ГЕОЛОГИЧЕСКИЕ НАУКИ

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PALEOENVIRONMENTAL CHANGES IN NORTHERN CHUKOTKA DURING MARINE ISOTOPE STAGES 12–17

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The continuous palynological record of sediments from the El'gygytgyn crater lake document the changes in vegetation during marine isotope stages 12–17, which span the interval between 424,000 and 712,000 years ago. An important chronological reference point for this interval is the Brunhes–Matuyama boundary (781,000 years ago), established by paleomagnetic analysis of the lake sediments. The regional vegetation of the warm interglacial stages was characterized by the widespread presence of larch forests, which included thickets of dwarf birch, alder, and dwarf pine. In the cold stages, a mosaic of herb tundra dominated, giving way to forest-tundra communities in the valleys of the Anadyr Plateau that surrounds the lake. In the interval between 424,000 and 712,000 years ago, the warmest climate occurred during MIS15, whereas the most severe cooling occurred during MIS12.

***Keywords*: Pleistocene, isotope stage, spore-pollen spectra, phytocenosis.**

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INTRODUCTION

The continuous palynological record from El'gygytgyn Lake reflects the response of vegetation in northern Chukotka to climate change from the Gelasian Stage through the Holocene (Melles et al., 2012; Wennrich et al., 2016). One of the more intriguing intervals includes marine isotope stages (MIS) 12–17, spanning the interval 424–712 thousand years ago (Lisiecki, Raymo, 2005). The isotope record suggests that this interval encompasses one relatively warm (MIS14) and two extremely cool glaciations (MIS12 and MIS16). Additionally, the interglaciations (MIS13 and MIS15) are characterized by multiple fluctuations in the oxygen isotope record, with peaks in the isotope curve suggesting interglacial conditions that were slightly cooler than present.

El'gygytgyn is an oval shaped lake that varies in width between 12 and 14 km. It is situated within an 18-km-wide meteor impact crater, which was formed 3.6 million years ago (Layer, 2000). The lake is located beyond the Arctic Circle in northern Chukotka (67º30′ N, 172º05′ E; Fig. 1). The surrounding peaks of the Anadyr Plateau rise to 600–1000 m above sea level (a.s.l.), while the elevation of the lake surface is 489 m a.s.l.

The interval that includes MIS12–MIS17 corresponds to the first half of the Ionian Age of the International Stratigraphic Scale of the Quaternary System (Yanina, 2014). The lower limit of the Ionian is defined by the boundary between the Brunhes and Matuyama magnetic epochs (781 thousand years ago) and is an important chronological benchmark for constructing the age model for the El'gygytgyn sediment core (Fig. 2). Of particular note in the interval of 424–712 thousand years ago is that the pollen zones reflecting the plant communities that developed in periods synchronous with MIS12–MIS17 are characterized by an unstable composition in the spore-pollen spectra. Such spectra are more typical, for example, of interstadial MIS3, as recorded in a sediment core from Elikchan-4 Lake (Fig. 1) in Northern Priokhotye (Lozhkin, Anderson, 2011), where isotope stages considered relatively warm may include pollen zones more consistent with cool isotope stages.

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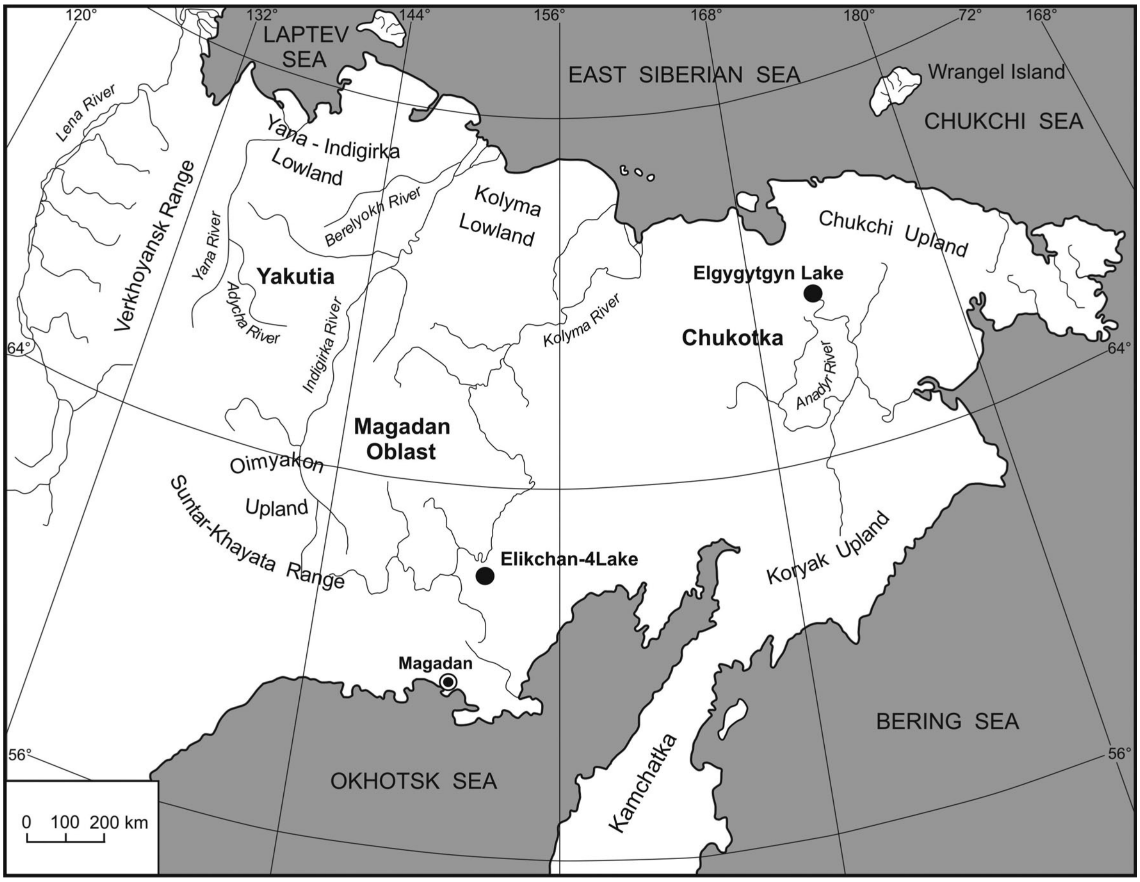

Fig. 1. Map showing the locations of El'gygytgyn and Elikchan-4 Lakes in Western Beringia.

Рис. 1. Географическое положение озера Эльгыгытгын и озера Эликчан-4 на карте Западной Берингии.

Studies of the interval 424-712 thousand years ago were made possible by the International Expedition "El'gygytgyn Drilling Project", which raised a 317 m long sediment core (well 5011-1) in the center of the lake. The core consisted of silt with an admixture of fine-grained sand (Melles et al., 2012; Nowaczyk et al., 2013; Lozhkin, Anderson, 2020).

When reconstructing plant communities developed in the interval 424–712 thousand years ago, features of the modern spore-pollen spectra, collected at the water-sediment interface of Lake El'gygytgyn, are considered (Lozhkin et al., 2002).

The vegetation in the vicinity of the lake is mainly characterized by lichens and herbs (Kozhevnikov, 1993). On the hills the vegetation cover is often discontinuous. Low shrubs of *Salix krylovii* E. Wolf, *S. alaxensis* Cov. occupy protected areas in the inflowing stream valleys and along the outflowing Enmyvaam River. *Betula exilis* Sukacz. is limited to areas with an accumulation of organic matter. On the Anadyr Plateau there is a mosaic of low shrub and graminoid tundra with small populations of *Pinus pumila* (Pall.) Regel and *Duschekia fruticosa* (Rupr.) Pouzar.

Wind-blown pollen of *Pinus pumila*, *Betula exilis*, and *Duschekia fruticosa* dominate the modern spore-pollen spectra from the lake's bottom sediments. In these samples, pollen from *Duschekia fruticosa* is up to 35 %, *Betula* – 20%, *Pinus pumila* – 15 %, and the total amount of shrub pollen can be up to 45 %. Thus, the composition of the modern spore-pollen spectra from the bottom sediments of Lake El'gygytgyn reflects the regional vegetation and is not indicative of the low pollen productivity of plant communities currently growing near the lake.

RESEARCH METHODS

Palynological analysis of lake sediments in the interval between 424 and 712 thousand years ago was done following standard methods established for the study of sediments from arctic lakes and estuaries (PALE, 1994). To ensure consistency, this method has been used to prepare all palynological samples throughout the El'gygytgyn core. When reconstructing the vegetation based on the palynological data, the sum of all terrestrial arboreal and nonarboreal pollen grains was taken as 100 %. Spore percentages are based on the pollen

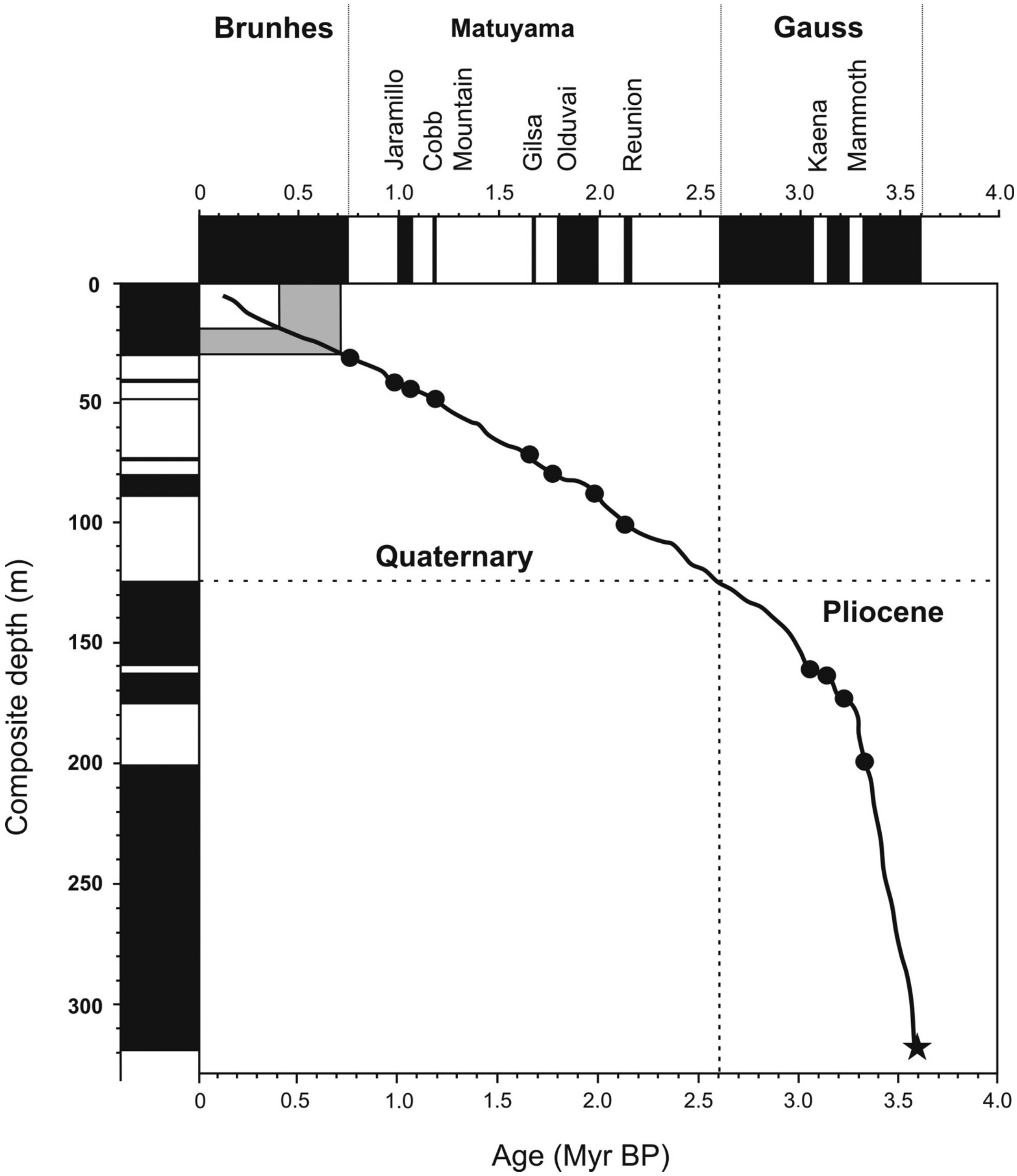

Fig. 2. Correlation of magnetic characteristics of Lake El'gygytgyn sediments with the paleomagnetic scale of normal and reverse polarity. The vertical column on the left side of the figure shows the magnetic characteristics of the lake sediments, the upper horizontal column corresponds to the general paleomagnetic scale. The boundaries of magnetic events are marked with black dots. The curve connecting them provides information on the age of different levels of the lake sediments (Nowaczyk et al., 2013).

Рис. 2. Сопоставление магнитных характеристик осадков оз. Эльгыгытгын с палеомагнитной шкалой нормальной и обратной намагниченности. Вертикальная колонка в левой части рисунка показывает магнитные характеристики осадков озера, верхняя горизонтальная – отвечает общей палеомагнитной шкале. Границы магнитных событий отмечены черными точками. Соединяющая их кривая дает информацию о возрасте различных уровней осадков озера (Nowaczyk et al., 2013).

sum. In each sample, at least 300 pollen grains of terrestrial plants were counted.

The spore-pollen diagram shows the relationships between vegetation groups (on the left side of the diagram – trees and shrubs; herbs; spores) and individual main and minor pollen and spore taxa. Major and minor pollen and spore taxa are shown in Fig. 3 and Fig. 4, respectively.

Difficulties in carrying out palynological analysis of some samples occurred because of low pollen concentrations, especially those samples deposited during cold stages. In these cases, samples with very low pollen concentrations were duplicated by samples from neighboring levels. Samples taken from interstadials and interglacial sediments are usually abundant in pollen and spores.

Calculating spore-pollen percentages and constructing the pollen diagrams were performed using the "Tilia" and "Tilia-graph" computer programs (http://museum.state.il.us./pib/grimm/tilia).

POLLEN ZONES AND THEIR CORRELATION WITH ISOTOPIC STAGES

Based on the relationship of vegetation groups and percentage variations in the main pollen and spore taxa, 9 pollen zones have been distinguished for the 424–712 thousand years ago interval of the El'gygytgyn sediment record. These pollen zones reflect the changes corresponding to glacial, interglacial, and interstadial climates.

Pollen zones E1 and E2 characterize the vegetation during MIS17, zones E5 and E6 – MIS15, E7 and E8 – MIS13. The boundaries of the pollen zones correspond to the boundaries of the isotope stages: the upper boundary of pollen zone E2 corresponds to the boundary of MIS17 and MIS16, the boundary of pollen zones E3 and E4 – to the boundary of MIS16 and MIS15, the upper boundary of pollen zone E5 corresponds to the boundary of MIS15 and MIS14, the boundary of pollen zones E6 and E7–MIS14 and MIS13, the boundary of MIS13 and MIS12 corresponds to the middle part of the pollen zone E8.

FEATURES OF THE PALYNOLOGICAL SPECTRA

A common feature of the palynological record between 424 and 712 thousand years ago is the consistent appearance of *Larix* pollen. The amount of *Larix* pollen can reach 7 % in pollen zones related to both "warm" and "cold" isotope stages. In the pollen spectra of all palynological samples of this interval, *Betula* pollen is noted. Generally, *Betula* pollen is one of the dominants of the spectra of warm stages (up to 50 %). In the spectra of isotope stages indicative of climate cooling (MIS12, MIS14, MIS16), the amount of *Betula* pollen varies from 5 % to 24 % (MIS14). The *Alnus* pollen percentages reach 50–60 % in the spectra of "warm" isotope stages, sharply decreasing in the cool stages (to 3–5 %). Noticeable quantities of *Pinus* s/g Haploxylon pollen (up to 35 %) are only found in the interglaciations.

Poaceae pollen plays a major role in the pollen record of the interval 424–712 thousand years ago. Pollen values reach 50–65 % in the spectra of pollen zones characterizing cold stages (MIS12, MIS14, MIS16), and decreases in the stages that correspond to interglaciations (MIS13, MIS15, MIS17). The comparatively high percentages of *Artemisia* pollen in the spectra is noteworthy, especially in the stages associated with cooling climates (up to 35 %). In the samples of both "warm" and "cold" stages, herb pollen is always present (note that relatively high percentages of herb pollen is usually characteristic of glacial stages in Western Beringia) – Cyperaceae (up to 20 % in MIS12, MIS14, MIS16; up to 10 % in MIS13, MIS15, MIS17) and Caryophyllaceae (up to 8 %). The increase in the amount of *Artemisia* pollen in the spectra corresponds to an increase in the percentages of *Selaginella rupestris* spores (up to 15 %). The warming stages include peaks of *Sphagnum* spores (up to 100 %).

CHARACTERISTICS OF POLLEN ZONES AND PLANT COMMUNITIES

The response of vegetation in Northern Chukotka to climate change during MIS17 is reflected in the palynological complexes of pollen zones E1 and E2.

The dominant taxa in the E1 pollen zone are *Betula* (up to 35 %) and Poaceae (up to 35 %) with a conspicuous presence of *Salix* (up to 10 %) and Cyperaceae (up to 15 %). Shrub *Betula* probably played an important role in both the local and regional vegetation. Tree *Betula* possibly formed scattered stands on the hillslopes surrounding the lake. The low pollen percentages of *Alnus* clearly show that shrub *Alnus* (possibly *Duschekia fruticosa*) was not characteristic of the vegetation in the Lake El'gygytgyn region during the first half of MIS17 nor was it found growing in small, isolated thickets in the most protected habitats. However, an important shrub taxon was shrub willow, which formed dense thickets in the valleys of streams and along the Enmyvaam River. Pollen of Poaceae, Cyperaceae, and forbs indicate a wide distribution of open meadow communities. High percentages of *Sphagnum* spores in the spectra of zone E1 indicate increased effective moisture in the meadows, the presence of swampy terrain, and, probably, the development of bogs. Analysis of the spore-pollen spectra of pollen zone E1 allows us to conclude that the regional and local vegetation was represented by shrub-herb tundra, replaced in some areas by forest-tundra, primarily formed by species of *Betula*.

Pollen zone E2 highlights a significant change in plant communities in the second half of MIS17. If pollen of tree and shrub taxa did not exceed 23 % in pollen zone E1, then in the spectra of zone E2 the percentages of arboreal pollen are up to 70 %. The pollen of this group also becomes more diverse in composition. The comparatively high percentages of *Alnus* pollen (30 %) clearly indicate not only the widespread distribution of shrub forms of *Alnus* (*Duschekia fruticosa*), but also the occurrence of tree-size species (*Alnus hirsuta*) in the gallery forests of the floodplains. The presence of *Larix* pollen (5 %) highlights the establishment of larch forests, which had a dense shrub understory of *Pinus pumila*, *Duschekia fruticosa*, *Betula*, and *Salix*. The spectra of pollen zone E2 also suggest a sharp reduction in areas of open meadows, both in the vicinity of the lake and regionally. These meadow communities consisted of Poaceae, Cyperaceae, and forbs. The E2 pollen zone spectra show that the vegetation that developed in the second half of MIS17 reflect an interglacial climate. The relatively "warm" first half of MIS17 should probably be considered an interstade.

The spore-pollen spectra of MIS16 (pollen zone E3) are characterized by high pollen percentages and diversity of herbaceous plants (see Fig. 3, 4).

Poaceae is the most abundant pollen taxa in the spectra, reaching up to 70 %. Significant roles are played by Cyperaceae pollen (up to 25 %), *Artemisia* pollen (up to 25 %), and *Selaginella rupestris* spores (10 %). This assemblage suggests the widespread existence of rocky slopes and screes, as well as wet and moderately wet sedge-grass meadow communities on the lower valley slopes. *Larix* pollen is consistently present during MIS16, indicating the establishment of larch forest-tundra near the lake and in the valleys of the Anadyr Plateau. Given that *Salix* pollen is poorly preserved in sediments, it is likely that it a common shrub in the vegetation. Pollen zone E3 reflects a severe climatic cooling during MIS16.

A sharp change in the spore-pollen spectra is observed at the MIS15–MIS16 boundary. This change is reflected by the pollen zone E4 assemblage, which dominated by *Betula* (up to 25 %), *Alnus* (up to 40 %), Poaceae (up to 55 %), Cyperaceae (up to 25 %), and *Artemisia* (up to 20 %). The consistent occurrence of *Larix* pollen (3–4 %) indicates the continued presence of this deciduous conifer. However, the main feature of pollen zone E4 is the variability in the spore-pollen spectra. This inconsistency reflects the replacement of larch forest-tundra by larch forest with the inclusion of tree and shrub birch, *Duschekia fruticosa* and, probably less often, *Pinus pumila*. Such changeability in the spore-pollen spectra was first seen in the continuous palynological record of sediments from Lake Elikchan-4 (located in Northern Priokhotye on the border with the Kolyma Basin) and reflects the variability in plant communities during the MIS3 interstade (Lozhkin, Anderson, 2011). Pollen zone E4 also indicates a wide distribution of sedge-grass-forb meadows in the poorly drained substrates in the lowland, and of *Artemisia-Selaginella rupestris* communities on well drained and/or eroding slopes.

Pollen zone E5 characterizes larch forests with a shrub understory of *Pinus pumila*, *Duschekia fruticosa*, *Betula*, and *Salix*. *Pinus pumila* possibly formed a belt of shrub tundra beyond altitudinal treeline. In the floodplains, gallery forests consisted of *Alnus hirsuta*, *Populus*, *Chosenia*, and *Larix*. The pollen of trees and shrubs that dominate the zone E5 spectra reflect the establishment of forest communities that developed during an interglacial period.

In pollen zone E6, which depicts the plant communities during MIS14, the pollen percentages of trees and shrubs are noticeably reduced (up to 20 %). Nevertheless, the presence of *Larix* pollen (up to 5 %) reflects the regional distribution of larch forest-tundra or even the existence of open larch forests with an undergrowth of shrub *Betula* in the vicinity of the lake. The low percentages of *Alnus* pollen are of note. Unlike previously, during MIS14 shrub *Alnus* was neither characteristic of the vegetation either bordering Lake El'gygytgyn or on the Plateau. Furthermore, it is likely that isolated thickets growing in the more protected habitats within the crater were rare or absent. Large areas in the vicinity of the lake were occupied by open meadow communities, reflected in the pollen spectra by Poaceae, Cyperaceae, and Ranunculaceae. The noticeable presence of *Artemisia* pollen and *Selaginella rupestris* spores mark the development of xeric plant communities on well-drained, rocky slopes. The vegetation reflected in the spore-pollen spectra of pollen zone E6 probably developed under interstadial conditions.

Pollen zone E7 also represents interstadial plant communities that were present during MIS13. The vegetation included larch forest-tundra and *Alnus-Betula-Pinus pumila* shrub tundra. The dominance of Poaceae pollen in this zone confirms the widespread distribution of open sedge-grass meadows near Lake El'gygytgyn. The high percentages of *Sphagnum* spores (the peaks reaching 100 %) clearly indicate the increase in mesic to wet habitats within the meadows and possibly the development of local bogs and swamps.

Pollen zone E8 is characterized by the dominance of pollen of trees and shrubs (up to 75 %) with peaks

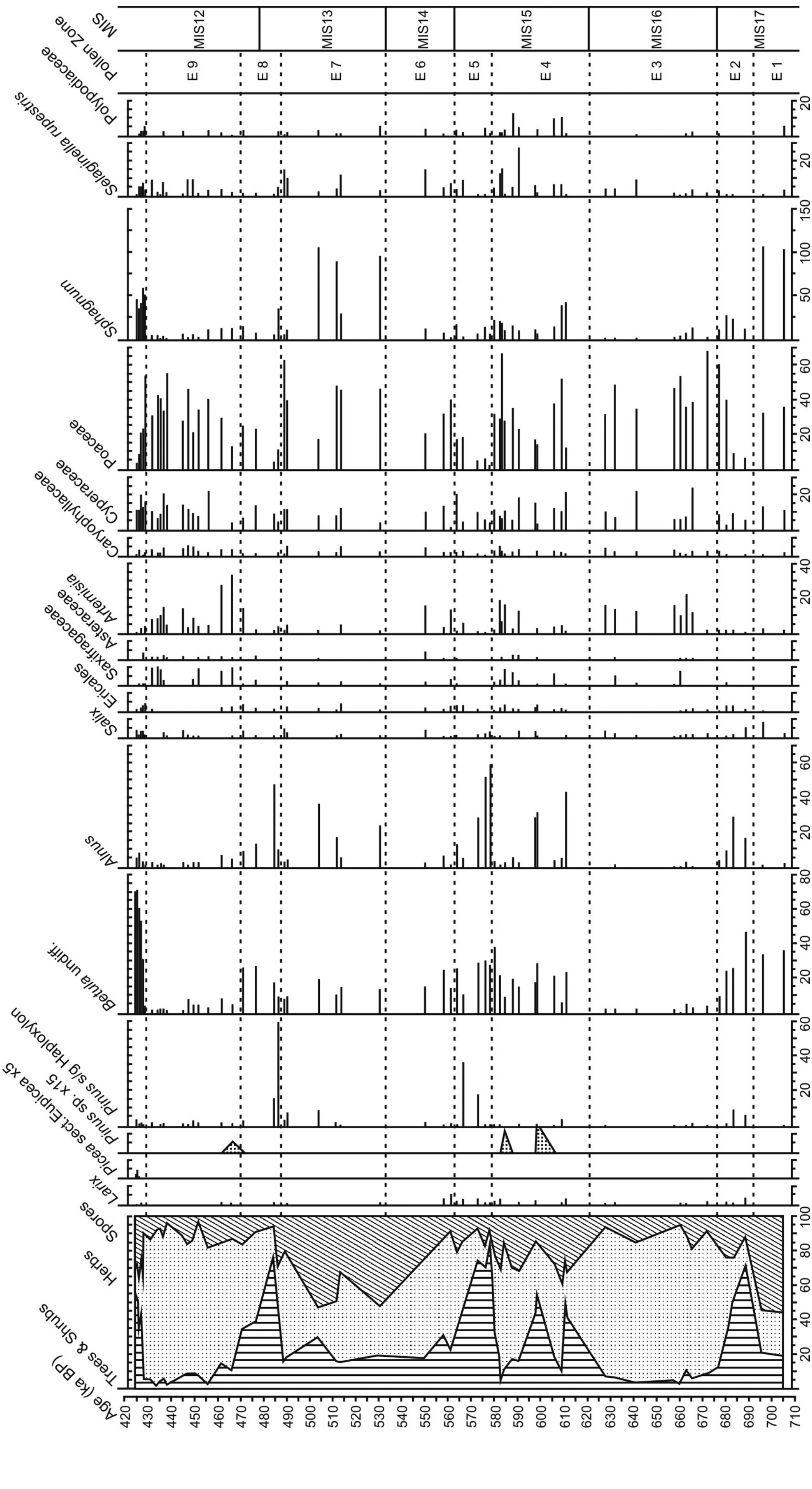

Fig. 3. The ratio of vegetation groups and percentages of the main pollen and spore taxa from Lake El'gygytgyn sediments (MIS12–MIS17).

Рис. 3. Соотношение групп растительности, основных пыльцевых и споровых таксонов в спектрах осадков оз. Эльгыгытгын (MIS12–MIS17).

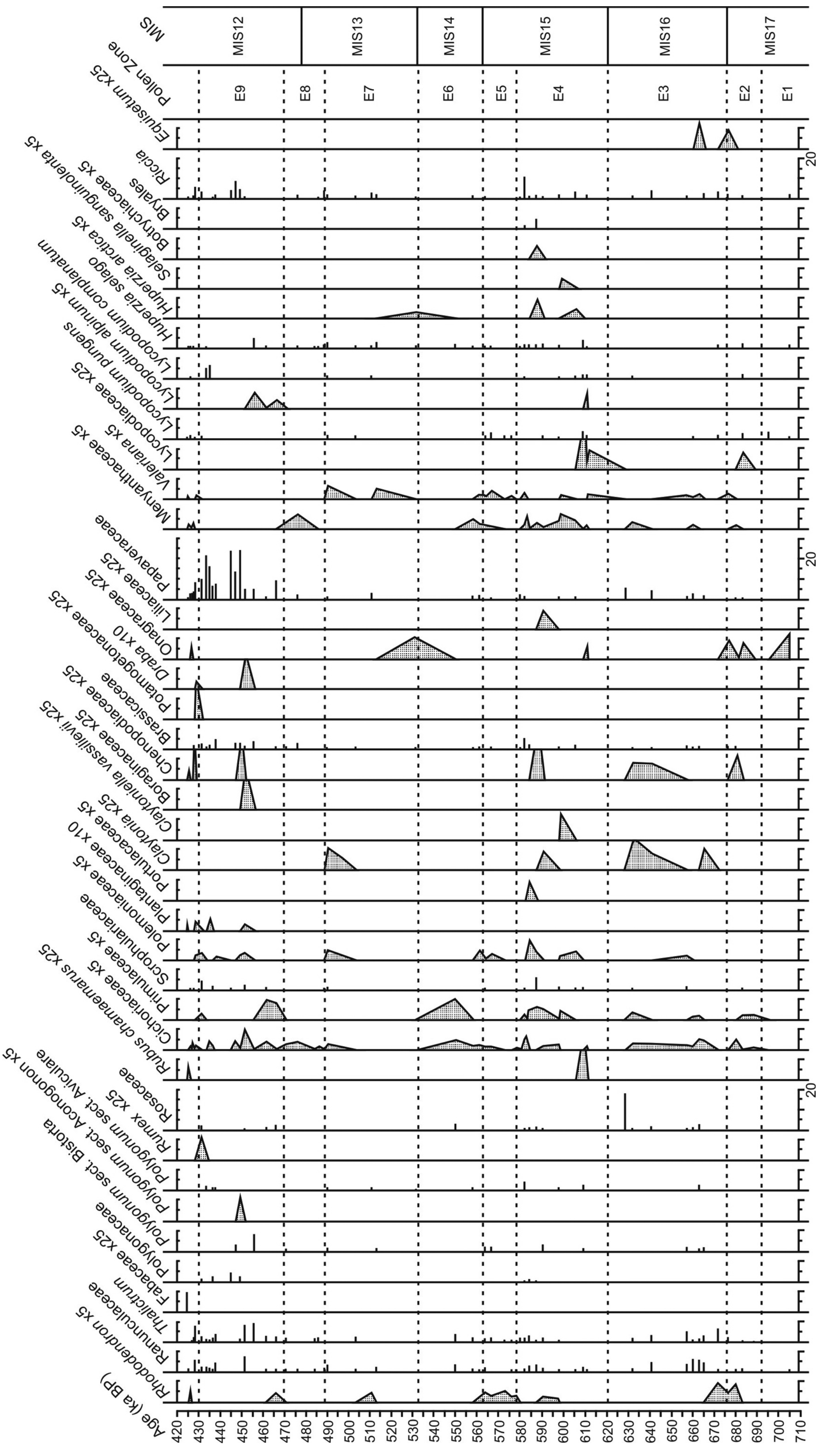

Fig. 4. Minor pollen and spore taxa in the spectra of Lake El'gygytgyn sediments (MIS12–MIS17).

Рис. 4. Второстепенные пыльцевые и споровые таксоны в спектрах осадков оз. Эльгыгытгын (MIS12–MIS17).

in *Alnus* (up to 45 %) and *Pinus pumila* (up to 55 %). The role of sedge-grass meadows is markedly reduced, and the low percentages of *Sphagnum* spores suggest the establishment of dry climatic conditions. Zone E8 characterizes the vegetation at the interglacial MIS12–MIS13 boundary.

In MIS12 (pollen zone E9), both the local and regional vegetation was herb tundra dominated by grass and sedge. The rare pollen of shrubs (*Betula*, *Alnus*, *Pinus* subgen. Haploxylon) found in the spectra probably represents long-distance wind transport from more southern regions of Western Beringia. The most common shrub in the tundra was willow, represented by prostrate forms and/or by small thickets growing in protected areas of the valleys. Rocky slopes and well-drained sites at lower elevations were occupied by communities of wormwood, polar poppies, and Siberian club moss. Landscapes with similar "dwarf" tundra currently are found on Wrangel Island, which is located 600 km north of Lake El'gygytgyn. The presence of single grains of *Larix* pollen in samples at the boundary of MIS12 and MIS13 may indicate the presence of small, isolated stands limited to the most protected areas in the valleys.

MIS12 precedes MIS11, the latter being one of the warmest isotopic stages in the continuous palynological record from Lake El'gygytgyn (Figs. 3, 4).

CONCLUSIONS

The palynological record that spans the interval from 424–712 thousand years ago as preserved in the sediments of Lake El'gygytgyn documents the response of high latitude vegetation to interglacial (MIS13, MIS15, MIS17), glacial (MIS16, MIS12) and interstadial (included in MIS15, MIS13, and MIS14) climates. The widespread distribution of larch forests, with thickets of dwarf birch, alder, and dwarf pine, typified the regional vegetation during the warmest climates. During the cold stages, a mosaic of herb tundra established near the lake. This herb tundra was replaced by forest-tundra communities in the valleys of the Anadyr Plateau. Between 424–712 thousand years ago, the climate was warmest during MIS15. The deepest cooling occurred in MIS12. The persistent presence of larch pollen in the spectra clearly indicates that even in extremely severe climatic conditions that manifested during this portion of El'gygytgyn record, larch forest-tundra persisted in areas of the Anadyr Plateau and within the El'gygytgyn crater. This vegetation differed sharply from the herb dominated tundra that characterized many glacial intervals in the Arctic during the Middle and Late Pleistocene.

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REFERENCES

Kozhevnikov, Yu. P., 1993. Vascular Plants in the Vicinities of Lake El'gygytgyn, *Nature of the El'gygytgyn Depression (Problems of Study and Protection)*. Eds. V. F. Bely, I. A. Chereshnev. Magadan, NEISRI FEB RAS, 62–82 [In Russian].

Layer, P., 2000. Argon-40/Argon-39 Age of the El'gygytgyn Impact Event, Chukotka, Russia, *Meteoritics and Planetary Science*. 35, 591–599.

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

Lozhkin, A. V., Anderson, P. M., 2011. Forest or No Forest: Implications of the Vegetation Record for Climatic Stability in Western Beringia during Oxygen Isotope Stage 3, *Quaternary Science Reviews*. 30, 2160–2181.

Lozhkin, A. V., Anderson, P. M., 2020. Environmental Changes in the Eastern Arctic 1.6975–1.965 Ma, Palynological Investigations from El'gygytgyn Lake, Northeastern Russia, *Review of Palaeobotany and Palynology*. 279 (2), 104242. DOI:10.1016/j.revpalbo.2020.104242.

Lozhkin, A. V., Anderson, P. M., Belaya, B. V., Stetsenko, T. V., 2002. Reflections on Modern Pollen Rain of Chukotka from Bottom Lake Sediments, *Quaternary Paleogeography of Beringia*. Magadan, 40–50.

Melles, M., Brigham-Grette, Ju., Minyuk, P. S., Nowaczyk, N. R., Wennrich, V., DeConto, R. M., Anderson, P. M., Andreev, A. A., Coletti, A., Cook, T. L., Haltia-Hovi, E., Kukkonen, M., Lozhkin, A. V., Rosén, P., Tarasov, P., Vogel, H., Wagner, B., 2012. 2.8 Million Years of Arctic Climate Change from Lake El'gygytgyn, NE Russia, *Science*. 337, 315–320.

Nowaczyk, N. R., Haltia, E. M., Ulbricht, D., Wennrich, V., Sauerbrey, M. A., Rosen, P., Vogel, H., Francke, A., Meyer-Jacob, C., Andreev, A. A., Lozhkin, A. V., 2013. Chronology of Lake El'gygytgyn Sediments – A Combined Magnetostratigraphic, Palaeoclimatic and Orbital Tuning Study Based on Multi-Parameter Analyses, *Climate of the Past*. 9, 2413–2432.

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

Yanina, T. A., 2014. On the New Stratigraphic Scale of the Quaternary System. *Bulletin of Moscow University. Series 5. Geography*. 1, 85–87 [In Russian].

ПАЛЕОЭКОЛОГИЧЕСКИЕ ИЗМЕНЕНИЯ НА СЕВЕРЕ ЧУКОТКИ В МОРСКИЕ ИЗОТОПНЫЕ СТАДИИ 12–17

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В непрерывной палинологической летописи осадков кратерного оз. Эльгыгытгын изотопные стадии 12–17 охватывают интервал 424–712 тыс. л. н. Важным хронологическим репером для этого интервала является граница Брюнес – Матуяма (781 тыс. л. н.), установленная при палеомагнитном анализе осадков озера. Региональная растительность теплых межледниковых стадий характеризовалась широким распространением лиственничных лесов, зарослей кустарниковых берез, ольховника, сосны стланиковой. В холодные стадии доминировали мозаичные травянистые тундры, сменявшиеся в долинах окружающего озеро Анадырского плоскогорья лесотундровыми сообществами. В интервале 424–712 тыс. л. н. климатические параметры были наиболее высокие в MIS15 изотопную стадию. Наиболее глубокое похолодание проявилось MIS12.

***Ключевые слова*: плейстоцен, изотопная стадия, спорово-пыльцевые спектры, фитоценоз.**

ЛИТЕРАТУРА

Кожевников Ю. П. Сосудистые растения в окрестностях озера Эльгыгытгын // Природа Эльгыгытгынской котловины (проблемы изучения и охраны) / Под ред. В. Ф. Белого, И. А. Черешнева. Магадан: СВКНИИ ДВО РАН, 1993. С. 62–82.

Янина Т. А. О новой стратиграфической шкале четвертичной системы // Вестник Московского университета. 2014. Серия 5. География. № 1. С. 85–87.

Layer P. Argon-40/Argon-39 age of the El'gygytgyn impact event, Chukotka, Russia // Meteoritics and Planetary Science. 2000. Vol. 35. P. 591–599.

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

Lozhkin A. V., Anderson P. M. Forest or no forest: Implications of the vegetation record for climatic stability in Western Beringia during Oxygen Isotope Stage 3 // Quaternary Science Reviews. 2011. No. 30. P. 2160–2181.

Lozhkin A. V., Anderson P. M. Environmental changes in the eastern Arctic 1.6975–1.965 Ma, Palynological investigations from El'gygytgyn Lake, Northeastern Russia // Review of Palaeobotany and Palynology. Vol. 279. No. 2. Art. 104242. DOI:10.1016/j.revpalbo.2020.104242.

Lozhkin A. V., Anderson P. M., Belaya B. V., Stetsen-ko T. V. Reflections on modern pollen rain of Chukotka from bottom lake sediments // Quaternary Paleogeography of Beringia. Magadan, 2002. P. 40–50.

Melles M., Brigham-Grette Ju., Minyuk P. S., Nowaczyk N. R., Wennrich V., DeConto R. M., Anderson P. M., Andreev A. A., Coletti A., Cook T. L., Haltia-Hovi E., Kukkonen M., Lozhkin A. V., Rosén P., Tarasov P., Vogel H., Wagner B. 2.8 Million Years of arctic climate change from Lake El'gygytgyn, NE Russia // Science. 2012. Vol. 337. P. 315–320.

Nowaczyk, N. R., Haltia, E. M., Ulbricht, D., Wennrich, V., Sauerbrey, M. A., Rosen, P., Vogel, H., Francke, A., Meyer-Jacob, C., Andreev, A. A., Lozhkin, A. V. Chronology of Lake El'gygytgyn sediments – A combined magnetostratigraphic, palaeoclimaticand orbital tuning study based on multi-parameter analyses // Climate of the Past. 2013. Vol. 9. P. 2413–2432.

PALE. Research Protocols for PALE: Paleoclimates of Arcti clakes and estuaries. PAGES Workshop Report Series. Bern, 1994. 56 p.