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ПАЛЕОЛИМНОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ В РОССИИ: ОТ КАЛИНИНГРАДА ДО КАМЧАТКИ

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SEDIMENT RECORD OF THE EARLIEST STAGE OF THE EVOLUTION OF LAKE KANOZERO (SW KOLA PENINSULA): NEW DATA FOR REGIONAL DEGLACIATION RECONSTRUCTIONS AND RELATIVE SEA-LEVEL STUDIES[#]

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The multi-proxy study of the lowermost part of the sediment sequence of Lake Kanozero (south-western part of the Kola Peninsula, ca. 53 m a.s.l.) revealed the evidences for marine waters penetration into the basin during the earliest stage of its evolution. The diatom analysis inferred the conditions of a large brackish-water basin. Sediments composition and very low organic content also supported large-basin and low-productivity environments. Based on the pollen study, this stage covers a cooling period preceding the Allerød (tentatively assigned to the Older Dryas) and the onset of the Allerød. Periglacial vegetation typical of the cold and dry climate prevailed in the area for the most of the period. The subsequent transition to the freshwater conditions inferred from the diatom study took place in the Allerød, according to the pollen data. Except for a minor decrease in the fine sand fraction, no other corresponding changes were observed in the sediment record suggesting no major shifts in sedimentary environments. In the late Allerød and throughout the Younger Dryas, Lake Kanozero remained a large, low-productive freshwater basin. Our results indicate that ice-free conditions with aquatic sedimentation in the Kanozero depression had already existed in the Older Dryas. This assumes earlier deglaciation of the study area than it was previously thought. The study also suggests that brackish conditions in the White Sea basin established earlier than reported before. While the previous studies found no signals of marine transgression above ca. 41 m a.s.l., our results indicate that the local marine limit in the study area exceeds ca. 53 m a.s.l.

Keywords: isolation basins, sediments, diatoms, pollen, White Sea, relative sea-level changes, Late Glacial

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INTRODUCTION

Lake sedimentary archives are known to contain valuable records of ecosystem and environmental changes of the past (Cohen, 2003). For instance, in the regions within the limits of the Last Glacial Maximum, e. g. in NW Russia, invaluable information on the environmental changes during the Late Glacial to Holocene transition can be inferred from lake sediments. Besides, coastal-lake sediment records in these regions are widely used in studies of relative sea-level (RSL) changes resulted from isostatic/eustatic processes (Gehrels, 2013; Horton, Sawai, 2010; Shennan et al., 2015 and references therein).

The White Sea region and the Kola Peninsula experienced an impact of the last glaciation and subsequent isostatic rebound as the Scandinavian Ice Sheet retreated. Therefore, lake sedimentary archives in this area enable reconstructing environmental changes related to deglaciation and shoreline displacement (e. g. Corner et al., 1999; Romanenko, Shilova, 2012; Subetto et al., 2012; Korsakova et al., 2016; Kolka, Korsakova, 2017; Kuznetsov et al., 2022; Tolstobrova et al., 2022; Kublitskiy et al., 2023; Ludikova et al., 2023 etc.).

Lake Kanozero, located in the SW part of the Kola Peninsula (fig. 1, (a)) is famous by the ancient stone-carvings abundant on its islands. The evidence of the early human presence on its shores has recently raised interest to the lake's paleoenvironments. The litho- and biostratigraphic study of the upper part of the sediment sequence from Lake Kanozero covering the end of the Late Glacial and the Holocene has been performed and published elsewhere (Sapelko et al., 2022). The environmental transformation from the

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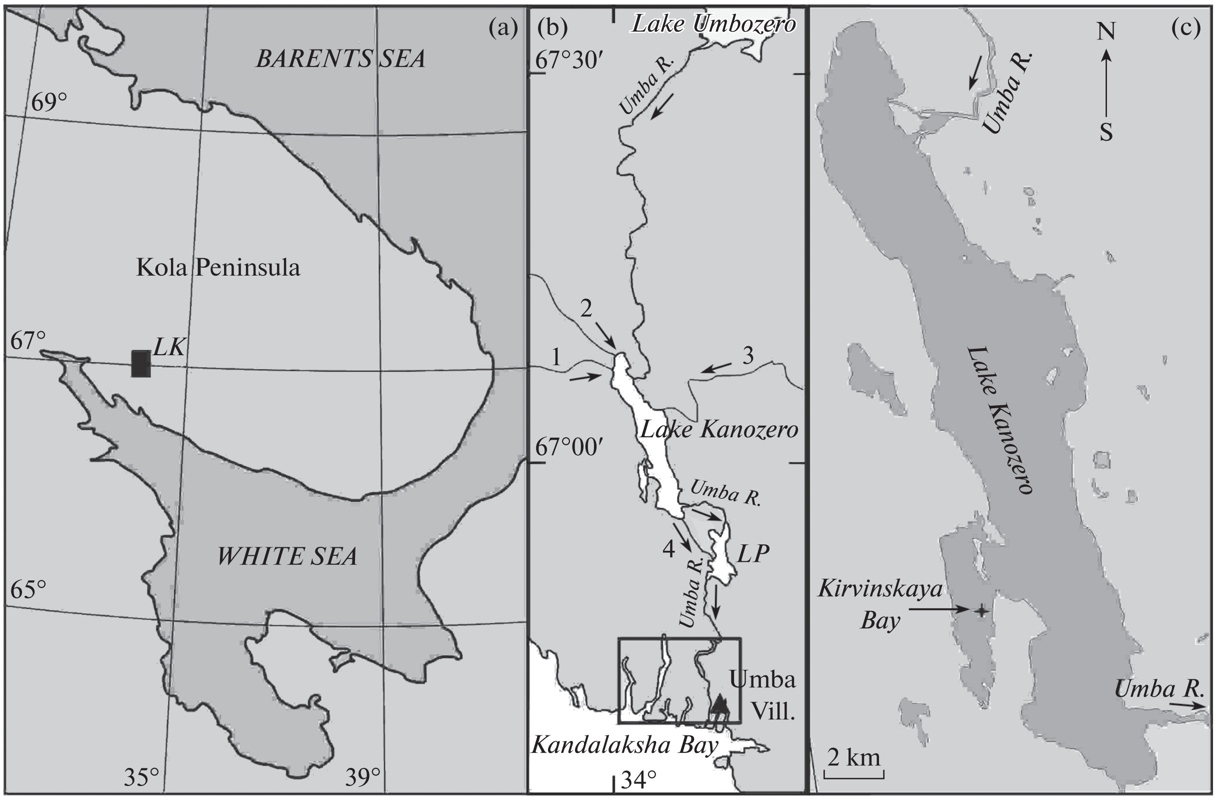

Fig. 1. Location map of the study site (a). LK = Lake Kanozero. Study area – closer look (b). 1 – River Chyornaya; 2 – River Kana; 3 – River Muna; 4 – River Rodvinga; LP – Lake Ponchozero; black frame – the area of the previous isolation basin studies (Kolka et al., 2013). Sampling site (c).

Рис. 1. Местоположение – общая схема (a); детализированная схема (b); точка пробоотбора (c). LK – Канозеро; *реки:* 1 – Черная, 2 – Кана, 3 – Муна, 4 – Родвинга; LP – Пончозеро; черный прямоугольник – область исследования в работе (Kolka et al., 2013).

shallow-water zone of a large cold-water oligotrophic basin to more productive lake resulted from the Early Holocene climate amelioration was revealed. Subsequent water-level lowering was also reconstructed that resulted in weakening of the water exchange between the lake's main basin and a bay where the sampling point was located (Sapelko et al., 2022).

The lowermost sediments containing the record of the earliest stages of the lake's evolution, however, remained beyond the scope of that study. A brief discussion on the diatom record of these stages was provided by Ludikova et al. (2022). In the present paper, we discuss the results of the multy-proxi study (diatoms, pollen, loss-on-ignition and grain-size) of the lowermost part of the sediment sequence of Lake Kanozero aimed at paleoenvironmental reconstruction of the initial stages of its development.

MATERIALS AND METHODS

Study site. Lake Kanozero is a large basin in the middle course of the River Umba, SW Kola Peninsula (fig. 1). The lake's elevation is 52.7 m above sea level (a. s. l.). The lake basin is NW-SE-oriented and has an elongated shape, ca. 26 km long and up to 5 km wide. The water area is 84.3 km^2, the water volume is 0.27 km^3. The lake's mean depth is 3.2 m, maximum depth is 10.6 m (Elshin, Kuprijanov, 1970). The shortest distance from the lake (its southern end) to the White Sea coast is ca. 28 km.

The main inflow of Lake Kanozero is the River Umba that enters the lake from the NE. Secondary tributaries include the rivers Chyornaya and Kana in the NW and Muna in the east. Two rivers, Kitsa (Umba) and Rodvinga, outflow from the southern end of Lake Kanozero, and after passing through Lake Ponchozero, ca. 5.5 km to the SW, the River Umba finds its way to the Kandalaksha Bay of the White Sea (fig. 1, (b)).

The lake is located within the hummocky moraine plain formed during the last glaciation. The present vegetation in the lake's surroundings is typical of the northern taiga subzone. Extensive peatbogs are also common for the surrounding landscapes.

Coring, lab treatment and analyzing. The 3.4 m-long sediment core was retrieved at 1.7 m-depth in the Kirvinskaya Bay (67°3′33″ N, 34°6′12″ E), a sheltered bay in the SW part of Lake Kanozero (fig. 1, (c)). Two elongated peninsulas and the Kirvinskiy Island in between make the Kirvinskaya Bay partly isolated from the main basin of the lake. The sediments were sampled with the “Russian type” peat corer from a boat. The sediment samples were collected with 2 to 10-cm intervals.

The age of the gyttja bottom (at ca. 460 cm) was determined using ^{14}C accelerator mass spectrometry (AMS) at the Laboratory of radiocarbon dating, University of Helsinki, Finland (Sapelko et al., 2022). Loss-on-ignition, diatom and pollen analyses were performed at the Institute of Limnology of the Russian Academy of Sciences, while grain-size distribution was analyzed at the Laboratory of Rational Environmental Management, Faculty of Geography of Herzen State Pedagogical University.

The loss-on-ignition (LOI) analysis was performed according to the standard procedure adopted at the Institute of Limnology. A total of 30 ca. 1-cm thick samples were powdered, dried for 2 hours at 105 °C and remained to cool to room temperature. After weighing the samples, ignition of organic matter was performed (6 hours at 500°C). Cooled samples were weighed again for subsequent calculation of weight losses (%) after ignition.

For grain-size analysis, the pretreatment procedure described in Vaasma (2008) was applied. A total of 22 samples were analyzed. To oxidize organic matter, sediment samples were mixed with 40% hydrogen peroxide (H_2O_2) and heated to 80 °C. H_2O_2 was continually added until the reaction stopped. A drop of a carefully stirred sample was taken for the analysis using a 0.1 ml pipette. Laser-diffraction size analysis was conducted using LaSca-1C Laser Particle Size Analyzer. For each sample, measurement was carried out three times, and the results were averaged.

Sediment treatment for diatom analysis (19 samples) followed the standard procedure (Davydova, 1985) using 30% H_2O_2 to destroy organic matter. Clay particles were removed by repeated decantation. Diatom identification follows Proshkina-Lavrenko (1949, 1950), Krammer and Lange-Bertalot (1986–1991), Strelnikova (2006). As identification of resting spores of *Chaetoceros* is often problematic using a light microscope, only a few species were identified to the species level. Therefore, all *Chaetoceros* resting spores were subsequently aggregated as *Chaetoceros* spp. The diatom species were subsequently grouped according to their habitats and salinity preferences (Proshkina-Lavrenko, 1949, 1950; Krammer, Lange-Bertalot, 1986–1991; Davydova, 1985). Chrysophyte (golden algae, Chrysophyceae) cysts were counted alongside with diatoms with no attempt of taxonomic identification. Concentrations of diatom valves and chrysophyte cysts in 1 g of dry sediments were subsequently calculated following Davydova (1985). The ratio of cysts to diatoms (CY:DI) was calculated according to Smol (1985). The diatom diagram was plotted using the paleoecological software C2 Version 1.7 (Juggins, 2007).

Chemical treatment for pollen analysis (25 samples) was performed using the standard procedure (Grichuk, 1940; Berglund, Ralska-Jasiewiczowa, 1986) with potassium-cadmium (Cd_2J+KJ) heavy liquid. Pollen diagram was drawn using the Tilia program (Grimm, 2004). Since pollen was almost lacking in a number of samples from the lowermost part, those samples were not included in the diagram. When calculating the percentage for each taxa the total amount of pollen of the trees, herbs and spores was taken for 100%. Pollen counts (total sum of pollen) that approximate pollen concentration in a sediment sample were also plotted on the diagram.

RESULTS

Lithology, LOI and grain-size distribution. The sediments under study are light bluish-gray silt (561- ca. 467 cm) with indistinct color banding in its lower part, gradually passing via gyttja silt to gyttja starting from ca. 467 cm (fig. 2).

In the lower silt, the LOI values do not demonstrate any significant variations generally ranging from 2.1% to 3.2% with only a minor decline to 1.9% at 472 cm. With the transition to gyttja silt at ca. 467 cm, the LOI values gradually increase and reach ~10% at 462 cm (fig. 3).

Grain-size analysis revealed the predominance of fine-grained particles (mean particle diameter varies from 0.02 to 0.036 mm). The size fraction of 0.01–0.05 mm, which is coarse silt according to Logvinenko (1974) classification, is the most abundant (>70% of the sample volume). An exception is 483–481 cm interval where it drops to 17%. Fine silt (0.005–0.01 mm) content varies from 8% to 14%, increasing to 65% at 483–481 cm. Clay (<0.001–0.005 mm) and fine sand (0.05–0.25 mm) particles do not exceed 16% and 14%, respectively (tabl. 1, fig. 3).

Diatoms. Based on the shifts in diatom assemblages composition and proportions of the ecological groups, three local diatom zones (DZs) were visually recognized (figs. 4, 5).

In DZ-1 (560–526 cm), resting spores of planktonic brackish-marine *Chaetoceros* spp. (with *C. holsaticus*, *C. neogracilis*, *C. socialis*, *C. wighamii* being the most common) contribute up to 60% of the total diatoms. Other planktonic taxa include occasionally found marine *Thalassiosira* spp. and *Coscinodiscus* spp. rarely exceeding 1%. In the lower part of DZ-1, benthic brackish-water *Fragilaria fasciculata*, *Mastogloia smithii* and *Cocconeis scutellum* are abundant, while proportions of halophilous *Achnanthes hauckiana* and salinity-indifferent *Epithemia adnata* and *Rhopalodia gibba* increase upwards. The total benthic accounts for 37–56%. Diatom valve and chrysophyte cyst concentrations are low, not exceeding 8 million

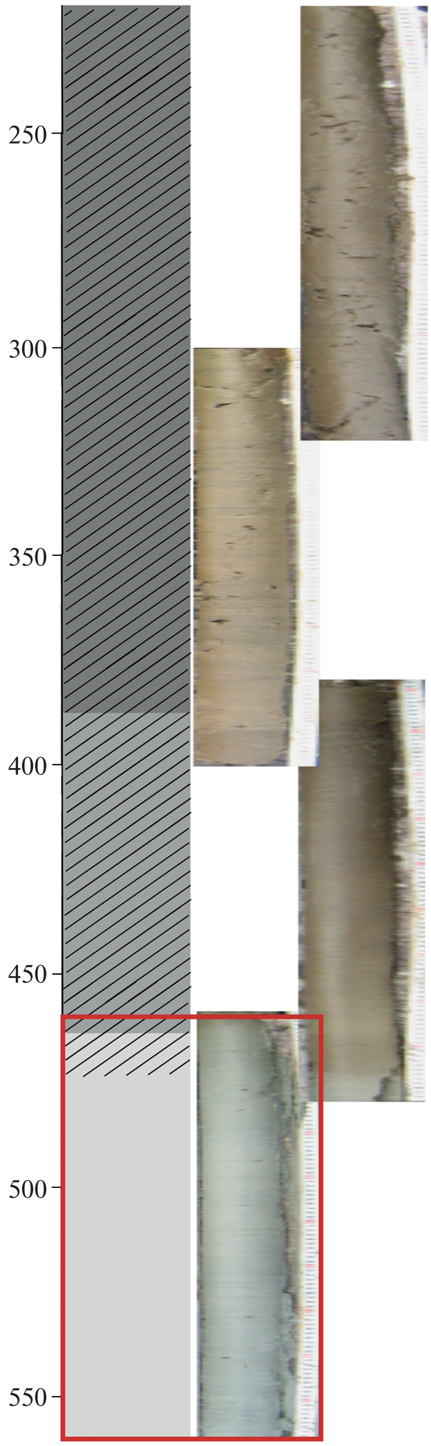

Fig. 2. Sediment sequence of Lake Kanozero. Light gray – silt, shadowed gray – greenish-brown gyttja, shadowed dark gray – brown gyttja. Red rectangle – sediment record in focus of the present study.

Рис. 2. Разрез донных отложений Канозера. Светло-серый – алеврит, серый со штриховкой – зеленовато-бурая гиттия, темно-серый со штриховкой – бурая гиттия. Красным прямоугольником обозначена часть разреза, рассматриваемая в настоящей статье.

and 200 thousand in g^{-1} dry sediment, respectively. The CY:DI ratio is low as well (1.8–5.6%).

In DZ-2 (526–518 cm), resting spores of *Chaetoceros* spp. rapidly decrease in abundance and disappear from the diatom record. The total planktonic decreases correspondingly. A proportion of small benthic Fragilariaceae drastically increases and reach >40% near the upper boundary of DZ-2. Their most abundant representatives include salinity-indifferent *Staurosira venter* and *Staurosirella pinnata*. Brackish-water *M. smithii* and *Tryblionella levidensis*, halophilous *A. hauckiana*, *Diploneis smithii* var. *pumila* and *Epithemia sorex*, and salinity-indifferent *E. adnata* and *R. gibba* are abundant as well. The halophilous taxa reach their highest proportion (35%) in DZ-2. Abundances of the total benthic rise to 97–100%. A notable increase in the diatom and cyst concentrations is observed in the upper DZ-2 (to 23 million and 1 million, respectively). The CY:DI ratio ranges from 7.4 to 11%.

In DZ-3 (518–460 cm), brackish-water species disappear from the record. Proportions of halophilous taxa decrease to 3–6%, while freshwater salinity-indifferent species became dominating. Benthic diatoms prevail (86–99%) with high abundances of small-celled Fragilariaceae (40–60%). Benthic *Amphora pediculus*, *Cocconeis neodiminuta*, *Navicula aboensis* and *Navicula jaernefeltii* are also common. Besides, *Aulacoseira ambigua*, typical of lacustrine plankton is also sporadically found. Diatom concentrations are high (26–48 million in g^{-1} dry sediment) rapidly increasing in the uppermost part of DZ-3. Chrysophyte cysts are less abundant (0.8–9 million). The CY:DI ratio is highly variable (5–17%).

Pollen. Three local pollen-assemblage zones (PZs) were recognized in sediment sequence under study (fig. 6).

PZ-1 (561–530 cm) is characterized with the lowest pollen content. Herbs pollen predominates (up to 64%) with Poaceae, Cyperaceae and *Artemisia* being the most abundant. *Betula nana* accounts for up to 50% of the total arboreal pollen reaching its maximum. *Pinus* and *Betula* pollen is also observed. The proportion of spores is the lowest (0–21%). They are mainly represented by *Bryales* and *Lycopodium clavatum*.

In PZ-2 (530–504 cm), pollen content reaches its maximum. Proportion of arboreal pollen increases to 67%. *Pinus* and *Betula* prevail, and minor amounts of *Picea* appear in the pollen record. Despite of the decreased proportion, *Betula nana* is constantly present in PZ-2. Sporadically found pollen of *Alnaster* and *Salix* is recorded for the first time. Herbs pollen slightly decreases although still remains noticeable (to 47%). Cyperaceae and *Artemisia* dominate among herbs, while the percentage of Poaceae decreases in the lower part of the zone and increases again upwards. Starting from the middle part of PZ-2, Chenopodiaceae pollen is recorded. Pollen of *Empetrum* (Ericaceae), *Ephedra*

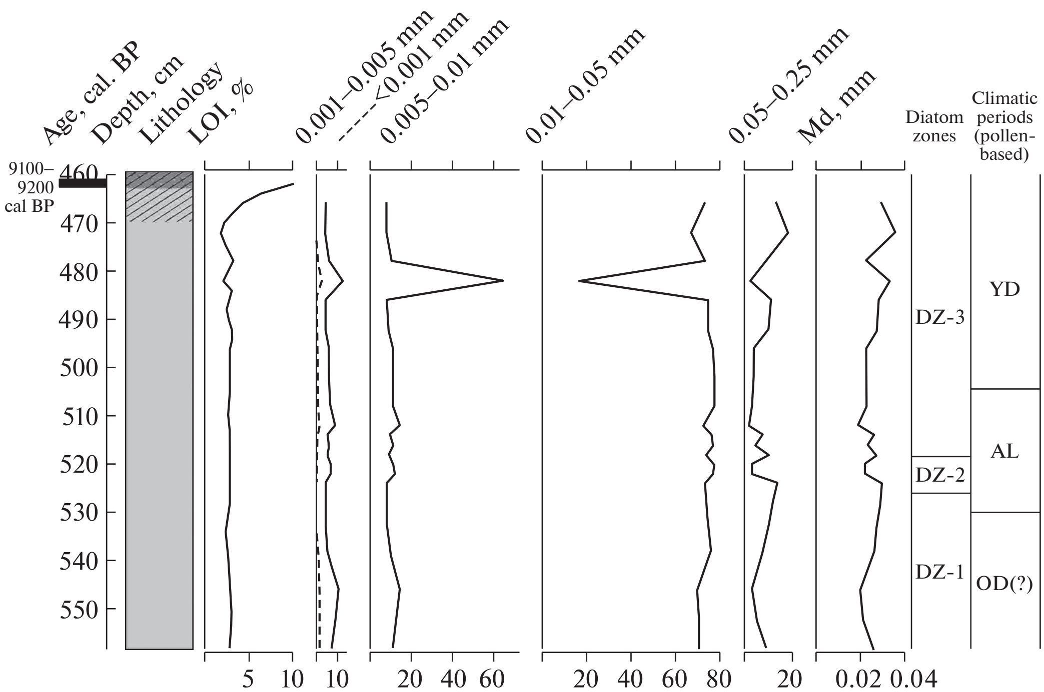

Fig. 3. Lithology, LOI, grain size distribution (%) for the lower ca. 1-m sediments of Lake Kanozero. Lithology: light gray – silt, shadowed light gray – gyttja silt, shadowed gray – greenish-brown gyttja.

Рис. 3. Литология, ППП, гранулометрический состав (%) нижней части (ок. 1 м) донных отложений Канозера. Литология: светло-серый – алеврит, заштрихованный светло-серый – гиттиевый алеврит, заштрихованный серый – зеленовато-коричневая гиттия.

and *Saxifraga* is observed as well. Spores reach their maximum proportion (up to 60%). *Bryales* spores prevail, while Polypodiaceae, *Lycopodium clavatum* and *Equisetum* are also found in considerable amounts. Besides, *Lycopodium annotinum, Selaginella selaginoides* and *Sphagnum* are occasionally recorded. Sporadic finds of *Isoëtes* spores and green alga *Botryococus braunii* are characteristic of PZ-2 only.

In PZ-3 (504–485 cm), pollen content decreases. Arboreal pollen decreases as well, rising again by the upper part of the zone (29–50%). *Betula nana* pollen predominates while the proportions of *Pinus* and *Betula* decline. *Alnaster* and *Juniperus* are sporadically found. Herbs pollen remains abundant (25–30%) with the predominance of Poaceae that rises again in this zone. Cyperaceae, Chenopodiaceae and *Artemisia* pollen is constantly recorded. *Empetrum* (Ericaceae) pollen is only occasionally found. Proportion of spores decreases (25–44%). *Bryales* and Polypodiaceae are the most abundant while *Equisetum, Lycopodium clavatum, Lycopodium annotinum, Selaginella selaginoides* and *Sphagnum* are commonly observed as well.

DISCUSSION

Microfossils, sediments and local paleoenvironment. Compositional changes in the diatoms assemblages revealed three stages of the earlier evolution of Lake Kanozero. At the initial stage (DZ-1), the predominance of brackish-marine and brackish-water species indicates the influence of marine waters. High abundance of planktonic taxa (*Chaetoceros* spp.), in

Table 1. Minimal, mean and maximum values of LOI and sediment particles in the lower part of the sediment sequence of Lake Kanozero

Таблица 1. Минимальные, средние и максимальные значения ППП и содержания осадочных частиц в нижней части разреза донных отложений озера Канозера

%	LOI	fine clay (0–0.001 mm)	coarse clay (0.001–0.005 mm)	fine silt (0.005–0.01 mm)	coarse silt (0.01–0.05 mm)	fine sand (0.05–0.25 mm)
min	1.9	0.33	4.47	7.99	16.79	1.80
max	9.9	2.24	13.35	64.67	77.78	18.86
mean	3.2	0.74	6.71	12.90	71.83	7.81

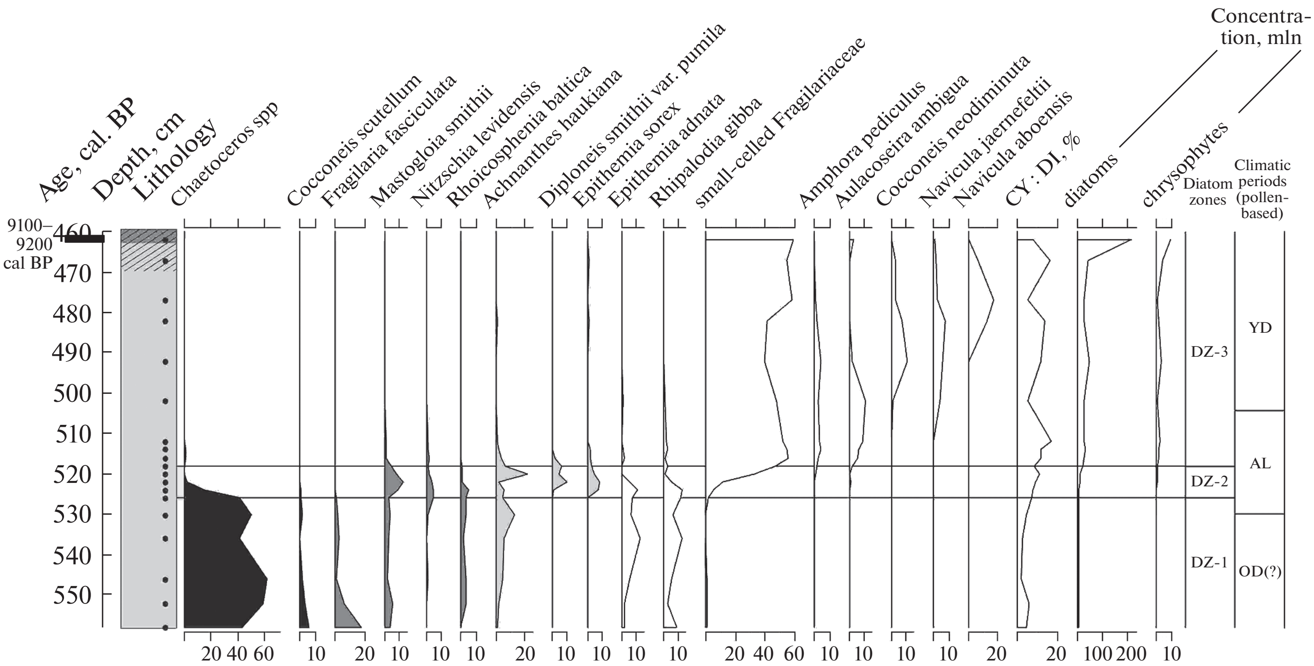

Fig. 4. Diatom diagram for the lower ca. 1-m sediments of Lake Kanozero: species abundances (%), "cysts to diatoms" ratio (%), diatom valves and chrysophyte cysts concentrations (g^{-1} dry sediment). Black circles indicate the position of the analyzed samples.

Рис. 4. Диатомовая диаграмма для нижней части колонки донных отложений Канозера: основные виды (%), отношение "цисты/диатомовые" (%), концентрация створок диатомей и цист хризофитов (в 1 г сухого осадка). Черными точками на литологической колонке отмечено положение проанализированных образцов.

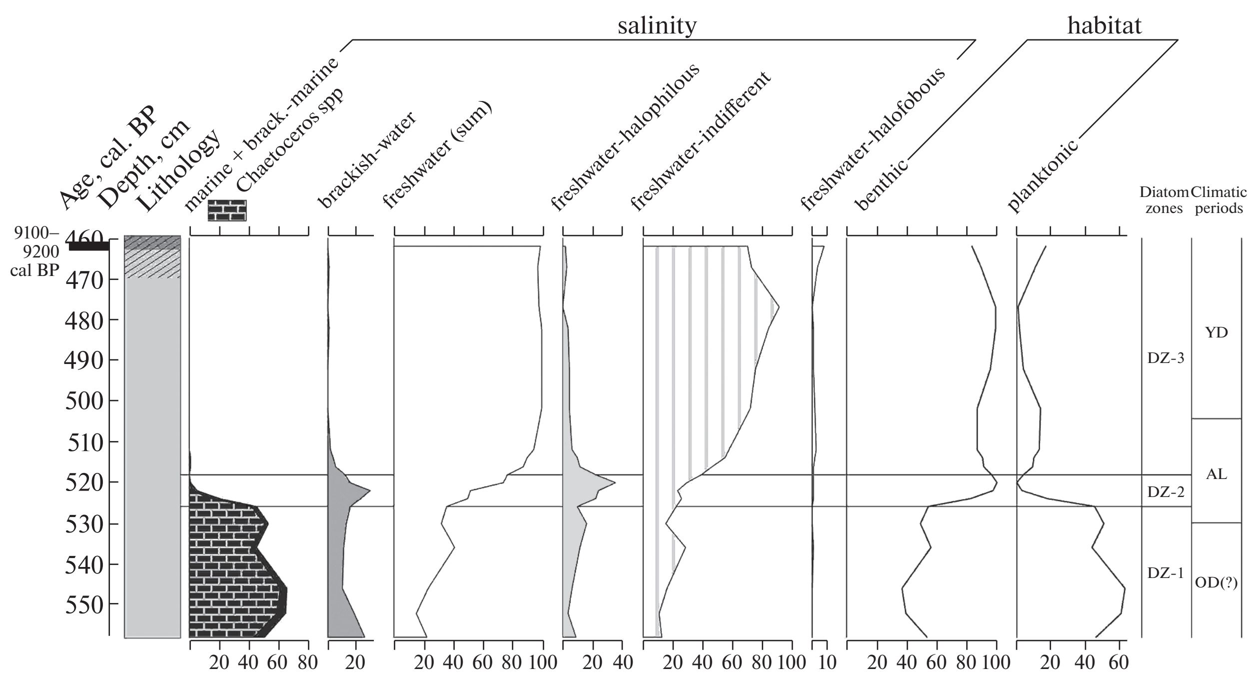

Fig. 5. Diatom diagram for the lower ca. 1-m sediments of Lake Kanozero: ecological groups according to salinity preferences and habitats.

Рис. 5. Диатомовая диаграмма для нижней части колонки донных отложений Канозера: экологические группы по солености и местообитанию.

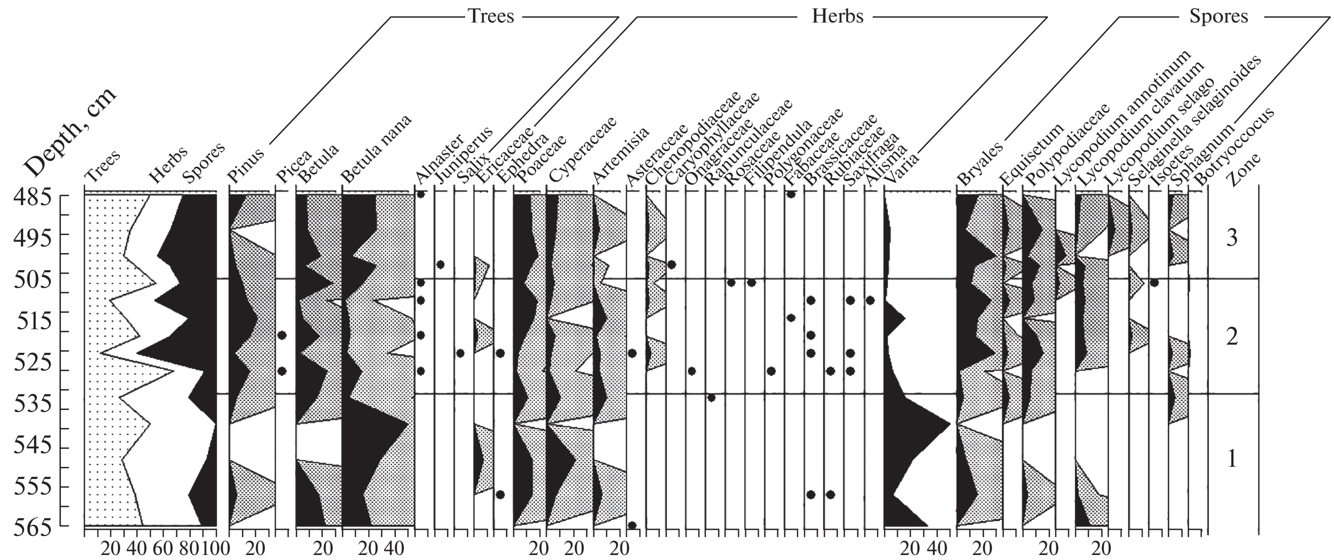

Fig. 6. Pollen diagram of the lower part of the sediment sequence of Lake Kanozero.
Рис. 6. Спорово-пыльцевая диаграмма нижней части разреза донных отложений Канозера.

turn, points to relatively large depths of the basin. The most abundant representatives of *Chaetoceros* genus at this stage can thrive in a wide range of salinities. According to Strelnikova (2006), the salinity range for *C. holsaticus* is 5.3–33.2‰, for *C. neogracilis* – 8.1–30‰, for *C. socialis* – 2.8–33.2‰, and for *C. wighamii* – 2.1–33.2‰. Therefore, brackish-water conditions can be thought of. At present, various species of *Chaetoceros* flourish in the phytoplankton of the White Sea (salinity ca. 26‰) altogether with *Thalassiosira* spp. and *Coscinodiscus* spp. (Il'yash et al., 2003). Representatives of these three genera also dominate in the surface-sediment diatom assemblages (Polyakova, Novichkova, 2018). In our record, however, *Chaetoceros* spp. predominate while both *Thalassiosira* spp. and *Coscinodiscus* spp. were only occasionally found. Such disproportion apparently reflects the environments in the paleobasin rather differing from the present White Sea.

However, local paleoenvironments are more reliably inferred from benthic diatoms as those are incorporated to the sediments directly from their source community (Vos, de Wolf, 1988). In our record, brackish-water and salinity-indifferent species predominate among the benthic taxa, followed by freshwater halophilous species which strongly suggests brackish environments or fluctuating salinities. Low concentrations of diatoms and chrysophytes indicate unfavorable conditions for the growth of these microalgae probably attributed to nutrients limitation. High input of suspended mineral particles into the basin, in turn, could have "diluted" the microfossil concentrations in the sediments. For chrysophytes, the salinity can also be an important limiting factor as only few Chrysophyceae species occur in marine or brackish waters. It is supported by low CY:DI values that are also characteristic for the "marine stage" in other coastal isolation basins of the White Sea coast (Ludikova et al., 2023). A notable lack of sponge spicules that are the siliceous microfossils commonly abundant in the sediments of the "marine stage" (Ludikova et al., 2023) point to extremely unfavorable conditions for these invertebrates. As sponges are fed by suspended organic detritus, the primary limiting factor could be the low productivity of the basin.

Low-productive environments with high sediment supply are also suggested from low organic content in the sediments. This apparently reflects severe climate and environmental conditions when no nutrients were supplied to the basin from undeveloped soils while the erosion intensity was high. The predominance of the silt-size particles may evidence for low-energy environments where the influence of waves, tides and currents is minor. At present, silt accumulation takes place on the slopes of the White Sea depression at some distance from the coast (Nevesskiy et al., 1977). Besides, silty fraction also dominates in the sediments near the large rivers mouths such is the present-day seaward part of the delta of the River Severnaya Dvina (Nevesskiy et al., 1977). Slightly increasing proportion of fine sand may reflect a shift towards lower depths and slightly more energetic environments.

This stage was tentatively pollen-dated to the Older Dryas, i. e. a climate cooling that preceded the Allerød (PZ-1), and also includes the very onset of the Allerød (lower PZ-2). The Older Dryas chronozone in our record is distinguished by the low abundances of arboreal pollen. Generally, the composition of the pollen spectra is similar to those of the Younger Dryas. However, very low pollen abundances in PZ-1 (much lower

Table 2. Pollen data for the Late Glacial on the Kola Peninsula
Таблица 2. Данные спорово-пыльцевого анализа для позднеледниковья Кольского п-ова

Lakes	Older Dryas	Allerød	Younger Dryas	References
Kanozero	*Betula* – Poaceae – Cyperaceae – *Artemisia* – Chenopodiaceae	*Betula* – *Pinus-Picea* – *Alnaster* – *Salix* – *Ephedra* – *Saxifraga* *Empetrum* – *Artemisia* –	*Betula* – *Betua nana* – Poaceae – Cyperaceae – *Artemisia* – Chenopodiaceae	This article
Churozero	*Betula* – *Artemisia* – Poaceae – Cyperaceae – Chenopodiaceae	*Betula* – *Pinus-Picea* – *Salix* – *Artemisia* – Cyperaceae	*Betula* – *Pinus* – *Salix* – Cyperaceae – *Artemisia* – Chenopodiaceae	Pavlova et al., 2011
Imandra		*Pinus* – *Artemisia*	*Artemisia*	Lenz et al., 2021
KP-2			*Salix* – *Betula* – *Betula nana* – *Artemisia* – Poaceae – Cyperaceae	Kremenetski et al., 2004
Yarnyshnoe			*Salix* – *Betula* – *Artemisia* – Chenoodiaceae	Snyder et al., 2000

than in the Younger Dryas sediments) suggest colder and drier climate that hindered the spread of the vegetation.

On the Kola Peninsula, the Younger Dryas age of the sediments is the most reliably confirmed by pollen studies of the lateglacial sediment records. However, in the sediments of Lake Churozero, central Kola Peninsula, two episodes of the Dryas cooling separated by the Allerød warming were recorded (Pavlova et al., 2011). In Lake Churozero, low pollen abundances were similarly recorded in the sediments attributed to the Older Dryas chronozone (Pavlova et al., 2011). The composition of the Older Dryas pollen spectra there also demonstrates similarity to those of the Younger Dryas (tabl. 2). No radiocarbon-dated pollen records of the Older Dryas are known by far in the Kola region.

Our pollen data thus support severe environmental conditions that were inferred from the sediments lithology, low abundances of siliceous microfossils and low organic content. The pollen data suggest that the vegetation cover was almost lacking in the study area at this early stage. Open landscapes with periglacial herbs-dominated communities with *Artemisia*, Poaceae and Cyperaceae were characteristic for this time period indicating cold and dry climate and unfavorable conditions for vegetation and soils development. By the end of this stage, the transition to warmer and more humid climate is inferred from the pollen record (lower PZ-2) which favored a spread of forest-tundra vegetation. No corresponding changes in the diatom assemblages and sediment composition were observed, though.

At the next stage (DZ-2), a rapid decline in planktonic *Chaetoceros* spp. and other marine and brackish-marine taxa, and increase in benthic brackish-water, halophilous and salinity-indifferent species indicate decreasing salinity and water depth resulted from the isolation and transition to lacustrine environments. An explosive rise of small-celled Fragilariaceae observed at this stage is typical of the succession from marine to freshwater coastal-lake environments, and was recorded in the sediment sequences prior to, during and just after the isolation (Stabell, 1985). At present, small-sized fragilarioids are characteristic for the surface sediments of the coastal basins, both currently isolating and recently isolated from the White Sea, i. e. regardless of their isolation status (e. g. Shilova et al., 2020). Apparently, thriving of these taxa is not solely attributed to salinity changes since the isolation process is commonly accompanied by other environmental instabilities, e. g. increased turbidity, fluctuating salts content and shifting nutrients supply. This all favors the growth of pioneer, fast-reproducing species widely distributed along various environmental gradients, such are many of small Fragilariaceae that are highly competitive under unstable, changing conditions (Weckström, Juggins, 2005).

Increasing CY:DI values accompanied by a minor increase in cysts concentrations observed at this stage support freshening of the basin and the transition to the environments more favourable for chrysophytes. Similar rise in proportions of cysts was recorded at the transitional stage in other isolation basin studies (Dreßler et al., 2009; Ludikova et al., 2023). Diatom concentrations also slightly increase as a result of the mass growth of small-celled fragilarioids. It may also reflect a transition to lower-energy conditions with decreasing influence of a larger basin.

Various isolation basin studies have demonstrated clear lithological signals of isolation in their sediment records (Corner et al., 1999; Kolka, Korsakova, 2017). Besides, rapidly rising organic content (expressed as increased LOI) during the marine-freshwater transition was recorded in coastal lakes isolated from the White Sea during the Holocene (Kuznetsov et al., 2022). In Lake Kanozero, however, the onset of the isolation has left no visually recognizable signature such as changing sediment composition, color, etc. Neither the transition to autochthonous organic sedimentation was recorded as the LOI values showed no corresponding change. Slightly decreased proportion of fine sand might be the only evidence of changes in sedimentation environment.

According to the pollen data, this stage corresponds to the Allerød interstadial (PZ-2). It is supported by increased pollen concentration in the sediments that is much higher than in PZ-1 and PZ-3. Besides, in the preceding and the following periods the arboreal vegetation was mainly represented by dwarf birch, while in the Allerød birch and pine pollen became more abundant. Their increased proportions in the pollen records are typical of this warm period (Sapelko, 2017). An occurrence of spruce pollen also supports the Allerød age of the sediments. *Alnaster fruticosa* is constantly observed in the pollen record as well. Being presently common in permafrost regions and undemanding to soils, it could have grown on the coasts of the Kanozero basin. *Salix*, *Ephedra*, *Saxifraga* and *Empetrum* typical for the Late Glacial and specifically for the Allerød interstadial, were also common for the study area at this stage. The composition of the pollen spectra thus indicates that tundra-like vegetation communities transformed to forest-tundra communities.

There are few sites in the Kola Peninsula where the sediments attributed to the Late Glacial climate warming were described (e. g., Pavlova et al., 2011; Lenz et al., 2021) (tabl. 2). The warming is commonly marked by the increased abundance of arboreal pollen. An increase of *Picea* pollen is an important indication of the Allerød in the Kola Peninsula and other regions (Borzenkova et al., 2015). In Lake Imandra, western Kola Peninsula, the increase in arboreal pollen with the predominance of *Pinus* was characteristic for the Allerød warm episode (Lenz et al., 2021). An occurrence of shrubs pollen is another indication of warming. For instance, in Lake Churozero the spread of *Salix* is inferred during the Allerød chronozone. Pollen of *Salix*, *Ephedra*, *Saxifraga* and *Empetrum* often found in lateglacial sediments is typical of the Bølling-Allerød sediments in the area of the Last Glaciation (Engels et al., 2022).

Constantly low organic content in our sediment record, however, indicates no corresponding increase either in the basin's productivity or allochthonous organic matter supply. Despite some climate amelioration, the lake was still oligotrophic and received large amounts of suspended mineral particles from the catchment. This might reflect rather severe environmental conditions. A lack of any noticeable changes in the sediment composition also suggests that after the isolation the Kanozero basin remained rather large, which could have obscured the signals of isolation-related or climate-driven shifts in sedimentation environments.

Subsequent disappearance of brackish-water diatoms and a notable decrease in abundances of halophilous taxa indicate establishing of freshwater conditions in Lake Kanozero (DZ-3). Predominance of benthic diatoms and an overall composition of the diatom assemblages reflect sedimentation in the shallow-water part of a large cold-water low-productivity lake with slightly alkaline pH.

In these lacustrine environments, however, minerogenic allochthonous sedimentation proceeded since the LOI values remained as low as at the previous stages. Low productivity of the lake's ecosystem apparently resulted from severe climatic conditions. Poor soils and vegetation development in the lake's catchment restricted nutrients input to the lake. Almost unchanged distribution of particle sizes indicates rather stable sedimentation environments. The only exception is an episode of a notable shift in medium-coarse silt and fine silt ratio accompanied by minor increase in clay particles and decrease in fine sand that predated the increase in organic content. No corresponding changes were recorded in either diatom composition or LOI values, though. Apparently, this event is not related to changing water depth and might reflect decreased erosion or river activity.

This stage is pollen-dated to the late Allerød – Younger Dryas (upper PZ-2 – PZ-3), and the transition to colder climate is inferred from decreased pollen abundances and arboreal pollen decline. After the Allerød warming, *Alnaster fruticosa* and *Empetrum* still grew sporadically in sheltered depressions. *Empetrum* heathlands were spread as well, which together with dwarf birch could indicate initial soils development.

Dated Younger Dryas sediments were revealed elsewhere in the Kola Peninsula (e. g., Kremenetski et al., 2004; Pavlova et al., 2011; Lenz et al., 2021 etc.). Decreased abundances of arboreal pollen is the most prominent indication of the Younger Dryas cooling recorded in other sediment sequences. The onset of the Holocene, in turn, is marked by its rapid increase, which was also recorded in Lake Kanozero (Sapelko et al., 2022) and other sites (Snyder et al., 2000; Kremenetski et al., 2004; Pavlova et al., 2011; Lenz et al., 2021). In the Younger Dryas, periglacial communities prevailed in the region, while the composition of dominating taxa was determined by the local environments. Vegetation communities with *Artemisia*, Poaceae, Cyperaceae и Chenopodiaceae were the most common (tabl. 2).

An increase in organic content and gradual silt to gyttja transition might indicate climate amelioration around the Late Glacial-Holocene boundary. However, the absolute and pollen-based chronologies disagree in estimating the onset of the organic sedimentation in Lake Kanozero. According to pollen data (Sapelko et al., 2022), the Younger Dryas-Holocene

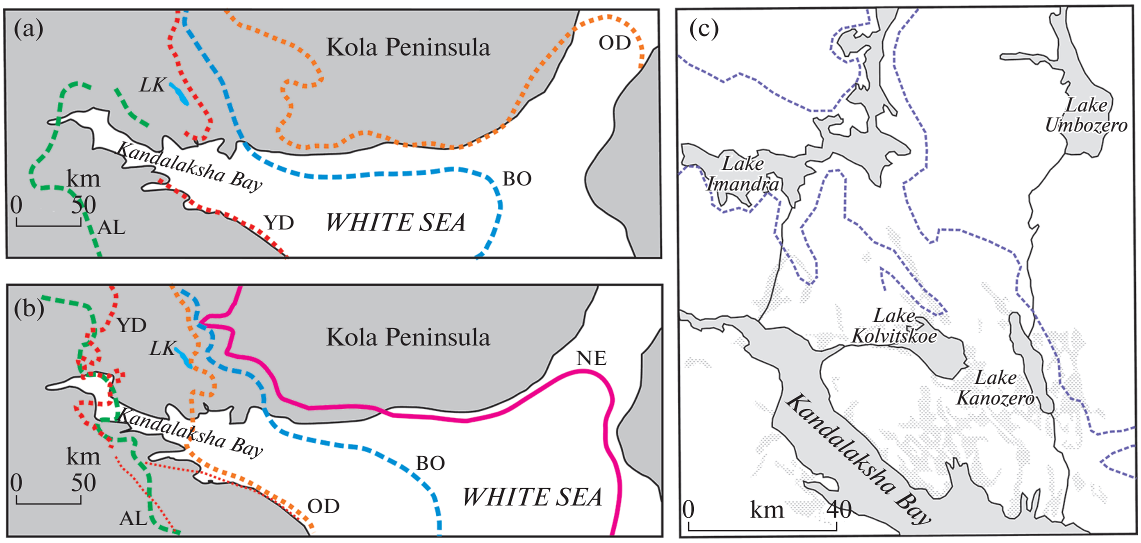

Fig. 7. Late-glacial ice-marginal zones (after: (a) – Yevzerov (2015), (b) – Korsakova et al. (2023)) during: NE – Neva stage, BO – Bølling Interstadial, OD – Older Dryas Stadial, AL – Allerød Interstadial, YD – Younger Dryas Stadial. LK stands for Lake Kanozero. (c) – limits of the late-glacial brackish-water basin (dashed violet line; after Lavrova, (1960)), and location of the sediments of the late-glacial marine transgression (shaded areas; after Semyonova, Rybalko (2012)).

Рис. 7. Пояса краевых ледниковых образований позднеледниковья (NE – невской стадии, BO – межстадиального потепления бёллинг, OD – стадиального похолодания среднего дриаса, AL – межстадиального потепления аллерёд, YD – стадиального похолодания позднего дриаса, по (a) – Евзеров (2015), (b) – Korsakova et al. (2023). LK – Канозеро. (c) – пределы распространения позднеледникового солоноватоводного бассейна (фиолетовая пунктирная линия; по Лаврова (1960)), местонахождение осадков позднеледниковой морской трансгрессии (заштрихованная площадь; по Семенова, Рыбалко (2012)).

transition was recorded in the lower part of gyttja suggesting that the organic sedimentation started around the end of the Late Glacial – beginning of the Holocene. The radiocarbon dating of the gyttja bottom, in turn, yielded ca. 9100–9200 cal. yrs BP indicating that the transition to organic sedimentation could have occurred later in the Early Holocene. The study of gyttja revealed the conditions of the freshwater lake that experienced some changes in trophic state and depth during the Holocene (Sapelko et al., 2022). No signal of marine transgressions was recorded in the Holocene sediment sequence.

Implications for deglaciation and marine limit studies. During the Last Glacial Maximum, the Kola region and the White Sea depression were occupied by the eastern flank of the Scandinavian Ice Sheet that expanded eastward and reached the NW tip of the Kanin Peninsula (Demidov et al., 2006; Hughes et al., 2016). The deglaciation of the Kola Peninsula and the White Sea took place between ca. 15–16 cal. ka BP and ca. 12 cal. ka BP (Hughes et al., 2016). However, the deglaciation pattern and chronology still remain rather uncertain.

Earlier studies suggested that the White Sea depression had been already ice-free by the end of the Oldest Dryas as the ice sheet retreated far westward (Lavrova, 1968). In recent decades, various and partly contradictory deglaciation schemes were proposed thus providing different timing of deglaciation of the Kanozero basin. Three distinctive ice marginal belts were described on the Kola Peninsula by Yevzerov and Nikolaeva (2000) and Yevzerov (2015). The belt III formed during the Oldest Dryas cooling and preceding warming episode, while the formation of the belts II and I correspond to the Bølling – Older Dryas and Allerød – Younger Dryas climate oscillations, respectively (Yevzerov, 2015). These studies suggest that in the Older Dryas, i. e. ca. 14 cal. ka BP, ice-marginal zone was located >50 km to the east of Lake Kanozero (fig. 7, (a)) that must have been covered by glacial ice. According to Stroeven et al. (2016), ca. 14 cal. ka BP the ice sheet covered the western and central Kola Peninsula including the Kanozero basin. Similarly, Boyes et al. (2023) assumed that ice-free conditions only existed in the eastern Kola Peninsula at that time. They also inferred a significant readvance of the White Sea ice lobe ca. 14 cal. ka BP partly in response to the climatic cooling during the Older Dryas (Boyes et al., 2023). Alternatively, the correlation scheme of ice marginal formations proposed by Vashkov and Nosova (2022) placed the Older Dryas ice margin just a few km to the east of the Kanozero basin, while the deglaciation of the study area took place in the Allerød.

A notable retreat of the ice margin ca. 13 cal. ka BP is suggested although the precise position of the ice margin on the Kola Peninsula remains uncertain. An activation of the so-called Kanozero ice stream that moved to the SE through the Kanozero basin in response to the collapse of the White Sea lobe and related ice sheet configuration and volume changes, was also documented for this period (Boyes et al., 2023). Korsakova et al. (2023) mapped the ice-free conditions in our study area starting from the Allerød as the ice margin retreated westward up to the head of the Kandalaksha Bay (fig. 7, (b)). It agrees with Stroeven et al. (2016) who reconstructed deglaciation of the study area in the Late Allerød, between ca. 13 and 12.7 cal. ka BP. The lack of any large-basin sediments in the coastal lakes at > ca. 41 m a.s.l., south of Lake Kanozero, was interpreted as a result of blocking of their depressions by dead-ice masses that lost contact with the active ice lobe in the Allerød (Kolka et al., 2013).

The reconstructions by Yevzerov and Nikolaeva (2000), Semyonova and Rybalko (2012) and Boyes et al. (2023) indicate that in the Younger Dryas the ice margin was still located a few km to the east of the study site (fig. 7, (a)), and thus the depression of Lake Kanozero was not ice-free yet. The ice sheet subsequently retreated from the Kanozero basin between 12 and 11 cal. ka BP.

Our results, however, suggest that aquatic sedimentation in the Kanozero depression already took place during the cold interval pre-dating the Allerød and tentatively assigned to the Older Dryas. This may assume earlier deglaciation of the study area than it was previously suggested.

It is commonly believed that glacial-lacustrine environments in the White Sea depression transformed to glacial-marine in the late Allerød (Lavrova, 1968; Nevesskiy et al., 1977; Yevzerov et al., 2007; Kolka, Korsakova, 2017). However, some studies suggest that glacial-marine environments in the Kandalaksha Bay also existed during the Oldest and Older Dryas chronozones (Alyavdin et al., 1977; Djinoridze et al., 1979; Kalugina et al., 1979). According to our data, Lake Kanozero could already be a part of a larger brackish basin prior to the Allerød.

The results of the present study also contribute to the reconstruction of spatial limits of this basin. According to Lavrova (1960), the late-glacial brackish (glacial-marine) basin occupied the northern coasts of the Kandalaksha Bay and penetrated as far inland as the present depressions of the lakes Ponchozero and Kanozero (fig. 7, (c)). She also suggested that accumulation of thick laminated clays found to the north of Lake Kanozero took place in a freshened marine bay. Bluish-gray indistinctly laminated clays near the mouth of the River Rodvinga, south of Lake Kanozero, containing brackish-water and brackish-marine diatoms, were also referred to as glacial-marine (Lavrova, 1960). Thus one could think of the Late Glacial marine transgression that has exceeded the present elevation of Lake Kanozero which is ca. 53 m a.s.l. In support to this, the map of the Quaternary deposits shows late-glacial marine sediments along the shores of Lake Kanozero (fig. 7, (c)) (Semyonova, Rybalko, 2012). However, studies of coastal isolation basins near Umba Village only recorded signals of the late-glacial marine transgression in the lakes at ≤41 m a. s. l. while no large-basin sediments were found in lake depressions at ≥55 m a. s. l. (Kolka et al., 2013). It was therefore suggested that the basins below ca. 41 m a. s. l. were already ice-free by the late Allerød, while the lakes at higher elevations remained blocked by dead ice until the late Preboreal.

Our finds of rich brackish-water diatom flora in the pre-Allerød sediments of Lake Kanozero indicate earlier onset of the marine transgression and no dead-ice blocking of the Kanozero basin. The RSL thus should have exceeded the present elevation of our study site (ca. 53 m a. s. l.). The marine waters must have penetrated as far inland as up to the NW end of the lake, at least, i. e. ca. 50 km from the present White Sea coast, which agrees with Lavrova (1960). According to pollen data, the RSL dropped below ca. 53 m a. s. l. sometime in the Allerød when a resultant transition from brackish- to freshwater environments in Lake Kanozero took place.

This does not correlate, however, with the results obtained by Kolka et al. (2013) who inferred the onset of RSL rise ca. 13.2 cal. ka BP, i. e. in the late Allerød. The transgression reached at least ca. 41 m a. s. l., lasted during the Younger Dryas and terminated ca. 10.3 cal. ka BP when the RSL regressed below ca. 41 m a. s. l. (Kolka et al., 2013; Kolka, Korsakova, 2017). Matching the evidences from Lake Kanozero and the Umba Village area, one could think of two phases of the late-glacial transgression, the earlier predated the Allerød, and the later started in the late Allerød. This assumption, however, looks highly speculative given the present state of knowledge, and strongly demands validation by further studies.

Previously published results of the diatom study of the upper part of the sediment sequence (gyttja) demonstrated that Lake Kanozero remained freshwater during the Holocene (Sapelko et al., 2022). This provides no grounds for positioning the Holocene marine sediments on the central-western and central-eastern parts of the lake's shores as was suggested by (Legkova et al., 2003; Semyonova, Rybalko, 2012).

CONCLUSIONS

Our study has revealed the evidences for marine waters penetration into the basin of Lake Kanozero at the earliest stage of its evolution that was tentatively pollen-dated to the Older Dryas – the onset of the Allerød. The predominance of planktonic diatoms with a broad salinity tolerance and the presence of typical brackish-water benthic species in the diatom record reflect the environments of a large brackish basin. Fine-grained particles prevailing in the sediment record suggest rather large depths while low organic content supports low-productivity environments. Cold and dry climate conditions unfavorable for vegetation and soils development were inferred from the pollen record.

The subsequent isolation from the brackish basin and transition to lacustrine environments inferred from the diatom record was pollen-dated to the Allerød. Thus Lake Kanozero, an 84.3 km^2-large waterbody can be defined as a huge isolation basin. Only a minor decrease in the fine sand fraction was revealed while no other corresponding changes were observed in the sediment record. Despite of the climate amelioration, inferred from the spread of forest-tundra vegetation, the basin remained low-productive and received large amounts of suspended mineral particles from the catchment.

The predominance of freshwater diatoms, low organic content and accumulation of fine-grained particles indicate that in the late Allerød and throughout the Younger Dryas, Lake Kanozero remained a large, low-productive freshwater basin.

The study revealed ice-free conditions and aquatic sedimentation in the Kanozero depression already in the pre-Allerød times. Therefore we may assume earlier deglaciation of the study area than it was previously suggested.

Our results also indicate earlier onset of the lateglacial marine transgression and can specify its level. In the Older Dryas, the RSL has exceeded the present elevation of Lake Kanozero, ca. 53 m a. s. l., and marine waters penetrated as far inland as up to the NW end of the lake, i. e. ca. 50 km from the present White Sea coast. The RSL dropped below ca. 53 m a. s. l. already in the Allerød, and since that freshwater conditions persisted in Lake Kanozero.

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ОСАДОЧНАЯ ЛЕТОПИСЬ РАННЕЙ СТАДИИ РАЗВИТИЯ КАНОЗЕРА (ЮЗ ЧАСТЬ КОЛЬСКОГО ПОЛУОСТРОВА): НОВЫЕ ДАННЫЕ ДЛЯ РЕКОНСТРУКЦИЙ ДЕГЛЯЦИАЦИИ РЕГИОНА И ИЗМЕНЕНИЙ УРОВНЯ МОРЯ[1]

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Комплексное исследование нижней части толщи донных отложений Канозера (юго-западная часть Кольского п-ова, 53 м над у. м.) выявило свидетельства проникновения соленых вод в его бассейн на ранней стадии его эволюции. По результатам диатомового анализа реконструированы условия крупного солоноватоводного водоема. Литологический состав донных отложений и крайне низкое содержание органического вещества свидетельствуют об обстановках большого низкопродуктивного бассейна. По данным спорово-пыльцевого анализа этот этап охватывает период похолодания среднего дриаса и начало аллереда. На данном этапе в основном преобладала перигляциальная растительность, типичная для холодного и сухого климата. Переход к пресноводным условиям, о котором свидетельствуют изменения состава диатомовых комплексов, произошел в аллереде. Помимо незначительного уменьшения содержания песчаной фракции, в составе донных отложений никаких изменений отмечено не было, что свидетельствует об отсутствии заметных изменений в обстановках осадконакопления в ходе изоляции. С конца аллереда и в течение всего позднего дриаса озеро Канозеро оставалось крупным низкопродуктивным пресноводным бассейном. Наши результаты свидетельствуют о том, что котловина Канозера была свободна от ледникового льда уже в среднем дриасе, когда здесь происходило субаквальное осадконакопление. Это предполагает, что дегляциация района исследования произошла раньше, чем считалось прежде. Полученные данные также указывают на более раннее установление солоноватоводных условий в беломорской котловине. Тогда как предыдущие исследования не выявили свидетельств морской трансгрессии на отметках >41 м над у. м., наши результаты показывают, что верхняя морская граница в районе исследования превышает 53 м над у. м.

Ключевые слова: изоляционные бассейны, донные отложения, диатомовые водоросли, пыльца, Белое море, изменения уровня моря, позднеледниковье

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