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Beringia: Impact on paleoclimates of northeast Asia and North Pacific during Last Pleistocene glaciation

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A R T I C L E I N F O

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A B S T R A C T

The Beringian land bridge that emerged repeatedly during ice ages was of great importance in the energy and matter redistribution within the "continent – ocean" system and had a pronounced effect on air streams and surface marine currents in the North Pacific region. The paper considers an important and still unsettled paleogeographic problem of the Arctic Northeast of Asia: could Beringia have been covered with an ice sheet at the last glacial maximum? and what was the natural refrigerator impact on regional climate and paleo-oceanography of the Northern Pacific? Based on studies of diatoms and pollen spectra recovered from deposits dated to the last glacial time, Western Beringia was essentially ice-free at that time. This may be attributed to a deficiency of moisture supply from the Pacific due to changes in vectors and intensity of the North Pacific currents. The thick snow cover needed for glacier formation could not accumulate. Western Beringia was dominated by a unique landscape of cold and dry tundra-steppe, its topography being complicated with arcuate ridges – end moraines of alpine and cirque glaciers. The glaciation of the region developed according to the North Yakutia scenario.

1. Introduction

The polar regions exert a noticeable influence on global atmospheric and oceanic circulation and therefore are of crucial importance in the climate formation processes on the Earth. A correct forecast of future climate changes depends implicitly on whether this influence can be properly estimated. In this context, knowledge about climate changes in the past and their connection with global climatic events is of great importance, as it provides a basis for prognostic model development. Climate of the past is reconstructed by way of studying signals registered in natural records, such as ice sheets, marine and terrestrial sediments. Another kind of record of no less interest for investigators is sediments of continental lakes where sedimentation proceeds at a high rate almost continuously. As a result, such sediments contain comprehensive information on paleogeographic changes.

Beringia was a vast land that emerged periodically during regressive stages of the World Ocean. When the ocean level dropped to 130–140 m below the present-day one, the Bering Strait was closed and the exposed Arctic and North Pacific shelves formed the Beringian land mass that included Northeast Asia, Alaska and a part of Yukon in Canada. The Bering land bridge connecting Asia and North America was much wider than both the Alaska and Chukchi peninsulas. The resulting cessation of free water exchange between the Arctic and Pacific oceans, changes in areas and outlines of the Chukchi and Bering seas, as well as in the solar energy input, and contrast between heating of the Beringian land and that of surface water of the Arctic and Pacific oceans, all added up to considerable changes in inception and functioning of the regional air flow systems, in vectors and rate of the North Pacific surface currents, as well as in distribution of sediments within the "continent-ocean" system (Laukhin et al., 2006). That is suggested also by a sharp distinction between the climatic regime of Chukchi Peninsula (markedly cold and dry climate) and that of Alaska (somewhat warmer and wetter climate) (Alfimov and Berman, 2004).

As well, the land bridge that connected eastern Asia and North America played a key role in animal migrations between the large continents, being at the same time a kind of filter for some taxa. Undoubtedly, the Beringian land exerted a considerable influence on the dispersal of early humans, sensitive to climatic changes. The problem of the Beringia evolution and its impact on climate of Arctic and North Pacific regions is among the most important issues of modern natural science.

Discussions about the role of Beringia in arctic climate formation are mainly focused on three issues:

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- was Beringia completely covered with an ice sheet during the last glaciation?
- if so, could ice-covered Beringia act as a natural "refrigerator", having a synergistic effect on glacial environments, at least in arctic regions?
- how did changes in vectors and intensity of surface currents manifest themselves, and what was the interaction between Beringia and northern part of the Pacific at the LGM time?

Answers to the above questions may be different depending on which of scenarios of the Beringia glaciation development the specialist adheres to. The existing scenarios vary widely in estimates of alpine and marine glaciation development (Hopkins, 1982; Grosswald and Vozovik, 1984; Hughes, 1987; Hughes and Hughes, 1994). Among them, there are following:

- a conventional model – according to it, only high mountains were glaciated;
- glaciation is considered to be self-sustaining in case of shelf glaciation development;
- glaciation is considered to result from expansion of marine glaciation;
- glaciation resulted from coalescence of marine glaciation of the Chukchi Sea and alpine glaciers on the land, the single ice massif having expanded onto the western Bering shelf and its southern part along the continental margin.

The obtained data on distribution of moraine assemblages in the north of Chukchi Peninsula (Vankarem Lowland), together with analysis of diatoms recovered from the El'gygytgyn Lake sediments that present an uninterrupted paleoclimatic record spanning the last 3.5 million years, open the way to solving the above-listed problems.

2. Background

2.1. Vankarem lowland

The Vankarem gently sloping plain is located at the northern coast of the Chukchi Peninsula and adjoins the Vankarem lagoon (Fig. 1). Its hilly topography is usually interpreted in terms of a glacial model. From this point of view, elongated ridges discernible afield are considered to be end moraines or eskers, while flat surfaces between them are thought to be outwash plains. The model seems attractive, probably, because of diversity of the suggested geomorphologic, lithological and paleogeographic variants, so that plausible explanation can be easily found for every particular situation. The existing views on a wide expansion of the last glaciation in Northeast Asia may be partly attributed to that circumstance. However, it is only in the south of the lowland, near foothills, that the end moraines are confidently identified; they form arcuate ridges across the Vankarem and Kymyneiveem valleys (Kundyshev, 1992) (Fig. 2). In the north, any traces of glacier activity are hardly seen and cannot be identified as such unambiguously.

The problems may be solved by way of dating the sediments that the landforms are composed of. Pollen and diatom analyses are also advisable as they give insight into genesis of the sediments and climate conditions of their deposition.

2.2. El'gygytgyn Lake

El'gygytgyn Lake is situated 100 km north of the Arctic Circle in the northwestern part of Chukchi Peninsula (67°30′ N, 172°05′ E) at an elevation of 492.4 m a.s.l. (Fig. 3). The lake basin was formed presumably by a meteorite impact 3.6 million years ago (Dietz and McHone, 1976; Gurov et al., 1980). The lake is encircled with gently sloping layers of ignimbrites, rhyolite-dacitic and andesitic tuff and basalts. No traces of Quaternary glaciations have been found in the lake vicinity (Glushkova, 1993). On that ground, El'gygytgyn Lake is considered to be the oldest of all the known Arctic lakes (Nowaczyk et al., 2002). The lake has a diameter of 11.5 km and a surface area of 117. 5 km^2, and the maximum depth 175 m is measured NE of its center. The lake has about 50 inflows, small ephemeral streams, the largest one being Lagerny stream, and the only outflow is the Enmyvaam River. The water catchment area amounts to ~293 km^2 (Nolan et al., 2003). Vegetation around the lake is mostly of lichen tundra type (hypoarctic tundra) (Yurtsev, 1974).

Lake El'gygytgyn is very cold. In August 2000, water temperature was 3.08 °C near its center and up to 4–5 °C in shallow waters. Occasionally, the lake remains ice-covered year round. Typically, ice cover up to 2 m thick persists for 9–10 months; it begins to decay in mid-June, and is recommenced again in late September

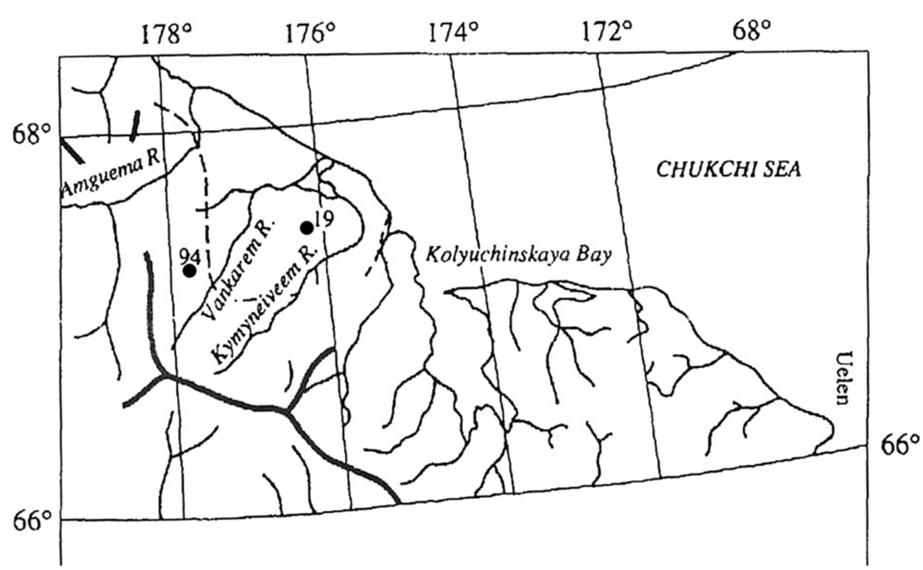

Fig. 1. Location of Vankarem Lowland. (The dashed line shows the boundaries of the lowland, the heavy line – the main mountain ridges; figures indicate mines and boreholes).

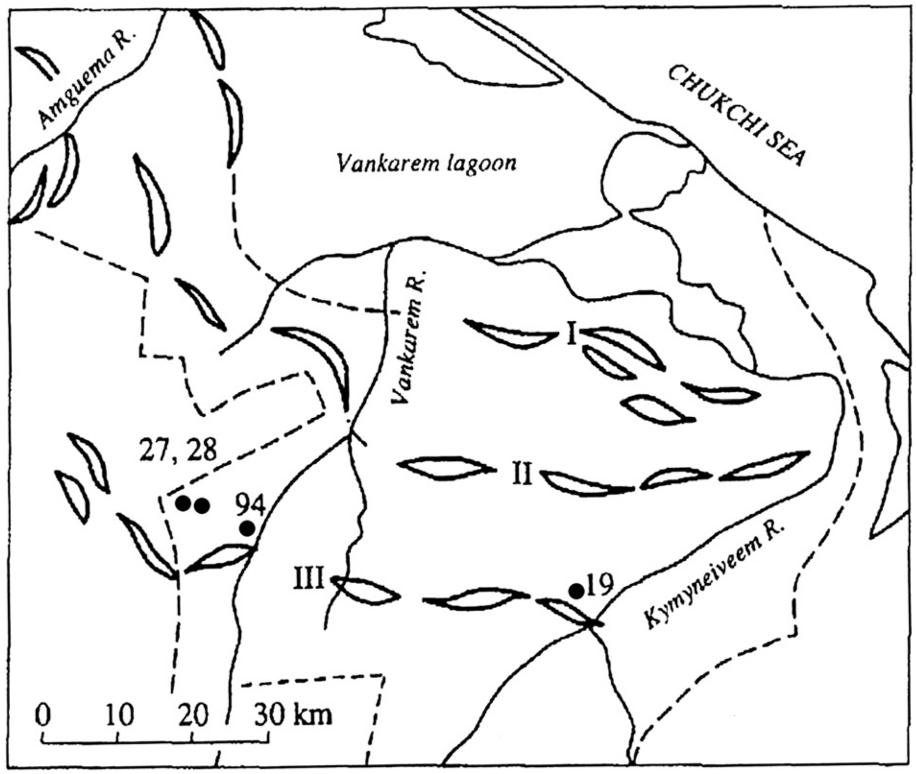

Fig. 2. End moraines (I–III) of three stages of glaciations (27, 28, 94 – mines, 19 – borehole) (after Laukhin et al., 2006).

(Chereshnev and Skopets, 1993; Nolan et al., 2003). Water in the lake is noted for low mineralization and transparency to a depth of almost 20 m, which may be attributed to a low productivity of phytoplankton. Lake El'gygytgyn is an oligotrophic, or even an ultra-oligotrophic water body (Cremer and Wagner, 2003).

In May 1998 and 2003 field studies were performed as a part of the International project "Paleoclimate record of El'gygytgyn Crater Lake: Reconnaissance" with participation of specialists from the USA (J. Brigham-Grette, M. Nolan), Russia (O.Yu. Glushkova, P.S. Minyuk), and Germany (P. Overduin, A. Zielke). Two piston cores were recovered, PG1351 (1283 cm long) and LZ1024 (1670 cm) (Fig. 3). The results of the core multidisciplinary studies are stated in 11 papers published in a special issue of Journal of Paleolimnology (2007, vol. 37); they demonstrated the Lake El'gygytgyn sediments to be a source of rich information on paleoclimates.

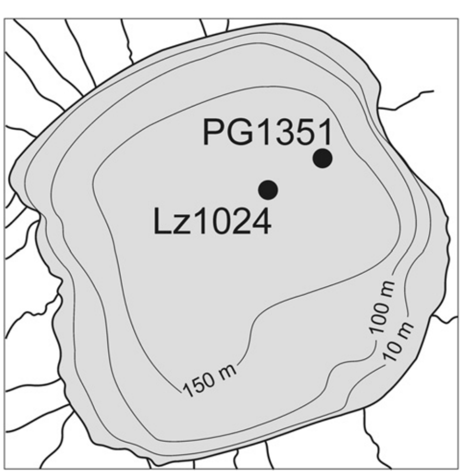

Fig. 3. Location of cores in Lake El'gygytgyn (after Juschus et al., 2007).

3. Results and discussion

3.1. Vankarem Lowland

Assuming the last glaciation was of limited expansion in NE Asia (Laukhin et al., 2006), the glacial landforms in the region are of conspicuously fresh appearance, particularly three ridges of stadial end moraines (Fig. 2). In the west of Vankarem Lowland, north of ridge III, sediments of the second half of Late Pleistocene have been thoroughly studied in a series of pits (27, 28, 94). The end moraine of ridge III is found to occur above the till associated with ridge II, which in turn overlies glacio-lacustrine silts related to ridge I. Diatom assemblages recovered from the silts contain mostly benthic and marsh forms of arcto-boreal and north-boreal type (*Navicula*, *Pinnularia*, *Stauroneis*, *Cymbella*, *Hantzschia)*. Below the ridge I till, there are fluvial sediments dated by radiocarbon to 40.1–39.3 ka BP (Laukhin et al., 2006). All three moraines are younger than 39 ka BP, and their deposition (at least of ridge I) proceeded in periglacial environments, as indicated by the diatom assemblages.

The same glacio-lacustrine silts yielded pollen spectra of arctic tundra, while those recovered from the underlying fluvial series are interpreted as spectra of shrub tundra with alder groves (that is, pollen spectra indicative of warmer environments than modern ones) (Kundyshev, 1992; Verkhovskaya, 1992; Laukhin et al., 1999). According to calculations by V.Klimanov (Laukhin et al., 1999), during the Karginsk interval, when the fluvial series was accumulated, July temperatures in the region were 2–5 C° above the present-day values. At the time of moraine ridge I formation (that is, the 1st stage of glaciation) the temperature was close to today's,

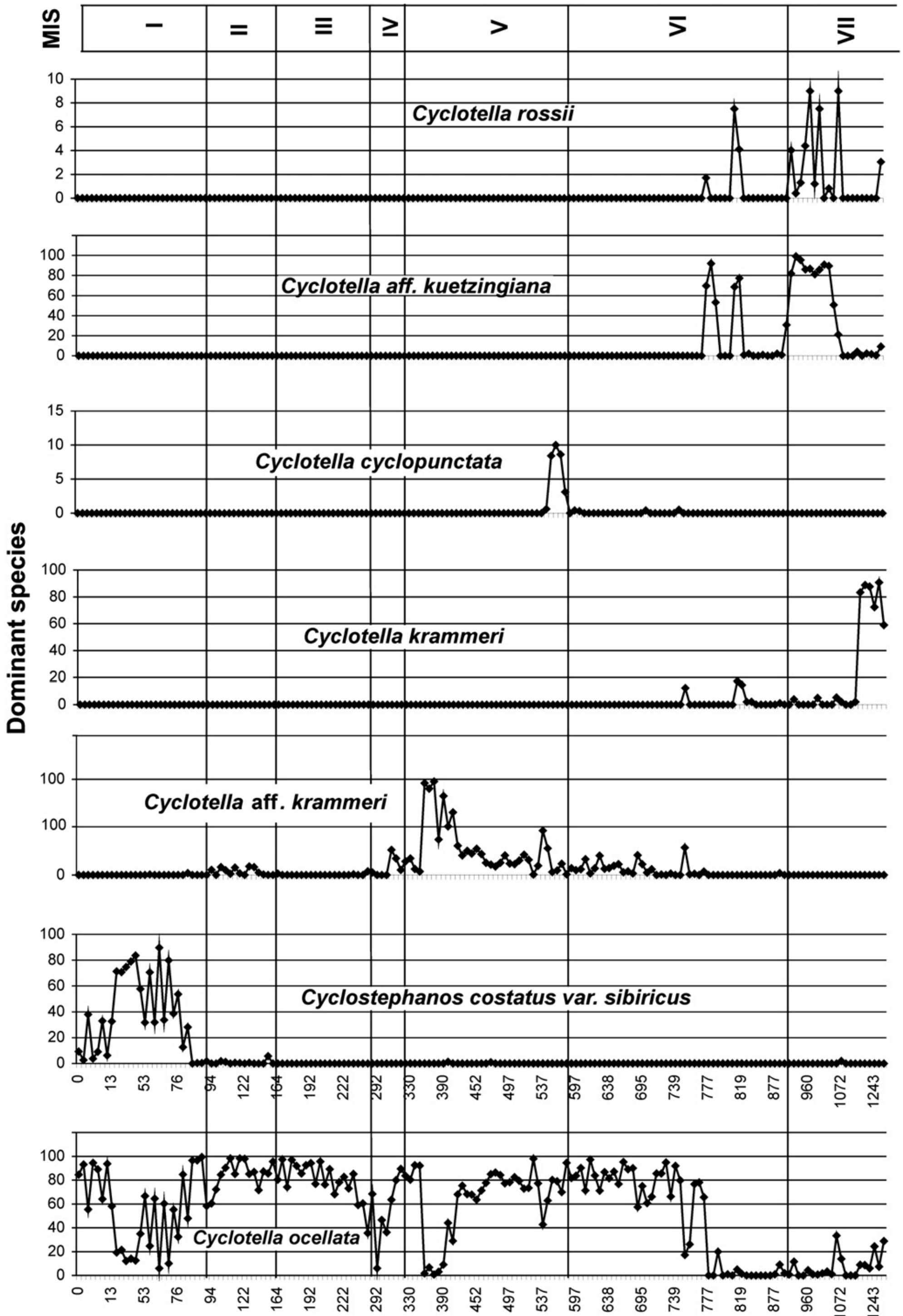

Fig. 4. Diatom diagram of Lake El'gygytgyn sediments.

though annual precipitation exceeded modern values by 100–150 mm. The glacier expansion onto the Vankarem Lowland at that time could be attributed to that increase in snowfall. Of special importance for the lower moraine dating (ridge I) is the presence of artifacts (nuclei) dated at approximately 30 ka BP (Kundyshev, 1992; Laukhin et al., 2006). The till exposed in borehole 19 is underlain and overlain with sediments of the late Karginsk transgression containing marine diatom assemblages with *Paralia sulcata* Ehr. (Pushkar and Cherepanova, 2001), as the transgression penetrated along the old Kymyneyveem R. valley. That supports the 1st moraine attribution to the Konoshchel cooling during the Karginsk (MIS 3), and the 2nd and 3rd moraines to the Sartan (MIS 2).

3.2. Lake El'gygytgyn

Piston core PG1351, 1283 cm long, from the lake bottom sediments (lacustrine mud and silt, with diatomaceous ooze in some intervals) was sampled at 2 cm intervals for the purpose of finding paleoclimatic cyclicity on a thousand year scale (Cherepanova et al., 2007). Mud in Lake El'gygytgyn contains practically mono-

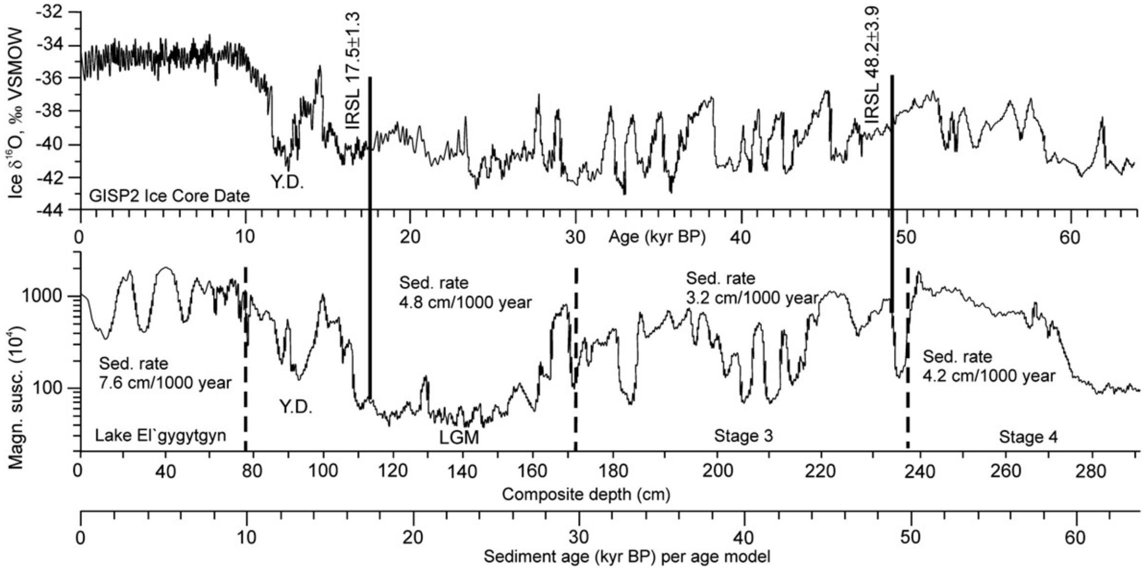

Fig. 5. Sedimentation rate in Lake El'gygytgyn (after Brigham-Grette et al., 2007).

dominant diatom assemblages with well preserved valves, characterizing practically the entire thickness of the core (Fig. 4). The species developed in favorable environments had larger valves and relatively delicate structure, unlike the diatoms inhabiting colder water. The latter had usually coarser, silicified valves and were smaller. That feature, along with species diversity and frequency of occurrence, was used as an additional criterion in identification of cold periods (since even sediments attributed to those periods contain diatom valves).

During warmer intervals, diatom ecotopes (habitats) increase in number. The relatively better heated littoral zone expands in area. Locally, water temperature may be considerably higher than in the main water mass, so species typical of water basins of lower latitudes may survive. Taking that into consideration, the focus is on some groups of diatoms indicative, directly or indirectly, of temperature. These are marsh forms: *Stauroneis phoenicenteron*, *Pinnularia viridis*, *Eunotia glacialis* and representatives of genus *Surirella*, and their valves are more abundant in interglacial sediments. Another ecological group is sessile species, mostly belonging to *Cymbella* genus. Their presence suggests a higher intensity of hydrodynamics which, in turn, depends on higher temperature. It is noteworthy that species with larger valves – *Cymbella elginensis*, *C. hilliardii* – are indicators of more active hydrodynamic regimes, while small-valve taxa – *C. silesiaca*, *C. minuta* – suggest weaker hydrodynamics. The next group includes the benthic forms *Amphora libyca, A. inariensis*, *Caloneis hyalina* var. *robusta*, *Diploneis elliptica*, as well as north-alpine *Achnanthes biorethii* and *Gomphonema acutiusculum*. Those species inhabited the littoral zone under conditions of attenuated hydrodynamics, during colder periods. During those periods, ice most likely melted only within a narrow near-shore zone, while the central part could remain ice-covered.

An analysis of diatom flora recovered from Lake El'gygytgyn sediments distinguished a number of assemblages in the studied PG1351 core (Fig. 4) which may correspond to sediments of certain climatic stages. Both cores have been dated by thermoluminescence and radiocarbon methods (Minyuk et al., 2003; Juschus et al., 2007), providing grounds for correlation of the identified assemblages with marine isotope stages.

As the focus is mostly on the lake evolution beginning with Karginsk Interglacial, the assemblages from that part of the sequence will be described in detail below.

3.2.1. Interval 0–84 cm

Sediments within this interval are dominated by meroplankton *Cyclotella ocellata* (32.4–89.1%) and *Stephanodiscus costatus* var. *sibirica* (31.8–89.7%). Of the other species, the most common are benthic *Stauroneis phoenicenteron* (up to 14.4%), *Pinnularia viridis* (up to 8.5%), representatives of *Surirella* genus (as much as 13.5%), sessile *Cymbella elginensis* (up to 12.6%), *C. silesiaca* (to 12.6%), *C. hilliardii* (up to 10.3%), and *Eunotia glacialis* (to 12.4%). Toward the lower boundary of the interval, valves of *Stephanodiscus costatus*

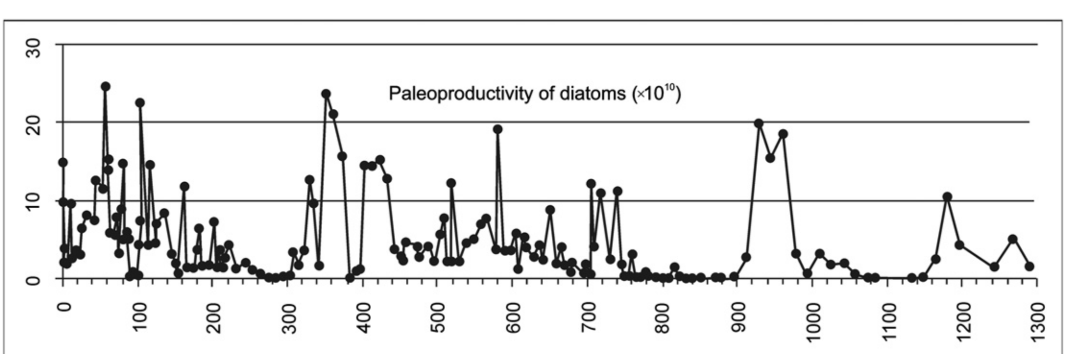

Fig. 6. Diatom paleo-productivity in Lake El'gygytgyn in the course of the last 350 ka.

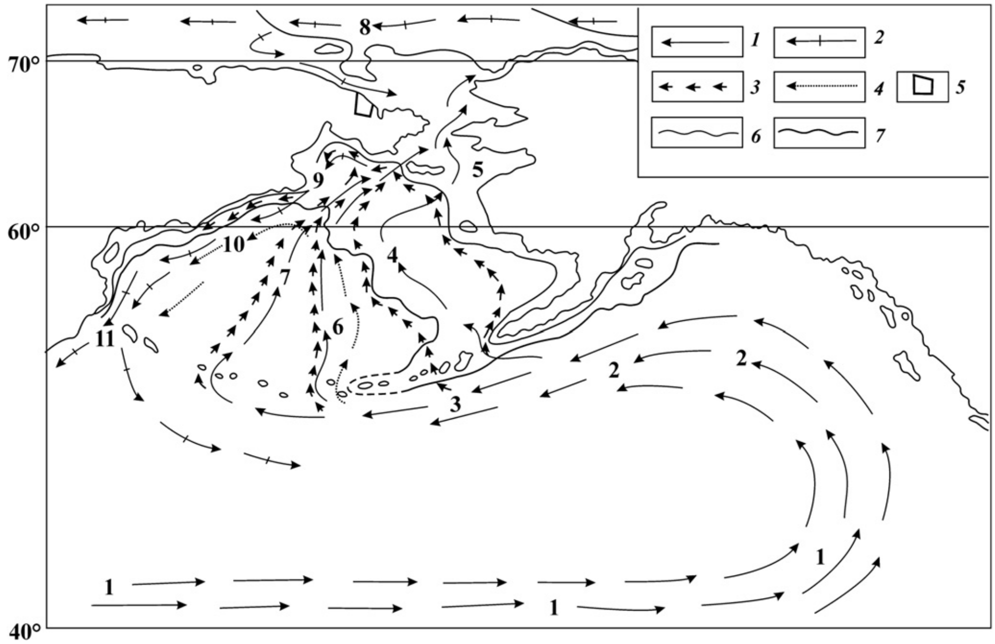

Fig. 7. Scheme of modern currents and paleo-currents (MIS 2–3) in the Bering Sea (after Laukhin et al., 2006)
Modern currents: 1 – warm (1–7), and 2 – cold (8–11): 1 – North Pacific, 2 – Alaskan, 3 – Aleutian, 4 – Transversal, 5 – Laurentian, 6 – Tanaga, 7 – Ottu, 8 – West Arctic, 9 – Anadyr, 10 – Kamchatka, 11 – Oyashio; 3 – currents of the late MIS 3 at the sea level 50 below the present-day one; 4 – currents at the time of maximum regression of MIS 2; 5 – position of the Vankarem lowland; 6 – coastline at the sea level 50 m below that of today; 6 – coastline at the maximum of regression (–130 to –140 m).

var. *sibirica* gradually decrease in diameter from 39–42 to 19–22 μm, while those of *Cyclotella ocellata* increase from 4–5 to 8–10 μm. That might have been due to changes in water density resulting in that coarse and thick valves of *Stephanodiscus costatus* var. *sibirica* grow smaller, and thin delicate *Cyclotella ocellata* valves become larger. The interval is distinct for the relatively high diversity of diatom species. Abundance of diatom valves in the sediments suggests a considerable productivity of the lake in the past. Sediments of the interval could be correlated with MIS 1.

3.2.2. Interval 84–140 cm

The interval is distinguished for a noticeable decrease in valve abundance (between 94 and 100 cm in particular), a decline in the diatom species diversity (2–12 taxa in a statistical sample), and a conspicuous predominance of one species – *Cyclotella ocellata* (60.5–99.5%), while abundance of other taxa decreases drastically. Most common are north-alpine species, such as sessile *Fragilaria arcus* var. *arcus* (up to 11.1%) and benthic *Achnanthes biorethii* (up to 7.5%), as well as north-boreal benthic *Navicula pupula* var. *baicalensis* (up to 8.9%) and *Diploneis elliptica* (up to 7.5%). It is in this interval that valves of *Stephanodiscus costatus* var. *sibirica* first appear, the species becoming dominant in paleo-assemblages in the upper part of the sequence. The observed reduction in diatom valve number in comparison with the overlying interval suggests a longer, and occasionally even year-round, period of ice cover. Relatively high frequency of benthic species occurrence may be interpreted as an indicator of attenuated wind action in the near-shore area, suggesting that the central part of the lake remained ice-covered for a full year and only a narrow littoral zone was ice-free. The lake at that time was meromictic, with bottom water mass isolated from the upper layer. On the whole, this interval may be correlatable with MIS 2 (Sartanian).

3.2.3. Interval 140–264 cm

The interval is marked by relative increase of valve abundance in the sediments, as well as by higher diversity of diatom species (as many as 55 taxa in the statistical sample at 144 cm level). The dominating species is planktonic *Cyclotella ocellata* (68.5–97.0%). Among others, the most common are sessile *Cymbella elginensis* (up to 10.9%), *C. hilliardii* (up to 10.4%), and benthic *Stauroneis phoenicenteron* (as much as 20.2%), all having large valves. The latter suggests an increased exposure of the littoral shallows to wind action, so that species with small valves could not develop within the littoral zone. This interval is correlated with MIS 3 (Karginsk Interglacial). Similar results have been obtained for core LZ1024.

Isotope dates were used to construct curves of sedimentation rates (Fig. 5). This enabled the rate of diatom paleo-productivity to be estimated at climatically different epochs (Fig. 6). Even within the 84–140 cm interval, the productivity could be as high as 15×10^{10} valves cm^{-2} ky^{-1}.

The diatom analysis allows an important conclusion that diatoms existed and developed in the lake even in the cold epochs. It also follows from the above that the ice cover on the lake was not thick enough to prevent penetration of sunlight necessary for photosynthesis. Therefore there could not be a continuous ice sheet in the lake basin during Sartanian time, as the near-shore shallows became ice-free during the short summers and benthic diatom flora could develop in those zones.

4. Conclusion

Paleogeographic factors could determine the development of glaciation during MIS 3 and MIS 2 in Beringia. The North-Yakutian type of glaciation in Western Beringia most likely resulted from moisture deficit preventing development of large continental glaciers. The same is true of the Lake El'gygytgyn region. The deficit of moisture at that time may be attributed to the fact that the northern shelf was exposed over a great area, the northern coastline shifted 300–700 km northward and that of Bering Sea – 600–850 km southward from the Chukchi Peninsula. The given figures are the maximum regressions. The process of the coastline retreat was rather slow, and it took a long time for the emerged shelf to reach its maximum width.

The regression affected the North Pacific currents. At present, some branches of the West Arctic cold current flow past the northern coast of the Chukchi Peninsula. On the south of the peninsula the warm North Pacific current passes into the Alaskan current, and further west into Aleutian current. The latter flows between the Aleutian Islands into the Bering Sea as several warm currents known as Transversal Current, Laurentian, Tanaga and Ottu currents. Toward the Chukchi Peninsula they become colder and return to the Pacific as cold currents under the names of Anadyr, Kamchatka, and Oyashio currents (Fig. 7). It seems that the Beringian land bridge barred all those currents south of St. Lawrence Island and the Chukchi coast. The sea level at MIS 3 was 50 m below that of today. It is not inconceivable to suggest that the highest level of the Bering Sea coincided with the time of maximum warming of MIS 3 in NE Asia, that is about 40–33 ka BP. At that time both Alaskan and Aleutian warm currents did not go north (as they do at present), but came closer to the southern Chukchi coast and could bring precipitation in quantity sufficient to form glaciers of Koryak-Kamchatka type in the mountains of the Chukchi Peninsula. That accounts for the maximum expansion of glaciers onto the Vankarem Lowland about 30 ka BP. At the very beginning of MIS 2, however, summer winds from the Pacific still could bring moisture enough for the glaciers to expand onto the lowland. Moraine ridges II and III in the south of the Vankarem Lowland correspond to stages of regression from −50 m to −140 m. Only since the LGM has the glaciation of the region developed according to the North-Yakutian type. Therefore, the 1st stage of the last glaciation on the Vankarem Lowland (ridge I) marks the beginning of cooling at the time when the regression was at its minimum; the 2nd and 3rd stages correspond to subsequent sea level dropping from −50 m to −100 m at the beginning of MIS 2.

During the subsequent regression, the southern coast of Beringia was shifted as far south as Cape Navarin and its northern coast 300 km north of the present-day Chukchi peninsula coastline. At that time the Siberian High moved to the Arctic, which undoubtedly resulted in formation of northerlies of monsoon type and therefore in dramatic changes in surface current system in the North Pacific.

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