025), resulting from carbonate leaching from the catchment area (cf. Pelechaty et al., 2013) and

the dissolution of Bølling-Allerød calcareous gyttja (Fig. 6A; cf. Müller et al., 2006; Woszczyk, 2016).

The wetland vegetation near the Kakoryca-4 terrace remnant was dominated by Cyperaceae and Typhaceae communities (Fig. 7). The terrace surface was covered with trees, mainly birch (Fig. 7). The warmer climate of the Early and Middle Atlantic led to a substantial increase in the abundance of broadleaf taxa (*Corylus*, *Quercus*, *Ulmus*, *Tilia*, and *Fraxinus*) in the regional closed-canopy pine-broadleaf forests (Fig. 10). Areas occupied by *Alnus* expanded significantly as well (Fig. 10). The presence of *Viscum* and *Hedera* pollen indicates hot summers and mild winters (Fig. 10; Fig. S20; cf. Sobkowiak-Tabaka et al., 2020).

In the Ivanisovka reference core, the Atlantic period is represented by several closely similar LPAZs, including *Ulmus-Corylus-Alnus*, *Pinus-Picea-Q.m.*, and *Quercus-Ulmus-Corylus-Fraxinus-Tilia*, none of which are supported by radiocarbon dates (Zernitskaya, 2022). The pollen record from Ivanisovka core closely corresponds with that from the Sporovo II core (Fig. 10) and likewise shows that during the Early and Middle Atlantic, broadleaf taxa (*Corylus*, *Quercus*, *Ulmus*, *Tilia*, and *Fraxinus*) became more abundant within the regional closed-canopy pine-broadleaf forests of the Yaselda River basin (Zernitskaya, 2022).

In the Bobrovichskoe reference core, the Atlantic period corresponds to the *Ulmus-Quercus-Fraxinus-Tilia-Corylus-Alnus* LPAZ, for which two radiocarbon dates of 6,230±80 BP (7,253–7,009 cal BP; Middle Atlantic) and 5,630±90 BP (6,490–6,310 cal BP; Late Atlantic) were obtained (Zernitskaya, 2022). The pollen record from the Bobrovichskoe core shows very good agreement with the Ivanisovka and Sporovo II cores (cf. Zernitskaya, 2022; Fig. 10), confirming that during the Early and Middle Atlantic, the abundance of broadleaf taxa (*Corylus*, *Quercus*, *Ulmus*, *Tilia*, and *Fraxinus*) increased substantially within the regional closed-canopy pine-broadleaf forests of the Yaselda River basin (Zernitskaya, 2022).

The discovered flint trapeze of the Kudlaevka culture may suggest that its communities were present on the Kakoryca-4 terrace at the beginning of the Early Atlantic period (Fig. 9B; cf. Kalechyts and Kolasau (2021, 2023)).

In the Early and Middle Atlantic, hunter-gatherer communities of the Late Mesolithic Janisławice culture functioned at the Kakoryca-4 site. The presence of these human communities is evidenced by an *in situ* flint core attributed to the Janisławice culture (Fig. 9B). The Kakoryca-4 terrace remnant was a natural elevation above the surrounding

waters of Lake Sporovskoye (Fig. 1C). Groups of people could have easily accessed the site by boat (cf. Gibaja et al., 2024; Glørstad, 2025), particularly during spring high-water periods. They might also have reached the site from the south, crossing shallow areas between the terrace remnants, especially during low water levels. The Kakoryca-4 terrace remnant likely served as a seasonal campsite, for example during the summer, providing its temporary inhabitants with access to the lake's resources.

In light of our reconstruction of the AT-1 and AT-2 transgression of Lake Sporovskoye, it is important to emphasize that accurate identification of sediment origine is crucial for reconstructing lake-level transgressions and regressions. As noted by Tsvirko (2023), Belarusian researchers often misidentify the coarse detritus gyttja as peat. For instance, Krutous (1990) reported peat layers in the bottom sediments of Lake Sporovskoye, despite their high content of aquatic plant macrofossils (e.g. *Stratiotes*, *Nymphaea*, *Nuphar*, *Chara*, etc.; see Fig. 13 in Tsvirko, 2023). A similar misidentification occurred for the Ozerne wetland (Kryvaltsevich and Simakova, 2004), where the entire core of deposits was classified as peat, even though it contained *Nymphaea* and *Nuphar* pollen grains along with an admixture of silt. In our study, the Early and Middle Atlantic transgression of Lake Sporovskoye was reconstructed based on the presence of coarse detritus gyttja in the vicinity of the Kakorytsa-4 site, containing numerous macro- and microfossils of fully submerged and floating-leaved plants (Figs. 7 and 10).

5.7 Late Atlantic (6,800 to ~5,900 cal BP; 4,800 to ~3,900 cal BC; Janislawice culture (?), Pripyat-Neman culture of the Dubičiai-type)

A clear record of shallowing and regression of Lake Sporovskoye was identified for the Late Atlantic period, i.e. for the interval approximately between 6,940–6,680 and 5,922–5,661 cal BP (Figs. S16 and S22).

Most likely, at the beginning of this period, around 6,940–6,680 cal BP (Fig. S22), the lake partially or completely retreated from the area between the Kakoryca-4 and Kakoryca-8 terrace remnants (Figs. 1C, 2A and 3). Following the lake retreat, overbank backswamp organic mud started to accumulate in the depression between these terrace remnants (unit a₄ in the KO-8 core; Figs. 2A and 3; Figs. S11 and S22A). The onset of organic mud accumulation at about 6,940–6,680 cal BP was probably related to a phase of increased Yaselda River activity, when the river valley was affected by strong floods. For Belarusian rivers, two phases of increased fluvial activity that may correlate with the Yaselda record have been identified: 6,600–6,000 BP (~7,570–6,685 cal BP) and 5,700–

5,050 BP (~6,601–5,727 cal BP) (Kalicki, 2006). The retreat of the lake from the area between the Kakoryca-4 and Kakoryca-8 terraces opened a land route from the south to the Kakoryca-4 site, facilitating access to the Kakoryca-4 site for prehistoric communities (Figs. 1C and 2A).

At the same time, Lake Sporovskoye still bordered the northern slopes of the Kakoryca-4 terrace remnant but became much shallower (Fig. 1C). This shallowing of the lake is indicated by a decrease in the abundance and diversity of aquatic plant macrofossils (KK-3 LMAZ; Fig. 7) and aquatic plant pollen (SPII-3b LPAZ; Fig. 10) in the coarse detritus gyttja found north of the Kakoryca-4 site. Fully submerged plant communities retreated to deeper parts of the lake (disappearance of *Chara*, *Caulinia minor*, *Najas marina*, *Ceratophyllum submersum* and *Potamogeton* macrofossils in KK-3 LMAZ; disappearance of *Potamogeton* and *Myriophyllum* pollen in SPII-3b LPAZ). Large floating-leaved species, such as *Stratiotes aloides* and *Nuphar*, also shifted to deeper water areas (decrease in the number of macrofossils of these taxa in KK-3 LMAZ), for example, to the area near the Sporovo II core (SPII-3b LPAZ; Figs. 1C and 10). The aquatic environment north of the Kakoryca-4 terrace remnant became predominantly colonized by *Nymphaea* and small floating-leaved plants such as *Salvinia natans* and *Lemna minor* (KK-3 LMAZ; Fig. 7). As a result of the shallowing of the lake, the area covered by telmatic and wetland vegetation in the vicinity of the site expanded, being dominated by Cyperaceae and Typhaceae (Figs. 7 and 10). The shallowing of the lake also led to the expansion of moist areas around the Kakoryca-4 site, promoting the spread of *Salix* and Polypodiaceae (Fig. 10).

The shallowing and partial regression of the lake was most likely driven by the progressive infilling of the lake depression with sediments. A relatively large amount of sediment had been accumulated in the lake during the Early and Middle Atlantic due to its intense overgrowth. According to our rough estimates, during AT-1 and AT-2, approximately 60–70 cm of gyttja (based on compressed sediments) was accumulated in the lake north of the Kakoryca-4 terrace remnant (Figs. 6B and 7). Over the same period, about 80 cm of gyttja (compressed sediments) was deposited in the deeper parts of the lake (Fig. 6A). During the Late Atlantic, an additional 25–30 cm of gyttja (compressed sediments) was accumulated, leading to further shallowing of the lake (Figs. 7 and 10).

Thus, during the Late Atlantic, the Kakoryca-4 site was still located on the shore of Lake Sporovskoye, offering prehistoric communities direct access to the lake (Fig. 1C). Although the lake experienced pronounced shallowing, it was still considerably larger than

at present. This is evidenced by the accumulation of Late Atlantic highly organic coarse detritus gyttja in the immediate vicinity of the Kakoryca-4 terrace remnant (Fig. 6AB), as well as by the deposition of highly organic sediments containing Characeae macrofossils between some terrace remnants (A-1 outcrop – Fig. 1C and Fig. S23A; age 6,281–6,205 cal BP).

The erosion of the Kakoryca-4 terrace slopes by slope and shoreline processes continued, likely driven in part by anthropogenic influence. This resulted in the accumulation of mineral matter (LOI = 25%; Fig. 9A) and the redeposition of older artefacts into the younger coarse detritus gyttja layers (for example, a “flint core of Kudlaevka culture” in Fig. 9B). It is possible that during the Late Atlantic, the erosion of the Kakoryca-4 terrace slopes was caused by more frequent and intense use of the site by Pripyat-Neman culture settlers. In general, the growth of the population in the Polesie region during the Neolithic period (Isayenko, 1976) may have contributed to the intensification of slope processes at numerous settlement sites.

During the Late Atlantic, the regional forests did not undergo significant changes. As before, mixed closed-canopy pine-broadleaf forests (*Quercus*, *Ulmus*, *Tilia*, and *Fraxinus*, as well as *Corylus* in the understorey) dominated (Fig. 10). The moist areas were densely overgrown with *Alnus* (Fig. 10; cf. Zernitskaya, 2022). Hot summer and mild winter conditions are indicated by the presence of *Hedera* and *Viscum* pollen (Fig. 10; Fig. S20; cf. Sobkowiak-Tabaka et al., 2020). In the Late Atlantic deposits of the PKK-1-2 core (Fig. 7) and squares 24 and 25 (Fig. 9B), no macrofossils of tree taxa were found, which can probably be explained by the presence of Early Neolithic communities at the site and the deforestation of the terrace remnant area.

The pollen records from the Ivanisovka and Bobrovichskoe reference cores closely match those from the Sporovo II core, supporting the interpretation that mixed pine-broadleaf forests dominated the Yaselda River basin (Zernitskaya, 2022). However, in contrast to the Sporovo II record (Fig. 10), the reference cores show a marked rise in *Quercus* pollen during the Late Atlantic (Zernitskaya, 2022).

According to the conventional chronology (Table S3), the presence of the Late Mesolithic Janisławice culture on the Kakoryca-4 terrace at the very beginning of the Late Atlantic cannot be entirely ruled out. Nevertheless, the Late Atlantic is primarily associated with the functioning of the Early Neolithic Pripyat-Neman culture at the site.

During the Late Atlantic, the regression and shallowing of Lake Sporovskoye (Figs. 1C, 7 and 10; Fig. S22A), together with population growth (Isayenko, 1976),

facilitated more intense use of the Kakoryca-4 site area by Early Neolithic communities. This was the period when the first pottery, attributed to the “forest” Neolithic Pripyat-Neman culture, appeared at the Kakoryca-4 terrace remnant. The site was occupied by groups of the Early Neolithic Pripyat-Neman culture of the Dubičiai-type. These groups of people appeared at the Kakoryca-4 around 6,391–6,294 cal BP (4,442–4,345 cal BC), as indicated by the age of coarse detritus gyttja directly covering Pripyat-Neman Dubičiai-type pottery (see PKK-1-2 core; Table 1; Fig. 8AB; Fig. S12D).

The large number of Pripyat-Neman pottery (even dominance), bone remains, and various flint and stone artefacts (3a LAZ – Fig. 9B; Table S6) suggests that the Pripyat-Neman communities used the Kakoryca-4 terrace relatively frequently, most likely for seasonal occupations following the recession of the spring floodwaters. Most likely, the main factor contributing to the long-term use of the Kakoryca-4 terrace by the Pripyat-Neman people was the regression and shallowing of Lake Sporovskoye, which gave the site an advantageous geomorphological position, providing direct access to the flow-through Lake Sporovskoye (Fig. 1C), the Yaselda River, and the adjacent wetlands and their resources. At the same time, the southern approach to the site became easier to traverse (Fig. 1C). During this period, communities of the Pripyat-Neman culture experienced a phase of increased Yaselda River activity, during which strong floods began to affect the river valley from 6,940–6,680 cal BP onward (Fig. S22A).

The main subsistence strategy of the Early Neolithic Pripyat-Neman communities involved hunting, fishing, and gathering (cf. Czebreszuk and Szmyt, 2003; Jóźwiak, 2018; Tkachou, 2018; Wieckowska-Lüth et al., 2021; Tkachev and Tkacheva, 2024; Dolbunova and Mazurkevich, 2025). Their economic activities apparently consisted of seasonal work carried out from temporary campsites, such as Kakoryca-4. These temporary sites were connected by land and water routes to areas where mineral resources (flint, stone, clay, etc.) were extracted. For example, based on the characteristics of flint artefacts discovered at the Kakoryca-4 site, it can be inferred that the moraine elevation near the village of Bezdezh served as a source of raw flint (Area rich in raw flint – Fig. 4; Fig. S9). It is also likely that stones and other mineral materials were transported to Kakoryca-4 from this moraine plateau (Fig. 4).

It is important to note that we found numerous large pollen grains of wild-growing Poaceae (with an axis $>40\ \mu\text{m}$ and a pore with an annulus diameter of around $10\ \mu\text{m}$) in deposits from various periods, including the Bølling-Allerød sediments (Fig. 10; Fig. S21). The indistinct annulus contours of these pollen grains prevented us from classifying them

as *Cerealia* (Fig. S21). Apparently, the periodic occurrence of such large wild *Poaceae* pollen grains in the sediments may have led some researchers to misidentify them as *Cerealia* pollen. This could explain reports of *Cerealia* pollen in Mesolithic and Early Neolithic deposits from the Belarusian Polesie (for example, in Zernitskaya et al., 2001; Velichkevich et al., 2002; Zernitskaya, 2022). Thus, when identifying *Cerealia* pollen, attention should be given not only to the grain size ($>40\ \mu\text{m}$) and the annulus diameter ($9\text{--}10\ \mu\text{m}$), but also to the distinctness of annulus outlines (Tsvirko, 2023).

According to several studies, the earliest appearance of *Cerealia* pollen in the Belarusian Polesie has been reported from the sediments of Lakes Bobrovichskoe and Peschanoe, as well as from the deposits of the Zditovo and Ozernoe wetlands, dated to 7,900–7,000 cal BP (Zernitskaya et al., 2001; Kryvaltsevich and Simakova, 2004; Zernitskaya and Mikhailov, 2009; Zernitskaya, 2022). However, we consider these conclusions regarding such an early onset of agriculture in Polesie to be highly questionable for several reasons.

First, the absence of photographic documentation of the earliest *Cerealia* pollen in these papers prevents independent verification of pollen grain size, the distinctness of annulus outlines, and the possibility of confusion with wild-growing *Poaceae* pollen.

Second, the age-depth model for the Peschanoe core relies primarily on palynological correlation rather than robust radiocarbon dating, apart from a single radiocarbon date ($11,800\pm180$ BP) from the bottommost horizon. In the Zditovo and Ozernoe cores, chronological models were also based on palynological correlation, with each diagram including only one radiocarbon date linked to or near the layer containing the earliest *Cerealia* pollen ($7,020\pm70$ BP for Zditovo; $6,630\pm125$ BP for Ozernoe).

Third, in the Bobrovichskoe and Ozernoe cores, *Cerealia* pollen occurs stratigraphically below the radiocarbon-dated horizons (e.g., $6,230\pm80$ BP in Bobrovichskoe), implying an even earlier appearance of agriculture, which raises further doubts.

Fourth, the Zditovo core is located within the Sporovskoye Lake basin, which we have studied and demonstrated to contain wild-growing *Poaceae* species producing large pollen grains since the Bølling-Allerød period (Fig. 10; Fig. S21).

Therefore, current palynological evidence for agriculture in the Late Mesolithic, Early Neolithic, and likely throughout the entire “forest” Neolithic of the Belarusian Polesie remains questionable and open to debate, particularly in the absence of corroborating archaeological data. Future research should focus on more reliable identification of

Cerealia pollen and the development of robust age-depth models supported by a larger number of radiocarbon dates.

5.8 End of the Late Atlantic, Early Subboreal, and Middle Subboreal (~5,900 to 3,700 cal BP; ~3,900 to 1,700 cal BC; Pripyat-Neman culture of the Dubičiai-type, Neman culture of the Dobry Bor-type, Corded Ware culture circle, Corded Ware culture circle with elements of the Globular Amphora culture and other cultures of the Late Neolithic–Early Bronze Age, Middle Dnieper culture)

At the very end of the Late Atlantic, approximately 5,900 cal BP (core KO-4 with ^{14}C age of 5,922–5,661 cal BP; Fig. S16), Lake Sporovskoye had completely retreated from the Kakoryca-4 terrace remnant area (Fig. 1C). Following the lake's regression, floodplain backswamp black organic mud began to accumulate north of the Kakoryca-4 terrace (unit a4; Fig. 6B). The accumulation of these organic muds proceeded very slowly, in the interval between the end of the Late Atlantic and the end of the Middle Subboreal. Such slow accumulation resulted in the mixing of archaeological artefacts from different cultural periods (ranging from the Pripyat-Neman culture to the Corded Ware culture circle) within a relatively thin layer of black organic mud (3b LAZ in Fig. 9B; Fig. S31).

The observed regression of Lake Sporovskoye was most likely caused by the infilling of the lake depression with sediments during the entire Atlantic period (Fig. 6AB; Tsvirko, 2023), and possibly by climatic changes at the AT-3/SB-1 transition (cf. Davis et al., 2003; Gruszczyński et al, 2019; Mroczkowska et al., 2021; Zernitskaya, 2022). A comparable pattern was recorded in Lake Lozoviki in Northern Belarus, where peat started to accumulate from the beginning of the Subboreal (Novik et al., 2010; Zernitskaya, 2022)

As a result of the regression, the shoreline of Lake Sporovskoye shifted to the area of the Sporovo II core, where it persisted during the first half of the Early Subboreal approximately until 4,957–4,842 cal BP (Figs. 1C, 3, 6A, and 10). A telmatic Lozy wetland developed near the Sporovo II core (Fig. 3), where highly organic peat accumulated between high and low water levels in the lake (unit h₁ – Fig. 6A; cf. Tobolski, 2021). Pollen data indicate that during high water levels, *Stratiotes aloides*, *Nuphar*, *Myriophyllum*, and *Potamogeton* grew in the Lozy wetland when it was inundated by lake water (SPII-4a and SPII-4b LPAZ; Fig. 10). During low water levels, the Lozy wetland was overgrown with nearshore and wetland vegetation, including *Sparganium*-type and Cyperaceae (Fig. 10). Periodic drying allowed oxygen to penetrate the telmatic peat, leading to pollen corrosion (undeterminable – Fig. 10). The overgrowth and infilling of the Lozy telmatic wetland with

sediments led to a gradual retreat of the Lake Sporovskoye shoreline, as indicated by increasing proportions of Cyperaceae pollen (Fig. 10). At approximately 4,957–4,842 cal BP (Fig. 6A; Table 1), the shoreline retreated further east away from the Sporovo II core area (Fig. 1C), and as a result, the telmatic Lozy wetland was transformed into a peat-forming terrestrial fen. Under these terrestrial conditions, peat accumulation was counterbalanced by intensified aerobic decomposition, resulting in the absence of net sedimentation. Consequently, a long-lasting depositional hiatus began at the Lozy wetland (Figs. 10, 6A). This depositional hiatus in the Lozy terrestrial fen is indicated by sharp fluctuations in the percentage curves of regional (e.g., *Corylus*, *Quercus*) and local (e.g., *Sparganium*-type) vegetation (at a depth of 25 cm b.g.l. in Fig. 10), as well as by the low thickness of the deposits overlying the telmatic peat (0–25 cm b.g.l.; Fig. 10).

The regression of Lake Sporovskoye at approximately 5,900 cal BP resulted in a displacement of the Yaselda River mouth toward the area immediately east of the Kakoryca-4 terrace (Fig. 1C – probably south of the Sporovo II core). From that time onwards, the river channel was located very close to the Kakoryca-4 terrace, approaching it from the north (roughly its present-day position – Fig. 1C). We assume that during the period from ~5,900 to 3,700 cal BP, the Kakoryca-4 terrace remnant provided convenient and direct access to the Yaselda River channel, as well as to the lake through the river (Fig. 1C), which was likely one of the main factors contributing to the frequent occupation of the terrace remnant by Neolithic and Early Bronze Age communities.

Following the regression, the Yaselda River began to form its floodplain, eroding calcareous and coarse detritus gyttja (units l₁, l₂, l₅, and l₆) in the area between the present-day channel and the oxbow lake (Fig. 3).

Following the regression of Lake Sporovskoye, fluvial activity led to the development of the Iržave backswamp, where the accumulation of overbank organic mud took place between ~5,900 and 3,700 cal BP (unit a₄; Fig. 6B). This organic mud is very rich in mineral matter, particularly fine-grained sand, which indicates episodes of strong flooding (Fig. 6B; Fig. S16). Most likely, most of the organic mud layer was deposited during phases of increased Yaselda River activity, when strong floods affected the valley of the river. For Belarusian rivers, several phases of increased activity have been identified within the interval 5,900–3,700 cal BP: 5,700–5,050 BP (~6,601–5,727 cal BP), 4,750–4,200 BP (~5,578–4,652 cal BP), and 3,400–3,100 BP (~3,819–3,220 cal BP) (Kalicki, 2006). The accumulation of organic mud at the Iržave backswamp most likely occurred during these phases defined by Kalicki (2006) for Belarusian rivers.

During these phases of increased Yaselda River activity, strong floods inundated the Iržave backswamp, forming temporary surface water bodies in which aquatic vegetation (mainly *Salvinia natans*, *Lemna trisulca*, and *Stratiotes aloides*) and telmatic/wetland vegetation (*Typha latifolia*, *Typha angustifolia*, *Alisma plantago-aquatica*, and *Sagittaria sagittifolia*) developed (KK-4 LMAZ; Fig. 7). It is likely that strong floods, during which the organic mud accumulated in the Iržave backswamp, promoted intense erosion of calcareous and coarse detritus gyttja (units l₁, l₂, l₅, and l₆) in the area between the present-day Yaselda River channel and the oxbow lake (Fig. 3).

The phases of increased Yaselda River activity, during which organic mud was accumulated, alternated with periods of breaks in sedimentation (hiatuses), during which older artefacts were mixed with younger ones within the organic mud layer (3b LAZ in Fig. 9B). These periods of depositional hiatuses may be identified by the following evidence. First, the organic mud layer is dominated by plant tegmen fragments that are resistant to aerobic conditions (cf. Yakubovskaya, 1985), including tegmens of *Alisma plantago-aquatica*, *Sagittaria sagittifolia*, *Typha angustifolia*, *Typha latifolia*, and *Nuphar lutea* (unit a₄ in Fig. 7). Second, within the organic mud layer and at its boundary, there are intervals with very low taxonomic diversity and an exceptionally high amount of tegmen remains (depth of 49–40 cm; only 5–6 taxa represented mainly by tegmens of *Typha latifolia*, *Alisma plantago-aquatica*, *Sagittaria sagittifolia*, *Nymphaea alba*, *Nuphar lutea*; Fig. 7). Third, within the organic mud layer and at its boundary, there are abrupt peaks in macrofossil abundance for some taxa (e.g., *Typha angustifolia*, *Typha latifolia*, *Sagittaria sagittifolia*, *Salvinia natans*; Fig. 7). Consequently, as a result of periodic depositional hiatuses, the black overbank organic mud layer became the most artefact-rich geological layer (unit a₄, roughly corresponding to the 30–40 cm excavation layer with a total of 599 artefacts; Fig. 9B; Fig. S31; Table S6). The presence of a large number of artefacts from different chronological periods concentrated within a thin layer of black organic mud also suggests frequent depositional hiatuses (Fig. 9B).

Organic mud accumulation at the Iržave backswamp ended approximately 3,700 cal BP, probably due to a northward migration of the Yaselda River channel away from the Kakoryca-4 terrace remnant, roughly toward the present-day oxbow lake (Fig. 3). The displacement of the Yaselda River channel most likely took place during a phase of increased fluvial activity dated in Belarusian river valleys to 3,400–3,100 BP (~3,819–3,220 cal BP) (Kalicki, 2006). As a result, a long-lasting depositional hiatus began at the Iržave wetland, as indicated by multiple lines of evidence. First, radiocarbon dating shows

that the sediments overlying organic mud unit a₄ are very young, about 529–504 cal BP (Fig. 6B; Table 1). Second, this hiatus is indicated by the abrupt increases and decreases in the abundance of certain macrofossils in the overlying unit a₃ or at the boundary between units a₄ and a₃ (e.g., Poaceae, *Glyceria fluitans*, *Mentha longifolia*, *Juncus*, *Typha angustifolia*, *Typha latifolia*, *Stachys palustris*, *Eleocharis palustris*, *Oenanthe aquatica*, *Sparganium erectum*, *Stratiotes aloides*, *Salvinia natans*, *Lemna minor*; Fig. 7).

During the period from ~5,900 to 3,700 cal BP, erosional processes on the slopes of the Kakoryca-4 terrace remnant – particularly during phases of increased Yaselda River activity – led to the redeposition of older artefacts, including Kudlaevka culture flint trapeze and backed bladelets, into younger organic mud layer a₄ (3b LAZ; Fig. 9B). It is likely that some of the mineral matter was supplied to the organic mud layer a₄ not only through alluvial overbank accumulation but also through deluvial erosion of the terrace slopes (LOI = 36%; Fig. 9A).

With the onset of the Subboreal, the composition of closed-canopy pine-broadleaf forests in the Yaselda River basin changed significantly. The beginning of the Subboreal was characterised by a decrease in the abundance of *Corylus*, coinciding with the succession of *Quercus* (SPII-4a LPAZ; Fig. 10). The first half of the Early Subboreal was also marked by a decline in *Ulmus* and *Fraxinus*, accompanied by an expansion of *Pinus*-covered areas (SPII-4b LPAZ; Fig. 10). Such a shift in the regional forest composition may indicate Subboreal climatic cooling (cf. Davis et al., 2003; Zernitskaya, 2022; Herzsuh et al., 2023). An increase in *Picea* pollen values may also indicate moderately cooler and wetter climatic conditions (SPII-4a and SPII-4b LPAZs; Fig. 10; cf. Zarzycki et al., 2002; Kittel et al., 2021; Wieckowska-Lüth et al., 2021).

In the reference core Ivanisovka, the Subboreal corresponds to the *Betula-Quercus-Carpinus* LPAZ, for which a single radiocarbon date of 4,370±190 BP (5,308–4,724 cal BP) was obtained (Zernitskaya, 2022). Pollen assemblages from the Ivanisovka core also indicate forest transformation at the onset of the Subboreal in the Yaselda River basin, showing that the abundance of *Corylus*, *Ulmus*, *Fraxinus*, and *Tilia* declined significantly. At the same time, high values of *Quercus* were observed, together with an increase in *Pinus* and *Picea* (Zernitskaya, 2022). In contrast to the Sporovo II core (Fig. 10), the Subboreal deposits of the Ivanisovka reference core contained much higher proportions of *Carpinus* pollen (Zernitskaya, 2022), which may indicate the expansion of this taxon into drier areas farther from Lake Sporovskoye (cf. Zarzycki et al., 2002).

The Subboreal period in the Bobrovichskoe reference core is represented by the *Pinus-Quercus-Corylus-Carpinus* LPAZ, dated by three radiocarbon dates of 4,800±80 BP (5,599–5,333 cal BP), 4,470±90 BP (5,288–4,976 cal BP), and 3,450±80 BP (3,830–3,587 cal BP) (Zernitskaya, 2022). Pollen data from the Bobrovichskoe core also show that the onset of the Subboreal was marked by a decline in *Corylus*, *Ulmus*, and *Fraxinus*, accompanied by increasing proportions of *Quercus*, *Pinus*, and *Picea* in regional forests. A slight rise in *Carpinus* pollen is observed during the Early Subboreal, whereas higher *Carpinus* values were characteristic of the second half of the Subboreal (Zernitskaya, 2022).

During the very end of the Late Atlantic, approximately between 5,900 and 5,800/5,700 cal BP, communities of the Pripyat-Neman culture continued to occupy the Kakoryca-4 terrace remnant, as evidenced by abundant pottery fragments within the organic mud layer (3b LAZ with unit a4; Fig. 9B). Communities of the Pripyat-Neman culture regularly visited the Kakoryca-4 terrace, as evidenced by the large amount of pottery they left behind (3b LAZ; Fig. 9B). The terrace was probably used as a seasonal campsite. These groups of people witnessed major environmental changes after ~5,900 cal BP, including the regression of Lake Sporovskoye (Fig. 1C), a phase of increased Yaselda River activity, and the development of the Iržave backswamp. During this period, occupation of the Kakoryca-4 terrace was closely tied to the Yaselda River flowing immediately north of the site, and to its mouth and the nearby Lake Sporovskoye to the east.

Communities of the “forest” Neolithic Neman culture of the Dobry Bor-type most likely appeared on the Kakoryca-4 terrace remnant during the Early Subboreal, after 5,800/5,700 cal BP, and probably used this terrace until they were replaced by Corded Ware culture circle communities (Table S3). The large number of Neman culture artefacts found in the organic mud layer (3b LAZ; Fig. 9B) indicates that these communities frequently visited the Kakoryca-4 terrace. As in previous periods, the Kakoryca-4 terrace was most likely used for temporary, seasonal occupation, which is evidenced by the absence of identified prehistoric residential or economic structures at the site. The Kakoryca-4 terrace was probably occupied mainly after the retreat of floodwaters. The Neman culture communities also witnessed major environmental changes to which they had to adapt, including climatic cooling (Davis et al., 2003; Mroczkowska et al., 2021; Zernitskaya, 2022; Herzschuh et al., 2023) and transformation of regional forests at the onset of the Subboreal (Fig. 10; Zernitskaya, 2022), a phase of increased Yaselda River activity

(~between 5,900 and 3,700 cal BP), as well as a further regression of Lake Sporovskoye away from the Kakoryca-4 terrace remnant around 4,957–4,842 cal BP (Figs. 1C and 10). The activities of Neman culture societies at the Kakoryca-4 terrace were also strongly connected to the Yaselda River running immediately north of the terrace remnant, as well as to its mouth and the nearby Lake Sporovskoye to the east (Fig. 1C). The presence of a large amount of Neman culture artefacts in the overbank organic mud layer (3b LAZ; Fig. 9B) indicates that communities of this culture were adapted to the phase of increased Yaselda River activity.

After 4,700/4,500 cal BP, Corded Ware culture circle communities seem to have gradually replaced the Neman culture communities on the Kakoryca-4 terrace. Evidence for this comes from the markedly higher number of Corded Ware culture circle pottery fragments in the uppermost layer of Excavation-3 (64 fragments) compared with 18 and 17 fragments of Neman and Pripyat-Neman culture pottery, respectively (layer 0–30 cm; Table S6). The Corded Ware culture circle pottery fragments – in addition to typical forms – exhibits stylistic influences from the Globular Amphora culture, the Neman culture, the Middle Dnieper culture, Epi-Corded Ware cultures, and other traditions. The large number of artefacts of the Corded Ware culture circle (3b LAZ; Fig. 9B) indicates frequent presence of these communities on the Kakoryca-4 terrace remnant, which was likely used until the end of the Middle Subboreal, i.e., until approximately 3,900/3,700 cal BP (Table S3). The occupation of the Kakoryca-4 terrace by Corded Ware culture circle communities was also closely connected to the Yaselda River flowing immediately north of the terrace, as well as to its mouth and the nearby Lake Sporovskoye to the east (Fig. 1C). It appears that during the period of Corded Ware culture circle activity, the Kakoryca-4 terrace remnant existed under relatively stable environmental conditions. A possible exception was the phase of increased Yaselda River activity (~between 5,900 and 3,700 cal BP), during which severe flooding and the deposition of organic mud in the Iržave backswamp likely occurred.

Between 4,600 and 3,700 cal BP (Table S3), the Kakoryca-4 terrace was occasionally visited by communities of the Middle Dnieper culture, leaving behind only a small number of pottery fragments.

No direct evidence for agricultural activity between ~5,900 and 3,700 cal BP was recorded in the deposits surrounding the Kakoryca-4 site. A single pollen grain of cf. *Cerealia*, discovered in the telmatic peat layer of the Lozy wetland and dated to 4,957–4,842 cal BP (3,008–2,893 cal BC; corresponding to the Neman culture; Fig. 10; Table S3), raises doubts as to whether it truly represents *Cerealia* or rather wild-growing *Poaceae*

(Fig. 8CD). Numerous flint axes attributed to the Neman culture (Fig. 9B) and the Corded Ware culture circle, including those found outside squares 24 and 25, provide evidence for intense deforestation of the Kakoryca-4 terrace remnant and nearby territories after 5,800/5,700 cal BP. These axes were undoubtedly used for wood processing; however, whether this deforestation was carried out for agricultural purposes remains uncertain. Some antler axes or hoe tools (found outside squares 24 and 25) may have been used for soil digging; however, it is also possible that prehistoric people engaged in digging activities for non-agricultural purposes, such as gathering.

It is likely that agricultural activity was first introduced to the Kakoryca-4 site (or to nearby rounded terrace remnants of the Lake Sporovskoye basin) by communities of the Corded Ware culture circle. The spread of early agriculture and cattle-breeding in the Belarusian Polesie in the 3rd–Early-2nd millennium BC was associated with these societies, as well as with the Globular Amphora culture, the Middle Dnieper culture, and the Epi-Corded Ware cultures, all of which combined farming with hunting, fishing, and gathering (Kryvaltsevich, 1999, 2004b, 2016b; Kalechits, 2018). We suggest that the small, rounded elevations, such as Kakoryca-4 and other nearby terrace remnants, provided favourable conditions for agricultural activities. In the Polesie region, elevated landforms (including those subject to seasonal flooding) surrounded by wetlands have been used for agriculture and cattle-breeding even in the recent past, as documented in historical data sets (Mašynski, 2014).

5.9 Late Subboreal and Subatlantic (3,700 to 529–504 cal BP; 1,700 cal BC to 1,421–1,446 cal AD; Trzciniec Cultural Circle, communities of the Iron Age and the Middle Ages)

This time interval is less recognized due to the poor geological record. Also, a relatively small number of artefacts dated to this period were found at the Kakoryca-4 site.

Throughout the Late Subboreal (3,700–3,000 cal BP), a long-lasting depositional hiatus persisted in the Lozy and Iržave terrestrial fens, where peat accumulation was counterbalanced by intensified aerobic decomposition, resulting in the absence of net sedimentation.

During the Late Subboreal, communities of the Middle Bronze Age Trzciniec Cultural Circle rarely visited the Kakoryca-4 terrace remnant, as can be inferred from the small number of their pottery fragments left at the site (Kryvaltsevich et al., 2023). It is likely that, due to the migration of the Yaselda River channel toward the area of the present-

day oxbow lake during a phase of increased fluvial activity (about 3,700 cal BP; Fig. 1C), as well as the continued eastward regression of Lake Sporovskoye (Fig. 1C), the Kakoryca-4 terrace had lost its advantageous geomorphological position.

At the onset of the Subatlantic period, Lake Sporovskoye was likely larger than it is today (Fig. 1C), as indicated by a radiocarbon age of 2,863–2,784 cal BP obtained from coarse detritus gyttja containing a *Nymphaea alba* seed at a depth of 45–47 cm in the UZS-1-2 core (Fig. S23B; Table 1). It seems that the regression of Lake Sporovskoye, which began approximately 6,940–6,680 cal BP, proceeded gradually, affecting different parts of the basin at various times during the Late Atlantic, Subboreal and Subatlantic (Fig. 1C; Fig. S23B). The lake successively underwent overgrowth, sediment infilling, and regression – with lacustrine conditions giving way to telmatic and fen environments.

Meanwhile, the Lozy and Iržave terrestrial fens experienced a long-lasting depositional hiatus that lasted through most of the Subatlantic period (from 3,000 to 529–504 cal BP, i.e., up to the Late Middle Ages; Figs. 7 and 10).

In the Subatlantic, the Kakoryca-4 terrace was used – probably for agricultural purposes – by communities of the Iron Age (somewhere between 2,650 and 1,550 cal BP) and the Middle Ages (somewhere between 1,550 and 529–504 cal BP), as evidenced by artefacts found outside Excavation-3 (Kryvaltsevich et al., 2023). The small number of artefacts from these periods may indicate that groups of people spent relatively short periods of time on the Kakoryca-4 terrace remnant.

An important palaeogeographical event in the history of the Yaselda River occurred in the Early Subatlantic (SA-1), shortly after 2,306–2,151 cal BP (357–202 cal BC, i.e., during the Early Iron Age), and was characterized by several years of severe floods (Fig. 6C). We interpret this as a phase of increased Yaselda River activity. At the beginning of this phase, one of the intense floods led to the abandonment of the former Yaselda River channel and the formation of an oxbow lake north of the Kakoryca-4 terrace remnant (Figs. 1BC and 3). The river channel migrated closer to the Kakoryca-4 site, reaching approximately its present-day position (Fig. 3). We therefore estimate the age of this oxbow lake at roughly ~2,306–2,151 cal BP (Figs. 1BC and 3). Following this channel lateral migration, flood rhythmite deposits developed (unit a₂ at a depth of 141.5–89 cm; Fig. 6C).

The identified phase of increased Yaselda River activity corresponds to the phases of increased activity documented for the Belarusian rivers Neman, Western Dvina, and Dnieper (Kalicki, 2006; Zernitskaya, 2022). Most likely, after this phase of

increased Yaselda River activity, a long-lasting depositional hiatus began in the area around the KO-9 core and persisted until the Late Middle Ages (Fig. 6C).

The phase of increased Yaselda River activity likely influenced land-use strategies of local communities after 357–202 cal BC (Fig. 6C; Table S3). Due to intense flooding, increased erosion activity, the formation of oxbow lake, and the lateral migration of the Yaselda channel, people may have used the Kakoryca-4 and nearby terrace remnants less frequently. It is important to consider that in the Iron Age and the later historical period, economic strategies and settlement patterns underwent significant changes. The settlement structure became more stable, with a shift towards larger, permanent settlements located on elevated, non-flooded landforms (for example, river/lake terraces or higher elevations), where agriculture gained greater importance (Jeharejčanka et al., 1999).

5.10 Late Subatlantic (529–504 cal BP to the present; 1,421–1,446 cal AD to the present; communities of the Late Middle Ages, Modern Period and Contemporary era)

Around 529–504 cal BP, a new phase (or phases) of increased Yaselda River activity began, during which strong floods led to the onset of peaty organic mud accumulation in the Iržave backswamp (unit a₃; Figs. 3, 6B and 7). Flooding of the Yaselda River supplied a substantial amount of mineral matter – mainly silt, along with a small amount of sand – into the sediments of the Iržave wetland (Fig. 6B; cf. Kittel et al., 2020). During these severe floods, temporary surface water bodies formed in the Iržave backswamp, in which aquatic vegetation (*Chara*, *Potamogeton*, *Myriophyllum*, *Nitella*, *Batrachium*, *Stratiotes aloides*, *Salvinia natans*, *Lemna*) and telmatic/wetland vegetation (*Sparganium erectum*, *Oenanthe aquatica*, *Eleocharis palustris*, *Alisma plantago-aquatica*, Cyperaceae, etc.) developed (KK-5 and KK-6 LMAZs; Fig. 7). Ostracoda communities also thrived in these temporary surface water bodies of the flooded Iržave backswamp (KK-5 LMAZ; Table S4). Most likely, during periods of Yaselda River flooding, the Lake Sporovskoye level rose, and its waters spread into adjacent wetlands, including the Iržave backswamp. The presence of *Chara* macrofossils suggests hard-water conditions in Lake Sporovskoye (KK-5 LMAZ; Fig. 7; cf. Pukacz et al., 2014; Kittel et al., 2025).

Strong flooding during the phase(s) of increased Yaselda River activity, along with a rise in the water level in Lake Sporovskoye, affected the Lozy wetland, periodically inundating it and creating shallow temporary stagnant water bodies on its surface. This is indicated by a slight increase in mineral matter content in the fen peat (unit h₂; Fig. 6A), as

well as by the presence of *Nymphaea* pollen (SPII-5a LPAZ; Fig. 10). Following the recession of floodwaters and the disappearance of temporary surface water bodies, oxygen penetration into the peat deposits of the Lozy wetland resulted in pollen corrosion and damage (SPII-5 LPAZ, undeterminable; Fig. 10).

It appears that during the phase(s) of increased Yaselda River activity, large areas of the Lake Sporovskoye basin were flooded, leading to the formation of temporary water bodies on the surface of the more distant wetlands surrounding the lake. This is evidenced by the presence of *Potamogeton* macrofossils in the uppermost deposits of the KO-20 core (depth 11–16 cm) and the A-1 outcrop (depth 4–14 cm), both situated far from the present shoreline of the lake (Fig. 1C; Figs. S22B and S23A). During the described phase(s) of increased Yaselda River activity, the accumulation of organic mud layers a_4 and a_3 resumed in the wetland near the KO-9 core (depth of 0–26 cm; Fig. 6C).

Judging from a radiocarbon date of 256–34 cal BP obtained from deposits containing *Potamogeton* macrofossils in KO-20 core, depth 11–16 cm (Fig. S22B), the described phase(s) of increased Yaselda River activity probably lasted from approximately 529–504 cal BP to 256–34 cal BP (from 1,421–1,446 cal AD to 1,694–1,917 cal AD; Fig. 6B; Fig. S22B). It is possible that this phase(s) of increased Yaselda River activity continued until the large-scale artificial drainage melioration undertaken across the Belarusian Polesie in the 19th–20th centuries AD (Konoplev, 2013; Zernitskaya, 2022). The data obtained from the Yaselda River valley are in good agreement with records from other river valleys in Belarus, Poland, and Western Europe, where phases of increased fluvial activity are documented for the 15th–16th centuries and for the 18th/19th century (Kalicki, 2006).

The significant reduction of macrofossils of aquatic plants and plants of telmatic/wetland habitats in the uppermost layer of the Iržave wetland (KK-6 LMAZ; Fig. 7) may indicate the gradual termination of the phase(s) of increased Yaselda River activity around 256–34 cal BP. The only exceptions were isolated aquatic macrofossils of *Batrachium*, *Lemna*, *Salvinia natans* (KK-6 LMAZ; Fig. 7), and *Anisus vortex* (KK-6 LMAZ; Table 2; Fig. S15AB). Comparatively high LOI values observed in the uppermost deposits of the Iržave wetland (depth 0–5 cm in Fig. 6B; Fig. S16) and in the sediments of core KO-9 (depth 0–5 cm; Fig. 6C) may also indicate the gradual termination of the phase(s) of increased Yaselda River activity. It is possible that after the completion of the Yaselda River phase(s) of increased activity, the Lozy and Iržave wetlands were transformed into terrestrial fens with a depositional hiatus.

During the phase(s) of increased Yaselda River activity, the regional vegetation was dominated by pine forests with an admixture of oak, spruce, and a small amount of hornbeam (LPAZ SPII-5; Fig. 10). Wetlands were densely colonised by willow (SPII-5 LPAZ; Fig. 10).

During the phase(s) of increased Yaselda River activity (from 529–504 to 256–34 cal BP; or from 1,421–1,446 to 1,694–1,917 cal AD), the Kakoryca-4 terrace remnant was used by communities of the Late Middle Ages and the Modern Period (Table S3). During the Late Middle Ages, local populations cultivated *Panicum miliaceum* on arable fields located on the Kakoryca-4 terrace remnant (the seed grain dated to 529–504 cal BP; Table 1; Fig. 8E–G). A considerable number of ruderal plant macrofossils (*Chenopodium glaucum*, *Chenopodium album*, *Atriplex*, *Urtica*), pasture/fallow land macrofossils (*Ranunculus* sp., Poaceae), as well as cultivated land macrofossils (*Persicaria lapathifolia*, *Stellaria media*, *Polygonum*, *Rumex acetosella*, *Scleranthus annuus*, *Panicum miliaceum*), indicate intense agricultural use of the Kakoryca-4 terrace area during the Late Middle Ages and the Modern Period (KK-5 and KK-6 LMAZ; Fig. 7). The activity of Modern Period communities on the Kakoryca-4 terrace remnant is indicated by the presence of their pottery fragments (Kryvaltsevich et al., 2023). The periodic floods during the phase(s) of increased Yaselda River activity seemingly did not significantly limit the agricultural exploitation of the Kakoryca-4 terrace. The Kakoryca-4 terrace remnant was most likely used only for agriculture, not for residential or economic structures, as suggested by the small number of artefacts from the Middle Ages and the Modern Period (Kryvaltsevich et al., 2023).

Pollen assemblages from the Lozy wetland (SPII-5 LPAZ; Fig. 10), particularly from the uppermost layer (SPII-5b LPAZ), also indicate human activity during the phase(s) of increased Yaselda River activity (from 529–504 to 256–34 cal BP). This is reflected in higher proportions of ruderal plant pollen (*Artemisia* and Chenopodiaceae), elevated values or occurrences of pollen from pasture/fallow-land plants (Poaceae, *Plantago major-media*, *Rumex*, *Plantago lanceolata*), and the presence of pollen from plants growing on cultivated land (Brassicaceae and *Polygonum aviculare*) (SPII-5 LPAZ; Fig. 10). An increase in NAP and a decline in *Corylus*, *Ulmus*, *Tilia*, and *Fraxinus* may reflect deforestation in the study area (SPII-5b LPAZ; Fig. 10).

According to our field observations, Kakoryca-4 and the nearby terrace remnants are currently used for farming (Fig. S10B), cattle grazing, beekeeping, fishing, and recreation. Some terrace remnants are occupied by residential buildings – the entire Kakoryca village

is situated on such terrace remnants. Today, the Kakoryca-4 terrace remnant and its surroundings are under state protection as part of the Sporovsky Biological Reserve.

CONCLUSIONS

1. Our research has shown that the sediments previously described in Belarusian scientific literature as “lacustrine-alluvial” were, in fact, formed by a sand-bed braided river during the Weichselian glaciation (most likely during the Middle and/or Upper Plenivistulian).
2. Lake Sporovskoye was formed during the Bølling-Allerød, probably as a result of thermokarst processes. For most of its history, the lake was larger than at present. A significant part of the organic deposits that currently make up the Lake Sporovskoye basin was formed under lacustrine conditions (i.e. as coarse detritus gyttja). Most likely, Lake Sporovskoye functioned as a flow-through system throughout its entire history, beginning with its formation in the Bølling-Allerød period.
3. The deposits in the vicinity of the Kakoryca-4 terrace remnant preserve a clear record of the transgressions of Lake Sporovskoye, including during the BA (approximately between 14,417–14,057 and 14,310–13,638 cal BP, modelled age), mid-PB (~10,763–10,606 cal BP), BO-2 (~between 9,778–8,898 and 9,127–8,657 cal BP, modelled age), and AT-1–AT-2 (~between 9,127–8,657 and 7,571–6,401 cal BP, modelled age). A record of shallowing and regression of the lake is identified for AT-3 (~between 6,940–6,680 and 5,922–5,661 cal BP, unmodelled age), end AT-3–SB-1 (~between 5,922–5,661 and 4,957–4,842 cal BP, unmodelled age), and SA-1 (after 2,863–2,784 cal BP). Phases of increased Yaselda River activity are identified for the mid-BO (~9,500–9,300 cal BP), AT-2 (~7,800–7,600 cal BP), AT-3 (after 6,940–6,680 cal BP), end AT-3–SB-2 (~between 5,900 and 3,700 cal BP, unmodelled age), SA-1 (shortly after 2,306–2,151 cal BP), and the 2nd half of SA-3 (~between 529–504 and 256–34 cal BP, unmodelled age). Additional palaeogeographical data are required to confirm the fragmentary evidence for the transgressions of Lake Sporovskoye during the YD, the early and late PB, and BO-1.
4. Human occupation of the Kakoryca-4 terrace remnant began in the Younger Dryas with the Final Palaeolithic Swiderian culture and continued throughout the Preboreal–Late Atlantic with the Mesolithic Kudlaevka culture and Janisławice

culture. The most intense occupation occurred during the Late Atlantic and the Early to Middle Subboreal, by Neolithic and Early Bronze Age communities, resulting in the formation of the most artefact-rich layer of geological deposits at the site. The earliest Neolithic communities at the site were represented by the Pripyat-Neman culture of the Dubičiai-type. A radiocarbon date was obtained from the coarse detritus gyttja directly covering Dubičiai-type Pripyat-Neman pottery.

5. The intense occupation of the Kakoryca-4 terrace by Neolithic and Early Bronze Age communities (AT-3–SB-2) was most likely determined by the regression of Lake Sporovskoye, which gave the site an advantageous geomorphological position. During the Late Atlantic, lake regression brought the shoreline to the area north of the Kakoryca-4 terrace, providing direct access to the lake from the site and, through the lake, to the Yaselda River, whose mouth had shifted closer to the terrace. At the same time, the southern approach to the terrace became easier to traverse. During the Early and Middle Subboreal, the Kakoryca-4 terrace provided direct access to the Yaselda River and, through it, to Lake Sporovskoye, which was located closer to the site than it is today.
6. During the Early and Middle Atlantic, the transgression of Lake Sporovskoye caused the Kakoryca-4 terrace to be surrounded by lake waters, which most likely led to less intense use of the terrace by Mesolithic communities.
7. No direct evidence of early agricultural activity was found at the Kakoryca-4 site; the only direct evidence relates to the Late Middle Ages (a *Panicum miliaceum* seed).
8. A critical review of the literature shows that currently there are no reliable pollen data indicating the presence of agriculture in Belarusian Polesie during the Late Mesolithic, the Early Neolithic, or the entirety of the “forest” Neolithic. Pollen grains identified by some authors as *Cerealia* and dated to 7,900–7,000 cal BP most likely originated from wild-growing *Poaceae*.
9. The accumulation of numerous artefacts of different ages (with a time gap of about 1,000 years between the Pripyat-Neman culture and the Corded Ware culture circle) within a relatively thin layer of black organic mud resulted from frequent breaks in sedimentation (hiatuses).
10. The natural conditions near the Kakoryca-4 terrace did not allow the accumulation of a thick, hiatus-free sequence of geological deposits during the

Neolithic and Early Bronze Age. This prevented the stratigraphic separation of artefacts belonging to different Neolithic and Early Bronze Age cultures into distinct sedimentary layers.

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**SUPPLEMENTARY MATERIAL FOR CHAPTER I
(REFERRED TO IN THE TEXT AS “ONLINE SUPPLEMENTARY
MATERIAL (OSM)”)**

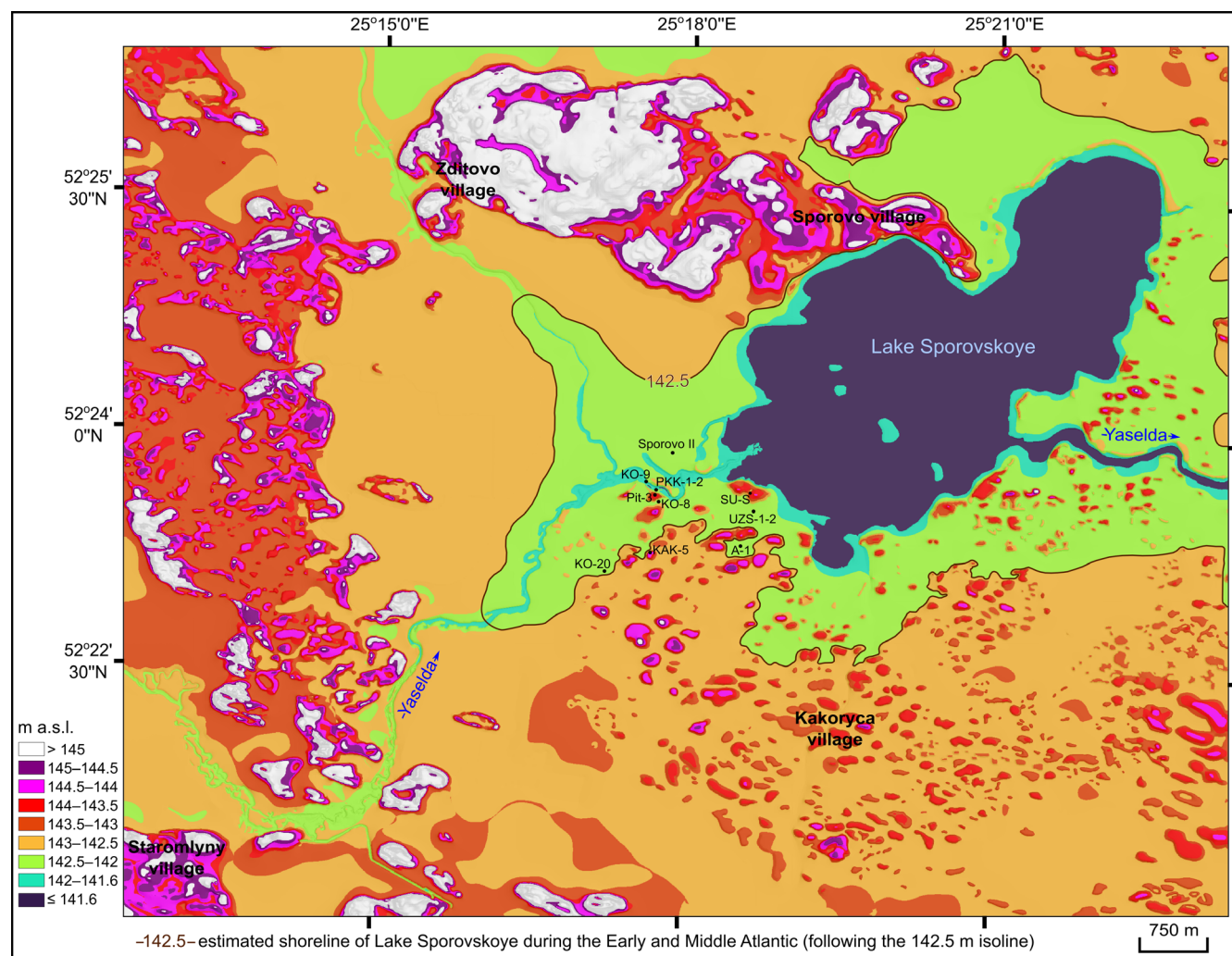


Fig. S1. Study area with reference cores and outcrops in the vicinity of the Kakoryca-4 site in the basin of the Yaselda River and Lake Sporovskoye on a fragment of a digital elevation model (DEM)

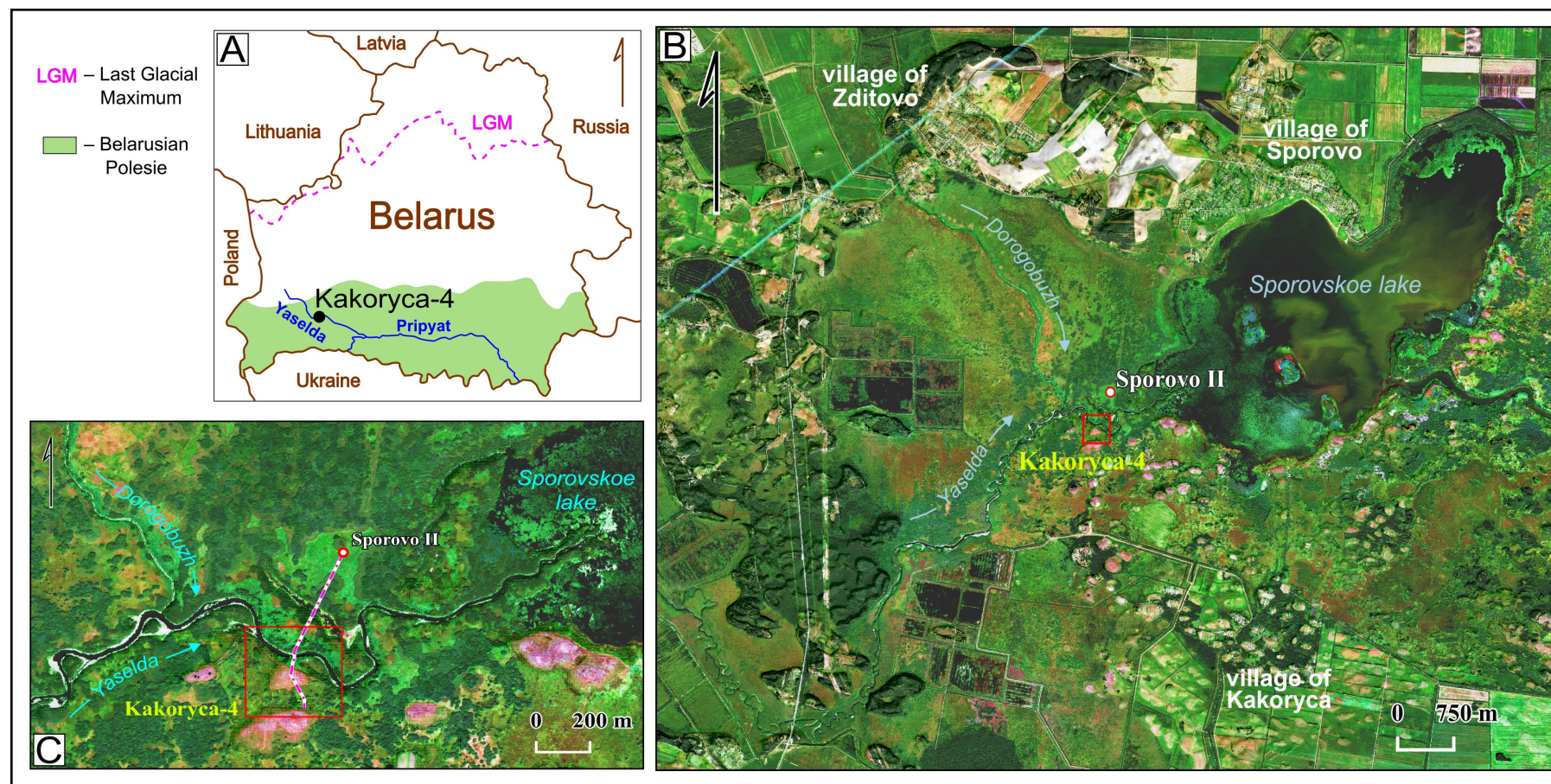


Fig. S2. The Kakoryca-4 archaeological site on the territory of Belarusian Polesie (A) in the basin of the Yaselda River and Lake Sporovskoye (B–C), with studied Sporovo II core and geological cross-section line (C). B and C – fragments of the early autumn multispectral image of the “WorldView-2” satellite, presented in natural colours (red, green, blue). See Trifonov, 2021



Fig. S3. Google Earth satellite image of higher sandy “lacustrine-alluvial” elevations (mid-channel bars of a sand-bed braided river in our interpretation) to the southwest of Lake Sporovskoye, with the location of reference cores and outcrops. Core KO-9 with coordinates
 $52^{\circ}23'41.639''\text{N } 25^{\circ}17'29.713''\text{E}$

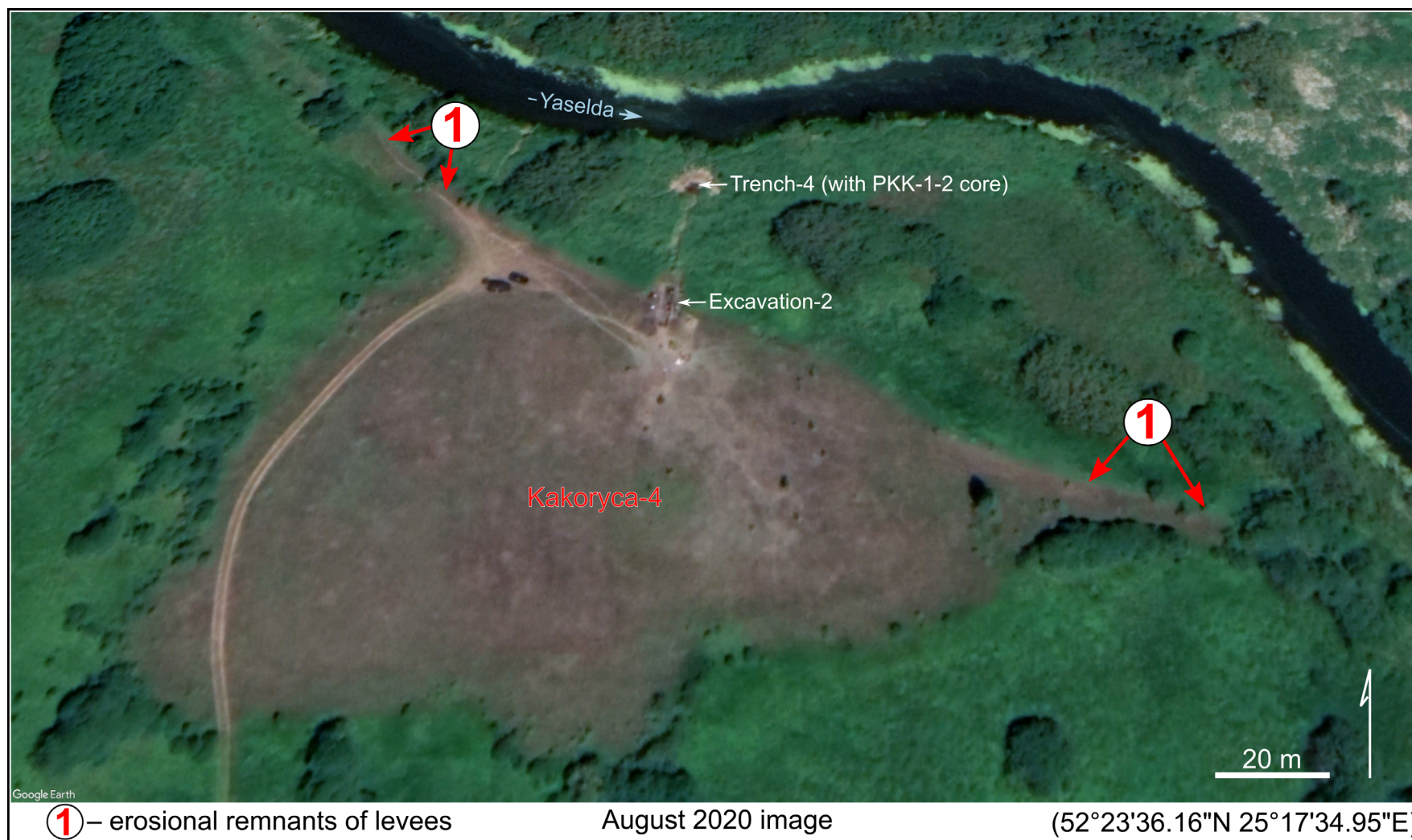


Fig. S4. Google Earth satellite image of the studied “lacustrine-alluvial” elevation (mid-channel bar of a sand-bed braided river) with the archaeological site Kakoryca-4 in August 2020. Excavation-2 and Trench-4 are visible in the image

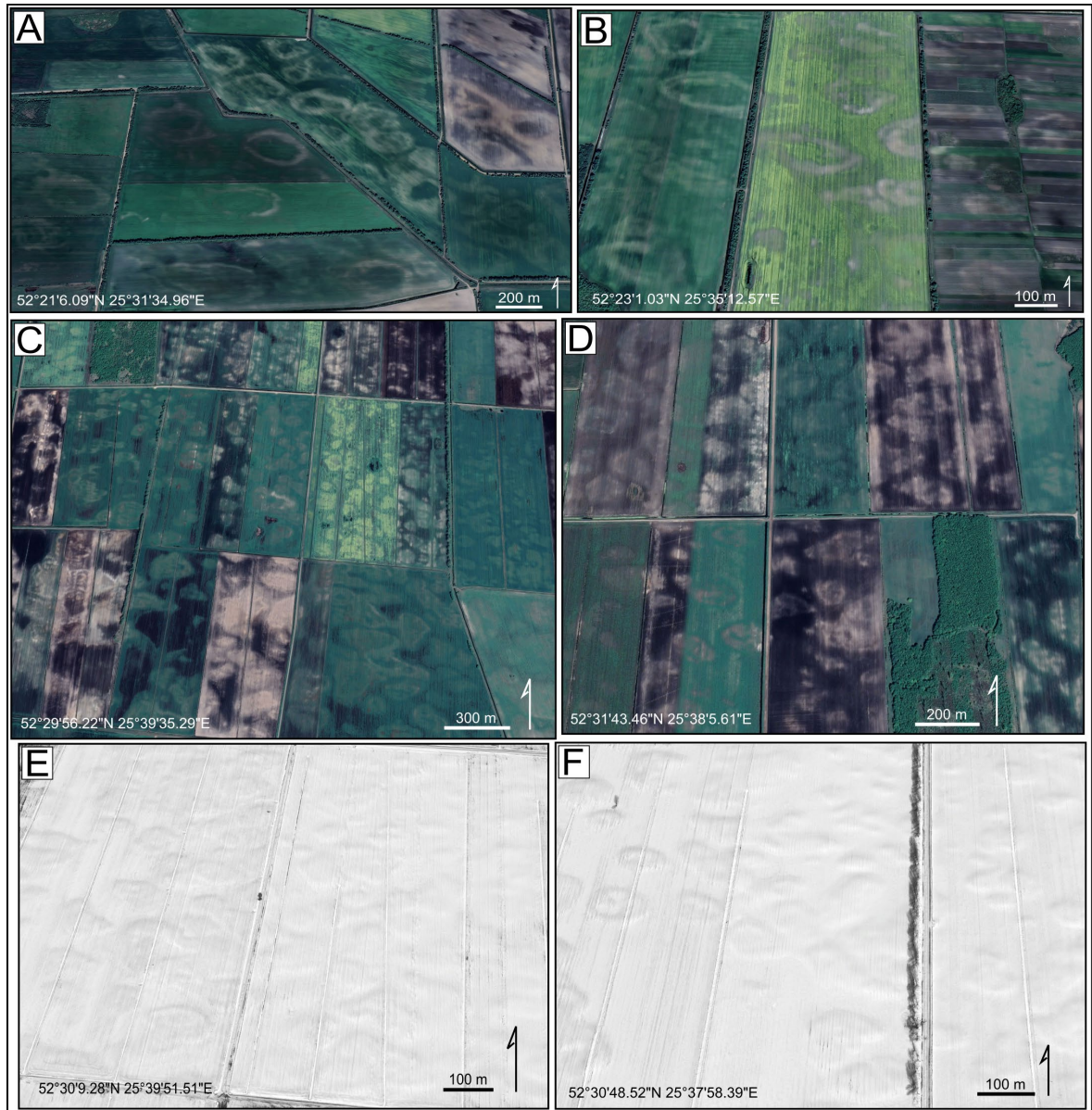


Fig. S5. Google Earth satellite images of the lower “lacustrine-alluvial” elevations (mid-channel bars of a sand-bed braided river) ploughed together with the surrounding artificially drained wetlands to the northeast and southeast of Lake Sporovskoye. Some of these elevations have a depression in the central part (A and B)

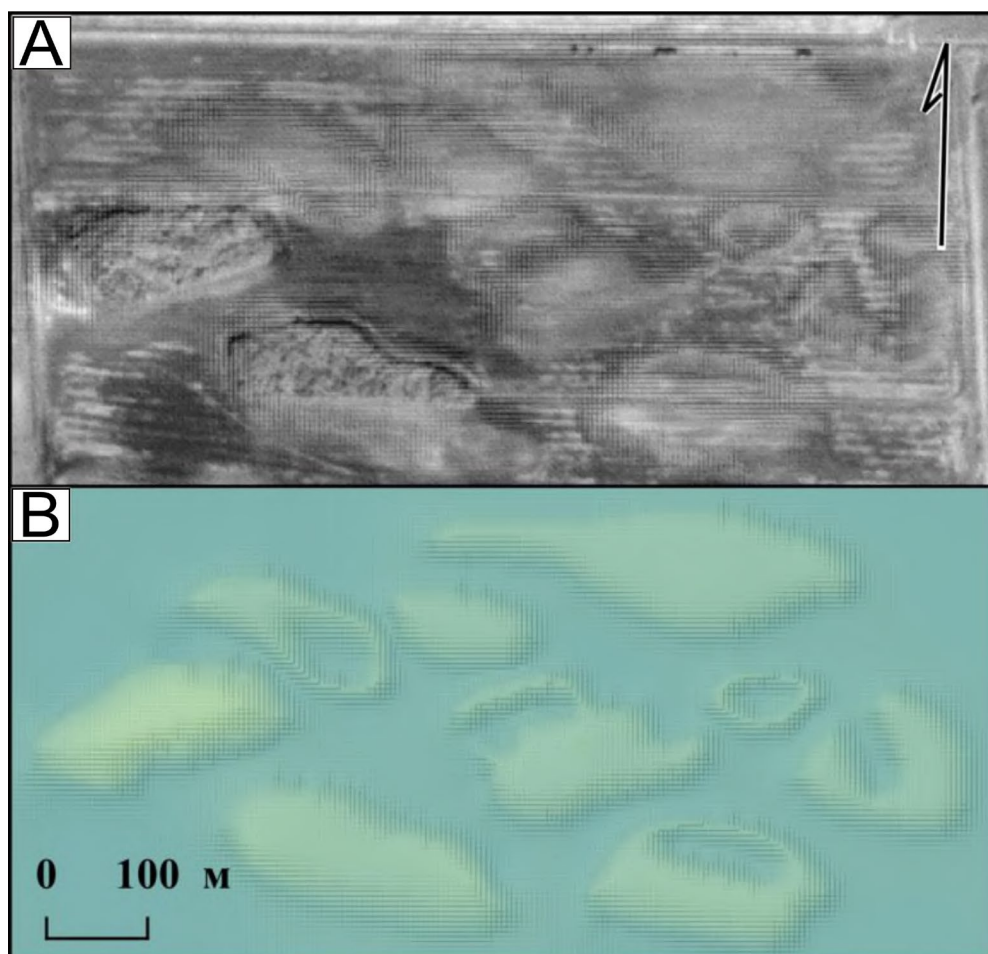


Fig. S6. The higher (with forest cover) and lower (ploughed together with the surrounding artificially drained wetland) “lacustrine-alluvial” elevations (mid-channel bars of a sand-bed braided river) on the panchromatic image of the BelKA artificial Earth satellite (A), and on the digital elevation model (DEM) (B). Some of the elevations have a depression in the central part. Location: 52°21'5.33"N 25°22'32.76"E. BelKA – Belarusian Cosmic Apparatus, acronym from Belarusian language. For details, see Trifonov, 2021



Fig. S7. Fragment of the early autumn multispectral image of the “WorldView-2” satellite, presented in natural colours (red, green, blue), near the villages of Motol’ and Tyshkovichi ($52^{\circ}19'37.00''\text{N}$ $25^{\circ}34'9.14''\text{E}$). The lower “lacustrine-alluvial” elevations (mid-channel bars of a sand-bed braided river) ploughed together with the surrounding artificially drained wetlands. Some of the elevations have a depression in the central part. Between the elevations, the traces of flow (paths of a braided river in our interpretation) are clearly visible. See also Trifonov, 2021



Fig. S8. The lower "lacustrine-alluvial" elevations separated by traces of flow (paths of a braided river)

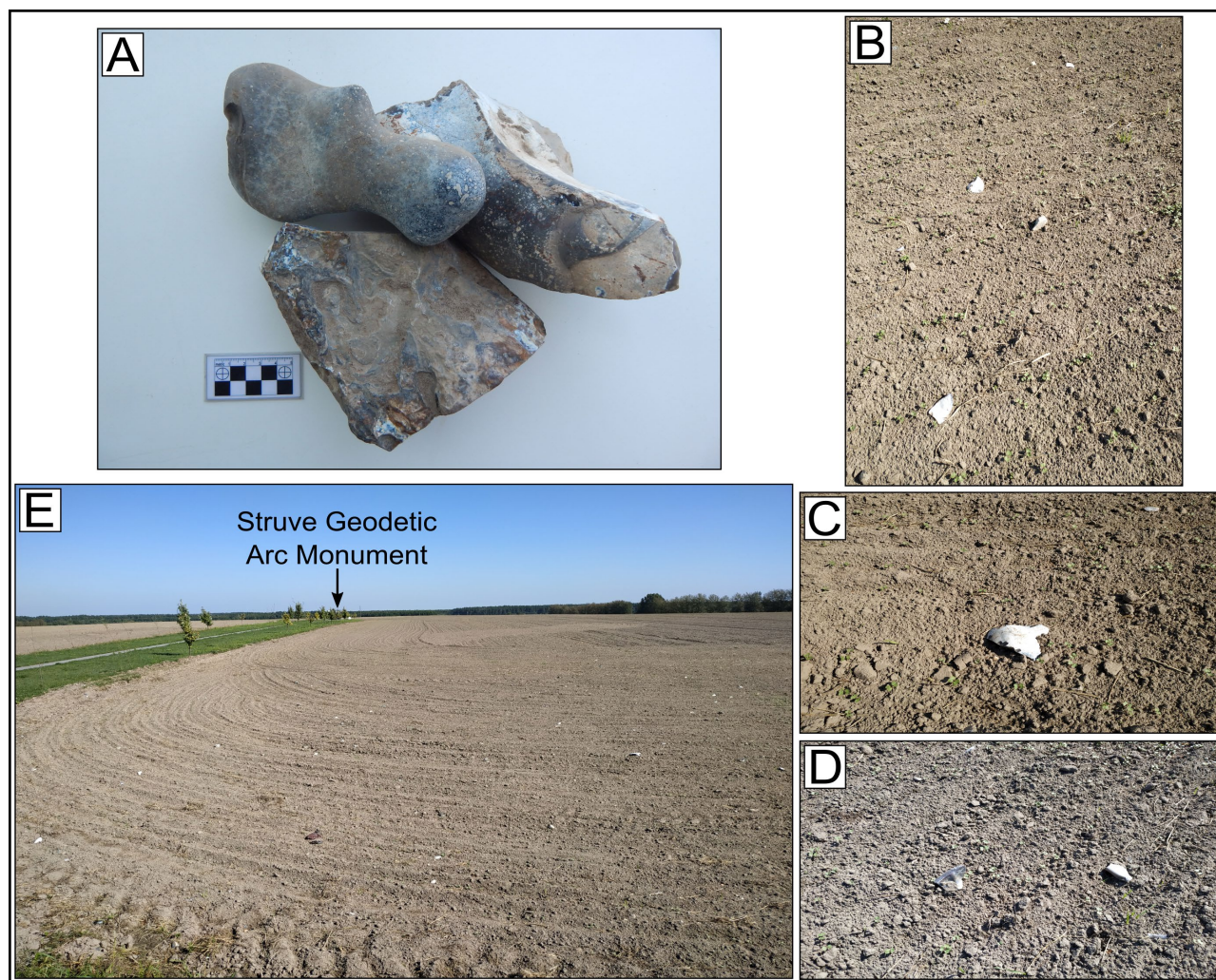


Fig. S9. Raw flint (A) from the ploughed surface of a terminal moraine elevation (in B–E raw flint can be seen as white spots) to the west of Bezdezh village, near the Struve Geodetic Arc Monument ($52^{\circ}19'28.75''\text{N}$ $25^{\circ}17'8.16''\text{E}$). We consider this site to be a flint extraction location used by prehistoric communities. Photos by D. Tsvirko in 2019 (B–E) and M. Kryvaltsevich (A)

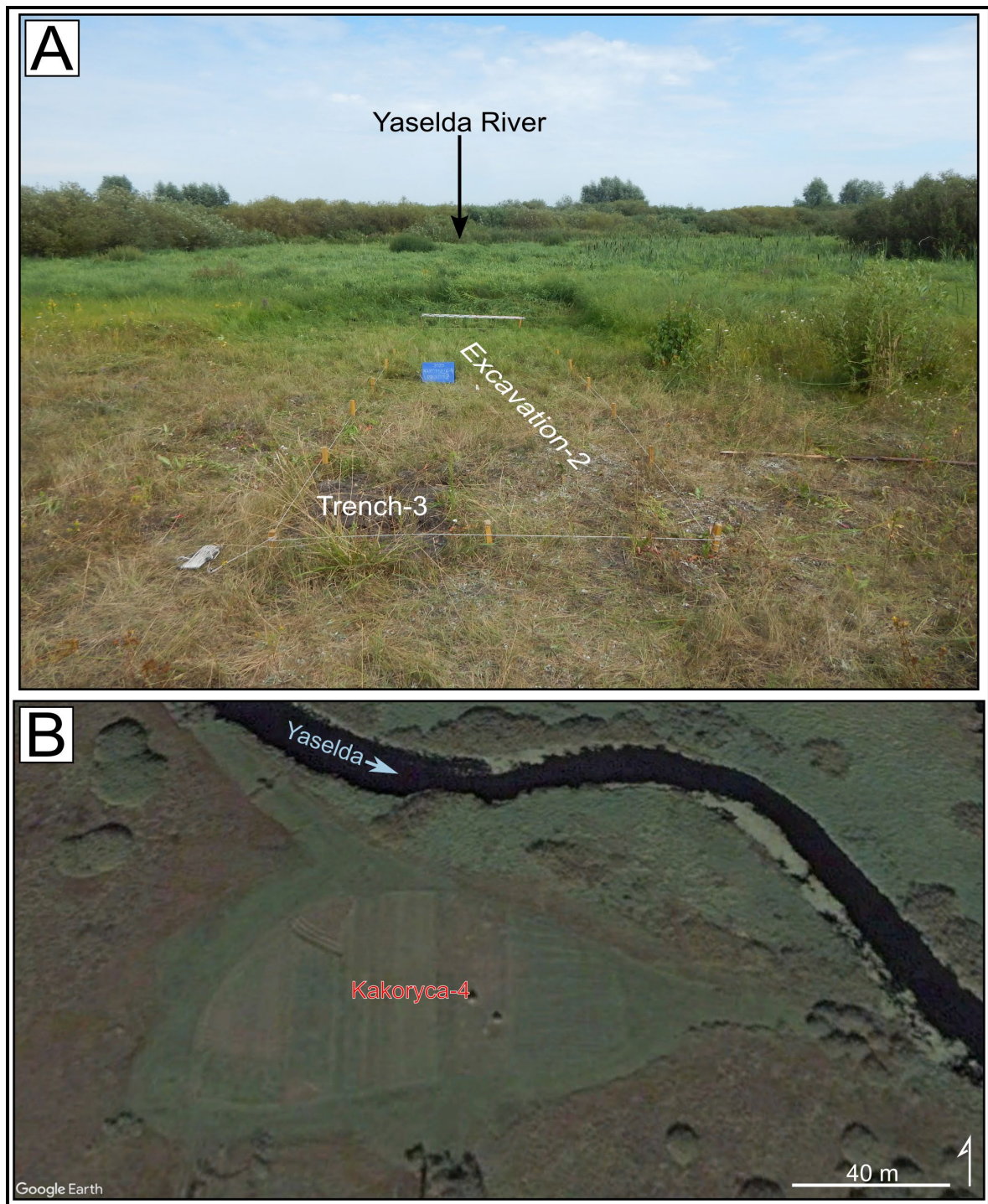


Fig. S10. Vegetation cover at the Kakoryca-4 archaeological site (52°23'36.16"N 25°17'34.95"E). A – Present-day vegetation cover at the Kakoryca-4 site (photo by M. Kryvaltsevich in 2020). B – Google Earth satellite image from September 2007 showing agricultural land on the Kakoryca-4 site

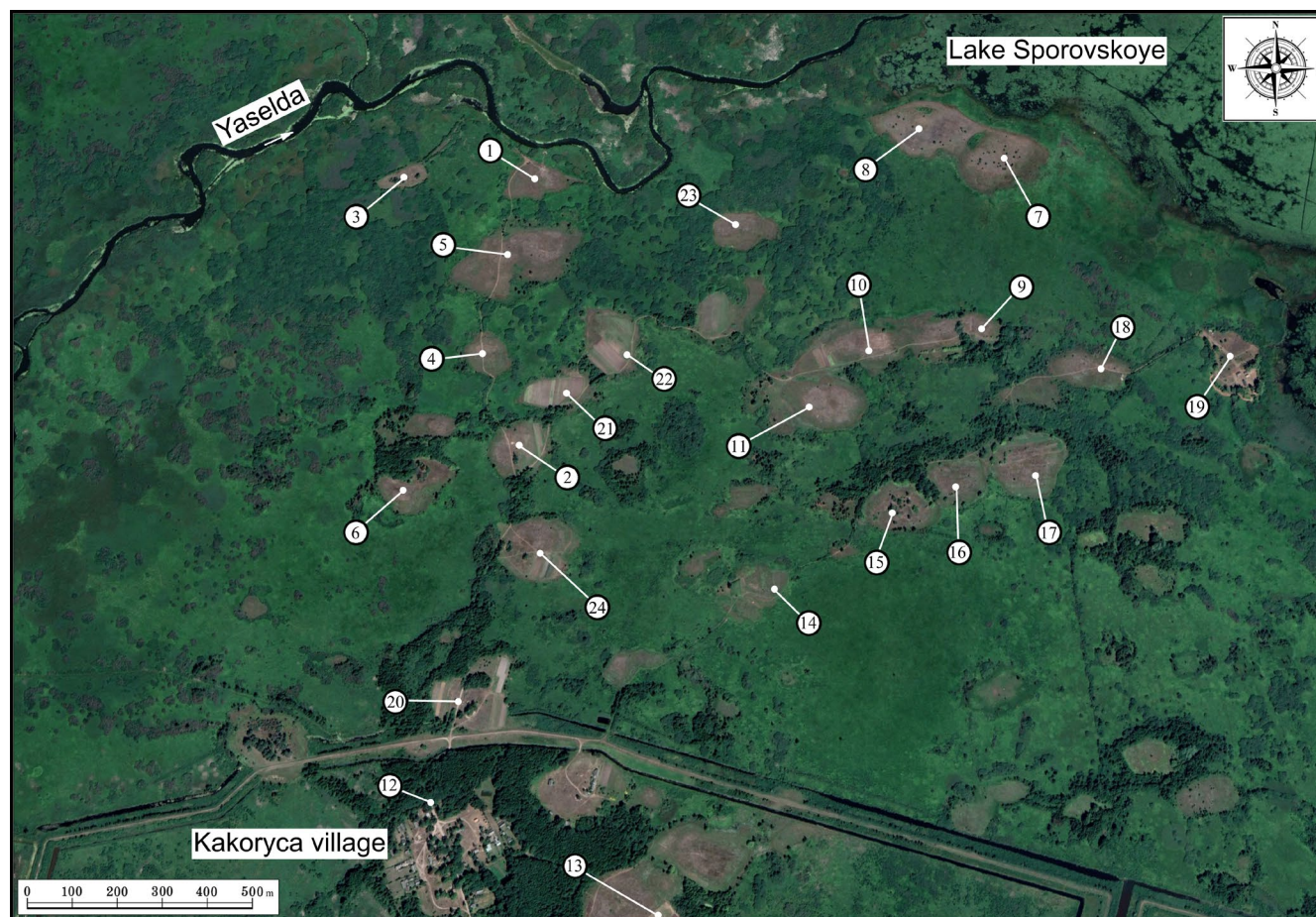


Fig. S11. Archaeological sites discovered on the rounded terrace remnants (“lacustrine-alluvial” elevations) southwest of Lake Sporovskoye.
 1 – Kakoryca-4; 2 – Kakoryca-5; 3 – Kakoryca-6; 4 – Kakoryca-7; 5 – Kakoryca-8; 6 – Kakoryca-9; 7 – Kakoryca-10A; 8 – Kakoryca-10B;
 9 – Kakoryca-11A; 10 – Kakoryca-11B; 11 – Kakoryca-11C; 12 – Kakoryca-12; 13 – Kakoryca-13; 14 – Kakoryca-14; 15 – Kakoryca-15;
 16 – Kakoryca-16; 17 – Kakoryca-17; 18 – Kakoryca-18; 19 – Kakoryca-19; 20 – Kakoryca-20; 21 – Kakoryca-21; 22 – Kakoryca-22;
 23 – Kakoryca-23; 24 – Kakoryca-29



Fig. S12. Trench-4 and its walls with identified lithological units (A–D). D – outcrop and borehole parts of the PKK-1-2 core on eastern wall of Trench-4 (sed core – core for sedimentological analysis; macro core – core for plant macrofossil analysis); in green is the age of the coarse detritus gyttja (6,391–6,294 cal BP) directly covering the Pripyat-Neman culture pottery found at a depth of 50 cm

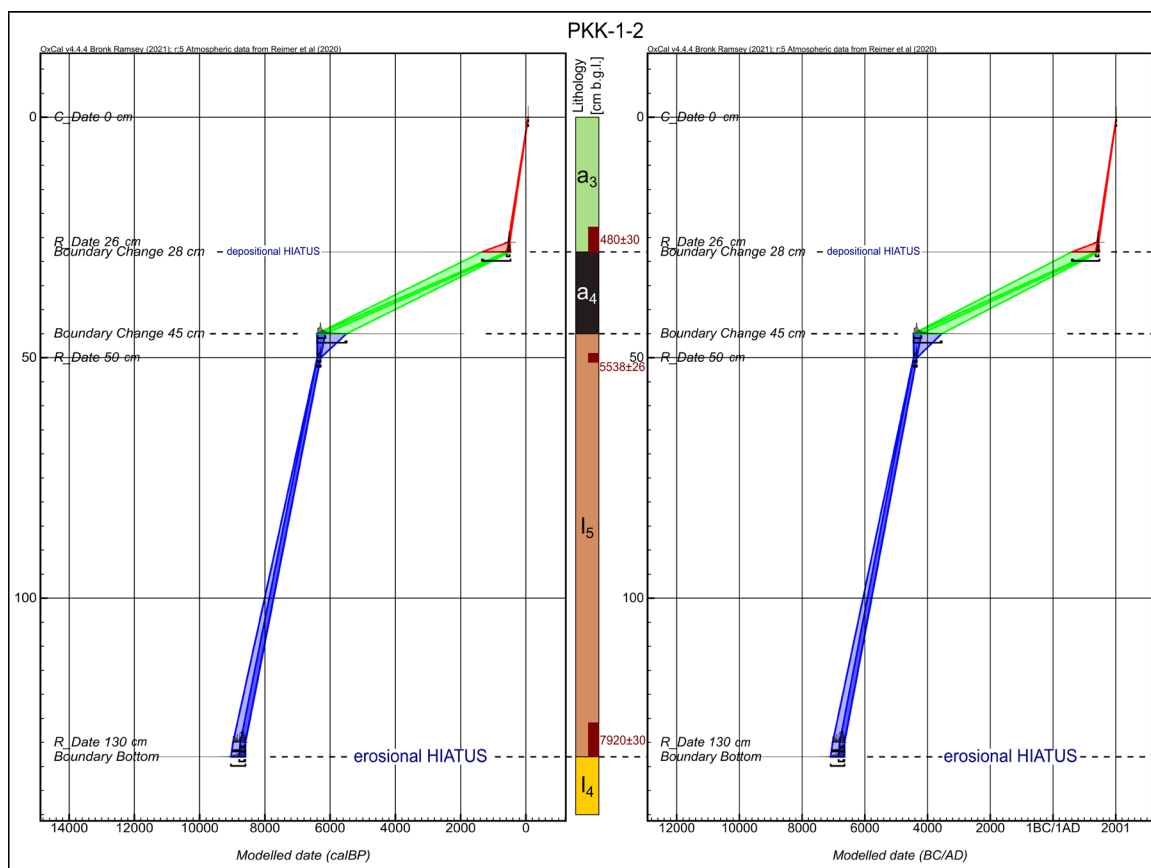


Fig. S13. The age-depth models (cal BP and cal BC/AD) for the PKK-1-2 core

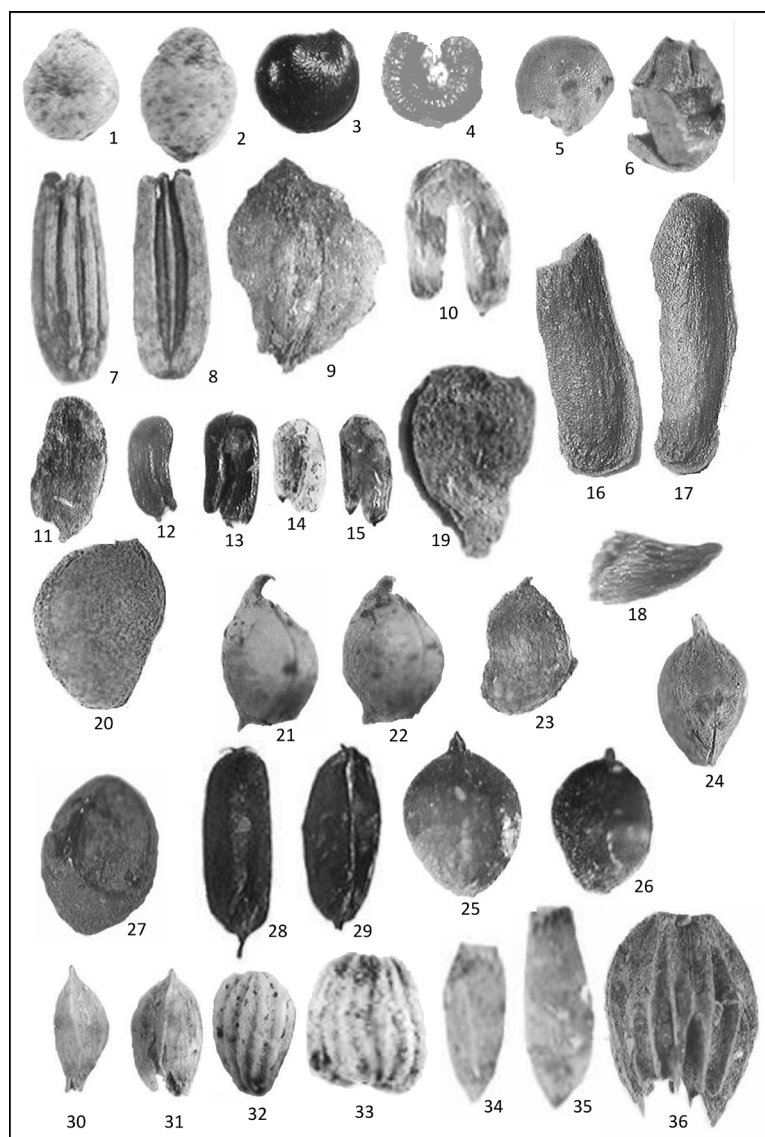


Fig. S14. Plant macrofossils from the PKK-1-2 core (identification and photos by T. Yakubovskaya). **1** and **2** – *Salvinia natans*, megaspores, microscope magnification x60; **3** – *Chenopodium glaucum*, seed, x40; **4** – *Elatine hydropiper*, seed, x40; **5** – *Nuphar lutea*, embryotega, x50; **6** – *Nymphaea alba*, seed, x10; **7** and **8** – *Oenanthe aquatica*, semi-fruit on both sides, x10; **9** and **10** – *Sagittaria sagittifolia*, fruit and tegmen, x8 and x15; **11–15** – *Alisma plantago-aquatica*, fruit, seeds and tegmens, x15; **16–18** – *Stratiotes aloides*, seeds and spine, x8 and x30; **19** – *Potamogeton pectinatus*, endocarp, x15; **20** – *Potamogeton* cf. *lucens*, endocarp, x15; **21** and **22** – *Potamogeton pusillus*, endocarps, x15; **23** – *Potamogeton gramineus*, endocarp, x15; **24** – *Carex rostrata*, fruit, x10; **25** and **26** – *Schoenoplectus lacustris*, fruits, x10; **27** – *Panicum miliaceum*, seed, x15; **28** and **29** – *Glyceria fluitans*, seeds, x15; **30** and **31** – *Cyperus fuscus*, fruits, x30; **32** – *Lemna minor*, seed, x50; **33** – *Lemna trisulca*, seed, x50; **34** and **35** – *Typha latifolia*, tegmens, x30; **36** – *Sparganium erectum*, endocarp, x8

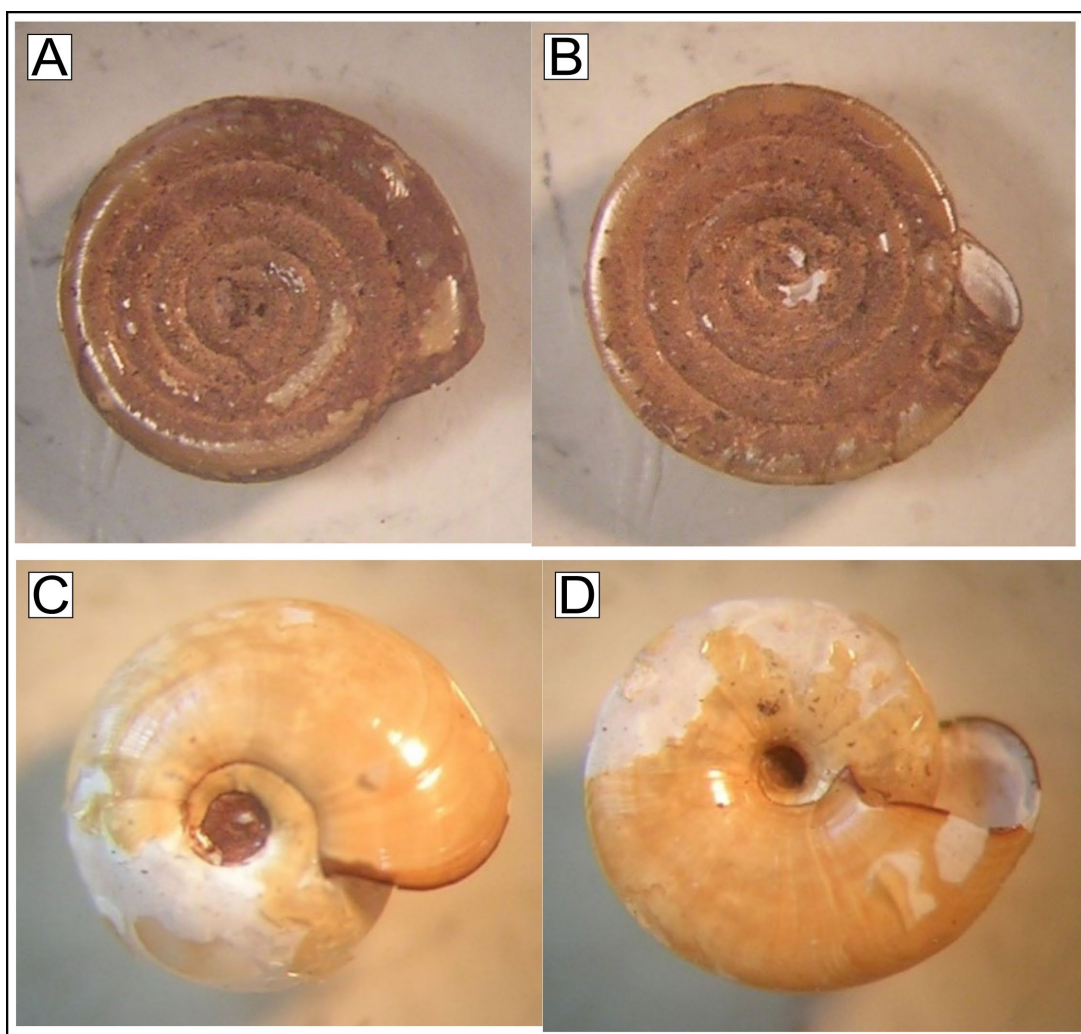


Fig. S15. Shells of *Anisus vortex* (A and B) and *Segmentina nitida* (C and D) from the sample 0–7 cm of the PKK-1-2 core (photos by A. Sanko)

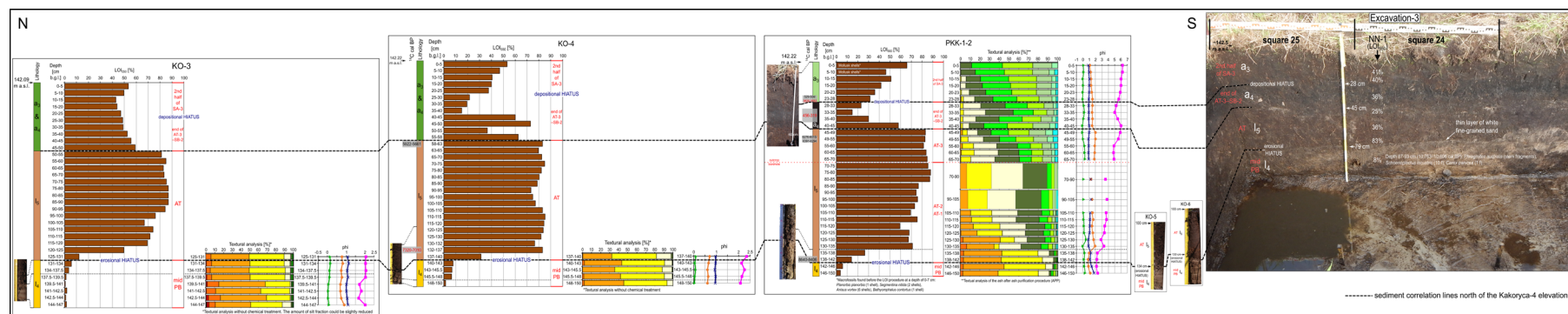


Fig. S16. Correlation of geological cores and outcrops located between the Kakoryca-4 elevation and the present-day channel of the Yaselda River (photos by M. Kryvaltsevich and D. Tsvirko). KO-3 (52°23'38.769"N 25°17'35.675"E), KO-4 (52°23'38.53"N 25°17'35.58"E), PKK-1-2 (52°23'38.448"N 25°17'35.545"E), KO-5 (52°23'38.204"N 25°17'35.304"E), KO-6 (52°23'37.822"N 25°17'35.289"E). Depth is given in cm below ground level [cm b.g.l.]

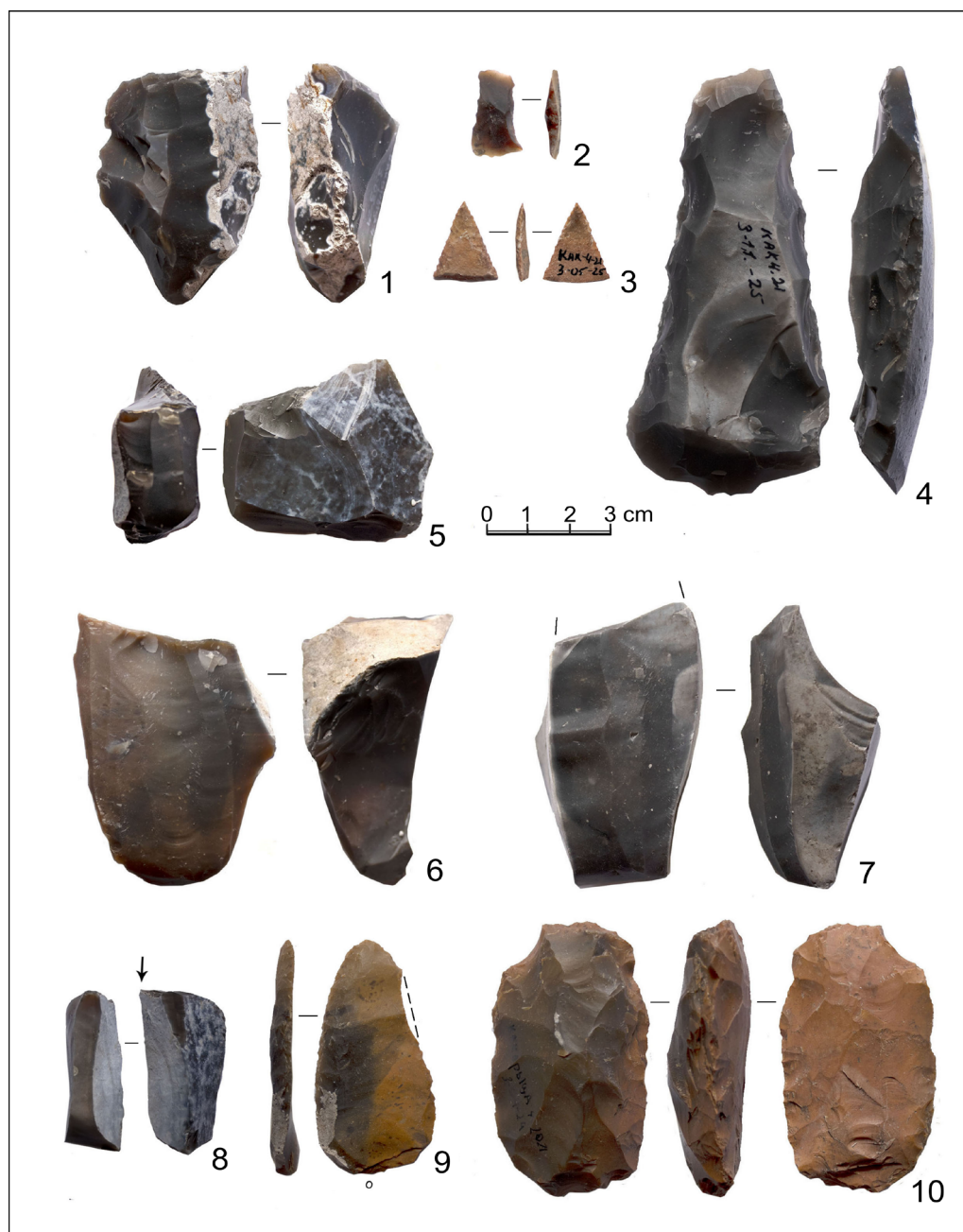


Fig. S17. Flint artefacts from squares 24 and 25 of the Excavation-3, Kakoryca-4 archaeological site. 1 – core of Kudlaevka culture (sq. 24, layer 40–50 cm b.g.l.); 2 – trapeze of Kudlaevka culture (sq. 24, layer 30–40 cm); 3 – triangle projectile point of Neman culture–Corded Ware culture circle (sq. 25, layer 40–50 cm); 4 – adze of Mesolithic period (sq. 24, layer 100–110 cm); 5 – core of Janisławice culture (sq. 24, layer 60–70 cm); 6 – core of Neman culture–Corded Ware culture circle (sq. 25, layer 30–40 cm); 7 – fragment of core of Neman culture–Corded Ware culture circle (?) (sq. 25, layer 80–90 cm); 8 – burin on truncation of Swiderian–Kudlaevka cultures (?) (sq. 24, layer 60–70 cm); 9 – knife of Neman culture–Corded Ware culture circle (sq. 24, layer 30–40 cm); 10 – axe of Neman culture (sq. 24, layer 30–40 cm)

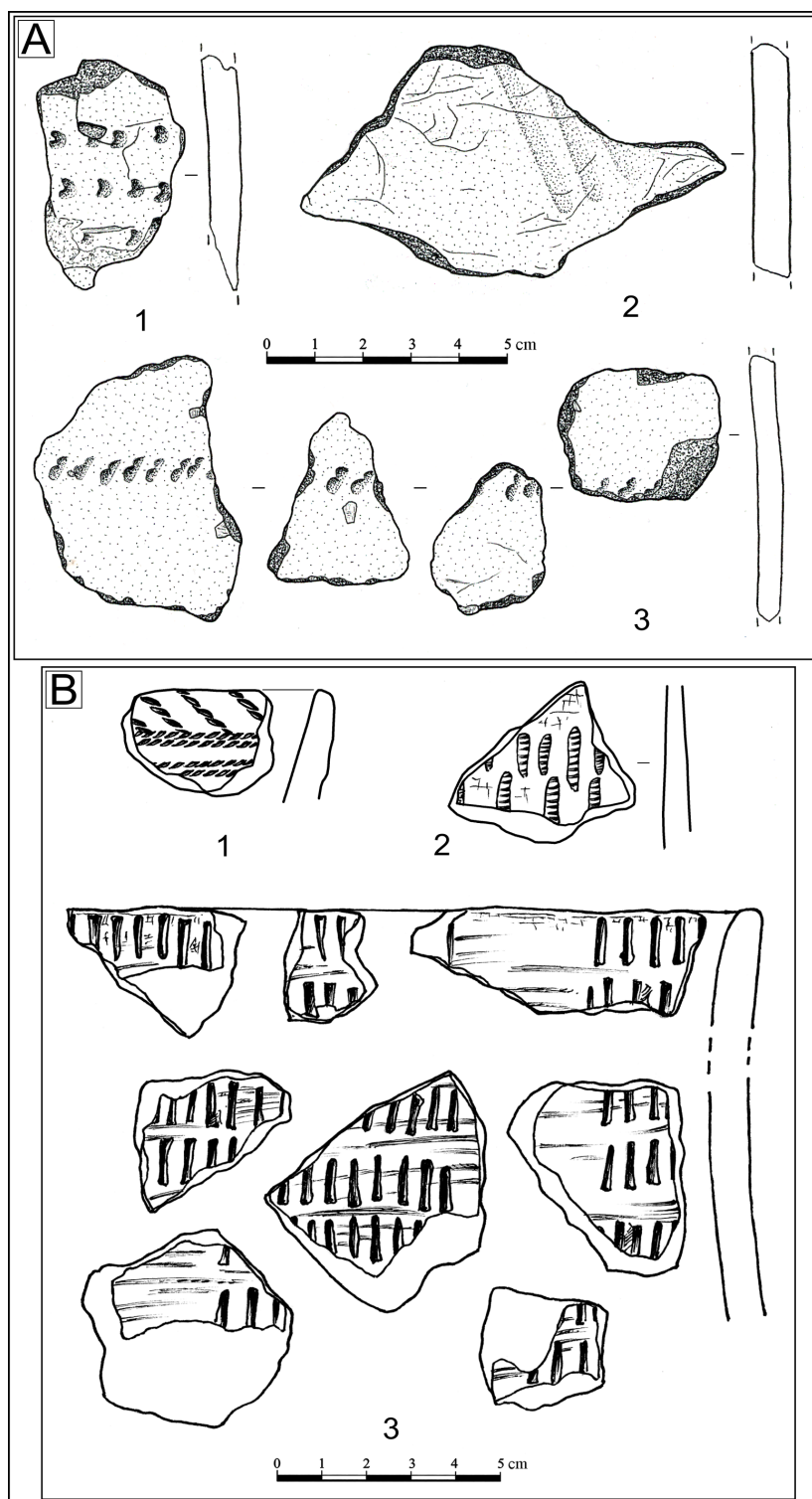


Fig. S18. Drawings of pottery artefacts from squares 24 and 25 of the Excavation-3, Kakoryca-4 archaeological site. **A** (sq. 24, layer 30–40 cm, drawings by A. Tkachou): 1 and 2 – Pripyat-Neman culture (Dubičiai-type); 3 – Neman culture (Dobry Bor-type). **B** (layer 30–40 cm, drawings by M. Kryvaltsevich): 1 (sq. 24) and 2 (sq. 25) – Corded Ware culture circle; 3 (sq. 25) – Corded Ware culture circle with elements of the Globular Amphora culture

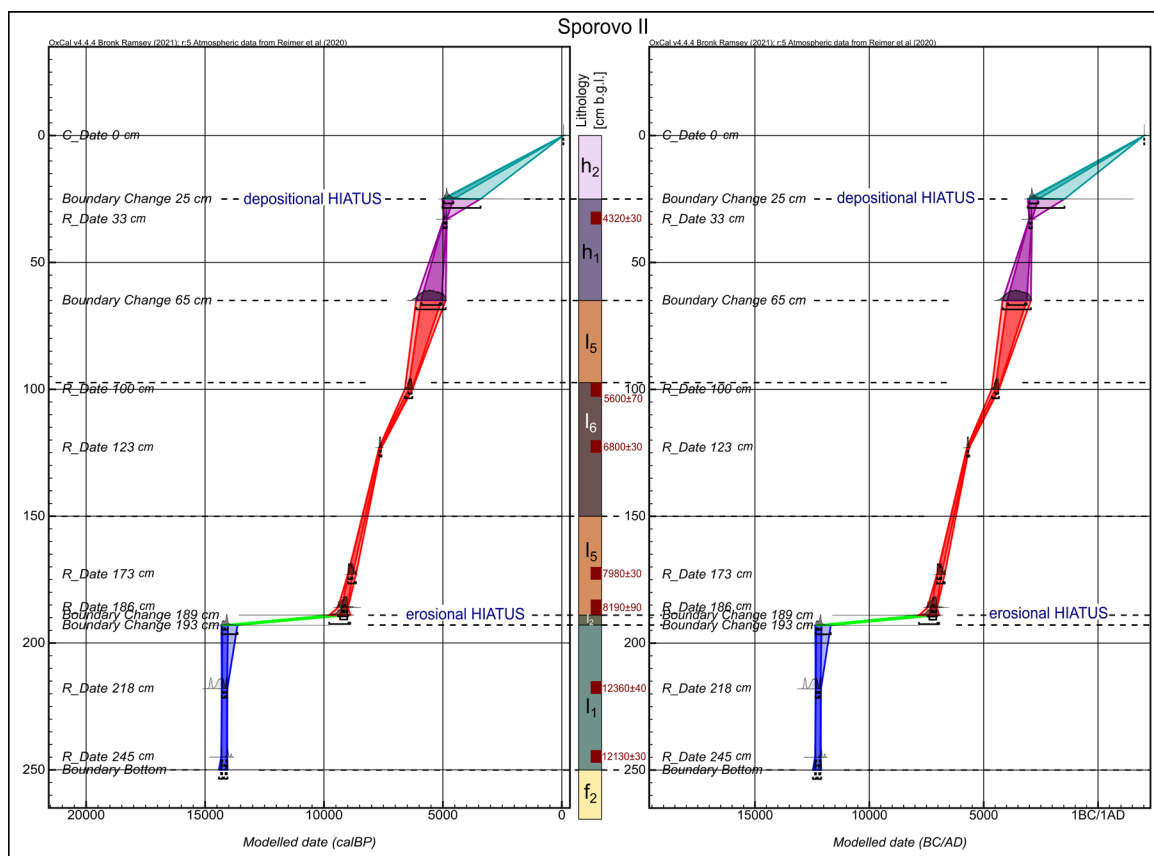


Fig. S19. The age-depth models (cal BP and cal BC/AD) for the Sporovo II core

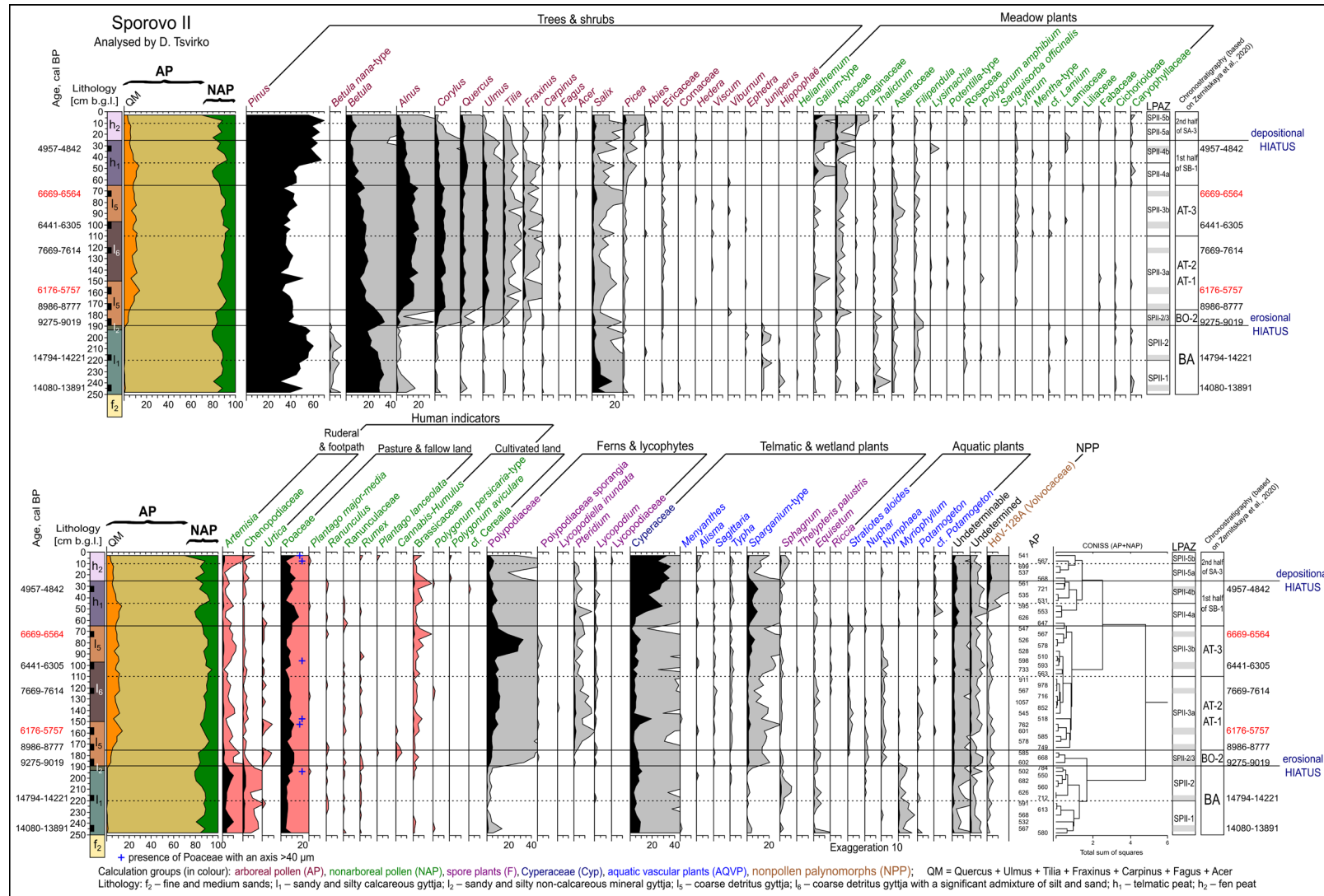


Fig. S20. The extended percentage spore-pollen diagram from the Sporovo II core (52°23'52.797"N 25°17'44.802"E; analysed by D. Tsvirko) (Tsvirko, 2023)

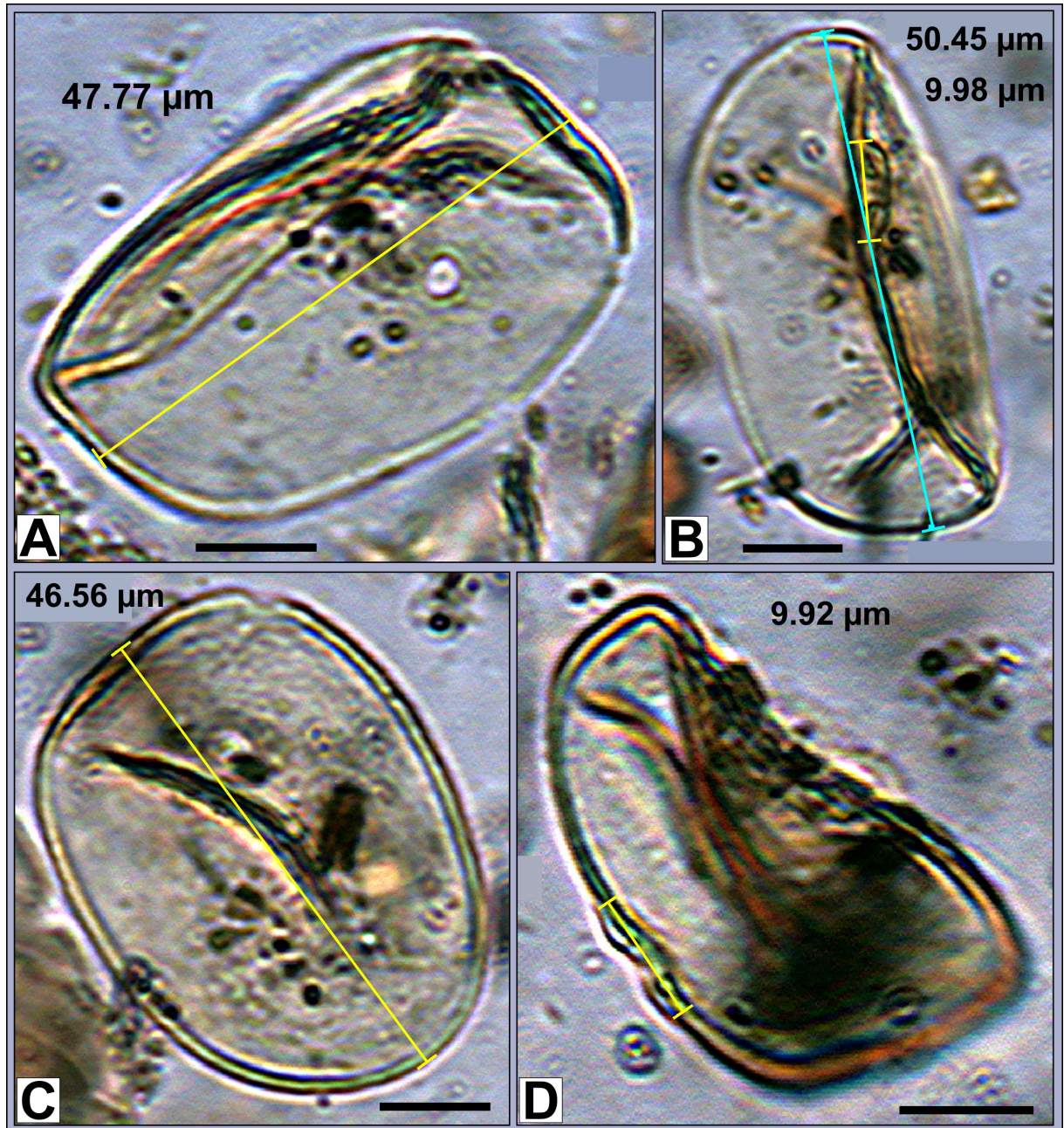


Fig. S21. Examples of wild-growing Poaceae pollen grains from the Sporovo II core, with an indistinct annulus contours. A and B – Poaceae with the longest axis size of 47.77–50.45 μm and the annulus size of 9.98 μm (the same grain in different positions; sample depth: 145–150 cm; approximate age 8,200 cal BP or 6,200 cal BC); C and 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 (Tsvirko, 2023)

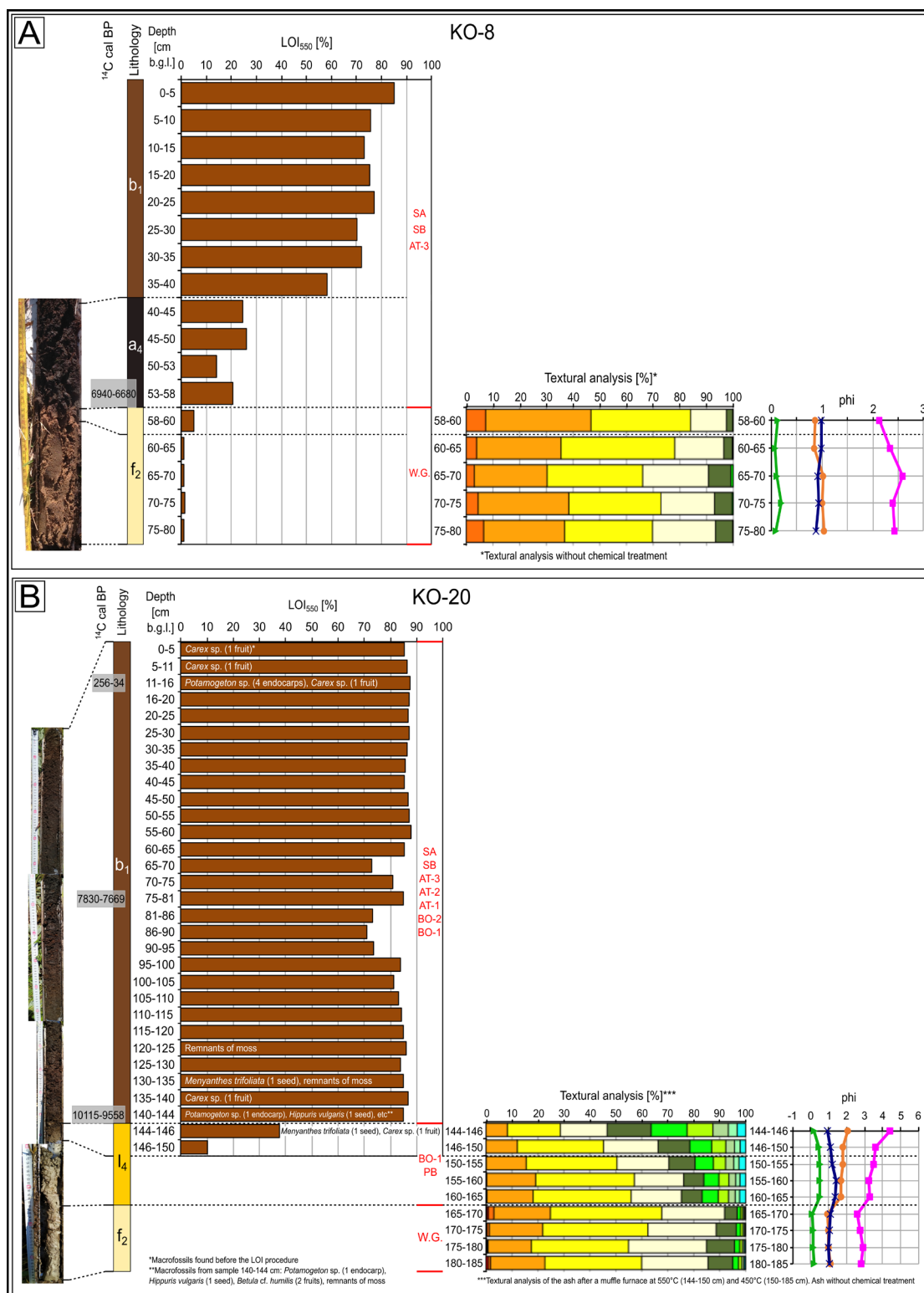


Fig. S22. Sedimentological diagrams of the KO-8 (A) and KO-20 (B) cores with identified lithological units (photos by D. Tsvirko). Cores: KO-8 (52°23'34.16"N 25°17'37.29"E), KO-20 (52°23'06.259"N 25°17'06.947"E). Abbreviations: W.G. – Weichselian glaciation, BA – Bølling-Allerød, YD – Younger Dryas, PB – Preboreal, BO – Boreal, AT – Atlantic, SB – Subboreal, and SA – Subatlantic

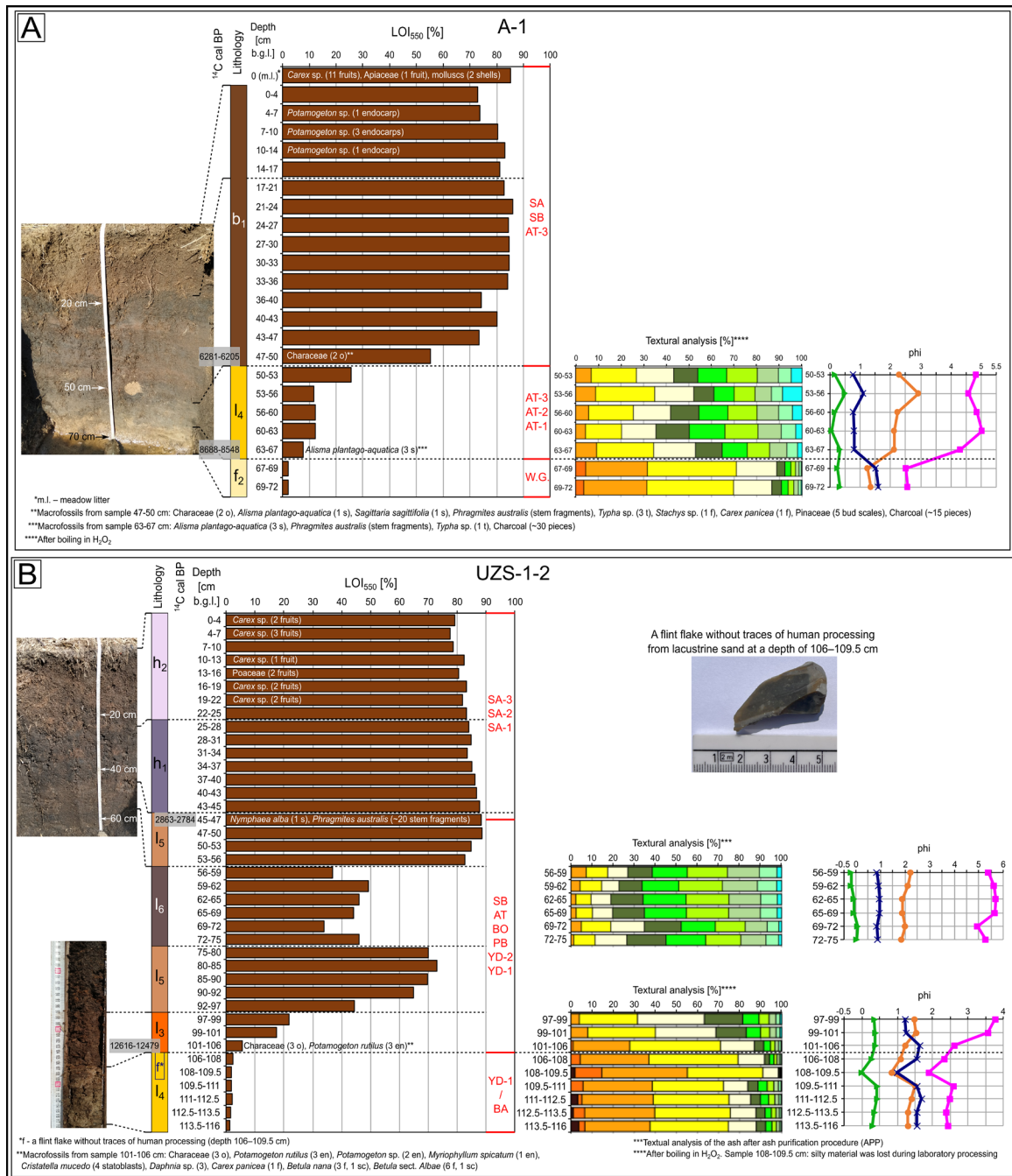


Fig. S23. Sedimentological diagrams of the A-1 outcrop (A) and UZS-1-2 core (B) with identified lithological units (photos by D. Tsvirko). A-1 (52°23'18.853"N 25°18'25.898"E), UZS-1-2 (52°23'31.367"N 25°18'33.788"E). For the explanation of abbreviations, see caption to Fig. S22

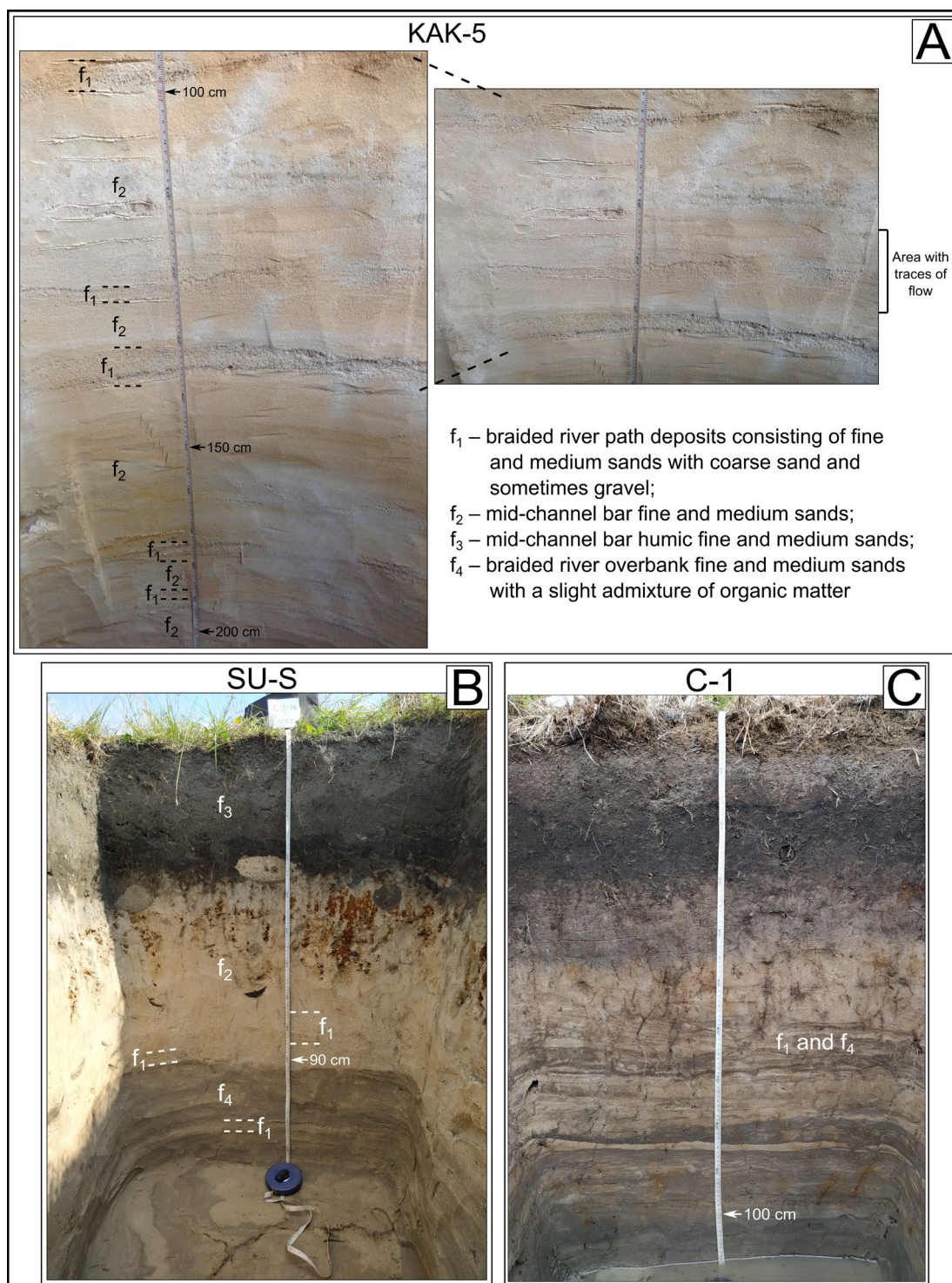


Fig. S24. Photos of the KAK-5 (A), SU-S (B), and C-1 (C) outcrops with identified lithological units (photos by D. Tsvirko). KAK-5 (52°23'14.82"N 25°17'33.04"E), SU-S (52°23'38.466"N 25°18'31.220"E), C-1 (52°23'39.607"N 25°18'31.939"E). Depth is given in cm below ground level [cm b.g.l.]

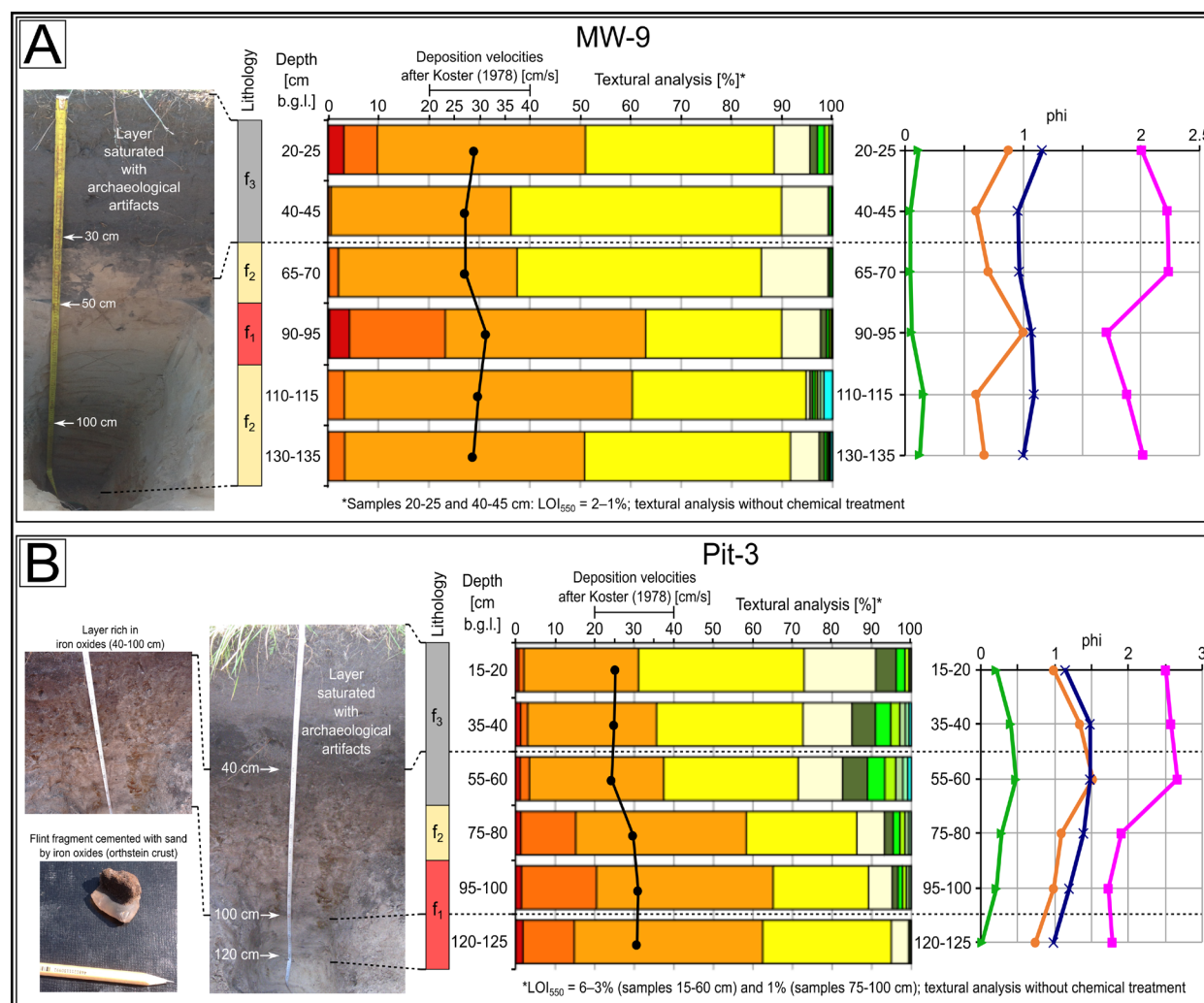


Fig. S25. Sedimentological diagrams of the MW-9 (A) and Pit-3 (B) outcrops with identified lithological units (photos by D. Tsvirko).

MW-9 (52°23'36.69"N 25°17'35.04"E), Pit-3 (52°23'37.345"N 25°17'35.247"E)

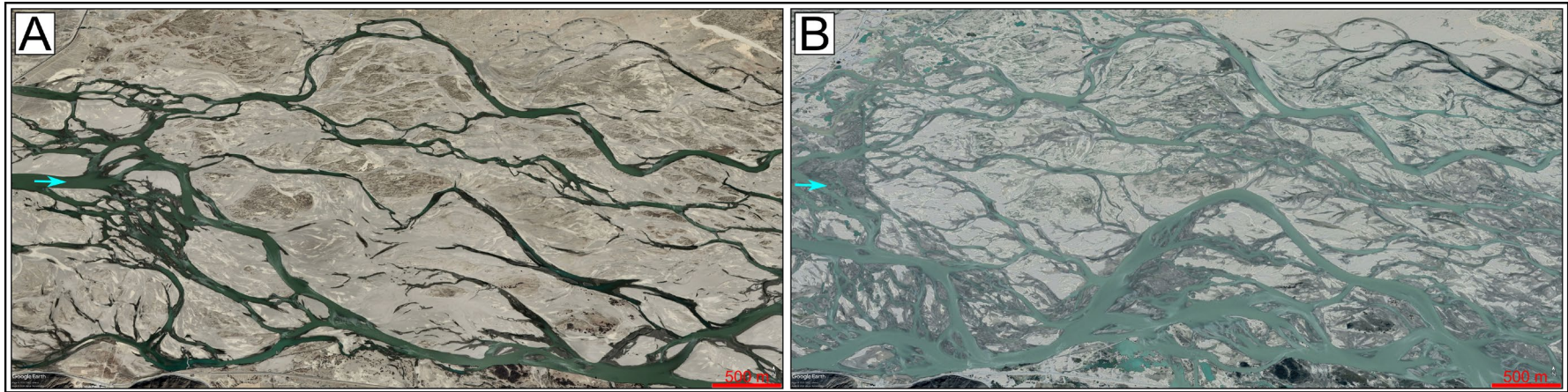


Fig. S26. Google Earth satellite images of the present-day sand-bed braided river Yarlung Tsangpo in China (29°20'18.95"N 88°51'55.94"E), showing numerous paths and mid-channel bars during the dry season (A – March 2021) and the flood season (B – September 2013) (cf. Han et al., 2023)



Fig. S27. Google Earth satellite image of the fluvioglacial plain (dated to the Dnieper stage) south of Khomsk village, with remnants of ice- and/or sand-wedge polygons

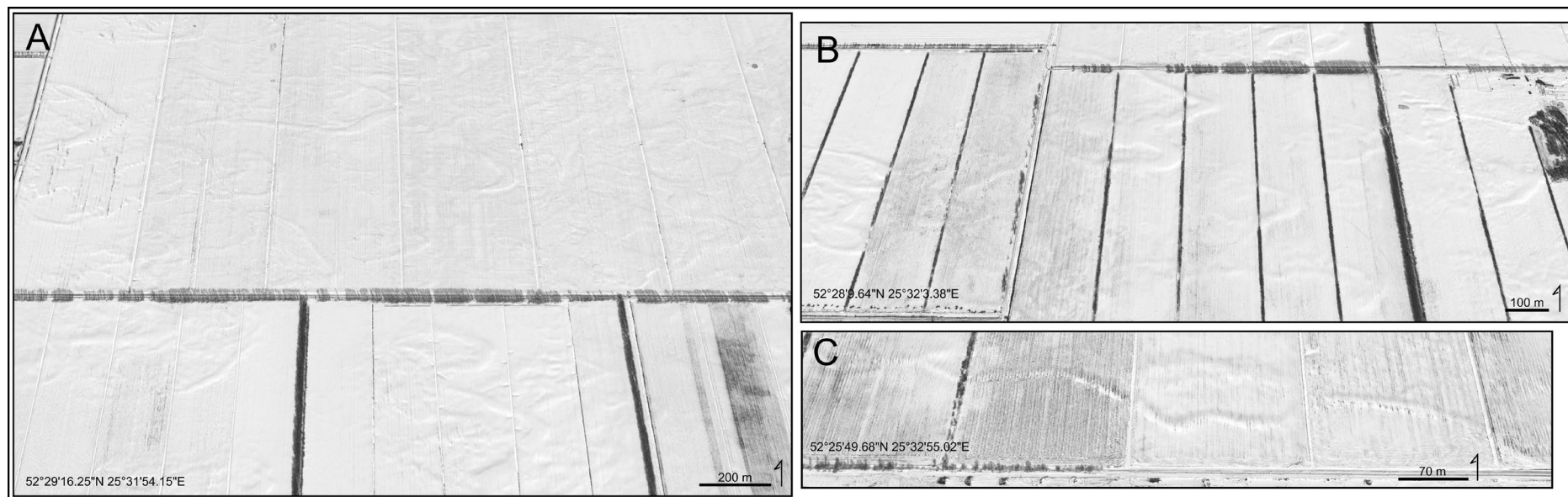


Fig. S28. Google Earth satellite images showing numerous dunes (A–C) across the study basin of the Yaselda River

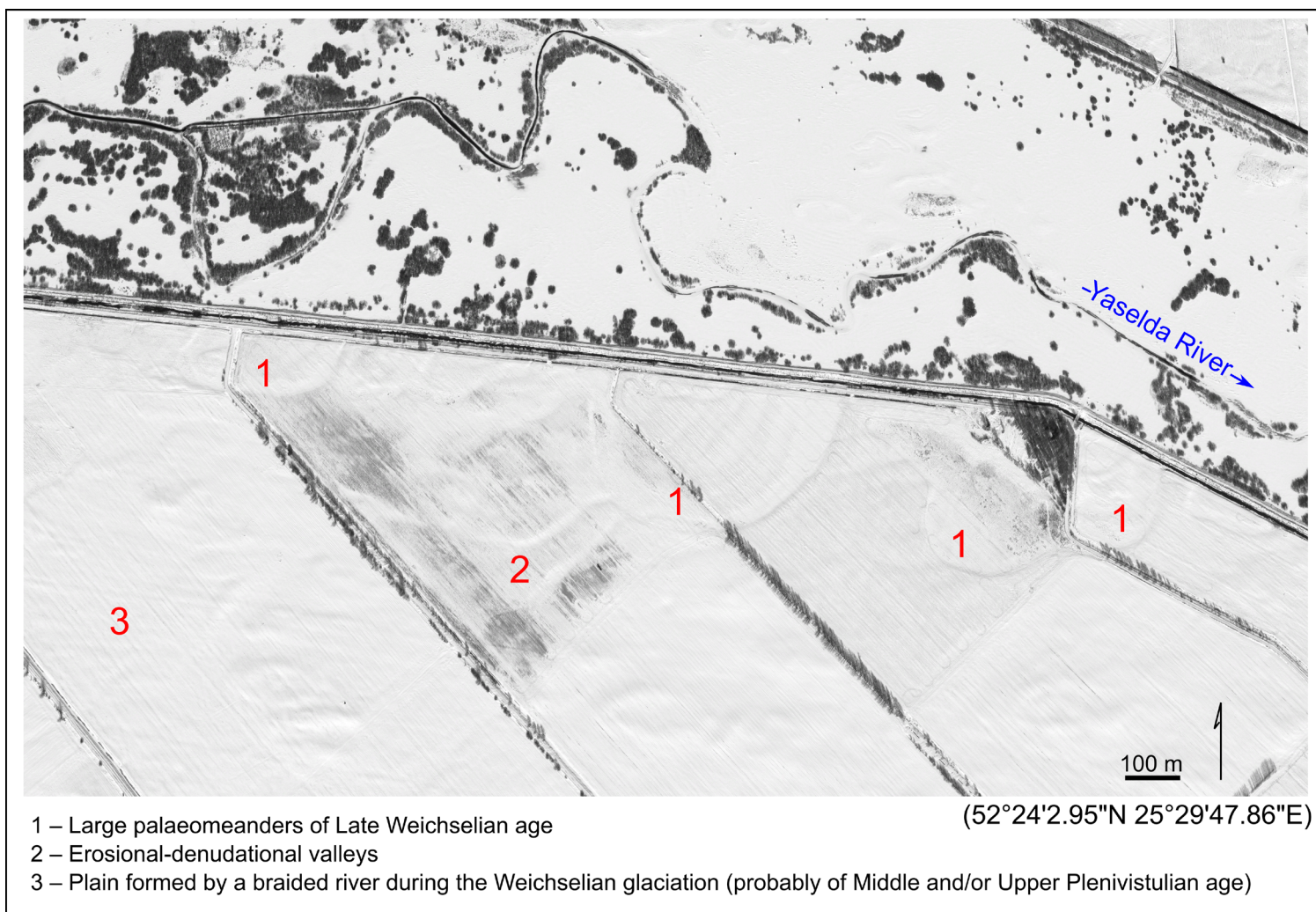


Fig. S29. Google Earth satellite image of the Yaselda River valley, showing the narrow present-day river channel, and large palaeomeanders (1) cutting through the plain of braided stream (“lacustrine-alluvial”) deposits (3)

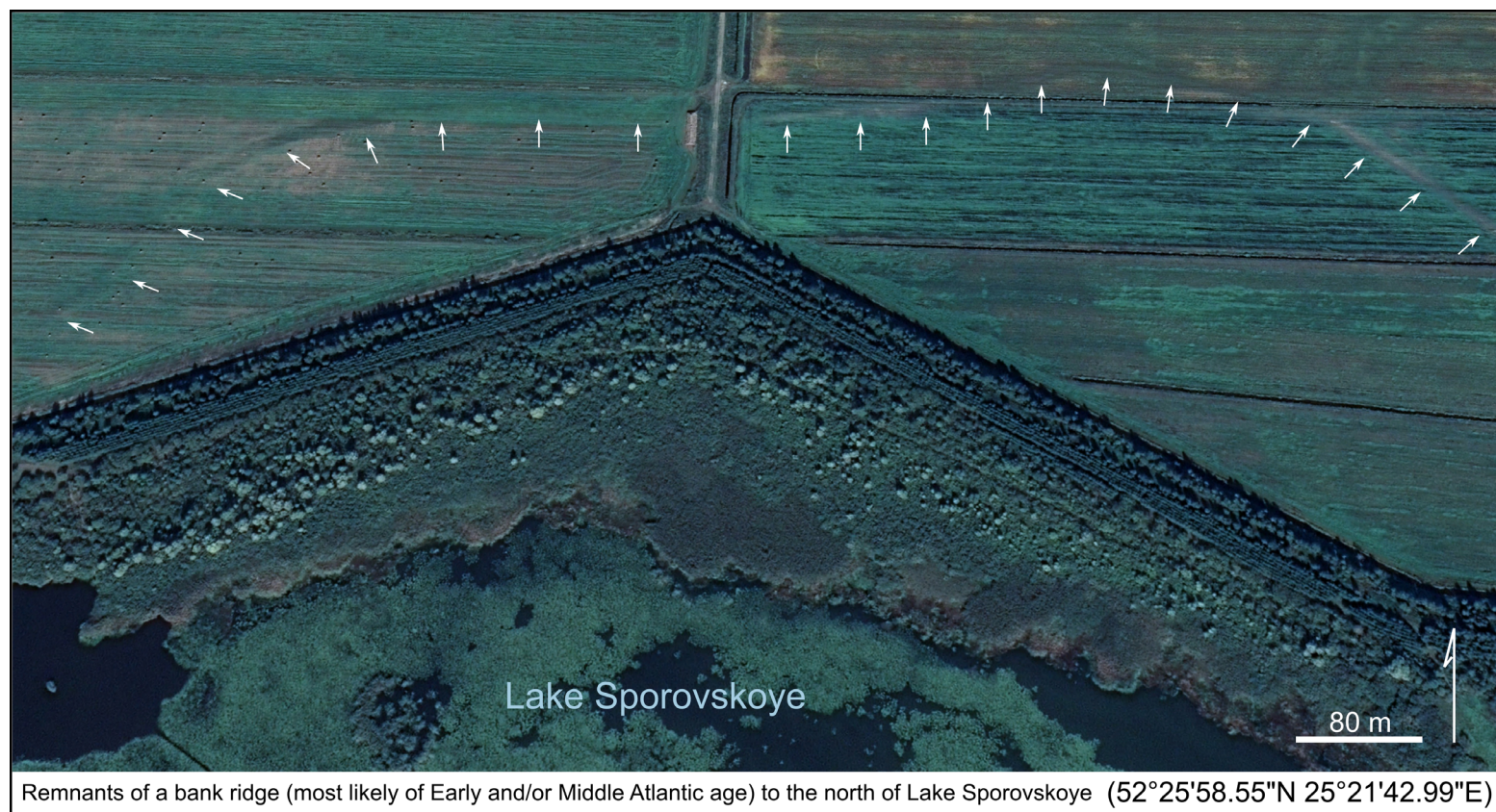


Fig. S30. Google Earth satellite image showing the remnants of a bank ridge to the north of Lake Sporovskoye, formed during the Early and Middle Atlantic transgression of the lake

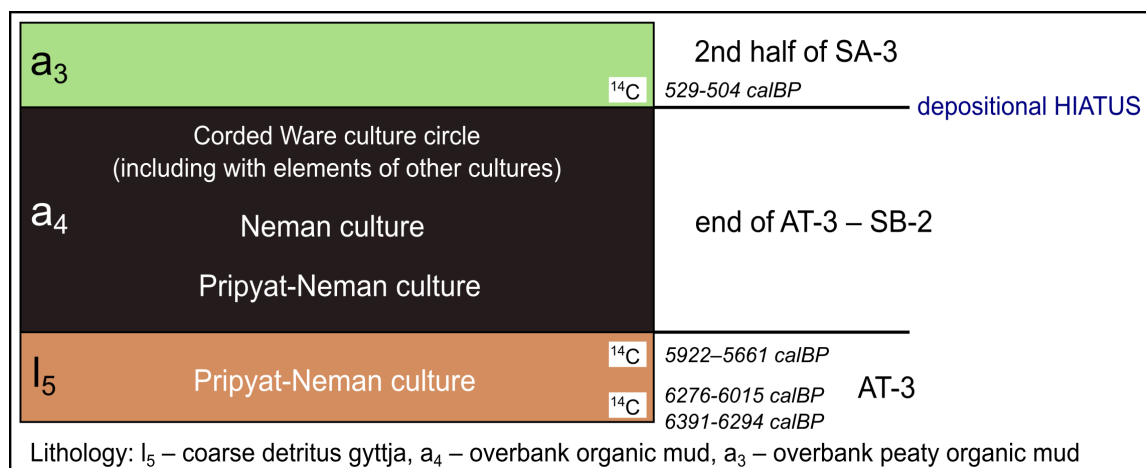


Fig. S31. The most artefact-rich geological layer at the Kakoryca-4 site (overbank black organic mud layer a₄, corresponding to the excavation layer 30–40 cm in Excavation-3)

Table S1. The total number of artefacts found at the Kakoryca-4 site for the period 2018–2021

2018 (trenches by Iou)	2019 (excavation and trench by Kryvaltsevich)	2020 (excavation and trench by Kryvaltsevich)	2021 (excavation by Kryvaltsevich)	Total
232	5,944	48,727	8,487	63,390

Table S2. The sampling strategy for laboratory analyses. The width of the slices could vary depending on lithological boundaries

Core/outcrop name	Depth [cm b.g.l.]	Analyses performed	Field sampling method	Sampling strategy
Reference biogenic cores				
Sporovo II	270	Macroscopic description, geochemistry, sedimentology, ^{14}C , <u>palynology</u> , plant macrofossils	Instorf hand drill	5-cm slices
PKK-1-2	150 (sed core) and 165 (macro core)	Macroscopic description, geochemistry, sedimentology, ^{14}C , <u>plant macrofossils</u> , malacology, archaeology	Instorf hand drill and sampling from outcrop wall	For plant macrofossils analysis: 10-cm slices (depth 165–60 cm) and 5-cm slices (depth 60–0 cm); for other analyses: 5-cm slices
Survey biogenic cores and outcrops				
KO-3	147	Macroscopic description, geochemistry, sedimentology	Instorf hand drill	5-cm slices
KO-4	150	Macroscopic description, geochemistry, sedimentology, ^{14}C	Instorf hand drill	5-cm slices
KO-5	150	Macroscopic description	Instorf hand drill	-
KO-6	150	Macroscopic description	Instorf hand drill	-
NN-1	110	Macroscopic description, geochemistry, ^{14}C , plant macrofossils, <u>archaeology</u>	Sampling from outcrop wall	Selected samples
KO-8	80	Macroscopic description, geochemistry, sedimentology, ^{14}C	Instorf hand drill	5-cm slices
KO-9	198	Macroscopic description, geochemistry, sedimentology, ^{14}C , plant macrofossils	Instorf hand drill	5-cm slices
KO-20	185	Macroscopic description, geochemistry, sedimentology, ^{14}C , plant macrofossils	Instorf hand drill	5-cm slices
UZS-1-2	116	Macroscopic description, geochemistry, sedimentology, ^{14}C , plant macrofossils, archaeology	Instorf hand drill and sampling from outcrop wall	3-cm slices
A-1	72	Macroscopic description, geochemistry, sedimentology, ^{14}C , plant macrofossils	Sampling from outcrop wall	3-cm slices

Table S2 (continued)

Core/outcrop name	Depth [cm b.g.l.]	Analyses performed	Field sampling method	Sampling strategy
Outcrops of mineral deposits				
KAK-5	220	Macroscopic description, geochemistry, <u>sedimentology</u>	Sampling from outcrop wall	Slices of different widths
SU-S	126	Macroscopic description, geochemistry, <u>sedimentology</u>	Sampling from outcrop wall	5-cm slices
MW-9	135	Macroscopic description, geochemistry, sedimentology, archaeology	Sampling from outcrop wall	Selected samples
Pit-3	125	Macroscopic description, geochemistry, sedimentology, archaeology	Sampling from outcrop wall	Selected samples
C-1	110	Macroscopic description	Outcrop wall	-

Table S3. The commonly accepted chronology of prehistoric and historical periods on the territory of Belarus (modified by the authors)

Period	Archaeological culture	Approximate age [cal BC]	Approximate age [cal BP]	Approximate duration [years]	Climatic periods (based on Zernitskaya et al., 2020)	References
Contemporary era	-	after 1,914 cal AD (Early-20th century AD to present)	from 36	110	SA-3	Elizarov et al., 2016
Modern Period	-	1,500 to 1,914 cal AD (16th to Early-20th centuries AD)	500 to 36	410		
Middle Ages	-	450 to 1,500 cal AD (5th to 16th centuries AD)	1,550 to 500	1,000	SA-2, SA-3	
Iron Age	-	650 cal BC to 450 cal AD (7th cent. BC to 5th cent. AD)	2,650 to 1,550	1,100	SA-1, SA-2	
Iron Age	Milograd culture	650 to 150 cal BC (7th to 2nd centuries BC)	2,650 to 2,150	500	SA-1	Loshenkov, 2011
Late Bronze Age	-	1000 to 800/600	3,000 to 2,800/2,600	400	SA-1	Kryvaltsevich, 2006b
Middle Bronze Age	Trzciniec Cultural Circle	1,700/1,600 to 1,000	3,700/3,600 to 3,000	700	SB-3	Kryvaltsevich, 2006b and 2016b; Makarowicz, 2010
Late Neolithic – Early Bronze Age	Middle Dnieper culture	2,600 to 1,700	4,600 to 3,700	900	SB-1, SB-2	Kryvaltsevich, 2006a
	Corded Ware culture circle (CWC) and Epi-CWC period	2,700/2,500 to 1,900/1,700 (End 1st half 3rd – Early-2nd mill.)	4,700/4,500 to 3,900/3,700	1,000	SB-1, SB-2	Kryvaltsevich, 2004a, 2006ab and 2011; Piličiauskas et al., 2018
Late Neolithic	Globular Amphora culture	2,700/2,500 to 1,900 (Early/2nd qtr of the 3rd – Early-2nd mill.)	4,700/4,500 to 3,900	800	SB-1, SB-2	Szmyt, 2010; Zuyeva, 2009; Kryvaltsevich, 2016a; Vaitovich, 2016, 2019 and 2020

Table S3 (continued)

Period	Archaeological culture	Approximate age [cal BC]	Approximate age [cal BP]	Approximate duration [years]	Climatic periods (based on Zernitskaya et al., 2020)	References
"Forest" Neolithic	Neman culture (Dobry Bor-type)	3,800/3,700 to 1,800	5,800/5,700 to 3,800	2,000	SB-1, SB-2	Piličiauskas, G., 2002; Charniauskis, 2011; Jóźwiak, 2018
	Pripyat-Neman culture (Dubičiai-type)	5,500/4,500 to 3,800/3,700 (Mid-6th/Early-5th mill. – about 3,800/3,700)	7,500/6,500 to 5,800/5,700	1,800	AT-3	Charniauskis, 2011; Jóźwiak, 2018; Tkachou, 2019; Tkachev and Tkacheva, 2024
Late Mesolithic	Janisławice culture	7,500/6,500 to 5,500/4,500 (Mid-8th/Early-7th – Mid-6th/Early-5th mill.)	9,500/8,500 to 7,500/6,500	3,000	end of BO, AT-1, AT-2, beginning of AT-3	Asheichyk, 2017; Kalechyts and Kolasau, 2023
Early Mesolithic	Kudlaevka culture	9,500/8,500 to 7,500/6,900 (Mid-10th/Early-9th – Late-8th mill.)	11,500/10,500 to 9,500/8,900	2,600	PB, BO, beginning of AT-1	Zaliznyak, 2009; Vashanau and Tkachova, 2025
Final Palaeolithic	Swiderian culture	10,800 to 8,500 (Early-11th – Mid-9th mill.)	12,800 to 10,500	2,300	YD, first half of PB	Stupak, 2006; Gudaitienė et al., 2019; consultations with E. Kalechits, A. Kolosov, and A. Harshkou

Table S4. Lithology and non-plant macrofossils from the PKK-1-2 core

Depth [cm b.g.l.]	Lithological unit	LOI [%]	Corresponding LMAZ	Other macrofossils (analysed by T. Yakubovskaya)
0–7	Backswamp peaty organic mud (a ₃)	65.7–46.3	KK-6	Insect fragments; insect egg shells; well-preserved mollusc shells; charred grass stems; modern plant roots
7–28		50.9–31.3	KK-5	Ostracoda shells (depth 13–18 cm); >34 insect fragments; insect egg shells (depth 7–13 cm); charcoal pieces; pieces of wood; modern plant roots
28–45	Backswamp organic mud (a ₄)	57.7–14.8	KK-4	21 insect fragments; insect egg shells (depth 28–33 cm); charcoal pieces; modern plant roots; megaspores of <i>Salvinia natans</i> and one fruit of <i>Schoenoplectus lacustris</i> were covered with iron oxide or "rust" (depth 40–45 cm)
45–70	Lacustrine coarse detritus gyttja (l ₅)	84.6–81.3	KK-3	2 insect fragments (depth 60–70 cm); many charcoal pieces, including many large ones (up to 1 cm in size); small pieces of wood (depth 60–70 cm); modern plant roots; megaspores of <i>Salvinia natans</i> were covered with iron oxide or "rust" (depth 45–49 cm)
70–133 (70–142)		87.9–14.1	KK-2	2 fish teeth (depth 110–120 cm); fragments of mollusc shells (depth 126–133 cm); Ostracoda shells (depth 126–133 cm); 11 insect fragments; charcoal pieces, including large ones; pieces of wood (including rounded)
133–165 in macro core (142–150 in sed core)	Lacustrine fine and medium sands and silt with a significant admixture of organic matter (l ₄)	6.0–3.7	KK-1	2 fish scale fragments and 1 fish vertebra (depth 133–141 cm); Ostracoda shells (depth 150–160 cm); fragments of mollusc shells (depth 150–160 cm); 5 insect fragments; 2 charcoal pieces up to 0.5 cm in size; 2 pieces of wood (depth 150–160 cm); probably small lumps of white carbonates, up to 1 mm in size (depth 150–160 cm)

Table S5. Local plant macrofossil assemblage zones (LMAZ) from the PKK-1-2 core. Abbreviations: s – seed; sfr – seed fragment; f – fruit; ffr – fruit fragment; semif – semi-fruit; en – endocarp; enfr – endocarp fragment; mgs – megaspore; t – tegmen; sp – spine; sc – scale; o – oogonium; spk – spikelet; emb – embryo. Macrofossils are given in absolute values

LMAZ	Depth [cm b.g.l.]	Lithological unit	Description (maximum and minimum number of macrofossils)
KK-6	0–7	Backswamp peaty organic mud (a ₃)	The zone included 1 sample. Poaceae (77, s/spk), <i>Oenanthe aquatica</i> (14, semif), <i>Typha latifolia</i> (10, t), <i>Lemna minor</i> (8, s), <i>Carex</i> (4, f/ffr), <i>Salvinia natans</i> (4, mgs), <i>Sparganium erectum</i> (3, en), <i>Batrachium</i> (1, f), <i>Bidens tripartita</i> (1, f), <i>Mentha longifolia</i> (1, f), <i>Iris pseudacorus</i> (1, s)
KK-5	7–28		The zone included 4 samples. <i>Salvinia natans</i> (1,060–25, mgs), <i>Oenanthe aquatica</i> (625–201, semif), <i>Alisma plantago-aquatica</i> (306–52, f/s/t), Poaceae (250–75, s/spk), <i>Typha latifolia</i> (180–5, t), <i>Sagittaria sagittifolia</i> (156–1, f/s/t), <i>Stratiotes aloides</i> (60–10, sp), <i>Juncus</i> (50–2, s), <i>Lemna minor</i> (36–8, s), <i>Eleocharis palustris</i> (35–17, f), <i>Mentha longifolia</i> (35–4, f), <i>Schoenoplectus lacustris</i> (23–7, f/ffr), <i>Stachys palustris</i> (20–1, f/ffr), <i>Juncus</i> cf. <i>effusus</i> (14, s), <i>Sparganium erectum</i> (11–6, en), <i>Glyceria fluitans</i> (10–5, s), <i>Potentilla anserina</i> (8–4, f), <i>Lycopus europaeus</i> (7–5, f), <i>Carex rostrata</i> (6–1, f), <i>Cyperus fuscus</i> (5–2, f), <i>Chara</i> (4–2, o), <i>Potamogeton gramineus</i> (4–2, en), <i>Viola</i> (4–1, s), <i>Panicum miliaceum</i> (2, s), <i>Rumex acetosella</i> (2, f), <i>Chenopodium album</i> (2–1, s), <i>Menyanthes trifoliata</i> (2–1, s), <i>Nitella</i> (1, o), <i>Batrachium</i> (1, f), <i>Myriophyllum</i> cf. <i>verticillatum</i> (1, en), <i>Atriplex</i> (1, s)
KK-4	28–45	Backswamp organic mud (a ₄)	The zone included 3 samples. <i>Typha latifolia</i> (3,400–240, t), <i>Salvinia natans</i> (3,310–300, mgs), <i>Alisma plantago-aquatica</i> (680–530, t), <i>Alisma plantago-aquatica</i> (660, f/s/t), <i>Sagittaria sagittifolia</i> (251–122, f/s/t), <i>Juncus</i> (40–1, s), <i>Carex</i> (33–6, f/ffr), <i>Typha angustifolia</i> (30, t), <i>Oenanthe aquatica</i> (28–7, semif), <i>Stratiotes aloides</i> (22, sp), <i>Atriplex</i> (20, s), <i>Stachys palustris</i> (18–1, f/ffr), <i>Nuphar lutea</i> (2, t), <i>Chenopodium album</i> L. (2, s), <i>Stratiotes aloides</i> (1, s/sfr)

Table S5 (continued)

LMAZ	Depth [cm b.g.l.]	Lithological unit	Description (maximum and minimum number of macrofossils)
KK-3	45–70	Lacustrine coarse detritus gyttja (l ₅)	The zone included 4 samples. <i>Typha latifolia</i> (1,000–5, t), <i>Salvinia natans</i> (350–15, mgs), <i>Alisma plantago-aquatica</i> (150–45, t), <i>Schoenoplectus lacustris</i> (45–3, f/ffr), <i>Alisma plantago-aquatica</i> (40–1, f/s/t), <i>Oenanthe aquatica</i> (17–2, semif), <i>Typha angustifolia</i> (10–2, t), <i>Stratiotes aloides</i> (8–3, sp), <i>Lemna minor</i> (7–2, s), <i>Nymphaea alba</i> (5–2, s/sfr), <i>Sagittaria sagittifolia</i> (5–1, f/s/t), <i>Mentha longifolia</i> (4–1, f), <i>Nymphaea alba</i> (3–2, t), <i>Cyperus fuscus</i> (3–1, f), <i>Stratiotes aloides</i> (2, s/sfr), <i>Chenopodium glaucum</i> (2, s), <i>Nuphar lutea</i> (2–1, s/sfr/emb)
KK-2	70–133		The zone included 7 samples. <i>Stratiotes aloides</i> (200–60, sp), <i>Cyperus fuscus</i> (54–12, f), <i>Chenopodium glaucum</i> (49–4, s), <i>Schoenoplectus lacustris</i> (27–3, f/ffr), <i>Nuphar lutea</i> (19–2, s/sfr/emb), <i>Typha latifolia</i> (17–7, t), <i>Stratiotes aloides</i> (13–1, s/sfr), <i>Nymphaea alba</i> (10–1, s/sfr), <i>Chara</i> (7–2, o), <i>Sparganium emersum</i> (6–2, en), <i>Sparganium minimum</i> (6–1, en), <i>Typha angustifolia</i> (5–2, t), <i>Potamogeton</i> (5–1, en/enfr), <i>Urtica</i> cf. <i>dioica</i> (4–2, f/ffr), <i>Alisma plantago-aquatica</i> (4–1, f/s/t), <i>Eleocharis palustris</i> (4–1, f), <i>Salvinia natans</i> (4–1, mgs), <i>Betula alba</i> (4–1, f/sc), <i>Betula</i> (2, f), <i>Lemna minor</i> (2–1, s), <i>Najas marina</i> (1, sfr), <i>Caulinia minor</i> (1, s/sfr), <i>Ceratophyllum submersum</i> (1, f/ffr), <i>Hippuris vulgaris</i> (1, f), <i>Lemna trisulca</i> (1, s)
KK-1	133–165	Lacustrine fine and medium sands and silt with a significant admixture of organic matter (l ₄)	The zone included 4 samples. <i>Stratiotes aloides</i> (23–1, sp), <i>Nuphar lutea</i> (7–2, s/sfr/emb), <i>Chara</i> (5–1, o), <i>Stratiotes aloides</i> (4–2, s/sfr), <i>Nymphaea alba</i> (2–1, s/sfr), <i>Cyperus fuscus</i> (2–1, f), <i>Schoenoplectus lacustris</i> (2, f/ffr), <i>Typha latifolia</i> (2, t), <i>Cyperaceae</i> (2, f), <i>Chenopodium glaucum</i> (2, s), <i>Alisma plantago-aquatica</i> (1, f/s/t), <i>Oenanthe aquatica</i> (1, semif), <i>Potamogeton pectinatus</i> (1, en), <i>Urtica</i> cf. <i>dioica</i> (1, f/ffr), <i>Urtica</i> (1, f/ffr), <i>Eupatorium cannabinum</i> (1, ffr), <i>Cirsium palustre</i> (1, f), <i>Alnus glutinosa</i> (1, f)

Table S6. Distribution of artefacts and ecofacts by depth in the squares 24 and 25 of Excavation-3 (depth 30–110 cm b.g.l.), as well as findings from the entire Excavation-3 with an area of 10 m² (depth 0–30 cm b.g.l.). Kakoryca-4 archaeological site

Excavation-3 (sq. 24 and 25)	Depth [cm b.g.l.]									Total number for sq. 24 and 25
	0–30 (for the entire Excavation-3, i.e. 10 m²)	30–40	40–50	50–60	60–70	70–80	80–90	90–100	100–110	
Flint artifacts										
Burin on truncation of Swiderian–Kudlaevka culture (?)	-	-	-	-	1	-	-	-	-	1
Mesolithic adze	-	-	-	-	-	-	-	-	1	1
Core of Kudlaevka culture	-	-	1	-	-	-	-	-	-	1
Trapeze of Kudlaevka culture	-	1	-	-	-	-	-	-	-	1
Backed bladelets of Kudlaevka culture	-	2	-	-	-	-	-	-	-	2
Core of Janisławice culture	-	-	-	-	1	-	-	-	-	1
Axe of Neman culture	-	1	-	-	-	-	-	-	-	1
Core of Neman culture–Corded Ware culture circle	-	1	-	-	-	-	-	-	-	1
Core fragment of Neman culture–Corded Ware culture circle (?)	-	-	-	-	-	-	1	-	-	1
"Knife" of Neman culture–Corded Ware culture circle	-	1	-	-	-	-	-	-	-	1
Perforator with trough-like retouch of Neman culture–Corded Ware culture circle	1	-	-	-	-	-	-	-	-	-
Triangle projectile point of Neman culture–Corded Ware culture circle	1	-	1	-	-	-	-	-	-	1
Flake with polished surface of Corded Ware culture circle with elements of the Globular Amphora culture / Corded Ware culture circle	1	-	-	-	-	-	-	-	-	-

Table S6 (continued)

Excavation-3 (sq. 24 and 25)	Depth [cm b.g.l.]									Total number for sq. 24 and 25
	0–30 (for the entire Excavation-3, i.e. 10 m²)	30–40	40–50	50–60	60–70	70–80	80–90	90–100	100–110	
Pottery artifacts										
Pripyat-Neman culture (Dubičiaiai-type)	17	34	9	-	-	-	-	-	-	43
Neman culture (Dobry Bor-type)	18	43	2	-	-	-	-	-	-	45
Corded Ware culture circle with elements of the Globular Amphora culture	-	9	-	-	-	-	-	-	-	9
Corded Ware culture circle	64	58	1	-	-	-	-	-	-	59
Small pottery fragments without certain cultural and chronological identification	18	3	-	-	-	-	-	-	-	3
Fragments of fired clay (brick?)	8	-	-	-	-	-	-	-	-	-
Artifacts/Ecofacts										
Bone and horn products, bones and horns with traces of processing and their fragments	2	-	1	-	-	-	-	-	-	1
Bones and their fragments without traces of processing	242	249	22	30	-	-	-	-	-	301
Stones and their fragments without traces of processing	21	15	15	-	-	-	-	-	1	31
Ecofacts										
Charcoal	+	+	+	+	+	+	+	+	+	+
Fragments of branches, tree bark and other woody remains	-	-	-	-	+	+	+	+	+	
Pine cones	-	-	-	-	-	-	-	-	+	

Table S6 (continued)

Excavation-3 (sq. 24 and 25)	Depth [cm b.g.l.]									Total number for sq. 24 and 25
	0–30 (for the entire Excavation-3, i.e. 10 m²)	30–40	40–50	50–60	60–70	70–80	80–90	90–100	100–110	
Total number										
Flint artifacts	430	188	75	26	14	6	14	4	15	342
Pottery artifacts	117	147	12	-	-	-	-	-	-	159
Pottery and flint artifacts	547	335	87	26	14	6	14	4	15	501
Artifacts	820	599	125	56	14	6	14	4	16	834
Ecofacts	264	265	38	31	2	2	2	2	4	346
Artifacts and Ecofacts	821	600	126	57	16	8	16	6	19	848

Table S7. Lithology and individual macrofossils and pollen from the Sporovo II core

Depth [cm b.g.l.]	Lithological unit	LOI [%]	Corresponding LPAZ [cm b.g.l.]	Macrofossils and pollen
0–25	Fen peat (h ₂)	87.6– 80.4	SPII-5b (0–10), SPII-5a (10–25)	A huge number of Cyperaceae pollen. Single pollen grain of <i>Nymphaea</i>
25–65	Telmatic peat (h ₁)	91.3– 88.9	SPII-4b (25–45), SPII-4a (45–65)	Macrofossils of <i>Ranunculus</i> and <i>Carex</i> . Pollen mainly from Cyperaceae and <i>Sparganium</i> -type. Single pollen grains of <i>Stratiotes aloides</i> , <i>Nuphar</i> , <i>Myriophyllum</i> and <i>Potamogeton</i>
65–97	Lacustrine coarse detritus gyttja (l ₅)	87.8– 74.9	SPII-3b (65–97)	Macrofossils of <i>Carex</i> and <i>Stratiotes aloides</i> . Pollen of <i>Sparganium</i> -type, Polypodiaceae, as well as <i>Stratiotes aloides</i> , <i>Nymphaea</i> and <i>Nuphar</i>
97–150	Lacustrine coarse detritus gyttja with a significant admixture of silt and sand (l ₆)	68.3– 50.0	SPII-3b (97– 110), SPII-3a (110–150)	Macrofossils of <i>Potamogeton</i> , <i>Stratiotes aloides</i> , Nymphaeaceae and <i>Carex</i> , as well as a fish scale. Pollen of <i>Stratiotes aloides</i> , <i>Nymphaea</i> , <i>Nuphar</i> , <i>Potamogeton</i> and <i>Myriophyllum</i>
150–189	Lacustrine coarse detritus gyttja (l ₅)	78.9– 38.8	SPII-3a (150– 175), SPII-2/3 (175–189)	Macrofossils of <i>Potamogeton</i> and <i>Carex</i> . Pollen of <i>Stratiotes aloides</i> , <i>Nymphaea</i> , <i>Nuphar</i> , <i>Potamogeton</i> and <i>Myriophyllum</i>
189–193	Lacustrine sandy and silty non- calcareous mineral gyttja (l ₂)	27.5	SPII-2 (189–193)	Pollen of <i>Myriophyllum</i>
193–250	Lacustrine sandy and silty calcareous gyttja (l ₁)	17.4– 8.6	SPII-2 (193– 220), SPII-1 (220–250)	Macrofossils of <i>Potamogeton</i> . Pollen of <i>Myriophyllum</i> , <i>Nymphaea</i> , <i>Nuphar</i> and <i>Potamogeton</i>
250–270	Fluvial fine and medium sands (f ₂)	-	-	-

Table S8. Chronology of the stratigraphic units (modified by the authors)

Stratigraphic units, modified based on Dzieduszyńska et al. (2020), Zernitskaya et al. (2020), Zernitskaya (2022) and Naughton et al. (2023)		Approximate age [cal BP]
Holocene	Late Subatlantic (SA-3)	from 1,000
	Middle Subatlantic (SA-2)	2,000 to 1,000
	Early Subatlantic (SA-1)	3,000 to 2,000
	Late Subboreal (SB-3)	3,700 to 3,000
	Middle Subboreal (SB-2)	4,000 to 3,700
	Early Subboreal (SB-1)	5,800 to 4,000
	Late Atlantic (AT-3)	6,800 to 5,800
	Middle Atlantic (AT-2)	8,000 to 6,800
	Early Atlantic (AT-1)	9,000 to 8,000
	Late Boreal (BO-2)	9,500 to 9,000
	Early Boreal (BO-1)	10,200 to 9,500
	Preboreal (PB)	11,700 to 10,200
Late Weichselian (the termination of MIS 2)	younger part of Younger Dryas (YD-2)	12,400 to 11,700
	older part of Younger Dryas (YD-1)	12,800 to 12,400
	Allerød (AL)	13,900 to 12,800
	Older Dryas (OD)	14,050 to 13,900
	Bølling (BØ)	14,700 to 14,050
	Oldest Dryas (OldestD)	18,000 to 14,700
Middle Weichselian (or Plenivistulian; M.W.), ~75–15 ka BP (MIS 4–2)		
Early Weichselian, ~115–75 ka BP (MIS 5d–a)		

CHAPTER II

ANTHROPOCENE HUMAN ACTIVITY IN THE POLLEN RECORD FROM AN OXBOW LAKE IN THE BUG RIVER VALLEY (EASTERN POLAND)

INTRODUCTION

1.1 Research issue

Palaeoecological studies often aim to trace signals of human activity in biogenic geological deposits. Geological evidence of agriculture and associated deforestation – particularly in Prehistory – has long been a key area of research interest. Pollen analysis is one of the principal methods for identifying records of agricultural activity and forest-clearance episodes, as it reveals changes in both regional and local vegetation (cf. Behre, 1981; Berglund and Ralska-Jasiewiczowa, 1986; Poska et al., 2004; Zernitskaya, 2011; Tsvirko, 2017; Makohonienko et al., 2023).

The materials presented in Chapter 2 contribute to the ongoing discussion concerning the reflection of modern human economic activity – primarily agriculture – in pollen assemblages (cf. Behre, 1981 and 1988; Poska et al., 2004; Kołaczek, 2010; Zernitskaya, 2011; Święta-Musznicka et al., 2013; Tsvirko, 2017; Brown et al., 2019; Związek et al., 2024). The study was conducted for the Zarzetka core, which consists of modern deposits. The Zarzetka core served as a reference sequence and its data were used to identify traces of modern agriculture and deforestation and to compare them with the situation in the Kakoryca-4 and Ostrowite areas. The ecological groups of human indicators identified in the pollen diagrams of the Sporovo II core (Chapter 1, Fig. 10; Fig. S20) and the OST2B core (Chapter 3; Fig. 23) were established based on the analysis of the pollen record from the Zarzetka core and a review of the relevant literature presented below.

In Chapter 2, the following hypothesis is tested: the bottom sediments accumulated over the last 40 (or 60) years may contain a high abundance of pollen indicators of human activity. The pollen record from these sediments can be used as a reference profile that reflects human land-use activity.

The sediments of the Zarzetka oxbow were selected to test this hypothesis for several reasons. First, the Zarzetka oxbow is located in an area characterised by intense agricultural activity in recent decades (as evidenced by Google Earth satellite images and our field observations). Second, radiocarbon dating shows that the sediments of the Zarzetka core

are very young, having accumulated within the past 40 (or 60) years. Consequently, contemporary human economic activity is expected to be clearly reflected in the pollen assemblages from the Zarzetka core.

1.2 Objective

The purpose of the study was to examine how modern human economic activity is expressed in pollen records, using deposits from the Bug River valley floor in Eastern Poland as a case study.

1.3 Location

The studied Zarzetka core was taken from an oxbow lake located in the Bug River valley floor near the Zarzetka village (Eastern Poland; Fig. 12). Approximate coordinates of the Zarzetka core are 52°38'7.61"N 21°43'45.79"E. Our field observations revealed that overgrowth of the oxbow lake is progressing primarily from the gently inclined western shore, near which the studied core of biogenic deposits was collected (Fig. 13A). Our reconnaissance coring showed that the bottom sediments in the central part of the oxbow lake were composed of channel sands.

MATERIAL AND METHODS

2.1 Geological field works and lithology

The Zarzetka core was taken in May 2024 from a boat at the boundary between aquatic vegetation and the open-water area (Fig. 13A). At the location where the core was taken, the water depth was roughly 30 cm. In the Zarzetka core sampling area, the bottom sediments consisted of biogenic deposits, with a thickness of approximately 50 cm. The sediment column was sampled using a Uwitec surface corer (Fig. 13B). The lithological description of the core was based on macroscopic examination of the deposits and on the results of pollen analysis.

As a result, a 55-cm core of oxbow bottom sediments was obtained. The bottommost deposits of the Zarzetka core, below 55 cm, consist of channel alluvial sands. Higher in the core (depth 55–0 cm), the sediments are composed of fine detritus gyttja, with a significant admixture of sand in the 55–53 cm interval (Fig. 15).

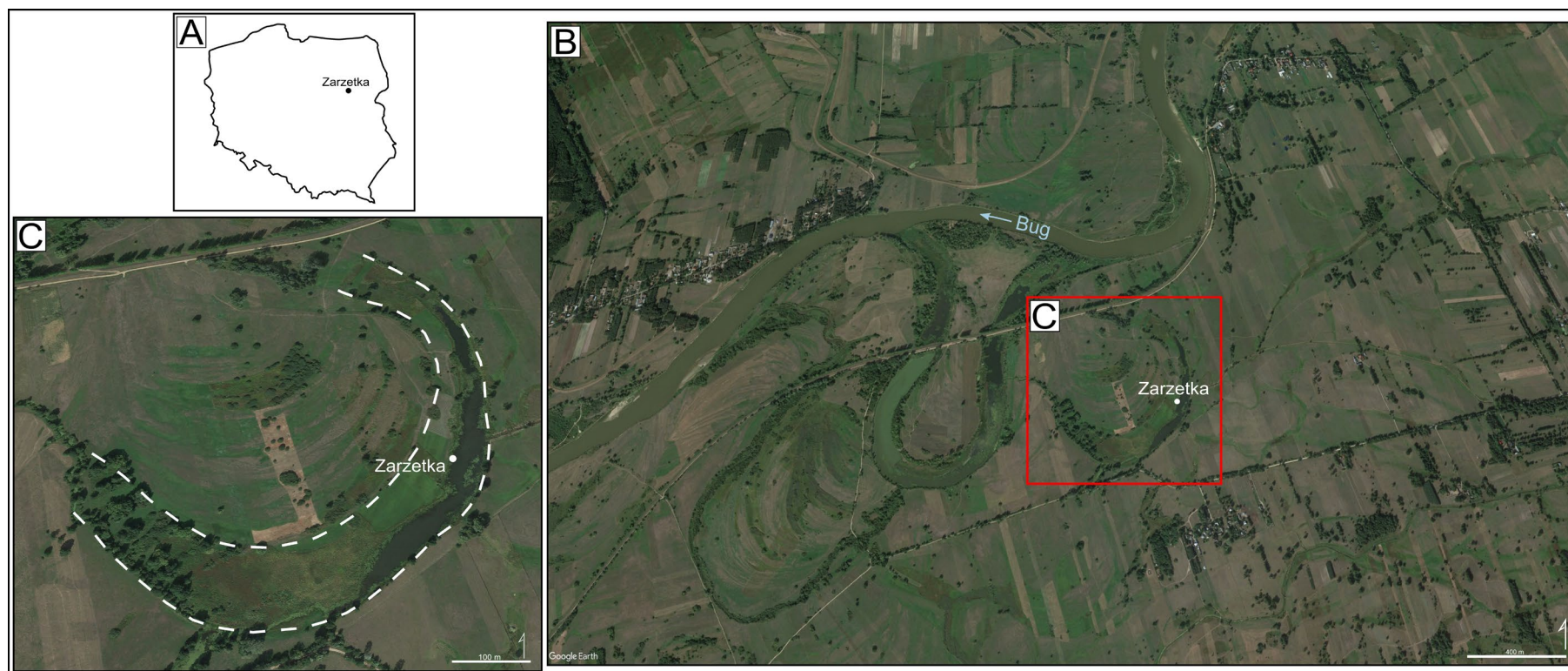


Fig. 12. Location of the Zarzetka core on the territory of Eastern Poland (A) in the basin of the Bug River (B–C). B and C – Google Earth satellite images from September 2019. White dashed lines mark the approximate boundaries of the overgrowing oxbow



Fig. 13. A – Google Earth satellite image (May 2025) showing the Zarzetka core sampling site near the western, heavily overgrown shore of the oxbow lake; B – field expedition in May 2024 using a Uwitec surface corer to collect the studied Zarzetka core (photo by M. Obremska)

2.2 Radiocarbon analysis

For radiocarbon analysis, plant macrofossil material was sampled from a depth of 55–54 cm b.g.l., from a layer of fine detritus gyttja with a significant admixture of sand. The radiocarbon dating of this sample aimed to determine the onset of biogenic sediment accumulation in the Zarzetka core.

Radiocarbon dating of this sample was carried out using the AMS technique at the Beta Analytic testing laboratory in Miami (USA). Calibration of the radiocarbon date (a post-bomb ^{14}C date) was performed using the High Probability Density Range Method (HPD; Bronk Ramsey, 2009) with the IntCal 20 + NHZ1 database (Reimer et al., 2020; Hua et al., 2022). The calibrated age (cal AD) is given with a 57.2% probability.

2.3 Pollen analysis

A total of 28 samples, each 1 cm^3 in volume, were taken for pollen analysis. Samples for analysis were collected at 2 cm intervals. The samples underwent standard laboratory preparation, including treatment with HCl, KOH, sieving, HF, and acetolysis after Berglund and Ralska-Jasiewiczowa (1986) and Faegri and Iversen (1989). After preparation, the samples were mounted in glycerol and stained with fuchsin. All laboratory processing was performed at the Institute of Geological Sciences PAS in Warsaw (Poland).

During microscopic analysis, more than 500 arboreal pollen grains (AP) were counted in each sample. The results of the pollen analysis were processed using the Tilia

software (Grimm, 1992). The CONISS cluster analysis (Grimm, 1987) was conducted using data from AP and NAP (arboreal pollen and nonarboreal pollen).

The proportions of arboreal pollen (AP) and nonarboreal pollen (NAP) were calculated based on the total sum $AP + NAP = 100\%$. Pollen grains of local aquatic and telmatic/wetland plants, as well as spores, were excluded from this total sum. The percentages of Cyperaceae (Cyp), aquatic vascular plants (AQVP), spore plants (F), and nonpollen palynomorphs (NPP) were calculated separately based on the sums $AP + NAP + Cyp$ (or $AQVP$ / or F / or NPP) = 100%. The taxa included in these calculation groups are indicated in colour in Fig. 15. The percentages of undeterminable (severely damaged or strongly deformed pollen and spores; Unable) and undetermined (pollen and spores that were not identified; Uned) were calculated from the sums $AP + NAP + Cyp + AQVP + F + Unable$ (or $Uned$) = 100%. During microscopic analysis, corroded pollen (perforated; see Fig. 25 in Chapter 3 for photos of corroded pollen) was counted among the identified pollen grains of *Betula*, *Corylus*, and *Alnus* (BCA). The proportion of corroded pollen was calculated using the sum $BCA + corroded = 100\%$.

RESULTS

3.1 ^{14}C chronology

The accumulation of fine detritus gyttja with a significant admixture of sand began approximately 40 (or 60) years ago, as indicated by the radiocarbon date of $-1,580 \pm 30$ BP (1,983–1,985 cal AD) from a depth of 55–54 cm b.g.l. (Table 3; Figs. 14 and 15).

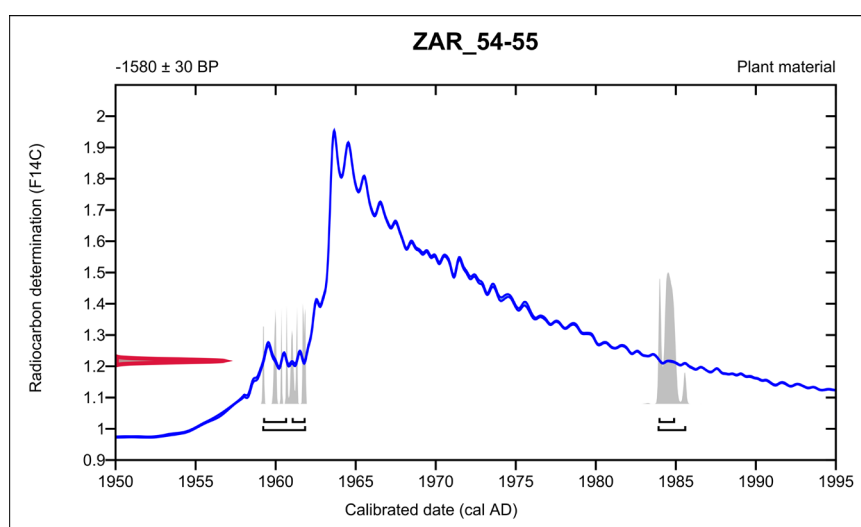


Fig. 14. Calibration of the $-1,580 \pm 30$ BP radiocarbon date obtained from the Zarzetka core deposits

Table 3. Radiocarbon dating of one sample of plant macrofossil material from the deposits of the Zarzetka core

Depth [cm b.g.l.]	Age conv [BP]	Percent Modern Carbon [pMC]	Laboratory No.	Age [cal AD, prob. 57.2%]	Age [cal AD, prob. 38.1%]	Dated material	Notes
54–55	-1580±30	121.74±0.45	Beta-699933	1983–1985	1959–1961	plant	AMS technique

3.2 Pollen data

Based on visual evaluation and CONISS cluster analysis, three local pollen assemblage zones (LPAZ) were identified in the Zarzetka core: ZR-1, ZR-2, and ZR-3 (Fig. 15; Table 4).

Table 4. Local pollen assemblage zones (LPAZ) identified in the Zarzetka core and their description

LPAZ	Depth [cm b.g.l.]	Lithological unit	Description
ZR-3 <i>Pinus</i>	0–32	fine detritus gyttja	This zone showed an increase in <i>Pinus</i> (30.6–23.4%), as well as an absolute maximum for <i>Alnus</i> (26.4%) and <i>Betula</i> (12.5%). As a result, the amount of AP increased. Absolute minimum was observed for <i>Salix</i> (1.3%) and Poaceae (15.1%). The zone was also characterized by high abundances of <i>Plantago lanceolata</i> (3.1–1.0%) and <i>Rumex acetosa-acetosella</i> (3.0–1.0%), as well as an absolute maximum for <i>Urtica</i> (5.4%) and Cichorioideae (2.2%). The amount of Cerealia undiff. (1.8–0.4%) and <i>Secale cereale</i> (0.7–0.1%) reached an absolute minimum. <i>Zea</i> pollen (0.1%) appeared for the first time. Accordingly, the total amount of Cerealia pollen was the lowest (2.3–0.8%). <i>Fagopyrum</i> pollen (0.1%) was also found
ZR-2 NAP	32–44		The most characteristic feature of the zone was a gradual decline of <i>Pinus</i> (absolute minimum 19.2%) and <i>Quercus</i> (absolute minimum 0.6%). This correlated with an increase in NAP (absolute maximum 45.1%), including Poaceae (absolute maximum 26.4%), <i>Rumex acetosa-acetosella</i> (absolute maximum 4.6%), <i>Plantago lanceolata</i> (3.3–1.6%), and <i>Urtica</i> (4.8–1.8%). The amount of <i>Salix</i> reached an absolute maximum of 8.4%. A decline in the share of <i>Secale cereale</i> (1.6–0.6%) was observed. Compared with ZR-1, the proportion of Cerealia undiff. (2.2–1.4%) slightly decreased. The total amount of Cerealia pollen (3.1–2.2%) was slightly lower than in ZR-1
ZR-1 <i>Pinus</i> - Cerealia	44–55	fine detritus gyttja, also with a significant admixture of sand	This zone was characterized by an absolute maximum for <i>Pinus</i> (36.2%), Cerealia undiff. (3.4%) and <i>Secale cereale</i> (2.1%). The total amount of Cerealia pollen reached an absolute maximum of 5.5% at the bottom and then declined to 2.5% in the upper part of the zone. A few pollen grains of <i>Fagopyrum</i> (0.1%) were also noted. A significant share belonged to <i>Salix</i> (5.4–3.9%). Low values were found for <i>Urtica</i> (1.6–0.6%), <i>Rumex acetosa-acetosella</i> (2.4–1.2%), and <i>Plantago lanceolata</i> (3.3–1.1%)

In general, it was possible to identify common features for the entire Zarzetka profile. For example, the core was characterized by the constant presence of pollen from aquatic plants such as *Lemna*, *Nuphar*, *Nymphaea*, *Myriophyllum*, and *Potamogeton*, as well as *Pediastrum* algae. A large amount of corroded pollen was also observed throughout the section, along with the constant presence of fungi, Cyperaceae, *Sparganium*-type, *Typha latifolia*, and undeterminable. The presence of corroded pollen – recorded among *Betula*, *Corylus*, and *Alnus* – was used as an indicator of periodic drying of the lake littoral zone during episodes of low water level.

The most distinctive feature of the Zarzetka core was the high abundance of pollen from *Cerealia* undiff. and *Secale cereale* (Fig. 16), as well as the large amount of pollen from the synanthropic taxa *Urtica*, *Plantago lanceolata*, and *Rumex acetosa-acetosella*.

Throughout the entire profile, other synanthropic plants, such as *Ambrosia*, *Artemisia*, Chenopodiaceae, *Centaurea cyanus*, and several others, were constantly recorded.

Across the entire core, high amounts of *Alnus*, *Betula*, and *Salix* were observed. Pollen grains of shrubs such as *Juniperus*, *Frangula*, *Rhamnus*, *Sambucus*, and *Viburnum*, along with spores of *Pteridium aquilinum*, were constantly documented.

INTERPRETATION AND DISCUSSION

Due to the limited amount of data, in particular the lack of a robust age-depth model and historical cartographic data, only preliminary reconstructions of human economic activity in the immediate vicinity of the Zarzetka oxbow can be proposed, based mainly on pollen data. On the basis of the obtained pollen results, three consecutive periods in the history of local vegetation around the Zarzetka oxbow can be identified, starting from 1,983–1,985 cal AD (Table 3; Fig. 15).

LPAZ ZR-1 (55–44 cm b.g.l.; from 1,983–1,985 cal AD). This period was characterised by the highest amounts of pollen of cultivated plants (maximum values of *Cerealia* undiff. and *Secale cereale*, and the frequent presence of *Fagopyrum*), accompanied by a considerable abundance of pollen of characteristic weeds (maximum values of Brassicaceae, and the frequent presence of *Centaurea cyanus*, *Polygonum* spp., and *Cannabis-Humulus*; Fig. 15). It is likely that such a large amount of pollen of cultivated plants can be explained by the much more intense use of the land directly adjacent to the oxbow for arable agriculture. The comparatively low values of fallow/pasture-land indicators (*Plantago lanceolata*, *Rumex acetosa-acetosella*, and Poaceae), as well as

comparatively low NAP values, also point to intense use of the land adjacent to the oxbow for arable agriculture (Fig. 15).

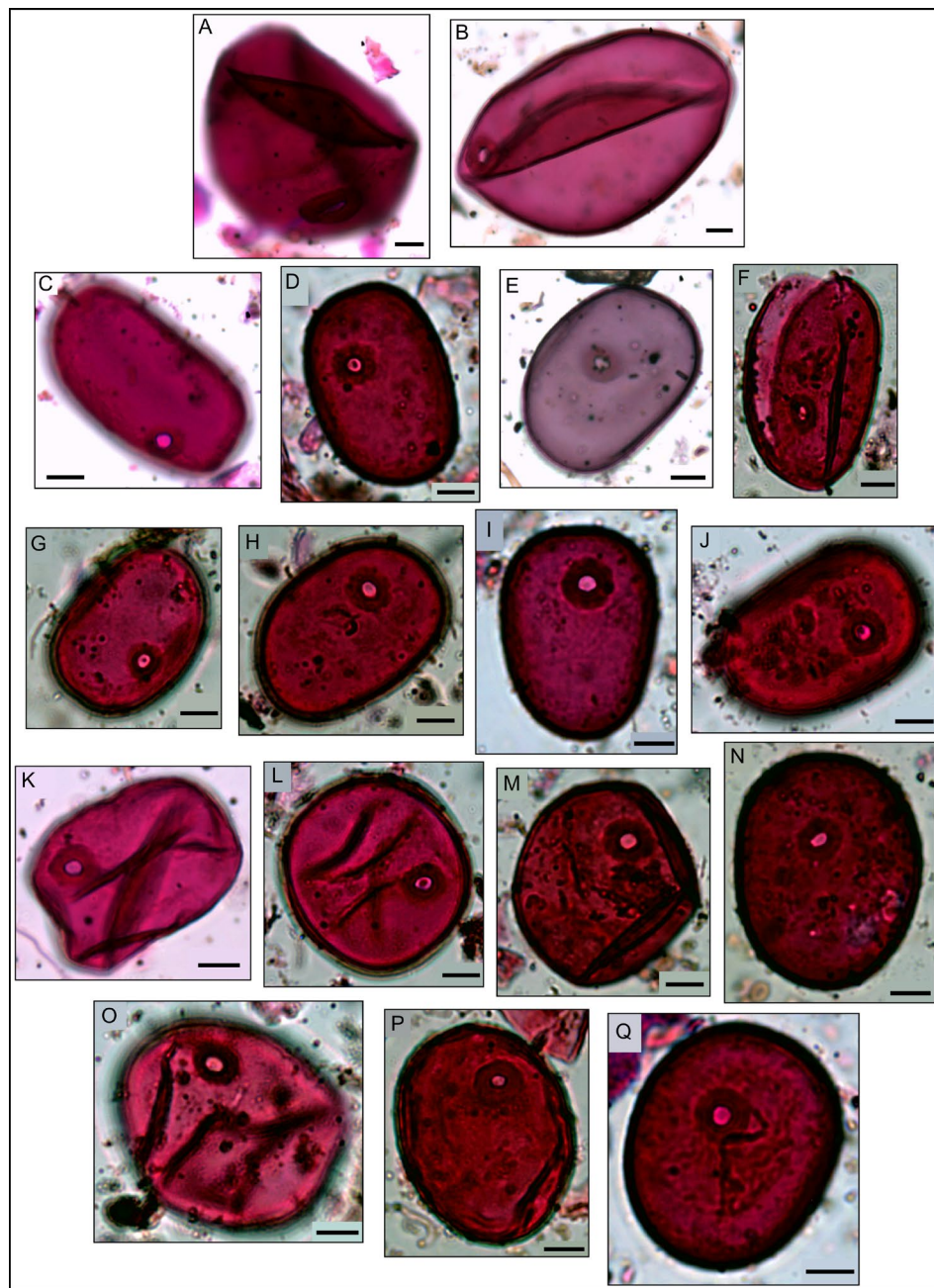


Fig. 16. Selected pollen grains of cultivated plants from the Zarzetka core (photos by D. Tsvirko). A – *Zea* (sample depth 5–4 cm); B – *Zea* (11–10 cm); C – *Secale cereale* (35–34 cm); D – *Secale cereale* (43–42 cm); E, F – *Secale cereale* (47–46 cm); G – *Secale cereale* (49–48 cm); H, I – *Secale cereale* (51–50 cm); J – *Secale cereale* (53–52 cm); K – *Cerealia* undiff. (35–34 cm); L – *Cerealia* undiff. (45–44 cm); M, N – *Cerealia* undiff. (47–46 cm); O, P – *Cerealia* undiff. (49–48 cm); Q – *Cerealia* undiff. (53–52 cm). Scale bars = 10 μ m for all specimens

LPAZ ZR-2 (44–32 cm b.g.l.). This period was characterised by the highest proportions of pollen of fallow/pasture-land plants (maximum values of NAP, Poaceae, and *Rumex acetosa-acetosella*, and high values of *Plantago lanceolata*; Fig. 15). It is likely that during this period, a significant part of the territory adjacent to the oxbow was for an extended period of time left fallow, which led to the spread of herbaceous and shrubby communities (maximum values of *Salix*; Fig. 15; Table 4). The decline in the *Pinus* and *Quercus* curves most likely reflects not deforestation, but the spatial expansion of fallow areas during this period, which enhanced the pollen influx from herbaceous communities (Fig. 15).

LPAZ ZR-3 (32–0 cm b.g.l.). This period was characterised by high proportions of pollen of fallow/pasture-land plants (*Plantago lanceolata* and *Rumex acetosa-acetosella*), the highest values of ruderal plants (mainly *Urtica*), and the lowest values of pollen from cultivated plants (*Cerealia undiff.*, *Secale cereale*, *Zea*, and *Fagopyrum*; Fig. 15). Based on these pollen data, it is likely that during the described period a significant part of the territory in the immediate proximity of the oxbow was mainly used for pasture and/or haymaking. For this purpose, local communities cleared the areas adjacent to the oxbow, removing *Salix*, as indicated by the sharp decline in the amount of pollen of this taxon (at a depth of 32 cm b.g.l.; Fig. 15). This interpretation is also supported by high values of *Urtica* (Fig. 15), which indicate nitrogen-enriched soils, most likely resulting from intense human and livestock activity (cf. Behre, 1981).

It is important to emphasize that the regional vegetation did not change significantly throughout all identified periods. Open, treeless areas dominated in every period, with changes occurring only in the type of human economic activity.

All identified periods contain a clear record of anthropogenic deforestation for agricultural purposes. This anthropogenic deforestation, and the resulting openness of the study area, can be inferred from: (1) high proportions of NAP (approximately 30–40%, mainly due to Poaceae); (2) the dominance of *Pinus*; (3) the constant presence of light-demanding *Juniperus* (cf. Zarzycki et al., 2002); (4) the presence of *Pteridium aquilinum*; (5) low proportions of *Quercus*, *Corylus*, *Ulmus*, *Tilia*, *Fraxinus*, *Carpinus*, and *Fagus*; and (6) a substantial amount of cultivated plants and other indicators of agricultural activity (*Cerealia undiff.*, *Plantago lanceolata*, etc.).

In general, the Zarzetka core showed a large number of indicators of human activity, which were classified into groups according to published sources (Fig. 15).

Following Behre (1981), Poska et al. (2004), and Kołaczek (2010), the most reliable pollen indicators of cultivated land were *Cerealia undiff.*, *Secale cereale*, *Zea*, *Fagopyrum*, and *Centaurea cyanus*. In conjunction with these taxa, *Polygonum persicaria*-type, *Polygonum aviculare*, and Brassicaceae can also be considered indicators of cultivation (after Behre, 1981). *Cannabis-Humulus* and *Convolvulus arvensis* were likewise classified as cultivated land indicators, following Poska et al. (2004), Kołaczek (2010), Święta-Musznicka et al. (2013), Brown et al. (2019), and Związek et al. (2024).

Based on Behre (1981), high values of *Plantago lanceolata* were regarded as the most reliable indicator of pasture and fallow land, since this taxon is common in such environments (for an example of *Plantago lanceolata* on fallow land, see also our field observations in Fig. 17). In association with high quantities of *Plantago lanceolata*, high values or the constant presence of Poaceae, *Rumex acetosa-acetosella*, Ranunculaceae, and *Plantago major-media* were also interpreted as indicators of pasture and fallow land (after Behre, 1981; Święta-Musznicka et al., 2013). *Rumex acetosa-acetosella* was placed in the pasture/fallow group because its pollen curve visually corresponded with that of *Plantago lanceolata* (Fig. 15).



Fig. 17. Vegetation of a fallow field (A), including *Plantago lanceolata* (B). Photographs were taken at a fallow field near the Minsk–Brest highway, south of the town of Byaroza (photos by D. Tsvirko, May 2018)

Based on the data provided by Behre (1981, 1988), the nitrophilous species *Artemisia*, *Chenopodiaceae*, and *Urtica* were assigned to the ruderal/footpath group. The invasive species *Ambrosia*, introduced into Poland in the 18th–19th centuries (Woźniak and Soroka, 2015; Bilińska et al., 2017), was also included in this group, as it prefers ruderal habitats (Kasprzyk et al., 2011; Essl et al., 2015; Louna-Korteniemi et al., 2025).

It should be noted that the gyttja sediments of the Zarzetka core experienced periodic desiccation, which led to pollen corrosion as a result of oxygen intrusion into the deposits (corroded pollen; Fig. 15). Periodic desiccation of the oxbow littoral zone is further indicated by high proportions of undeterminable pollen and spores (Fig. 15).

For most of the time, however, the Zarzetka core deposits were under aquatic conditions, as evidenced by the constant presence of pollen of aquatic plants and microremains of algae (*Lemna*, *Nuphar*, *Nymphaea*, *Myriophyllum*, *Potamogeton*, and *Pediastrum*; Fig. 15). The lithology of the sediments (fine detritus gyttja) also indicates that limnic conditions prevailed during sediment accumulation. At the same time, gyttja accumulation at the Zarzetka core site took place in close proximity to the shoreline, as evidenced by the constant presence of coprophilous and soil-related fungi (Fig. 15), along with *Sparganium*-type, *Typha latifolia*, and substantial amounts of Cyperaceae (Fig. 15).

CONCLUSIONS

1. The literature review conducted as part of this study enabled the classification of plant taxa in the Zarzetka pollen diagram as indicators of (1) cultivated land, (2) pasture and fallow land, and (3) ruderal and footpath environments.
2. Pollen analysis of the Zarzetka core revealed a strong signal from synanthropic plants, reflecting intense contemporary human economic activity in the studied section of the Bug River valley. The Zarzetka core is proposed as a reference profile representing the environment of the Anthropocene.
3. Cerealia pollen grains from the Zarzetka core – including their size measurements and visual characteristics documented in the collected photomicrographs – could serve as reference material for comparison when identifying Cerealia pollen in deposits from other sites and profiles.

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CHAPTER III

RECORD OF HUMAN ACTIVITY, VEGETATION COVER CHANGES, AND SEDIMENTATION PROCESSES IN THE PALAEOLAKE OST2B NEAR THE OSTROWITE ARCHAEOLOGICAL SITE (NORTHERN POLAND)

INTRODUCTION

1.1 Research issue

The accurate identification of the origin of biogenic sediments is crucial for constructing reliable palaeoecological reconstructions. As demonstrated by Tobolski (2021), some biogenic deposits may appear visually very similar while differing in origin; for instance, coarse detritus gyttja is often mistakenly identified as peat (Tsvirko, 2023). Pollen and macrofossil analyses provide tools not only to reconstruct regional and local vegetation but also to determine the origin of sediments. Reliable indicators of lacustrine and wetland depositional environments are necessary for correct interpretation of sediment origin. Chapter 3 was designed to identify pollen and macrofossil indicators of peat and gyttja sediments, using the deposits of palaeolake OST2B as an example.

In this chapter, the author also assesses the applicability of pollen indicators of human activity for reconstructing past economic practices.

The diversity of deposits in palaeolake OST2B, together with the advanced pollen and plant macrofossil analyses, made it possible to shed light on these issues. In this chapter, the following hypotheses are tested.

Tested Hypothesis 1: high abundances of corroded pollen, undeterminable pollen and spores, as well as coprophilous and soil-related fungi, can be used as indicators of peat deposits.

Tested Hypothesis 2: the telmatic zone of a lake is not merely a zone existing between high and low water levels (limno-terrestrial conditions), as proposed by Tobolski (2021), but is primarily a zone characterized by well-developed wetland vegetation, resulting from the natural evolution of lake reservoir into mire. In the sedimentary record, the presence of a telmatic zone can be inferred from high abundances of macro- and microfossils of wetland and nearshore vegetation, together with a minor admixture of aquatic plant macro- and microfossils, including *Chara* and *Pediastrum* algae.

Tested Hypothesis 3: groups of human pollen indicators, created on the basis of published literary sources and the author's own analysis of palaeoecological data from the Zarzetka core (see Chapter 2), can be used to detect different phases of human activity in the OST2B core.

Furthermore, by comparing pollen records from the palaeolake OST2B, located within a morainic landscape, and Lake Mały Suszek (10 km NE of palaeolake OST2B), within a glaciofluvial plain (Miotk-Szpiganowicz, 1992), Hypothesis 4 was tested: that the succession of tree and shrub vegetation is controlled by the geological structure of the catchment area.

The palaeolake OST2B was chosen to test the proposed hypotheses for several reasons. Firstly, it was a small lake (Fig. 18AB) and relatively shallow (approximately 3 m of biogenic deposits; Fig. 19). Such small and shallow water bodies are particularly prone to significant water level fluctuations (Piccioni et al., 2021), which may lead to changes in depositional conditions (Dearing, 1997; Tobolski, 2021) or even to the periodic complete desiccation of the lake (Laird et al., 1996). These features make palaeolake OST2B well suited for testing Hypotheses 1 and 2. Moreover, previous palaeoecological studies in Eastern Pomerania have primarily concentrated on the analysis of sediments from large lakes (Hjelmroos-Ericsson, 1981a and 1981b; Miotk-Szpiganowicz, 1992; Milecka and Bogaczewicz-Adamczak, 2006; Kowalewski and Barabach, 2010; Lamentowicz et al., 2019; Pleskot et al., 2020), while advanced studies of small kettle hole deposits have remained limited (Leszczyk, 2023, 2024; Kittel et al., 2025).

Secondly, the palaeolake OST2B is located in the immediate vicinity of the Ostrowite archaeological complex. In Eastern Pomerania, this is one of the largest archaeological complexes, with finds dated from the Late Palaeolithic to the Middle Ages (Drozd-Lipińska et al., 2013; Sikora et al., 2017, 2018, and 2022; Leszczyk et al., 2022, 2023a, 2023b, and 2025; Tsvirko et al., 2023; Kittel et al., 2025). A distinctive feature of the complex is the presence of artefacts associated with the Early Neolithic Linear Pottery culture (Kittel et al., 2025). Communities of this culture were the first farmers in Eastern Pomerania and are associated with the emergence of permanent settlements in the region (Sikora and Trzciński, 2014, 2021; Kittel et al., 2025). Therefore, the rich archaeological record surrounding palaeolake OST2B provides an opportunity to test Hypothesis 3.

Thirdly, previous palaeoecological studies in Eastern Pomerania have focused primarily on lakes located within glaciofluvial zones (Hjelmroos-Ericsson, 1981a and 1981b; Miotk-Szpiganowicz, 1992; Błaszkievicz et al., 2015; Słowiński et al., 2015;

Lamentowicz et al., 2019), whereas considerably less attention has been given to lakes situated on morainic plateaus (Leszczyk, 2023, 2024; Kittel et al., 2025). Therefore, the analysis of the pollen record from the palaeolake OST2B provides an opportunity to test Hypothesis 4.

1.2 Objective

The overall aim of the study was to reconstruct palaeoenvironmental changes in the vicinity of palaeolake OST2B based on the analysis of its deposits using palaeoecological methods and multi-proxy study.

1.3 Location

The palaeolake OST2B is located in the Northern Krajna Lakeland in Eastern Pomerania (Northern Poland; Fig. 18A). The studied palaeolake is situated within the area that was covered by the last Fennoscandian Ice Sheet during the Weichselian glaciation (Kittel et al., 2025). In the vicinity of palaeolake OST2B, the relief is dominated by hummocky and flat/undulating moraine plateaus, tunnel valleys, and numerous small and large rounded closed depressions (the so-called “kettle holes”; Fig. 18B). Some of these closed depressions, including OST2B, are currently filled with biogenic and calcareous deposits (see “biogenic plains” in Fig. 18B). After the retreat of the Weichselian ice sheet from the study area, these kettle holes were filled with blocks of dead ice. The melting of these dead ice blocks, as a result of climatic warming and ground water circulation, led to the formation of wetlands and lakes in some of the depressions (Błaszczewicz, 2011), including the palaeolake OST2B and also neighbouring OST1 basin (Kittel et al., 2025). Our research focuses on the analysis of the biogenic and calcareous sediments of palaeolake OST2B.

Archaeological excavations at the Ostrowite archaeological complex allowed to uncover the artefacts belonging to the Late Palaeolithic (Bromme-Lyngby and Swiderian cultures, ca. 13,800–11,500 cal BP), the Mesolithic (Komornica and Chojnice-Pienki cultures, ca. 12,000–8,000 cal BP), the Early Neolithic (Linear Pottery culture), the Early Iron Age (Wielka Wieś phase of the Pomeranian culture), as well as the Roman Period (Wielbark culture) and the Middle Ages (Sikora et al., 2017, 2018, 2022). The first traces of the earliest permanent settlement at the Ostrowite site were dated to approximately 7,200–7,000 cal BP and are associated with the Early Neolithic Linear Pottery culture. Communities of the Linear Pottery culture were the first farmers in Central Europe

(Cofta-Broniewska and Koško, 1982, 2002; Czerniak, 1994; Czekaj-Zastawny, 2017). Past human activity in the close vicinity of the palaeolake may have affected its ecology and is recorded in the OST2B deposits.

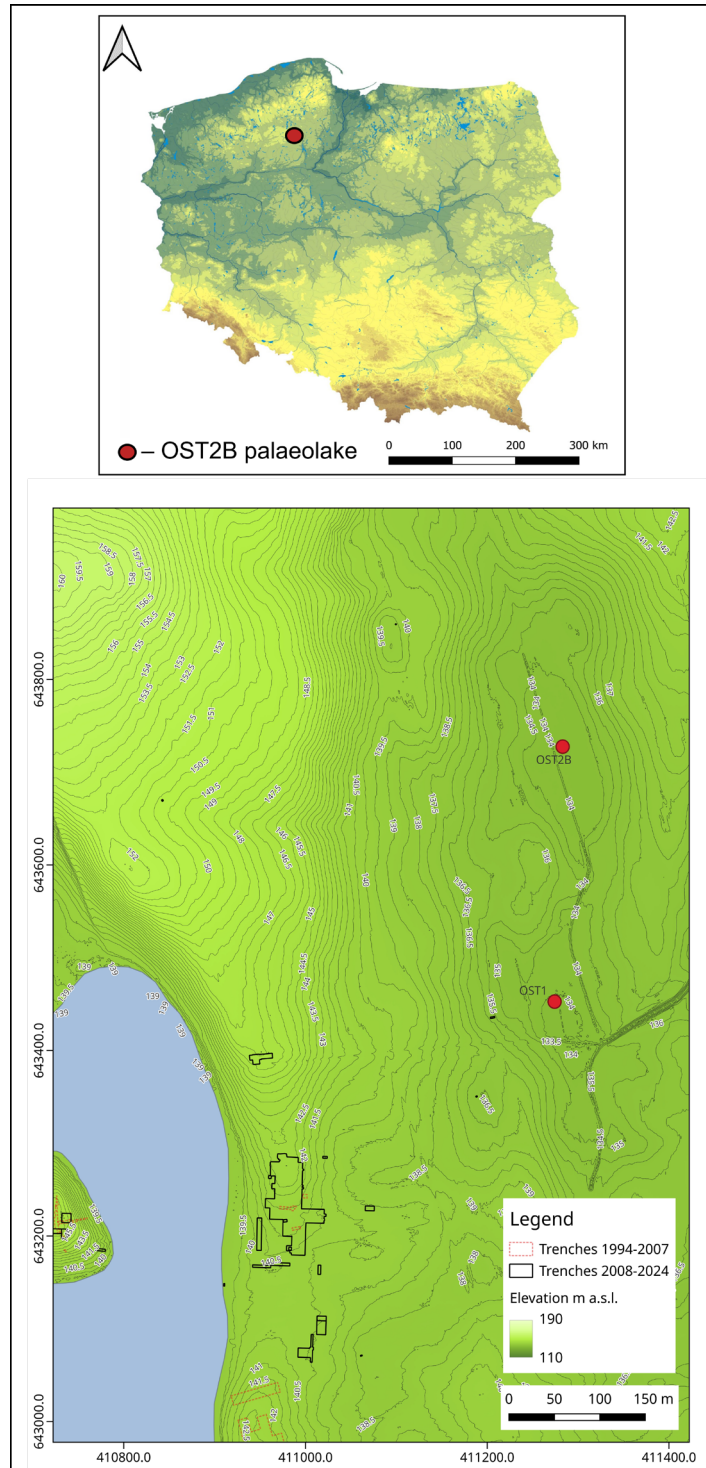


Fig. 18A. Location of the studied palaeolake OST2B and the reference paleolake OST1 (Kittel et al., 2025) in Northern Poland and on a fragment of a digital elevation model (provided by Jerzy Sikora)

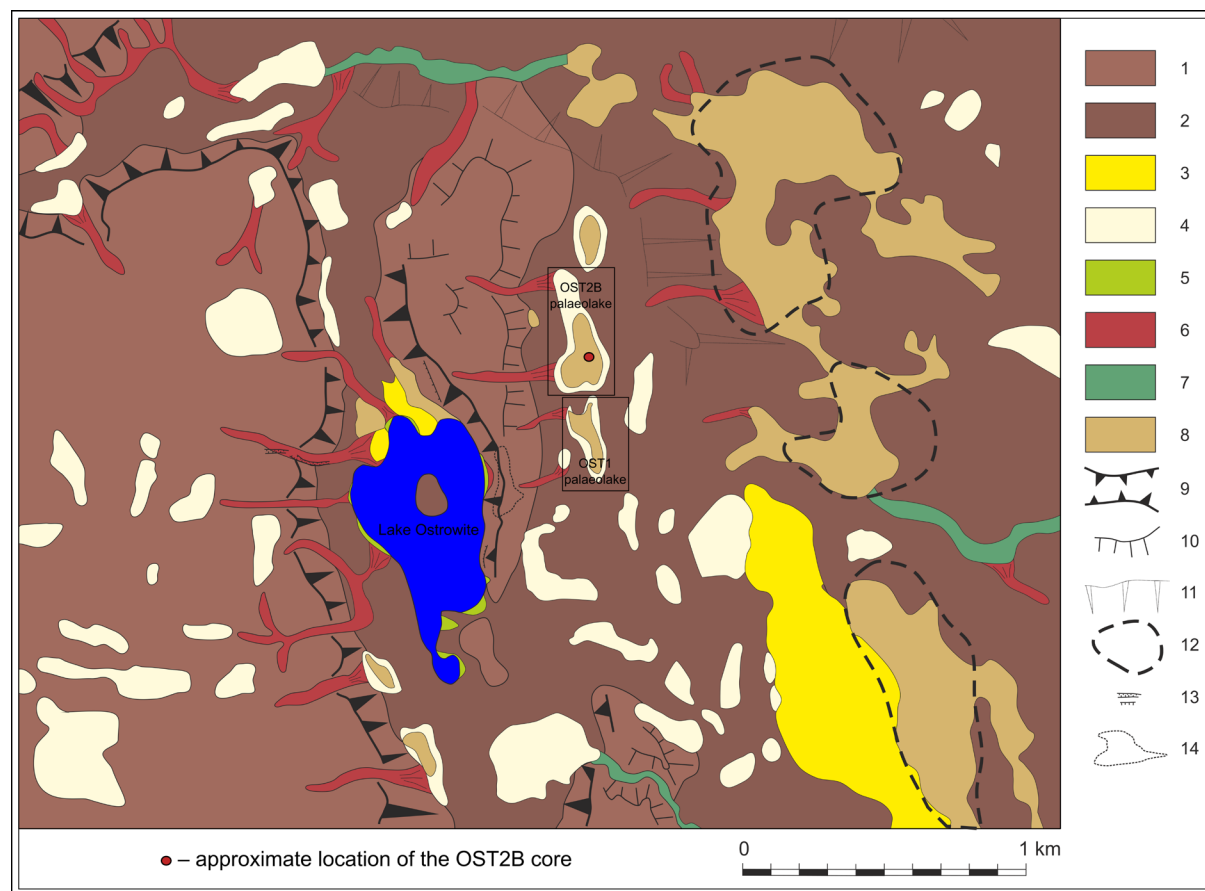


Fig. 18B. Geomorphological map of the study area (Sikora et al., 2018) showing the palaeolakes OST2B and OST1 (Kittel et al., 2025) and the following designations: 1 – hummocky moraine plateau; 2 – flat and undulating moraine plateau; 3 – kames; 4 – closed depressions; 5 – lacustrine terraces; 6 – denudation valleys and accumulative fans; 7 – river valley floors; 8 – biogenic plains; 9 – tunnel valleys; 10 – morphological edges; 11 – long slopes; 12 – larger melting depressions; 13 – anthropogenic erosional cuts and edges of agricultural terraces; 14 – range of the archaeological site

MATERIAL AND METHODS

2.1 Geological field works

During the fieldwork conducted in October 2020, a 465-cm-long core of geological deposits was collected from the lowest part of palaeolake OST2B (referred to as the OST2B core; Fig. 19). The absolute height of the OST2B core sampling site was 133.85 m a.s.l. The OST2B core (53°39'03.0"N 17°39'26.4"E) was extracted using a manual INSTORF corer with a 5-cm-diameter, 50-cm-long chamber.

Previously, the entire OST2B palaeolake was investigated by reconnaissance coring, and two transverse cross-sections were constructed, allowing a better understanding of its geological structure and the characteristics of the infilling deposits (see Figs. 7 and 9 in Leszczyk, 2023).

At present, an artificial pond, excavated in December 2020, occupies the location where the OST2B core was taken (Fig. 20B). During the excavation of this artificial pond in December 2020 (Fig. 21AB), fragments of tree trunks (later identified by Prof. M. Krąpiec as *Salix* wood) were discovered at a depth corresponding to the basal peat layer in the OST2B core. One of these *Salix* wood fragments was sampled for radiocarbon analysis to determine the age of the basal peat layer in the studied kettle hole (Fig. 21C).

2.2 Sampling strategy

After the completion of the fieldwork, subsamples from the OST2B core were collected for different analyses, including geochemical, pollen, and plant macrofossil analyses. The selection of subsamples from the OST2B core was carried out at the laboratory of the Institute of Geocology and Geoinformation, Adam Mickiewicz University (AMU), Poznan.

Sampling for geochemical and pollen analyses was generally conducted at 5 cm spacing, although the sampling resolution could vary depending on lithological boundaries and the visual characteristics of the sediments.

The material for plant macrofossil analysis was selected mainly between samples for pollen and geochemical analyses. Samples for plant macrofossil analysis were taken at 3.5-cm intervals, beginning with the 5.5–9 cm b.g.l. sample.

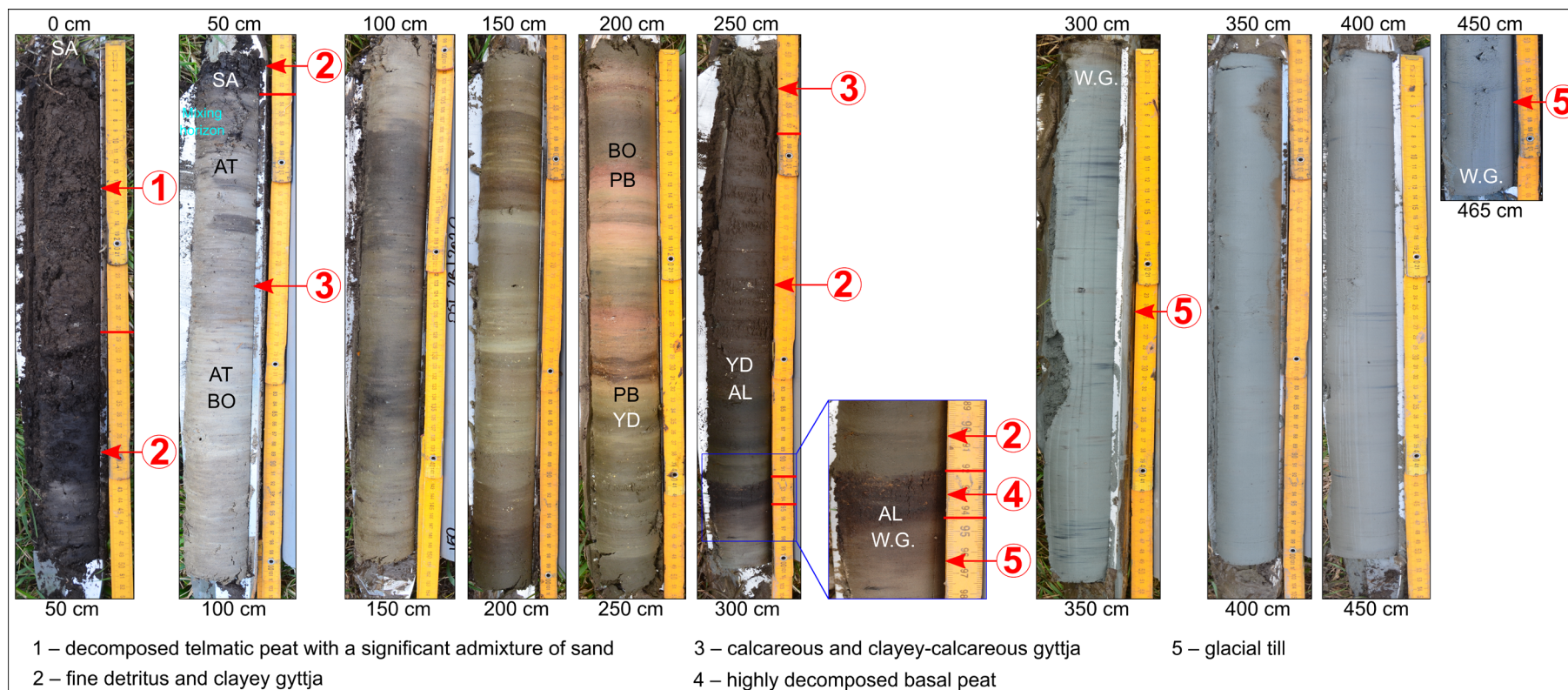


Fig. 19. Field photographs of the OST2B core taken immediately after drilling (photos by P. Kittel, 2020). The core was not cleaned before taking photographs, so the photo-recorded depths of lithological boundaries may differ slightly from those measured in the laboratory.

Designations in the figure: W.G. – Weichselian glaciation; AL – Allerød; YD – Younger Dryas; PB – Preboreal; BO – Boreal; AT – Atlantic; SA – Subatlantic



Fig. 20. Google Earth satellite images with the approximate location of the OST2B core. A – Ploughed agricultural field at the OST2B coring site, September 2020. B – Artificial pond at the OST2B coring site, September 2021

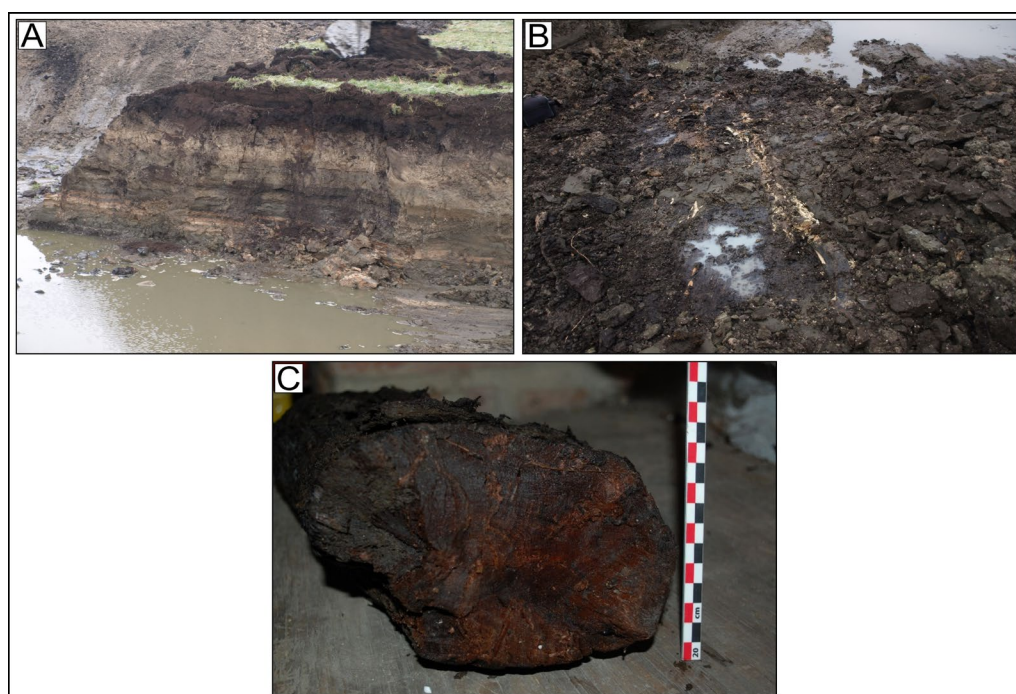


Fig. 21. Excavation of the artificial pond in December 2020 (A), during which a basal peat layer with inclusions of *Salix* wood fragments was exposed (B). One of these *Salix* wood fragments (C) was dated to 13,492–13,325 cal BP. Photos by Ł. Trzciński

2.3 Geochemical analysis and lithology

For the geochemical analysis, 72 samples were collected from the 0–350 cm b.g.l. depth interval. During the geochemical analysis, the amounts of organic matter (LOI_{550}), calcium carbonate (CaCO_3 , LOI_{925}), and mineral matter ($\text{SiO}_{2\text{bio}} + \text{SiO}_{2\text{ter}}$) in the sediments were determined. The contents of organic matter and calcium carbonate were measured by the loss on ignition (LOI) method using a muffle furnace at 550°C (4 hours) and 925°C (2 hours), respectively (after Dean, 1974; Myślińska, 1999; Heiri et al., 2001; Żurek, 2010). The amount of mineral matter was calculated by subtracting the organic matter and calcium carbonate from 100% (cf. Kittel et al., 2025). This basic geochemical analysis of the sediments was carried out by D. Okupny in the geochemical laboratory of the Institute of Marine and Environmental Sciences at the University of Szczecin.

The lithological units in the OST2B core were identified on the basis of macroscopic evaluation of the deposits, geochemical analysis (organic matter, CaCO_3 , mineral matter), as well as results of pollen and plant macrofossil analyses.

2.4 Pollen analysis

For the pollen analysis, 66 samples (each 1 cm³) were collected from the 0–297 cm b.g.l. depth interval. The studied samples were subjected to standard laboratory procedures involving HCl, KOH, sieving, HF, and acetolysis (after Berglund and Ralska-Jasiewiczowa, 1986; Faegri and Iversen, 1989). After processing, the samples were mounted in glycerol and stained with fuchsin. The laboratory preparation for the spore-pollen analysis was carried out at the Institute of Geoecology and Geoinformation of Adam Mickiewicz University in Poznań (Poland).

More than 500 arboreal pollen grains (AP) were counted in each sample during microscopic analysis, except for one sample from the basal peat, in which only about 300 grains could be counted due to the low pollen concentration. The percentage spore-pollen diagram was constructed using the Tilia software (Grimm, 1992). The CONISS cluster analysis (Grimm, 1987) was carried out based on AP and NAP (arboreal pollen and nonarboreal pollen).

The percentages of arboreal pollen (AP) and nonarboreal pollen (NAP) were calculated from the total sum $\text{AP} + \text{NAP} = 100\%$. Pollen grains of local aquatic and telmatic/wetland plants, as well as spores, were excluded from this total sum. Percentage values for Cyperaceae (Cyp), aquatic plants (AQVP), spore plants (F), and nonpollen palynomorphs (NPP) were calculated separately based on the sums $\text{AP} + \text{NAP} + \text{Cyp}$ (or

AQVP / or F / or NPP) = 100%. The taxa included in these calculation groups are indicated in colour in the pollen diagram (see Fig. 23 below). The percentages of undeterminable (heavily damaged or deformed; Unable) and undetermined (was not identified; Uned) pollen and spores were calculated from the sums AP + NAP + Cyp + AQVP + F + Unable (or Uned) = 100%. In our study, corroded pollen (perforated) was counted among the identified pollen grains of *Betula*, *Corylus*, and *Alnus* (BCA). The percentage of corroded pollen was calculated using the sum BCA + corroded = 100%.

2.5 Plant macrofossil analysis

For the plant macrofossil analysis, 63 samples were taken from the 0–298 cm b.g.l. depth interval. Laboratory preparation and microscopic analysis of the samples were carried out by J. Rennwanz, PhD at the Institute of Archaeology and Ethnology of the Polish Academy of Sciences in Poznan in accordance with the commonly accepted methodology (Lityńska-Zajac and Wasylikowa, 2005; Tobolski, 2021). The studied samples were soaked and wet-sieved through 2.0, 0.5 and 0.2 mm meshes. The recovered organic material was separated into size fractions and stored in a preservative solution (distilled water, glycerol, alcohol, and thymol; cf. Kittel et al., 2025). Plant macrofossils were identified using a Nikon SMZ-800 stereoscopic microscope. After analysis, some plant macrofossils were selected for radiocarbon dating.

The plant macrofossil diagram was constructed using the Tilia software (Grimm, 1992). In the diagram, macrofossils are presented in absolute values. The obtained taxa were divided into ecological groups according to Stachowicz-Rybka (2011).

2.6 Radiocarbon analysis and chronology

Radiocarbon dating of terrestrial plant fruits and seeds (AMS technique) and a fragment of *Salix* wood (LSC technique) was conducted in three laboratories: Absolute Dating Laboratory in Krakow (Poland; lab. code: MKL), Poznan Radiocarbon Laboratory (Poland; Poz), and Laboratory of Ion Beam Physics in Zurich (Switzerland; ETH).

Calibration of the radiocarbon dates was carried out using the OxCal 4.4 online program (Bronk Ramsey, 2024), with the “IntCal 20” curve (Reimer et al., 2020). The youngest radiocarbon date of -609 ± 58 BP was calibrated using the “Bomb 21 NH1” curve (Hua et al., 2013) (see Table 6).

In this paper, we used the Late Glacial and Holocene chronology (see Table 5) developed by Kuc et al. (1998), Walanus and Nalepka (2004, 2010), Michczyńska et

al. (2008), and Starkel et al. (2013). This chronology closely corresponds to the Belarusian scheme proposed by Zernitskaya et al. (2020) and Zernitskaya (2022).

Besides palynostratigraphy, the chronology of the OST2B core was established using an OxCal P_Sequence model (Bronk Ramsey, 2008). An age-depth model based on nine radiocarbon dates was constructed for this core. The radiocarbon dates $10,880 \pm 110$ (290 cm b.g.l.) and $8,850 \pm 150$ (252 cm b.g.l.) were not included in the model due to the very low carbon content of the samples (0.03mgC and 0.05mgC, respectively), the large uncertainties of the measurements, and their poor agreement with the resulting age-depth model. It should be noted, however, that the date $10,880 \pm 110$ (290 cm b.g.l.) does not contradict the palynostratigraphic interpretation. The OxCal age-depth model for the OST2B core is available online at the following link: https://drive.google.com/drive/folders/14PZ242nzb79hxdblc0GyKysrLsKCv2_h?usp=sharing

In the diagrams, a red rectangle within the basal peat layer marks the radiocarbon date obtained from the *Salix* wood fragment sampled outside the OST2B core but from the same basal peat horizon (Figs. 22A, 22B, 23 and 24). Radiocarbon dates that were not included in the age-depth model are marked in grey (Fig. 22B). In the geochemical, pollen, and plant macrofossil diagrams, as well as in the interpretation and discussion sections, the modelled age is given as a 68.3% probability interval (Figs. 22A, 23 and 24).

Table 5. Conventional chronology of the stratigraphic units used in Chapter 3

Stratigraphic units, based on Kuc et al. (1998), Walanus and Nalepka (2004, 2010), Michczyńska et al. (2008), and Starkel et al. (2013)		Approximate age [cal BP]
Holocene	Subatlantic (SA)	from 2,750
	Subboreal (SB)	5,600 to 2,750
	Atlantic (AT)	8,850 to 5,600
	Boreal (BO)	10,200 to 8,850
	Preboreal (PB)	11,500 to 10,200
Late Weichselian	Younger Dryas (YD)	12,650 to 11,500
	Allerød (AL)	14,000 to 12,650

RESULTS

3.1 Lithology, geochemistry and chronology

Six lithologic units were identified in the OST2B core. The lowermost deposits of the OST2B core are represented by **glacial till** (465–298 cm b.g.l.), with mineral matter

($\text{SiO}_{2\text{bio}} + \text{SiO}_{2\text{ter}}$) content exceeding 90%, as well as a low admixture of CaCO_3 (7.5–0.6%) (Table 7; Fig. 22A). The accumulation of this glacial till occurred during the Weichselian glaciation (Studencki, 2009 and 2011).

Above (298–293 cm b.g.l.), there is **highly decomposed basal peat**, with an organic matter content of 38.1–9.4% and an absence of carbonates (Table 7; Fig. 22A). The accumulation of the basal peat layer took place during the Allerød, as evidenced by pollen data (Fig. 23). According to the age-depth model, this sediment layer was deposited between 13,495–13,320 and 13,490–13,232 cal BP (Table 6; Fig. 22B).

Higher in the core (293–258 cm b.g.l.) is **fine detritus and clayey gyttja**, with an organic matter content often exceeding 50%. Another distinctive feature is the absence of carbonates in these deposits (Table 7; Fig. 22A). According to the palynostratigraphic interpretation, the deposition of this sediment layer started during the Allerød and ended in the Younger Dryas (Fig. 23). The age-depth model indicates that the accumulation of this gyttja layer took place between 13,490–13,232 and 12,996–11,497 cal BP (Table 6; Fig. 22B).

Above lies a thick layer of **calcareous and clayey-calcareous gyttja** (258–59 cm b.g.l.). The main distinctive feature of this layer is a high carbonate content (Table 7; Fig. 22A). The amount of carbonates gradually increased from 5.4% in the lower part of the layer to 61% in the upper part. According to the palynostratigraphy, the accumulation of these deposits began during the Younger Dryas and ended in the Atlantic period (Fig. 23). The age-depth model shows that the accumulation of this layer took place between 12,996–11,497 and 8,163–7,300 cal BP (Table 6; Fig. 22B).

Higher in the profile, between 59 and 53 cm b.g.l., a so-called “**mixing horizon**” was distinguished (Fig. 22A). This layer consists of Atlantic calcareous and clayey-calcareous gyttja mixed with relatively young plant remains, as indicated by the age of 654–553 cal BP obtained from a fruit of *Cirsium* cf. *palustre* (Table 6). The carbonate content in this sediment layer decreased to 44.2% (Table 7). The mixing horizon is also characterized by a darker colour compared to the underlying Atlantic calcareous and clayey-calcareous gyttja (Fig. 19). Based on the age-depth model, the mixing horizon was formed between 660–554 and 665–500 cal BP (Fig. 22B).

Higher in the core (53–28 cm b.g.l.) is **fine detritus and clayey gyttja**. The main distinguishing feature of this gyttja layer is the high content of organic matter (51.3–37.8%). In comparison with the underlying gyttja, the carbonate content in this unit decreased markedly, reaching a minimum value of 4.5% (Table 7; Fig. 22A). According to

the age-depth model, this sediment layer was deposited during the Late Subatlantic, between 665–500 and -5–-49 cal BP (Fig. 22B). However, it should be taken into account that the radiocarbon date of -609 ± 58 (1–41 cal BP), which was included in the age-depth modelling, was obtained from plant macrofossil material that was most likely redeposited as a result of ploughing of the upper approximately 30 cm of the sediments (Table 6; Figs. 20A and 22B).

The uppermost layer (28–0 cm b.g.l.) consists of **decomposed telmatic peat with a significant admixture of sand (probably also includes fen or bog peat)**. A distinctive feature of this peat layer is the high mineral matter content (maximum 74.8%). The carbonate content decreased compared to the underlying layer, reaching a minimum value of 1.8% (Table 7; Fig. 22A). The deposition of this layer took place during the Late Subatlantic. The described unit was affected by ploughing in modern times (Fig. 20A), which most likely caused mixing of the upper ~30 cm of sediments.

3.2 Pollen data

Twelve local pollen assemblage zones (LPAZ) were identified on the basis of visual evaluation and CONISS cluster analysis (Fig. 23; Table 8).

3.3 Plant macrofossil data

Seven local plant macrofossil assemblage zones (LMAZ) were identified based on visual assessment (Fig. 24; Table 8).

In defining these zones, the boundaries of the pollen assemblage zones (LPAZ) were also considered because: (1) some intervals contained relatively few macrofossils (except MO-4 and MO-5 LMAZs); (2) the pollen zones generally correspond well with the distribution of plant macrofossils in the OST2B core (especially for MO-4 and MO-5 LMAZs); and (3) taking into account the LPAZ boundaries allows for emphasizing the strong local signal of *Betula* during the Boreal, expressed both in the high pollen counts and the abundant occurrence of its macrofossils.

Table 6. Radiocarbon dating of plant macrofossils from the OST2B core. Radiocarbon dates that were not included in the age-depth model are shown in *italics*

Sample depth [cm b.g.l.]	Approximate depth [cm b.g.l.]	Age conv [BP]	Laboratory No.	Age [cal BP, prob. 68.3%]	Age [cal AD/BC, prob. 68.3%]	Modelled age [cal BP, prob. 68.3%]	Dated material	Notes
30.5–34	32.5	-609±58	ETH-153173	-3 – -55	1,954–2,006 cal AD	1 – -41	<i>Stellaria palustris</i> (1 seed)	AMS technique. The dated seed was collected from a layer that had been affected by agricultural ploughing and sediment mixing. Most likely redeposited material
55.5–59	57.5	634±63	ETH-153174	657–555	1,294–1,395 cal AD	654–553	<i>Cirsium</i> cf. <i>palustre</i> (1 fruit)	AMS technique
70.5–74	72.5	7225±105	ETH-156450	8,171–7,960	6,222–6,011 cal BC	8,173–7,965	<i>Urtica dioica</i> (3 fruits)	
90.5–94	92.5	8147±84	ETH-153172	9,263–8,999	7,314–7,050 cal BC	9,141–8,780	<i>Betula</i> sect. <i>Albae</i> (10 fruits)	
150–155	152.5	8430±40	Poz-161824	9,524–9,430	7,575–7,481 cal BC	9,524–9,435	<i>Betula</i> sect. <i>Albae</i> (13 fruits)	
195–200	197.5	8910±70	Poz-162891	10,180–9,909	8,231–7,960 cal BC	10,183–9,957	<i>Betula</i> sect. <i>Albae</i> (15 fruits)	
231.5–234	232.5	9536±45	MKL-A6510	11,069–10,720	9,120–8,771 cal BC	11,069–10,720	<i>Carex rostrata</i> (2 fruits)	
250–254	252	<i>8850±150</i>	Poz-162892	10,163–9,730	8,214–7,781 cal BC	–	<i>Betula</i> sect. <i>Albae</i> (5 fruits)	
275.5–279	277.5	11136±41	MKL-A6511	13,113–12,998	11,164–11,049 cal BC	13,113–12,998	<i>Carex rostrata</i> (3 fruits)	
288.5–291	290	<i>10880±110</i>	Poz-162894	12,913–12,730	10,964–10,781 cal BC	–	<i>Betula</i> sect. <i>Albae</i> (4 fruits)	
–	–	11580±90	MKL-5127	13,571–13,345	11,622–11,396 cal BC	13,492–13,325	<i>Salix</i> wood fragment	LSC technique. The dated <i>Salix</i> wood fragment was sampled outside the OST2B core but from the basal peat layer that is also present in the OST2B core

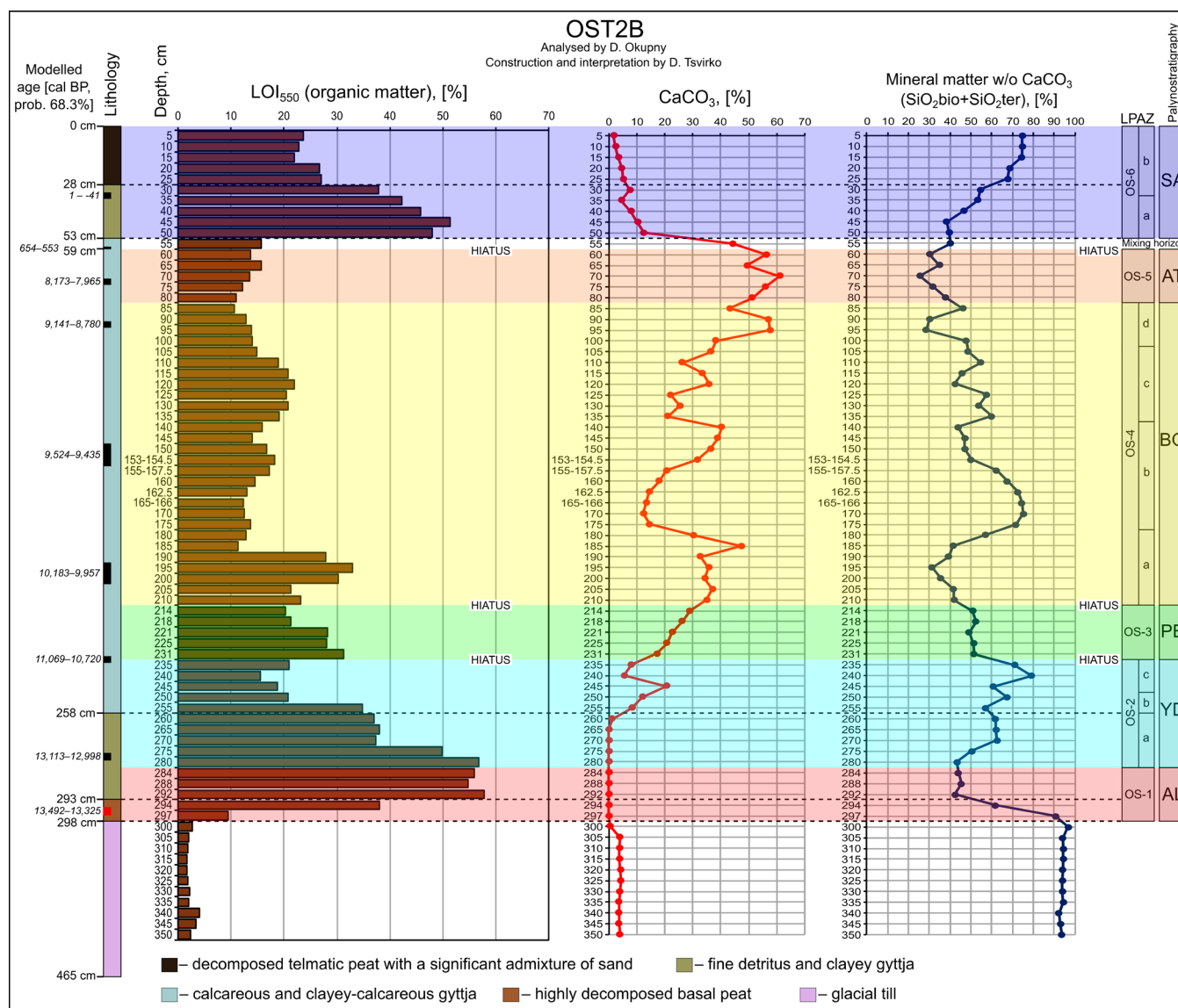


Fig. 22A. Geochemical diagram of the OST2B core with identified lithological units and radiocarbon dates

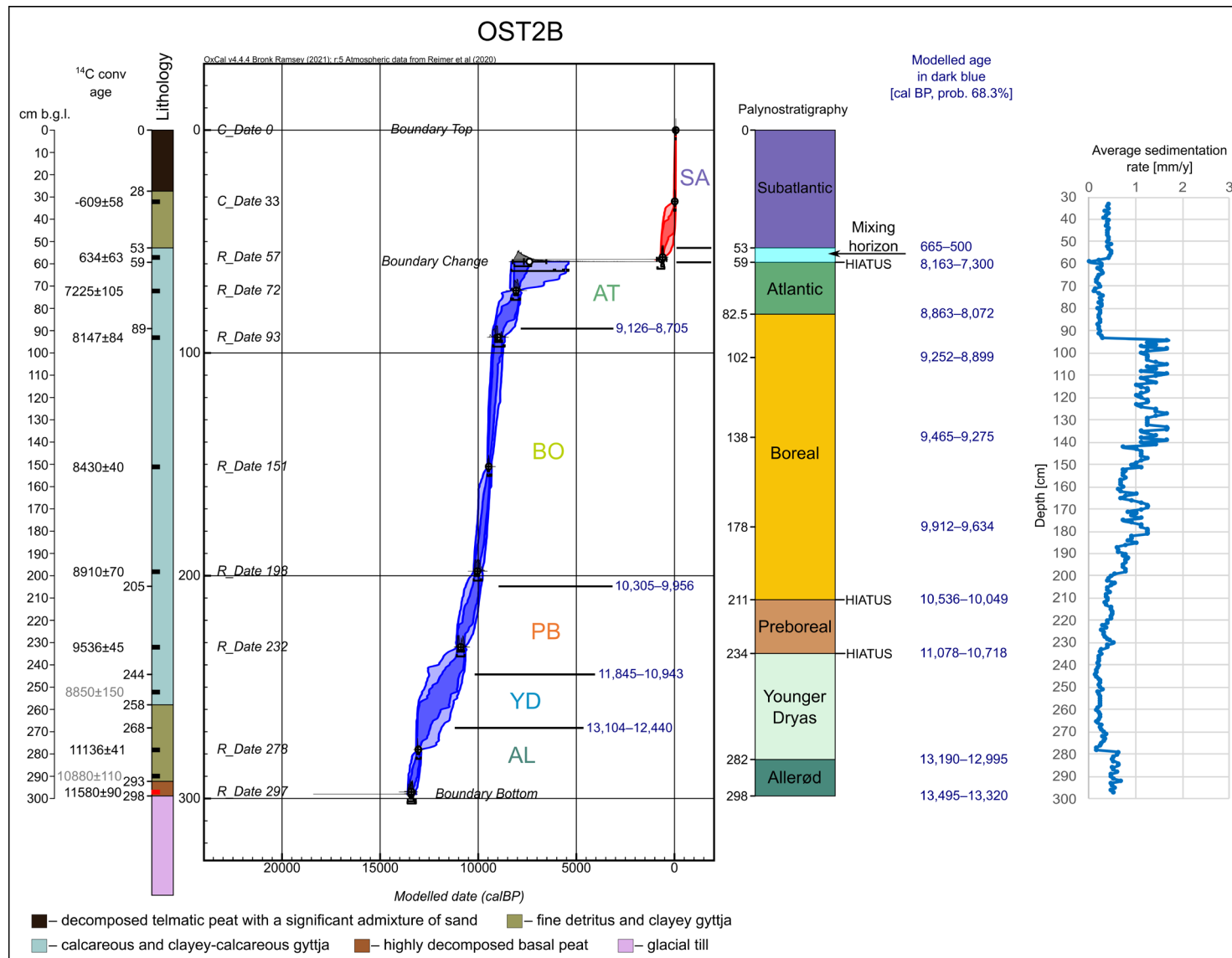


Fig. 22B. Lithology, chronology, and average sedimentation rate for the OST2B core

Table 7. Lithological units recognized in the OST2B core and their geochemical and palaeobotanical characteristics

Depth [cm b.g.l.]	Lithological unit	LOI ₅₅₀ (organic matter) [%]	CaCO ₃ [%]	Mineral matter (SiO ₂ bio+SiO ₂ ter) [%]	Distinctive features	
					Pollen analysis [%]	Plant macrofossil analysis [absolute values]
0–28	decomposed telmatic peat with a significant admixture of sand (probably also includes fen or bog peat)	27.1– 22.0	5.2–1.8	74.8–67.7	The layer was characterized by a high abundance of corroded pollen (37.5–22.2), as well as undeterminable pollen and spores (5–1.3). The layer contained a large number of fungi, including <i>Sporormiella</i>-type (9.6–1.6), <i>Glomus</i> cf. <i>fasciculatum</i> (4.6–0.9), <i>Sordaria</i>-type (4–1.9), <i>Chaetomium</i> (6.5–2.8), <i>Diporotheca</i> (1.3–0.3), and <i>Podospora</i>-type (0.5–0.1). Cyperaceae (20.1–11.9) and <i>Sphagnum</i> (4.6–2.2) were the dominant components of the wetland vegetation. <i>Pediastrum</i> algae (0.6–0.1) were almost completely absent. A small number of aquatic plants were recorded, including <i>Potamogeton</i> (0.2), <i>Myriophyllum verticillatum</i> (0.3), <i>Nymphaea</i> (0.1), <i>Nuphar</i> (0.2), and <i>Lemna</i> (0.1)	The layer was primarily characterized by the constant presence of <i>Stellaria palustris</i> (3–1). A single macrofossil of <i>Chara</i> (1) was recorded
28–53	fine detritus and clayey gyttja	51.3– 37.8	12.6– 4.5	54.5–38.4	A distinctive feature of the layer was the high content of corroded pollen (32–12.8) and undeterminable pollen and spores (2.6–1.1). The fungi <i>Glomus</i> cf. <i>fasciculatum</i> (1.1–0.1), <i>Sordaria</i>-type (1.5–0.1), and <i>Diporotheca</i> (0.1) were constantly recorded. The amount of <i>Pediastrum</i> algae was strongly reduced (1.6–0.1). Large quantities of <i>Sphagnum</i> (6.9–1.4), <i>Typha latifolia</i> (1.9–0.4), and <i>Sparganium</i>-type (1.1–0.1) were recorded. At the same time, a large number of aquatic plants, such as <i>Potamogeton</i> (0.6–0.3), <i>Myriophyllum verticillatum</i> (4.2–0.1), <i>Nymphaea</i> (0.7–0.1), <i>Nuphar</i> (0.5–0.1), and <i>Lemna</i> (0.3–0.1), were present	The deposits were characterized by high abundances of <i>Chara</i> (15). The presence of <i>Stellaria palustris</i> (1) was also recorded

Table 7 (continued)

Depth [cm b.g.l.]	Lithological unit	LOI ₅₅₀ (organic matter) [%]	CaCO ₃ [%]	Mineral matter (SiO ₂ bio+SiO ₂ ter) [%]	Distinctive features	
					Pollen analysis [%]	Plant macrofossil analysis [absolute values]
53–59 (mixing horizon)	calcareous and clayey- calcareous gyttja	15.7	44.2	40.2	The mixing horizon was characterized by the presence of pollen of <i>Potamogeton</i> (0.1), <i>Myriophyllum verticillatum</i> (0.2), <i>Nymphaea</i> (0.1), <i>Lemna</i> (0.5), <i>Sphagnum</i> (1.1), <i>Sparganium</i> -type (0.4), <i>Typha latifolia</i> (1.4), and <i>Drosera</i> (0.1). High amounts of corroded pollen (21.8) and undeterminable pollen and spores (4.6) were recorded. In addition, low values of <i>Pediastrum</i> (3) were noted, as well as the presence of <i>Sordaria</i> -type (0.7) and <i>Glomus</i> cf. <i>fasciculatum</i> (0.1)	The mixing horizon was distinguished by the presence of macrofossils of <i>Chara</i> (8), <i>Oenanthe aquatica</i> (5), <i>Cirsium</i> cf. <i>palustre</i> (1), and <i>Ranunculus sceleratus</i> (1)
59–258		34.9– 10.6	61.0–5.4	79.0–25.5	A large amount of aquatic plants was recorded in the gyttja layer, including <i>Potamogeton</i> (0.8–0.1), <i>Myriophyllum spicatum</i> (2.1–0.2), <i>Nymphaea</i> (5.4–0.1), and <i>Lemna</i> (1.4–0.1), as well as <i>Pediastrum</i> algae (80.5–1.2). Fungi were almost completely absent	The gyttja layer was mainly distinguished by a large amount of <i>Chara</i> (65–1), <i>Najas marina</i> (10–1), and <i>Nymphaea alba</i> (19–1)
258– 293	fine detritus and clayey gyttja	57.7– 37.0	1.23–0	62.6–42.3	The gyttja layer was characterized by a high abundance of pollen from aquatic plants, including <i>Potamogeton</i> (6.0–0.1), <i>Myriophyllum spicatum</i> (2.8–0.1), and <i>Nuphar</i> (0.3–0.1), as well as <i>Pediastrum</i> algae (64.5–15.2). Fungi were almost completely absent	The presence of a small number of <i>Chara</i> (5–1), <i>Najas marina</i> (1), <i>Nymphaea alba</i> (2), and <i>Potamogeton</i> spp. (1). The deposits were also characterized by a large number of <i>Carex</i> spp. (12–1)
293– 298	highly decomposed basal peat	38.1– 9.4	0	90.6–61.9	A distinctive feature of the basal peat was the high content of corroded pollen (40.4–31.2), undeterminable pollen and spores (4.2–3.0), as well as <i>Sporormiella</i> -type (14.3–5.2), <i>Glomus</i> cf. <i>fasciculatum</i> (3.5–3.4), and <i>Sordaria</i> -type (26.2–4.3)	–
298– 465	glacial till	4.0–1.7	7.5–0.6	96.6–90.0	–	–

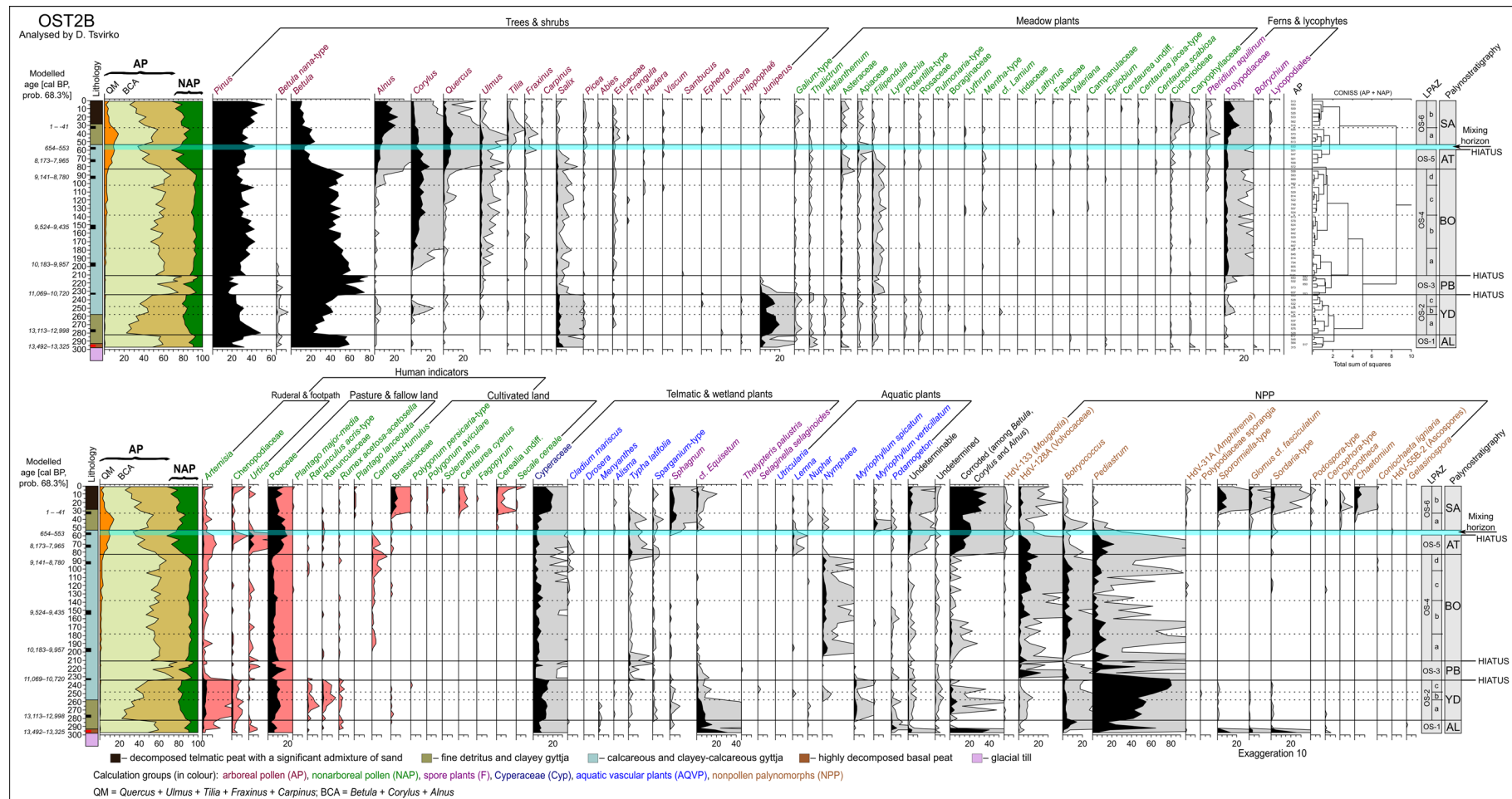


Fig. 23. Percentage pollen diagram from the OST2B core (analysed by D. Tsvirko)

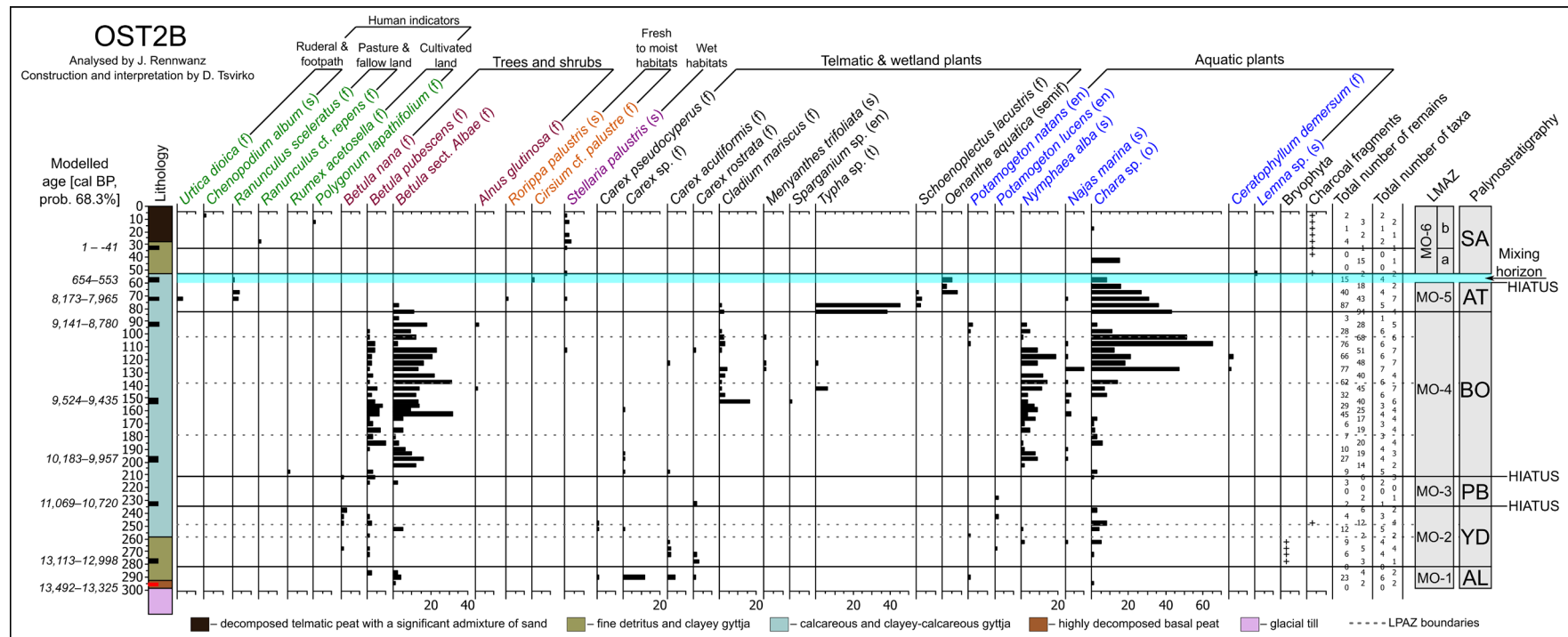


Fig. 24. Plant macrofossil diagram from the OST2B core (analysed by J. Rennwanz, interpretation by D. Tsvirko)

Table 8. Local pollen (LPAZ) and plant macrofossil (LMAZ) assemblage zones identified in the OST2B core

LPAZ	Depth [cm b.g.l.]	Pollen analysis [%]	LMAZ (plant macrofossils in absolute values)	Palynostratigraphy	Lithological unit
OS-6b <i>Pinus</i> - Cerealia	0–33	Zone OS-6b was primarily characterized by absolute maxima of <i>Pinus</i> (53.1) and <i>Alnus</i> (23.4), and very high NAP values (maximum 31.7%). Significant decreases were observed in <i>Corylus</i> (3.8–2.2), <i>Quercus</i> (3.5–0.9), <i>Ulmus</i> (0.7–0.1), <i>Tilia</i> (1.4–0.3), and <i>Fraxinus</i> (0.5–0.1). <i>Juniperus</i> pollen was recorded (0.5–0.1). The zone also showed absolute maxima of Brassicaceae (6.9), <i>Centaurea cyanus</i> (1), Cerealia undiff. (2.1), and <i>Secale cereale</i> (0.9)	MO-6b LMAZ. Macrofossils of <i>Chenopodium album</i> (1), <i>Ranunculus</i> cf. <i>repens</i> (1), and <i>Polygonum lapathifolium</i> (1) were found in this zone. The zone was characterized by an absolute maximum of <i>Stellaria palustris</i> (3). A single <i>Chara</i> remain was noted	SA	decomposed telmatic peat with a significant admixture of sand (0–28 cm); fine detritus and clayey gyttja (28–33 cm)
OS-6a <i>Quercus</i> - NAP	33–53	Zone OS-6a was distinguished by absolute maxima of <i>Quercus</i> (10), <i>Ulmus</i> (3.4), <i>Tilia</i> (1.8), and <i>Fraxinus</i> (1.4). High values of <i>Corylus</i> (7.2–6.8) and <i>Alnus</i> (15.3–7.3) were also observed. <i>Betula</i> values increased (24–18.5). <i>Juniperus</i> pollen reappeared (0.1). In this zone, the first occurrence of Cerealia undiff. (0.3–0.1) and <i>Secale cereale</i> (0.1) was recorded	MO-6a LMAZ. The zone contained neither macrofossils of trees and shrubs nor human indicators. The zone was characterized by high values of <i>Chara</i> (15)		fine detritus and clayey gyttja
53–59 cm – Mixing horizon (with macrofossils of <i>Cirsium</i> cf. <i>palustre</i> dated to 654–553 cal BP)					calcareous and clayey-calcareous gyttja
59 cm – HIATUS					
OS-5 <i>Corylus</i> - <i>Quercus</i> - NAP	59–82.5	Zone OS-5 was primarily characterized by very high NAP values (maximum 31.7%), with an absolute maximum of Poaceae (19.6). This zone was distinguished by an absolute maximum of <i>Corylus</i> (18.2), high values of <i>Quercus</i> (7.7–2.9), and <i>Alnus</i> (5.6–3), as well as low values of <i>Betula</i> (30.5–13.4). An absolute maximum of <i>Urtica</i> (5.6) and an absolute maximum of Chenopodiaceae (1.6) were also recorded, along with high values of <i>Artemisia</i> (1.4–1) and <i>Cannabis-Humulus</i> (1–0.1)	MO-5 LMAZ. Macrofossils of <i>Urtica dioica</i> (3), <i>Ranunculus sceleratus</i> (4–3), as well as <i>Betula</i> sect. <i>Albae</i> (11–3) were recorded. The zone was characterized by absolute maxima of <i>Typha</i> sp. (45), <i>Schoenoplectus lacustris</i> (3), and <i>Oenanthe aquatica</i> (8), as well as high abundances of <i>Chara</i> (43–16)	AT	

Table 8 (continued)

LPAZ		Depth [cm b.g.l.]	Pollen analysis [%]		LMAZ (plant macrofossils in absolute values)	Palynostratigraphy	Lithological unit
OS-4 <i>Corylus</i> - <i>Ulmus</i> - <i>Pinus</i>	d	82.5–102	The OS-4 zone exhibited high values of <i>Pinus</i> (43–24.3), <i>Betula</i> (60.3–37.3), and AP (93.5–86.9), as well as low values of NAP (13.1–6.5). Onset of the continuous <i>Corylus</i> curve. <i>Corylus</i> values showed a gradual increase, with an absolute minimum in the lower part of the zone (0.1) and high values in the upper part (up to 13.9). <i>Ulmus</i> values also increased gradually, from 0.3% in the lower part of the zone to 2.2% in the upper part	Zone OS-4d showed low values of <i>Pinus</i> (30.4–24.3), and high values of <i>Corylus</i> (12.3–9.7), <i>Ulmus</i> (2.2–1), <i>Quercus</i> (1.3–0.4), and <i>Alnus</i> (2.9–0.9)	MO-4 LMAZ. An absolute maximum of <i>Betula</i> sect. <i>Albae</i> (32), an absolute maximum of <i>Betula pubescens</i> (10), and an absolute maximum of <i>Alnus glutinosa</i> (2) were recorded. Absolute maxima of <i>Cladium mariscus</i> (16), <i>Nymphaea alba</i> (19), <i>Najas marina</i> (10), and <i>Chara</i> (65) were also noted	BO	calcareous and clayey-calcareous gyttja
	c	102–138		Zone OS-4c was distinguished by high values of <i>Corylus</i> (13.9–8.1) and <i>Ulmus</i> (2.1–0.7). Onset of the continuous <i>Alnus</i> curve (0.5–0.1)			
	b	138–178		Zone OS-4b was characterized by a gradual increase in <i>Corylus</i> values (3.5–8.7) and high values of <i>Pinus</i> (43–28.9). Onset of the continuous <i>Quercus</i> curve (0.3–0.1)			
	a	178–211		Zone OS-4a was distinguished by an absolute minimum of <i>Corylus</i> (0.1) and high values of <i>Betula</i> (60.3–51.2)			
211 cm – HIATUS							
OS-3 <i>Betula</i> - <i>Ulmus</i>		211–234	Zone OS-3 was characterized by an absolute maximum of <i>Betula</i> (78.1). An absolute maximum of AP (95) was also observed. Onset of the continuous <i>Ulmus</i> curve (0.6–0.1)		MO-3 LMAZ. Macrofossils of <i>Betula</i> sect. <i>Albae</i> (2) and <i>Betula pubescens</i> (4–1) were recorded, as well as a single fruit of <i>Betula nana</i> (1). Remains of <i>Potamogeton lucens</i> (2) were noted	PB	calcareous and clayey-calcareous gyttja
234 cm – HIATUS							

Table 8 (continued)

LPAZ		Depth [cm b.g.l.]	Pollen analysis [%]		LMAZ (plant macrofossils in absolute values)	Palynostratigraphy	Lithological unit
OS-2 <i>Juniperus</i> - NAP	c	234–248	Zone OS-2 showed an absolute maximum of <i>Juniperus</i> (19.3), high NAP values (20.7–13), and an absolute maximum of <i>Artemisia</i> (4.5). An absolute maximum of <i>Betula nana</i> -type (1.2), high values of <i>Salix</i> (4.9–2.3), and single pollen grains of <i>Hippophaë</i> (0.2–0.1) were also recorded. High values of Chenopodiaceae (1.2–0.4) were observed, together with a few grains of <i>Helianthemum</i> (0.3–0.1) and <i>Selaginella selaginoides</i> (0.3)	–	MO-2 LMAZ. The zone showed the presence of macrofossils of <i>Betula pubescens</i> (2–1), <i>Betula</i> sect. <i>Albae</i> (5), as well as an absolute maximum of <i>Betula nana</i> (3). The zone was characterized by remnants of aquatic plants, particularly <i>Chara</i> (8–1)	YD	calcareous and clayey-calcareous gyttja
	b	248–258		Zone OS-2b was defined by a significant decrease in <i>Juniperus</i> values, with the minimum reaching 5.8%			
	a	258–282		–			fine detritus and clayey gyttja
OS-1 <i>Betula</i>		282–298	Zone OS-1 was characterized by a high abundance of <i>Betula</i> (59.1–48.9), high AP values (92.6–86.1), the presence of <i>Juniperus</i> (5.2–1), and an absolute maximum of <i>Salix</i> (7.5). A few pollen grains of <i>Betula nana</i> -type (0.6–0.2) and <i>Hippophaë</i> (0.2) were recorded		MO-1 LMAZ. Macrofossils of <i>Betula</i> sect. <i>Albae</i> (4–1) and <i>Betula pubescens</i> (2) were found. The zone was characterized by an absolute maximum of <i>Carex</i> sp. (12), as well as the presence of <i>Potamogeton natans</i> (1) and <i>Chara</i> (1)	AL	fine detritus and clayey gyttja (282–293 cm); highly decomposed basal peat (293–298 cm)

INTERPRETATION AND DISCUSSION

4.1 Allerød (298–282 cm b.g.l.; OS-1 LPAZ; MO-1 LMAZ), modelled age: from 13,495–13,320 to 13,190–12,995 cal BP

The formation of the investigated OST2B kettle hole reservoir began during the Allerød, as indicated by a radiocarbon age of 13,492–13,325 cal BP obtained from a *Salix* wood fragment collected from the basal peat layer (Table 6; Figs. 22A, 22B). The Allerød global warming (cf. Köhler et al., 2011; Druzhinina et al., 2023) resulted in intense melting of dead ice blocks. At the initial stage, a wetland developed on the surface of the dead ice block, where peat sedimentation took place (accumulation of so-called basal peat; Fig. 22A; Table 7). The newly formed wetland was densely overgrown by *Salix*, as evidenced by the presence of many *Salix* wood fragments (Fig. 21BC) and an absolute maximum of the *Salix* pollen curve (Fig. 23; Table 8). A substantial part of the wetland surface was covered by Cyperaceae and Poaceae (Fig. 23).

Periodic water level fluctuations in the wetland, as well as seasonal freezing, led to oxygen intrusion into the peat deposits, causing corrosion and damage to pollen and spores (Table 7; Fig. 23, showing an absolute maximum of the corroded pollen curve and high values of undeterminable pollen and spores; Fig. 25; Havinga, 1967; Twiddle and Bunting, 2010). The high abundance of coprophilous fungi *Sporormiella*-type, *Sordaria*-type and *Cercophora*-type in the peat (Fig. 23; Table 7) may indicate a high density of herbivorous animals that periodically visited the studied wetland (Lee et al., 2022; Gauthier et al., 2025). High values of *Glomus* cf. *fasciculatum* spores in the basal peat layer (Fig. 23; Table 7) rather indicate colonisation of wetland plant roots by these fungi than soil erosion (Kołaczek et al., 2013).

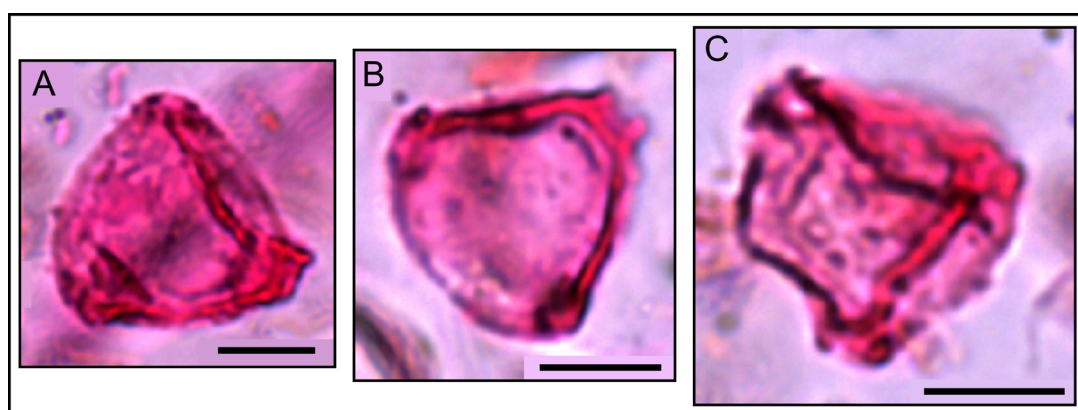


Fig. 25. Examples of corroded *Betula* pollen grains from the basal peat layer at a depth of 294 cm (photos by D. Tsvirko)

Further melting of the buried dead ice block led to the transformation of the wetland into a lake at approximately 13,490–13,232 cal BP (293 cm) (Fig. 22B). Thus, during the Allerød, the thermokarst Lake OST2B emerged. In the newly formed lake, accumulation of non-calcareous fine detritus and clayey gyttja with a high organic matter content began (Fig. 22A; Table 7). A substantial part of the lake was occupied by aquatic plants, with *Potamogeton* being the most dominant (Fig. 23, showing an absolute maximum of the *Potamogeton* pollen curve; Fig. 24). *Myriophyllum spicatum* and *Nuphar* were present in lower abundances (Fig. 23). The wetland-to-lake transformation also resulted in increased abundances of *Pediastrum* algae (Fig. 23; Table 7). The nearshore vegetation was represented mainly by *Carex* species (Fig. 24; Table 7).

Regional vegetation during the Allerød was represented mainly by open-canopy birch forests (Figs. 23 and 24). Open areas were colonized by *Juniperus* and *Hippophaë*. Among shrubs, *Betula nana* was present (Fig. 23; Table 8).

In the reference OST1 core (53°38'54.1"N 17°39'26.2"E), located approximately 200 m SSW of core OST2B (Fig. 18A), the Allerød period corresponds to the *Betula-Pinus* LPAZ (607–551 cm, labelled as “Bølling-Allerød”), which, according to the age-depth model, is dated to the interval between 13,738–13,520 and 12,408–11,888 cal BP (Kittel et al., 2025). The Allerød pollen records from cores OST2B and OST1 are nearly identical. The OST1 assemblage is also characterized by very high values of *Betula* and *Salix*, as well as low abundances of *Pinus*, *Betula nana*-type, *Juniperus*, and herbaceous taxa (Kittel et al., 2025). The high calcium carbonate content in the Allerød deposits of core OST1 (Kittel et al., 2025) may indicate enhanced leaching of carbonates from the surrounding Weichselian moraine sediments (Pełechaty et al., 2013), driven by increased moisture related to intensive melting of dead ice blocks and the permafrost.

In the reference sediments of Lake Mały Suszek (53°42'58.59"N 17°46'16.35"E), located approximately 10 km NE of Lake OST2B, the Allerød sequence corresponds to the *Pinus-Betula*-Gramineae LPAZ (Miotk-Szpiganowicz, 1992). This Allerød layer was dated by only single radiocarbon date to 11,810±140 BP (13,798–13,502 cal BP).

The Allerød pollen records from cores OST2B and Mały Suszek exhibit both similarities and notable differences. Similar to the OST2B core, the Allerød sequence of Lake Mały Suszek is characterized by relatively low abundances of *Juniperus* and herbaceous taxa, as well as by substantial amounts of *Salix*. The principal difference lies in the dominance of *Pinus* in Lake Mały Suszek (up to 63.7%), accompanied by comparatively low *Betula* values (up to 36.1%) (Miotk-Szpiganowicz, 1992). In contrast,

the vegetation around Lake OST2B and Lake OST1 was dominated in the Allerød by *Betula* (maximum 59.1% in the OST2B core), while *Pinus* occurred in much lower proportions (19.4–32.5% in the OST2B core) (Fig. 23; Table 8).

These differences in Allerød arboreal vegetation are most likely explained by variations in the geological substrate of the lake catchments. Morainic sediments in Ostrowite (Fig. 18B) favoured the expansion of *Betula* and hindered the spread of *Pinus*, whereas glaciofluvial (i.e. outwash) sands and gravels in the surroundings of Lake Mały Suszek (Miotk-Szpiganowicz, 1992) promoted the development of pine-dominated vegetation.

It should also be noted that Miotk-Szpiganowicz (1992) identified a so-called “pre-Allerød” phase of vegetation development in the record from Lake Mały Suszek (see the *Pinus*-Cyperaceae LPAZ). This phase is marked by a sharp decrease in the *Pinus* pollen curve (from a maximum of 71.8%), high proportions of Cyperaceae and Gramineae, and very low percentages of *Betula* (around 9%). Hjelmroos-Ericsson (1981b) assigned this “pre-Allerød” phase to the Older Dryas. However, a radiocarbon date of $11,810 \pm 140$ BP ($13,798$ – $13,502$ cal BP) obtained from the Mały Suszek core suggests that this phase may represent an early stage of Allerød vegetation succession. Consequently, the attribution of the “pre-Allerød” phase to the Early Allerød appears more plausible. Further detailed palynological and radiocarbon investigations are required to clarify the precise stratigraphic position of the “pre-Allerød”.

In this context, we note that pollen assemblages from the layer of silty sand in the OST1 core (607–633 cm b.g.l., labelled as “Bølling-Allerød (?)” by Kittel et al., 2025) could also have formed during this “pre-Allerød” (or Early Allerød) phase. In the OST1 core, this phase is characterized by a sharp decline in *Pinus* pollen accompanied by increasing *Betula* and Poaceae values. The clay layer (>633 cm b.g.l.), which lies below the “pre-Allerød” deposits, should therefore be attributed to the Older Dryas rather than to the Oldest Dryas, as suggested by the authors of the OST1 study (Kittel et al., 2025).

The results from palaeolake OST2B concerning the timing of dead ice block melting correspond well with those from other reservoirs in Northern Poland. In general, in this region, the main phase of melting of buried dead ice blocks took place during the Bølling-Allerød interval (Błaszkiwicz, 2011), since the Bølling-Allerød period represents the most pronounced phase of global warming during the Late Weichselian (Błaszkiwicz, 2011). The melting of a dead ice block is also documented in the Allerød sediments of Lake Mały Suszek (Miotk-Szpiganowicz, 1992), where a basal peat layer was dated to $11,810 \pm 140$ BP

(13,798–13,502 cal BP) is overlain by Allerød gyttja. Notably, Lake Sporovskoye also formed during the Bølling-Allerød interval (see Chapter 1).

It should also be emphasized that, according to our reinterpretation, the melting of the dead ice block in the OST1 kettle hole began during the Older Dryas (see the clay layer >633 cm b.g.l. in Kittel et al., 2025), somewhat earlier than in the OST2B kettle hole, where dead ice melting could be related to the Allerød (Fig. 23). This chronological difference between OST1 and OST2B can likely be explained by the lower hypsometric position of the OST1 depression during the Older Dryas, which limited meltwater drainage and promoted the long-term persistence of stagnant water at the dead ice surface. The thermal effect of this stagnant water on the underlying dead ice block enhanced melting and ultimately led to the formation of the OST1 lake basin (Błaszczewicz, 2011). It is also important to emphasise that the OST1 depression was smaller and deeper than OST2B. Consequently, a large dead ice block concentrated within a limited area of the OST1 depression may have produced more meltwater, thereby accelerating the melting process.

4.2 Younger Dryas (282–234 cm; OS-2 LPAZ; MO-2 LMAZ), modelled age: from 13,190–12,995 to 11,078–10,718 cal BP

A rapid climatic cooling during the Younger Dryas, characterized by a decline in winter temperatures and reduced precipitation and, hence, increased continentality (Pawłowski et al., 2015; Marks, 2023; Naughton et al., 2023), led to an expansion and dominance of open, treeless, and dry areas around Lake OST2B. This is indicated by an increase in light-demanding and drought-tolerant pollen taxa, in particular the absolute maximum of *Juniperus*, the presence of *Hippophaë* and *Ephedra*, a high proportion of NAP (especially Poaceae), the absolute maximum of *Artemisia*, high values of Chenopodiaceae, and the presence of *Helianthemum* (Fig. 23; Table 8; on the ecology of these taxa, see Zarzycki et al., 2002; Pawłowski et al., 2015; Wang et al., 2022). Cold climatic conditions are indicated by the presence of *Selaginella selaginoides* spores and the absolute maxima of the *Betula nana* pollen and macrofossil curves (Figs. 23 and 24; Table 8; cf. Zarzycki et al., 2002).

During the Younger Dryas, the regional vegetation cover around Lake OST2B exhibited a mosaic pattern. Small open-canopy pine-birch forests were alternated with vast open and treeless areas (Figs. 23 and 24).

The moist areas around Lake OST2B were heavily overgrown with *Salix*, and *Betula nana* (Fig. 23; cf. Zarzycki et al., 2002). Moist places were also colonized by *Selaginella selaginoides* (Fig. 23; cf. Zarzycki et al., 2002).

The nearshore vegetation was primarily composed of Cyperaceae, among which *Carex* species were the most abundant (Figs. 23 and 24). *Sphagnum* also formed a substantial component of the nearshore vegetation (Fig. 23). In the water of Lake OST2B, *Myriophyllum spicatum* became dominant, with a noticeable presence of *Potamogeton*, *Nuphar*, *Nymphaea*, and *Najas marina* (Figs. 23 and 24). The widespread occurrence of *Chara* algae (Fig. 24) indicates hard-water conditions associated with carbonate leaching from the surrounding Weichselian moraine plateau. This, in turn, resulted in decalcification of the catchment area (Kittel et al., 2025; and for other areas: Pełechaty et al., 2013; Pukacz et al., 2014). The cold climate of the Younger Dryas provided optimal conditions for the development of *Pediastrum* algal communities (Fig. 23).

Several important events occurred during the Middle Younger Dryas (LPAZ OS-2b). First, beginning in the Middle Younger Dryas, the type of sedimentation changed, and carbonate sediments started to be deposited in Lake OST2B (Fig. 22A). Second, a pronounced decline in *Juniperus* abundance was observed during the Middle Younger Dryas (Fig. 23; Table 8). This decline may reflect a local expansion of open-canopy pine-birch forests in the vicinity of Lake OST2B (Fig. 23).

In the reference core OST1 (Kittel et al., 2025), the Younger Dryas is represented by the *Juniperus-Artemisia-Cyperaceae* LPAZ (551–467 cm), which, according to the age-depth model, is dated to the interval between 12,408–11,888 and 11,181–10,364 cal BP. Pollen records from cores OST2B and OST1 show an almost identical pattern. The OST1 record further confirms the dominance of open, treeless areas throughout the Younger Dryas, as reflected by the high values of light-demanding taxa (Kittel et al., 2025).

In the reference sediments of Lake Mały Suszek, the Younger Dryas is characterised by the *Juniperus-Gramineae-Cyperaceae-Artemisia* LPAZ, for which no radiocarbon dates were obtained (Miotk-Szpiganowicz, 1992).

For the first half of the Younger Dryas, the pollen record from core OST2B is generally in good agreement with data from the reference Mały Suszek core (Miotk-Szpiganowicz, 1992). Pronounced differences emerge in the second half of the Younger Dryas. During this interval, in the glaciofluvial landscape surrounding Lake Mały Suszek, the abundances of *Pinus* and *Betula* increased significantly, accompanied by a strong decline in light-demanding taxa (*Juniperus*, *Artemisia*, *Chenopodiaceae*, *Helianthemum*,

and NAP). Assuming that the palynostratigraphic interpretation of Miotk-Szpiganowicz (1992) is correct, these changes indicate that extensive open-canopy pine-birch forests became dominant around Lake Mały Suszek already during the younger part of the Younger Dryas. Consequently, the extent of open, treeless areas in the vicinity of Lake Mały Suszek decreased markedly (Miotk-Szpiganowicz, 1992).

In contrast, in the moraine landscape at Ostrowite, open and largely treeless areas continued to dominate throughout the younger part of the Younger Dryas (Fig. 23; Kittel et al., 2025). The contrasting vegetation patterns observed during the Late Younger Dryas were most likely driven by differences in geological structure, which played a significant role in controlling vegetation cover succession.

4.3 Preboreal (234–211 cm; OS-3 LPAZ; MO-3 LMAZ), modelled age: from 11,078–10,718 to 10,536–10,049 cal BP

Apparently, the Preboreal (with a duration from 11,500 to 10,200 cal BP according to Kuc et al., 1998, Walanus and Nalepka, 2004 and 2010, Michczyńska et al., 2008, and Starkel et al., 2013; Table 5) began with a break in sedimentation. Evidence for this hiatus includes: (1) a radiocarbon age of 11,078–10,718 cal BP marking the onset of Preboreal sediment accumulation in Lake OST2B (Fig. 22B); and (2) abrupt changes in the pollen curves of *Betula*, *Pinus*, *Salix*, AP, NAP, Cyperaceae, and other taxa (Fig. 23). This hiatus was most likely related to a prominent regression of Lake OST2B during the Early Preboreal (between 11,500 and 11,078–10,718 cal BP).

Approximately 11,078–10,718 cal BP (Fig. 22B), Lake OST2B underwent a transgression, leading to the resumption of carbonate deposits accumulation (Fig. 22A; Table 7).

Preboreal climate warming, characterized by an increase in both winter and summer temperatures, as well as annual precipitation and, hence, a decrease in continentality (Pawłowski et al., 2015; Kramkowski et al., 2023), led to a significant expansion of open-canopy forest cover and a marked reduction in treeless areas in the vicinity of Lake OST2B. This is evidenced by a decline in light-demanding taxa, including *Juniperus*, *Hippophaë*, NAP, *Artemisia*, Chenopodiaceae, and *Helianthemum* (Fig. 23; on the ecology of these taxa, see Zarzycki et al., 2002; Pawłowski et al., 2015). The regional landscape became dominated by open-canopy birch forests (Fig. 23; Table 8). During the Preboreal, *Ulmus* (continuous curve reaching 0.6–0.1%) expanded into the study area and, together with pine

and birch, may have formed the first small, localized patches of relatively dense forest (Fig. 23).

The moist areas around Lake OST2B experienced a pronounced decline in *Salix* abundance (Fig. 23). *Typha latifolia* became an important component of the nearshore vegetation (Fig. 23). In the lake, the abundance of *Myriophyllum spicatum* declined strongly, while *Potamogeton* became the dominant aquatic plant (Figs. 23 and 24). Compared to the preceding period, the abundance of *Pediastrum* algae in the lake decreased substantially (Fig. 23).

Apparently, the Preboreal ended with a short-term break in sedimentation caused by a regression of Lake OST2B. This hiatus is indicated by abrupt changes in the pollen curves of *Betula*, *Pinus*, AP, NAP, Polypodiaceae, and Poaceae (Fig. 23; Table 8).

Comparison of the pollen data obtained from the palaeolake OST2B with those from the nearby palaeolake OST1 (Kittel et al., 2025) reveals a very similar, almost identical pollen record for the Preboreal period. In the OST1 sequence, the Preboreal is represented by the *Betula*-Poaceae LPAZ (at a depth of 467–445 cm), which, according to the age-depth model, formed between 11,181–10,364 and 10,587–10,010 cal BP (Kittel et al., 2025). The Preboreal pollen record from the palaeolake OST1 confirms a reduction in open, treeless areas, as indicated by a decline in light-demanding taxa, and indicates that open-canopy birch forests dominated the moraine landscape, with only a minor contribution from pine. Moreover, the pollen record from OST1 corroborates the absence of *Corylus* in the surroundings of both palaeolakes OST2B and OST1 during the Preboreal, as well as the appearance of *Ulmus* (Fig. 23; Kittel et al., 2025).

In the reference sediments of Lake Mały Suszek (Miotk-Szpiganowicz, 1992), the Preboreal is represented by the *Pinus*-*Betula* LPAZ (1,125–1,100 cm) and the *Pinus*-*Betula*-*Corylus* LPAZ (1,100–970 cm). For the *Pinus*-*Betula*-*Corylus* LPAZ, one radiocarbon date of 9,320±180 BP (10,737–10,249 cal BP) was obtained.

Comparison of pollen records from lakes OST2B (Fig. 23) and Mały Suszek (Miotk-Szpiganowicz, 1992) reveals both similarities and marked differences in Preboreal vegetation development. In both areas, the Preboreal was characterised by a pronounced decline in *Juniperus*, a reduction in NAP, and the appearance of *Ulmus* (continuous *Ulmus* curves reaching up to 3.1% in the Mały Suszek core and 0.6–0.1% in the OST2B core).

However, the surroundings of Lake Mały Suszek were distinguished by very high *Pinus* values (up to 57%), and by relatively low proportions of *Betula*. Moreover, *Corylus* expanded in the Lake Mały Suszek area already during the Early Preboreal, considerably

earlier than in Ostrowite area, where it appeared only during the Boreal. A similar pattern was observed for *Quercus* and *Alnus*, which reached the Lake Mały Suszek area in the Late Preboreal (Miotk-Szpiganowicz, 1992) but appeared near Ostrowite only during the Boreal (continuous curves in Fig. 23). Another difference was that during the second half of the Preboreal, *Ulmus* was considerably more abundant in the forests surrounding Lake Mały Suszek (pollen curve up to 3.1%) than in those near Lake OST2B (up to 0.6%) (Fig. 23; Miotk-Szpiganowicz, 1992).

These differences are most likely related to contrasting geological structure. During Preboreal climatic warming, the morainic substrate in Ostrowite (Fig. 18B) favoured the dominance of *Betula* and the development of open-canopy birch forests (Fig. 23). In contrast, well-drained glaciofluvial sands and gravels surrounding Lake Mały Suszek (Miotk-Szpiganowicz, 1992) promoted the rapid spread of *Pinus*, *Corylus*, and *Ulmus*, and later also *Quercus* and *Alnus*. As a result, in the second half of the Preboreal the surroundings of Lake Mały Suszek were already characterized by mature, closed-canopy pine-broadleaf forests (composed of pine, birch, elm, oak, and hazel; according to Miotk-Szpiganowicz, 1992), whereas throughout the entire Preboreal period the moraine landscape in Ostrowite was dominated by open-canopy birch forests (Fig. 23; Kittel et al., 2025).

Thus, the comparison shows that the geological structure of catchment played an important role in controlling tree and shrub succession during the Early Holocene. It should be noted that the role of geological substrate (soil chemistry and soil physics, including the lithological features of the substrate) in controlling vegetation succession has been previously recognized by Burga et al. (2010), Chiverrell et al. (2023), Ramskogler et al. (2023), and Tanner et al. (2023, 2024).

4.4 Boreal (211–82.5 cm; OS-4 LPAZ; MO-4 LMAZ), modelled age: from 10,536–10,049 to 8,863–8,072 cal BP

A substantial part of the deposits studied in the OST2B core was accumulated during the Boreal period (Figs. 22A and 22B). Throughout the Boreal, carbonate sediments were deposited in Lake OST2B, with a noticeable increase in CaCO₃ content toward the end of the period (at a depth of 102–82.5 cm; Fig. 22A). This rise in calcium carbonate content may reflect more humid climatic conditions during the Late Boreal. Increased humidity likely enhanced the leaching of carbonates from the catchment, which were subsequently supplied to the lake sediments through the activity of *Chara* algae (Fig. 24) (Pełechaty et

al., 2013; Pukacz et al., 2014; Dobrowolski et al., 2015; Kittel et al., 2025). This part of the OST2B profile was also distinguished by the highest average sedimentation rate (Fig. 22B).

An increase in the CaCO₃ content toward the end of the Boreal is also observed in sediments from the adjacent palaeolake OST1, at depths of approximately 300–250 cm b.g.l., dated to the interval from 9,310–9,175 to 9,058–8,769 cal BP (Kittel et al., 2025). It should be emphasized that the authors of the study based on the OST1 core applied a subdivision of the Holocene after Starkel et al. (2013), which differs from the chronological framework used in the present study (Table 5). Consequently, according to our interpretation, the Boreal period should also include part of the OST1 core that was assigned to the Early Atlantic, i.e. the *Betula-Corylus-Cyperaceae* LPAZ (~380–255 cm), dated to the interval from 9,698–9,479 to 9,140–8,913 cal BP (Kittel et al., 2025).

Additional evidence for more humid climatic conditions during the Late Boreal comes from the Lake Sporovskoye basin, where the Late Boreal marks the onset of a new and stable lake transgression (see Chapter 1).

During the Boreal, Lake OST2B was heavily overgrown with aquatic vegetation, primarily *Nymphaea*, *Najas marina*, and *Chara* (Figs. 23 and 24). The expansion of *Chara* algae (Fig. 24) suggests hard-water conditions (Pełechaty et al., 2013; Pukacz et al., 2014).

The nearshore vegetation was dominated by Cyperaceae, represented mainly by *Cladium mariscus* and *Carex* species (Figs. 23 and 24). In addition, a significant part of the nearshore area was occupied by *Typha latifolia*, *Sparganium*-type, and *Menyanthes trifoliata* (Figs. 23 and 24). Throughout the Boreal, moist areas around Lake OST2B were densely overgrown with *Betula*, as evidenced by numerous macrofossils of *Betula* sect. *Albae* and *Betula pubescens* (Fig. 24). Consequently, the high *Betula* pollen values observed during the Boreal most likely reflect a strong local signal that overrepresents the regional importance of birch (Fig. 23).

The Boreal was a period during which closed-canopy pine-broadleaf forests consisting of pine, birch, elm, oak, and hazel formed in the Lake OST2B area. The transformation from open-canopy birch forests to closed-canopy pine-broadleaf forests occurred gradually.

LPAZ OS-4a (Early Boreal; 211–178 cm; modelled age: from 10,536–10,049 to 9,912–9,634 cal BP)

At the very beginning of the Boreal, open-canopy birch forests still dominated the landscape, although their extent was reduced compared to the Preboreal (Fig. 23). At the

same time, the area occupied by small, localized patches of relatively dense forest slightly increased. This is indicated by increased abundances of *Ulmus* and *Pinus*, as well as by the appearance of *Corylus* in the study area (the onset of the continuous curve), which formed a shade-tolerant shrubby understorey within these denser forest patches (Fig. 23; Table 8).

In the reference core OST1 (Kittel et al., 2025), the Early Boreal corresponds to the *Betula*-Polypodiaceae LPAZ (445–380 cm), which is dated according to the age-depth model to the interval between 10,587–10,010 and 9,698–9,479 cal BP. The Early Boreal pollen records from cores OST1 and OST2B are very similar. The Early Boreal sediments of core OST1 are also characterized by high values of *Betula*, the appearance of *Corylus*, and increased abundances of *Ulmus* (Kittel et al., 2025).

LPAZ OS-4b (Middle Boreal; 178–138 cm; modelled age: from 9,912–9,634 to 9,465–9,275 cal BP)

During the transitional Middle Boreal period, a large closed-canopy pine-broadleaf forest developed in the study area. The extent of this forest steadily increased throughout the Middle Boreal. This is evidenced by rising values of *Corylus* (3.5–8.7%), high values of *Pinus* and *Ulmus*, and the onset of *Quercus* expansion (Fig. 23; Table 8). The establishment of a closed forest canopy is chiefly reflected in the spread of *Corylus* (Fig. 23), a shade-tolerant understorey shrub capable of regeneration under low-light conditions (Catoni et al., 2015; Franzén et al., 2025).

In the reference core OST1 (Kittel et al., 2025), the Middle Boreal corresponds to the lower part of the *Betula*-*Corylus*-Cyperaceae LPAZ (approximately 380–310 cm b.g.l.), which is dated, according to the age-depth model, to the interval between 9,698–9,479 and 9,348–9,216 cal BP. The Middle Boreal pollen records from cores OST1 and OST2B are again very similar. The Middle Boreal sediments of core OST1 are also characterized by a gradual increase in *Corylus*, the appearance of *Quercus*, increasing *Ulmus*, high *Pinus* values, and very abundant *Betula* (Kittel et al., 2025).

LPAZs OS-4c and OS-4d (Late Boreal; 138–82.5 cm; modelled age: from 9,465–9,275 to 8,863–8,072 cal BP)

During the Late Boreal, the regional moraine landscape was dominated by mature closed-canopy pine-broadleaf forests. This is indicated by very high values of *Corylus* (up to 13.9%), high *Ulmus* values, together with the presence of *Quercus*. During this period, moist areas around Lake OST2B became colonized by *Alnus* (Figs. 23 and 24; Table 8).

In the reference core OST1 (Kittel et al., 2025), the Late Boreal corresponds to the upper part of the *Betula-Corylus-Cyperaceae* LPAZ (approximately 310–255 cm b.g.l.), which is dated, according to the age-depth model, to the interval between 9,348–9,216 and 9,140–8,913 cal BP. The Late Boreal pollen records from cores OST1 and OST2B are again very similar. The Late Boreal sediments of core OST1 are also characterized by high values of *Corylus* and *Ulmus*, an increase in *Quercus*, and the appearance of *Alnus* (Kittel et al., 2025).

In the reference sediments of Lake Mały Suszek, the Boreal period corresponds to the lower part of the *Pinus-Betula-Corylus-Alnus* LPAZ (approximately 970–870 cm of the core), which is dated by two radiocarbon dates of 8,900±170 BP (10,215–9,755 cal BP; correlates with the Early Boreal LPAZ OS-4a in the OST2B core) and 7,850±140 BP (8,979–8,484 cal BP; Late Boreal / Early Atlantic transition) (Miotk-Szpiganowicz, 1992). During the Boreal, pine-broadleaf forests in the vicinity of Lake Mały Suszek experienced a pronounced increase in *Quercus*. With the onset of the Boreal (around 10,215–9,755 cal BP), *Alnus* rapidly spread in moist habitats around Lake Mały Suszek (Miotk-Szpiganowicz, 1992).

Thus, these observations indicate a distinct temporal lag in forest development. Mature, closed-canopy pine-broadleaf forests (characterized by high *Corylus* values and a substantial contribution of *Ulmus* and *Quercus*) were already established on the glaciofluvial deposits near Lake Mały Suszek during the Late Preboreal (Miotk-Szpiganowicz, 1992). In contrast, on the moraine plateau around lakes OST2B and OST1, similar forest communities developed only during the Late Boreal (LPAZs OS-4c and OS-4d in Fig. 23; Kittel et al., 2025). Considering the Late Preboreal age of 10,737–10,249 cal BP from the Mały Suszek sequence and the Late Boreal age of 9,141–8,780 cal BP from the OST2B core, this lag may have been on the order of ~1,000 years (Fig. 23; Miotk-Szpiganowicz, 1992).

4.5 Atlantic (82.5–59 cm; OS-5 LPAZ; MO-5 LMAZ), modelled age: from 8,863–8,072 to 8,163–7,300 cal BP, period of Mesolithic groups penetration

The accumulation of calcareous and clayey-calcareous gyttja continued during the first half of the Atlantic period (Figs. 22A, 22B). Increased climatic humidity during this interval is inferred from the very high calcium carbonate content recorded in the OS-5 LPAZ sediments (absolute maximum; Fig. 22A), resulting from enhanced leaching of carbonate sediments in the catchment area and the biological activity of *Chara* algae

(Pelechaty et al., 2013). At the very beginning of the Atlantic period, large amounts of carbonate sediments were also deposited in Lake OST1 (deposits at depths of approximately 255–200 cm dated to the interval between 9,140–8,913 and 8,194–8,035 cal BP in Kittel et al., 2025).

During the formation of the OS-5 LPAZ in the first half of the Atlantic, the lake littoral periodically dried out, as indicated by the high abundance of corroded pollen and undeterminable pollen and spores (Fig. 23). These results show that not only peat (as proposed by Tobolski, 2021), but also gyttja can exist between high and low water levels in the lake (limno-terrestrial conditions), being periodically subjected to drying and aeration. As can be seen, these periodic desiccations of the littoral areas with gyttja deposits did not result in peat accumulation, as evidenced by the absence of wetland and nearshore vegetation succession in the OS-5 LPAZ. This was probably due to the short duration of such drying episodes and large oscillations of the water table, as well as the presence of a carbonate substrate that was unfavourable for the development of a mire vegetation and peat accumulation.

Periodic desiccation apparently affected only part of the littoral zone, not the entire Lake OST2B. For most of the time, however, the OS-5 deposits were under aquatic conditions, as evidenced by: (1) high abundances of *Chara* and *Pediastrum*, along with the presence of *Najas marina*, *Potamogeton*, *Nymphaea*, *Utricularia*, and *Lemna* pollen and macrofossils (Figs. 23 and 24); and (2) low organic matter content combined with very high carbonate values, reaching an absolute CaCO_3 maximum (Fig. 22A).

The shoreline zone was inhabited by *Typha latifolia*, *Sparganium*-type, *Oenanthe aquatica*, as well as Cyperaceae, among which *Schoenoplectus lacustris* and *Cladium mariscus* were particularly prominent (Figs. 23 and 24). The nearshore area was also colonized by *Rorippa palustris* and *Stellaria palustris* (Fig. 24). Moist areas near the lake were occupied by alder and willow (Fig. 23).

Regional closed-canopy forests during the first half of the Atlantic were composed mainly of pine, oak, elm, as well as hazel in the understorey (Fig. 23; Table 8).

During the first half of the Atlantic (OS-5 LPAZ), the area surrounding Lake OST2B was intensively used by Mesolithic communities, belonging to the Komornica culture or to Chojnice-Pienki culture (Kittel et al., 2025). These prehistoric communities may have cleared birch stands around Lake OST2B in order to facilitate access to the lake and its resources, as indicated by a sharp decline in *Betula* pollen and a pronounced increase in NAP values, with an absolute maximum of Poaceae (Fig. 23; Table 8). Such local

deforestation is also indicated by the abrupt disappearance of *Betula* macrofossils (MO-5 LMAZ; Fig. 24). The frequent presence of these Mesolithic societies along the lakeshore is indicated by very high amounts of pollen and macrofossils of ruderal nitrophilous plants, such as *Urtica*, *Chenopodiaceae*, and *Artemisia* (Figs. 23 and 24; Table 8). In this case, the presence of substantial amounts of pollen and macrofossils of *Ranunculus sceleratus*, *Ranunculus acris*-type, *Ranunculaceae*, and *Rumex acetosa-acetosella* most likely also indicates ruderal conditions (Figs. 23 and 24).

In the reference OST1 core, the first half of the Atlantic period corresponds to the *Quercus-Alnus-Corylus-Ulmus* LPAZ (~255–172 cm), dated to the interval between 9,140–8,913 and 7,429–7,338 cal BP (Kittel et al., 2025). The pollen record from the OST1 core is in good agreement with that from the OST2B core. The OST1 sequence also shows a marked increase in *Quercus*, an absolute maximum of *Corylus*, and high values of *Ulmus* and *Alnus*. At the same time, a decline in *Betula*, an increase in herbaceous taxa (particularly *Poaceae* and *Artemisia*), and a rise in synanthropic plants are observed (Kittel et al., 2025). These patterns provide additional evidence for intense activity of Mesolithic communities in the vicinity of both small lakes OST1 and OST2B, including birch clearance and the development of ruderal environments.

In the reference Mały Suszek core, the first half of the Atlantic period corresponds to the upper part of the *Pinus-Betula-Corylus-Alnus* LPAZ and the lower part of the *Pinus-Betula-Corylus-Alnus-Ulmus* LPAZ (Miotk-Szpiganowicz, 1992). A radiocarbon date of 7,180±130 BP (8,171–7,867 cal BP) was obtained for the *Pinus-Betula-Corylus-Alnus-Ulmus* pollen zone. Both zones are characterized by high abundances of *Ulmus*, *Quercus*, and *Corylus* (Miotk-Szpiganowicz, 1992), which are in good agreement with the data from the OST2B and OST1 cores.

The first half of the Atlantic period ended with a very long break in sedimentation in the OST2B depression. Evidence for this long-lasting depositional hiatus is provided by radiocarbon dates of 8,173–7,965 cal BP from ca. 72.5 cm and 654–553 cal BP from ca. 57.5 cm of the profile, which were obtained from closely spaced depths but display a substantial age gap (Fig. 23; Table 6). This hiatus was most likely related to the complete desiccation and the temporary disappearance of Lake OST2B.

It is noteworthy that, after the disappearance of Lake OST2B, the OST1 depression transformed into a wetland approximately 7,220–7,029 cal BP (Kittel et al., 2025). The OST1 wetland persisted during the second half of the Atlantic period, and likely for some time into the Subboreal period, as indicated by the age-depth model (interval between

5,718–5,582 cal BP and 5,627–901 cal BP, according to the prob. 95.4%) (Kittel et al., 2025). Overall, the OST1 core provides a poor record of the Subboreal and Subatlantic periods, which are represented by a small volume of sediments lacking radiocarbon age control.

4.6 Subatlantic (59–0 cm; mixing horizon; OS-6 LPAZ; MO-6 LMAZ), modelled age: after 660–554 cal BP

The long-lasting depositional hiatus ended during the Late Middle Ages. Most likely, water returned to the OST2B depression approximately 660–554 cal BP (1,290–1,396 cal AD) (Fig. 22B). Initially, this led to the redeposition of the uppermost part of the Atlantic calcareous and clayey-calcareous gyttja and its mixing with newly supplied organic matter. As a result of these processes, a mixing horizon was formed in the OST2B depression (Fig. 22A, at a depth of 59–53 cm). According to the age-depth model, its formation occurred between 660–554 and 665–500 cal BP (Fig. 22B). Apparently, the mixing horizon was formed in response to increased climatic humidity and/or to anthropogenic landscape transformation (e.g. forest clearance, agricultural development).

OS-6a LPAZ and MO-6a LMAZ (53–33 cm), period of arable agriculture

Subsequently, approximately 665–500 cal BP (1,285–1,450 cal AD), during the Late Middle Ages, a water body developed in the OST2B depression, in which the stable accumulation of fine detritus and clayey gyttja with high organic matter content (often exceeding 40%) and low carbonate concentrations began (Figs. 22A, 22B). These sediments were deposited in a lacustrine environment affected by periodic desiccation. During exposure phases, oxygen penetrated the gyttja, as reflected by high proportions of corroded pollen and undeterminable pollen and spores (Fig. 23). A decline in *Pediastrum* further indicates frequent drying events (Fig. 23). Desiccation probably affected only part of the littoral zone near the coring site, while the lake as a whole did not dry out. These findings once again demonstrate that between high and low water levels not only peat (as suggested by Tobolski, 2021) but also gyttja can occur.

Despite these short-term desiccation episodes, the deposits of pollen zone OS-6a were formed predominantly under aquatic conditions, as evidenced by the high abundance of pollen and macrofossils of aquatic plants. *Myriophyllum verticillatum* was particularly abundant, along with the presence of *Potamogeton*, *Chara*, *Utricularia*, *Nymphaea*, *Nuphar*, and *Lemna* (Figs. 23 and 24). Nevertheless, Lake OST2B was likely smaller in

size, as indicated by increased frequencies of *Sphagnum* spores and coprophilous and soil-related fungi, including *Sporormiella*-type, *Sordaria*-type, *Podospora*-type, *Glomus* cf. *fasciculatum*, *Chaetomium*, and *Diporotheca* (Fig. 23).

The nearshore area was overgrown with Cyperaceae, *Typha latifolia*, and *Sparganium*-type (Fig. 23). A substantial part of the nearshore zone was covered by *Sphagnum* (Fig. 23). Moist areas around the lake were increasingly colonized by alder (Fig. 23).

Around 665–500 cal BP (1,285–1,450 cal AD), during the Late Middle Ages, the land surrounding Lake OST2B was primarily used for cereal cultivation, as indicated by the appearance of *Cerealia* undiff. and *Secale cereale* pollen (Fig. 26), along with arable weeds such as *Polygonum persicaria*-type and Brassicaceae (Fig. 23). Intense human activity maintained a significant part of the surrounding landscape treeless, as reflected by high herb pollen (NAP) values, particularly Poaceae (Fig. 23). The mosaic pattern of the landscape, with forest patches alternating with open areas, is further suggested by the reappearance of light-demanding *Juniperus* (Fig. 23).

Regional forests were composed mainly of pine and oak, with a significant admixture of elm, linden, and ash, as well as hazel in the understorey (Fig. 23).

OS-6b LPAZ and MO-6b LMAZ (33–0 cm), period of extensive arable agriculture, possible mixing of the uppermost part of the profile due to ploughing of the former reservoir area

Determining the age of the onset of sediment accumulation in the OS-6b LPAZ is problematic because these deposits have been continuously affected by modern agricultural ploughing, resulting in their mixing, as indicated by Google Earth satellite image (Fig. 20A). The radiocarbon age of 1–41 (1,954–2,006 cal AD) from a depth of 30.5–34 cm was most likely obtained from redeposited macrofossil material displaced by ploughing (Table 6). Nevertheless, it can be assumed that the OS-6b pollen zone was formed during the Modern Period and Contemporary era.

During OS-6b formation, Lake OST2B decreased significantly in size, probably due to overgrowth and infilling of the lake depression with sediments. Telmatic peat began to accumulate around the coring site, as evidenced by the dominance of wetland vegetation (Cyperaceae, *Sphagnum*, and *Stellaria palustris*) and a small admixture of aquatic plants (*Chara*, *Potamogeton*, *Myriophyllum verticillatum*, *Nymphaea*, *Nuphar*, and *Lemna*;

Figs. 23 and 24). This small admixture of aquatic plant remains indicates that, despite its reduced size, Lake OST2B still existed during OS-6b formation.

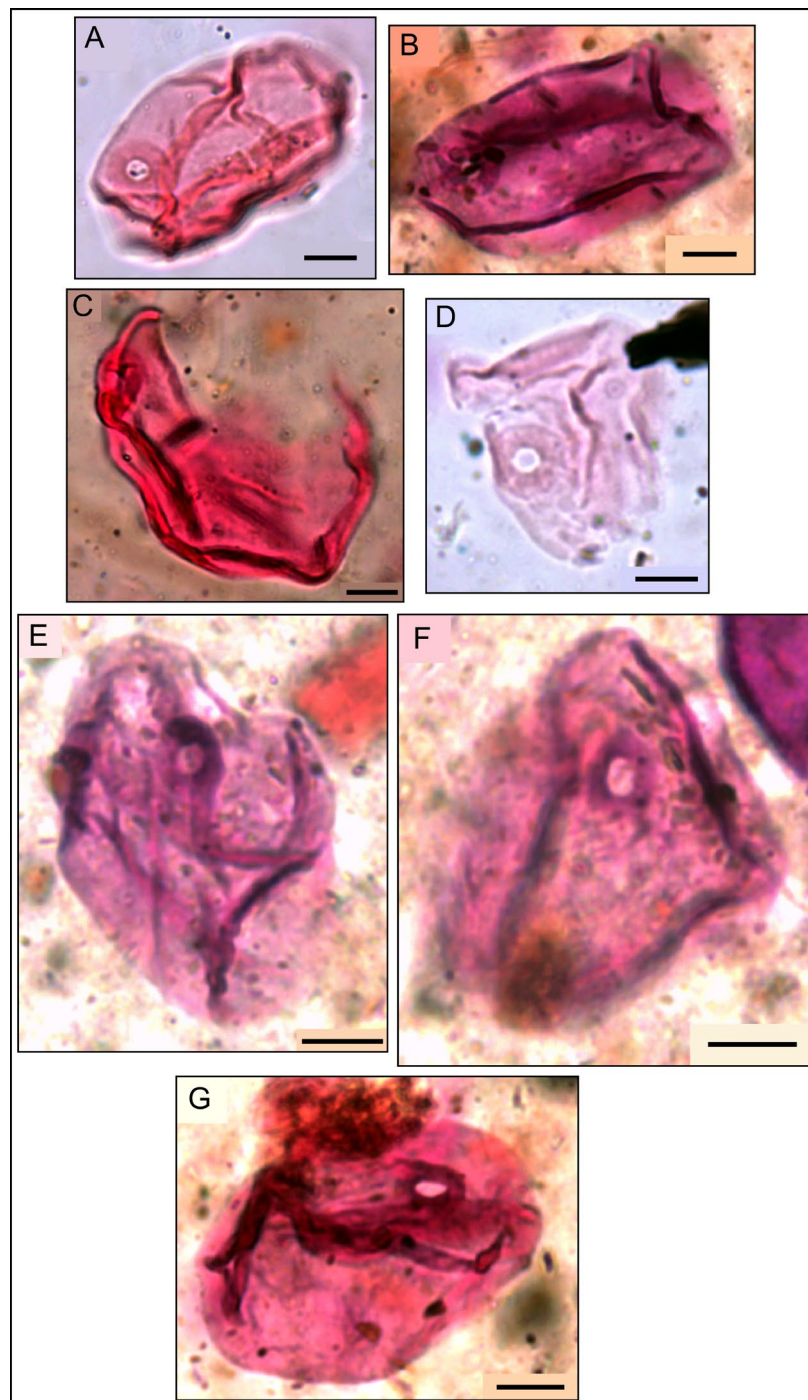


Fig. 26. Selected pollen grains of cultivated plants from the OST2B core (photos by D. Tsvirko). The pollen grains are strongly corroded and damaged. A – *Secale cereale* (sample depth 25 cm); B – *Secale cereale* (50 cm); C – *Cerealina undiff.* (5 cm); D – *Cerealina undiff.* (25 cm); E, F – *Cerealina undiff.* (30 cm); G – *Cerealina undiff.* (50 cm). Scale bars = 10 μm for all specimens

It is likely that, further overgrowth transformed the lake completely into a wetland, and telmatic peat accumulation was replaced by fen or bog peat deposition. Pollen assemblages, however, indicate the presence of aquatic plant remains in the upper part of the OS-6b LPAZ (Fig. 23). This can probably be explained by agricultural ploughing and mixing of sediments, as a result of which some aquatic plant remains were redeposited into the upper layers of the OS-6b zone.

Increased amounts of corroded pollen and undeterminable pollen and spores indicate frequent oxygen penetration into the peat deposits (Fig. 23). The onset of peat accumulation led to the deposition of large quantities of remains of coprophilous and soil-related fungi, particularly *Sporormiella*-type, *Sordaria*-type, *Podospora*-type, *Glomus* cf. *fasciculatum*, *Chaetomium*, and *Diporotheca* (Fig. 23). The high abundance of *Glomus* cf. *fasciculatum* spores in the telmatic peat layer (Fig. 23) likely reflects colonisation of wetland plant roots by these fungi rather than soil erosion (Kołaczek et al., 2013). *Pediastrum* algae were nearly absent in the peat deposits (Fig. 23).

The most distinctive feature of the OS-6b zone is the record of modern extensive arable agriculture and the associated deforestation. Large-scale deforestation is suggested by reduced values of *Quercus*, *Ulmus*, *Tilia*, *Fraxinus*, and *Corylus*, along with increased *Pinus* and high herb (NAP) proportions (Fig. 23). Expansion of open, treeless areas is also indicated by increased *Juniperus* pollen values (Fig. 23).

The main purpose of large-scale deforestation was to increase the area of arable land. This is evidenced by very high amounts of *Cerealia* undiff. and *Secale cereale*, the presence of *Fagopyrum*, and associated arable-field weeds, particularly very high abundances of Brassicaceae and *Centaurea cyanus*, as well as the presence of *Polygonum persicaria*-type, *Polygonum aviculare*, *Polygonum lapathifolium*, and *Scleranthus* (Figs. 23 and 24). Some arable fields were likely periodically left fallow, as suggested by frequent presence of *Plantago lanceolata*, *Rumex acetosa-acetosella* and *Ranunculus* cf. *repens* pollen and macrofossils (Figs. 23 and 24).

Ploughing of large areas led to enhanced slope erosion (Zalinian et al., 2025) and, consequently, to the delivery of a significant amount of sand into the peat deposits (Fig. 22A).

Following large-scale deforestation, regional forests consisted mainly of pine, with minor oak and hazel contributions (Fig. 23). Moist areas near the OST2B wetland were colonized by alder (Fig. 23).

In the reference core OST1, the Late Subatlantic is most likely represented by the *Pinus*-Liguliflorae LPAZ (Kittel et al., 2025). This zone is characterized by high *Pinus* values, increased abundances of herbaceous taxa, and numerous indicators of human activity (including cultivated and synanthropic plants), together with low *Corylus* values and relatively high amounts of *Quercus*. The *Pinus*-Liguliflorae LPAZ identified in core OST1 probably correlates with the OS-6 LPAZ in core OST2B (Fig. 23). However, the absence of radiocarbon age control and the limited sediment thickness of the *Pinus*-Liguliflorae LPAZ prevent a reliable correlation between these zones.

In the reference Mały Suszek core, the Late Subatlantic is represented by the *Pinus* LPAZ (Miotk-Szpiganowicz, 1992), which is characterized by high *Pinus* values, elevated proportions of herbaceous taxa, and numerous indicators of human activity (including a large amount of *Cerealia* pollen), accompanied by low *Corylus* and *Ulmus* values, relatively high *Quercus* values, and increasing *Juniperus*. The *Pinus* LPAZ from the Mały Suszek core probably correlates with the OS-6 LPAZ in the OST2B core (Fig. 23). However, the absence of radiocarbon dates prevents a reliable correlation between these two zones.

It should also be noted that the Subatlantic sediments of Lake Mały Suszek contained substantial amounts of *Carpinus* and *Fagus* pollen (Miotk-Szpiganowicz, 1992). During the Late Subatlantic (*Pinus* LPAZ), the abundances of these taxa in the Mały Suszek core decreased significantly (e.g. *Carpinus* values of 1–3%; Miotk-Szpiganowicz, 1992). A similarly pronounced decline in *Carpinus* and *Fagus*, accompanied by an increase in *Cerealia* pollen, is observed in the Late Subatlantic deposits of Lake Wielkie Gacno, dated by a single radiocarbon age of 780±50 BP (728–673 cal BP; Hjelmroos-Ericsson, 1981a). It should be noted that Lake Wielkie Gacno (53°47'34.06"N 17°33'35.77"E) lies on a glaciofluvial plain, approximately 17 km NW of the palaeolake OST2B. Thus, the absence or occurrence of only sporadic *Carpinus* and *Fagus* pollen grains in the Late Subatlantic deposits of cores OST2B and OST1 (OS-6 and *Pinus*-Liguliflorae LPAZs, respectively; Fig. 23; Kittel et al., 2025) can most plausibly be explained by human economic activity and extensive forest clearance.

CONCLUSIONS

1. Increased proportions of corroded pollen (perforated) may indicate a wetland origin of the organic deposits and can therefore serve as an indicator of telmatic accumulation with episodes of water level decline and desiccation. Such

processes were also recognised in basal peat. However, a high abundance of corroded pollen cannot always be interpreted as evidence of wetland conditions, as a large amount of corroded pollen may also occur in gyttja deposits due to periodic desiccation of the lake littoral zone (resulting from a significant drop in water level) and subsequent oxygen penetration into the dried gyttja horizon.

2. A large number of undeterminable pollen and spores (mechanically damaged or deformed) may also indicate sediment aeration and periods of repeated wetting and drying. The undeterminable pollen curve visually corresponded to the corroded pollen curve. Accordingly, a high abundance of undeterminable pollen and spores may serve as an indicator of telmatic peat accumulation, but this should be interpreted with caution because the number of undeterminable pollen and spores can also be elevated in gyttja subject to periodic aeration. A similar pattern was observed in the basal peat.
3. A large number of coprophilous and soil-related fungi, including *Sporormiella*-type, *Sordaria*-type, *Podospora*-type, *Glomus* cf. *fasciculatum*, *Cercophora*-type, *Chaetomium*, and *Diporotheca*, can serve as an indicator of telmatic peat sedimentation. In basal peat, the values of these taxa were also increased. In addition, a relatively small amount of *Pediastrum* algae may also serve as an indicator of telmatic peat accumulation.
4. The telmatic zone of a lake should not be considered merely as a zone between high and low water levels, as proposed by Tobolski (2021), but rather as a zone characterized by well-developed wetland and nearshore vegetation. As our results on the sediments of the palaeolake OST2B show, gyttja can also exist between high and low water levels. Telmatic peat should be primarily defined as deposits dominated by pollen and macrofossils of nearshore and wetland vegetation (especially Cyperaceae), with a minor admixture of aquatic plant remains (for example, *Nuphar*, *Nymphaea*, *Potamogeton* and others). In contrast, gyttja deposits were characterized by a high abundance of pollen and macrofossil remains of aquatic plants and a reduced proportion of wetland and nearshore vegetation.
5. Based on data from the OST2B core, environmental reconstructions were carried out starting from the Allerød period. The study primarily focused on reconstructing changes in both regional and local vegetation, as well as in the

types of sediments deposited in the palaeolake OST2B. The obtained results were compared with data from other well-studied sites.

6. Three phases of anthropogenic activity were identified in the vicinity of palaeolake OST2B based on the ecological grouping of human-activity indicators. The first phase was characterized by the activity of Mesolithic communities (either the Komornica culture or the Chojnice-Pienki culture), which is reflected in birch clearance and the spread of ruderal habitats in the immediate vicinity of palaeolake OST2B. The second phase involved arable farming near the palaeolake, carried out by Late Medieval communities. The third phase was marked by very extensive arable cultivation and large-scale deforestation in the OST2B catchment by Modern Period and Contemporary era societies.
7. The pollen records from the palaeolakes OST2B and OST1, situated on a moraine plateau, show a very high degree of similarity and are almost identical in terms of the development of plant cover.
8. Pollen records from cores OST2B and Mały Suszek reveal substantial differences in vegetation succession during the Late Weichselian and the Holocene, most likely controlled by catchment geology. Glaciofluvial substrates favoured early pine expansion (Allerød, Late Younger Dryas, Preboreal) and the earlier development of closed-canopy pine-broadleaf forests (Late Preboreal), whereas morainic deposits promoted open-canopy birch forests (Allerød, Preboreal), open treeless areas (Younger Dryas), and delayed forest canopy closure until the Late Boreal. Apparently, these differences in vegetation succession can be explained by differences in soil chemical and physical properties, including the different lithology of the substrate.
9. Temporal delays in the succession of certain taxa (e.g., *Corylus* and *Quercus*) observed in the deposits of lakes OST2B and Mały Suszek underscore the importance of correlating sediment cores using radiocarbon-based depth/age models, since pollen-based correlations alone may not always be reliable.

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CHAPTER IV

FINAL REMARKS AND CHALLENGES OF THE RESEARCH PROCESS

The author's experience shows that great caution is required when interpreting the origin of biogenic and organo-mineral deposits in areas where their formation is influenced by processes occurring in fluvial, lacustrine, and wetland environments and by human activity. Such conditions were observed in the vicinity of the Kakoryca-4 archaeological site, where sediment formation was affected by the activity of the Yaselda River, the dynamics of Lake Sporovskoye, and wetland processes.

The principal challenge of this PhD thesis was the interpretation of the origin of deposit layers a₄ and a₃ located north of the Kakoryca-4 archaeological site (Figs. 6B and 7; Fig. S16; Chapter 1). On the one hand, these deposits contained a mixture of macrofossils of nearshore and wetland vegetation, as well as aquatic plants (Fig. 7 in Chapter 1). For this reason, the author initially classified them as telmatic peat deposits. Unit a₄ was interpreted as black telmatic peat with a significant admixture of sand and silt, whereas unit a₃ was classified as brown telmatic peat with a significant admixture of silt (Appendix 2; Tsvirko et al., 2024). The initial hypothesis suggested that units a₄ and a₃ were formed in a shallow telmatic environment influenced by lacustrine, wetland, and alluvial processes. According to consultations with specialists in plant macrofossil analysis, these deposits could be interpreted as shallow lacustrine or telmatic sediments.

On the other hand, the author was consistently concerned about the substantial admixture of mineral material, including fine-grained sand, in units a₄ and a₃, which indicated a strong influence of the Yaselda River on sediment accumulation. In unit a₄, loss on ignition (LOI) values were frequently below 30%, whereas in unit a₃ LOI values ranged approximately between 30 and 60% (Fig. 6B).

Ultimately, the author adopted the view that alluvial processes played the primary role in the formation of units a₄ and a₃. Accordingly, unit a₄ should be interpreted as overbank organic mud, while unit a₃ represents overbank peaty organic mud (Fig. 6B). The author maintains the interpretation that these organic muds a₄ and a₃ were accumulated in backswamp conditions during periods of intense flooding of the Yaselda River. Strong floods inundated the floodplain of the Yaselda River, leading to the formation of temporary surface water bodies in which aquatic vegetation (*Salvinia natans*, *Lemna*, *Stratiotes*

aloides, *Potamogeton*, etc.) and nearshore/wetland vegetation (*Typha*, *Alisma plantago-aquatica*, *Sagittaria sagittifolia*, Cyperaceae) developed (Fig. 7). Accordingly, the mixture of aquatic and nearshore/wetland macrofossils observed in units a₄ and a₃ can be explained by this interpretation. This mixture of remains also indicates the limno-terrestrial conditions that existed in the backswamp.

Thus, the interpretation of the origin of biogenic and organo-mineral deposits in river valleys should consider not only the taxonomic composition of plant macrofossils, but also the proportion of organic matter and the textural composition of the mineral fraction.

Another challenge in writing this dissertation concerned the reliable identification of Cerealia pollen and its differentiation from wild-growing Poaceae. In the author's earlier publications (Tsvirko, 2019a, 2019b; Tsvirko and Zernitskaya, 2019; Trifonov et al., 2020; Tsvirko et al., 2021a, 2021b), the identification of Cerealia pollen was based on the pollen grain size exceeding 40 µm according to Simakova (2003).

However, numerous consultations with specialists in pollen analysis revealed that Cerealia pollen should be identified not only by its large size (>40 µm) and relatively large annulus diameter (9–10 µm), but also by the distinct and sharply defined outline of the annulus (Tsvirko, 2023; see Fig. 16 in Chapter 2). As a result, it became evident that in some earlier publications (e.g., the Sporovo II core; Trifonov et al., 2020; Tsvirko et al., 2021a, 2021b; see also Fig. S21 in Chapter 1) the author had incorrectly identified Cerealia pollen, confusing it with pollen of wild-growing Poaceae, relying solely on pollen grain size following Simakova (2003) without considering the sharpness of the annulus boundary.

To improve the reliability of identification, the author assembled a personal reference collection of photomicrographs of Cerealia pollen from modern sediments of the Zarzetka oxbow lake (see Fig. 16 in Chapter 2). This collection served as comparative material for distinguishing Cerealia pollen from wild-growing Poaceae in sediments near the Kakoryca-4 and Ostrowite archaeological sites (Chapters 1 and 3).

It is worth noting that the pollen assemblages from the Sporovo II, Zarzetka, and OST2B cores show a certain degree of similarity (Figs. 10, 15, and 23 in Chapters 1–3). Several sediment horizons in these cores are characterised by high proportions of corroded pollen and undeterminable pollen and spores. This suggests that the deposits were formed under comparable environmental conditions. These conditions involved periodic and significant fluctuations of the water table and repeated partial or complete desiccation of the studied basins. Such processes allowed oxygen to penetrate the sediments, resulting in

corrosion and damage to pollen and spore grains (Fig. 25 in Chapter 3; Havinga, 1967; Twiddle and Bunting, 2010).

The author of this dissertation counted corroded pollen only for selected taxa – *Betula*, *Corylus*, and *Alnus* – in the Zarzetka and OST2B cores (Chapters 2 and 3). However, pollen of other taxa was also affected by corrosion, for example, *Cerealia* pollen from the uppermost deposits of the OST2B core (depth 0–50 cm b.g.l.; Figs. 23 and 26). This observation further supports the interpretation that the uppermost deposits of the OST2B core, which contain *Cerealia* pollen, were formed under conditions of frequent basin desiccation and pronounced water table fluctuations.

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GENERAL CONCLUSIONS

- 1) A model of the palaeogeographical evolution of the Kakoryca-4 site surroundings was constructed. For selected time periods, reconstructions of geological processes, regional and local vegetation, transgressions and regressions of Lake Sporovskoye, as well as phases of floods and erosional activity of the Yaselda River were elaborated. Possible responses of prehistoric societies to natural changes have been proposed (Chapter 1).
- 2) This dissertation research contributes to a better understanding of the process of Neolithisation in Eastern Europe. The author challenges previous pollen-based interpretations that suggested the presence of agriculture in Southern Belarus during the Late Mesolithic, the Early Neolithic, and throughout the “forest” Neolithic. These interpretations were most likely the result of the incorrect identification of *Cerealia* pollen and its confusion with pollen of wild-growing *Poaceae*.
- 3) On the basis of the literature review presented in this dissertation (see the Introduction), it can be concluded that the Kakoryca-4 archaeological site is currently the most comprehensively studied site in Belarus from the perspective of environmental archaeology. The author of this dissertation has made a significant contribution to the development of this discipline by conducting a multidisciplinary investigation of this site in Belarus.
- 4) The author of this dissertation has also contributed significantly to the development of palaeogeographical studies of Southern Belarus. In particular, a new interpretation of the origin of the so-called “lacustrine-alluvial” deposits – one of the most characteristic sediment types in this region – has been proposed. These deposits are interpreted as sediments formed by a sand-bed braided river (see Chapter 1). Furthermore, new interpretations of the transgression and regression phases of Lake Sporovskoye have been proposed based on the analysis of plant macro- and microfossils preserved in biogenic deposits.
- 5) The groups of human pollen indicators established on the basis of the literature review and the investigation of the Zarzetka core (Chapter 2) were subsequently applied in the pollen analysis of deposits from the Kakoryca-4 archaeological site (Chapter 1) and the Ostrowite archaeological site (Chapter 3).

- 6) Cerealia pollen grains from the Zarzetka core – their size measurements and visual characteristics documented in the collected photomicrographs – served as comparative reference material for identifying Cerealia pollen in deposits from the Kakoryca-4 and the Ostrowite archaeological sites. The comparison demonstrated that the Sporovo II core (Chapter 1) contained pollen grains of wild-growing Poaceae rather than Cerealia.
- 7) Pollen studies based on the OST2B and Zarzetka cores have shown that not only peat but also gyttja deposits can occur between high and low water levels in the lake (limno-terrestrial conditions), where they can be periodically subjected to drying and aeration. This was evidenced by the high proportion of corroded and undeterminable pollen in the gyttja deposits of the OST2B and Zarzetka cores. Periodic desiccation of littoral areas with gyttja deposits does not always result in peat accumulation. Therefore, the telmatic zone of a lake should not be defined solely as the area between high and low water levels, as suggested by Tobolski (2021), but rather as a zone characterised by well-developed wetland and nearshore vegetation (Chapters 2 and 3).
- 8) Limno-terrestrial conditions are likewise typical of floodplain backswamp environments, in which organic muds are deposited, containing a mixture of macrofossils of nearshore/wetland and aquatic vegetation (Chapter 4).
- 9) This research resulted in the identification of pollen and macrofossil indicators characteristic of peat and gyttja deposits (Chapters 1–3). Furthermore, sedimentological, geochemical, and plant macrofossil indicators of floodplain backswamp deposits were described based on the PKK-1-2 core (Chapters 1 and 4).

APPENDIX 1

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 km², 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

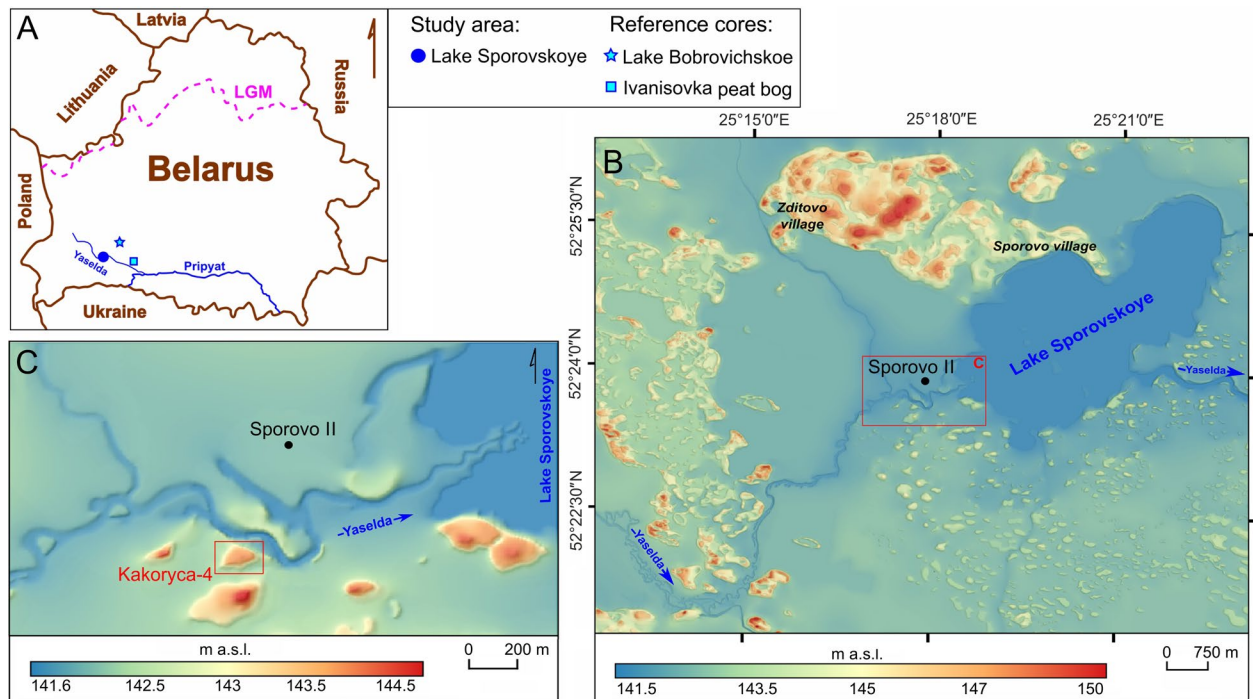


Figure 1. Location of the studied Sporovo II core in the basin of the Yaselda River and Lake Sporovskoye (B, C), beyond the border of the last glaciation (A), together with the location of reference spore-pollen cores of Lake Bobrovichskoe and the Ivanisovka peat bog (Trifonov, 2021; Tsvirko et al., 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 ($52^{\circ}23'36.657''\text{N}$, $25^{\circ}17'34.355''\text{E}$) provoked

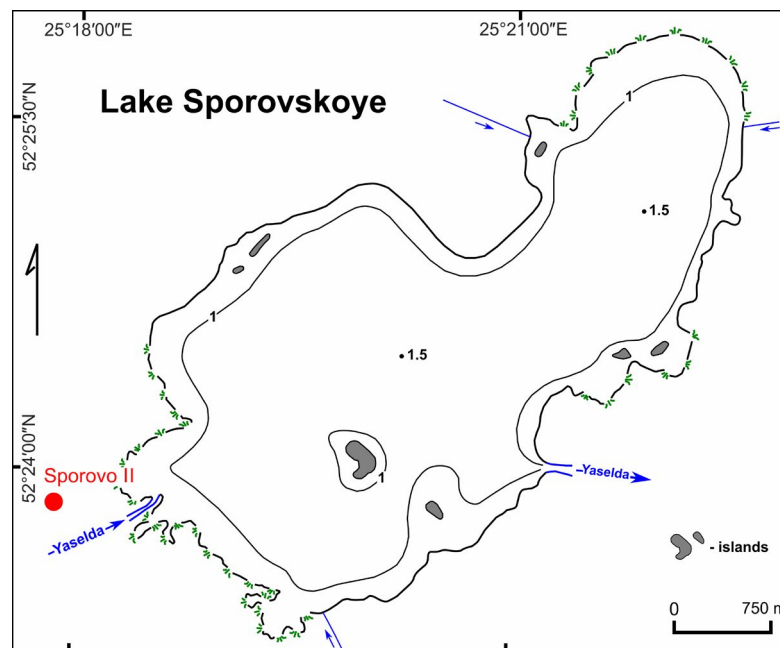


Figure 2. Bathymetric survey of Lake Sporovskoye, depths are given in meters (modified by the author based on Vlasov et al., 2004)

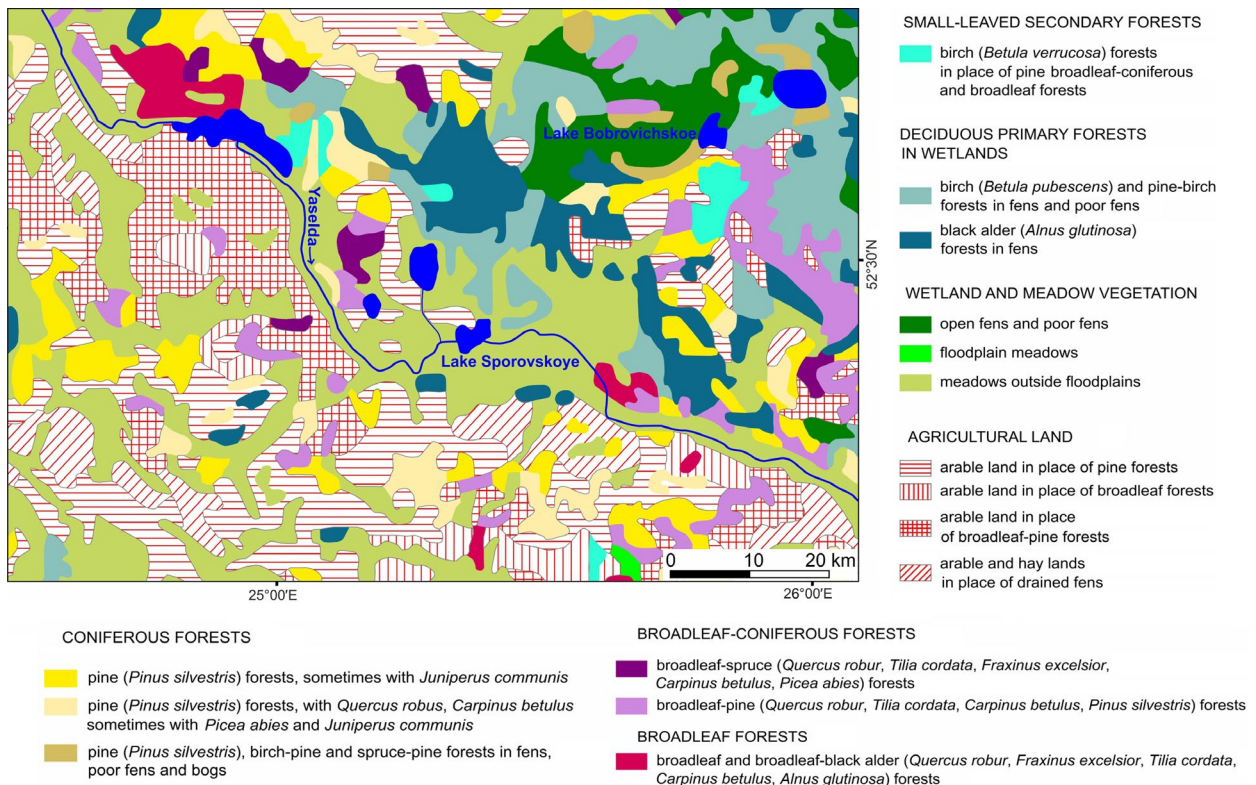


Figure 3. Map of modern vegetation in the vicinity of Lake Sporovskoye (modified by the author based on Natsionalnyi atlas Belarusi, 2002)

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 (TIn-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 Kako-ryca-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 palaeo-data 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 ($52^{\circ}23'52.797''N$ $25^{\circ}17'44.802''E$) 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

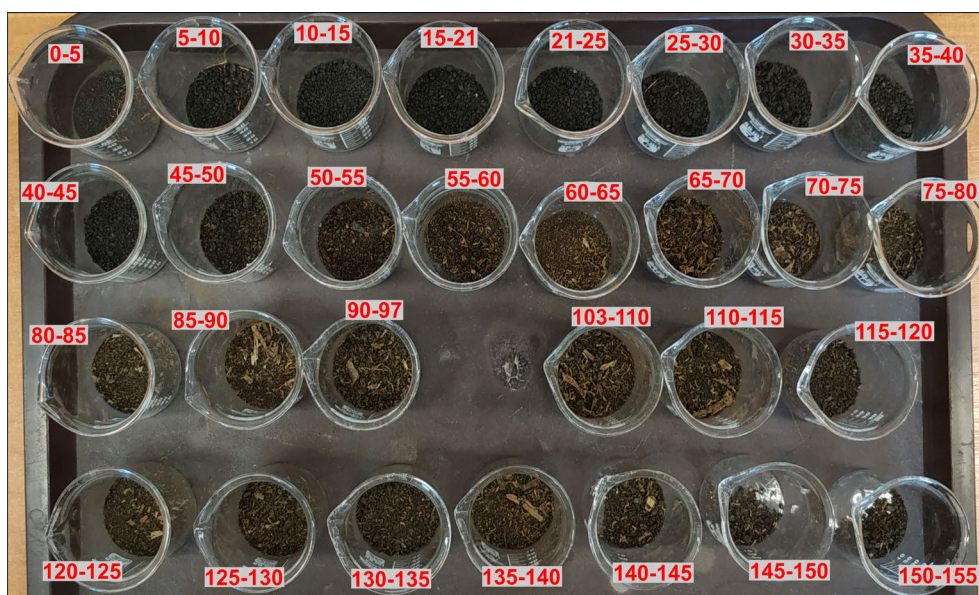


Figure 4. Organic samples from the Sporovo II core after drying at 50°C and grinding in a porcelain mortar; the upper peat samples (~0–50 cm) are darker in colour (photo by D. Tsvirko)

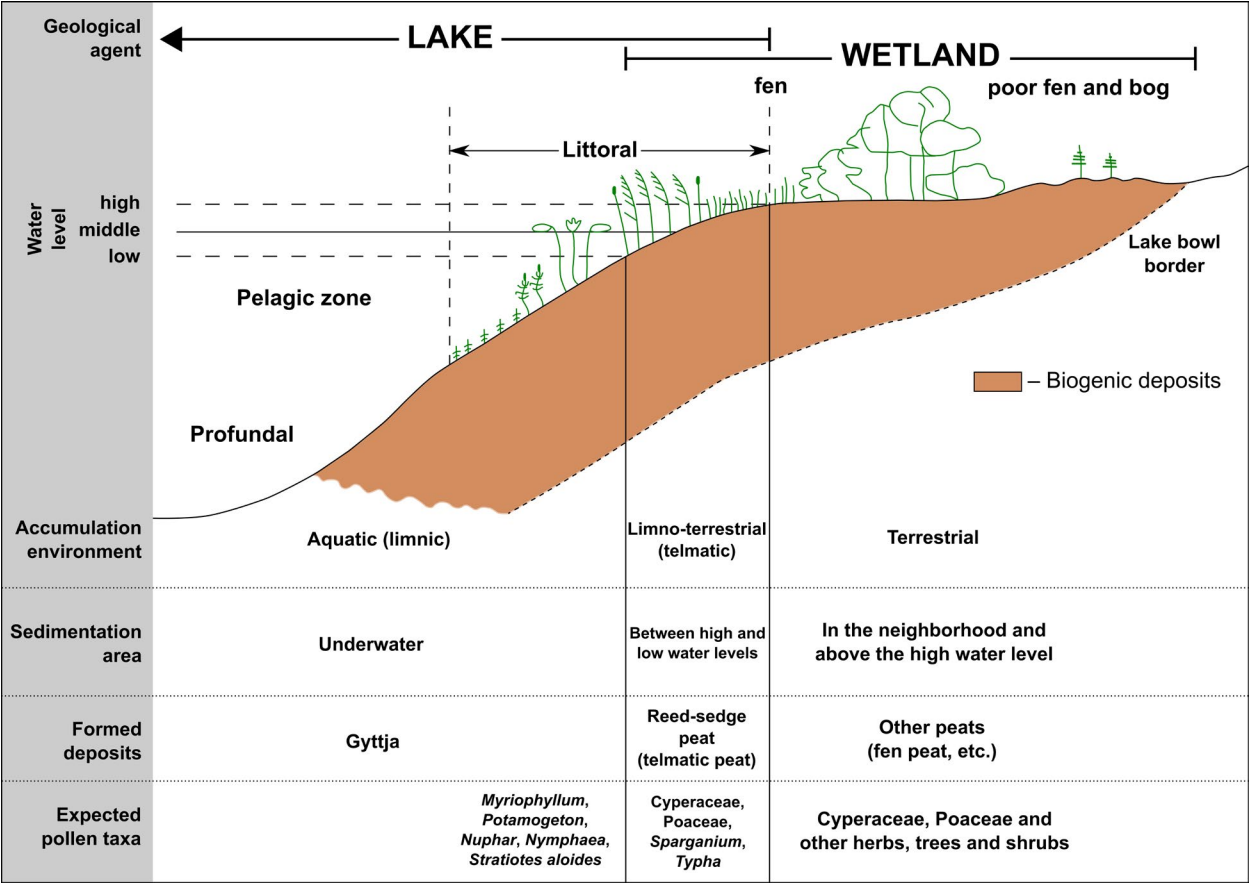


Figure 5. Biogenic accumulation in the lake reservoir and its peaty shore (according to Tobolski, 2021; modified and supplemented by D. Tsvirko)

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).

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

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.

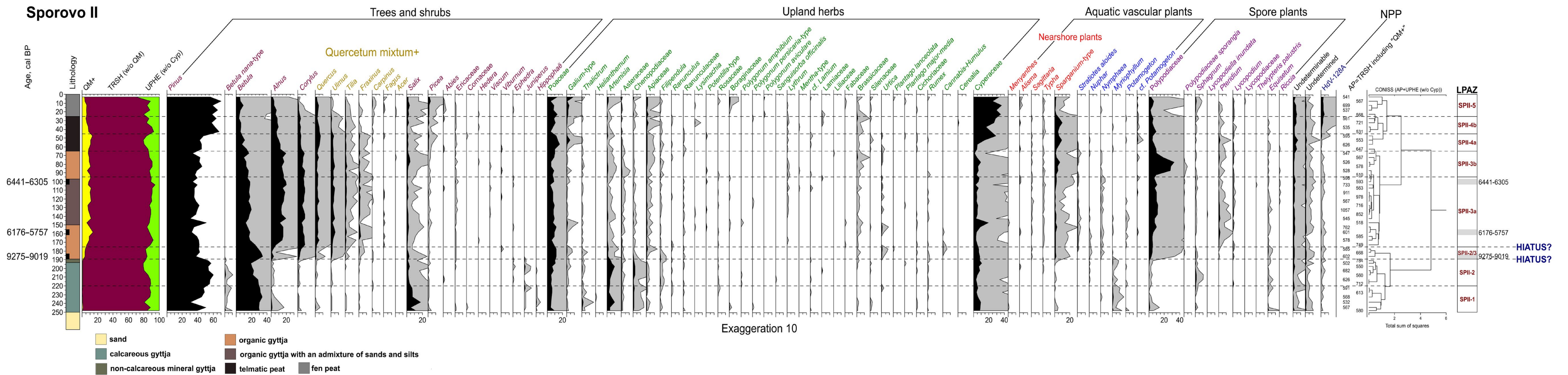


Figure 6. Spore-pollen diagram (percentage) from the Sporovo II core (analysed by D. Tsvirko). QM+ – *Quercus* + *Ulmus* + *Tilia* + *Fraxinus* + *Carpinus* + *Fagus* + *Acer*; TRSH (w/o QM) – trees and shrubs without QM+; UPHE (w/o Cyp) – upland herbs without Cyperaceae

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

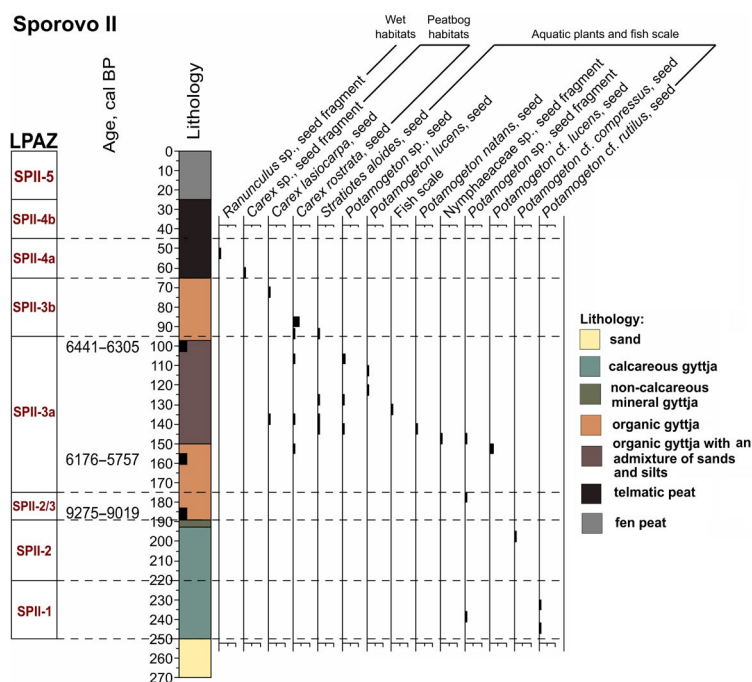


Figure 7. Single macroremains from the Sporovo II core (analysed by M. Słowiński, construction and interpretation by D. Tsvirko)

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

Sporovo II

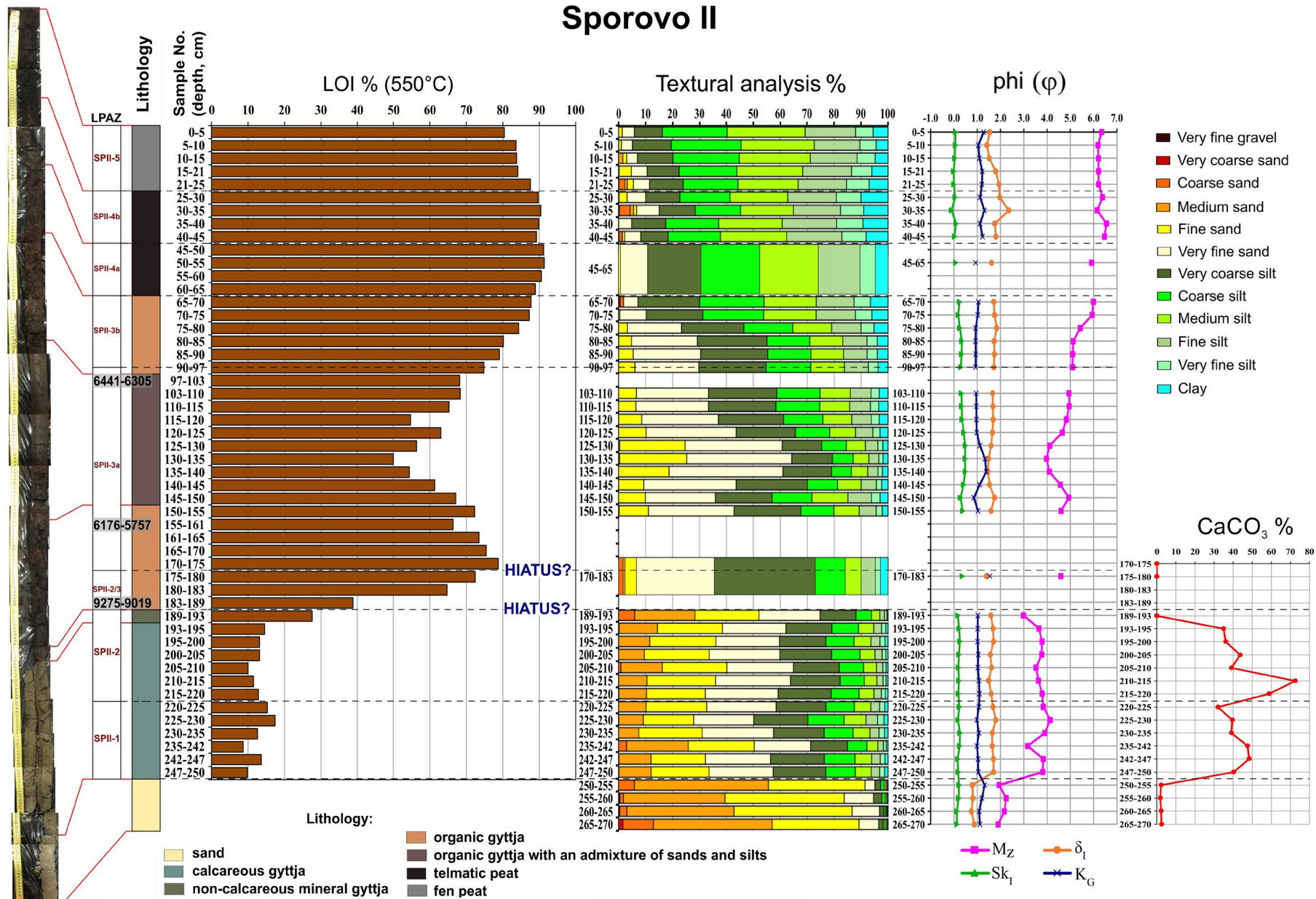


Figure 8. Sedimentological diagram of the Sporovo II core with identified lithological units (based on Tsvirko et al., 2021b; modified and supplemented by D. Tsvirko; photos by D. Tsvirko)

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, <i>Galium</i> -type, Undeterminable. Absence or single finds of <i>Pediastrum</i> .
25–45	Telmatic peat	89.26–90.45	Medium silt (Mz: 6.15–6.55 ϕ)	SPII-4b (25–45)	Pollen of Cyperaceae, <i>Sparganium</i> -type, Undeterminable. Absence or single finds of <i>Pediastrum</i> .
45–65		88.94–91.34	Coarse silt (Mz: 5.91 ϕ)	SPII-4a (45–65)	Pollen of Cyperaceae, Poaceae, <i>Galium</i> -type, <i>Sparganium</i> -type, Undeterminable, single grains of <i>Stratiotes aloides</i> , <i>Nuphar</i> , <i>Myriophyllum</i> and <i>Potamogeton</i> . Absence or single finds of <i>Pediastrum</i> (45–60 cm); many finds of <i>Pediastrum</i> (60–65 cm). Seeds of <i>Ranunculus</i> and <i>Carex</i> .
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 <i>Sparganium</i> -type, Polypodiaceae, <i>Stratiotes aloides</i> , <i>Nymphaea</i> , <i>Nuphar</i> . Medium or many finds of <i>Pediastrum</i> . Seeds of <i>Carex</i> and <i>Stratiotes aloides</i> .
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 <i>Stratiotes aloides</i> , <i>Nymphaea</i> , <i>Nuphar</i> , <i>Potamogeton</i> , <i>Myriophyllum</i> . Many finds of <i>Pediastrum</i> . Seeds of <i>Potamogeton</i> , <i>Stratiotes aloides</i> , <i>Nymphaeaceae</i> and <i>Carex</i> , 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 <i>Stratiotes aloides</i> , <i>Nymphaea</i> , <i>Nuphar</i> , <i>Potamogeton</i> , <i>Myriophyllum</i> . Many finds of <i>Pediastrum</i> . Seeds of <i>Potamogeton</i> and <i>Carex</i> .
189–193	Non-calcareous mineral gyttja	27.54	Fine sand (Mz: 2.98 ϕ)	SPII-2 (189–193)	Pollen of <i>Myriophyllum</i> . Many finds of <i>Pediastrum</i> .
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 <i>Myriophyllum</i> , single grains of <i>Nymphaea</i> , <i>Nuphar</i> and <i>Potamogeton</i> . Many finds of <i>Pediastrum</i> . Seeds of <i>Potamogeton</i> .
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 sedimentation 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).

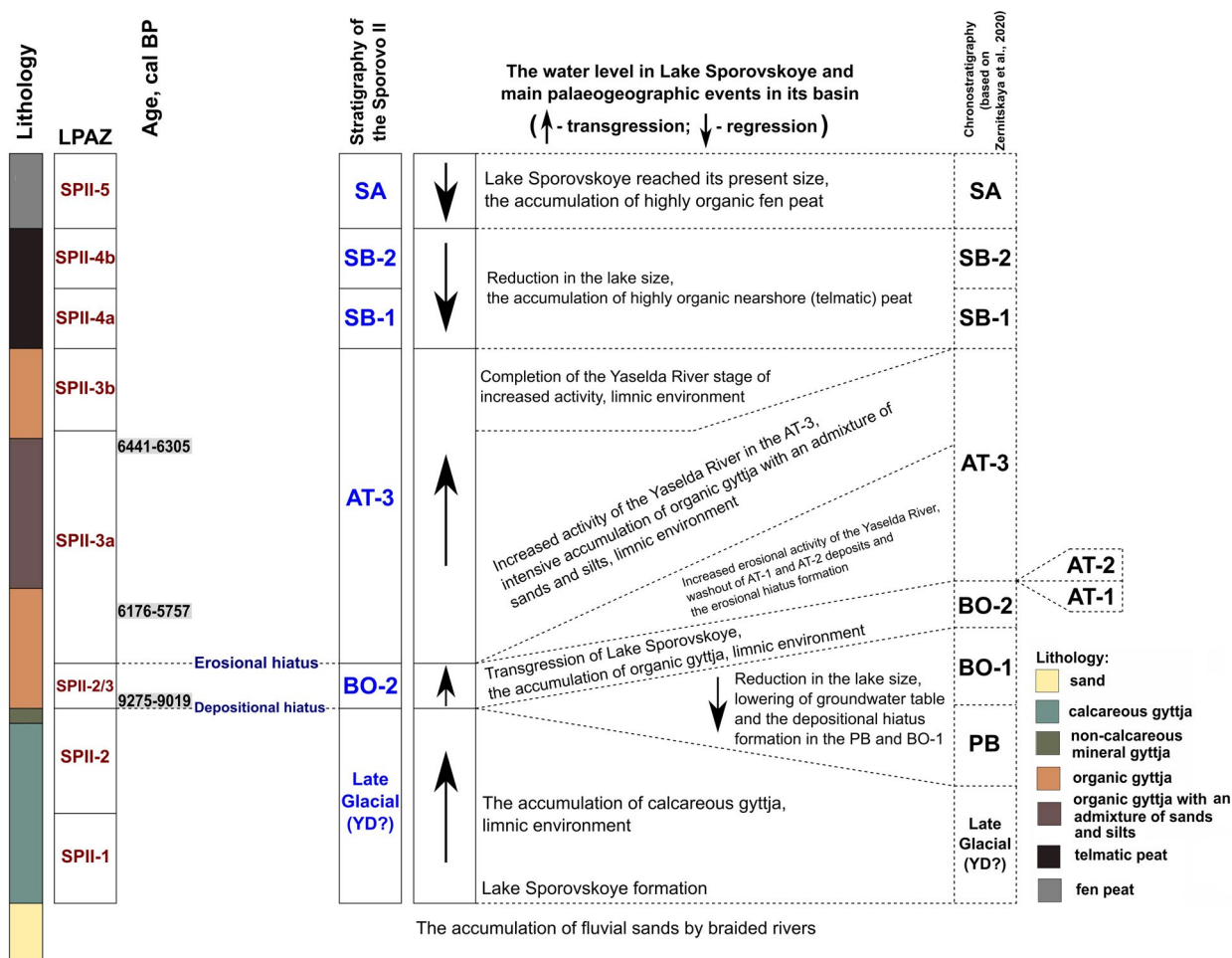




Figure 10. Pollen grains from the calcareous gyttja and non-calcareous mineral gyttja (250–189 cm) of the Sporovo II core (photos by D. Tsvirko). **A, B.** *Artemisia* (the same grain in different positions; sample depth: 189–193 cm); **C, D.** *Chenopodiaceae* (two different grains; sample depth: 189–193 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 sedimentation 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 sedimentation 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

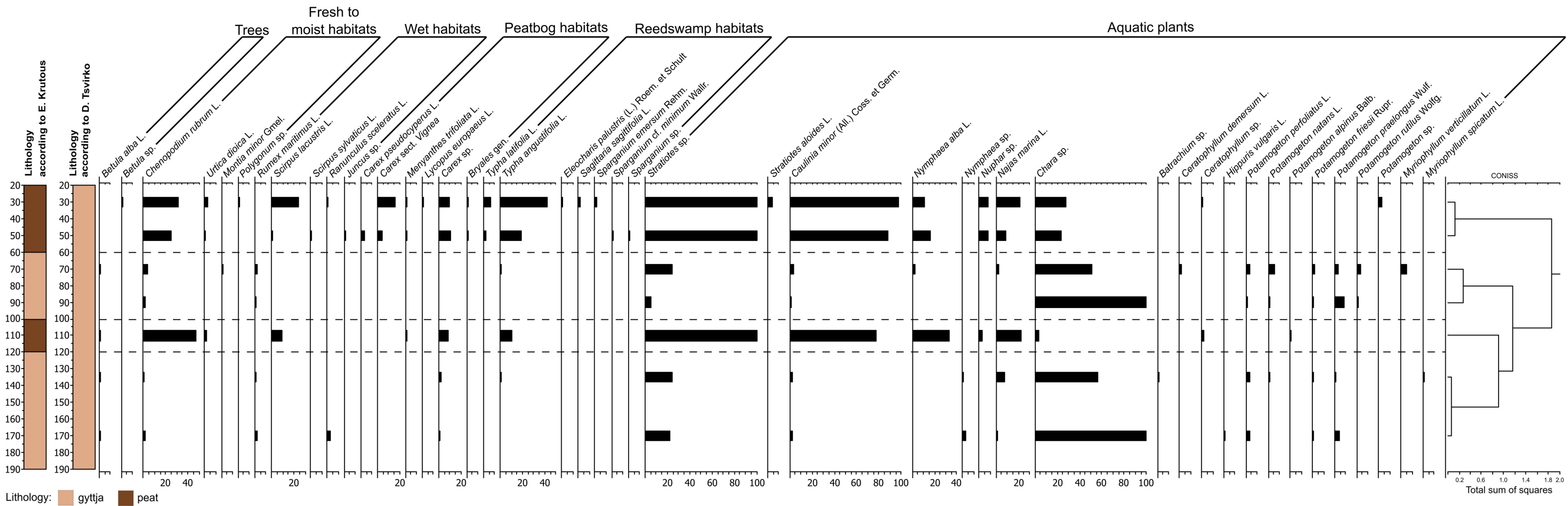


Figure 13. Carpological diagram from the bottom sediments of Lake Sporovskoye (analysed by E. Krutous (1990), construction and interpretation by D. Tsvirko)

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 Gościąg 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.

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

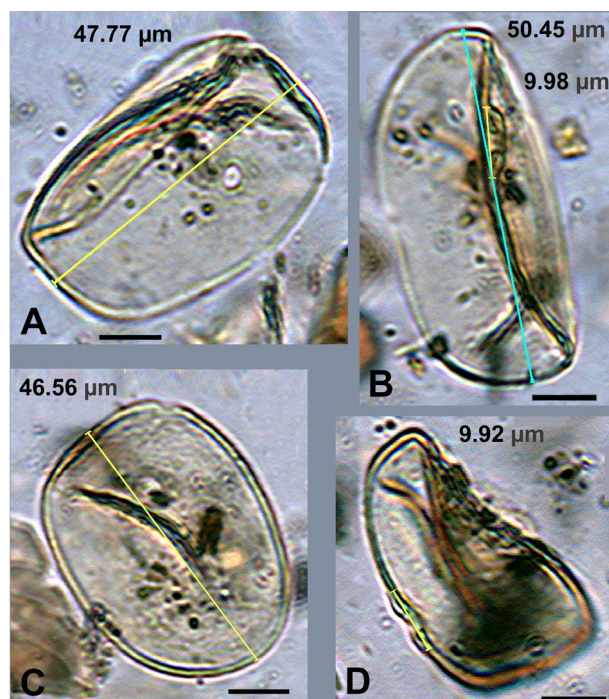


Figure 15. Examples of *Poaceae* pollen grains with an indistinct annulus from the Sporovo II core, which were previously misinterpreted as *Cerealia* (photos from Tsvirko et al., 2021a). **A, B.** *Poaceae* with the longest axis size of 47.77–50.45 µm and the annulus size of 9.98 µm (the same grain 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

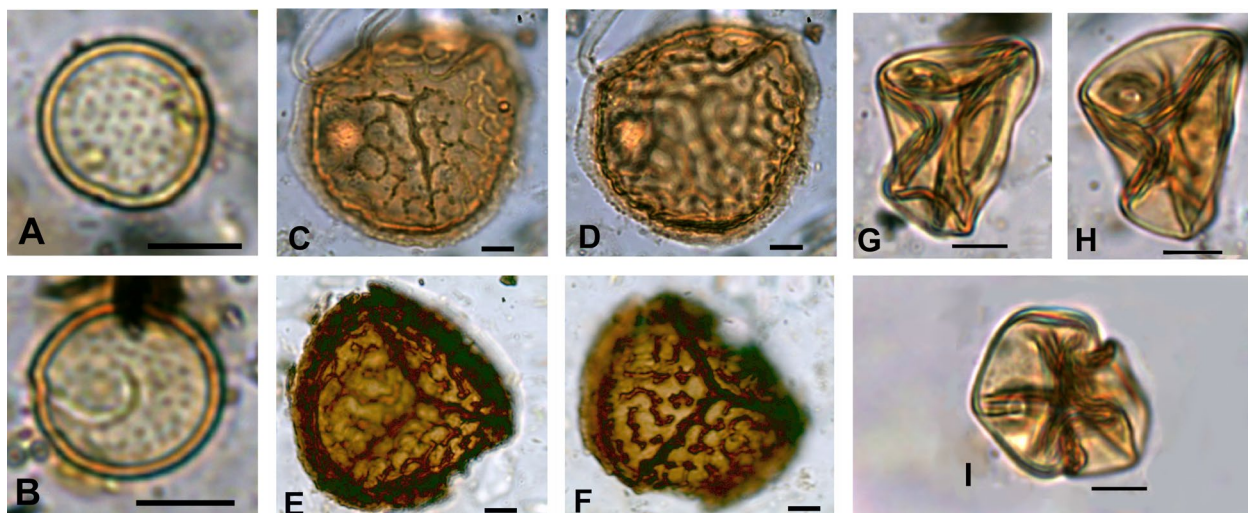


Figure 16. Selected NPPs, spores and Cerealia pollen from the Sporovo II core (photos by D. Tsvirko). **A.** HdV-128A or Volvocaceae (sample depth: 0–5 cm); **B.** HdV-128A or Volvocaceae (sample depth: 35–40 cm); **C, D.** *Riccia* (the same grain; sample depth: 97–103 cm); **E, F.** *Riccia* (the same grain; sample depth: 110–115 cm); **G–I.** Cerealia (sample depth: 30–35 cm). Scale bars = 10 μ m 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 μ m 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 μ m), 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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APPENDIX 2

Ash admixtures formed during the loss on ignition (LOI) procedure and their impact on laser textural analysis results

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Abstract: We present an experimental study that explores the feasibility of using the ash from biogenic deposits for laser textural analysis. The results have demonstrated that conducting ash textural analysis without prior chemical treatment can lead to unreliable results. Among other things, this is due to the “contamination” of the ash with aggregates formed by metal oxides and carbonates during ignition (LOI₅₅₀ procedure) in a muffle furnace. Metal oxides and carbonates can create aggregates with silt and clay grains. As a result, the material coarsens, mainly to very coarse and coarse silt fractions. It is illustrated that the ash after LOI₅₅₀ has been contaminated with oxides and carbonates of iron (Fe), potassium (K), magnesium (Mg), calcium (Ca), manganese (Mn), sodium (Na), zinc (Zn), lead (Pb) and copper (Cu). Thus, we suggest a method of using 10% HCl to purify the ash from metal oxides and carbonates (so-called ash purification procedure or APP). The analysis in this paper focuses on the grain size composition of ash, both untreated and HCl-treated. The obtained results have been compared and discussed in detail.

Keywords: loss on ignition, biogenic deposits ash, laser textural analysis, ash purification procedure (APP), metal oxides and carbonates

INTRODUCTION

Peat, gyttja, and other biogenic deposits consist of a combination of organic matter (organic component), primarily derived from plant remains, and mineral particles of different origin (mineral component). In river valleys, the main sources of the influx of mineral particles into peat and gyttja deposits are floods, aeolian deposition, and slope processes. Textural (grain size distribution) analysis of the mineral component of biogenic deposits is highly valuable. It can be useful for tracking

changes in deposition processes and the origin of mineral fractions, which is helpful for palaeogeographical reconstructions or identifying lithological boundaries. The primary issue revolves around the challenge of isolating the mineral portion of biogenic deposits from their organic counterpart. A feasible option could be utilizing ignition in a muffle furnace to remove the organic substances from deposits. Currently, the loss on ignition (LOI₅₅₀) method is extensively applied, and the resulting ash can be used for textural analysis. In some studies, researchers have already utilized the

untreated ash obtained after ignition for textural analysis (Kittel et al. 2014, 2016, 2020, Żarczyński et al. 2019).

Ignition in a muffle furnace at a temperature of 950°C (or 925°C) can also be used to remove organic matter, as well as calcium carbonate (CaCO_3) from sediments (Heiri et al. 2001). Another method for removing organic matter is boiling in hydrogen peroxide H_2O_2 (Mikutta et al. 2005). However, our research is focused only on the study of the ash obtained after ignition at a temperature of 550°C – LOI_{550} .

This paper demonstrates that the ash remaining after LOI_{550} procedure differs from the mineral component of biogenic deposits. Additionally, the LOI_{550} readings do not accurately indicate the amount of organic matter present in the examined deposits. After the furnace, the ash becomes filled with metal oxides and carbonates that are produced during ignition at 550°C. This leads to contamination of the mineral component of biogenic deposits and to a decrease in the actual amount of organic matter present in the final results. During ignition at 550°C, the organic component of biogenic deposits is not entirely removed from the samples. Instead, the released carbon dioxide (CO_2) reacts with metals to form metal carbonates. The formation of new compounds that contaminate and add weight to the resulting ash also involves ambient oxygen (O_2). An additional problem is formation of aggregates of these newly established oxides and carbonates with silt and clay grains.

Accordingly, our study has the following objectives:

- Create a procedure for purifying the ash from secondary metal oxides and carbonates (for instance, Fe_2O_3 , K_2CO_3 , MgCO_3 and CaCO_3) that are produced during ignition at a temperature of 550°C.
- Perform a spectral analysis with SPEKOL11 equipment on the HCl acid solutions obtained during the ash purification procedure (APP). This will help estimate the amount of iron and its oxides present in the studied ash. Determine other metals present in the acid solutions using the atomic absorption spectroscopy (AAS) method.
- Conduct a laser textural analysis with a Malvern Panalytical Mastersizer 3000 equipment on the ash purified from metal oxides and carbonates (the HCl-treated ash), as well as on the ash that has not been purified from these compounds (the untreated ash) and compare the results.

Some of the findings from this study have been previously published in conference proceedings by Tsvirko et al. (2022a, 2022b). This research revises and adds to our previous perspectives as presented in our past publications. In particular, it was not previously taken into account that iron carbonates FeCO_3 and $\text{Fe}_2(\text{CO}_3)_3$ decompose during the heating process to 550°C, and iron carbonates are not preserved in the ash after a muffle furnace (Kissinger et al. 1956). In our previous publications, we called the ash purification procedure (APP) as the HCl cleaning procedure or HCLP (Tsvirko et al. 2022a, 2022b, Tsvirko 2023).

MATERIALS AND METHODS

Fifteen samples (nos. 3–15 and 31, 32) from the core PKK-1-2 (Figs. 1, 2, Table 2) were used for analyses (see also Table S1 and Figure S1 in the [online supplementary material \(OSM\)](#)). The core was taken from a fen located near the channel of the Yaselda River in southern Belarus (Tsvirko et al. 2021a). The studied deposits were characterized by different amounts of organic matter: biogenic deposits (coarse detritus gyttja, black/brown telmatic peat, fen peat according to Markowski (1980) and Tobolski (2021) classifications), and sandy deposits with a small amount of organic matter (Fig. 3). The analysis of plant macrofossils was used to identify the origin of these geological sediment layers. Coarse detritus gyttja was characterized by a predominance of macroremains of fully submerged plants and plants with floating leaves (*Chara*, *Potamogeton*, *Nuphar*, *Nymphaea*, *Stratiotes aloides*, etc.). Telmatic peat was characterized by a predominance of macroremains of semi-submerged and nearshore vegetation (*Typha*, *Alisma plantago aquatica*, *Sagittaria sagittifolia*, *Juncus*, *Mentha longifolia*, Poaceae, etc.), with a still significant admixture of remains of fully submerged plants and plants with floating leaves (*Chara*, *Potamogeton*, *Lemna*, *Salvinia natans*, *Stratiotes aloides*, etc.).

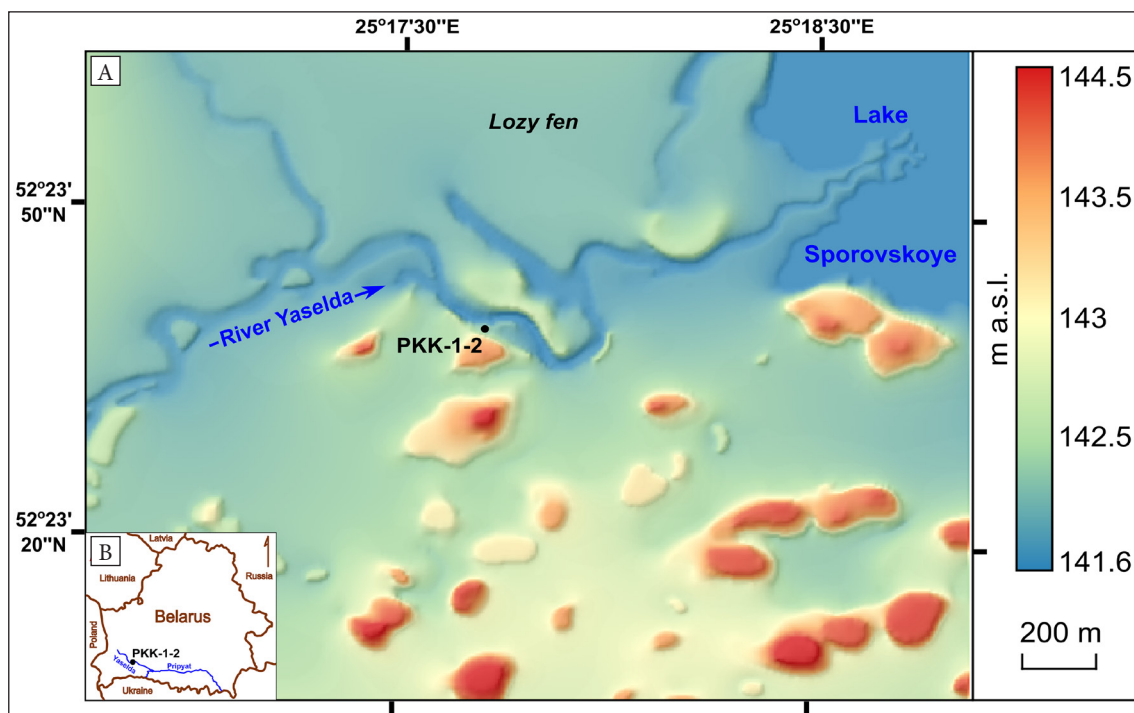


Fig. 1. Location of the studied PKK-1-2 core in the basin of the Yaselda River and Lake Sporovskoye (A) in southern Belarus (B) (Tsvirko et al. 2021b, Tsvirko 2023)

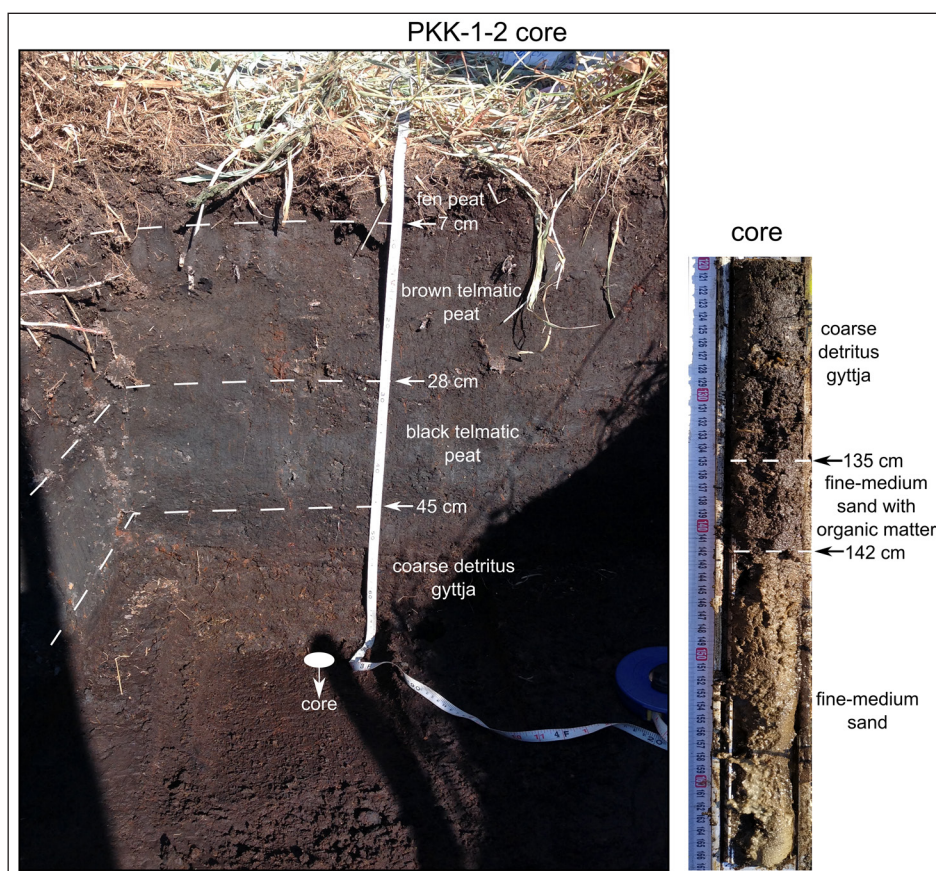


Fig. 2. Deposits of the PKK-1-2 core (52°23'38.448"N 25°17'35.545"E). The photos represent only the part of the studied deposits with marked lithological boundaries (photos by D. Tsvirko, August 2020)

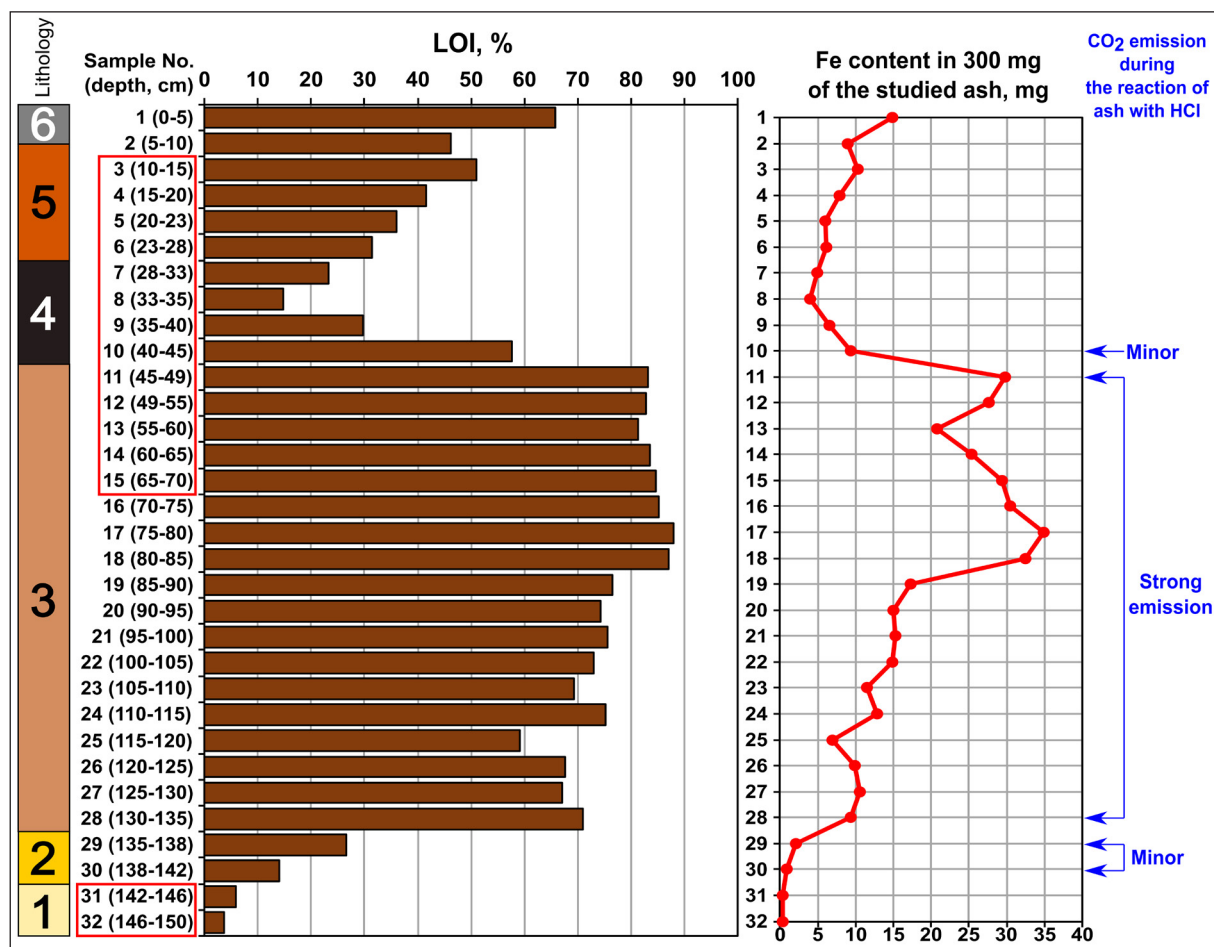


Fig. 3. Core PKK-1-2 with LOI₅₅₀ values, the amount of iron in 300 mg of ash (based on SPEKOL11 analysis and on initial masses of ash used for APP at room temperature), and the designation of samples that had CO₂ emission during the reaction of ash with HCl. The main studied samples are marked with red squares. Lithology: 1 – fine-medium sand, 2 – fine-medium sand with organic matter, 3 – coarse detritus gyttja, 4 – black telmatic peat, 5 – brown telmatic peat, 6 – fen peat

Also, the studied core PKK-1-2 can be characterized as an organic peat soil, without visible gley features, but with iron precipitation associated with groundwater level fluctuations and visible in geochemical analysis (Fig. 3).

The samples were dried at 50°C (24 hours) and carefully ground in a porcelain mortar. Before ignition, the samples were dried at a temperature of 105°C (1 hour), and the empty crucibles at 550°C (1 hour) to remove any remaining moisture. The samples were then subjected to combustion in a muffle furnace at 550°C for 8 hours. To determine the LOI₅₅₀ values, the weight of dry samples and dry crucibles were measured both before and after ignition, following the procedure outlined by Dean (1974) and Heiri et al. (2001). It has to

be noted that the weight of the dry samples and crucibles was measured immediately after drying them (at 105°C), or after the muffle furnace cooled to 100°C (i.e. without storage in the laboratory). Desiccators were not used in this study, but we strongly recommend them. The initial results of loss on ignition (LOI₅₅₀) are shown in Table 2 and Figure 3.

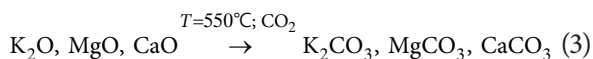
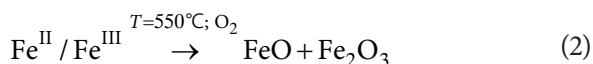
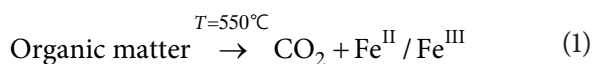
After the LOI₅₅₀ process, the ash was thoroughly homogenized and split into two subsamples. Subsample one was analyzed for its textural features (grain size distribution) using laser particle sizer without pre-treatment. For subsample two, the ash was chemically pre-treated with 10% HCl before undergoing grain size analysis with laser particle sizer (see Figure S2 in the OSM).

After that, a comparison of the grain size distributions was made.

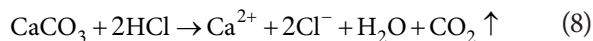
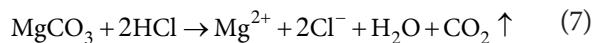
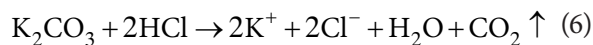
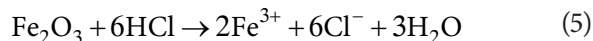
The ash purification procedure (APP)

We investigated whether the formation of metal oxides and carbonates in a furnace heated to 550°C can impact the accuracy of grain size distribution measurements for the mineral component of biogenic deposits. Therefore, a procedure for purifying the ash from these compounds was proposed. During the study, there was a significant focus on estimating iron oxides FeO and Fe₂O₃, but it is worth noting that ignition can also result in the formation of compounds with other metal elements, such as: K₂O, K₂CO₃, MgO, MgCO₃, CaO, CaCO₃, Mn₂O₃, Na₂O, Na₂CO₃, ZnO, PbO, CuO, Cu₂O and others.

Metal oxides and carbonates are formed when metal cations (for instance, Fe²⁺/Fe³⁺, K⁺, Mg²⁺, Ca²⁺) contained in organic matter react with carbon dioxide (CO₂) released during ignition, as well as oxygen (O₂) from the surrounding air at high temperatures (Bruchajzer et al. 2017). This reaction follows the equations below:



To ensure accurate results of grain size distribution analysis, it is recommended to purify the studied portion of ash containing metal oxides and carbonates using 10% HCl acid (ACS reagent grade). Similar use of acids for the removal of iron oxides was previously described, for example, by Kowalska and Królak (1967) and Surgiewicz (2013). This purification process can prevent the potential impact of aggregates formed by metal compounds on the textural results:



Here are the steps to apply the ash purification procedure (APP):

1. The ash was mixed in plastic test tubes (for 50 mL) with 30 mL of 10% HCl (the ratio is approximately 1 to 5).
2. The resulting mixture was heated in a water bath to 70°C for 20–30 minutes, and then maintained under regular stirring at a temperature between 70–80°C for 30 minutes (see Figure S3 in the OSM).
3. After the heating process, the test tubes were cooled to room temperature and then subjected to centrifugation for 5 minutes at 4000 rpm. As part of the experiment, the remaining yellowish acid solutions were transferred into separate tubes for spectral analysis (see Figure S4 in the OSM).
4. Following that, the ash underwent 1–2 rounds of centrifugation in distilled water (50 mL) and was subsequently dried at room temperature in the same test tubes. Thus, this procedure effectively purified the ash, removing metal oxides and carbonates, and prepared it for laser textural analysis (Fig. 4).
5. Additionally, we weighed the air-dried ash to two decimal places before and after the ash purification procedure to determine the amount of metal oxides and carbonates removed.

It should be noted that the ash mass measurement before and after the ash purification procedure was conducted following long-term storage of samples at room temperature, which has resulted in moisture inclusion in the ash mass (e.g. see Table S2 in the OSM – Dry ash before/after HCl treatment).

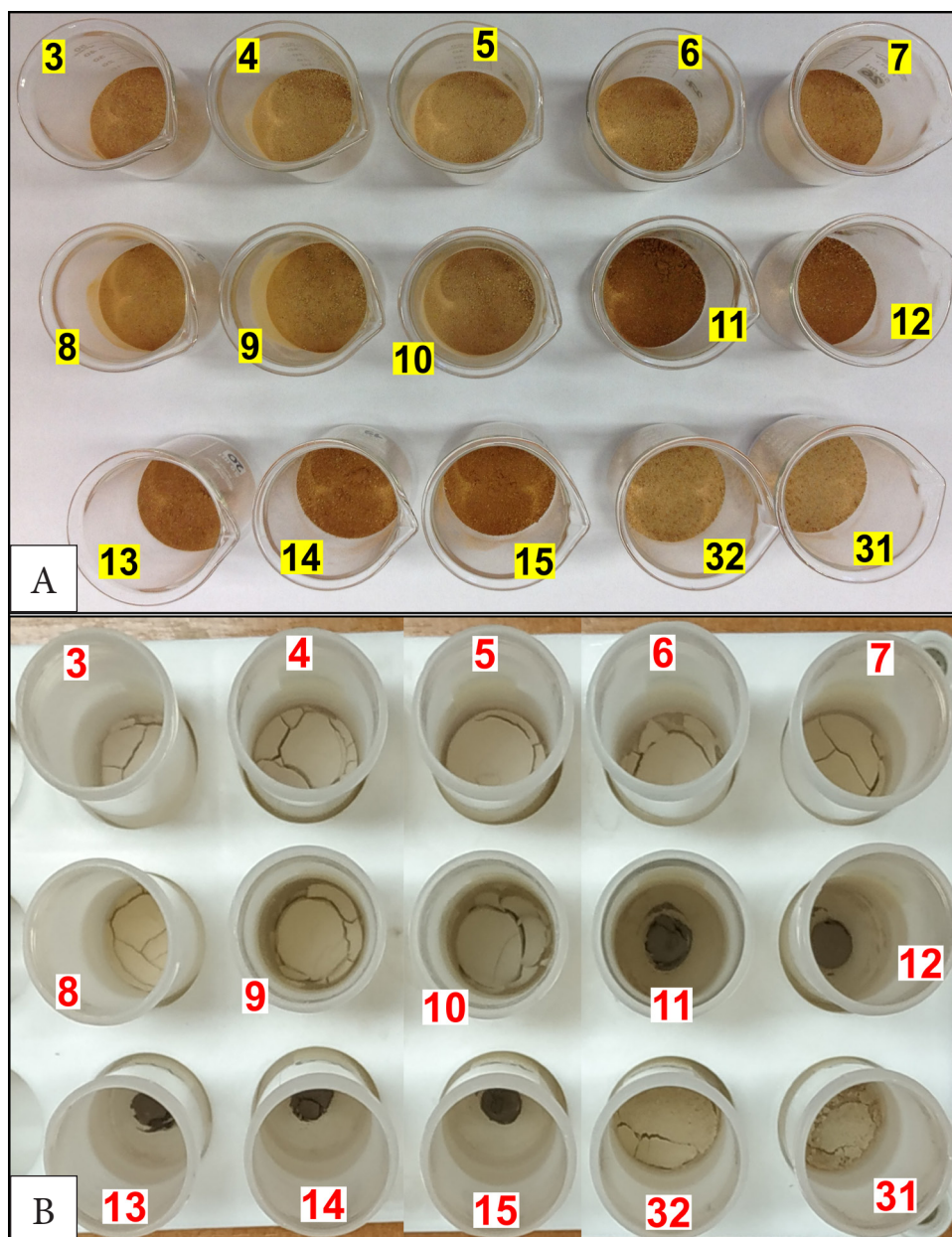


Fig. 4. View of the studied dry ash before (A) and after (B) the ash purification procedure. The redness has disappeared (photos by D. Tsvirko, 2022)

Spectral analysis of the HCl acid solutions

After obtaining yellowish acid solutions through APP, 10% HCl was added to each of them up to 50 mL. These solutions were then analyzed using a SPEKOL11 spectrophotometer (on the use of SPEKOL11 see also Tołoczko 2016) to determine the iron content in the ash samples (see Figure S5 in the OSM). To achieve this, eight reference HCl solutions with a known mass and concentration of

iron chloride powder (FeCl_3) were prepared, each 50 mL in quantity (see Figure S6 in the OSM).

The transmission (T) of each reference solution was measured at wavelengths of 420, 460 and 500 nm. To ensure accuracy, each reference sample underwent five repeated transmission measurements, averaging for each wavelength (Table 1). The relationship between transmission and the mass of iron in solution at wavelengths of 420, 460, and 500 nm are given in Figures S7–S9 in the OSM.

Table 1

Mass and molar concentration of iron in reference samples I–VIII and corresponding average transmission values for wavelengths of 420, 460, and 500 nm

Reference sample number	Mass of Fe in 50 mL of HCl solution [mg]	Molar concentration [mol/dm ³]	T (transmission)		
			420 nm	460 nm	500 nm
I	344.276	0.1233000	0.10	0.10	24.64
II	172.138	0.0616500	0.10	0.30	48.12
III	86.069	0.0308240	0.22	2.96	67.94
IV	34.428	0.0123300	0.34	22.48	86.54
V	17.214	0.0061650	1.14	46.50	91.04
VI	6.886	0.0024660	13.52	70.64	92.64
VII	3.443	0.0012330	35.50	83.48	95.66
VIII	1.721	0.0006165	57.74	89.84	96.22

Explanations: values in bold were used to create the graphs in Figures S7–S9 in the OSM.

To determine the mass of iron present in the studied solutions post APP, the transmission (T) for each sample was measured using a spectrophotometer. Subsequently, the achieved mass of iron in 50 mL of HCl solution was calculated using the given formulas:

$$\text{For 420 nm, } x = \frac{\ln(83.983)}{0.2516} - \frac{\ln(T)}{0.2516} \quad (9)$$

$$\text{For 460 nm, } x = \frac{\ln(91.881)}{0.04002} - \frac{\ln(T)}{0.04002} \quad (10)$$

$$\text{For 500 nm, } x = \frac{\ln(97.425)}{0.004018} - \frac{\ln(T)}{0.004018} \quad (11)$$

where x – mass of iron in the studied 50 mL of HCl solution [mg], T – transmission of the studied 50 mL of HCl solution.

Atomic absorption spectroscopy (AAS)

After conducting analysis on SPEKOL11 equipment, four acid solutions obtained from APP (samples nos. 3, 4, 11 and 15) were analysed using a Solaar 969 Unicam device (on the use of this device see also Okupny et al. 2020, 2022) for AAS. Through atomic absorption spectrometry, it was possible to identify the presence of other metals aside from iron in post APP solutions.

The main purpose of the analysis using AAS was the qualitative determination of metals present

in HCl solutions. For this reason, we decided to analyse only four HCl solutions.

Laser textural analysis

Both ash sample sets (HCl-treated and untreated) were analyzed with a Malvern Panalytical Mastersizer 3000 (see Figure S10 in the OSM), after careful grinding in a porcelain mortar and ultrasonic treatment for 2 minutes in an Ultrasonic Processor Sonicator VCX 130 (see Figure S11 in the OSM). There was no sieving of the samples, since the size of all mineral particles was less than 2 mm.

The grain size distribution results were obtained by statistical processing the initial grain size distribution data using Gradistat Version 9.1 software (Blott & Pye 2001). This initial grain size distribution data included textural results for both untreated and HCl-treated ash, measured on a scale of 1/4 phi. The textural fractions were defined after Udden (1914) and Wentworth (1922) given in micrometres [μm]: coarse sand ($500 \leq x < 1,000$), medium sand ($250 \leq x < 500$), fine sand ($125 \leq x < 250$), very fine sand ($63 \leq x < 125$), very coarse silt ($31 \leq x < 63$), coarse silt ($16 \leq x < 31$), medium silt ($8 \leq x < 16$), fine silt ($4 \leq x < 8$), very fine silt ($2 \leq x < 4$) and clay (< 2).

To compare two values, we calculated the percentage difference between them using the Formula (12). This was done for mean grain size M_z

values after Folk and Ward (1957) and the textural groups values.

$$x = \frac{A - B}{B} \cdot 100 \% \quad (12)$$

where: x – percentage difference between two M_z or textural groups values of one sample [%], A – higher M_z or textural group value, B – lower M_z or textural group value.

To estimate the actual organic matter content (OMC after APP) in the samples, excluding metal oxides and carbonates formed during ignition, we used the following formulas:

$$M_{8h_HCl} = M_{8h} - \frac{M_{8h} \cdot P_r}{100} \quad (13)$$

where: M_{8h_HCl} – ash mass immediately after the muffle furnace, without metal oxides and carbonates [g], M_{8h} – ash mass immediately after the muffle furnace [g] (see Table S1 in the OSM), P_r – the percentage decrease in ash mass after undergoing APP, calculated by comparing the mass of ash (at room temperature) before and after HCl treatment [%] (see Table 2).

$$\text{OMC after APP} = 100 - \frac{M_{8h_HCl} \cdot 100}{M_s} \quad (14)$$

where: OMC after APP – organic matter content (OMC) after purifying the studied ash from metal oxides and carbonates using APP [%], M_{8h_HCl} – ash mass immediately after the muffle furnace, without metal oxides and carbonates [g], M_s – mass of the entire sample (with organic and mineral components) before ignition [g] (see Table S1 in the OSM).

Microscopic analysis

During the study, we obtained photographs of untreated and HCl-treated ash using a light microscope. Some finds discovered during microscopic analysis of the ash were identified and documented.

RESULTS

HCl treatment results

For the fifteen ash subsamples in the study, the ash purification procedure (APP) was used twice. We recommend performing APP multiple times if

redness remains in the ash and the acid solution has a deep yellow color (as per points 1–3 of APP, until the acid solution becomes transparent, see Figure S4B in the OSM).

The purification process effectively removed metal oxides and carbonates from the ash and led to a weight reduction from 6.45 to 72.62% for biogenic deposits and up to 1% for inorganic deposits (Table 2).

For samples with a high content of organic matter such as samples nos. 11–15, there was a noticeable decrease in ash mass of over 50%. During the interaction of ash samples nos. 11–15 with HCl, there was a violent reaction, resulting in the release of CO_2 . This reaction may indicate a large amount of metal carbonates formed during LOI_{550} procedure. Other samples with lower LOI_{550} values did not show any reaction with CO_2 release or had minor CO_2 emissions (as sample no. 10). It should be noted that CO_2 emissions only occurred during HCl reaction with ash. Pre-check of samples nos. 10–12 and 14 before the process of ignition showed that there was no reaction between HCl and biogenic samples. This suggests that carbonates were specifically formed during the ignition of biogenic samples in a muffle furnace (LOI_{550} procedure).

Also, for the studied samples, we calculated the actual OMC (Fig. 5) by using the percentage values by which the ash mass decreased after the ash purification procedure (Table 2 – P_r), as per Formulas (13) and (14). The data required for this are presented in Table S1 in the OSM.

Spectral analysis results

Through spectral analysis using the SPEKOL11 equipment, we were able to estimate the initial amount of iron and its oxides present in the ash before chemical treatment. The results from the transmission measurement were used to determine the mass of iron in the yellowish solutions obtained after APP, which are presented in Table 3. In our study, only the acid solutions obtained after a single application of APP on the ash were analysed. As a result, we estimated the amount of iron in the ash based on these solutions, but it is possible that more iron could be present. A small amount of iron might be present in the solutions also after the second application of APP.

Table 2
The studied ash samples and their mass reduction after APP

Sample number	Sample depth [cm]	LOI ₅₅₀ [%]	Masses at room temperature		Mass loss (P_r) [%]	Lithological unit	Remarks
			Dry ash before HCl treatment [g]	Dry ash after HCl treatment [g]			
3	10–15	50.940	1.15	0.95	17.39	Brown telmatic peat	No visible CO ₂ emission during the reaction of ash with HCl
4	15–20	41.494	1.68	1.48	11.90		
5	20–23	35.921	1.56	1.40	10.26		
6	23–28	31.313	1.22	1.08	11.48		
7	28–33	23.163	2.43	2.22	8.64	Black telmatic peat	Some minor CO ₂ emission visible during the reaction of ash with HCl
8	33–35	14.790	2.48	2.32	6.45		
9	35–40	29.797	1.56	1.36	12.82		
10	40–45	57.714	1.60	1.20	25.00	Coarse detritus gyttja	Strong CO ₂ emission visible during the reaction of ash with HCl
11	45–49	83.088	0.84	0.23	72.62		
12	49–55	82.766	0.82	0.31	62.20		
13	55–60	81.286	0.88	0.43	51.14		
14	60–65	83.588	0.57	0.24	57.89		
15	65–70	84.611	0.34	0.10	70.59	Fine-medium sand	No visible CO ₂ emission during the reaction of ash with HCl
31	142–146	5.958	5.97	5.91	1.01		
32	146–150	3.715	5.92	5.89	0.51		

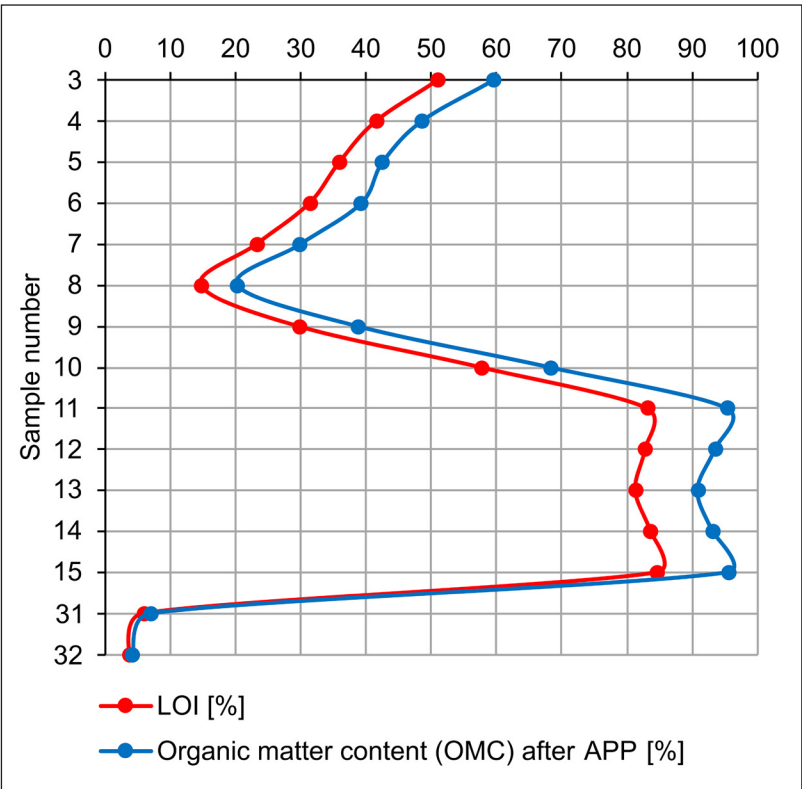


Fig. 5. The LOI₅₅₀ values in comparison to the organic matter content (OMC) after purifying the studied ash of metal oxides and carbonates using APP

To compare the results, we also calculated the mass of iron in 300 mg of the ash (Table 3; 300 mg is the smallest mass of ash sample used for the experiment). It can be concluded that the ash from highly organic samples nos. 11–15 and with

LOI₅₅₀ values >80% had the largest content of iron (Fig. 6). As expected, the samples with the highest weight loss after APP corresponded to the ones with the largest content of iron and, accordingly, its oxides (samples nos. 11–15).

Table 3

Transmission values, corresponding masses of iron in the solutions after a single use of APP, corresponding amount of iron oxides present in the ash before APP, and iron content in 300 mg of the studied ash

Sample number	T (transmission)			Mass of Fe in 50 mL of HCl solution [mg]	Corresponding mass in the ash before APP [mg]		Mass of Fe in 300 mg of ash used for APP (RT) [mg]
	420 nm	460 nm	500 nm		Fe ₂ O ₃	FeO	
3	0.3	19.0	81.3	39.382	56.306	50.664	10.273
4	0.3	15.8	84.0	43.990	62.895	56.593	7.855
5	0.3	26.3	86.1	31.258	44.690	40.213	6.011
6	0.4	33.6	91.0	25.137	35.939	32.338	6.181
7	0.3	18.3	85.3	40.320	57.647	51.871	4.978
8	0.3	24.7	85.4	32.826	46.933	42.230	3.971
9	0.3	23.3	88.0	34.284	49.017	44.106	6.593
10	0.3	12.4	81.2	50.045	71.551	64.383	9.383
11	0.3	2.8	69.7	83.346	119.163	107.224	29.766
12	0.3	4.5	73.1	75.373	107.764	96.967	27.575
13	0.3	8.0	78.9	60.996	87.208	78.471	20.794
14	0.3	13.4	83.1	48.107	68.781	61.889	25.319
15	0.3	24.3	86.5	33.234	47.516	42.755	29.324
31	8.6	70.2	97.4	6.725	9.615	8.652	0.338
32	12.8	74.4	98.8	7.477	10.690	9.619	0.379

Explanations: values in bold were used to calculate the masses; RT – mass at room temperature.

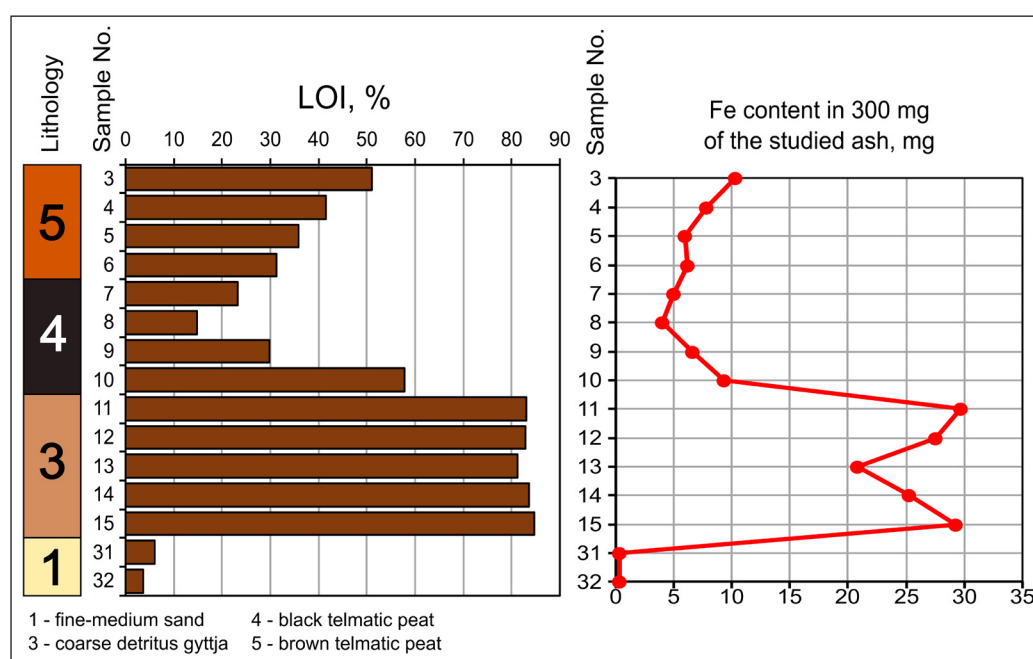


Fig. 6. The mass of iron present in 300 mg of the ash being studied. Based on spectral analysis of the solutions obtained after a single application of APP and on initial masses of ash used for APP at room temperature

Atomic absorption spectroscopy (AAS) results

Four HCl solutions (samples nos. 3, 4, 11 and 15) were subjected to AAS to identify the metal elements present. The solutions were found to contain iron (Fe), potassium (K), magnesium (Mg),

calcium (Ca), manganese (Mn), sodium (Na), zinc (Zn), lead (Pb) and copper (Cu), with iron being the most dominant.

Textural analysis results

Laser grain size distribution for both untreated and HCl-treated ash are shown in Figures 7 and 8.

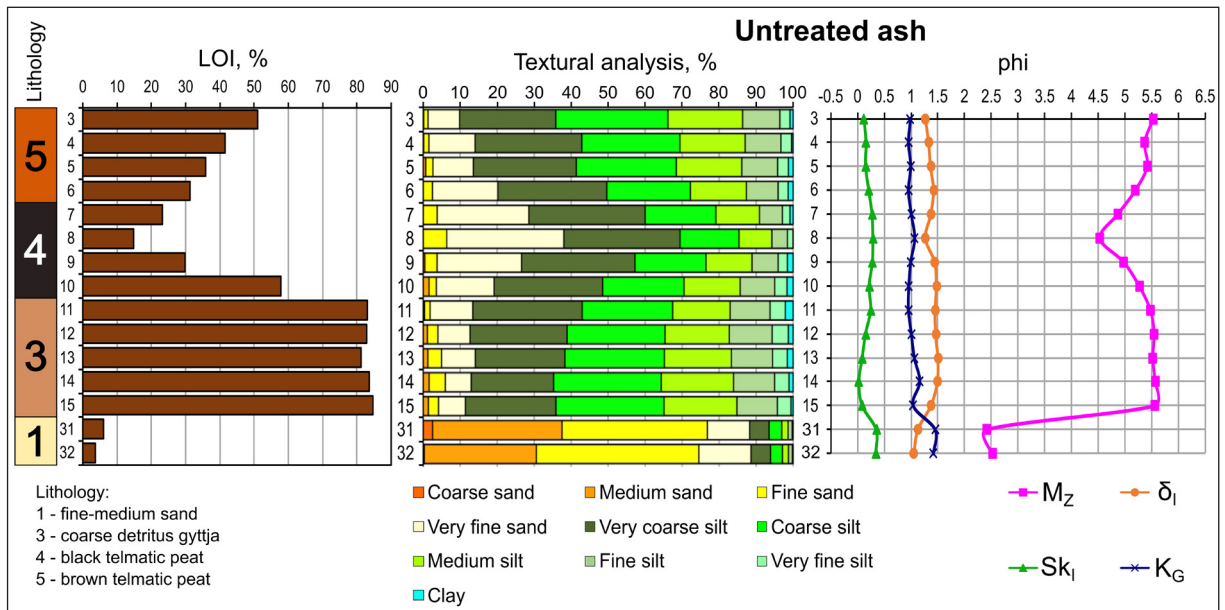


Fig. 7. Laser grain size distribution for untreated ash

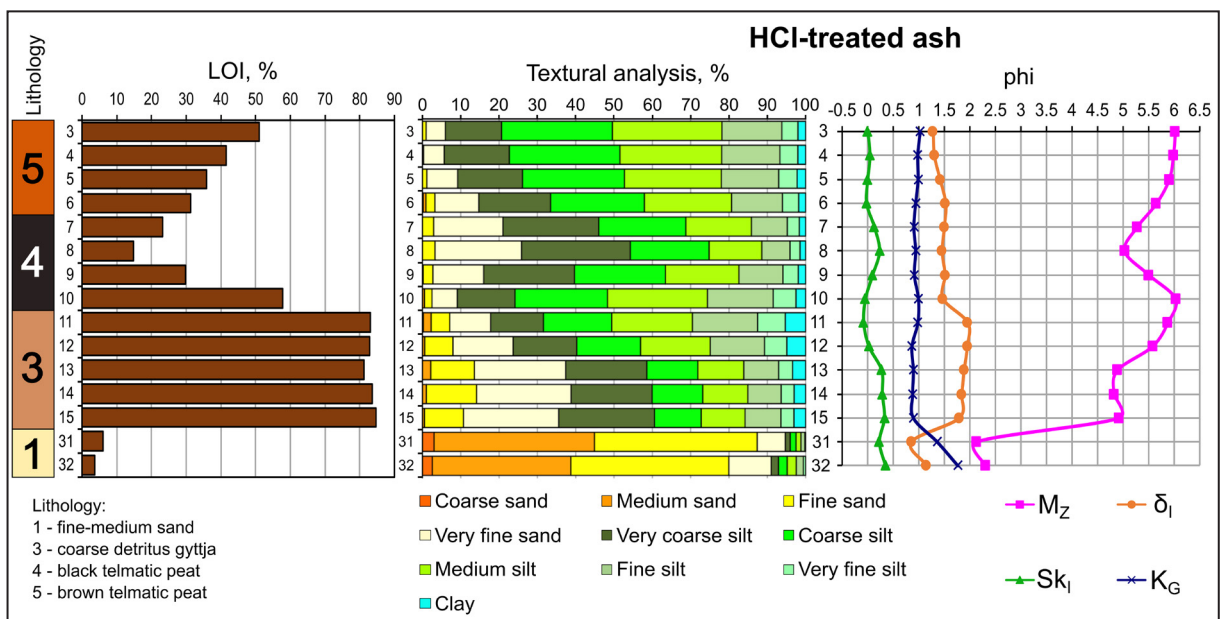


Fig. 8. Laser grain size distribution for HCl-treated ash

The results of calculating the mean grain size M_z (using Gradistat software) for the initial grain size distribution data, including the percentage difference in M_z values are shown in Table 4.

Table 4

The mean grain size M_z values for the initial grain size distribution data, along with their percentage differences (after Folk & Ward 1957)

Sample number	Mean grain size (M_z) [μm]		Difference by treatment [%]	Group of samples
	Untreated ash	HCl-treated ash		
3	21.62	15.36	41	I
4	24.18	15.78	53	
5	23.43	16.71	40	
10	25.98	15.35	69	
6	27.31	19.85	38	II
7	34.28	25.85	33	
8	43.23	30.57	41	
9	31.75	22.00	44	
11	22.49	16.99	32	III
12	21.41	20.98	2	
13	21.79	33.75	55	IV
14	21.15	35.33	67	
15	21.30	33.05	55	
31	188.20	227.71	21	V
32	174.64	201.33	15	

After analyzing the data, it was observed that both the untreated and HCl-treated ash samples can be categorized into various groups based on their features (Table 4 – Group of samples). The classification of these groups was determined based on the difference in the LOI_{550} values (Table 2), mean grain size M_z values (Table 4) and on the difference in the textural groups values that were obtained through statistical processing using the Gradistat software (Tables 5, 6).

The first group, consisting of samples nos. 3–5 and 10 (Table 5), showed a relatively large difference in mean grain size (M_z) values (40–70%, Table 4) and LOI_{550} ranging from 35 to 58%. Based on the results of the textural analysis of the ash after APP, this was a group of samples with a low

sand content (5.68–9.19%, $M_z \approx 6$ phi). However, the untreated ash samples had a higher amount of sand fraction ranging from 9.83 to 19.19% ($M_z = 5.3$ –5.5 phi). This group of samples had fewer admixture of medium, fine, and very fine silt particles in the untreated ash compared to the HCl-treated ash. Additionally, there was a significant difference in the amount of very coarse silt, with the untreated ash samples containing from 26.03 to 29.33% and the acid treated ash samples containing from 14.68 to 16.99%.

In the second group of samples, which included samples nos. 6–9 (Table 5), the LOI_{550} values ranged from 14 to 32%. The difference in the mean grain size M_z values was around 30–40% (Table 4). The LOI_{550} showed a trend of decreasing and then increasing values. An interesting observation was that the grain size distribution for both untreated and HCl-treated ash samples showed a clear wavy pattern of increase and then decrease of sand fraction (Figs. 7, 8). This means that the textural features were preserved regardless of the state of the ash, with the main difference being the amount of sand fraction. The untreated ash contained more sand (ranging 20.18–38.02%) compared to the samples treated with HCl (ranging 14.72–25.85%). Additionally, the untreated ash had a lower amount of medium, fine, and very fine silts compared to the HCl-treated ash but had a higher amount of very coarse silt.

The third group of samples (nos. 11, 12) showed similarities to the group IV, with LOI_{550} values exceeding 80% (Tables 2, 6). The difference in the mean grain size M_z values was one of the lowest and reached 2% for sample no. 12 and 32% for sample no. 11 (Table 4). This group was notable for its substantial clay admixture in the ash samples after the ash purification procedure ($M_z = 5.6$ –5.9 phi). Additionally, there was a higher percentage of sand fraction present in the ash samples after HCl treatment (17.8 and 23.65%) compared to the untreated samples (12.66 and 13.41%). The untreated ash also had a higher admixture of very coarse silt (26.25 and 29.58%) than the HCl-treated ash (13.76 and 16.64%). Furthermore, there was a higher percentage of coarse silt in the untreated ash compared to the ash after the HCl procedure.

Table 5
Grain size distribution in percentage for Groups I and II, with the percentage difference for the untreated and HCl-treated ash results

Group I	Sample 3			Sample 4			Sample 5			Sample 10		
	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]
Coarse sand	0.00	0.00	–	0.00	0.00	–	0.00	0.00	–	0.01	0.00	–
Medium sand	0.13	0.00	–	0.12	0.00	–	0.67	0.00	–	1.58	0.53	198
Fine sand	1.18	0.95	24	1.44	0.29	397	1.95	1.15	70	1.95	1.95	0
Very fine sand	8.52	5.02	70	12.45	5.39	131	10.92	8.04	36	15.65	6.61	137
Very coarse silt	26.03	14.68	77	28.87	16.99	70	27.86	16.93	65	29.33	15.04	95
Coarse silt	30.31	28.93	5	26.55	28.86	9	27.03	26.61	2	22.00	24.15	10
Medium silt	20.18	28.58	42	17.60	26.56	51	17.69	25.28	43	15.18	26.07	72
Fine silt	10.07	15.65	55	9.67	15.21	57	9.70	14.97	54	9.35	17.17	84
Very fine silt	2.74	4.20	53	2.88	4.68	63	2.91	4.80	65	3.32	5.97	80
Clay	0.85	2.00	135	0.43	2.02	374	1.27	2.22	75	1.64	2.50	53
SAND	9.83	5.97	65	14.01	5.68	147	13.54	9.19	47	19.19	9.09	111
MUD	90.17	94.03	4	85.99	94.32	10	86.46	90.81	5	80.81	90.91	12
Group II	Sample 6			Sample 7			Sample 8			Sample 9		
	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]
Coarse sand	0.00	0.20	–	0.00	0.00	–	0.00	0.00	–	0.00	0.00	–
Medium sand	0.00	0.70	–	0.00	0.00	–	0.00	0.00	–	0.46	0.20	130
Fine sand	2.51	2.35	7	3.78	2.94	29	6.38	3.28	95	3.30	2.52	31
Very fine sand	17.67	11.47	54	24.79	18.07	37	31.64	22.57	40	22.83	13.27	72
Very coarse silt	29.48	18.72	57	31.44	24.98	26	31.42	28.39	11	30.65	23.69	29
Coarse silt	22.60	24.49	8	19.14	22.75	19	15.92	20.56	29	19.21	23.73	24
Medium silt	15.12	22.75	50	11.76	17.11	46	8.90	13.76	55	12.43	19.19	54
Fine silt	8.56	13.27	55	6.18	9.36	51	4.20	7.36	75	7.07	11.48	62
Very fine silt	2.71	4.25	57	2.07	3.15	53	1.49	2.61	75	2.51	4.00	60
Clay	1.34	1.80	34	0.85	1.63	91	0.04	1.46	3175	1.55	1.92	24
SAND	20.18	14.72	37	28.57	21.01	36	38.02	25.85	47	26.59	15.99	66
MUD	79.82	85.28	7	71.43	78.99	11	61.98	74.15	20	73.41	84.01	14

Explanations: significant differences (in our opinion) are highlighted in bold; SAND – sum of sand fractions; MUD – sum of silt and clay fractions.

Table 6

Grain size distribution in percentage for Groups III, IV and V, with the percentage difference for the untreated and HCl-treated ash results

Group III	Sample 11			Sample 12					
	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]			
Coarse sand	0.00	0.23	–	0.00	0.00	–			
Medium sand	0.36	2.03	463	1.12	0.59	91			
Fine sand	1.50	4.88	225	2.86	7.39	158			
Very fine sand	11.55	10.67	8	8.68	15.68	81			
Very coarse silt	29.58	13.76	115	26.25	16.64	58			
Coarse silt	24.49	17.82	37	26.48	16.64	59			
Medium silt	15.50	21.09	36	17.35	18.18	5			
Fine silt	10.78	17.00	58	11.58	14.17	22			
Very fine silt	4.13	7.23	75	4.39	5.83	33			
Clay	2.11	5.30	151	1.28	4.90	282			
SAND	13.41	17.80	33	12.66	23.65	87			
MUD	86.59	82.20	5	87.34	76.35	14			
Group IV	Sample 13			Sample 14			Sample 15		
	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]
Coarse sand	0.00	0.01	–	0.00	0.00	–	0.00	0.00	–
Medium sand	1.26	2.16	71	1.60	1.02	58	1.41	0.53	166
Fine sand	3.70	11.41	208	4.39	13.12	199	2.73	10.18	273
Very fine sand	9.10	23.82	162	6.98	24.66	253	7.29	24.86	241
Very coarse silt	24.26	21.16	15	22.30	21.14	5	24.46	24.97	2
Coarse silt	26.89	13.32	102	29.07	13.21	120	29.22	12.20	139
Medium silt	18.13	11.99	51	19.57	11.78	66	19.70	11.43	72
Fine silt	11.14	9.10	22	11.10	8.70	28	10.91	9.37	16
Very fine silt	3.95	3.64	9	3.89	3.38	15	3.71	3.41	9
Clay	1.58	3.40	115	1.10	3.00	172	0.57	3.04	431
SAND	14.06	37.38	166	12.97	38.79	199	11.43	35.57	211
MUD	85.94	62.62	37	87.03	61.21	42	88.57	64.43	37
Group V	Sample 31			Sample 32					
	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]	Untreated ash [%]	HCl-treated ash [%]	Difference by treatment [%]			
Coarse sand	2.55	3.02	18	0.29	2.57	786			
Medium sand	34.98	41.87	20	30.30	36.14	19			
Fine sand	39.31	42.47	8	43.93	41.24	7			
Very fine sand	11.40	7.34	55	14.10	11.07	27			
Very coarse silt	5.27	1.29	308	5.29	1.90	178			
Coarse silt	3.43	1.51	127	3.20	2.26	41			
Medium silt	1.70	1.26	34	1.63	2.37	46			
Fine silt	1.10	1.05	5	1.06	1.85	74			
Very fine silt	0.26	0.18	44	0.20	0.59	194			
Clay	0.00	0.00	–	0.00	0.00	–			
SAND	88.24	94.70	7	88.62	91.02	3			
MUD	11.76	5.30	122	11.38	8.98	27			

Explanations: significant differences (in our opinion) are highlighted in bold; SAND – sum of sand fractions; MUD – sum of silt and clay fractions.

The fourth group is represented by samples nos. 13–15 (Table 6) with LOI_{550} values above 80%. The difference in the mean grain size M_z values was around 55–65% (Table 4). This group showed significant differences in the results of grain size distribution between samples of untreated and HCl treated ash. The amount of sand fraction in the analyzed samples was notably different, with HCl-treated ash having higher sand fraction admixture (over 35% of sands, and $M_z \approx 5$ phi) compared to untreated ash (less than 15%, and $M_z \approx 5.5$ phi respectively). Additionally, the ash samples from this group have more clay fraction after HCl treatment, while untreated ash showed a higher amount of coarse silt fraction (up to 30%).

The fifth group consisted of sand samples nos. 31 and 32 (Table 6) with LOI_{550} values <6%. This

group had a difference in the mean grain size M_z values of about 15–20%. Notably, the untreated ash had a more significant amount of silt fraction (11.38 and 11.76% in samples nos. 32 and 31, respectively) compared to the ash treated with HCl (5.3 and 8.98%). As a result, the mean grain size in phi scale (M_z) for the samples after APP was lower (with values tending towards 2 phi) than for the untreated ash samples (about 2.5 phi). The main difference among the silt fractions was the higher quantity of very coarse and coarse silts in the untreated ash samples (8.49 and 8.7%) compared to the HCl-treated samples (2.8 and 4.16%).

Microscopic analysis results

The results of the analysis of untreated and HCl-treated ash under a light microscope are presented in Figure 9.

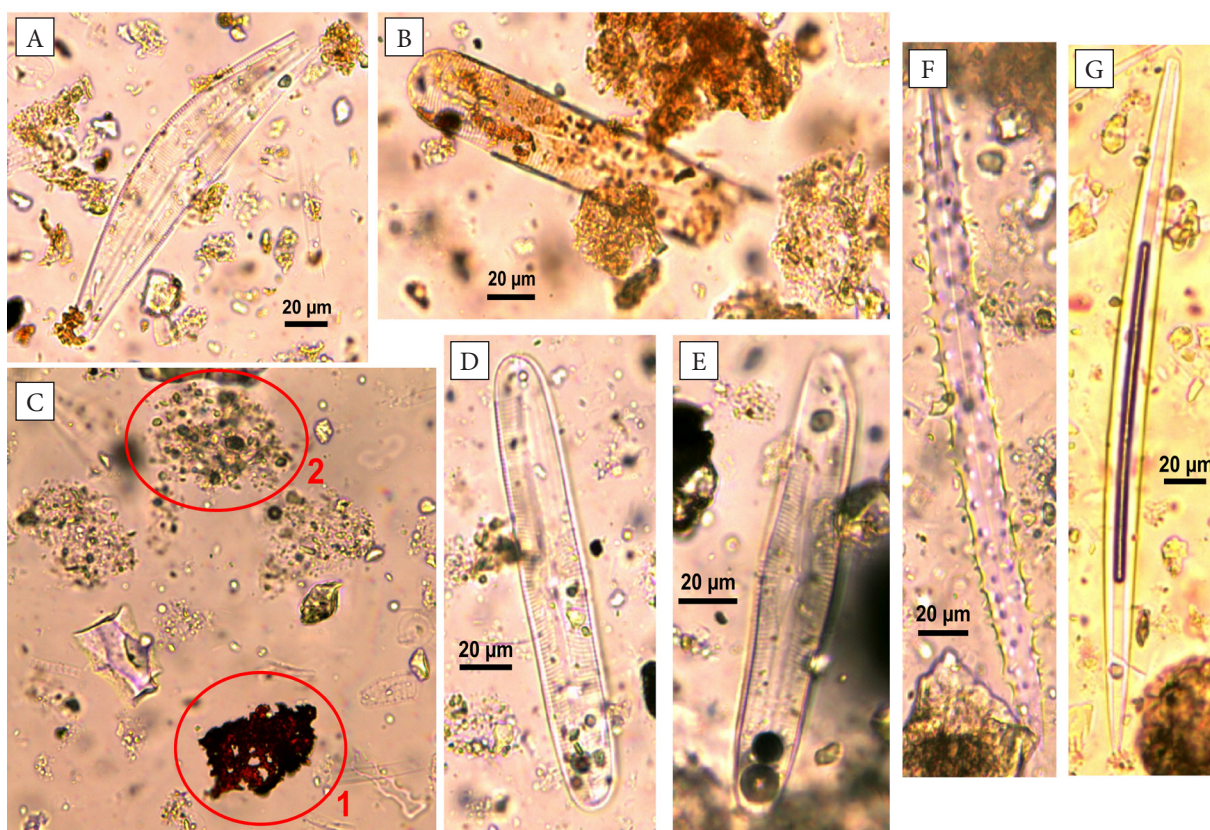


Fig. 9. Microscopic images of individual components of the studied ash from the core PKK-1-2 (photos by D. Tsvirko, 2023): A), B) diatoms *Cymbella* sp. (A) and *Pinnularia* sp. (B) from the untreated ash sample no. 3 (depth: 10–15 cm); C) HCl-treated ash sample no. 3 (depth: 10–15 cm) with a fragment of mineral particles probably bonded by metal compounds (1) and a fragment of mineral particles separated from metal compounds by APP (2), the photo without a scale bar; D), E) diatoms *Pinnularia* sp. from the HCl-treated ash sample no. 3 (depth: 10–15 cm); F), G) freshwater sponge spicules in the HCl-treated ash sample no. 4 (depth: 15–20 cm)

DISCUSSION AND INTERPRETATION

Ash mass loss after HCl treatment

After undergoing the ash purification procedure (APP), the ash being studied experienced a decrease in weight (Table 2). Spectral analysis revealed that this weight loss was partly due to the removal of iron compounds from the ash (Table 3), including iron oxides that had been formed during ignition in a muffle furnace (during LOI₅₅₀ procedure). Since before APP iron was in the form of oxides, the masses of these compounds were estimated using data from the SPEKOL11 spectral analysis (Table 3). The masses of iron oxides FeO and Fe₂O₃ were calculated based on the total mass of Fe found in the acid solution, and represented the maximum possible mass of iron oxide (FeO or Fe₂O₃) present in the ash sample (Table 3). However, it is most likely that part of the Fe was in the form of FeO, while the other part was in the form of Fe₂O₃.

If we compare the masses of iron oxides listed in Table 3 with the amount of disappeared ash at room temperature (Table 2), it becomes clear that the iron compounds did not occupy the entire size of the disappeared mass, but only part of it: Fe₂O₃ could potentially occupy from 16.03 to 35.63% of the disappeared mass, while FeO – from 14.42 to 32.06%. However, it should be noted that the percentage comparison provided was based on the mass at room temperature, and did not account for moisture absorbed by the ash. In our study, we did not use a desiccator, so moisture from the air at room temperature was included in the ash mass. In fact, it is important to consider that a greater volume of ash was occupied by iron oxides.

According to atomic absorption spectrometry results, the rest of the disappeared mass was likely constituted by other metal compounds such as K₂O, K₂CO₃, MgO, MgCO₃, CaO, CaCO₃, MnO₂, Na₂O, Na₂CO₃, ZnO, PbO, CuO, Cu₂O and others.

Environmental factors and metal content in biogenic deposits

The ash purification procedure resulted in the highest ash weight loss (ranging from 51.14 to 72.62% – Table 2) for samples nos. 11–15 which had LOI₅₅₀ values between 80 and 85%. These samples were highly organic, which apparently contributed to their ability to absorb a greater

amount of metal elements from the environment (on metal absorption see Rashid 1974, Brown et al. 2000, Krumins & Robalds 2015). For instance, the significant presence of Fe in samples nos. 11–15 (Fig. 6) could be due to its absorption from iron-saturated groundwater (on groundwater fluctuations and Fe see Bigham et al. 2002). However, it cannot be concluded that samples rich in organic always contain a substantial amount of absorbed metal compounds. Additional experiments on other highly organic samples, such as samples nos. 19–24 and 28 (with LOI₅₅₀ values ranging 69.33–76.42% – Table S2 in the OSM, Fig. 3), showed that the ash mass loss after the APP and the amount of metal elements and their oxides and carbonates were not as significant as for samples nos. 11–15. In this case, it is more appropriate to refer to the potential of a large amount of organic matter to absorb more metal elements from the environment.

It is important to consider that other environmental factors can impact the metal content in organic matter. Specifically, high levels of Fe observed in samples nos. 11–15 and additional samples nos. 16–18 (Fig. 3, Table S2 in the OSM) may be attributed to fluctuations in the level of groundwater saturated with Fe (on this topic see Bigham et al. 2002). During the profile sampling in August 2020, the groundwater level was at approximately 0.8 m below surface – which aligns with the range of these samples. We believe that in our case, the fluctuations in groundwater level were the key determinant in the distribution of metals compounds in the sediment profile.

In fact, metal cations, which were part of oxides and carbonates, may accumulate in biogenic deposits through various means. Groundwater saturated with metal elements has been identified as one possible source (on this topic see Bigham et al. 2002). Metal accumulation in living organisms during their vital activities is another potential source, especially for plant organisms that are fundamental in the formation of biogenic deposits. Plants require elements such as Fe, K, Mn, Na, Zn, Cu, and others to survive and develop (Vatansever et al. 2017, Kaur et al. 2023). One more possible source is metal contamination of biogenic deposits and plants as a result of anthropogenic activities (Patel et al. 2020). However, the APP described in this study effectively removed all these

metals from the ash. The authors suggest that these metal cations should be considered either as part of the organic component of biogenic sediments or as part of post-sedimentary processes (i.e. formation of metal compounds as a result of fluctuations in the groundwater level, natural decomposition, and the humification of organic matter, etc.). To avoid misinterpretations of the textural analysis results, it is necessary to remove these metal cations from the ash.

Actual organic matter content (OMC) in geological deposits

After removing both metal cations and their oxides and carbonates from the ash samples, we were able to estimate the actual OMC (Fig. 5). In fact, biogenic deposits had more organic matter than what was initially shown through the LOI_{550} method, which does not account for the formation of metal oxides and carbonates during the ignition process. When considering metal cations as part of the mineral component of biogenic sediments, the actual organic matter content will lie between the LOI_{550} values and the values of OMC after APP (Fig. 5).

Use of the ash for laser textural analysis

By applying the proposed procedure of using HCl acid to purify ash from metal oxides and carbonates, we gained insights into the problem of using the ash for textural analysis.

Based on our investigations, it has been established that relying on results of textural analysis for untreated ash from organic samples with LOI_{550} values exceeding 80% can lead to inaccurate interpretations. For instance, our analysis showed that untreated ash samples nos. 13–15 did not reflect the substantial sand fraction admixture as recorded after APP (Figs. 7, 8). Moreover, the results for untreated ash of highly organic samples nos. 11 and 12 did not mirror the actual grain size distribution. From the diagram presented in Figure 7, it is evident that the untreated ash samples nos. 11 and 12 had a sand fraction content that was nearly identical to samples nos. 13–15. However, upon analyzing the HCl-treated ash, it was revealed that the sand fraction admixture in samples nos. 11 and 12 was significantly lower (Fig. 8). It should also be noted that the untreated ash for samples nos. 11 and 12 obscured a considerable

amount of clay and medium silt fractions in the mixture. All these observations can be explained by the fact that such highly organic deposits, with high admixture of metals (Figs. 3, 6), form high amount of metal oxides and carbonates during ignition in a muffle furnace. Aggregates formed by these metal compounds and silt and clay particles impact on the results of grain size distribution analysis for the mineral component of biogenic deposits (i.e. for ash samples after LOI_{550} procedure).

Among the samples analyzed, the formation of metal carbonates took place almost exclusively in highly organic samples nos. 11–15 (Table 2). The untreated ash from these samples also had the strongest red color (Fig. 4A), but after interacting with HCl, it changed to grey color (Fig. 4B), along with the disappearance of most of the ash mass (Table 2). Accordingly, the amount of organic matter in the samples was an important factor that should be taken into account when planning textural analysis of the ash after LOI_{550} . This is because the more organic matter in sediments, the more CO_2 is released during ignition, which forms carbonates upon further reaction with metal oxides (Formula (3)). Additionally, the more organic matter in the sediments, the more metals can potentially be absorbed from the natural environment, which later form metal oxides and carbonates during ignition, “contaminating” the studied ash for textural analysis. Also, the more organic matter together with metals in the sediments, the greater volume of their ash will contain aggregates of metal oxides and carbonates.

The next detail was that the ash from the samples with lower organic matter content (around 30% or less), formed fewer metal compounds during ignition (Table 2). Our results show that this was the case for samples nos. 6–9, for which LOI_{550} values ranging from 14.79 to 31.31% and a high admixture of sand fraction was defined. This sand admixture was visible both in the results of textural analysis of the untreated ash and the HCl-treated ash (as shown in Figures 7, 8). Therefore, it is generally advisable to rely on the textural analysis data of the untreated ash, but only to observe the granulometric trend of the sand admixture. However, it is important to note that the textural analysis of untreated ash in such cases can only reveal the trend of sand admixture, while

the obtained quantitative values will not necessarily reflect the actual composition of the mineral component of biogenic deposits. The untreated ash samples nos. 6–9 contained significantly more sand-sized particles than the HCl-treated samples.

In our example, we encountered an unclear situation involving medium organic samples (nos. 3–5 and 10). For these samples LOI_{550} values range from 35.92 to 57.71% (Table 2). On the one hand, there seemed to be a slight presence of sand fraction in both the untreated ash and the HCl-treated ash (Figs. 7, 8). The amount of coarse silt was very similar for these samples (Table 5). However, on the other hand, the untreated ash contained more very coarse silt, while the HCl-treated ash had more medium, fine, and very fine silt fractions. To ensure more reliable results for ash textural analysis of medium organic samples, the authors recommend using the APP described in this paper.

During the analysis of sand samples nos. 31 and 32, an interesting discovery was made regarding the “contamination” of untreated ash. It was found that this “contamination” was mainly caused by silt particles. It was especially well seen in the case of untreated ash of sample no. 31 (which had a LOI_{550} of 5.96%), containing twice as much silt (primarily coarse and very coarse silt) as the HCl-treated ash (Table 6). However, overall results indicated that sand samples with minimal organic matter (LOI_{550} values <6%, Table 3) can be analyzed for ash texture without APP treatment. The grain size distribution analysis of both untreated and HCl-treated ash for samples nos. 31 and 32 showed that fine and medium sand fractions were dominant.

Based on the collected materials, we can draw some general conclusions. All untreated ash samples had an excess of very coarse silt or, in some cases, coarse silt when compared to the HCl-treated samples. Accordingly, metal oxides and carbonates formed in the muffle furnace had a significant impact on the amount of these fractions and can obscure the results of grain size distribution analysis. It is possible that metal oxides and carbonates grew on the surface of small silt particles, causing them to enlarge and become coarse and very coarse silts, and sometimes even very fine sand, as noted for samples nos. 3–10, 31 and 32. Metal compounds may have also grown on sand particles, increasing their size. It is also possible that

particles stuck together to form aggregates due to the formation of metal oxides and carbonates (Fig. 9C). Further studies and verification are needed to confirm these conclusions about the form of existence of metal compounds at the ash micro level after LOI_{550} procedure.

It is important to note that in samples nos. 11–15, 31 and 32 there was a distinct increase in the amount of sand fraction after HCl treatment (Table 6), which in some cases led to an increase in the mean grain size M_z (samples nos. 13–15, 31 and 32 – Table 4). For samples nos. 11–15, we explain this by a decrease in ash volume after the HCl procedure (Fig. 4). After undergoing HCl treatment, these samples exhibited a significant decrease in the amount of very coarse and coarse silt fractions. This resulted in relative increase of content of sand fraction. Thus, sand fraction constituted a higher proportion of the ash volume after HCl treatment. A decrease in the content of very coarse and coarse silt particles after APP also occurred for samples nos. 31 and 32.

A separate topic for research is how the temperature of 550°C affects the mineral component and whether mineral particles could be destroyed in the muffle furnace. Here we only note that the diatoms found during the microscopic analysis of the studied ash retained their sculpture after heating to 550°C (Fig. 9).

The suggested ash purification procedure (APP) can assist in identifying lithological boundaries when there is uncertainty. This approach is particularly useful in cases like ours, where samples nos. 6–9 showed a considerable sand content that could be indicative of lithological boundaries.

It is important to note, however, that our conclusions were based on a limited selection of samples (only fifteen in total). Nevertheless, the samples we presented were varied in composition and represent diverse deposit types.

CONCLUSIONS

The summary included the following findings from the research:

1. The ash purification procedure (APP) was introduced as a laboratory technique to purify ash from secondary metal oxides and carbonates that are formed during ignition at 550°C with absorption of O_2 and CO_2 from the

atmosphere. The quantity of metal oxides and carbonates in the ash is dependent primarily on the amount of metals found in the biogenic deposits before ignition. All these impurities distort the results of grain size distribution analysis of the untreated ash after LOI₅₅₀ procedure.

2. Following the implementation of the ash purification procedure (APP), there was a decrease in the ash mass as a result of elimination of secondary metal oxides and carbonates. The higher the presence of metal oxides and carbonates in the ash, the more significant the reduction in ash mass.
3. A particularly significant difference between the results of grain size distribution analysis for untreated and HCl-treated ash was documented for highly organic deposit samples containing substantial amounts of metal compounds. To avoid any possible misinterpretations, we recommend that the ash be purified of metal compounds before undergoing textural analysis.
4. According to the obtained results, the untreated ash of all investigated samples was featured by higher amount of very coarse and/or coarse silt fractions compared to the HCl-treated ash. This is due to the formation of aggregates of metal oxides and carbonates with mineral particles during LOI₅₅₀ procedure. Additionally, the untreated ash had a lower content of medium, fine, very fine silt, and/or clay fractions compared to the HCl-treated ash.

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