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PALYNOLOGICAL CHARACTERISTICS AND VOLCANIC ASH FROM SEDIMENTS OF CHISTOYE LAKE, NORTHERN PRIOKHOTYE

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Chistoye Lake (59º 32' N, 151º 48' E) is located 10 km from the northern coast of Taui Bay (Okhotsk Sea) in the central part of a tectonic depression that has been infilled with Paleogene and Neogene deposits. The lake originated as the result of glacial activity during the latest Pleistocene (MIS2). A 550-cm-long lacustrine sediment core was raised from Chistoye Lake using a piston sampler. The core is dominated by silt with layers of peat and sand at its base. The silt includes two tephra layers at 360–364 cm and 77–80 cm. The tephra layers have different geochemical, magnetic, and mineralogical properties. Volcanic ash like the lower tephra in the Chistoye core has been found in other lacustrine sites from the Upper Kolyma, Upper Indigirka, and Northern Priokhotye regions. Radiocarbon dating of organic remains that bracket this second tephra, corresponding to the lower tephra in Chistoye Lake, indicates an age of 7 650 ± 50 years ago, which is comparable with the age of the Kurile Lake – Iliyinskaya caldera forming eruption in Kamchatka. The younger tephra also has been noted in cores from other lakes in Northern Priokhotye and dated to 2 745 ± 10 years ago. A distinctive feature of this Late Holocene tephra is its high magnetic susceptibility. Extrapolation of a sedimentation rate based on the tephra ages suggests that the Chistoye record is approximately 11 700 years old. Palynological analysis of the Chistoye Lake material showed that all samples contain pollen redeposited from Neogene sediments (*Picea* sect. Eupicea, *Tsuga*, *Tilia*, *Corylus*, *Juglans*, *Ulmus*). These taxa can be easily discounted as contaminant, but other pollen types (e. g., *Pinus* subgen. Haploxylon, *Betula*, *Alnus*, Cyperaceae, Poaceae) are more problematic for interpreting the paleovegetation, because they represent plants that were present during the Holocene and/or the Late Pleistocene and during the Neogene. Nonetheless, the changes in the percentages of *Sphagnum* spores suggest a gradual increase in effective moisture during the Younger Dryas and Holocene. A multiproxy study of the sediments from Chistoye Lake, in conjunction with their palynological characteristics, shows the importance of analyzing magnetic properties to help determine the presence of tephra in the sediments. Volcanic ash layers in the lake sediments from northeastern Siberia are reliable chronostratigraphic markers that can supplement radiocarbon dates and improve the regional understanding of climate and vegetation changes during the Holocene.

***Keywords*: lake sediments, palynological analysis, volcanic ash, radiocarbon dating.**

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Chistoye Lake (59º 32' N and 151º 48' E), the largest lake in Northern Priokhotye, is located 10 km from the northern shore of Taui Bay (north-central Okhotsk Sea). The lake is 8.5 km long and 6 km wide, with a maximum water depth of 6.6 m. The elevation of the lake's surface is 91 m above sea level (a. s. l.). Chistoye Lake occupies the central part of a tectonic depression. This basin is bordered on its northwestern and southeastern margins by mountains with elevations of 400–500 m a. s. l. and 700–900 m a. s. l., respectively. The Chistoye depression is connected on its northern flank to the Lankovskaya depression. Yu. P. Baranova and S. F. Biske (1964) classified both basins as belonging to the Tauisk-Kava system of tectonic depressions, which formed in the Late Eocene (Belaya, 1988). According to geophysical soundings, the thickness of the Paleogene and Neogene deposits that fill the depressions reaches 200 m in the vicinity of Chistoye Lake and increases to 1800 m in the Lankovskaya depression. Paleogene conglomerates and sandstones are overlain by sands and silts that contain layers of lignites and brown coals of the Miocene Melkovodninskaya suite (Ankudinov et al., 1975). Deposits of the Melkovodninskaya suite are exposed in coastal cliffs (up to 9 m high) along the shores of Chistoye Lake.

The Lankovskaya and Chistoye Lake depressions are surrounded to the north by the Bilibin Range and to the southeast by the Kil Range. In these mountainous areas, glacial deposits and landforms produced during marine isotope stages (MIS) 4–2 (Lisiecki and Raymo, 2005) have been preserved. O. Yu. Glushkova (1983) showed that glacial development was greatest in the Bilibin Range. In the Lankovskaya depression, terminal moraines are common in the river valleys that drain the adjacent mountains. In MIS4, the glaciers apparently reached the central part of the Lankovskaya depression. In the upper and middle reaches of the Lankovaya River, the terminal moraines are separated by distances of 5–6 km to 15–20 km. Moraines are represented by arcing hills, which are 10–12 km long and 40–60 m in relative height. Glaciers of the "reticulated mountain cover type" likely developed duirng MIS4 in the Bilibin Ridge (Glushkova, 1983). The glaciers moved along the valleys to the Lankovskaya depression, where they united into a single glacier, which filled most of the depression. According to borehole data, the thickness of glacial deposits in the center of the Lankovskaya depression does not exceed 10 m. In contrast to MIS4, valley and cirque glaciers characterized MIS2. Thus, the areal coverage of MIS2 glaciers was smaller with the length of the largest glaciers estimated as 10–15 km.

Glaciation was less extensive in the Kil Range, the peaks of which rise to 867–908 a. s. l. as compared to that in the Bilibin Range (Glushkova, 1983). Cirque and valley glaciers with maximum lengths of 10 km occupied valleys that open toward Chistoye Lake. Moraines at distances of 3, 24, 37, and 48 km occur to the northeast of Chistoye Lake. A 50-m-high, arc-shaped moraine (absolute elevation 148 a. s. l.) that is found closest to the lake has been divided by modern watercourses into three large fragments. *Larix cajanderi* forest with thickets of *Pinus pumila* grows on the moraine surfaces and along their typically gentle slopes. Cyperaceae tundra, *Larix* forest-tundra, and open *Larix* forest characterize the vegetation in the vicinity of Chistoye Lake. The MIS2 moraines are typified by peculiar relief forms, which resemble bowls. These "bowls" contain numerous lakes of varying sizes. The origin of the present-day Chistoye Lake can be linked to glacial activity of the latest Pleistocene. The lake arose during glacial retreat, which left behind a set of morainal ridges.

A piston sampler (Wright at al., 1984) was used to raise a 550-cm-long sediment core from the center of Chistoye Lake at a water depth of 6 m. The core lithology is characterized by: 0–375 cm – silt, 375–396 cm – silt with sand, 396–480 cm – silt, 480–490 cm – peat, 490–510 cm – silt, 510–517 cm – peat, 517–537 cm – silt, and 537–550 cm – coarse-grained sand. The lacustrine silts include two layers of tephra: the lower layer occurs at a core depth of 360–364 cm and the upper layer at 77–80 cm (Minyuk et al., 2022). Note that for the sake of simplicity we will refer to these ash deposits as the upper and lower tephra. A comprehensive laboratory analysis revealed a noticeable difference between the two tephra in terms of geochemical composition and magnetic and mineralogical characteristics. The source of the lower tephra is linked to the largest Holocene volcanic eruption in southern Kamchatka, which resulted in the formation of the Kurile Lake – Iliyinskaya caldera about 7 600 ^{14}C years ago (Ponomareva at al., 2004).

The first find of a tephra layer in the sediments of lakes in northeastern Siberia occurred in 1984 during paleoenvironmental research at Elikchan-1 Lake. This site is located near the Okhotsk-Kolyma drainage divide (60° 45 N, 151°' 46' E), and the lake's history has been influenced by active thermokarst processes associated with the thawing of local ice veins. A 162-cm-long core was raised from the ice surface of Elikchan-1 Lake. The core included both lacustrine silts and peat. A layer of volcanic ash was found at a depth of 140–142 cm. Radiocarbon dates of 8 500 ± 100 years ago (MAG-876) at a depth of 155–157 cm and 8 800 ± 100 years ago (MAG-875) at 160–162 cm were obtained from the peat, which underlies the tephra. Similar ash deposits were found in the sediments of Elikchan-3 Lake and Elikchan-4 Lake (Grand Lake), the largest of the Elikchan lakes (Fig. 1, site 5). Both lakes are in the Okhotsk Sea watershed. Thus, the ash was informally referred to as the Elikchan tephra (see Lozhkin et al., 2016). The tephra layers uncovered within these lake cores are distinctly horizontal. However, they do vary in thickness. For example, the tephra in Elikchan-4 Lake varies from 1–2 cm to 5.5–6 cm.

As noted above, laboratory analyses showed that the Elikchan tephra was equivalent to the Kurile Lake tephra of Kamchatka (Lozhkin et al., 2016; Minyuk et al., 2022). A characteristic feature of the Elikchan tephra, as well as the tephra from the Kurile Lake caldera, is its rhyolitic composition: SiO_2 reaches 70.3 wt. %; $K_2O + Na_2O$ = 6.6 wt. %, and Na_2O dominates over K_2O (Minyuk et al., 2022). In terms of geochemical composition, the lower tephra at Chistoye Lake is comparable not only with the tephra in the sediments of Elikchan-4 Lake, but also with tephra found in the sediments of other glacial lakes in the Northern Okhotsk region and the upper reaches of the Kolyma and Indigirka drainages (Fig. 1, sites 4–13) (Anderson and Lozhkin, 2002; Korzun, 2017). Radiocarbon dates from these lacustrine sites indicate that this tephra is dated to 7 650 ± 50 years ago (Lozhkin at al., 2016), an age that is comparable with the Kurile Lake eruption in Kamchatka.

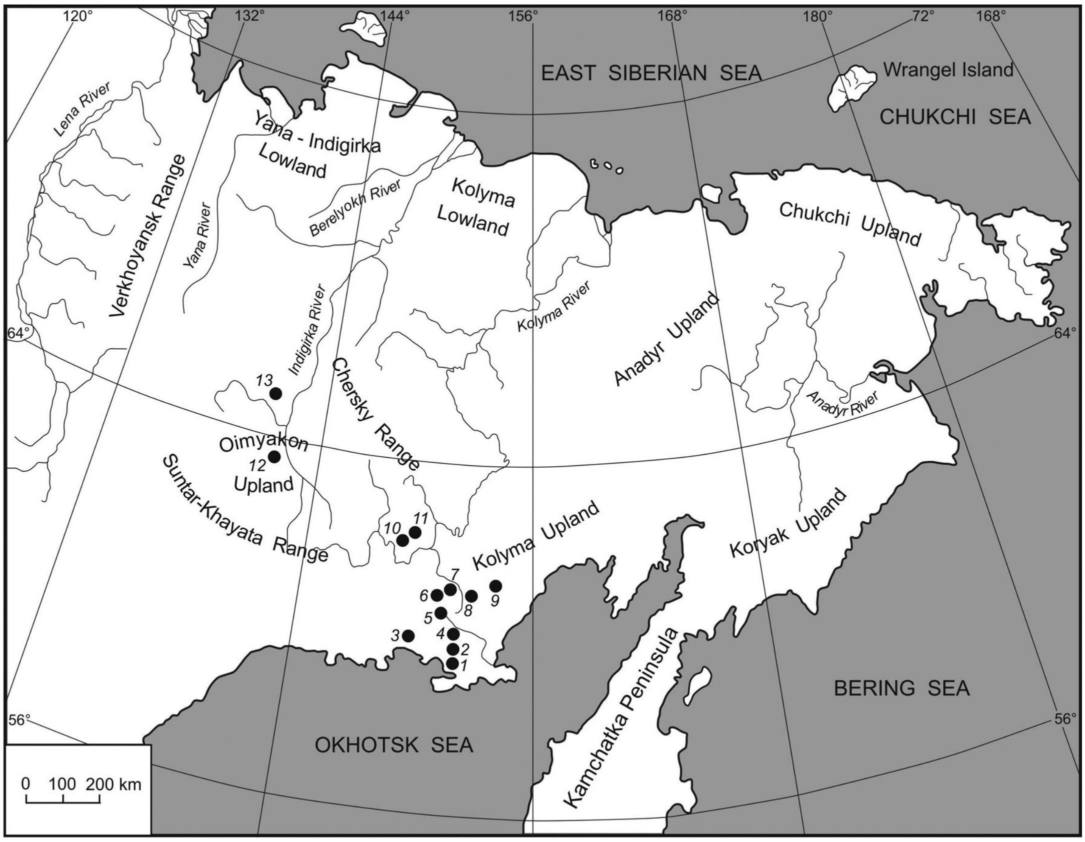

Рис. 1. Карта, показывающая нахождение озер с прослоями вулканического пепла (темный кружок): 1 – оз. Чистое, оз. Лесное; 2 – оз. Подкова; 3 – оз. Глухое; 4 – оз. Алут; 5 – Эликчанские озера; 6 – оз. Приятное, оз. Черное; 7 – оз. Голубое; 8 – оз. Талое; 9 – оз. Джульетта; 10 – оз. Эльгення; 11 – оз. Джека Лондона, оз. Соседнее; 12 – оз. Щучье; 13 – оз. Смородиновое

Fig. 1. Map showing the locations of lakes (dark circles), whose sediments contain layers of volcanic ash: 1 – Chistoye Lake and Lesnoye Lake; 2 – Podkova Lake; 3 – Glukhoye Lake; 4 – Alut Lake; 5 – Elikchan Lakes; 6 – Priyatnoye Lake, Chernoye Lake; 7 – Goluboye Lake; 8 – Taloye Lake; 9 – Julietta Lake; 10 – Elgennya Lake; 11 – Jack London Lake and Sosednee Lake; 12 – Tschuchye Lake; 13 – Smorodinovoye Lake

The thicknesses of the layers of Elikchan tephra vary within relatively wide limits in the different lakes of northeastern Siberia (see table), as well as differing in their structure (e. g., distinct, continuous layer vs. scattered inclusions of ash). The Elikchan tephra is common in glacial lakes in the Upper Kolyma region, although like in northern Priokhotye, it is variable in its depositional characteristics. As at Elikchan-3, a relatively thick tephra layer (12 cm) was found in the sediments of Goluboye Lake, which is located in the Talaya River basin in an area of active MIS2 glaciation. In other sites from the Upper Kolyma, tephra horizons have a complex structure. For example, the Elikchan tephra was found between 277–291 cm core depth at Priyatnoye Lake. This interval included horizontal layers of silt ranging in thickness from a few millimeters to 3.5 cm, and a layer of aquatic plants between 278–280 cm. Another variation in the tephra deposit was seen at Sosednee Lake. In the Sosednee core, at a depth of 68–72 cm, a discontinuous layer consisting of scattered inclusions of volcanic ash was found in the lacustrine silt, which contrasts with the compact and well-defined layers of tephra that are typical in other lakes of the Northern Okhotsk region and the Upper Kolyma basin. In glacial lakes in the upper reaches of the Indigirka River, 1600 km away from the source volcano, the thickness of the tephra layer sharply decreases to 1.5 mm in Tschuchye Lake (Fig. 1 site 12) and to 1 mm in Smorodinovoye Lake (Fig. 1 site 13). The variable thickness of the tephra horizon and its structural complexity in the lake records can be explained by the transport of material into a glacial lake from the surrounding slopes and inflowing streams, and not only by the fallout of volcanic ash onto the lake's surface.

One of the hallmarks of the upper layer of tephra in the Chistoye Lake sediments is its high magnetic susceptibility. Compared to the lower tephra, the upper (Elikchan) tephra contains less SiO_2 (64.65 wt. %), and the sum of $K_2O + Na_2O$ (7.57 wt. %), which indicate a dacitic composition (Minyuk et al., 2022). A tephra similar to the upper layer at Chistoye Lake was noted in the sediments of Glukhoye Lake (Fig. 1, site 3). The latter lake occurs in the western part of a tectonic depression, which stretches for

Table. **Thickness of tephra deposits in lake sediments from northeastern Siberia**
Таблица. **Толщина отложений тефры в озерных отложениях северо-восточной Сибири**

Site	Site number (see Fig. 1)	Latitude, Longitude	Thickness (cm) of the 7650±50 BP tephra	Thickness (cm) of the 2745±10 BP tephra
Chistoye Lake, Lesnoye Lake	1	59º 32' N, 151º 48' E 59° 35' N, 151º 52' E	4	3 1
Podkova Lake	2	59° 57' N, 152° 06' E		0.2
Glukhoye Lake	3	59° 45' N, 149º 55' E		29*
Alut Lake	4	60° 08' N, 152º 20' E	2	
Elikchan-1 Lake, Elikchan-3 Lake, Elikchan-4 Lake	5	60° 45' N, 151º 56' E 60° 45' N, 151º 53' E	2 15 1–2; 5.5–6	
Priyatnoye Lake, Chernoye Lake	6	60° 01' N, 151º 43' E	13 3	
Goluboye Lake	7	61° 07' N, 152º 16' E	12	
Taloye Lake	8	61° 02' N, 152º 20' E	3	
Julietta Lake	9	61° 33' N, 155º 07' E	0.2	
Elgennya Lake	10	62° 05' N, 149º 00' E	1.3	
Jack London Lake, Sosednee Lake	11	62° 10' N, 149º 30' E	3 4	
Tschuchye Lake	12	63º 26' N, 140º 59' E	0.15	
Smorodinovoye Lake	13	64º 46' N, 141º 07' E	0.1	

*Nodules of tephra dispersed throughout a 29 cm length of the sediment core

28 km along the coast of Taui Bay. The lake is bounded to the north by the Arman Mountains and is separated from the Okhotsk Sea by a 1.2-km-wide valley.

A sediment core from Glukhoye Lake was raised from the ice surface using a piston sampler. The core was 169 cm thick and dominated by silt, although replaced by sand at the base of the core. Between 13 and 42 cm, the lacustrine silt included point inclusions of volcanic ash. Palynological analysis of the Glukhoye sediments provided the first data on the responses of the vegetation of Northern Priokhotye to Late Pleistocene and Holocene climate change. Although the pollen zones identified in the sediments of the lake were not radiocarbon dated, their pollen characteristics and sequence are in excellent agreement with the pollen zones subsequently identified in the sediments of glacial lakes in other regions of northeastern Siberia (Western Beringia) (Lozhkin et al., 1995a; Lozhkin et al. et al., 1995b; Anderson and Lozhkin, 2002). The presence of an herbaceous pollen zone (core depth of 130–169 cm) clearly shows that Glukhoye Lake formed sometime during MIS2. Even though not radiocarbon dated, the biostratigraphy clearly indicates that the lake is sufficiently old to contain the Elikchan tephra. Additionally, the age of the Elikchan tephra approximates the first occurrence in Northern Priokhotye and the Upper Kolyma of *Pinus* subgen. Haploxylon (*Pinus pumila*) pollen (Anderson at al., 2014). Given these relationships, we might expect to find traces of the Elikchan tephra in the Glukhoye sediments at a depth of about 90 cm. However, no distinct tephra layer was present, even though the ash was clearly preserved in other coastal lakes such as Chistoye.

As seen in the above examples, the presence or absence of a tephra as well as the thickness of an ash layer in a lacustrine core is variable and depends on the local conditions of accumulation. The volume of tephra deposited in a lake is dependent on two main processes: settling of air-born ash directly on the water surface or through the in-wash of the tephra from lake shores and inflowing streams. Sediment mixing due to local factors (e. g., strong coastal storms resulting in wind mixing of sediments or heavy overland water flow flushing out a portion of the lake sediments) is the most probable cause of a tephra's apparent absence. In the latter case the use of additional analytical methods, such as magnetic susceptibility, would enhance the ability to either define tephra layers which are not clearly visible or deter-

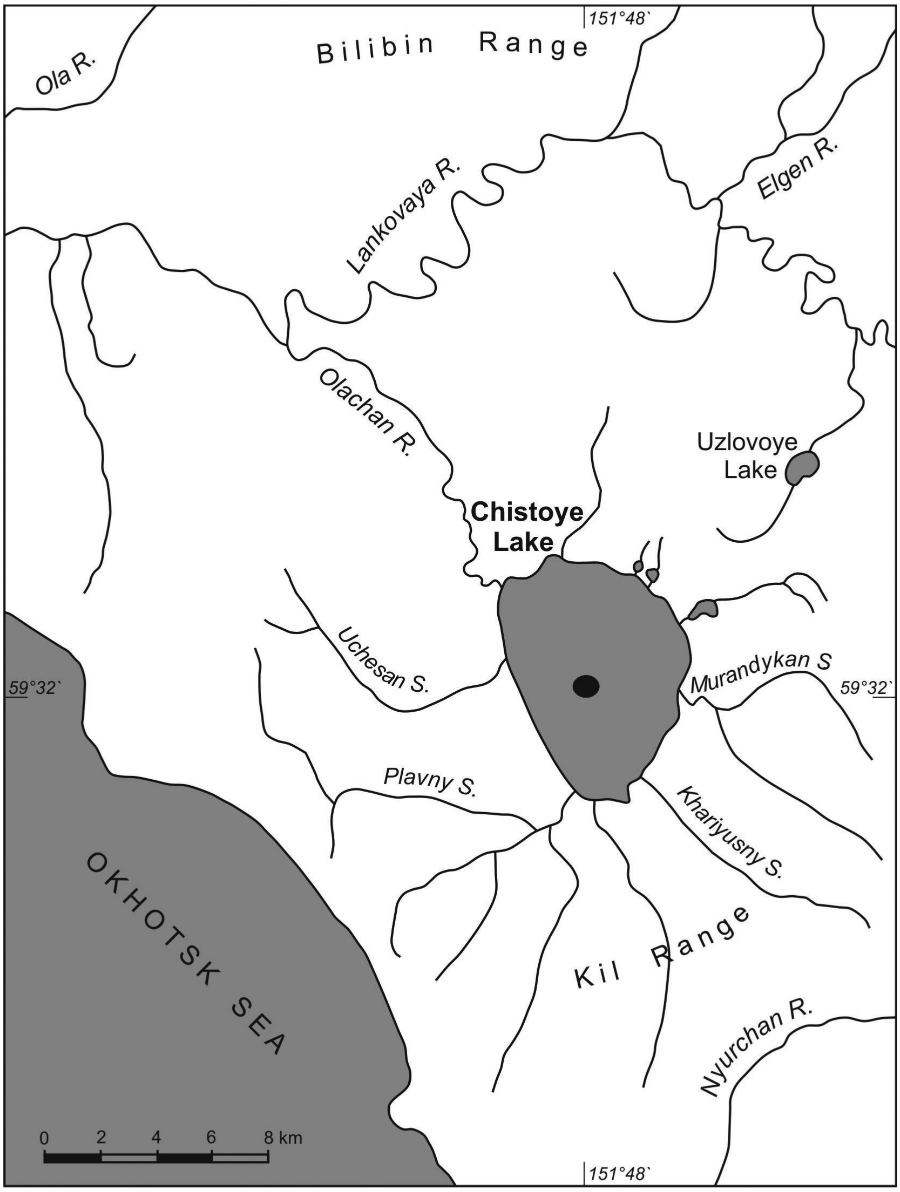

Рис. 2. Местоположение оз. Чистое и скважины, вскрывшей осадки озера (черный кружок)

Fig. 2. Location of Chistoye Lake and the coring site (black circle)

mine when the tephra has been dispersed within the sediments.

Radiocarbon dates of sediment cores from Lesnoye and Podkova Lakes (Fig. 1, site 1 and site 2, respectively) have helped in determining the age of the upper tephra found in the Chistoye core. Lesnoye Lake is located only 300 m from the northeastern shore of Chistoye Lake. It is a morainally dammed lake, as indicated by the boulder, pebble, and rubble deposits exposed along the southern shore of the lake. In the center of the lake at a water depth of 5 m, a piston sampler was used to raise a 337-cm-long core consisting only of lacustrine silt. Between 109 and 110 cm, a layer of 1 × 1 cm inclusions of volcanic ash occurred. Two radiocarbon dates were obtained above and below the tephra on wood and on unidentified plant remains, respectively: 110–115 cm, 2 900 ± 60 years ago (CAMS 18070); 31–35 cm, 1 060 ± 60 years ago (CAMS 29163). However, there is no visible trace of the Elikchan tephra despite the oldest radiocarbon date from the Lesnoye core being 14 290 ± 70 years ago (CAMS 27443; 300–302 cm). This date suggests that lake sedimentation began in the Late Pleistocene (Anderson at al., 1997). Interpolation of other radiocarbon dates from the Lesnoye core (4290 ± 120 years ago (CAMS 27445), depth of 140–142 cm; 7420 ± 120 years ago (CAMS 18063), depth of 215–220 cm; 8480 ± 60 years ago (CAMS27444), depth of 225–226 cm; 9680 ± 60 years ago (CAMS 18065), depth of 243–248 cm) combined with the successive changes in the spore-pollen spectra, which trace the shifts in the paleovegetation from herbaceous tundra to *Betula-Alnus* shrub tundra to *Larix* forest, indicate similarities between the Lesnoye and Glukhoye records. These results suggest the presence of one or more tephra would be expected in the Lesnoye core. Interpolation of the Lesnoye dates would suggest that the Elikchan tephra should be present near 222 cm core depth. Here again it appears that the volcanic ash has been mixed with lacustrine silts and might have been identified with use of magnetic susceptibility.

Podkova Lake is located 50 km to the north of Chistoye Lake within a complex of recessional moraines in the Bilibin Range. In the eastern part of Podkova Lake, at a water depth of 8 m, a 138-cm-long sediment core was raised using a piston sampler. A volcanic ash was found within the lacustrine silts at a depth of 72–72.2 cm. Based on the core's radiocarbon dates, the Podkova sediments were deposited during the Late Holocene. The age of the tephra layer was constrained by a date of 2 580 ± 90 years ago (CAMS 32946) at a depth of 66–68 cm and 3 840 ± 60 years ago (CAMS 46288) at 100–101 cm. Above the ash, radiocarbon dates of 2 060 ± 60 years ago (CAMS 32945) at 56–57 cm and 1 890 ± 80 years ago (CAMS 32944) at 49–50 cm were also obtained. A date of 5 420 ± 100 years ago (CAMS 32690; depth 136–138 cm) indicates the time of lake initiation. Interpolation of the radiocarbon dates from both the Podkova and Chistoye records indicate that the age of the upper layers of volcanic ash are synchronous with the upper tephra of Chistoye Lake at 2 745 ± 10 years ago.

A tentative basal age of 11,700 years ago for the Chistoye core has been calculated based on the extrapolation of the sedimentation rate between the two tephra layers. Palynological analysis of the Chistoye Lake sediments followed methods applied in the study of Arctic lakes and estuaries (PALE, 1994). When reconstructing the vegetation, the sum of all pollen grains was taken as 100 %. The PALE protocols recommend that at least 300 pollen grains from terrestrial plants should be counted in each sample. In fact, 500 or more pollen grains were identified in most samples from the Chistoye sediments. Each pollen taxon is given as a percentage of the sum of all identified and unidentified pollen grains. The percentages of spores and aquatic taxa also are based on the pollen sum. The results of the palynological analyses are presented as percentage diagrams (Figs. 3 and 4). Figure 3 shows the main pollen and spore taxa as well as the ratios of vegetation groups (i. e., pollen from woody and shrubby plants, pollen from subshrubs and herbaceous plants, and spore producing plants such as mosses and ferns). The percentages of minor pollen and spore taxa are depicted in Figure 4. All samples contain taxa that were redeposited from Neogene sediments, thereby complicating the paleovegetation interpretations. For example, the Chistoye samples consistently contained pollen from *Picea* sect. Eupicea, the amount of which varies from 1 to 10 % of the total number of pollen grains. Almost all samples include *Tsuga* pollen, ranging from fractions of a percent to 3 %. The total amount of these exotic (i. e., plants that do not currently grow in the region) conifers can reach 13 %. The moderately heat-loving taxa *Tilia*, *Corylus*, *Juglans*, and *Ulmus* are found as single pollen grains in at least 50 % of the samples. In the middle part of the core, pollen from broad-leaved trees and shrubs is 1 %. Although *Pinus* subgen. Haploxylon pollen in Quaternary records from northeastern Siberia typically indicates the presence of the shrub *Pinus pumila*, this pollen taxon also occurs during the Neogene, a time when tree *Pinus* grew in the region. More specifically, continuous palynological records from lakes in the Upper Kolyma and Northern Priokhotye show that the pollen of *Pinus* subgen. Haploxylon occurs as single grains or is absent altogether in the palynological spectra dating from the end of the Late Pleistocene into the Early Holocene (up to 8 000 years ago). Such features in the lacustrine pollen records suggest that the pollen of *Pinus* subgen. Haploxylon represents redeposition in the Chistoye Lake spectra between 380 and 550 cm. The percentages of *Pinus* pollen in this interval varies between 14 and 26 %. The pollen percentages of *Pinus* subgen. Haploxylon in the spectra that overlie the "lower" ash layer (i. e., the Elikchan tephra) are similar or noticeably less as compared to the modern pollen spectra from lake sediments in the Upper Kolyma and Northern Priokhotye. Unfortunately, it is not possible to determine the percentage of *Pinus* pollen that can be attributed to redeposition (e. g., the grains are not differentiated based on poorer preservation of the older Neogene pollen). Undoubtedly, a portion of the pollen of *Betula* and *Alnus* has also been redeposited, as well as the pollen of herbaceous plants and spores (for example, *Riccia*). In general terms, the pollen of exotic plants in the spectra of the Chistoye Lake sediments comprise a complex that is characteristic of the Miocene of the northeastern region of Siberia (Decisions…, 1978). Nonetheless, the pollen sum used for the Chistoye samples includes all terrestrial taxa, because the native and exotic pollen and spores cannot be differentiated.

The pollen analysis shows a strong similarity of all samples. The noticeable exception is the change in the percentages of *Sphagnum* spores, reflecting a gradual increase in effective moisture during the Younger Dryas and Holocene (note: ages are based on interpolated sedimentation rate between the two tephra). Based on relatively small changes in the pollen-spore percentages, four palynological zones can be delimited (Fig. 3), with the dating of the boundaries determined by the tephra-based age model. In the large Chistoye Lake, the average rate of sediment accumulation is 0.047 cm/year. In lower zone 1, the content of *Sphagnum* spores varies from 12–22 %. The upper boundary of zone 1 is at a depth of

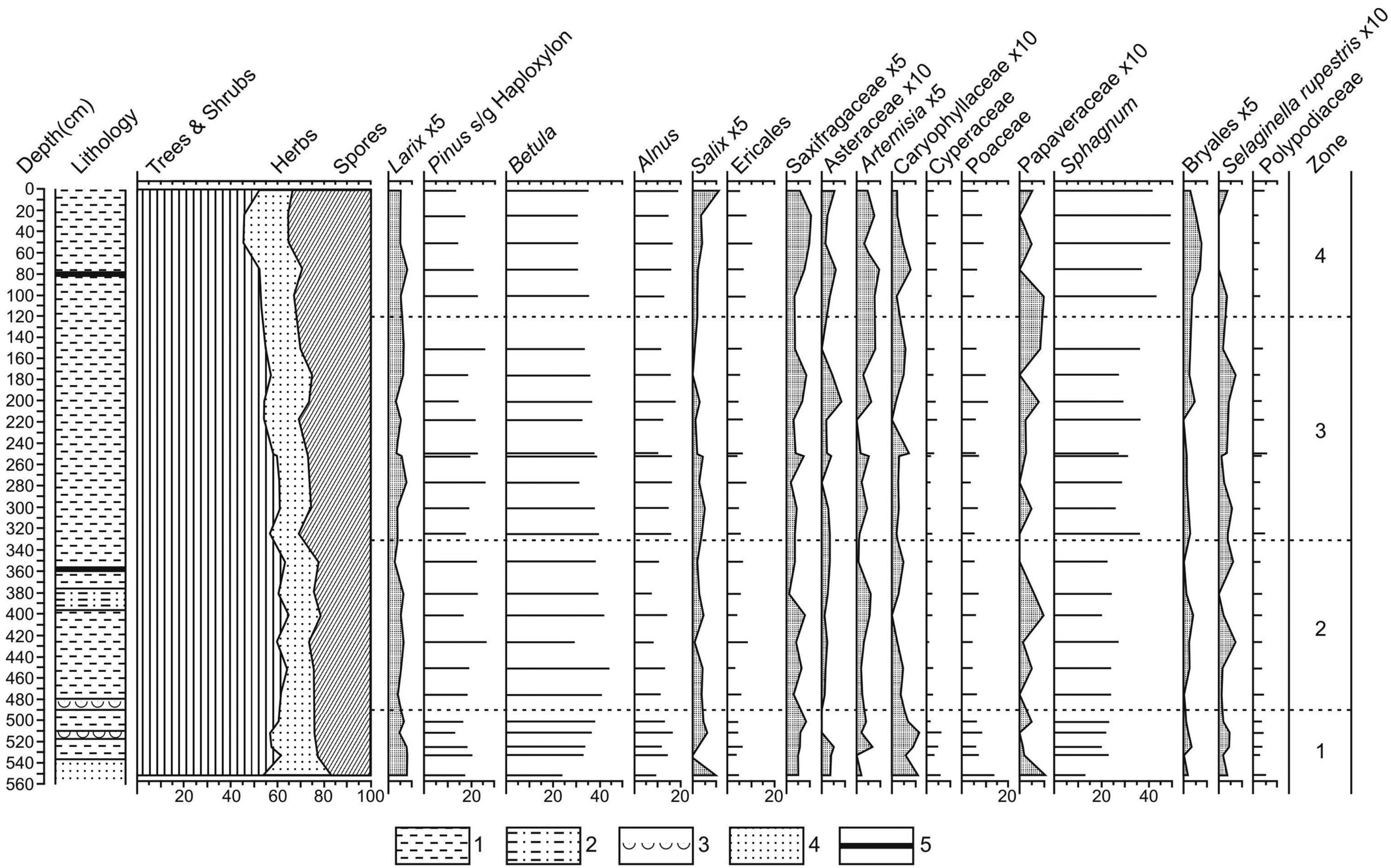

Рис. 3. Соотношение групп растительности, основных пыльцевых и споровых таксонов в спектрах осадков оз. Чистое. 1 – алеврит, 2 – алеврит с песком, 3 – торф, 4 – песок, 5 – вулканический пепел

Fig. 3. Percentage diagram showing the vegetation groups and the major pollen and spore taxa in the sediments from Chistoye Lake. 1 – silt, 2 – silt with sand, 3 – peat, 4 – sand, 5 – tephra

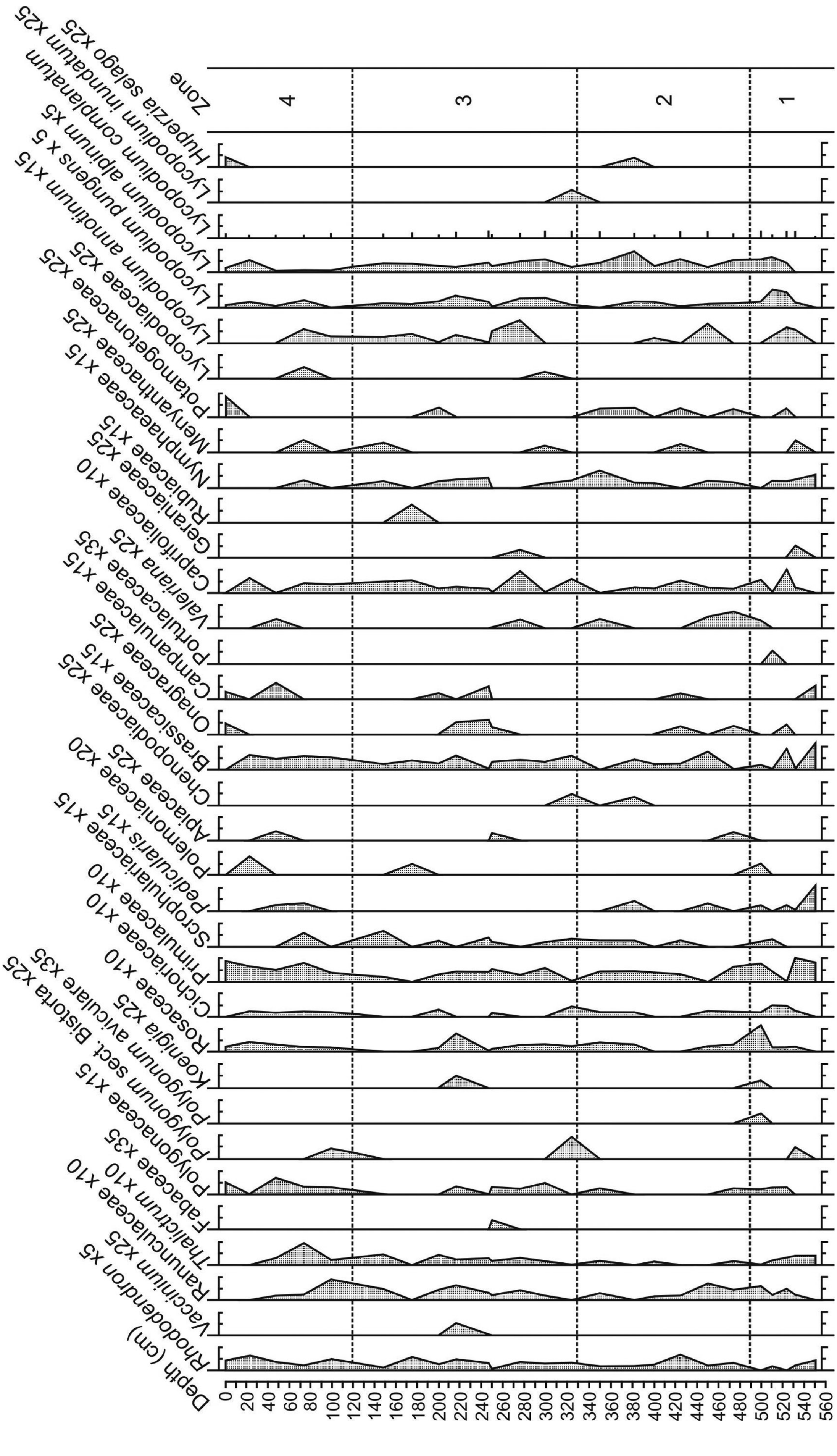

Рис. 4. Второстепенные пыльцевые и споровые таксоны в спектрах осадков оз. Чистое

Fig. 4. Percentage diagram showing the minor pollen and spore taxa in the sediments from Chistoye Lake

490 cm and has a tentative age of 10 425 years ago. In zone 2, the upper limit of which is 7.020 years ago at a depth of 330 cm, *Sphagnum* spores vary between 20 and 28 %. The upper boundary of zone 3 was drawn at 122 cm with an interpolated date of 4 000 years ago. *Sphagnum* spores in the spectra of this zone reach 36 %. The maxima of *Sphagnum* spores at 50 % characterize the spectra of zone 4. The proposed dates for the palynological zones do not contradict the dating of peat bogs formed in the Holocene near Chistoye Lake. A series of radiocarbon dates was obtained for peat horizons exposed in outcrops near the northeastern shore of the lake. Peat (59-106 cm depth as measured from the surface) in an outcrop located on the lake shore was dated from 4 335 ± 55 years ago (MAG-1457) to 5 830 ± 40 years ago (MAG-1453). In another outcrop on the shore of a lake with informal name of Good (300 m from Chistoye Lake) a peat horizon (14–92 cm depth) was dated from 1 275 ± 20 years ago (MAG-1463) to 3 440 ± 30 years ago (MAG-1469) (Anderson et al., 1997). A series of radiocarbon dates from 3 450 ± 90 years ago (MAG-2350) to 9 725 ± 250 years ago (MAG-2342) were obtained from a peatbog excavated in the interval 0–145 cm in an outcrop on the shore of Chistoye Lake (Minyuk et al., 2022).

The above summary demonstrates that tephra layers within lacustrine cores are reliable chronostratigraphic benchmarks and are useful aids in the reconstruction of Holocene climate and vegetation changes areas of northeastern Siberia. The presence of the Elikchan (or Kurile Lake) tephra in the sediments of Chistoye and other lakes of Northern Priokhotye and the Upper Kolyma and Indigirka basins further helps to constrain the timing of important vegetation changes such as the initial spread of *Pinus pumila* across the region. Furthermore, this tephra approximates the boundary between the Early and Middle Holocene. The presence of the younger tephra in the northeastern Siberian lakes provides additional time control for middle Late Holocene sediments. The Chistoye Lake study also shows the value of detailed sediment analyses using such methods as magnetic susceptibility for determining the presence of tephra that is not apparent with simple visual inspection of a sediment core.

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REFERENCES

Anderson, P. M., Belaya, B. V., Glushkova, O. Yu., Lozhkin, A. V., 1997. New Data About the Vegetation History of Northern Priokhot'ye during the Late Pleistocene and Holocene, Late Pleistocene and Holocene of Beringia. Magadan, Northeast Science Center Far East Branch Russian Academy of Sciences. 33–54 [In Russian.

Anderson, P. M., Lozhkin, A. V., 1996. Changes in the Vegetation and Climate of the Northern Priokhotye Region on the Boundary of the Pleistocene and Holocene, Reports of the Russian Academy of Sciences. 348, 3, 403–406 [In Russian].

Anderson, P. M., Lozhkin, A. V. (Edit.), 2002. Late Quaternary Vegetation and Climate of Siberia and the Russian Far East (Palynological and Radiocarbon Database), U. S. National Oceanic and Atmospheric Administration (NOAA), Russian Academy of Sciences. Magadan, North East Science Center. 370 [In English and Russian].

Anderson, P. M., Lozhkin, A. V., Minuyk, P. S., Pakhomov, A. Yu., 2014. Environmental Changes of the Okhotsk-Kolyma Divide from Glacial Lake Sediments during the Holocene, Russian Journal of Pacific Geology. 8, 6, 464–474.

Ankudinov, L. A., Baranova, Yu. P., Biske, S. F., Fradkina, A. F., 1975. Working Stratigraphic Scheme for the Division of Neogene Deposits of Neotectonic Depressions of the Northern Coast of the Sea of Okhotsk, Cenozoic of the North-East of the USSR. Magadan, Northeast Interdisciplinary Scientific Research Institute Far East Science Center USSR Academy of Sciences. 20–33 [In Russian].

Baranova, Yu. P., Biske, S. F., 1964. History of the Development of the Relief of Siberia and the Far East. Northeast of the USSR. Moscow, Nauka [In Russian].

Belaya, B. V., 1988. On the Age of the Cenozoic Deposits of the Lankovskaya Depression (According to Palynological Data), Continental Paleogene and Neogene of the North-East of the USSR. Northern Okhotsk. Vol. 2. Magadan, Northeast Interdisciplinary Scientific Research Institute Far East Branch USSR Academy of Sciences. 17–30 [In Russian].

Decisions of the II Interdepartmental Stratigraphic Conference on the Precambrian and Phanerozoic of the North-East of the USSR (Stratigraphic Schemes). Magadan, Northeast Interdisciplinary Scientific Research Institute Far Eastern Scientific Center of the Academy of Sciences of the USSR, 1978.

Glushkova, O. Yu., 1983. The History of the Development of the Relief of the Northern Okhotsk Region in the Late Pleistocene and Holocene, Stratigraphy and Paleogeography of the Late Cenozoic East of the USSR. Magadan, Northeast Interdisciplinary Scientific Research Institute Far East Science Center USSR Academy of Sciences. 114–123 [In Russian].

Korzun, Yu. A., 2017. Palynological Analysis of the Sediments of a Glacial Lake in the Upper Reaches of the Indigirka River, Bulletin of the North-Eastern Scientific Center of the Far Eastern Branch of the Russian Academy of Sciences. 1, 24–31 [In Russian].

Lisiecki, L. E., Raymo, M. E., 2005. A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic $\delta^{18}O$ Records, Paleoceanography. 20, 1–17. PA1003, DOI: 10.1029/2004PA001071.

Lozhkin, A. V., Anderson, P. M., Belaya, B. V., 1995a. Radiocarbon Dating of Pollen Zones in Lacustrine Sediments of the Kolyma-Okhotsk Interfluve, Reports of the Russian Academy of Sciences. 343, 3, 396–399.

Lozhkin, A. V., Anderson, P. M., Brubaker, L. B., Prokhorova, T. P., 1995b. The First Results of a Palynological Analysis of Sediments from Glacial Lakes in Chukotka, Reports of the Russian Academy of Sciences. 342, 4, 540–542.

Lozhkin, A. V., Brown, T. A., Anderson, P. M., Glushkova, O. Yu., Melekestsev, I. V., 2016. The Importance of Radiocarbon Dates and Tephra for Developing Chronologies of Holocene Environmental Changes from Lake Sediments, North Far East, Pacific Geology. 35, 4, 14–27.

Minyuk, P. S., Sotskaya, O. T., Tsygankova, V. I., Akinin, V. V., Burnatny, S. S., 2022. Holocene ash from Lacustrine Sediments of Priokhotsk Area: Distinctive Features, Reports of the Russian Academy of Sciences. 505, 1, 62–68 [In Russian].

PALE, 1994. Research Protocols for PALE: Paleoclimates of Arctic Lakes and Estuaries. PAGES Workshop Report Series, Bern.

Ponomareva, V. V., Kyle, P. R., Melekestsev, I. V., Rinkleff, P. G., Dirksen, O. V., Sulerzhitsky, L. D., Zaretskaia, N. E., Rourke, R., 2004. The 7600 (^{14}C) Year BP Kurile Lake Caldera Forming Eruption, Kamchatka, Russia: Stratigraphy and Field Relationships, Journal of Volcanology and Geothermal Research. 136, 199–222.

Wright, H. E. Jr., Mann, D. H., Glaser, P. H., 1984. Piston Corers for Peat and Lake Sediments, Ecology. 65, 657–659.

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ПАЛИНОЛОГИЧЕСКАЯ ХАРАКТЕРИСТИКА И ВУЛКАНИЧЕСКИЙ ПЕПЕЛ ОТЛОЖЕНИЙ ОЗЕРА ЧИСТОЕ, СЕВЕРНОЕ ПРИОХОТЬЕ

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Оз. Чистое находится в 10 км от северного берега Тауйской губы (Охотское море) в центральной части тектонической депрессии (59º 32' с. ш. и 151º 48' в. д.), выполненной отложениями палеогена и неогена. Образование оз. Чистое связывается с активностью ледников последней ледниковой стадии (MIS2). Керн озерных осадков длиной 550 см был поднят с помощью поршневого пробоотборника. Осадки представлены алевритом с прослоями торфа и песком в основании колонки. Алевриты включали прослои тефры на глубине 360–364 см и на глубине 77–80 см, различной по петрохимическому составу, магнитным и минералогическим характеристикам. Вулканический пепел, подобный тефре нижнего слоя в осадках оз. Чистое, обнаружен в осадках других озер Верхнеколымского и Верхнеиндигирского районов и Северного Приохотья. ^{14}C датирование органических остатков в озерных осадках, подстилающих и перекрывающих прослои тефры, аналогичной тефре нижнего слоя оз. Чистое, определяет возраст тефры 7 650 ± 50 лет назад, соответствующий возрасту тефры кальдеры Курильское озеро – Ильинская на Камчатке. Тефра, синхронная «верхней» тефре оз. Чистое, установлена также в других озерах Северного Приохотья и ее возраст определяется 2 745 ± 10 лет назад. Отличительным признаком этой тефры является ее высокая магнитная восприимчивость. Экстраполирование датировок прослоев тефры в осадках оз. Чистое приводит к выводу, что начало осадконакопления в озере относится к 11 700 лет назад. Палинологический анализ осадков оз. Чистое показал, что все образцы содержат пыльцу, переотложенную из неогеновых отложений (*Picea* sect. Eupicea, *Tsuga*, *Tilia*, *Corylus*, *Juglans*, *Ulmus*). Несомненно, часть пыльцы *Pinus* subgen. Haploxylon, *Betula* и *Alnus* также может быть переотложена, как и пыльца травянистых растений и споры. Таким образом, переотложенные пыльца и споры вносят серьезные изменения в спорово-пыльцевые спектры, продуцируемые современной растительностью Северного Приохотья. В связи с этим обращает внимание изменение в спектрах количества спор *Sphagnum*, отражающее постепенное увеличение влажности климата в течение позднего дриаса и голоцена. Комплексное исследование осадков оз. Чистое, особенно включая их палинологическую характеристикую, убедительно показывает важность анализа магнитных свойств прослоев пепла в осадках озер, формировавшихся в пределах тектонических впадин с толщами палеогеновых и неогеновых отложений. Прослои вулканического пепла в осадках озер северо-восточной Сибири являются надежными хроностратиграфическими реперами при реконструкции изменений климата и растительности региона в голоцене.

***Ключевые слова*: осадки озер, палинологический анализ, вулканический пепел, радиоуглеродное датирование.**

ЛИТЕРАТУРА

Андерсон П. М., Белая Б. В., Глушкова О. Ю., Ложкин А. В. Новые данные об эволюции растительного покрова Северного Приохотья в позднем плейстоцене и голоцене // Поздний плейстоцен и голоцен Берингии. Магадан : СВКНИИ ДВО Российской Академии наук, 1997. С. 33–54.

Андерсон П. М., Ложкин А. В. Изменение растительности и климата Северного Приохотья на границе плейстоцена и голоцена // Доклады Российской Академии наук. 1996. Т. 348, № 3. С. 403–406.

Андерсон П. М., Ложкин А. В. (Ред.). Позднечетвертичные растительность и климаты Сибири и Российского Дальнего Востока (палинологическая и радиоуглеродная база данных) // Национальное управление США по исследованию океана и атмосферы, Российская Академия наук. Magadan : North East Science Center, 2002. 370 p. (In English and Russian)

Анкудинов Л. А., Баранова Ю. П., Бискэ С. Ф., Фрадкина А. Ф. Рабочая стратиграфическая схема расчленения неогеновых отложений неотектонических впадин северного побережья Охотского моря // Кайнозой Северо-Востока СССР. Магадан, СВКНИИ ДВНЦ АН СССР, 1975. С. 20–33.

Баранова Ю. П., Бискэ С. Ф. История развития рельефа Сибири и Дальнего Востока. Северо-Восток СССР. Москва : Наука, 1964. 289 с.

Белая Б. В. О возрасте кайнозойских отложений Ланковской впадины (по палинологическим данным) // Континентальный палеоген и неоген Северо-Востока СССР. Северное Приохотье. Вып. 2. Магадан : СВКНИИ ДВО АН СССР, 1988. С. 17–30.

Глушкова О. Ю. История развития рельефа Северного Приохотья в позднем плейстоцене и голоцене // Стратиграфия и палеогеография позднего кайнозоя Востока СССР. Магадан : СВКНИИ ДВНЦ АН СССР, 1983. С. 114–123.

Корзун Ю. А. Палинологический анализ осадков ледникового озера в верховьях р. Индигирка // Вестник СВНЦ ДВО РАН. 2017. № 1. С. 24–31.

Ложкин А. В., Андерсон П. М., Белая Б. В. Радиоуглеродное датирование пыльцевых зон в озерных осадках Колымо-Охотского междуречья // Доклады Российской Академии наук, 1995а. Т. 343, № 3. С. 396–399.

Ложкин А. В., Андерсон П. М., Брубейкер Л. Б., Прохорова Т. П. Первые результаты палинологического анализа осадков ледниковых озер Чукотки // Доклады Российской Академии наук, 1995б. Т. 342, № 4. С. 540–542.

Минюк П. С., Соцкая О. Т., Цыганкова В. И., Акинин В. В., Бурнатный С. С. Голоценовые пеплы в озерных осадках Приохотья: отличительные признаки // Доклады Российской Академии наук, 2022. Т. 505, № 1. С. 62–68.

Решения II Межведомственного стратиграфического совещания по докембрию и фанерозою Северо-Востока СССР (стратиграфические схемы). Магадан : СВКНИИ ДВНЦ АН СССР, 1978.

Anderson P. M., Lozhkin A. V., Minuyk P. S., Pakhomov A. Yu. Environmental Changes of the Okhotsk-Kolyma Divide from Clacial Lake Sediments during the Holocene // Russian Journal of Pacific Geology, 2014. Vol. 8. No. 6. P. 464–474.

Lisiecki L. E., Raymo M. E. A Pliocene-Pleistocene stack of 57 globallydistributed benthic $\delta^{18}O$ records // Paleoceanography. 2005. Vol. 20. PA1003, DOI: 10.1029/2004PA001071, P. 1–17.

Lozhkin A. V., Brown T. A., Anderson P. M., Glushkova O. Yu., Melekestsev I. V. The Importance of Radiocarbon Dates and Tephra for Developing Chronologies of Holocene Environmental Changes from Lake Sediments, North Far East // Pacific Geology. 2016. Vol. 35, No. 4. P. 14–27.

PALE, 1994. Research Protocols for PALE: Paleoclimates of Arctic Lakes and Estuaries. PAGES Workshop Report Series, Bern. 53 p.

Ponomareva V. V., Kyle P. R., Melekestsev I. V., Rinkleff P. G., Dirksen O. V., Sulerzhitsky L. D., Zaretskaia N. E., Rourke R. The 7600 (^{14}C) Year BP Kurile Lake Calderaforming Eruption, Kamchatka, Russia: Stratigraphy and Field Relationships // Journal of Volcanology and Geothermal Research. 2004. Vol. 136. P. 199–222.

Wright H. E. Jr., Mann D. H., Glaser P. H. Piston Corers for Peat and Lake Sediments // Ecology. 1984. Vol. 65. P. 657–659.