

## The Riverine Past of Lake Seliger

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**Abstract**—Lake Seliger has been always classified as a former glacial water body, a remnant of a vast proglacial lake, which has existed since the disappearance of the last glacial Ice Sheet in the territory 18–19 thousand years ago. The study was focused on areas of southern pools of the lake looking like underflooded meandering river channels. Bottom sediments were drilled in three such areas and ground penetrating radar profiling was carried out on two areas. Lake silt, several meters thick, was found to overlay coarse sand, which is most likely of riverine origin. A feature in favor of this is a characteristic asymmetrical bed profile in the supposed parts of ancient river bends and the time of transition from active flow to the regime of stagnant water body since 14.5 thousand years ago: in that time, glacier edge already lied far from here, and glacial melt water did not penetrate into this area. The inundation of segments of river valleys and their transformation into lake pools was provoked by damming of the Selizharovka River, which originally flowed out from Lake Seliger near Ostashkov Town. About 14.5 thousand years ago, the rapidly growing delta of the Krapivenka River, a left tributary of the Selizharovka, started growing rapidly, damming the latter river. In the period of 2 thousand years, the damming effect extended over the entire 15-km segment of the valley and reached the source of the river in Lake Seliger. In the Holocene, the level rise continued, though at a lesser rate. The total rise of lake level was 7–8 m, which caused flooding of the lower reaches of the valleys of rivers emptying into the lake and transformed them into estuaries. It is shown that glacioisostatic deformations of the Earth crust could not reverse the flow from Seliger into the Baltic Basin. After the disappearance of the most recent glacier, Lake Seliger and its tributaries have always belonged to the Volga Basin; this is to be taken into account in the reconstruction of the Volga runoff and the water balance of the receiving water body (the Caspian Sea).

**Keywords:** the history of lakes, paleovalleys, bottom sediments, Lateglacial Period, Holocene

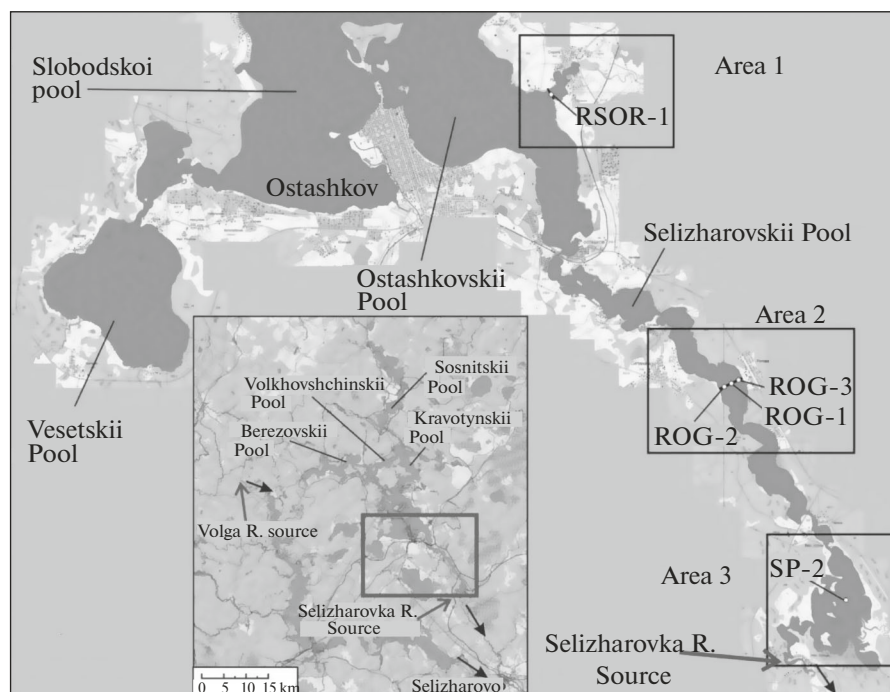
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### INTRODUCTION

Lake Seliger is the largest lake on the Valdai Hills, which serve as the main water divide of the East European Plain, separating the drainage basins of the Caspian, Black, and Baltic seas. Lying in the marginal zone of the latest glaciation, the Valdai Hills have a typical postglacial relief with terminal moraine ridges, kames, eskers, and glacial kettle holes. The origin of Lake Seliger basin is commonly attributed to glacial processes, i.e., glacial ploughing, uneven glacial accumulation, and the effect of flows of melt glacial water [1, 10, 14, 21, 22, 25]. The main arguments in favor of the glacial hypothesis are as follows: (1) the high indentation of the shore line; (2) the abundance of islands and bays of irregular and chaotic shape; (3) the presence of glacial and fluvio-glacial deposits and landforms in the lake basin [17]. The configuration of the lake basin, containing long pools, is sometimes attributed to the preglacial relief. According to data in [8, 16], the lake basin inherited the preglacial valley

network, which extended northwestward, and later was partially buried because of glacial accumulation.

The problems of the genesis of the bottom and shore landforms of Seliger pools have not been adequately covered in the published literature. The researchers focused mostly on studying the shapes and sizes of islands and measuring the length of the shoreline [4, 7, 20]. At the same time, the topography of pools (Fig. 1) shows some features of river morphology, which are difficult to explain based on the existing concepts. An example is the elongated and regularly bent shape of some Seliger pools (Selizharovskii, Berezovskii, Sosnitskii, Kravotynskii, and Volokhovshchinskii), which is typical of river valleys. The bed topography of the Selizharovskii, Berezovskii, and Volokhovshchinskii pools shows smoothly bent elongated troughs with shapes similar to river channels. Some rivers flowing into the lake (e.g., the Soroga River) have funnel-shaped mouths, extending toward the lake and forming bays—estuaries. No reliable data



**Fig. 1.** Schematic map of southern pools of Lake Seliger with study areas. The inset is a review schematic map of Lake Seliger and nearby areas.

on the history of lake level variations in the postglacial time are available. Some researchers of Stone Age dwelling sites on the shores of the Selizharovskii pool suggest a high level (much higher than it is now) of the lake in the final Mesolithic [5]. However, a dwelling site of the same time (7–8 thousand years ago) studied on the other shore of the lake lies as little as 1.5–3.0 m above the present-day lake level [18], thus contradicting the reconstruction mentioned above.

These facts show that Lake Seliger is not still adequately studied in terms of paleogeography. The genesis of the lake basin and its age are not clear. Reliable reconstructions of the history of level variations are not available. The wide occurrence of sand under lake silt [15] and the fluvial morphology of some Seliger pools are still to be explained.

This article presents the results of studies of the topography and bottom sediments of southern pools of Lake Seliger. The objective of the study is to reconstruct the early stages of lake history and to determine lake age and the genesis of the landforms in some areas.

## MATERIALS AND METHODS

Lake Seliger is a system of 24 semi-isolated bays (pools), which look as a cross in the planar view. According to data in [9, 13], the length of the lake from north to south is 60 km and that from west to east is 35 km. Lake water area is 212 km<sup>2</sup>, the mean depth is 5.8 at a maximum of 24 m. Lake drainage area is

2310 km<sup>2</sup>. At the normal level (205.48 m), the total lake water volume is 1.3 km<sup>3</sup>. The amplitude of level variations, recorded over the observation period, is 206 cm. The annual course of level variations shows two peaks, in spring and autumn. The shoreline is very sinuous and long; its length is 528 km. The lake contains >160 islands, the largest of which is Khachin Island. The lake receives >100 tributaries, the largest being the Krapivenka, Soroga, and Seremukha rivers. The only river that flows out from Lake Seliger is the Selizharovka, which empties into the Volga near Selizharovo Settlement. Since the mid-XX century, the lake suffers heavy anthropogenic load, which is among the causes of the change of the lake's state from oligotrophic into mesotrophic, and signs of eutrophy can be seen in some pools [2, 10–12].

In January–March 2018, field studies were carried out in three areas of the lake (Fig. 1): (1) Soroga R. mouth; (2) the central part of the Selizharovskii Pool at Rogozha V.; (3) the southern extension of the Selizharovskii Pool near Nizhnie Kotitsy V. Drilling of lake deposits was carried out from ice by a modified Livingstone piston sampler [30]. The core samples were packed in plastic containers on the site and transported into a laboratory. Profiling by Piton ground penetrating radar (GPR) was carried out in areas 1 and 2. The profiles were carried out with 2–3 repetitions with changes of the antennas, the central frequencies of which were 25, 50, and 100 MHz.

**Table 1.** Radiocarbon (AMS) dates by bottom sediments of Lake Seliger

No.	Laboratory number (IGAN <sub>AMS</sub> )	Core	Depth to the bed, m	Material	<sup>14</sup> C date, years BP ( $\pm 1\sigma$ )	Calibrated age, cal. years BP ( $\pm 1\sigma$ )
1	6174	RSOR-1	0.6	Plant detritus	490 $\pm$ 20	520 $\pm$ 10
2	6175	RSOR-1	0.85	Total organic carbon	2800 $\pm$ 20	2900 $\pm$ 30
3	6176	RSOR-1	1.6	Plant detritus	10860 $\pm$ 30	12730 $\pm$ 20
4	6184	RSOR-1	1.82	The same	10900 $\pm$ 35	12760 $\pm$ 30
5	6177	ROG-3	4.8–4.83	Total organic carbon	9855 $\pm$ 30	11250 $\pm$ 20
6	6178	ROG-3	6.12	Plant detritus	20680 $\pm$ 50	24920 $\pm$ 160
7	6179	ROG-2	0.76	Total organic carbon	4960 $\pm$ 25	5680 $\pm$ 30
8	6180	ROG-2	0.53–0.63	The same	5750 $\pm$ 50	6550 $\pm$ 60
9	6181	SP-2	3.2–3.25	The same	9510 $\pm$ 30	10850 $\pm$ 130
10	6182	SP-2	4.42	Plant detritus	11960 $\pm$ 35	13810 $\pm$ 70

Core samples from reference boreholes were used to determine the loss on ignition (LOI) and the magnetic susceptibility (MS); spores and pollen analysis was also carried out. The determination of LOI followed the standard procedure [23]. LOI 550°C reflects the concentrations of organic matter, and the difference LOI 950–550°C (LOI  $\Delta$ 950) characterizes the losses of CO<sub>2</sub> from carbonates [23, 26]. MS was measured for stratigraphic analysis of the deposits and correlation between the core samples. This characteristic depends on the concentrations and occurrence forms of magnetic particles in the sediments [3, 19], which are due to both the sources of materials and the biogeochemical processes in the sediment. The measurements were carried out with a portable susceptimeter ZH Instruments SM 30. The preparations for the pollen analysis were made with the use of V.P. Grichuk's separation procedure [6].

The radiocarbon analysis was carried out in centre of collective usage "Laboratory of Radiocarbon Dating and Electron Microscopy," Institute of Geography, Russian Academy of Sciences, and the Center for Isotopic Studies, the University of Georgia (USA). The bulk samples of lake silt and plant macroresidues were analyzed to determine 10 dates (Table 1) by the method of acceleration mass-spectrometry (AMS). The calibration, i.e., the reduction of <sup>14</sup>C dates to a calendar time scale was made in OxCal 4.3 software package [24] with the use of calibration curve IntCal13 [28]. The text of the article and figures give the calendar (calibrated) age in the form of *years BP*.

## RESULTS

### *Key Area 1*

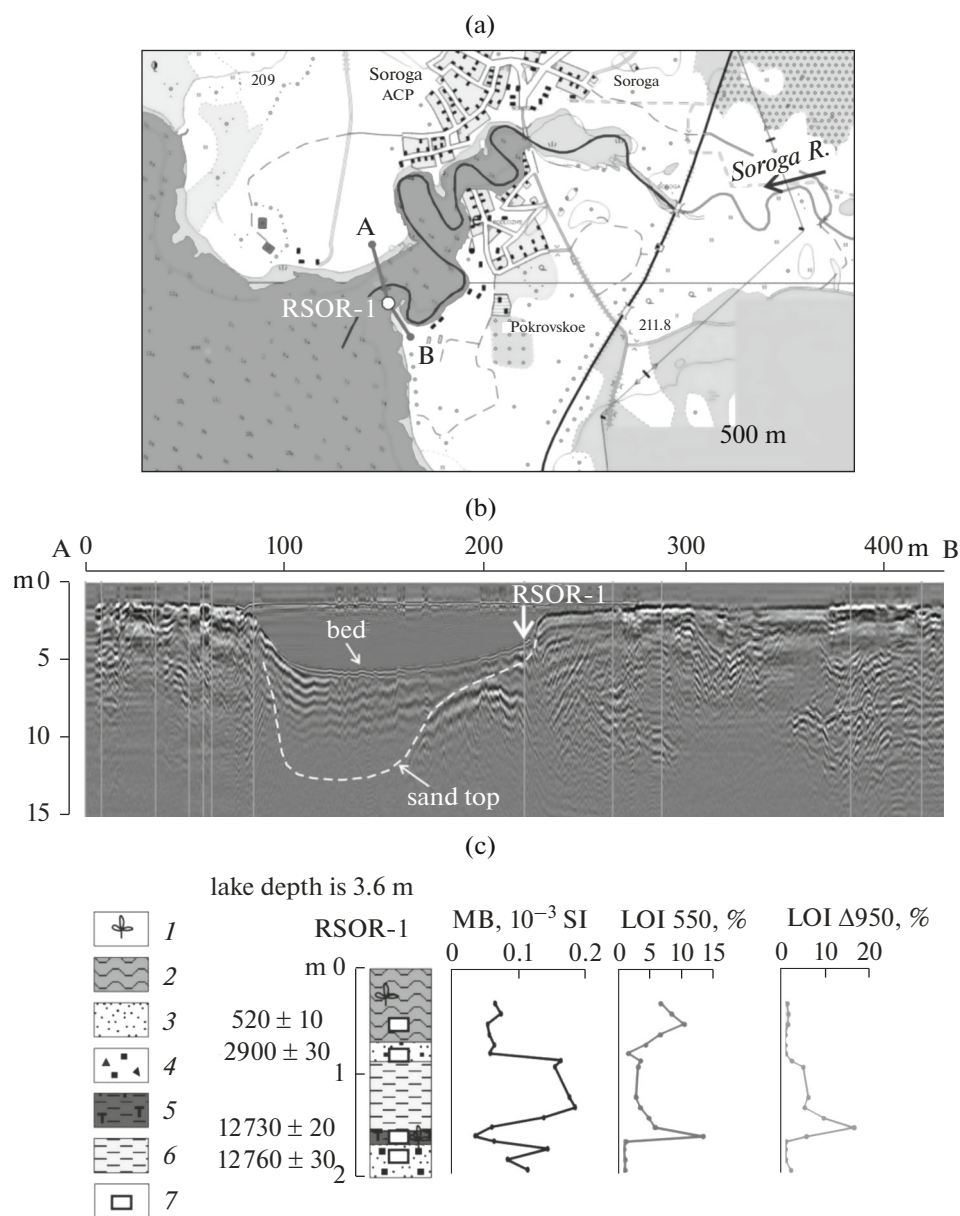
The Key Area 1 lies in a wide near-mouth bay (estuary) of the Soroga River, which empties into Ostashkovskii Pool from its eastern shore (Fig. 2a). The Soroga is the longest river flowing into the lake.

According to data in [10], it is 27 km long, its drainage area is 141.6 km<sup>2</sup>, mean annual water discharge is 1.26 m<sup>3</sup>/s, the annual runoff is 33.69 million m<sup>3</sup>, the annual volume of solid runoff, entering the lake as sediments, is 7.94 t. The gradient of the river is low, allowing the river, with its highly erodible banks, to meander intensely. In the lower part of the Soroga, its channel width increases appreciably (from 5 to 40 m), and its meanders become much larger. The Soroga estuary is 1.7 km long, and its width varies from 80 to 360 m. The planar configuration clearly shows rhythmic alternation of wider and narrower parts. The bank line is a series of rounded pockets. The depth of the estuary varies from 0.5 to 7 m at an average of 2–4 m. The bed topography is differentiated. Segments with maximal depth are common near concave banks, along which troughs lie, smoothly bending along the bank. Shallows are common near the concave banks.

In this area, a GPR profile was made, crossing the estuary in its lower part at the exit into the Ostashkovskii Pool (Fig. 2b). The estuary is narrower here with a distance between the shores of 250 m. The profile also crosses segments of the southern (low) and northern (high) shores. The total length of the profile is 430 m. One core (RSOR-1) lies on the profile.

Core RSOR-1 was drilled 15 m from the southern low shore, covered by reed. Lake depth at the drilling point is 3.6 m. The total length of the obtained core is 2 m. The core crossed five layers of bottom sediments (Fig. 2c): (1) 0.0–0.7 m—gyttja; (2) 0.7–0.9 m—fine sand; (3) 0.9–1.6 m—gray lacustrine loam; (4) 1.6–1.65 m—a layer, saturated by weakly decayed plant remains; (5) 1.65–2.0 m—poorly sorted sand, with gravel in some places, fine and layered in the upper part and coarse with gravel in the lower part.

The radiocarbon dates obtained for plant detritus from layers 4 and 5 show that the accumulation of the lower unit of sand finished 12.7 thousand years ago. The top sand layer and the overlying gyttja have formed



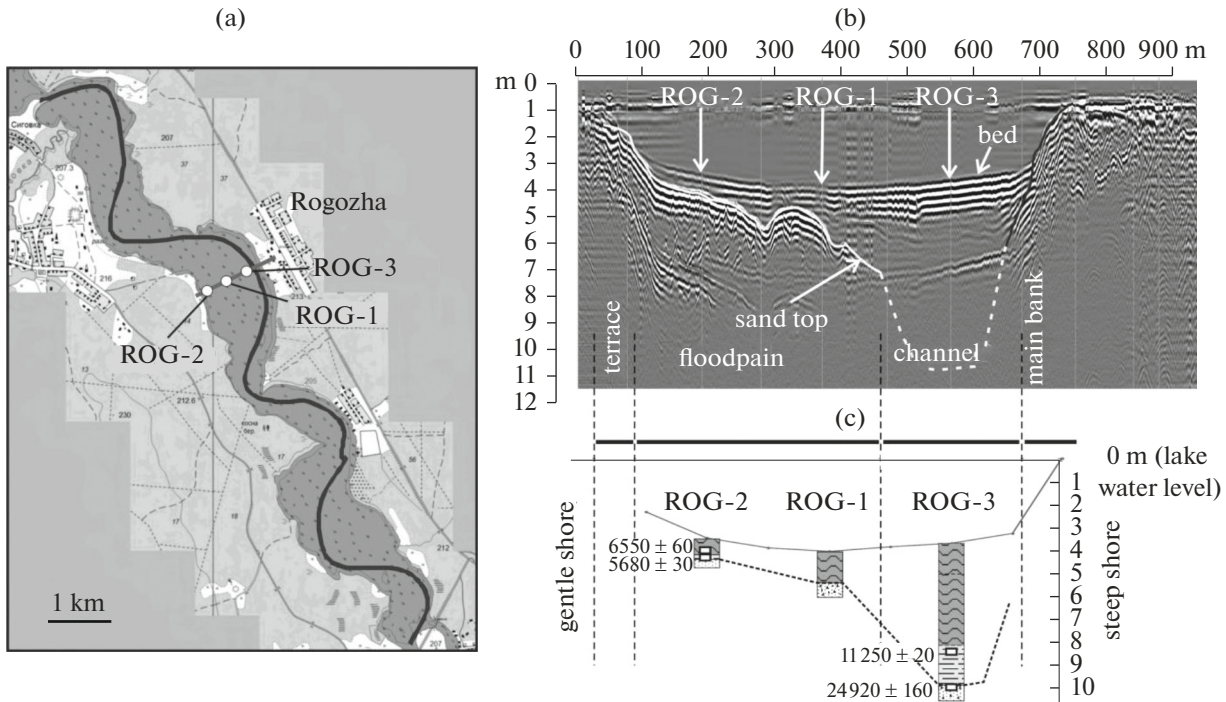
**Fig. 2.** Area 1 “Soroga.” (a) Schematic map of Soroga mouth area, line A–B is GPR profile, the white circle is RSOR-1 core, the sinuous line is the supposed position of the inundated channel of the Soroga R.; (b) GPR profile, antenna with a frequency of 100 MHz; (c) is the lithological column of core RSOR-1 with the results of analyses: MS is magnetic susceptibility; LOI is loss on ignition; (1) plant detritus, (2) organomineral silt (gyttja), (3) sand, (4) gravel and land waste; (5) peaty loams, (6) mineral silt (lacustrine loam), (7) sites of sampling for radiocarbon analysis. The dates are converted to the calendar time scale in the format “mean ±  $\sigma$ ” years BP (the reference year is 1950).

over the past 3 thousand years. The presence of the top sand layer may be an indication to the passage of a high flood and the erosion of the upper part of bottom sediments in this area.

The GPR profile shows an asymmetry of the transverse profile (Fig. 2b). A trough near the high northern shore is almost completely filled with sediments. Similar to the core RSOR-1, these sediments are likely represented by organic–mineral silt underlain by a

sand stratum. The trough is 50–70 m in width, the top of sand in trough thalweg extends down to 10–12 m below lake level (b.l.l.). The southern underwater shore slope is gentle and forms a step, where the top of the sand rises to 5–7 m b.l.l. The core RSOR-1 was drilled on this step.

The results of the lithological analysis of the core from core RSOR-1 (Fig. 2c) agree with the beds identified in the description. The beds 1 and 4 are rich in



**Fig. 3.** Area 2 “Rogozha.” (a) Map of the study area; the sinuous line is the supposed position of the inundated channel of the Soroga R.; (b) GPR profile, antenna with a frequency of 50 MHz; (c) drilling profile.

organic matter (up to 10–15%); however, the values of MS are low. The layer 4 has a higher LOI  $\Delta 950$ , indicating the presence of carbonates. The layer 4 has high values of MS at low concentrations of organic matter and carbonates. The layer 5, lying at the base of the formation, shows low values of all characteristics, suggesting its silicate composition and terrigenous nature.

#### Key Area 2

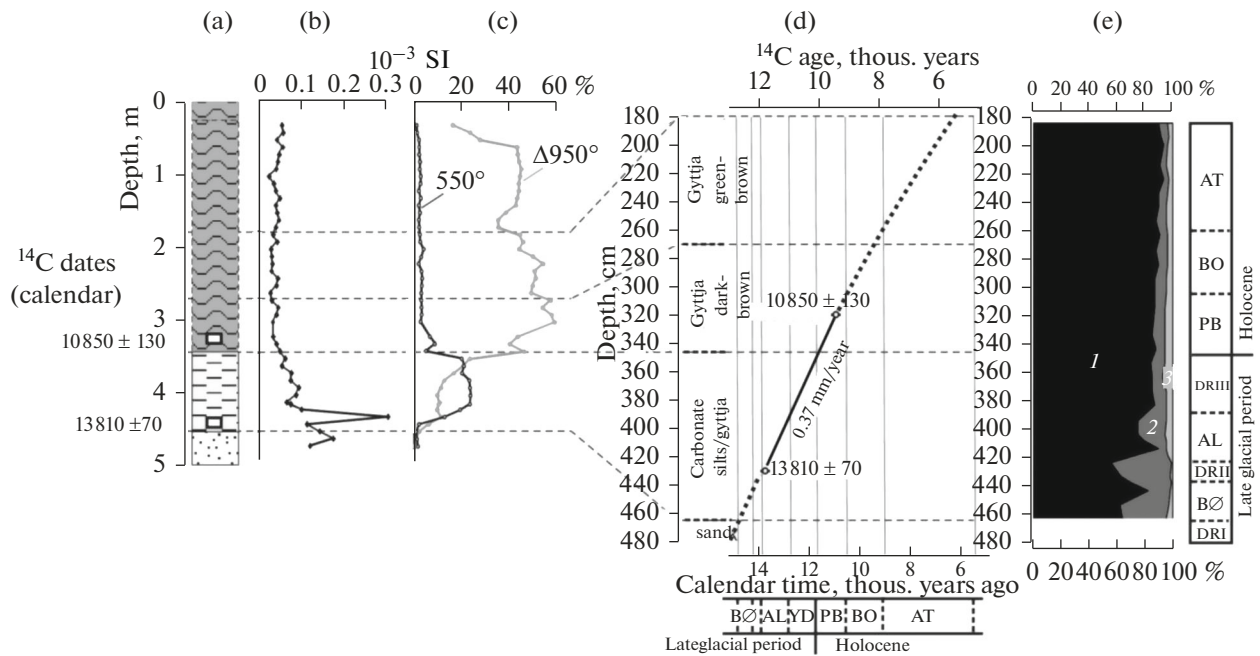
The key area 2 is located in the water area of the Selizharovskii Pool abeam Rogozhi Village (Fig. 3a). The pool in the area of the profile is 700 m wide. The eastern shore, where Rogozha Village is located, is high and concave in plan, while the western shore is low and convex. Depth measurements showed that the depths are generally maximal (3.5–4.0) in the central and eastern parts of the profile. Drilling (Fig. 3c) showed that gyttja thickness is largest (>4 m) near the eastern shore (core ROG-3). The gyttja is underlain by gray mineral loams 1.8 m in thickness. Coarse sand with gravel underlays the loams. In cores ROG-1 and ROG-2, the thickness of lacustrine deposits decreases considerably (to 1.0–1.5 m). The top of the sand lies much higher. According to radiocarbon dating, the change from loam to gyttja took place in the very early Holocene—after 11.3 thousand years ago. The gray loam underlying gyttja has formed in Lateglacial Period. The date  $24000 \pm 920$  calendar years ago, estimated by plant detritus from sands in the lower part of

core ROG-3, does not reflect the real age of the host sand. The obtained date falls within the stage when Seliger was covered by a glacier or just before this. It is likely that the plant remains were redeposited from more ancient deposits in the course of their postglacial erosion.

The GPR profile (Fig. 3b) clearly shows two boundaries: the bed and top of sand. The topography of sand top suggests the presence of a large buried trough along the eastern shore. The width of the trough is 200–230 m, and the depth below the lake water level is ~10 m. A bar ~80 m in width lies west of the trough near core ROG-2. The top of the sand in the crest of the bar lies up to 5 m b.l.l. Beyond the bar toward the western shore, the top of sand continues rising up to 3–4 m. The topography of sand top resembles a typical profile of the bed of a lowland river. The trough at the steep convex shore corresponds to the channel of a paleoriver; the bar in the near-edge part of the low bank is the natural levee, lying beyond which is an ancient floodplain.

#### Key Area 3

The Key Area 4 (Fig. 4) lies in Nizhnekotitskii Bay—the southern extension of the Selizharovskii Pool. The bay is 1.6 km wide and 2.9 km long. The Selizharovka River flows out of the southwestern part of the bay and the Krapivenka River, the largest tributary of Seliger, empties into its southeastern part. The



**Fig. 4.** The structure of lacustrine deposits in core SP-2 (area 3, lake depth is 3.65 m): (a) lithological column (the legend see in Fig. 2); (b) magnetic susceptibility; (c) loss on ignition; (d) the composition of pollen spectra: (1) tree pollen, (2) pollen of grass and shrubs, (3) spores. Climatic periods: DR1 is the Oldest Dryas, BØ is Bølling, DR2 is the Older Dryas, AL is Allerød, DR3 is the Younger Dryas.

Krapivenka mouth is a beak-shaped delta with a size of 900 m by 800 m. The bay contains 5–6 islands. The mean depth in the bay is 2.5–3.0 m at a maximum of 4 m. Core SP-2 lies in the central part of the bay, where a depth of 3.65 m was recorded (Fig. 1).

The length of the core sample from core SP-2 is 5 m (Fig. 4). Three layers were identified in the core sample: (1) 0.0–3.5 m—gyttja (2) 3.5–4.5 m—gray lacustrine loam; (3) 4.5–5.0 m—fine and medium-grained sand. The top gyttja bed (1) is rich in organic matter (up to 58%). At the same time, it contains no carbonates and shows low MS values. The loam in layer 2 shows high values of LOI  $\Delta 950$  (up to 25%), thus demonstrating a high proportion of carbonates in the sediments. An anomalously high peak of MS was recorded in the bottom part of layer 2. The sand in layer 3, which lies in the bottom of the section, shows low values of all measured characteristics, suggesting its silicate composition and terrigenous nature.

Pollen analysis was made for the bottom part of SP-2 core sample (Fig. 5). The pollen diagram reflects the development of vegetation in the area around the lake since the Lateglacial Period to the Boreal epoch of the Holocene. This diagram clearly shows all cold stages of the Lateglacial Period, separated by warm interstadial periods: the Younger Dryas (DR-1), Bølling (BØ), Older Dryas (DR-II), Allerød (AL), and the Oldest Dryas (DR-III). The time boundaries of the stages of the climate–stratigraphic Blytt–Sernander system are in general agreement with the boundaries of

local pollen zones, identified on the diagram and confirmed by the analysis of statistical similarity of the pollen spectra by CONISS software program from TILIA special software package. The time boundaries of the stages of Blytt–Sernander climate–stratigraphic scale are in general agreement with the local pollen zones shown on the diagram and confirmed by the analysis of the statistical similarity of pollen spectra using CONISS program from TILIA specialized package.

In the Lateglacial Period, the concentration of herbage plant pollen in the total composition of spectra reaches 40% during cold and relatively dry stages and drops to 15–20% during interstadial Bølling and Allerød warming periods. In the pollen composition of grass and low shrubs, the largest are the concentrations of warmwood (*Artemisia*), representatives of the families of sedge, pigweeds, and cereals. Pollens of heliophilic plants (*Helianthemum* sp., *Hippophaë rhamnoides*), xerophytes (*Ephedra*), and hypocoalpine selaginella species *Selaginella selaginoides* were also found. Dominating among wood species is the pollen of pine and birch. A pronounced *lower peak of spruce* (up to 40% of the total pollen of terrestrial plants) corresponds to Bølling and Allerød; this peak, as well as the more smooth peak of pine pollen, is divided into two parts by a drop, corresponding to the Older Dryas. A manifestation of a short-time (<400 years) cool period as distinct as that, very rarely

manifests itself in palynological data and deserves special attention.

In SP-2 column, this cold and relatively dry interval corresponds to the highest concentration and morphological diversity of the pollen of wormwood and an increase to the concentration of birch pollen. The warming in Allerød manifests itself in an increase in the abundance of spruce forests and the appearance of sporadic pollen particles of broad-leaved species of oak subgenus (*Quercus*, *Ulmus*, *Tilia*). Possibly, by that time, these species have not reached the area of Lake Seliger in the process of their expansion from the refugia of glacial time, though the boundaries of their areas should have moved much closer to this region. Conversely, hazel pollen (*Corylus*) can be seen throughout the Lateglacial Period in larger amount than in the Early Holocene; and its distribution in that period shows no correlation with warming stages. This fact, along with the presence of singular hornbeam pollen grains suggests that hazel pollen is redeposited here from the sediments of Mikulino interglacial period, which contain it in huge amounts. The cooling of the Younger Dryas corresponds to the highest in the section concentrations of birch pollen (up to 60% of the total pollen of terrestrial plants), a decrease in the share of pine pollen, and almost complete absence of spruce pollen. As was the case with the Middle Dryas, the concentration of willow pollen is relatively high (up to 10% of the total pollen of trees and brushes); the pollen of brush alder (*Alnaster*) can also be seen.

The beginning of the Holocene corresponds to the appearance of broad-leaved species, primarily, elm (*Ulmus*), in birch and pine forests. Later, oak and linden gradually became more widespread, and the structure of underbrush became richer (pollen of filbert (*Corylus*), elder (*Sambucus*), and arrowwood (*Viburnum*) was found). Dominating among herbaceous plants become cereals and sedge family, the diversity of mesophilic herbs increases, the pollen of erica brushes and spores of sphagnum mosses appear; fern spores are abundant. However, pollen of xerophilous plants, e.g., ephedra (*Ephedra*), and representatives of spurge family (*Euphorbiaceae*) can be seen in the layers of early Holocene, a fact that, likely, suggests relatively dry and warm summer and a wide occurrence of sand soils. The pollen of aqueous and coastal plants (cattail, bur reed), occur in small amounts; however, it is worth noting that, as long ago as the early Lateglacial Period, thirtboxes (*Nuphar*) and nymphaea (*Nymphaea*) lived in the lake, suggesting that water was warm enough in summer.

Overall, the obtained results suggest the conclusion that forest communities (thin forests and later northern taiga forests) first appear in the area under consideration as early as the late glacial warmings (Bølling and Allerød). The present-day vegetation pattern began to form here in the Early Holocene (Preboreal/Boreal) and had formed completely by the mid-

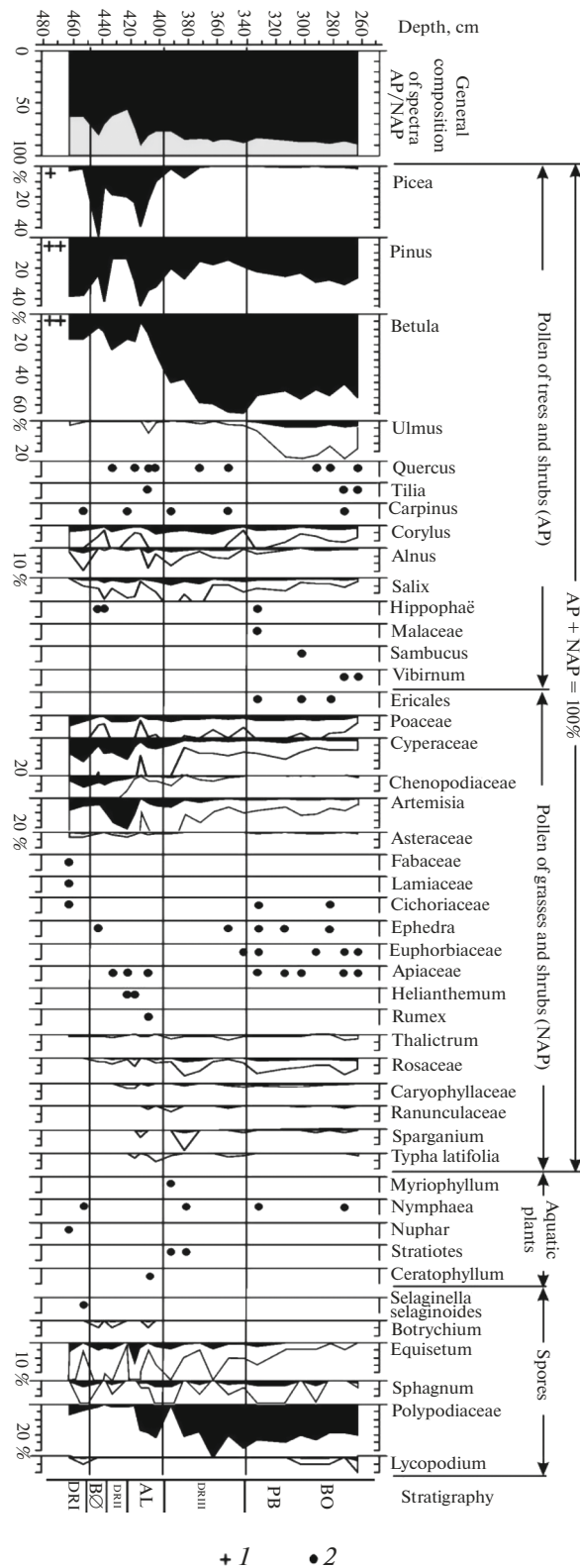


Fig. 5. Pollen diagram for the bottom part of core sample SP-2. (1) Singular findings of pollen grains; (2) pollen and spores in the amount of less than 1%; additional curves are given with 5-fold magnification.

Atlantic time. Climate-stratigraphic constructions by palinological data are in good agreement with the radiocarbon chronology and confirm its reliability. Radiocarbon dates and biostratigraphic data suggest the conclusion that the deposits exposed by the core were accumulating continuously during the Lateglacial Period and Holocene. Extrapolating the age determinations by the two available radiocarbon dates, we obtain that the top of the sand bed corresponds to the chronologic level of ~14.5 thousand years ago, and sapropel bottom, to 11.7 thousand years ago (Fig. 4d).

## DISCUSSION OF RESULTS

Lacustrine silt 1–3 and sometimes 6 m thick was found in all cores on lake bed. The upper part of the silt is of dark gray color (in some cases, with greenish cast) because of enrichment with organic matter (30–60%). This is Holocene sapropel (gyttja). Bottom silt layers in many cores are of light grey or blue-grey color, because they contain little organic matter (3–10%). This suggests that the sediment were forming under cold climate, i.e., in the end of the late glacial epoch. The silt is everywhere underlain by coarse sand, the transport of which suggests high enough water flow velocity. There are reasons to suppose that this is channel alluvium rather than deposits of glaciofluvial flows. First, the contours of either the estuary of the meandering Soroga River or the narrow Selizharovskii Pool clearly show regular bends resembling meandering channels (Figs. 2a, 3a). In the examined areas crossing such bends, the top of sands shows a typical asymmetric profile with largest depths near the concave bank (Figs. 2b, 3b). This is typical of river bends where the line of largest depths is near the concave bank. Second, the top of sand in profiles shows a higher surface of sand in the internal parts of the bends, which can be interpreted as meandering channel point-bars, which continue into the floodplain (Figs. 2b, 3b). Third, the peat layer above the sand in top RSOR-1 (Fig. 2) is an indication to a development stage under subaerial regime (i.e., in the open air, rather than under water), which would have been impossible if the hypothetical large proglacial lake had just slowly decreased its level.

Therefore, there are reasons to believe that the Selizharovskii Pool and the estuary of the Soroga River are inundated parts of river valleys. The cessation of river flow was due to the backwater effect of water level rise in the lake. Judging by the elevation of the paleochannels buried under silt and inundated in areas 1 and 2 (Figs. 2b, 3b), the magnitude of lake level rise can be estimated at 7–8 m. The change of the regime from riverine to lacustrine manifests itself geologically in the change from river sands to lake silts. According to radiocarbon dates (Fig. 4) and palynological data (Fig. 5), in the southern end of the Selizharovskii Pool, this change took place at the stage of passage from stadial (cold climatic oscillation) Early Dryas

(DR1) to interstadial (warm climatic oscillation) Bølling (BØ). Therefore, ~14.5 thousand years ago, the lake level rose above 197.4 m abs. The dates at the boundary between sand and lake silt in the Soroga River estuary (Fig. 2c) indicate that after 12.7 thousand years ago, water level exceeded the mark of 200.3 m abs. This means that during ~2 thousand years, the damming effect extended all over the 15-km valley segment and reached the source of the river in Lake Seliger. The level of the ancient floodplain in area 2 (201.5 m abs) was reached by the lake ~6 thousand years ago. In the second half of the Holocene, water level in the lake was slowly rising to its present level (Fig. 6).

What is the cause of the transformation of river system into lake system? Hypothetically, two scenarios are possible.

First, the general direction of river flow and the position of the main water divide could have changed because of glacioisostatic adjustments—a rise of land surface caused by the disappearance of the glacial loading. The rate and the total magnitude of this rise in the postglacial time increased northwestward toward the Gulf of Bothnia, the Baltic Sea, where the thickness of the glacier and, therefore, the load onto the Earth crust were maximal. Therefore, the postglacial rise was accompanied by a tilt of the land surface southeastward. While the river flow in the postglacial period was directed northward into the Pola river basin, such tilt, directed against the flow, theoretically could cause a drop of slopes to zero values resulting in damming of a part of the river system. However, the gradients of such tilt are too small to cause damming, and a special field study in the areas of possible northwestward water flow has not found any signs of such flow. Therefore, such scenario looks unlikely.

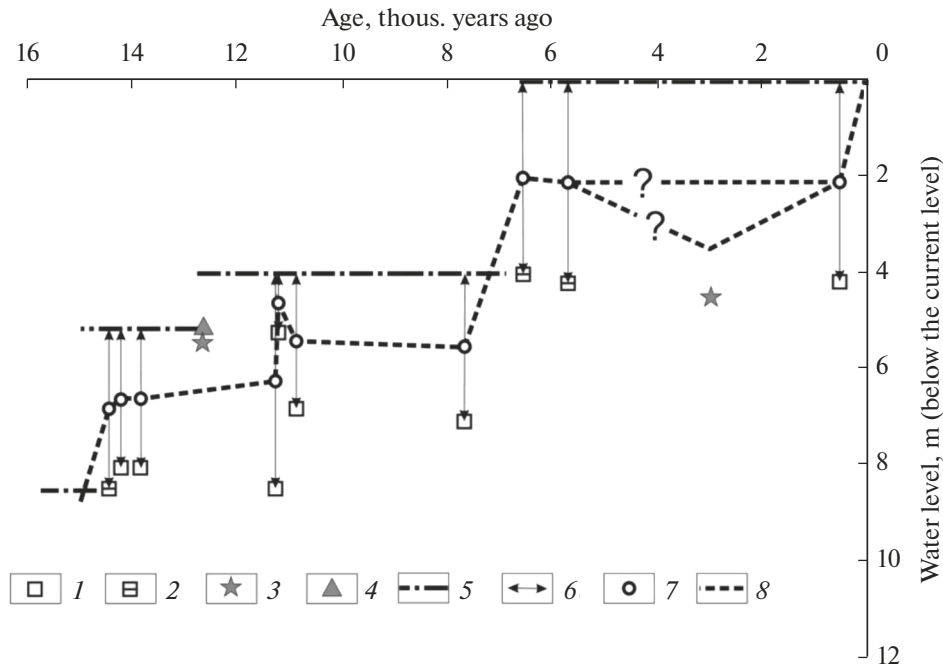
Another possible explanation of level rise in Seliger Lake is the damming of the valley of the Selizharovka River, which originally flowed out of Seliger Lake near Ostashkov Town, by a natural dam near Nizhnie Kotitsy Village. This scenario assumes that the flow over the future Selizharovskii Pool in the postglacial period was directed into the Volga basin, as it does now. The likely damming of the valley near Nizhnie Kotitsy Village is supported by the features listed below.

(1) The longitudinal profile of the waterway from Ostashkov to Selizharovo Settlement contains signs of a gentle bank near Nizhnie Kotitsy, upstream of which the wide and shallow Nizhnekotitskii bay is situated and downstream of which lies the source of the Selizharovka River.

(2) The mouth of the Krapivenka River is a relatively large beak-shaped delta, protruding into Nizhnekotitskii Bay from southeast, thus indicating to the active accumulation of river sediments in the bay.

(3) Satellite images of the middle reaches of the Krapivenka River show traces of large branching





**Fig. 6.** Water level variations in Lake Seliger system over the recent 14.5 thousand years. The curve was drawn based on the combined results of facial analysis and radiocarbon dating of deposits. (1) gytja, (2) bottom of gytja, (3) river sand, (4) peat, (5) maximal likely mean water level, (6) uncertainty interval, (7) middle point of the uncertainty interval, (8) variations of the mean long-term water level.

structures, which may be an indication to large volumes of runoff in the past. The high flow could cause intense input of sediments, which, because of low slopes, formed an inner delta. High values of climatic (not glacial) river flow in the Volga Basin as a whole and in the central part of the Russian Plain in the post-glacial period were established before in [27, 29].

(4) The western coast of Nizhnekotitskii Bay shows some signs of alluvial-deltaic accumulation, including lowland swampy area with abandoned meandering channels, which can be seen in space photographs. The delta lies at the mouth of a relatively large valley (with a width of up to 200 m and a depth of 10–15 m) with partially swampy bottom. Now, a creek with a source at Spitsino Village flows over the valley. The delta is likely of relic nature; it is related to the stage of high flow along the valley.

Therefore, we can suppose that Selizharovka R. paleovalley was dammed by large alluvial fans (inner deltas) of the Krapivenka River and a river that emptied into Nizhnekotitskii Bay from northwest. The growth rates of the alluvial dam (and the lake level) were maximal in the Lateglacial Period and the early Holocene (Fig. 6). This is likely due to the occurrence of high flow in river valleys, which delivered large amounts of sediments into the lowland Nizhnekotitskii Bay. In the second half of the Holocene, the rates of sediment input decreased and the growth of the height of the alluvial dam became slower. The lake level has been steadily rising since the moment of its formation;

therefore, the scenario of the lake level standing higher in the epoch of Mesolithic than it does now [5] has no confirmation.

## CONCLUSIONS

Lake Seliger in its individual areas (the largest of which is Selizharovskii Pool) is an inundated system of river valleys. The transformation of the river system into a lake system took place in the Lateglacial—in the period of Bølling–Allerød warming (14.5–12.5 thousand years ago). Water level in the lake has been rising during the Lateglacial and Holocene with the total rise of 7–8 m. The rate of lake level rise was maximal in the Lateglacial and early Holocene. The likely cause of the transformation of the river system into a lake was the alluvial damming of the paleovalley of the Selizharovka River by large fans (inner deltas), which formed due to the intense inflow of sediments from the valleys of two its tributaries—the Krapivenka River and a nameless creek, which originates at Spitsino Village. Once the area became free of the last glacier, the flow from the basin of Lake Seliger was always directed into the Volga basin, a fact that is to be taken into account in the reconstruction of the value of its flow and the water balance of the receiving water body (the Caspian Sea).

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