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Paleolimnological Studies in Russian Northern Eurasia: A Review

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Abstract—This article presents a review of the current data on the level of paleolimnological knowledge about lakes in the Russian part of the northern Eurasia. The results of investigation of the northwestern European part of Russia as the best paleolimnologically studied sector of the Russian north is presented in detail. The conditions of lacustrine sedimentation at the boundary between the Late Pleistocene and Holocene and the role of different external factors in formation of their chemical composition, including active volcanic activity and possible large meteorite impacts, are also discussed. The results of major paleoclimatic and paleoecological reconstructions in northern Siberia are presented. Particular attention is given to the databases of abiotic and biotic parameters of lake ecosystems as an important basis for quantitative reconstructions of climatic and ecological changes in the Late Pleistocene and Holocene.

Keywords: paleolimnology, lakes, bottom sediments, northern Eurasia, Russian Arctic, databases

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INTRODUCTION

Bottom sediments of lakes as a variety of geological archives are records that contain and store the information on ecological situations of the past at the regional and planetary level with a resolution from thousands and hundreds of years to 1 year (Subetto, 2009). In recent years, the interest to paleoecological, especially paleolimnological studies of the Northern Hemisphere has grown significantly, which is primarily due to the problem of global climate change, especially in high latitudes (*Climate Change*, 2007). The polar regions of the Northern Hemisphere include a vast number of lakes of different genesis and morphometry; their bottom sediments archived detailed data on changes of the climate, landscapes, and hydrology during the Pleistocene and Holocene.

Paleolimnological studies in the Russian Arctic were initiated by scientists of the Arctic and Antarctic Research Institute in 1960–1970 (Govorukha et al., 1965). In the 1980s, the Institute of Limnology of the Academy of Sciences of the Soviet Union and the related institutes carried out studies as part of the project "History of Lakes of the Soviet Union," which included investigation of a number of lakes in the Kola Peninsula, Bolshezemelskaya tundra, Taimyr Peninsula, and other northern regions of Eurasia (*Istoriya ozer Vostochno-Evropeiskoi…*, 1992; *Istoriya ozer Severa Azii…*, 1995). At the present time, an intensive study of Arctic lakes of Siberia is being carried out within the framework of international cooperation. However, although paleoecological studies are carried out in many Russian regions, the level of knowledge about paleoclimatic and paleoecological changes in the Russian part of northern Eurasia is much lower compared to Europe and the American continent.

The special issue of the *Siberian Journal of Ecology* "Paleoecological Studies in Russia" presents the latest studies of the leading Russian specialists who are engaged in the area of paleoecology and paleoclimate. The articles of the special issue provide the most recent data on paleological and paleoclimatic reconstructions, as well as the historical development of natural conditions in the areas of the northern Urals (Nazarova et al.), the south of the Taimyr Peninsula (Syrykh et al.), Central Siberia, central (Frolova et al.; Pavlova et al.) and northern (Rashke et al.) Yakutia, the Novosibirsk archipelago (Palagushkina et al.), the Baikal region (Bezrukova et al.), and the Far East (Razzhigaeva et al.).

This article presents a review of the current data on the paleoecological studies of the northern Eurasia within the Russian Arctic from the Kola Peninsula to Yakutia.

Studies in the European North of Russia

In recent decades, paleolimnological studies have been intensively carried out in the European north of Russia, which include reconstructions of natural and climatic situations during the postglacial time, the dynamics of the level of large basins along the periphery of the Baltic crystalline shield, and the identification of the causes and mechanisms of sharp climate changes at the boundary between the Pleistocene and Holocene (Subetto et al., 2003; Wohlfarth et al., 2007; Subetto, 2009; Andronikov et al., 2014). The bottom sediments of the lakes of the Karelian coast of the White Sea and Solovetsky Archipelago at different elevations have been studied, and provide reconstruction of changes in the water level of the White Sea during the postglacial time (Subetto, 2010; Subetto et al., 2012; Sapelko et al., 2014). Similar studies were previously performed for the eastern part of the Baltic Sea and Lake Ladoga (Dolukhanov et al., 2009); Rosentau et al., 2013; Sapelko et al., 2014; Ludikova, 2015; Syrykh et al., 2015). In 2014, paleogeographical studies were continued in the Onega Peninsula of the White Sea, where a section in Cape Veinavolok and lakes and bogs in the Konyukhovskaya Bay were surveyed. The data served as a basis for reconstructing of the chronology of movements of the coastline of the White Sea in the area of the Onega Peninsula (Leont'ev et al., 2016).

The development of lakes of the north is directly associated with the spread of Quaternary glaciations that formed the current relief and led to the emergence of lakes with different geneses, which can be divided into two large groups: periglacial lakes that were a part of large periglacial basins in the past and lakes that developed outside of large periglacial basins (thermokarst, dammed, accumulative subsidence, exaration, and other lakes) (Subetto, 2009).

The lakes of the periglacial genesis (relict lakes) are mainly located at relatively low absolute elevations in the area where large periglacial basins were widespread in the past. This group of lakes in northwestern Russia includes Lake Ilmen, the lakes of the northern lowland part of the Karelian Isthmus, the Ladoga region and Lake Ladoga, lakes of the coastal zone of the Baltic Sea, lakes Peipus and Onega, and large shallow lakes in the Vologda–Arkhangelsk region (Vozhe, Lacha, Beloe, Kubenskoe, and a number of other lakes). The large periglacial water bodies emerged no earlier than 14000 years ago as a result of the melting of the glacier of the last Valdai glaciation. These lakes are characterized by the presence of bottom sediments of a thick (up to tens of meters) mass of laminated clays in the lower part of sections; these sediments are of glaciolacustrine origin and were formed under the conditions of the seasonal entry of flows of deposits with thaw waters from the ice sheet (Subetto, 2009).

Thermokarst, moraine-dammed lakes or lakes that were generated as a result of fossil ice melting are usually characterized by thin layer (the first meters) of clay deposits in the base of the lacustrine sediment section, which have a poorly defined lamination and are mainly gray or brownish gray. As a rule, the lakes of this group, especially thermokarst lakes, have been formed later than relict lakes (10000 to 9000 years ago).

The change of cold arctic climatic conditions of the Late Pleistocene to the warm and humid conditions of the Holocene approximately 11700 years ago led to significant paleogeographical changes, including (Subetto, 2009) (1) rapid melting of the Scandinavian ice sheet; (2) the catastrophic shallowing of the Baltic Ice Lake by 25 to 28 m due to the glacial retreat from the middle Swedish upland, which resulted in a lowering in the erosion base level and the levels of lakes (the complete disappearance of periglacial basins); (3) melting of permafrost subsoils; (4) the succession of tundra–steppe cenoses by forest communities and the transition from azonality to zonality in the distribution of vegetation; and (5) the formation of a stable soil cover.

The entire complex of paleogeographical changes led to a change in the pattern of sedimentation in the lakes of the north of the European part of Russia. Gray mineral clay deposits change to gray, greenish brown, and organogenic silts (sapropels) up the lacustrine sediment section (Subetto, 2009). According to the data of numerous radiocarbon datings, the period of transition from the mineral type of bottom sediments to the organic type varies in the narrow range from 10500 to 10000 years ago. This indicates the delayed response of terrestrial and aquatic ecosystems to warming approximately 11700 years ago. The delayed response of lake ecosystems and terrestrial vegetation to the rapid (catastrophic) warming at the boundary between the Pleistocene and Holocene can be explained by the difference in the circulation of air masses in the northwest of the East European Plain from the areas adjacent to the North Atlantic. The extreme climate continentality and/or anticyclonic circulation due to the possible dominance of strong eastern winds to the south of the Scandinavian ice sheet might contribute to the permafrost preservation in northwestern Russia. The high-pressure zone over the area of permafrost distribution and the dominance of eastern winds presumably blocked the transfer of warm air masses from the west to the east over the period of almost 3000 years (12900–10000 years ago) (Subetto et al., 2003).

The structure of bottom sediments is also determined by the hypsometric position of lakes. The water body might (a) develop separately throughout its history from the time of its formation after the deglaciation of the area or (b) be a part of a large basin, which might then be connected with this basin again after its emptying and then be isolated again in the course of transgressions/regressions of the basin (Subetto, 2009; Kuznetsov et al., 2015). For instance, the lowland part of the Karelian Isthmus, which was flooded by the waters of the Baltic Ice Lake in the past, is characterized by a very sharp boundary between gray glaciolacustrine sediments and lacustrine Holocene sediments themselves, which often have a sand band between gray clays and overlying brown silts. This indicates the interruption of sedimentation due to a catastrophic drop in the water level of the Baltic Ice Lake at the boundary between the late Pleistocene and Holocene approximately 10300 ^{14}C (approximately 11500 calendar) years ago. In turn, this led to changes in the runoff and erosion profile, as well as to a decrease in the groundwater level and, as a consequence, a decrease in the level of lakes that are located within the catchment basin of the Baltic. The large surfaces of the bottom of the periglacial lake that protruded from under the water were exposed to severe erosion, which led to the discharge of a large amount of terrigenous material to relict lakes in the Karelian Isthmus, Lake Ladoga, and the Baltic.

The study of late-glacial sediments in Lake Medvedevskoe (Fig. 1; Karelian Isthmus, near Saint-Petersburg), the altitudinal position of which allowed it to avoid flooding by waters of the Baltic glacial lake after the deglaciation of the Karelian Isthmus, revealed a thin band of the Vedde volcanic ash in these sediments, which was formed 12000 years ago as a result of a very strong explosion of the Katla volcano, Iceland, (Wastegård et al., 2000; Subetto et al., 2003: Wohlfarth et al., 2007; Kuznetsov et al., 2015); the study also found the volcanic material that was presumably formed as a result of the explosion of the Laacher See volcano and, possibly, some other Late Pleistocene volcanoes in Western Europe and/or Iceland (Subetto, 2009). The bottom sediments of this lake became an object of study of the content of microelements as markers of a possible meteorite impact (Andronikov et al., 2014, 2015). According to the hypothesis proposed by Firestone et al. (2007), a large bolide (with a diameter of up to 4 km) exploded over the Laurentide ice sheet in North America shortly before the beginning of the Younger Dryas cooling, approximately 12900 years ago. The consequences of this catastrophic event (the so-called impact winter) might lead to sharp climate cooling. The assumption of a nonterrestrial cause of cooling in the Younger Dryas started a broad discussion that has still not answered the question of a possible meteorite impact approximately 12900 years ago (Firestone et al., 2007; Pinter et al., 2011). If the meteorite exploded over North America, the prevailing movement of air masses from the west to the east might move microparticles formed during the explosion quite large distances, especially to Western and Eastern Europe.

The features of the distribution of microelements in the bottom sediments of the Lake Medvedevskoe assume the effect of an event that left its marks in bottom sediments from a depth of approximately 5.90 m. These sediments are characterized by a sharp growth in concentrations of "meteorite" elements such as Ni, Cr, and Cu, as well as, presumably, elements of the platinum group. In addition, this horizon is characterized by a decrease in the content of rare earth elements, the concentration of which is rather low in meteorites. The geochemical 5.90 m marker is 11 cm lower than the Allerød–Younger Dryas boundary (12650 years ago), which is very close to the age of 12900 years ago that was proposed for the pre–Younger Dryas meteorite impact. Therefore, the content and features of the distribution of microelements in the sediments of Lake Medvedevskoe indicate that they contains material from sources that are not characteristic of lacustrine sediments in the region. Since the enrichment of sediments with marking microelements is very insignificant, it can be assumed that the area of northwestern Russia is, presumably, the most remote eastern region of the distribution of aerial material that was formed as a result of the assumed Late Pleistocene meteorite impact (Andronikov et al., 2014).

Paleolimnological Studies in Central and Northeastern Siberia

The Asian part of Russia is paleolimnologically less studied, although the demands for knowledge about the rate and trends of natural processes are high for the lakes. The territory of Yakutia includes over 709000 lakes. The diversity of lakes depends on the origin of their depressions as well as their coastal configuration, size, depth, and organic composition. With respect to their origin lakes can be thermokarst, karst, floodplain, fluviatile, deltaic, lagoon, tectonic, and glacial. Ninety-eight percent of lakes in Yakutia are of thermokarst origin; they are characterized by a small area and a small depth.

Limnological studies and an analysis of special aerophotographical cartographical materials and the morphometric, hydrological, hydrochemical, and hydrobiological features of lakes led to development of the regional classification of lakes on a landscape-genetic basis (Zhirkov, 2000). The basic morphogenetic types of lakes were distinguished as following: thermokarst lakes, water and erosion lakes, erosion–thermokarst lakes, karst lakes, tukulan lakes (sandy lakes), anthropogenic lakes, and trappean surface lakes. These lakes were then differentiated into subtypes, groups, and subgroups.

The reconstruction of the past limnic conditions of lakes on the basis of the composition of diatom complexes allowed to distinguish the Lower River Lena, Verkhoyansk, the River Viliui, and Middle River Lena geographical lake provinces in Yakutia, and the integrated analyses of lacustrine sediments revealed the stages of the development of lacustrine ecosystems in Yakutia for the first time (Pestryakova et al., 2008).

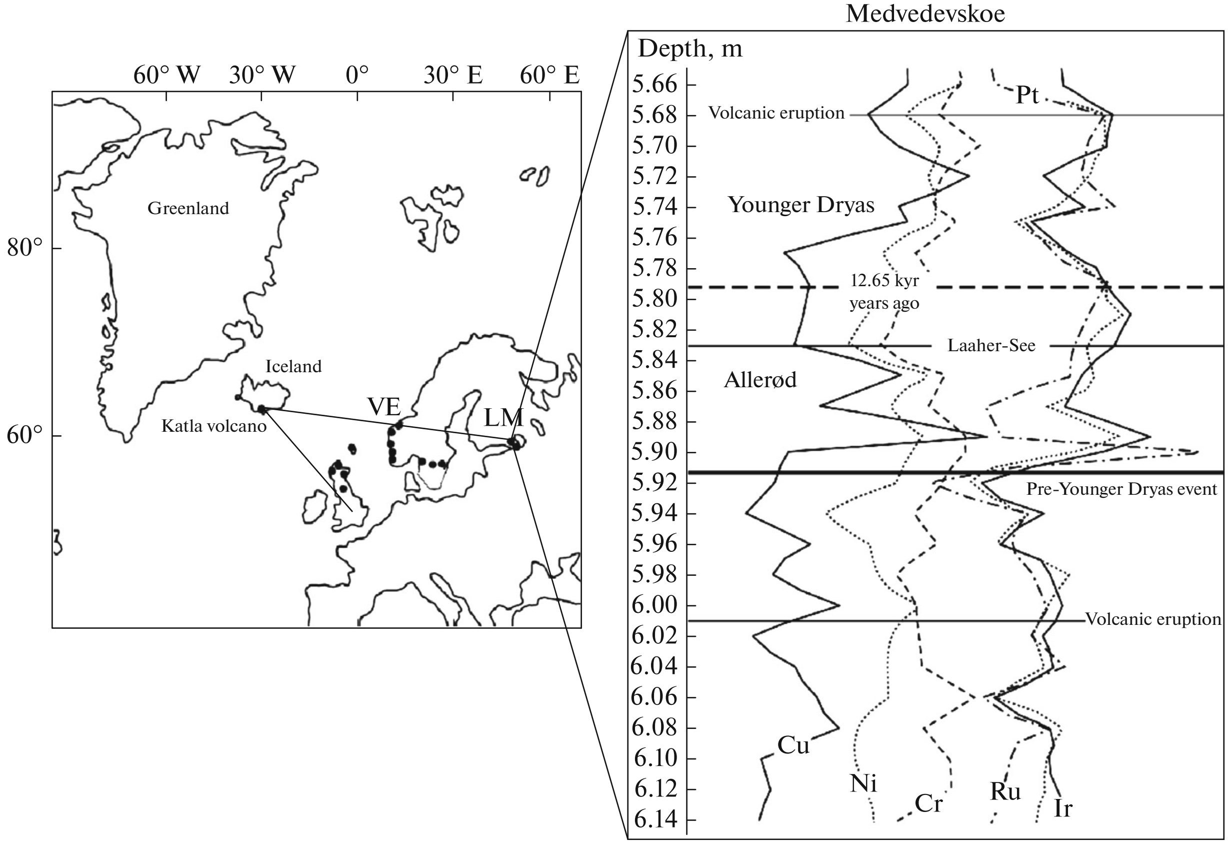

Fig. 1. On the left: geographical position of Lake Medvedevskoe (LM), the Katla volcano, and volcanic ash findings (VE). The lines show the Vedde ash (VE) spread fan and the points denote other areas of ash findings. On the right: The pattern of distribution of some "meteorite" elements in the sediments of Lake Medvedevskoe. The distribution of microelements is shown schematically rather than in absolute concentrations. (Subetto, 2009; Andronikov et al., 2014).

The amplitude of oscillation of lacustrine sedimentation rates was subject to global climate changes; this process simultaneously occurred in the Middle River Lena and the River Viliui provinces. The maximum lacustrine sedimentation was recorded during the Preboreal on the basis of the entry of allochthonous terrigenous material. The fluctuations of lake-water levels in the Holocene indicate the high sensitivity of the water balance of the lakes to changes in climatic conditions and are in a good agreement with vegetation changes that were reconstructed according to the data of the palynological analysis of bottom sediments, which suggests the uniform climatic nature of these changes (Pestryakova et al., 2012; Zibulski et al., 2016).

Since the late Atlantic, the progressive eutrophication of lakes has been recorded in the central part of the region (the Middle River Lena and the River Viliui provinces), which is mainly caused by the depletion of the volume and a decrease in the depth of the underlake complex in the catchment basins of lakes. Changes in the mineralization of lake waters have regional and local differences (Kumke et al., 2007). The contrast of phases of increased mineralization of lake waters significantly grows from north to south. The species diversity of diatoms grows everywhere during the Holocene under the conditions of gradual climate warming (Pestryakova et al., 2008). In the north (lakes Satagai, Vostochny Sevost'yan, and Ladannaakh), the relatively high abundance and diversity of diatoms were recorded during the subboreal time. However, their depletion is observed in the subatlantic, except for Lake Ulakhan Chabyda (the Middle River Lena province).

The reconstruction of climate changes in different regions of Yakutia and adjacent areas on the basis of biotic and abiotic indicators from the bottom sediments of lakes showed that the climate variations were nonsynchronous and region-dependant throughout the Late Pleistocene and Holocene (Fig. 2) (Biskaborn et al., 2016). The onset of the Holocene optimum in different regions of Siberia was most likely dependent on the time of the retreat of the Laurentide ice sheet, which was the source of origin of cold air masses to Siberia (Renssen et al., 2012). However, the reconstructed asynchrony of the end of the Holocene optimum may also be considered as a response of ecosystems to the decreasing contrast of seasonal insulation and the increasing continentality of Siberia (Laskar et al., 2004).

In recent years, active investigations of the stratigraphy of bottom sediments of lakes and reconstructing

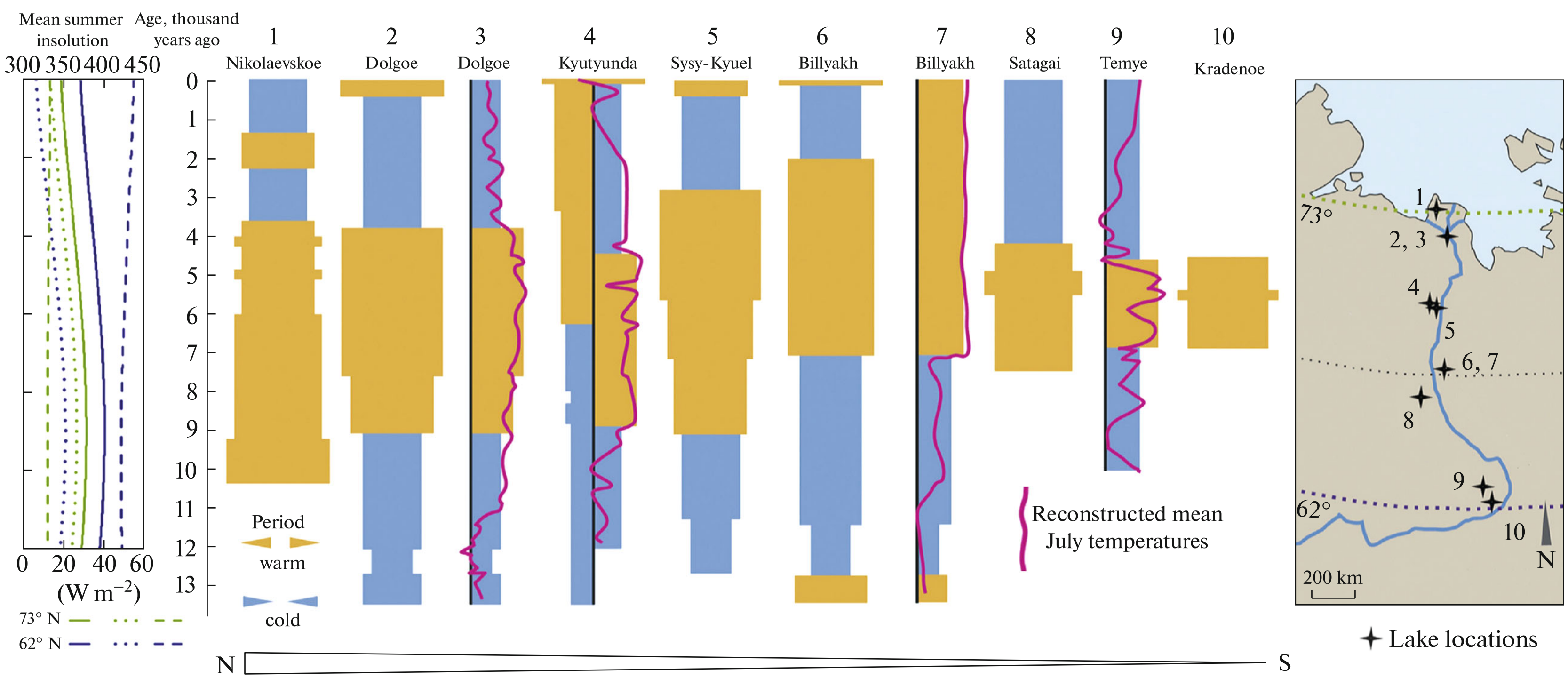

Fig. 2. Space–time diagram of the expression of the Holocene optimum in northeastern Siberia according to the result of paleoclimatic reconstructions ((1) Andreev et al., 2004; (2) Laing et al., 1999; (3) Klemm et al., 2013; (4) Biskaborn et al., 2016; (5) Biskaborn et al., 2012; (6) Müller et al., 2009; (7) Tarasov et al., 2013; (8) Popp, 2006; (9) Nazarova et al., 2013; and (10) Fradkina et al., 2005). According to Biskaborn et al. (2016).

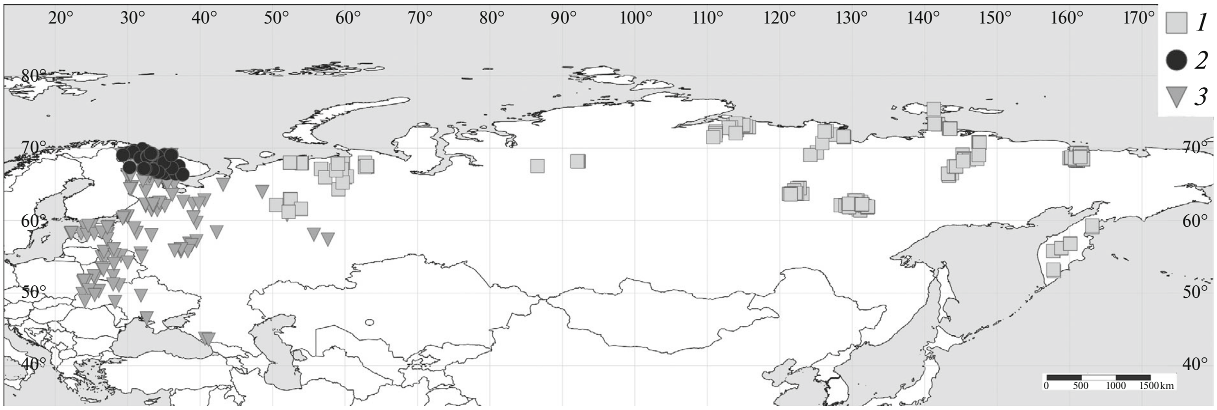

Fig. 3. Distribution of paleolimnologically studied lakes in Russia from the Databases, mentioned in this article. Notations: (*1*) lakes in the north and northeast of Eurasia (Palagushkina et al., 2012; Pestryakova et al., 2012; Nazarova et al., 2015; Klemm et al., 2013); (*2*) lakes of the Kola Peninsula. Q-Kola database (Subetto and Grekov, 2014; Grekov and Subetto, 2015); (*3*) paleolimnologically studied lakes of the European part of Russia. PaleoLake database (Subetto and Syrykh, 2014; Syrykh et al., 2014).

paleogeographical and paleoclimatic situations of the past have been started within the frame of international projects, such as Lake Elgygytgyn and Lakes of Siberia projects. Paleolimnological investigations of the unique meteoritic Lake Elgygytgyn will make it possible to reconstruct climate and environmental changes over the period of 3.6 million years (Melles et al., 2012). New data were obtained in cooperation with German scientists within the framework of the Lakes of Siberia project as a result of studying of the history of Yakutian lakes, such as Billyakh and Satagai (Diekmann et al., 2016; Müller et al., 2009; Nazarova et al., 2013; Schleusner et al., 2015). It was established that bottom sediments had been continuously accumulating in Lake Billyakh, located in the vicinity of the Verkhoyansk Ridge, for no less than 40000 years (Diekmann et al., 2016), which indicates the absence of considerable ice caps in the region during the maximum of the last glaciation. The data on the dynamics of climate and natural situations in the Late Pleistocene and Holocene were obtained for the northeast of Siberia (Herzschuh et al., 2009; Biskaborn et al., 2012, 2016; Klemm et al., 2015), and changes in the pattern of lacustrine organic accumulation, depending on the solar activity, were revealed (Pestryakova et al., 2008).

Databases

To systematize the data on the genesis of lakes of the European north of Russia, we develop a PaleoLake database (DB) (Subetto and Syrykh, 2014; Syrykh et al., 2014), in which the data on the lakes that were studied using paleolimnological methods are analyzed. This research is the continuation of the previously started studies on lake zonation and on the reconstruction of the stages of the development of lakes during the postglacial time and changes in the level regime of lakes in northern Eurasia (Harrison et al., 1996).

Similar studies are carried out in Europe and in American continent, which is indicated by recent publications (Sundqvist et al., 2014). The structure of the data metabase includes the name of the lake, its geographical position (geographical coordinates; the region in which the lake is located), morphometrical parameters (mean depth, maximum depth, area, and volume), and altitude above sea level, as well as the origin of the depression, the description of bottom sediments (sampling, type of material, and the thickness of sediments), types of analyses that were performed with respect to samples (the lithological, diatomaceous, geochemical, and palynological types), dating methods (radiocarbon analysis, AMS-spectrometry, etc.), and the sedimentation time interval. In addition, the DB contains the bibliographic sources that were used in this study. At the present time, the database includes the data on over 200 lakes.

To reconstruct changes in the natural environment of the late glaciation and Holocene in the Kola Peninsula, we compiled the Q-KOLA database (Subetto and Grekov, 2014). The base contains over 114 objects of paleogeographical information, such as bottom sediments of lakes and peat-bogs. Particular attention was paid to the age of sediments and to the conducted studies (Grekov and Subetto, 2015). In the future, it is planned to expand the database and create an interactive reference map on its basis (Fig. 3).

Studies on systematization of the data on environmental characteristics of lakes and the composition of the lacustrine flora and fauna are important for performing qualitative paleoclimatic reconstructions. The statistical models that were developed on the basis of regional calibration databases serve as a tool for reliable quantitative paleoreconstructions (Rudaya et al., 2016). Over the recent decades, these databases and models have been developed for chironomid analysis and have been widely used in Northern Europe, North Africa, and New Zealand, which makes it possible to reconstruct the paleoclimate with a high degree of accuracy (see the reviews of Ilyashuk, E. and Ilyashuk, B., 2004; Brooks, 2006; Nazarova et al., 2008).

The first worldwide Russian statistical models for reconstructing the mean July air temperatures (Nazarova et al., 2008, 2011, 2015; Self et al., 2011) were developed using a vast regional database on the lakes of the Russian Arctic and the Far East. The database includes the information on the chemistry and morphometrical characteristics of lakes, as well as types of the surrounding vegetation; the climatic indices of the adjacent area and the composition of the fauna of chironomids, cladocerans, rhizopods, and ostracods (Bobrov et al., 2013; Frolova et al., 2013, 2014; Nazarova et al., 2011, 2015); the diatom flora (Palagushkina et al., 2012; Pestryakova et al., 2012); and spores and pollen, which are concentrated in the surface layers of lacustrine bottom sediments (Klemm et al., 2013). The database currently includes data on 349 lakes; 85 of them are polygonal water bodies in different regions of the Urals, Siberia, and the Far East, including large river basins in southeastern Russia and Novosibirsk islands (Fig. 3). Ninety-six lakes that are included in the transect along northern Yakutia through the basins of the Anabar, Lena, Indigirka, and Kolyma rivers and cross several vegetation zones from Arctic tundra to taiga are used to create a statistical model for reconstructing the July air temperature on the basis of spore-pollen spectra (Klemm et al., 2013).

CONCLUSIONS

The analysis of paleolimnological studies showed that late-glacial and Holocene lake sediments in the north of Eurasia are still insufficiently and unevenly studied, despite an increased activity in the Arctic and subarctic sectors of the Russian Arctic in recent years. The data on the dynamics of the climate and development of vegetation were obtained mainly on the basis of investigation of sections of lacustrine sediments that cover separate periods (stages) of the Holocene. For this reason, the stratigraphical correlation of the sections of the Late Pleistocene and Holocene in different areas areas are often problematic and their paleogeographical record is still incomplete. All of this makes it difficult to reconstruct the continuous course of landscape and climatic changes in late glaciation and postglaciation and obtain the qualitative and quantitative parameters of the climate in the past. Further studies of bottom sediments of lakes in the north of Eurasia will make it possible to perform a more detailed reconstruction of the hydroclimatic conditions in the past, as well as the dynamics of the coastline of Arctic seas, and the evolution of lake ecosystems and to observe the trends of their further development and predict probable changes in the natural environment and climate in the future.

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