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Allerød–Younger Dryas Boundary (12.9–12.8 ka) as a "New" Geochronological Marker in Late Glacial Sediments of the Eastern Baltic Region

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Abstract: This paper is a contribution to the ongoing debate on the nature and drivers of the abrupt environmental shift at the onset of the Younger Dryas. The goal of this study is to identify key parameters that characterize the Allerød–Younger Dryas boundary, 12.9–12.8 ka in sedimentary sections, and are representative of broader paleobasin dynamics in the eastern Baltic region. Two new Late Glacial sediment archives, the Kulikovo and Sambian, provide data on this time interval. Geochronological and lithological (grain size and loss on ignition) analyses of the sequences indicate a change in sedimentation during 12.9–12.8 ka, which is manifested by a peak of terrigenous, coarser-grained material and an accompanying peak of organic matter in sediments. A review of the published data shows that this lithological situation is also characteristic of other paleobasins in the eastern Baltic region and beyond for layers dated to the onset of the Younger Dryas. This probably indicates an environmental event that caused a short-term increased input and deposition of organic matter, accompanied by a surge in erosional processes. The environmental shift triggered by the event is also recorded in a remarkable drop in pollen concentration and species diversity in the overlying layer. The sediment horizon in Late Glacial (Allerød–Younger Dryas) sequences corresponding to these parameters can be considered an important and reliable geochronological marker of the 12.9–12.8 ka interval. The organic-rich layer in the Kulikovo section, as well as other similar layers in the Baltic, can be considered a "black mat" phenomenon related to the onset of the Younger Dryas.

Keywords: Younger Dryas; lithology; sediments; grain size; loss on ignition; black mat; Baltic region

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1. Introduction

The Late Glacial was a period of highly dynamic environmental change, marked by significant climate fluctuations, glacial retreat, and the formation of new landforms and hydrological networks [1]. These changes also affected soil development and vegetation cover. Detailed investigations of local paleoenvironmental archives are essential not only to complement the global understanding of these processes but also to uncover regional variability and the local drivers of change.

One of the key issues in Late Glacial research is the Younger Dryas (YD) Stadial: the last abrupt climate reversal during the deglaciation of the Northern Hemisphere [1]. This event has been identified in numerous records worldwide, although its impact varied by region. Proposed causes include disruptions in oceanic and atmospheric circulation due to freshwater input from melting ice sheets [2], as well as a possible extraterrestrial impact event, supposing that a large, fragmenting asteroid/comet struck Earth and triggered major environmental shifts (continental drainage patterns, oceanic circulation, abrupt global climate changes) [3]. Despite ongoing debates [4–6], increasing evidence from the Northern Hemisphere, especially the Baltic region, highlights significant shifts in seasonal temperature and aridity [7–9], vegetation patterns, such as the reduced spreading of forests and species diversity [10,11], erosion, fire activity [12,13], and hydrological regimes [14,15] during the Allerød–Younger Dryas boundary (Al-YDB). The Al-YDB is often marked by specific soil types (e.g., Usselo and Finow), with sandy layers and high charcoal content [12], as well as by "black mats"—organic-rich layers indicating drastic environmental changes [13,16].

Recently, new Late Glacial sedimentary sections have been discovered in the south-eastern Baltic region (Kulikovo and Sambian sites, Kaliningrad Oblast, Russia), which potentially contain valuable information on the processes occurring at the Al-YDB (Figure 1). These sites are being investigated using a combination of methods, and while most results have been published separately [17–19], this study focuses specifically on the lithological characteristics (grain size and loss on ignition) of the Al-YDB layers. The goal is to identify key parameters that characterize this boundary and are representative of broader paleobasin dynamics in the region.

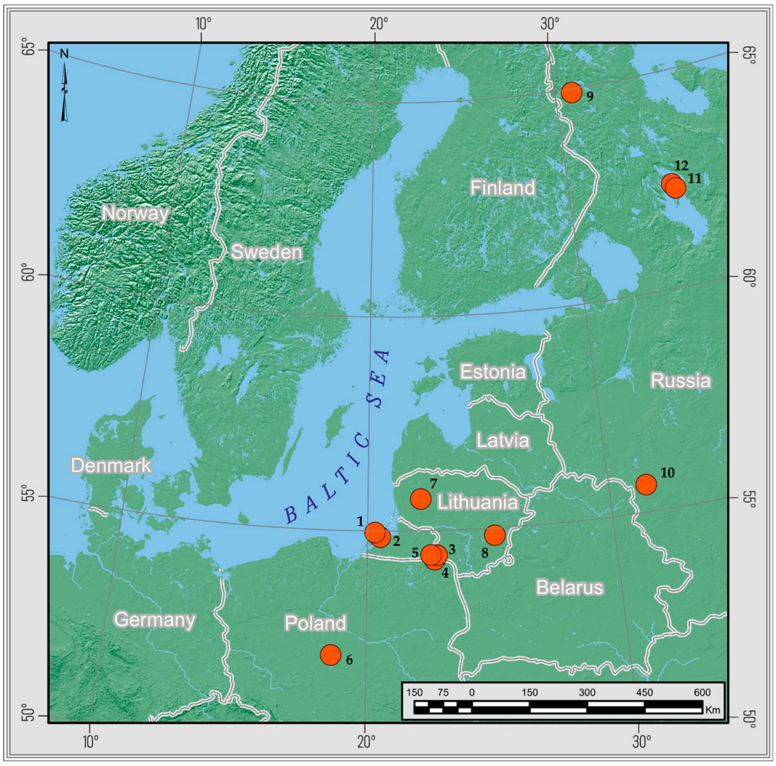

Figure 1. Location of the objects with Late Glacial (AL-YDB) layers considered in the text: (1) Kulikovo; (2) Sambian; (3) Kamyshovoe; (4) Chistoe; (5) Protochnoe; (6) Kozmin Las; (7) Lopaičiai; (8) Dukstelis; (9) Myantyulampi; (10) Serteya Mire; (11) Polevskoye; (12) Keratskoe.

This research represents an initial step towards a targeted study of the Al-YDB in eastern Baltic paleoarchives, particularly in lake sediments, to improve our understanding of Late Glacial environmental transformations.

2. Materials and Methods

2.1. Fieldwork and Sampling

Both sampling locations are situated in the northern part of the Sambian Peninsula, in the south-eastern Baltic region (Figure 1). The surface of this territory, represented mainly by undulating marginal moraines, was formed by the retreating Late Weichselian ice [20]. Morain hills formed by till deposits dominate the landscape, with sandy and silty depressions of glaciolacustrine and glaciofluvial origin.

The Kulikovo outcrop section (N54°56′12.9″; E20°21′31″) is 1.92 m long. Sediment samples were taken in metal boxes with a 7 cm diameter and 50 cm long and transported to laboratories for further processing and analyses. Sampling was carried out depending on the visible layering of the sediment (1–3 cm each). The Sambian paleolake sediment sequence (N54°50′00″; E20°30′00″) is 9.6 m long. The lower part of the sequence, up to 4.5 m, is presented in this paper. The sediment core was obtained using a Russian corer (1 m long chamber with a 5 cm inner diameter). Sampling for lithological analysis was carried out every 10 cm.

2.2. Geochronological Analysis

Five samples from the Kulikovo section and seven samples from the Sambian sequence were subjected to radiocarbon dating in the Lund University Radiocarbon Laboratory (Lund, Sweden) and the Saint-Petersburg University Radiocarbon Laboratory (Saint-Petersburg, Russia) (Tables 1 and 2). All dates were calibrated to calendar years before present (BP) using the IntCal20 calibration curve [21]. The age–depth models (ADM) were built using the Rbacon programme 3.1.0 [22].

Table 1. Geochronology of the Kulikovo section.

Depth, cm	Sample	Material	Age, ^{14}C	Age, cal yr BP (68.2% Probability)
45	LuS-18463	macroremains (wood)	10,940 ± 60	12,900–12,760
106	LuS-18462	macroremains (wood)	11,060 ± 60	13,075–12,920
163	LuS-18461	macroremains (wood)	11,790 ± 60	13,755–13,525
186	LuS-18460	macroremains (wood)	11,980 ± 80	14,020–13,785
192	LuS-17811	sediment (gyttja)	12,200 ± 60	14,185–14,040

Table 2. Geochronology of the Sambian sequence.

Depth, cm	Sample	Material	Age, ^{14}C	Age, cal yr BP (68.2% Probability)
220	LU-11433 *	peat	6670 ± 100	7620–7430
270	LU-11432 *	peat	6940 ± 90	7920–7680
349	LuS-19369	peat	7425 ± 45	8325–8185
734	LuS-19367	sediment (silty gyttja)	11,880 ± 70	13,800–13,605
801	LuS-19370	sediment (silty gyttja)	12,060 ± 70	14,040–13,805
884	LuS-19368	sediment (silty gyttja)	14,480 ± 80	17,805–17,480
958	LuS-19371	sediment (silt)	16,360 ± 160	19,930–19,540

* conventional; other—AMS dates.

2.3. Lithological Analysis (Grain Size and Loss on Ignition)

Overall, 68 samples from the Kulikovo section and 52 samples from the Late Glacial part of the Sambian sediment sequence were studied.

The grain size analysis was performed on a Malvern Mastersizer 3000 laser diffractometer with a Hydro EV receiver. Sample preparation included the removal of the carbonate component of the sediment with a 10% solution of hydrochloric acid and the removal of organic matter using 30% hydrogen peroxide. Samples were continuously rotated for 12 h with a 4% sodium pyrophosphate solution. Then, the material was dispersed using an ultrasonic bath (360 W) for 30 min before measurement on a laser diffractometer. The particle size distribution was determined using the Mie diffraction model [23].

Loss-on-ignition (LOI) analysis included the sequential heating of the samples in a muffle furnace at three temperatures (105 °C (dry weight), 550 °C (organic matter), and 950 °C (carbonate content)) and weighing on an electronic scale after each heating step [24].

The lithological description of sediments is based on granulometry and organic matter content [25].

3. Results

3.1. Geochronology

The results of the geochronological study are presented in Tables 1 and 2 and Figures 2 and 3.

The Kulikovo section spans an age range from 14,185 to 14,040 cal yr BP to at least 12,900 to 12,760 cal yr BP. The uncertainty of the age modelling changes through the sequence, from ±130 to 160 years for the lowest part to ±200 to 240 years for the top. ADM was not built for the 45–0 cm range due to the expected significant error. According to ADM, an applied sampling interval of 1–3 cm roughly corresponds to 6–30 years.

The Sambian sequence dating results show that sedimentation in the basin lasted from 19,930 to 19,540 cal yr BP to 7620 to 7430 cal yr BP. The ADM covers the 9.6–2.0 m interval, as the dating of the samples of the upper part is still in progress. The lower part of the ADM, up to 9655 ± 720 cal yr BP, is presented in this paper. The uncertainty of the age modelling varies from ±270 to ±910 years. According to ADM, 1 cm of sediment sequence roughly corresponds to 15 years, except for in the lower part (up to 8 m), where this can range between 10 and 40 years.

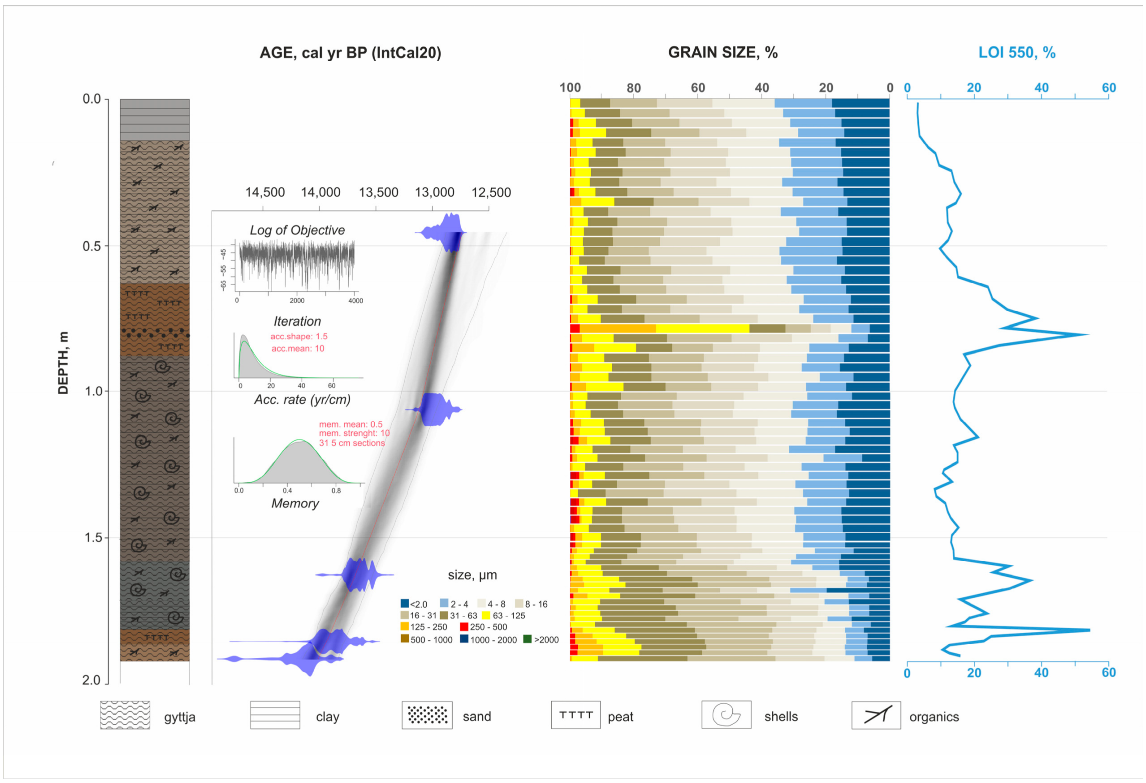

Figure 2. The Kulikovo section. Results of the geochronological and lithological analyses. Acc. rate: accumulation rate; LOI: loss on ignition.

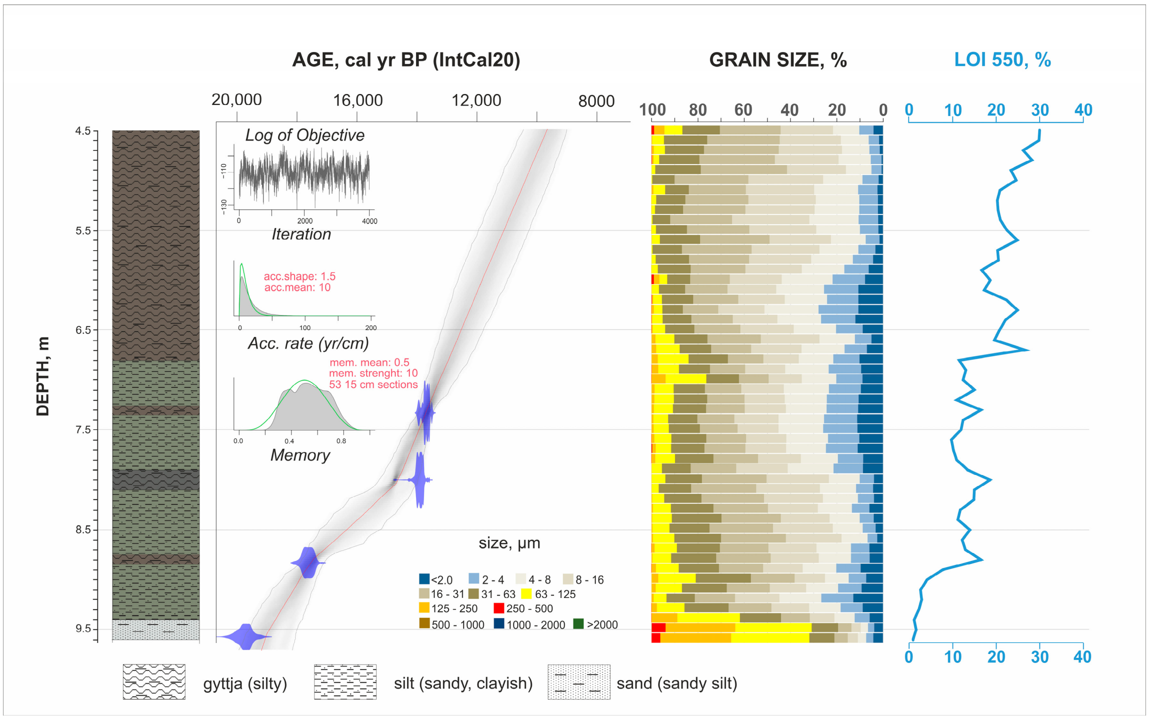

Figure 3. The Sambian sediment sequence. Results of the geochronological and lithological analyses. Acc. rate: accumulation rate; LOI: loss on ignition.

3.2. Lithology

Sediments of the Kulikovo section are dominated by clay (up to 36%) and silt (up to 84%). The proportion of sand varies from 2 to 22%. The exception is the layer at a depth of 78–79 cm, where the sand fraction sharply predominates, reaching 56%. Two major parts of the section can be distinguished in terms of prevailing grain fraction. The lower part (depths 192–162 cm) is less clayey, and here the content of sand and coarse or very coarse sandy silt reaches more than 60%. Upwards along the section, the proportion of clayey fractions increases, and from the depth of 157 cm, clayey silt (medium, fine, very fine) and clay start to prevail in the grain composition, except at the mentioned depth of 78–79 cm, where a significant increase in the sand fraction is observed. The organic matter content in sediments varies widely from 3 to 56%. Peak zones with increased values are distinguished at depths of 187–157 cm and 87–63 cm. Sediments from the Kulikovo outcrop were subdivided into eight lithological units according to organic matter value (Table 3). From a depth of 192 cm to 14 cm, the sediments are represented by layers of peaty dark brown or clayish grey or brown gyttja. Sediments contain a lot of organic matter, such as plant remains and shells. A bed of grey dense clay forms the upper part of the sequence (14–0 cm).

Sediments of the Sambian paleolake are dominated by clay (up to 28%) and silt (up to 88%). The proportion of sand varies from 2 to 70%. The peaks of sandy material are noted at depths of 9.0, 7.0, 6.8, and 4.5 m. Sediments at the depth of 9.6–9.4 m contain the highest amount of sand and sandy silt (very coarse and coarse) throughout the sequence: more than 80%. Above this depth, an increasing amount of clayey fractions can be observed. The values fluctuate between 50 and 70% along the major part of the core. Significant changes in the organic matter content are recorded: within 2–5% in the lowest part, with a sharp increase of up to 17–18% at a depth of 8.8. m, and with fluctuations within 918% until another jump of up to 27% at a depth of 6.7 m; there is then a decrease and irregular, gradual growth of up to 30% at 4.5 m.

Table 3. Lithostratigraphy of the Kulikovo section.

Depth, cm	Lithostratigraphy
0–14	Clay, grey, and dense
14–63	Gittja, clayish, grey, and light brown, with sparse organic matter
63–87	Gittja, peaty, and dark brown, with organic matter and a thin sandy interlayer
87–158	Gittja, clayish, dark grey, and brown, with organic matter and shells
158–171	Gittja and dark grey, with organic matter and shells
171–181	Gittja, clayish, and dark grey, with sparse organic matter and shells
181–186	Gittja, peaty, and dark brown
186–192	Gittja, clayish, and brown, with organic matter

The investigated sediment section consists of five units (Table 4). The bottom layer (9.6–9.4 m), formed by sand and sandy silt, is overlayed by laminated silt, sandy and clayish, and grey and olive in colour. Above it, two layers of gyttja (8.1–7.9 and 6.8–4.5 m) are formed in the basin, separated by a layer of laminated silt. Thin interlayers of gyttja can also be observed at depths of 8.8 and 7.3 m.

Table 4. Lithostratigraphy of the late Pleniglacial and Late Glacial parts of the Sambian sediment sequence.

Depth, m	Lithostratigraphy
4.5–6.8	Gyttja; silty; dark grey, brownish, and olive
6.8–7.9	Silt, sandy, clayish, and laminated; grey and olive; with an interlayer of silty gittja at 7.3 m
7.9–8.1	Gyttja, silty, and dark grey
8.1–9.4	Silt, sandy, clayish, and laminated; grey and olive; with an interlayer of silty gittja at 8.8 m
9.4–9.6	Sand; sandy silt

4. Discussion

The Kulikovo paleobasin is apparently one of the shallow waterbodies formed as a result of intense ice melting and water supply in the region during the Bølling interstadial [17]. The Sambian paleolake, along with some other nearby basins in the region (Kasuciai and Ginkunai lakes) [11,26], represents one of the earliest paleolakes that emerged during the initial stages of deglaciation in the south-eastern Baltic. Sedimentation in this paleobasin began in the late Pleniglacial and continued throughout the Late Glacial and the Holocene periods. Both of the sediment archives, the Kulikovo section and the Sambian paleolake, provide an opportunity to highlight the lithological features of the Al-YDB in the time interval of 12.9–12.8 ka.

In the Kulikovo section, according to the dates obtained, the Al-YDB can be placed between the depths of 106 cm (13,102 $\pm$ 160 cal BP) and 45 cm (12,773 $\pm$ 240 cal BP). A remarkable feature of this sediment interval is an organic-rich layer (87–63 cm) marked by an increased input of mineral coarse materials (78–79 cm, modelled age of 12,960 $\pm$ 210 cal BP), manifesting an essential environmental shift (Figure 4). It is likely that this layer can be considered an analogue of the "black mat", a phenomenon actively studied within the YD Impact hypothesis. "Black mats" are found at numerous Al-YDB sites on different continents [13,16,27], and the most studied are in the USA, where the classic black mat "type" was first discovered [27]. The term "black mat" applies to dark, organic-rich deposits (containing an increased amount of organic matter compared with strata above and below) but also to some marls and diatomites that are white or grey, rather than black, dated Al-YDB or to the YD chronozone [16]. According to the impact hypothesis, large quantities of organic matter are inferred from increased biotic degradation as a result of the catastrophic impact of environmental and climatic changes [13]. Haynes [16] considers these layers to be complex pedological features that appear to be a stratigraphic reflection of the YD climate and indicate a rise in local water tables, apparently because of more effective recharge, as a result of a cooler climate. Two major processes could form black mats: the deposition of organic-rich material, as happens in wetlands, for example, and soil formation, possibly due to the weathering of stable, organic-rich landscapes [16]. Regardless of the overarching reason for its genesis, black mats demonstrate sudden and essential changes in environmental (e.g., sedimentological) conditions in the chronological Al-YDB.

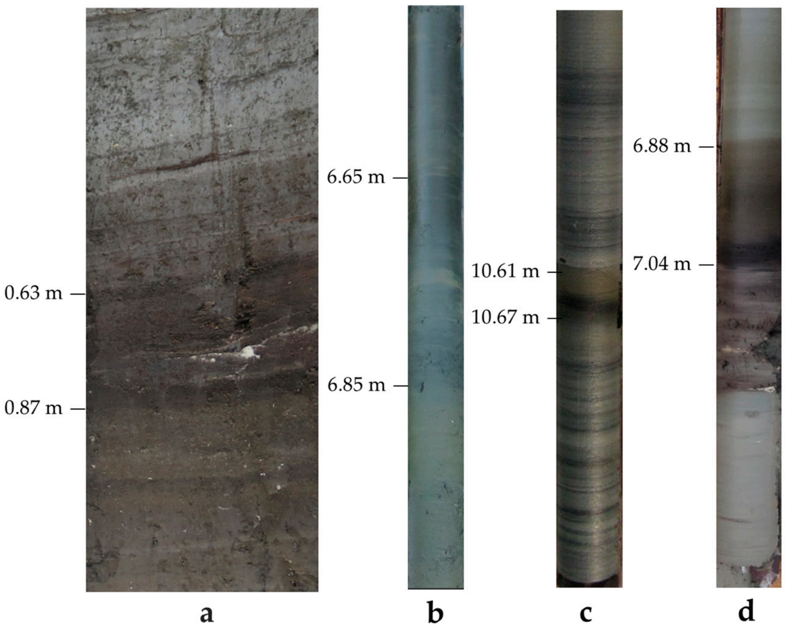

Figure 4. Visual change in lithostratigraphy in Late Glacial (AL-YDB) layers: (**a**) Kulikovo; (**b**) Sambian; (**c**) Kamyshovoe; (**d**) Chistoe.

Black mats contain various amounts of charcoal, or none at all, and it could be abundant immediately below the black mat [13,27]. Enrichment in charcoal and soot is explained by wildfires resulting from impact [13] and/or dryer climate conditions during this time interval [12]. Wolbach et al. [13] showed that the majority of sites with black mats also display peaks in proxies related to the YD Impact hypothesis (e.g., magnetic spherules, carbon spherules, high-temperature meltglass, and/or nanodiamonds). These two types of data are subjects for further research in the south-eastern Baltic sequences.

A review of the published data indicates that some layers discovered in Poland and Lithuania can also be an analogue of the "black mat" (Figure 5, Table 5). One of the examples is the sediment horizon found in the Kozmin Las location, the Warta River basin, in Central Poland [28]. The middle unit of the studied sequence, mainly composed of organic-rich deposits, had an assemblage of tree remains such as collapsed trunks, stumps, individual branches, and roots, covered by dark grey organic mud and brown-black strongly decomposed peat [28] (pp. 103–104). The radiocarbon dating showed that a forest may have existed in the earliest YD or covered the Al-YDB period and appears to have been destroyed during the onset of the YD by deteriorating hydrological conditions or a sudden catastrophic event (such as strong wind) [28].

Another example is the sediment section of Lopaičiai, the north-western part of Lithuania [29]. Here, on the layer of sand with a gravel admixture, a thin layer of gyttja and grey–brownish clay with organic matter and remnants of timber and plants was deposited during the 12.9 time interval, overlayed by a very thin (1 cm) interlayer of fine sand, showing a short-lasting episode of increased erosion [29]. The Lopaičiai and Kozmin Las data expose one more indicator of essential environmental shift that occurred at the Al-YDB, and that is a noticeable change in the composition of the vegetation cover above the Al-YDB, recorded by a decrease in pollen concentration [28] (p. 111), [29] (p. 168). The sudden drop in pollen concentration and/or taxa diversity is a characteristic feature for layers above the black mats at the sites where the latter are found [13,27], including the Kulikovo section (*in prep.*).

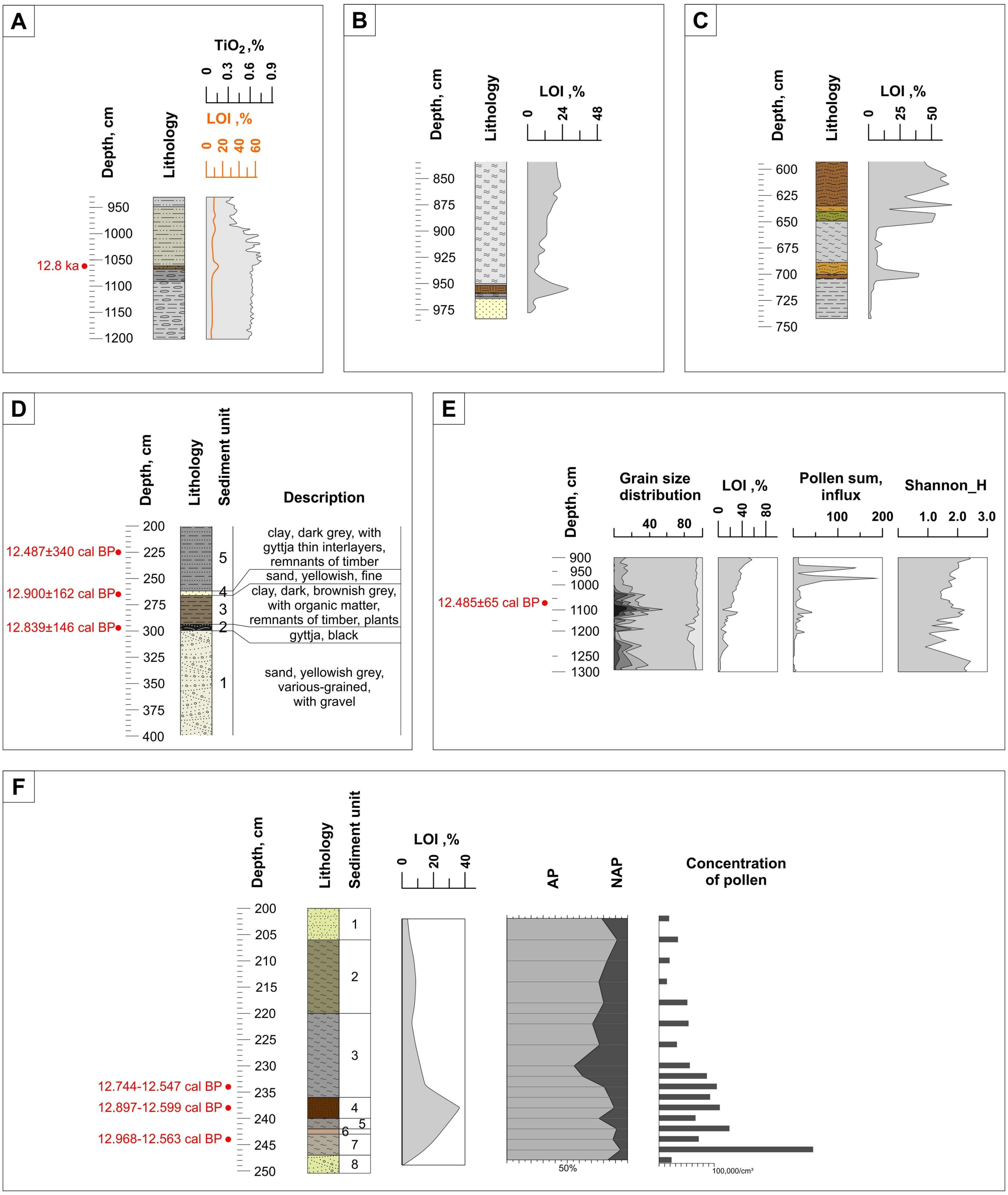

Figure 5. Layers with (supposed) AL-YDB in the eastern Baltic and their characteristics: (**A**) Kamyshovoe [30,31]; (**B**) Protochnoe [32]; (**C**) Chistoe [32]; (**D**) Lopaičiai [29]; (**E**) Dukstelis [33]; (**F**) Kozmin Las [28]. LOI: loss on ignition; AP: arboreal pollen; NAP: non-arboreal pollen. For explanation of numbers and different symbols please see the references provided.

Table 5. Objects with (supposed) AL-YDB layers in the eastern Baltic region and beyond.

No.	Location	Coordinates, m a.s.l.	Parameters	Available Dating	References
1	Kulikovo	N54°56′12.9″; E20°21′31″; 2	Visual change in lithostratigraphy, coarse material interlayer, granulometry, LOI, presence of organics, and pollen concentration	AMS ^{14}C, modelled age	This publication
2	Sambian	N54°50′00″ E20°30′00″; 13	Granulometry and LOI	AMS ^{14}C, modelled age	This publication
3	Kamyshovoe	N54°22′36.1″; E22°42′47″; 192	Visual change in lithostratigraphy, LOI, and geochemistry (TiO_2)	AMS ^{14}C, modelled age	[30,31]
4	Chistoe	N54°23′22.5″; E22°43′47″; 201.7	Visual change in lithostratigraphy and LOI	Biostratigraphy	[32]
5	Protochnoe	N54°24′18.7″; E22°36′43.4″; 153	Visual change in lithostratigraphy and LOI	Biostratigraphy	[32]
6	Kozmin Las	N52°4′51.3″; E18°40′03″; 97.5	Visual change in lithostratigraphy, LOI, presence of organics (wood), and pollen concentration	AMS ^{14}C	[28]
7	Lopaičiai	N55°44′37.47″; E22°11′34.28″; 178.7	Visual change in lithostratigraphy, coarse material interlayer, presence of organics (wood and other plants), and pollen concentration	AMS ^{14}C	[29]
8	Dukstelis	N54°50′10″; E25°09′59″; 156	Granulometry, LOI, pollen concentration, and Shannon Diversity Index	AMS ^{14}C	[33]
9	Serteya Mire	N 55°37′53″; E31°32′28″; 152.5	Visual change in lithostratigraphy, granulometry, LOI, geochemistry (erosion rate, Ca/Fe), and presence of organics	AMS ^{14}C	[34]
10	Myantyulampi	N64°54′51″; E30°54′52.8″; 12	Visual change in lithostratigraphy, coarse material interlayer, and presence of organics (burnt wood)	^{14}C	[35]
11	Polevskoye	N62°18′43″; E35°16′49″; 54.7	Visual change in lithostratigraphy, coarse material interlayer, and presence of organics	Biostratigraphy	[36]
12	Keratskoe	N62°19′39.9″; E35°15′42.2″; 54.6	Visual change in lithostratigraphy, coarse material interlayer, and presence of organics	Biostratigraphy	[36]

In the Sambian sequence, although changes in lithology are not so obviously visible as in the Kulikovo one, an environmental event (or a chain of such) also caused a change in sedimentation (Figure 4). This is reflected by a peak of coarser material at a depth of 7.0 m (and a smaller one at 6.8 m), followed by a peak of organic matter at a depth of 6.7 m during the interval of 13.2–12.8 ka (Figure 3). A review of previously studied data on Kamyshovoe lake (Vishtynets Upland, Kaliningrad region) has shown that a thin (6 cm) interlayer of greenish–brown gyttja considered to be from the Al-YDB, with a modelled age of 12.8 ka [30], can also be identified by a combination of lithological parameters. Thus, the organic matter peak and increased content of TiO_2 as an indicator of coarser-grained terrigenous material inflow are recorded at this depth [31]. Two more lakes on the Vishtynets Upland (Chistoye and Protochnoye) reflect a similar situation of a lithostratigraphic change when a thin interlayer with a significant organic matter peak is deposited in the Late Glacial part of the sequences [32] (Figures 4 and 5).

In the case of more complex stratigraphy, with multiple thin interlayers, for example, as in Dukstelis paleolake, in eastern Lithuania, the Al-YDB is most probably marked by a simultaneous peak of organic matter and an inflow of coarser terrigenous material (depth of 1100 cm) [33] (p. 7). Directly above this depth, visible changes in the paleobotanical data are recorded: a drop in the pollen influx and the Shannon Diversity Index [33] (p. 9).

Sediment layers with similar characteristics can also be found outside the eastern Baltic region (Figure 1, Table 5). An organic-rich layer dated to 12.9 ka at the Serteya Mire location (Western Dvina Lakeland, 650 km from the Baltic Sea) demonstrates the peaks of LOI and the erosion rate, along with other data, manifesting a pronounced environmental change [34]. The Lake Myantyulampi (Karelia) sediment sequence shows a change in lithostratigraphy (12.6 ± 1.8 ka), in which varve clay is covered by a coarse material interlayer with the presence of organic materials (burnt wood) [35]. A remarkable change in lithology is also characteristic of Karelian lakes Polevskoye and Keratskoe, where so-called "mix horizons" containing sand and organics (plant remains) separate Late Glacial clay and Early Holocene gyttja parts of the sequences [36].

The above examples allow us to conclude that in the time interval of 12.9–12.8 ka, a significant environmental event (or chain of events) occurred, which led to a change in the sedimentation conditions in many basins of the eastern Baltic region and beyond. The change is manifested by a peak of terrigenous, coarser-grained material and an accompanying peak of organic matter in sediments. The environmental shift that occurred is also recorded in a remarkable drop in pollen concentration and species diversity in the layer after the event. The sediment horizon in Late Glacial (Al-YD) sequences corresponding to these parameters can be considered one of the important and reliable geochronological markers of the 12.9–12.8 ka interval.

The nature of the event that led to abrupt and significant changes in the environment in many parts of the world remains a subject of ongoing debate [4–6]. From the review provided, it is evident that the Al–YDB is widely associated with erosion and coarse-grained sedimentation, potentially indicating energetic depositional events such as turbidity flows and flooding. One of the manifestations of these events in sediments can be turbidites: deposits of turbidity currents. According to the grain size of the suspended materials, turbidites can be muddy or sandy, often with abundant plant remains [37,38]. Targeted studies of the "mixed horizons" of the Polevskoye and Keratskoe lakes in Karelia allowed a hypothesis to be put forward about the turbidite origin of these layers [36]. Among the main causes of the paleoturbidity currents of the Late Glacial and Early Holocene period are increased paleoseismicity and the degradation of glacial lobes, causing the drainage of large proglacial basins [36,39]. While it is a matter of further research whether this hypothesis can be valid for the other objects mentioned in the article, it is necessary to note that one of the most important events specifically for the Baltic region may be the supposed first catastrophic drainage of the Baltic Ice Lake (BIL), dated at 12,846 cal yr BP [15]. nTthe Late Glacial Swedish varves it is accompanied by a sharp, within-one-varve-year change (decrease) in the varve thickness and an increase in the grain size in sediments, which suggest a large-scale change in the BIL circulation regime and/or changes in the sediment supply to the BIL [15]. This "regional" event does not contradict the existence of a more powerful trigger for the numerous environmental changes that occurred in the Baltic region and outside it during 12.9–12.8 ka.

A more precise identification of this geochronological boundary in sediments, based on the correlation of the above-mentioned and other parameters, will allow more insights to be obtained into processes that occurred at the start of the YD.

5. Conclusions

The Allerød–Younger Dryas boundary, 12.9–12.8 ka in the eastern Baltic, is marked by a significant environmental event (or chain of events), which led to a change in sedimentation conditions in many paleobasins of the region. The change is manifested by a peak of terrigenous, coarser-grained material and an accompanying peak of organic matter in sediments. The environmental shift that occurred during this time is also recorded in a remarkable drop in pollen concentration and species diversity in the layer after the event.

A review of the published data shows that this lithological situation is characteristic not only for new Late Glacial sedimentary sections (Kulikovo and Sambian sites, Kaliningrad Oblast, Russia) but also for other paleobasins in Lithuania and Poland, as well as central and northern Russia, for layers dated to the onset of the Younger Dryas. The sediment horizon in Late Glacial (Al-YD) sequences corresponding to the parameters listed above can be considered an important and reliable geochronological marker of the 12.9–12.8 ka interval. The organic-rich layer in the Kulikovo outcrop section, as well as other similar layers in the Baltic, can be considered a "black mat" phenomenon related to the onset of the Younger Dryas. The causes behind the formation of "black mats" and similar "organic-rich" layers in lake sediments are a matter of further research and debate.

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Abbreviations

The following abbreviations are used in this manuscript:

YD	Younger Dryas
Al-YDB	Allerød—Younger Dryas boundary
ADM	Age Depth Model
LOI	Loss-on-ignition
AP	Arboreal pollen
NAP	Non-arboreal pollen

References

1. Naughton, F.; Sanchez-Goni, M.; Landais, A.; Rodrigues, T.; Vazguez Riveiros, N.; Toucanne, S. The Younger Dryas Stadial. In *European Glacial Landscapes. The Last Deglaciation*; Palacios, D., Hughes, P., Garcia-Ruiz, J., Andres, N., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 51–59.
2. McManus, J.F.; Francois, R.; Gherardi, J.-M.; Keigwin, L.D.; Brown-Leger, S. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* **2004**, *428*, 834–837. [CrossRef] [PubMed]
3. Firestone, R.B.; West, A.; Kennett, J.P.; Becker, L.; Bunch, T.E.; Revay, Z.S.; Schultz, P.H.; Belgya, T.; Kennett, D.J.; Erlandson, J.M.; et al. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 16016–16021. [CrossRef]
4. Powell, J. Premature rejection in science: The case of the Younger Dryas Impact Hypothesis. *Sci. Prog.* **2022**, *105*, 1–43. [CrossRef] [PubMed]
5. Holliday, V.T.; Daulton, T.L.; Bartlein, P.J.; Boslough, M.B.; Breslawski, R.P.; Fisher, A.E.; Jorgeson, I.A.; Scott, A.C.; Koeberl, C.; Marlon, J.; et al. Comprehensive refutation of the Younger Dryas Impact Hypothesis (YDIH). *Earth Sci. Rev.* **2023**, *247*, 104502. [CrossRef]
6. Sweatman, M.; Powell, J.; West, A. Rejection of Holliday et al.'s alleged refutation of the Younger Dryas impact hypothesis. *Earth-Sci. Rev.* **2024**, *258*, 104960. [CrossRef]
7. Veski, S.; Seppä, H.; Stančikaitė, M.; Zernitskaya, V.; Reitalu, T.; Gryguc, G.; Heinsalu, A.; Stivrins, N.; Amon, L.; Vassiljev, J.; et al. Quantitative summer and winter temperature reconstructions from pollen and chironomid data between 15 and 8 ka BP in the Baltic–Belarus area. *Quat. Int.* **2015**, *388*, 4–11. [CrossRef]
8. Schenk, F.; Bennike, O.; Valiranta, M.; Avery, R.; Bjorck, S.; Wohlfarth, B. Floral evidence for high summer temperatures in southern Scandinavia during 15—11 cal ka BP. *Quat. Sci. Rev.* **2020**, *233*, 106243. [CrossRef]

9. Muller, D.; Tjallingii, R.; Płociennik, M.; Luoto, T.P.; Kotrys, B.; Plessen, B.; Ramisch, A.; Schwab, M.J.; Błaszkiewicz, M.; Słowinski, M.; et al. Newinsights into lake responses to rapid climate change: The Younger Dryas in Lake Gosciaz, central Poland. *Boreas* **2021**, *50*, 535–555. [CrossRef]
10. Kupryjanowicz, M. Postglacial development of vegetation in the vicinity of the Wigry Lake. *Geochronometria* **2007**, *27*, 53–66. [CrossRef]
11. Stančikaitė, M.; Šeirienė, V.; Kisielienė, D.; Martma, T.; Gryguc, G.; Zinkutė, R.; Mažeika, J.; Šinkūnas, P. Lateglacial and early Holocene environmental dynamics in northern Lithuania: A multi-proxy record from Ginkūnai Lake. *Quat. Int.* **2015**, *357*, 44–57. [CrossRef]
12. Kaiser, K.; Hilgers, A.; Schlaak, N.; Jankowski, M.; Kuhn, P.; Bussemer, S.; Przegietka, K. Palaeopedological marker horizons in northern central Europe: Characteristics of Lateglacial Usselo and Finow soils. *Boreas* **2009**, *38*, 591–609. [CrossRef]
13. Wolbach, W.; Ballard, J.; Mayewski, P.; Kurbatov, A.; Bunch, T.; Le Compte, M.; Adedeji, V.; Israde-Alcántara, I.; Firestone, R.; Mahaney, W.; et al. Extraordinary biomass-burning episode and impact winter triggered by the Younger Dryas cosmic impact <12,800 years ago. 2. Lake, marine, and terrestrial sediments. *J. Geol.* **2018**, *126*, 185–205.
14. Gałka, M.; Tobolski, K.; Bubak, I. Late Glacial and Early Holocene lake level fluctuations in NE Poland tracked by macro-fossil, pollen and diatom records. *Quat. Int.* **2015**, *388*, 23–38. [CrossRef]
15. Muschitiello, F.; Lea, J.M.; Greenwood, S.L.; Nick, F.M.; Brunnberg, L.; Macleod, A.; Wohlfarth, B. Timing of the first drainage of the Baltic Ice Lake synchronous with the onset of Greenland Stadial 1. *Boreas* **2015**, *45*, 322–334. [CrossRef]
16. Haynes, C.V. Younger Dryas "black mats" and the Rancholabrean termination in North America. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 6520–6525. [CrossRef]
17. Druzhinina, O.; Rudinskaya, A.; Filippova, K.; Lazukova, L.; Lavrova, N.; Zharov, A.; Skhodnov, I.; Burko, A.; van den Berghe, K. The Bølling–Allerød Transition in the Eastern Baltic: Environmental Responses to Climate Change. *Biology* **2023**, *12*, 821. [CrossRef]
18. Golyeva, A.A.; Druzhinina, O.A. Microbiomorphic analysis in the study of the late glacial natural environment: Preliminary results of the study of the Kulikovo section (Sambian Peninsula, Kaliningrad region). *Bull. Russ. Acad. Sci. Geogr. Ser.* **2024**, *88*, 77–89. (In Russian)
19. Rudinskaya, A.I.; Druzhinina, O.A.; Filippova, K.G.; Lazukova, L.I. New data on Late Glacial diatoms of the SE Baltic region based on the results of studying the Kulikovo section. *Limnol. Freshw. Biol.* **2024**, *4*, 612–617. [CrossRef]
20. *Geographical Atlas of the Kaliningrad Region*; CNIT: Kaliningrad, Russia, 2002; 302p. (In Russian)
21. Reimer, P.; Austin, W.E.N.; Bard, E.; Bayliss, A.; Blackwell, P.G.; Ramsey, C.B.; Butzin, M.; Cheng, H.; Edwards, R.L.; Friedrich, M.; et al. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal kBP). *Radiocarbon* **2020**, *62*, 725–757. [CrossRef]
22. Blaauw, M.; Christen, J.A. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal.* **2011**, *6*, 457–474. [CrossRef]
23. Özer, M.; Orhan, M.; Isik, N.S. Effect of Particle Optical Properties on Size Distribution of Soils Obtained by Laser Diffraction. *Environ. Eng. Geosci.* **2010**, *16*, 163–173. [CrossRef]
24. Heiri, O.; Lotter, A.F.; Lemcke, G. Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *J. Paleolimnol.* **2001**, *25*, 101–110. [CrossRef]
25. Subetto, D.A. *Donnyye otlozheniya ozer: Paleolimnologicheskiye rekonstruktsii [Lake sediments: Palaeolimnological reconstructions]*; RGPU im. A. I. Gertsena Pub.: Saint-Petersburg, Russia, 2009; 348p. (In Russian)
26. Kisieliene, D.; Stancikaite, M.; Merkevicius, A.; Namickiene, R. Vegetation responses to climatic changes during the late glacial according to palaeobotanical data in western Lithuania: Preliminary results. *Pol. Geol. Inst. Spec. Pap.* **2005**, *16*, 45–52.
27. Pino, M.; Abarzúa, A.; Astorga, G.; Martel-Cea, A.; Cossio-Montecinos, N.; Navarro, R.X.; Paz Lira, M.; Labarca, R.; Le Compte, M.A.; Adedeji, V.; et al. Sedimentary record from Patagonia, southern Chile supports cosmic-impact triggering of biomass burning, climate change, and megafaunal extinctions at 12.8 ka. *Nature* **2019**, *9*, 4413. [CrossRef]
28. Dzieduszyńska, D.; Kittel, P.; Petera-Zganiacz, J.; Brooks, S.; Korzeń, K.; Krapiec, M.; Pawłowski, D.; Płaza, D.; Płóciennik, M.; Stachowicz-Rybka, R.; et al. Environmental influence on forest development and decline in the Warta River valley (Central Poland) during the Late Weichselian. *Quat. Int.* **2014**, *324*, 99–114. [CrossRef]
29. Kabailienė, M.; Vaikutienė, G.; Macijauskaitė, L.; Rudnickaitė, E.; Guobytė, R.; Kisielienė, D.; Gryguc, G.; Mažeika, J.; Motuza, G.; Šinkūnas, P. Lateglacial and Holocene environmental history in the area of Samogitian Upland (NW Lithuania). *Baltica* **2015**, *28*, 163–178. [CrossRef]
30. Druzhinina, O.; Kublitskiy, Y.; Stancikaite, M.; Nazarova, L.; Syrykh, L.; Gedminiene, L.; Uogintas, D.; Skipityte, R.; Arslanov, K.; Vaikutiene, G.; et al. The Late Pleistocene–Early Holocene palaeoenvironmental evolution in the SE Baltic region: A new approach based on chironomid, geochemical and isotopic data from Kamyshovoye Lake. *Boreas* **2020**, *49*, 544–561. [CrossRef]

31. Kublitskiy, Y.; Kulkova, M.; Druzhinina, O.; Subetto, D.; Stancikaite, M.; Gedminiene, L.; Arslanov, K. Geochemical approach to the reconstruction of sedimentation processes in Kamyshovoye lake (SE baltic, Russia) during the Lateglacial and Holocene. *Minerals* **2020**, *10*, 764. [CrossRef]
32. Kublitsky, Y. The Dynamic of Nature Condition of SE Part of Baltic Region During Late Neopleistocene and Holocene. Ph.D. Thesis, Saint-Petersburg University, Saint-Petersburg, Russia, 2016; 150p. (In Russian).
33. Gedminiene, L.; Spiridonov, A.; Stancikaite, M.; Skuratovic, Z.; Vaikutiene, G.; Daumantas, L.; Salonen, S. Temporal and spatial climate changes in the mid-Baltic region in the Late Glacial and the Holocene: Pollen-based reconstructions. *Catena* **2025**, *252*, 108851. [CrossRef]
34. Kittel, P.; Mazurkevich, A.; Gauthier, E.; Kazakov, E.; Kublitskiy, Y.; Rzodkiewicz, M.; Mroczkowska, A.; Okupny, D.; Słowiński, M.; Szmańda, J.; et al. A great history in a small wetland: Human-environment relationships on the East European Plain in the last 13 thousand years. In Proceedings of the IAL IPA: Lakes, Memories of the Landscape, Bariloche, Argentina, 27 November–1 December 2022. [CrossRef]
35. Kuznetsov, D.; Subetto, D. *Stratiraphy of Lake Sediments of the Karelian Istmus*; GEOS: Moscow, Russia, 2019; 120p. (In Russian)
36. Ryazantsev, P.; Subetto, D. Turbidit sediments investigation in Onego Ice lake. In *Paleolimnology of Lake Onego: From the Onego Ice lake to the Present State*; Subetto, D., Ed.; Kar NC RAN: Petrozavodsk, Russia, 2022; pp. 92–106. (In Russian)
37. Zavala, C.; Arcuri, M. Intrabasinal and extrabasinal turbidites: Origin and distinctive characteristics. *Sediment. Geol.* **2016**, *337*, 36–54. [CrossRef]
38. Pszonka, J.; Zecova, K.; Wendorff, M. Oligocene turbidite fans of the Dukla Basin: New age data from the calcareous nannofossils and paleoenvironmental conditions (Cergowa beds, Polish–Slovakian borderland). *Geol. Carpathica* **2019**, *70*, 311–324. [CrossRef]
39. Turner, A.J.; Woodward, J.; Dunning, S.; Shine, A.J.; Stokes, C.R.; Cofaigh, C. Geophysical surveys of the sediments of Loch Ness, Scotland: Implications for the deglaciation of the Moray Firth Ice Stream, British-Irish Ice Sheet. *J. Quat. Sci.* **2012**, *27*, 221–232. [CrossRef]