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РЕКОНСТРУКЦИИ НА ОСНОВЕ ПАЛЕОБИОЛОГИЧЕСКИХ МЕТОДОВ

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ПРИРОДНАЯ СРЕДА ОКИНСКОГО ПЛАТО (ГОРЫ ВОСТОЧНОГО САЯНА) В ПОЗДНЕМ ЛЕДНИКОВЬЕ И ГОЛОЦЕНЕ: ПРИМЕР ПАЛИНОЛОГИЧЕСКОЙ ЛЕТОПИСИ ИЗ ОТЛОЖЕНИЙ ОЗЕРА ХИКУШКА

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Новая пыльцевая запись из донных отложений оз. Хикушка и реконструкция биомов дают представления об изменениях природной среды Окинского плато, расположенного в горах Восточного Саяна на юге Восточной Сибири, за последние 13490 калиброванных лет (к. л. н.). Реконструкции показывают преобладание тундрового биома в аллерёде, ок. 13490–12600 к. л. н., что свидетельствует о континентальном и холодном климате. Однако пыльцевая запись демонстрирует заметное участие в растительности в это время и деревьев, таких как ель (*Picea obovata)* и лиственница (*Larix sibirica)*. Кратковременное сокращение лесного биома ок. 12600–12500 к. л. н. может быть реакцией региональной растительности на похолодание климата в стадиал поздний дриас. Более четкого выражения этого похолодания в пыльцевой записи из отложений оз. Хикушка не найдено. Позже, ок. 12500–11200 к. л. н., реконструкция свидетельствует о сокращении степного и тундрового биомов за счет продолжающегося распространения *Picea* и *Larix*. Короткий интервал времени ок. 11200–10500 к. л. н. характеризуется максимальным распространением пихты *(Abies sibirica)* и таежного биома, свидетельствуя о самом влажном и умеренно-континентальном климате в высокогорной зоне Окинского плато за последние 13490 лет. В следующий интервал времени, ок. 10500 и 6500 к. л. н., происходило постепенное расширение таежного биома с преобладанием сосны обыкновенной *Pinus sylvestris*, что согласуется со многими другими палинологическими записями из умеренных широт Евразии. Лесной биом доминировал на исследуемой территории последние 6500 лет. Начиная примерно с 5000 к. л. н. лиственница и сосна сибирская (*Pinus sibirica)* начали приближаться к бассейну оз. Хикушка, означая повышение их верхней границы в горах Восточного Саяна, а растительность стала приобретать современный характер.

Ключевые слова: растительность, биомы, реконструкции, поздний плейстоцен, современное межледниковье, юг Восточной Сибири, донные отложения озер

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1. INTRODUCTION

Over the past ca. 14000 years, our planet has experienced significant climate changes resulted in warming after the glacial maximum – Greenland interstadial-1, cooling in Greenland stadial-1 and the Holocene optimum. The responses of inland ecosystems to these extreme climate events are useful for understanding past climate changes and its causes. The ecosystems of the mountain lakes and the processes of sedimentation within them and in their catchment as well as the on-land vegetation dynamics are very sensitive to register natural and anthropogenic changes. Thus, knowledge of natural vegetation during cold and warm periods in the East Sayan Mountains can not only help understand past changes in the natural environment and climate, but also predict future climate change trends and provide up-to-date reference information for environmental management.

Previous palaeoenvironmental studies in the East Sayan Mountains demonstrate clear environmental

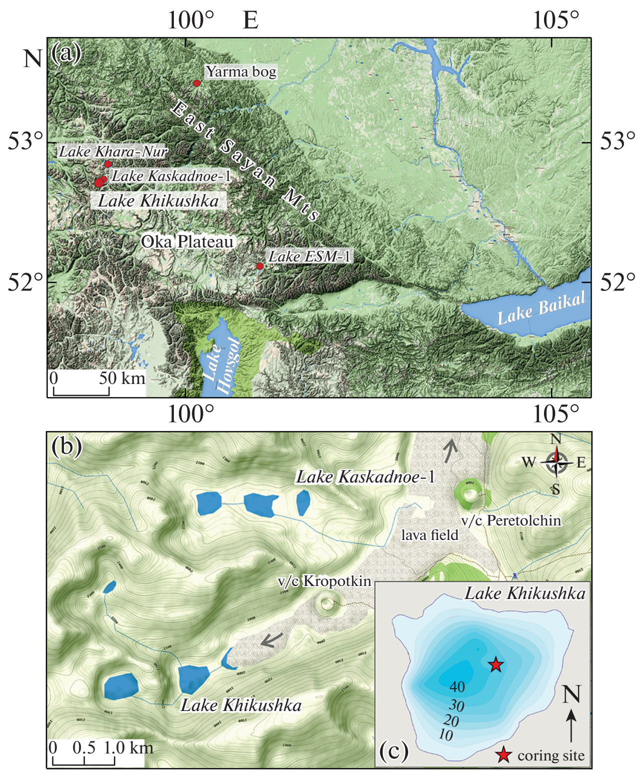

Fig. 1. (a) – Map based on the Shuttle Radar Topography Mission (SRTM) v.4.1 data (Jarvis et al., 2008) showing the position of the study area in the south of the Baikal region, and the position of Lake Khikushka on the Oka Plateau (big red dot). Other red dots correspond to the previously studied sections of lake and peat sediments of Holocene age in the East Sayan Mountains.

(b) – Position of Lake Khikushka near volcanic centers of Late Pleistocene-Holocene eruptions. The lava flow is shown in grey.

(c) – Bathymetric map with the coring site location. Numbers from 10 to 40 refer to the Lake's water depth in meters.

Рис. 1. (a) – Карта, базирующаяся на данных Shuttle Radar Topography Mission (SRTM) v.4.1 (Jarvis et al., 2008), показывающая положение изучаемой территории на юге Байкальского региона и положение оз. Хикушка на Окинском плато (большая красная точка). Остальные красные точки соответствуют ранее изученным разрезам озерно-торфяных отложений голоценового возраста в Восточном Саяне.

(b) – Положение оз. Хикушка вблизи вулканических центров позднеплейстоцен-голоценовых извержений. Поток лавы показан серым цветом.

(c) – Батиметрическая карта с указанием места отбора керна. Цифры от 10 до 40 обозначают глубину воды в озере в метрах.

changes, but records are short, not particularly well dated, or they lack high-resolution pollen data, and the records show different patterns of change (Mackay et al., 2012; Bezrukova et al., 2016; Bezrukova et al., 2021). They are thus difficult to compare with records from adjacent regions. The mixed signals among these sites and lack of temporal depth need to be resolved with a longer, high-resolution record. The goal of this study was to obtain a high-resolution and accurately dated palynological record suitable for reconstructions of regional vegetation and climate interactions, as well as for comparison with other high-resolution palaeoenvironmental archives from and outside East Siberia and for validation of Earth system modelling experiments.

2. STUDY SITE

The remoteness from the oceans and the high elevation of the area above sea level determine a strongly continental climate of the East Sayan Mountains (ESMs). According to the observation data of the Orlik and Ilchir meteorological stations closest to the region, the climate of the Oka Plateau is sharply continental, with a long and severe winter, cool summer during which occurs most of the annual precipitation. The average temperature difference of the warm and cold seasons reaches 52°C. The average annual precipitation sum approaches 430 mm (Solovieva, 1976). The permafrost is found at depths from 0.2 meters to 1.5–1.7 meters, and is the cause of the high swampiness of the valleys and slopes (Solovieva, 1976). Recent work indicates that the transitional periods (March-April-May and September-October-November) dominated by westerly precipitation (Kostrova et al., 2020), while during summer, inflows from the southwest and south-east increase. During winter months, regional climate is dominated by the Siberian anticyclone (Tubi et al., 2013).

The flow-through Lake Khikushka (elevation 1956 m above sea level) is a corrie lake (fig. 1) located in the upper reaches glacial trough valley occupied by the Jom-Bolok lava flow. Its water surface area is 0.3 km^2, with a maximum depth of 43 m. The lake is fed mainly by precipitation and groundwater discharge. The catchment area is 6.5 km^2 with elevations up to 2680 m a.s.l. Rocks of the surrounding mountains are Paleozoic intrusive rocks: plagiogranite, granodiorite, pegmatite, diorite, gabbro-diorite, gabbro, and gabbronorite. Loose sediments are presented by glacial mudflow and hillside formations and have Late Pleistocene to Holocene age. Young volcanic rocks (14.3–0.8 cal ka BP) of the Jom-Bolok field are absent in the lake catchment and appear only in the Jom-Bolok valley 0.35 km NE from the lake. They are olivine basalts and basanites and represent Hawaiian type lavas.

The proglacial Lake Khikushka occupies the lowest altitudinal position in the water reservoir cascade of the glacial cirque stairway. The basin of the lake is separated from the lava flow by a narrow bridge – corrie rigel, the outer wall of which is closely approached by the lava flow. The rigel is elevated only a few meters above both the surface of the lava flow and the water level of the lake, but does not connect with it. The lava flow moved from volcanoes and filling bottom of the Jom-Bolok valley almost completely, stopped less than 100 m from the rigel wall of the lowest corrie. The rest of the space in front of the lava flow is the small crescent-shaped basin about 10 m deep filled with wa-

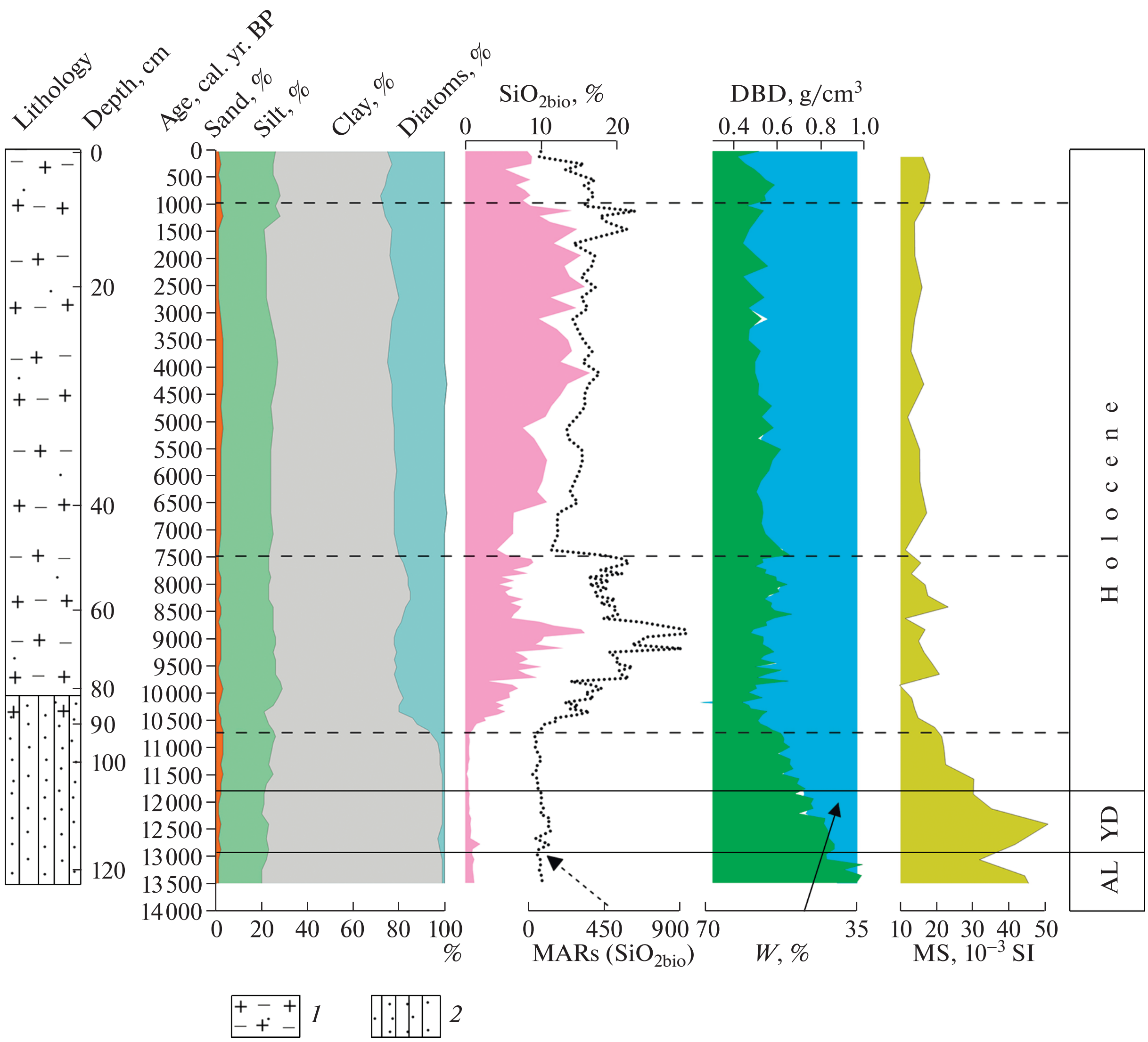

Fig. 2. Changes in selected sediment characteristics of the Lake Khikushka, where SiO_{2bio} refers to biogenic silica content; DBD – dry bulk density (green color); W – water content (blue color); MS – magnetic susceptibility; MARs – mass accumulation rates for SiO_{2bio}, calculated using the formula: MAR (mg cm^{-2} ka^{-1}) = 1000 × (SiO_{2bio}/100) × DBD × LSR, where LSR is linear sedimentation rate. *Lithology: 1* – soft terrigenic-biogenic silt rich in diatom valves; *2* – massive gray silty clay.

Рис. 2. Изменения некоторых характеристик донных отложений оз. Хикушка.

$SiO_{2био}$ – содержание биогенного кремнезема; DBD – плотность осадка в сухом состоянии (зеленый цвет); W – влажность отложений (синий цвет); MS – магнитная восприимчивость; MARs – массовые скорости накопления $SiO_{2био}$, рассчитанные по формуле: MAR (мг см$^{-2}$ 1000 лет) = 1000 × (SiO_2био/100) × × DBD × LSR, где LSR – линейная скорость седиментации. *Литологический состав: 1* – мягкий терригенно-биогенный ил, обогащенный створками диатомей; *2* – массивная серая алевритистая глина.

ter, flowing from the corrie lake cascade. The thickness of the lava here is such that the surface of its flow, which is now a bottom of the valley, has almost the same altitude as the bottom of the lowest corrie.

The vegetation of the subalpine belt occurs within the lake's basin and catchment and is mainly represented by herbaceous tundra alternating with dwarf shrub tundra consisting of dwarf birch *Betula nana* and willow *Salix*. Forbs communities are dominated by *Bergénia crassifólia*, a typical plant of rock outcrops and stony slopes of the subalpine and upper part of the forest belt in coniferous forests, as well as by *Verátrum lobeliánum,* which is a mesophyte species, preferring meadows and glades with a close occurrence of groundwater.

3. MATERIALS AND METHODS

3.1. Sediment recovery and sediment physical properties. Fieldwork on the Oka Plateau took place in 2015. A 3D6-beam digital depth sounder (Humminbird Matrix 748 3D) was used for the bathymetric survey (fig. 2).

Table 1. AMS ^{14}C dates and calibrated ages for the Lake Khikushka core. Calibration was performed using R package version 2.3.9.1. (Blaauw et al., 2019) and the calibration curve IntCal20 (Reimer et al., 2020)
Таблица 1. Радиоуглеродные и калиброванные значения датировок для керна из оз. Хикушка. Калибрование выполнялось с использованием пакета R версии 2.3.9.1. (Blaauw et al., 2019) и калибровочной кривой IntCal20 (Reimer et al., 2020)

Laboratory ID	Core depth, cm	^{14}C ages yr BP	^{14}C ages corrected on reservoir effect of 992 years	Calibrated 95.4% range, cal. yr BP	Modeled age, cal. yr BP
Poz-106376	2–3	1200 ± 30	208 ± 30	300–30	138
Poz-106377	15–16	2555 ± 30	1563 ± 30	1530–1360	1452
Poz-106388	44–45	7440 ± 40	6448 ± 40	7347–7190	7347
Poz-106552	98–99	10610 ± 50	9618 ± 50	11190–10750	10993
Poz-106553	114–115	11560 ± 60	10568 ± 60	12710–12120	12530

Coring was carried out using a rope-operated UWITEC Gravity Corer with PVC liners that had a 63-mm inner diameter. A complete lake sediment record was recovered, the base of the core penetrating the underlying glacial sediments. A 124-cm long core was retrieved from a water depth of ~32 m. Magnetic susceptibility (MS) was measured at 1-cm intervals using the MS2 Bartington magnetic susceptibility system with MS2C70 and MS2K sensors. Biogenic silica (SiO_2bio) was also measured at 1-cm intervals following the method of Mortlock and Froelich (1989). To determine SiO_2bio, the samples were dried at 60°C, ground and weighed (up to 500 mg) and then were treated with a solution of 2M Na_2CO_3 and kept in a thermostat for five hours at a temperature of 85°C, stirring periodically. After that, the concentration of SiO_2bio was determined by using a spectrophotometric (colorimetric) method with ammonium molybdate. Water content (W) and dry bulk density (DBD) at 1-cm intervals were derived using a routine volumetric approach (Avnimelech et al., 2001). The sediment lithology was described at 2-cm intervals using the smear-slide method with three replicates.

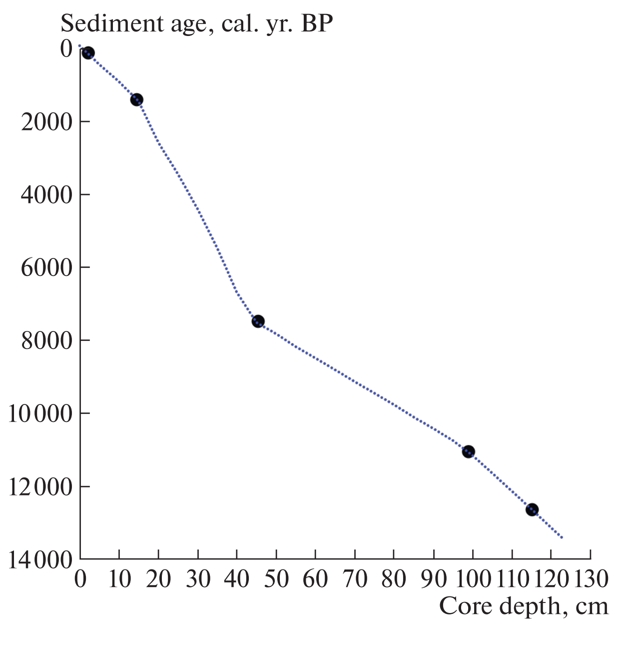

Fig. 3. Depth-age model applied to the Khikushka Lake pollen record.
Рис. 3. Модель глубина-возраст для пыльцевой записи из оз. Хикушка.

3.2. Chronology. As the terrestrial plant remnants and shells of aquatic mollusks are scarce in the sediments of Lake Khikushka, bulk organic sediment faction was used for radiocarbon dating. Five AMS^{14}C ages were obtained in the Poznan Radiocarbon Laboratory (table 1). Radiocarbon ages were then calibrated using R package version 2.3.9.1. (Blaauw et al., 2019) and the IntCal20 calibration curve (Reimer et al., 2020). The age-depth relationship was established employing linear interpolations between dated levels (fig. 3) and extrapolation of calibrated ages up to the core base.

3.3. Palynology. Sixty-two sediment samples (taken every 2 cm) were analyzed for pollen and spores. One tablet of *Lycopodium* marker spores, each containing an average of 18584 spores (batch no. 177745), was added to each sample prior to the chemical treatment for calculating concentrations of identified palynomorphs (Stockmarr, 1971). Samples were treated chemically using a standard procedure (Berglund et al., 1986). Pollen and spores were identified at magnifications of 400×, 600×, and 1000×, with the aid of published pollen keys and atlases (Kuprianova et al., 1972; Kuprianova et al., 1978; Reille, 1998; Demske D. et al., 2013) and a modern pollen reference collection stored at the Institute of Geochemistry, Irkutsk. At least 350 terrestrial pollen grains were counted in each sample; aquatic pollen, algae and spores were excluded from the pollen sum. Coniochaetaceae spores and conifer stomata were counted on the pollen slides (the maximum found was 22 per slide), and stomata morphology compared with photographs from published articles. Relative percentages for all terrestrial pollen

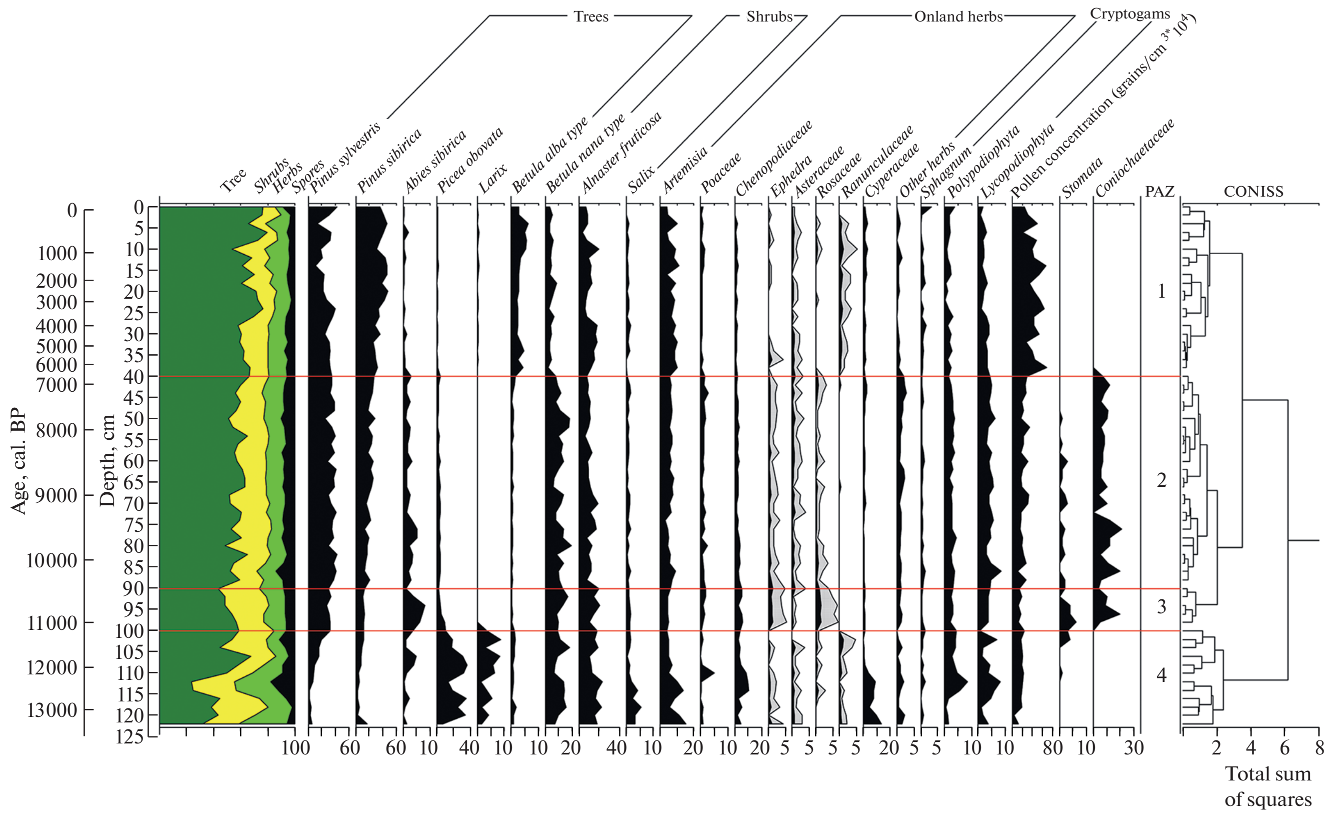

Fig. 4. AMS-based chronology and pollen percentage diagram of the most abundant arboreal and non-arboreal taxa, the representative NPPs of the Lake Khikushka sediment core plotted against the core depth and age axes. PAZ – pollen assemblage zones. The number of coprophilous fungi spores and conifer stomata is shown in pieces found on the pollen slide.

Рис. 4. Хронология на основе полученных датировок и диаграмма процентного содержания пыльцы наиболее распространенных древесных и недревесных таксонов, репрезентативных непыльцевых палиноморф из керна донных отложений оз. Хикушка, нанесенные на оси глубины и возраста керна. PAZ – локальные пыльцевые зоны. Количество спор копрофильных грибов и устьиц хвойных показано в штуках, обнаруженных на предметном стекле пыльцевого слайда.

taxa at each level were calculated from a terrestrial pollen sum taken as 100%. Percentages for cryptogam taxa (spores) were calculated based on the total sum of counted pollen and spores. The Lake Khikushka pollen diagram was constructed using the Tilia/Ti-lia-Graph/TGView software (Grimm, 2011). Local pollen assemblage zones (PAZ) were determined using the CONISS stratigraphically constrained cluster analysis method, based on the terrestrial pollen taxa.

The potential of the biome reconstruction (‘biomization’) method (Prentice et al., 1996) has been used for the quantitative interpretation of the pollen spectra from regional lakes (Tarasov et al., 2007; Tarasov et al., 2009; Kobe et al., 2020). The biomization method provides semi-quantitative and indirect climate information, but is “closer” to the actual vegetation and does not suffer as much from the no-analogue problem that quantitative approaches do. In order to perform the ‘biomization’ all terrestrial pollen taxa identified in the Khikushka record (fig. 4) were attributed to appropriate biomes using the taxon–plant functional type PFT–biome matrix already applied for the Lake Baikal Region pollen records (Tarasov et al., 2007; Tarasov et al., 2009; Kobe et al., 2020). For the demonstration in fig. 5 we kept only those biomes, which had the highest score at least for one analyzed pollen spectra.

Although normally qualitative, pollen-based proxies have been widely preferred for paleoclimate reconstructions because they have been intensively and extensively tested in modern bioclimatic settings. For instance, AP (%) was used as an index for temperature in alpine meadow-tundra zones based on an assumption that the elevation of the upper limit of forests could have lowered during colder times. It implies that a pollen sequence in an alpine meadow-tundra zone could be farther away from the upper limit of forest during colder times, thus a lower AP (%) representing a lower temperature (Mathis et al., 2014).

4. RESULTS

4.1. Sediment physical properties. The lower (124–82 cm) sediment layer in the Lake Khikushka core is

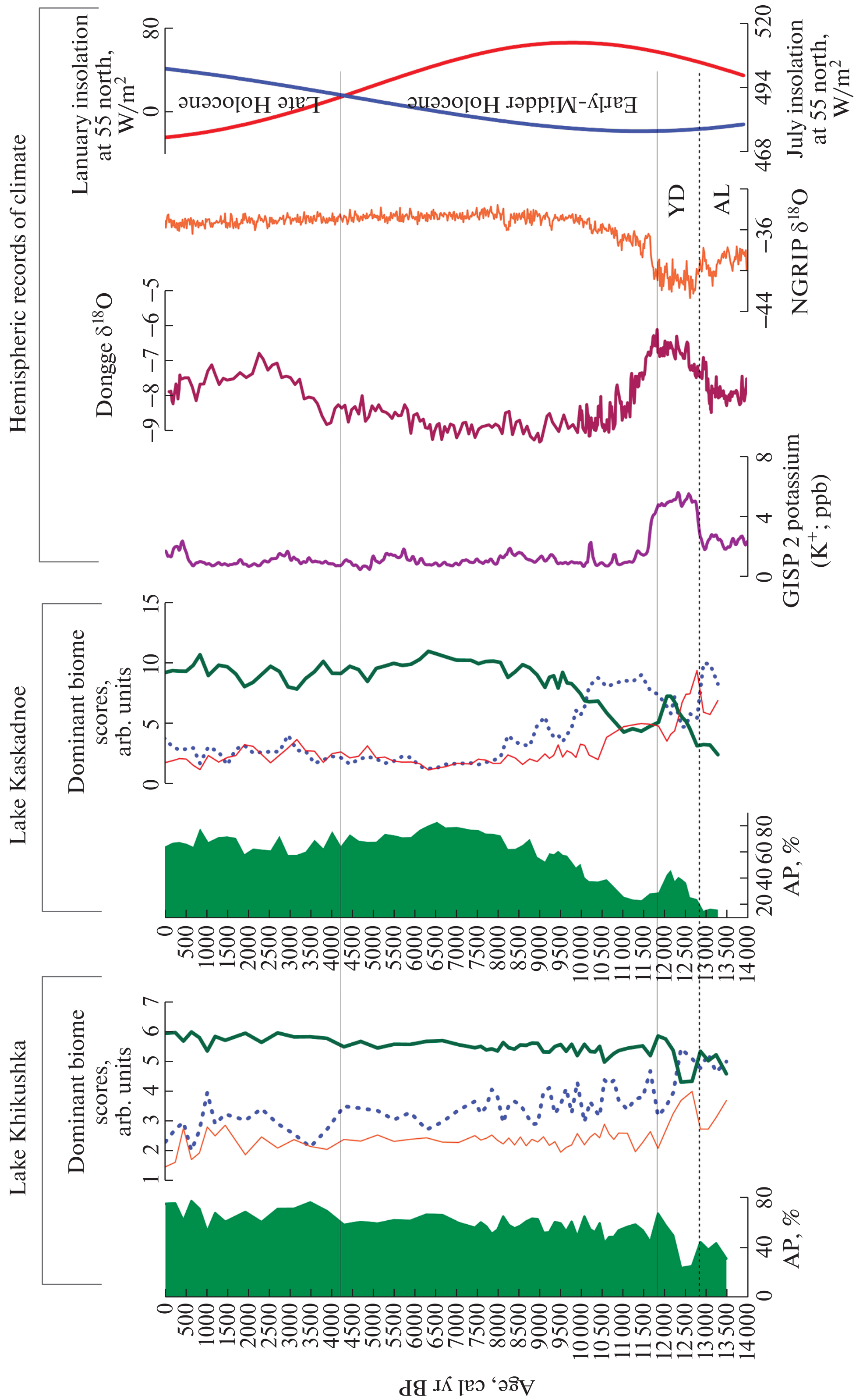

Fig. 5. Comparison of the NGRIP δ18O records from Greenland, as indicator of the Northern Hemisphere (NH) air temperature (Svensson et al., 2008) and from Chinese stalagmites (Yuan et al., 2004), as indicator of the Pacific monsoon intensity (Dongge δ18O), Gaussian smoothed (200 yr) GISP2 potassium (K+; ppb) ion proxy as indicator of the Siberian High strength (Mayewski et al., 1997; Meeker et al., 2002). The NH June and December insolation at 55°N (Laskar et al., 2004), numerical biome scores for tundra (blue dotted lines), steppe (orange) and taiga (green), as palaeoclimatic indicators in the Lake Khikushka and Lake Kaskadnoe catchments, and AP (%) as an index for temperature in alpine meadow-tundra zones plotted against the core age axes.

represented by gray silty clay. The upper (82–0 cm) part of the core is formed by biogenic-terrigenous silts (fig. 2).

The results of the sediment physical properties analysis (fig. 2) show the lowest values of W, SiO_2bio, MAR for SiO_2bio, and the highest values of MS, DBD in the gray clay layer, ~13490 and 10100 cal. yr BP. A maximum of MS was noted for the sediments formed during the YD stadial (fig. 2). The upper layer of biogenic-terrigenous silts (82–0 cm) is characterized by a significant increase in the SiO_2bio values, MAR for SiO_2bio, W and a decrease in MS, DBD.

The SiO_2bio values starts to increase in the upper clay layer, varying from 0.2 to 2.5% in the interval 124–88 cm, 13490–10500 cal. yr BP. It rises to 16% by 8800 cal. yr BP and decreases to 4% by ca. 7400 cal. yr BP. Then, SiO_2bio values gradually increase, reaching their maximum ca. approx. 4100–1500 cal. BP, and again decrease to 6–8% in the upper part of the sedimentary section. MAR of SiO_2bio change nearly synchronously with the change in the SiO_2bio content.

4.2. Chronology. The obtained dates suggested accumulation of the recovered core sediment during the Late Glacial and Holocene.

However, our results show that the radiocarbon age of the uppermost sediments (3–4 cm) turned out to be older than expected (table 1). Therefore, a reservoir effect could be an issue in Lake Khikushka. A simple linear age-depth relationship suggests that the age of the topmost centimeter from the Khikushka core is increased by 992 years. Therefore, when constructing the age model we corrected the AMS^{14}C dates subtracting the supposed reservoir age of 992 years from all radiocarbon dates prior to their calibration to calendar ages. According to the simple age-depth relationship, the lower part of the silty clay accumulated between ~ 13490 and 10100 cal. yr BP (fig. 3).

4.3. Palynology. The pollen diagram of the Khikushka Lake sediments is divided into four zones (fig. 4). The pollen concentration values and pollen percentages are given as averages for each zone.

Pollen zone 4 (124–100 cm, 13490–11200 cal. yr BP) shows the arboreal pollen (AP) percentages of 45%, mainly represented by *Picea obovata* (23%) and *Larix* (4.5%). *Pinus sylvestris*, *Pinus sibirica* and *Abies sibirica* pollen reaches 10, 8 and 2%, correspondingly. Among shrub pollen (28%), *Betula nana*-type, *Alnaster fruticosa* and *Salix* are abundant (11, 17, 2.3%, respectively). Herbaceous taxa (20%) are dominated by pollen of *Artemisia* (8%), Chenopodiaceae (5.2%) and Cyperaceae (6%). The average concentration of pollen and spores reaches 352000 grains cm^3.

The biome reconstruction suggests dominance of shrubby tundra followed by taiga forest. The steppe biome scores are lower than for tundra and forest biomes, though herbaceous communities played a significant role in the vegetation.

Pollen zone 3 (100–90 cm, 11200–10500 cal. yr BP) is characterized by an increase in arboreal pollen percentages up to 50%, mainly represented by *Pinus sylvestris* (31%), *Pinus sibirica* (13%) and *Abies sibirica* (6%). The abundances of shrub pollen are still the same. Among herbaceous taxa, dominant pollen species changed: abundances of *Artemisia* and Cyperaceae pollen decline to 5 and 1%, respectively (fig. 3). Average pollen and spore concentrations decline to 150000 grains cm^3. The tundra biome lost its dominant role in the vegetation and the landscape became more forested, though still rather open, as suggested by the results of biomization. This is also evidenced by the coniferous trees stomata found in the sediments.

Pollen zone 2 (90–40 cm, 10500–6500 cal. yr BP) highlights further increase in AP percentages up to 58%, dominated by *Pinus sylvestris* (36%). Contribution of shrub declines to 21% (fig. 4). Average concentrations of pollen and spores increase to 235000 grains cm^3. This zone also demonstrates stomata, fungi spores Coniochaetaceae and few *Sordaria* spores. The biome reconstruction reveals a continuing increase in the taiga biome scores (fig. 5).

Pollen zone 1 (40–4 cm, the last 6500 cal. years) demonstrates significant increase in AP (67%) such as *Pinus sibirica* (37%), *Pinus sylvestris* (28%), and *Larix* (0.3%). The contribution of tall birch *Betula alba*-type reaches 5%. Shrub pollen taxa decline to 15%. This zone is characterized by significant increase in *Artemisia* percentages (8%), Chenopodiaceae (5.2%) and Ranunculaceae (2%). No stomata have been found in this zone. Average concentrations of pollen and spores increase up to 440000 grains cm^3. Few fungal spores are characteristic of this zone. Biome reconstruction suggests a continuing increase for the taiga biome scores along with highly unstable tundra biome.

5. DISCUSSION

On the Oka plateau, there is currently only one pollen record, whose age is close to the Lake Khikushka record. This is the record from Lake Kaskadnoe (Bezrukova et al., 2021), which lies 3 km north-east of Lake Khikushka (fig. 1). Both lakes lie in a similar geologic-

Рис. 5. Сравнение записей NGRIP $\delta^{18}O$ из Гренландии как индикатора температуры воздуха в северном полушарии (СП) (Svensson et al., 2008) и из китайских сталагмитов (Yuan et al., 2004) как индикатора интенсивности тихоокеанского муссона (Dongge $\delta^{18}O$), GISP2 запись изменения ионов калия (K+; ppb) как индикатора интенсивности Сибирского антициклона (Mayewski et al., 1997; Meeker et al., 2002). Инсоляция в июне и декабре на 55° с.ш. северного полушария (Laskar et al., 2004) и AP (%) как показатель температуры в зонах альпийских лугов и тундр.

geomorphological conditions and are of glacial origin, therefore a reservoir effect could be an issue in Lake Kaskadnoe sediments as well. For comparative analysis of both records, we adjusted the previously published preliminary age model obtained for Lake Kaskadnoe. A linear age-depth relationship obtained using AMS ^{14}C dates suggests that the age of the topmost centimeter from Lake Kaskadnoe core is ca. 980 years. Therefore, when constructing the age model we corrected the AMS^{14}C dates subtracting the supposed reservoir age of 980 years from all radiocarbon dates prior to their calibration.

The newly generated pollen record from Lake Khikushka (fig. 4) helps in the reconstruction of environmental changes on the Oka Plateau during the last 13 400 cal. yr BP. This interval includes a Late Glacial warm climate oscillation, known as the Allerød (AL) interstadial, and the Younger Dryas (YD) cold climate oscillation (stadial) in the Greenland ice records, as well as the entire Holocene. The pollen spectra composition demonstrates significant participation of boreal trees (about 40%) in the vegetation cover between 13490 and 12 600 cal. yr BP, i.e. during the AL interstadial (fig. 4). High values for *Picea* and *Larix* pollen combined with low percentages of *Abies* pollen reflect the spread of these arboreal taxa in the vicinity of the lake as the pollen of these arboreal taxa, in particular *Larix* and *Abies*, may not be transported over long distances (Lozhkin et al., 2007; Pidek et al., 2013). More frequent occurrence as compared with the present-day values of *Picea* and *Larix* pollen suggests sharp continental climate with cold winter and signifies the environment where the permafrost layer is close to the surface. Seasonal permafrost thaw could provide sufficient soil moisture for *Picea* and *Larix*, most adapted to growing on long-frozen soils (Bezrukova et al., 2005). Single *Larix* stomata may indicate the trees growing closely to the lake's basin.

However, the vegetation had a patchy character, dominated by dwarf shrub tundra with *Betula nana*, *Alnaster* and *Salix*. Significant areas were occupied by steppe associations with *Artemisia* and Chenopodiaceae. The biome scores (fig. 5) support our conclusion that the tundra biome predominates closely followed by steppe.

High values for MS and DBD and low SiO_2bio in the clay layer reflect significant input of the terrigenous material, likely transported across the catchment by glacial meltwater. Clay-size fraction is usually a part of sediments in the depocenter of the lake, and the higher is the content of clay fraction, the higher is the water level at a drilling site (Xiao et al., 2012). Therefore, variations in clay-size fraction content can reflect relative changes in water level. Though, such fractions may also suggest long-term ice-cover period, when authigene sediments showing insignificant contribution of aeolian input and riverine runoff, are deposited (Asikainen et al., 2007). The last mechanism seems more realistic for sedimentation in Lake Khikushka during the Late Glacial-Early Holocene time.

In contrast, the Kaskadnoe record shows a more considerable spread of steppe biome (fig. 5). Both lakes functioned as low-productive ecosystems with very low SiO_2bio concentrations. Later, between ca. 12 600 and 11 200 cal. yr BP, the spore-pollen spectra suggest a reduction of the steppe and tundra biomes in Lake Khikushka catchment due to spread of *Picea* and *Larix* (fig. 4). The YD cold oscillation, well recorded in global key climatic records, is not well pronounced in Lake Khikushka record. Though, a short-term reduction of the forest biome at ca. 12 600–12 500 cal. yr BP could be a response to the climate deterioration during the YD stadial.

The Pleistocene/Holocene boundary is formally defined at 11 700 calendar yr b2k (before AD 2000) (Walker et al., 2009). In Khikhuska pollen record, this time span is marked by fast and sharp decline in the *Picea* percentages (fig. 4), though more noticeable changes in the vegetation cover were reconstructed later, at about 11 200 cal. yr BP. The area experienced a significant spread of *Abies* (most likely of elfin type as today) and a gradual expansion of *Pinus sylvestris* in the mid-mountain belt. The results of the biome reconstruction show that in Lake Khikushka catchment the onset of the Holocene saw a decline in the steppe biome scores at ca. 11 700 cal. yr BP (fig. 5) and expansion of the forest vegetation. The lake system was still low-productive (fig. 2). For Lake Kaskadnoe, the biome reconstruction reveals sharp decline in the *Picea* percentages and higher scores for the tundra biome at ca. 11700 cal. yr BP.

A short interval between ca. 11 200 to 10 500 cal. yr BP is marked by maximum distribution of *Abies* (fig. 4), and the strengthening of the taiga biome in the Lake Khikushka area. The vegetation cover still demonstrated a patchy character with a greater spread of shrub tundra as shown by the biome reconstruction. The biome reconstruction for Lake Kaskadnoe shows that the predominance of the tundra biome marks the onset of the Holocene. The continuous presence of conifer stomata (fig. 4) indicate further expansion of largely dark coniferous woodland.

As shown by the reconstructions the interval between ca. 10 600 and 6500 cal. yr BP reveals progressive expansion of the taiga biome on the Oka Plateau and in the ESMs (Mackay et al., 2012). This trend is in line with many other pollen records from Eurasia (Binney et al., 2017). The Khikushka pollen record demonstrates a marked increase in *Pinus sylvestris* and *Pinus sibirica* percentages since ca. 11 000 cal. yr BP. It is unlikely that both pines could grow in the vicinity of the lake in the Early-Middle Holocene.

So, *Pinus sylvestris* and *Pinus sibirica* pollen is likely to indicate long-distance air transport. There are several lines of evidence that support this conclusion. First, the current upper limit of *Pinus sylvestris* in the

ESMs lies 400 m lower than Lake Khikushka basin, and the nearest patches of *Pinus sibirica* occur at about 1700 m a.s.l., in Lake Khara-Nur basin (Bezrukova et al., 2016). Second, *Pinus* pollen is known for its long-distance dispersal (≫10 km) from the source (Birks et al., 2000). Third, an increased *Pinus* pollen percentage reflects a comparatively open landscape of any site. In case of lakes Khikushka and Kaskadnoe, the degradation of *Picea* and *Larix* could lead to higher openness of the landscape and arrival of *Pinus* pollen. Low pollen concentrations support the conclusion about the long transport of arboreal pollen. Higher pollen concentration in the Kaskadnoe core between 11 500 and 7500 cal. yr BP, likely, reflect a wide spread of *Alnaster fruticosa*, which is a prolific pollen producer (Huntley et al., 1983). A marked decline in MS and DBD values in the Khikushka lake core during ca. 10 500–7500 cal. yr BP (fig. 2) suggests a lower input of terrigenous material likely due to complete melting of local glacier. The lake becomes a more productive system, favorable for diatom algae. This interval reveals the highest biogenic silica accumulation (fig. 2). Discontinuous presence of Coniochaetaceae spores may suggest the presence of herbivorous animals using this site as grazing ground.

The results of the biome reconstruction show that the forest biome was dominant in the study area for the last 6500 cal. yr BP mainly owing to the high pollen percentages of both *Pinus* and *Betula alba*-type (fig. 4). It likely reflects higher upper limit of these trees. Highest percentages of shrubby taxa contributed to higher scores of tundra biome for the last 6500 cal. yr BP. The presence of *Larix* pollen in sediments, deposited later than 5000 cal. yr BP (fig. 4) suggests that the *Larix* stands were close to the lake. The expansion of *Larch* open forests occurred in Lake Kaskadnoe catchment soon after 4500 cal. yr BP (Bezrukova et al., 2021). After ca. 5000 cal. yr BP, the vegetation cover in catchment areas of both lakes was similar to the present one, and some *Larix* stands grew on slopes and in the vicinity of lake basins.

Understanding the drivers of regional vegetation and biome change in the past is important for understanding the interactions between projected climate changes, vegetation, and human-induced landscape modification. The reconstructed trends in scores of forest, steppe, tundra biomes and AP index (fig. 5) are parallel to air temperature changes in the Northern Hemisphere, Siberian anticyclone activity, archived in records from Greenland ice cores (Svensson et al., 2008; Mayewski et al., 1997; Meeker et al., 2002), and East Asian summer monsoon (EASM) intensity recorded in the stalagmites from China (Yuan et al., 2004).

The recent studies indicate that the southeastern moisture transport played a significant role in the south of East Siberia during the early Holocene (Bezrukova et al., 2010; Kostrova et al., 2016), that was induced by a higher than present level of summer insolation and a more intensified EASM (fig. 5), while westerly moisture transport in the middle latitudes of Eurasia became stronger in the Late Holocene (Rudaya et al., 2009). At present, the westerly moisture transport plays a leading role in the study region throughout the year (Kostrova et al., 2020), which is a typical features of the Late Holocene. At the same time, moisture from the Pacific region is also traced in modern precipitation that confirms the plausibility of the early Holocene scenario (Kostrova et al., 2020). Hence, a pollen-based climate and environment reconstruction for the Oka Plateau reflects the major climate changes in the North Atlantic and the North Pacific regions (fig. 5).

The spread of *Pinus sylvestris* and *Pinus sibirica* in the ESMs reconstructed between ca. 10 500 and 6500 cal. yr BP falls in the interval of higher-than-present summer insolation (fig. 5), which in turn promoted a stronger summer monsoon and a more intense south-easterly moisture transport to the south of East Siberia during the Early Holocene. The highest summer temperatures and atmospheric precipitation are reconstructed for this interval in many regions of south East Siberia (Binney et al., 2017) and are regarded as the Holocene Thermal Maximum. However, the increase in precipitation on the Oka Plateau could be offset by higher summer temperatures (and higher evaporation). At the same time, lower-than present winter insolation (fig. 5) resulted in a stronger Siberian anticyclone, which blocked the westerly moisture transport and stipulated dry winter conditions. This scenario that was reproduced in climate modelling experiments (Kleinen et al., 2011) can satisfactorily explain the disappearance of *Picea* and *Larix* in Lake Khikushka areas as well as *Picea* and *Abies* in Lake Kaskadnoe catchment during the Early and Middle Holocene. Wherein, the higher temperatures combined with higher atmospheric precipitation could cause a rise in the upper timberline limits of *Pinus sylvestris* and *Pinus sibirica* in the ESMs. An expansion of pines at higher elevations shortly after local deglaciation in the study area as opposed to their significantly later spread (7500–6000 cal. yr. BP) on plains of south East Siberia (Bezrukova et al., 2010; Kobe et al., 2020) could be related to early spring melting and a longer growing season due to higher summer insolation.

A reconstructed spread of *Larix* after 5000 cal. yr BP in the vicinity of both lakes and approach of *Pinus sibirica*, are in parallel to a decrease in summer insolation and an increase in winter insolation, which in turn, led to weakening in the activity of both summer monsoon (fig. 5) and winter anticyclone. Moreover, the westerlies, bringing rain and snow precipitation to the middle latitudes of Eurasia, Altai Mountains (Rudaya et al., 2009) and Baikal Region (Bezrukova et al., 2010; Kostrova et al., 2020) became stronger.

Detailed mineralogical studies of the Lake Khikushka sediments had shown that feldspars, quartz, phyllosilicates, and amphibole prevail in them. Mathematical modeling of complex XRD patterns allowed to identify chlorite, illite, illite-smectite, chlorite-smectite, muscovite, vermiculite, and kaolinite among layered silicates (Solotchin et al., 2021). The quantitative ratios of these minerals change significantly from the Pleistocene to the Holocene supporting shifts in regional climate reconstructed on our pollen record.

6. CONCLUSIONS

Based on pollen data from the Lake Khikushka, we reconstructed the variations in local and regional vegetation, biomes, and climate during the Late Glacial and Holocene in the high-elevated Oka Plateau, East Sayan Mountains, and the surrounding areas. Our data revealed new insights into the late Quaternary climate and environmental history of the Oka Plateau.

Predominantly open steppe- and tundra-like vegetation dominated the area during the AL interstadial, with noticeable participation of boreal trees. A short-term reduction of the forest biome at ca. 12600–12500 cal. yr BP could be a response of regional vegetation to climate deterioration during the YD stadial. The strengthening of the forest biome between 12500 and 11200 cal. yr BP occurred due to the expansion of *Picea* and *Larix*. Climate warming and decrease in effective moisture after 11200 cal. yr BP led to the degradation of dark coniferous forests in the study area and to a gradual expansion of *Pinus sylvestris* and *Pinus sibirica* in the ESMs. Warmest climate existed during the Early-Middle Holocene, ca. 11200–6500 cal. yr BP. The *Larix* stands may have re-established in the study region soon after 5000 cal yr BP. This trend is in parallel to a decrease in summer insolation and an increase of winter insolation. The vegetation cover on the Oka Plateau became similar to modern ~5000 cal. yr BP.

Environment of the Oka Plateau (East Sayan Mountains) in the Late Glacial and Holocene: a Case Study of a Complex Record From the Lake Khikushka Sediments

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A new pollen record and biome reconstructions from the Lake Khikushka provide insights into environmental and climate changes of the so far unstudied area of the Oka Plateau in the East Sayan Mountains, south East Siberia over the last 13490 cal. yr BP. The tundra biome predominates ca. 13490–12600 cal. yr BP, closely followed by taiga and steppe suggesting cold continental climate where the permafrost layer was close to the surface. The reconstruction demonstrates significant participation of boreal trees such as *Picea obovata* and *Larix sibirica* in the vegetation at this time. Later, ca. 12600–11200 cal. yr. BP. the reconstruction suggests a reduction of the steppe and tundra biomes due to a further spread of *Picea* and *Larix*. A short interval ca. 11200–10500 cal. yr BP is marked by maximum distribution of *Abies* and the strengthening of the taiga biome. The interval between ca. 10500 and 6500 cal. yr. BP reveals progressive expansion of the pine-dominated taiga biome that is in line with many other pollen records from Eurasia. The taiga biome was dominant in the study area for the last 6500 cal. yr BP. Since ca. 5000 cal. yr BP the *Larix* stands were close to the lake. Vegetation became similar to the modern after ~5000 cal. yr BP.

Keywords: vegetation and biomes, reconstruction, Late Pleistocene, the modern interglacial, south of East Siberia, lacustrine sediments

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