

Diatom stratigraphy of the last 250 ka at Lake El'gygytyn, northeast Siberia

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Abstract Diatom species counts were conducted on 171 sediment samples from the 13-m-long core PG1351 from Lake El'gygytyn, northeast Siberia. The planktonic *Cyclotella ocellata*-complex dominates the diatom assemblage through most of the core record, persisting through a variety of climate conditions. Periphytic diatoms, although less abundant, have greater diversity and greater down-core assemblage variation. During warm climate modes, longer summer ice-free conditions may have allowed more complex diatom communities to develop in shallow-water habitats,

and enhanced circulation may have increased transport of these diatoms to deeper parts of the lake. Zones of low overall diatom abundance further support inferred intervals of low lake productivity during times of extended lake ice and snow cover. More data on the modern spatial and temporal distribution of diatom species in the Lake El'gygytyn system will improve inferences from core records.

Keywords Diatoms · Lake El'gygytyn · Siberia · Paleoclimate · Quaternary

This is the *last* in a series of eleven papers published in this special issue dedicated to initial studies of El'gygytyn Crater Lake and its catchment in NE Russia. Julie Brigham-Grette, Martin Melles, Pavel Minyuk were guest editors of this special issue.

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Introduction

Sediment records from Lake El'gygytyn provide a unique archive of past environments. Occupying a 3.5 million-year-old impact crater that has not experienced glaciation (Glushkova et al. 1994; Layer 2000), the lake contains a long history of continental environmental change in an arctic setting (Fig. 1). Diatom assemblages accumulating in lake-bottom sediment provide one means of evaluating the complex response of the lake system to climate changes occurring on glacial-interglacial timescales (e.g., Colman et al. 1995; Edlund and Stoermer 2000; Swann et al. 2005). Core records from long-lived lakes may also provide insight into diatom evolution and provide a means of biostratigraphic correlation (e.g., Khursevich et al. 2001a, b, 2005).

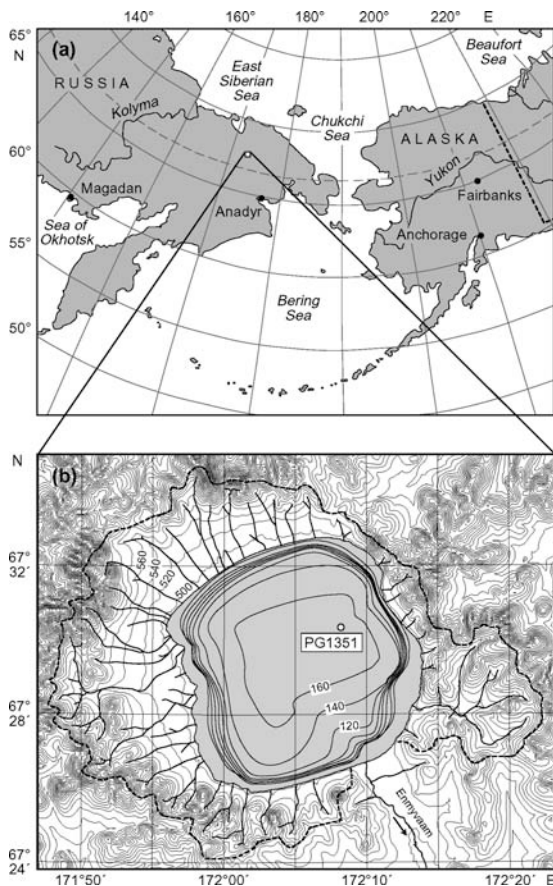


Fig. 1 Location of Lake El'gygytyn in NE Chukotka, 100 km north of the Arctic Circle

Prior research on Lake El'gygytyn diatoms provides data on the recent flora of the lake. Initial studies describe species in bottom sediments obtained from short cores (Sechkina 1956; Zhuze and Sechkina 1960). More recent studies describe the periphytic and planktonic taxa in lake surface sediments (Kharitonov 1980, 1993), and planktonic diatoms in water samples and sediment traps (Cremer et al. 2005). Cremer and Wagner (2003) interpret Holocene variations in diatom assemblages from a 38-cm sediment core.

This study examines the diatoms in the first long sediment record recovered from the lake in 1998 (core PG1351). According to revised chronological models, this core record extends to ca. 250 ka (Nowaczyk et al. 2007; Forman et al. 2007). The objectives of this study are, first, to use diatom assemblage changes through time to understand changes in past lake conditions and,

second, to provide guidance for future investigations of diatoms from longer sediment records.

Site information

Lake El'gygytyn, an approximately 12-km diameter lake, is situated in an impact crater in northeastern Siberia ($67^{\circ}30' N$, $172^{\circ}05' E$). Approximately 50 small streams enter the lake, draining the catchment within the approximately 18 km-diameter crater. The lake reaches a maximum depth of 170 m near its center and has shallow shelves that extend from 10's of meters to greater than 1 km from the lake margin (Nolan and Brigham-Grette 2007). Shallow lagoons contained by gravel bars are sometimes present near inlet streams. A single outlet drains the lake toward the southeast. The modern lake is monomictic and ultra-oligotrophic (Nolan and Brigham-Grette 2007). Recent observations of lake-ice conditions document initial open water in the form of a moat in June/July, complete melting in July/August, and initial ice formation in October (Nolan et al. 2003). Nolan and Brigham-Grette (2007) and Cremer et al. (2005) provide more details of the limnology and climatic setting of Lake El'gygytyn.

Materials and methods

Samples for diatom analysis were prepared from core sediment samples using standard techniques (Proshkina-Lavrenko et al. 1974). Sediment samples were treated with dilute sodium tripolyphosphate and hydrogen peroxide to disperse the sediment and to remove organic matter. Semi-quantitative diatom concentration estimates were calculated from valve counts per slide transect by maintaining consistent sediment sample weights and pretreatment solution volumes, and by pipetting a known volume of diatom suspension onto cover slips. Although methods for measuring absolute diatom concentrations may provide highly variable results (Wolfe 1997), these data should provide a reasonable estimate of down-core variations in diatom concentration. The sampling interval of core analyzed for diatoms

varies with core depth, ranging from 1 to 2 cm in the upper portion of the record to 16 cm or greater near the base of the record. Accordingly, the time interval between samples varies between approximately 150 years and 3000 years.

Diatom species determinations were made at 2000× (Zeiss Amplital) using a variety of taxonomic references. In general, a few centric diatom species dominate the core assemblage. To avoid losing important paleoecological data from the less abundant, but more diverse, pennate diatoms, all species were counted on slide transects until greater than 200 valves of the abundant taxa were observed. On subsequent transects, only less abundant taxa were counted until greater than 100 valves of the less abundant species were observed.

Wherever possible, the taxonomy has been updated to reflect recent genus-level revisions to be consistent with other recent diatom research on Lake El'gygytgyn (Kharitonov 1980; Cremer and Wagner 2003). The species-level taxonomy of some of the abundant centric diatoms in the lake, for example, the *Cyclotella ocellata*-complex (including *Cyclotella ocellata* Pantocsek, *Cyclotella krammeri* Håkansson, *Cyclotella kuetzingiana* Thwaites, and *Cyclotella rossii* (Grunow) Håkansson) is controversial (e.g., Hegewald and Hindáková 1997; Håkansson 2002; Cremer and Wagner 2003; Cremer et al. 2005). Individual species within this complex are differentiated in counts to maintain information on down-core morphological variations in these diatoms. However, in this manuscript, the *C. ocellata*-complex is generally lumped for discussion. Most taxa of the *Navicula pupula*-complex have been transferred to the genus *Sellaphora* (Mann 1989; Mann et al. 2004). Further study of *Navicula pupula* var. *baikalensis* Skvortzov identified at Lake El'gygytgyn may justify the transfer of this variety to *Sellaphora*.

Results

Nearly 300 taxa were identified in 171 core samples. Diatoms are abundant in most core samples (Fig. 2). In a few core zones, calculated diatom concentrations are particularly low (<10⁵ valves per gram of sediment). However, observed diatom valves within these zones generally show no

signs of dissolution or abrasion. A few planktonic species, (e.g., *C. ocellata*-complex, *Pliocaenicus costatus sensu lato* (Skabitchchevsky) Flower, Ozornina et Kuzmina, and *Cyclotella* aff. *cyclopuncta* Håkansson et Carter), comprise greater than 80% of the diatom assemblage of most of the samples (Fig. 2). Zones of less clear dominance of planktonic species correspond to zones of low overall diatom abundance, although both planktonic and periphytic forms decline in abundance in these zones. Down-core variations in the assemblages of planktonic and the less abundant periphytic species are presented separately.

Planktonic diatoms

Below 84 cm, the *C. ocellata*-complex dominates the planktonic diatoms (Fig. 2). Above this level, *P. costatus* abruptly appears in high abundance in the core samples. Above 20 cm, the *C. ocellata*-complex again increases relative to *P. costatus* as previously observed in short cores from the lake (Cremer and Wagner 2003). *C. aff. cyclopuncta* occurs in significant numbers in only one core zone between 520 cm and 560 cm. Additional morphological variation within the *C. ocellata*-complex, including valve diameter, relative size of the central area, and number of punctae, is observed in the core records. For example, between 84 cm and 20 cm average valve diameter of *P. costatus* increases from 19–22 μm to 39–42 μm while the *C. ocellata*-complex decreases from 8–10 μm to 4–5 μm. In the lower portions of the core, particular morphological variants of the *C. ocellata*-complex rise and decline abruptly and tend to dominate particular core intervals.

Paleoenvironmental interpretation of the planktonic diatom assemblages is complicated by the taxonomic uncertainty, by the wide autecological tolerance of the most abundant *C. ocellata*-complex in the core, and by the sporadic occurrence of more uncommon species. Various identified diatoms within this complex are found in a broad spectrum of environments ranging from ultra-oligotrophic to eutrophic, with no clear autecological preference of particular forms within the complex (e.g., Wunsam et al. 1995). Besides Lake El'gygytgyn, *P. costatus* is reported from east Siberia, Alaska and Latvia (Flower et al. 1998).

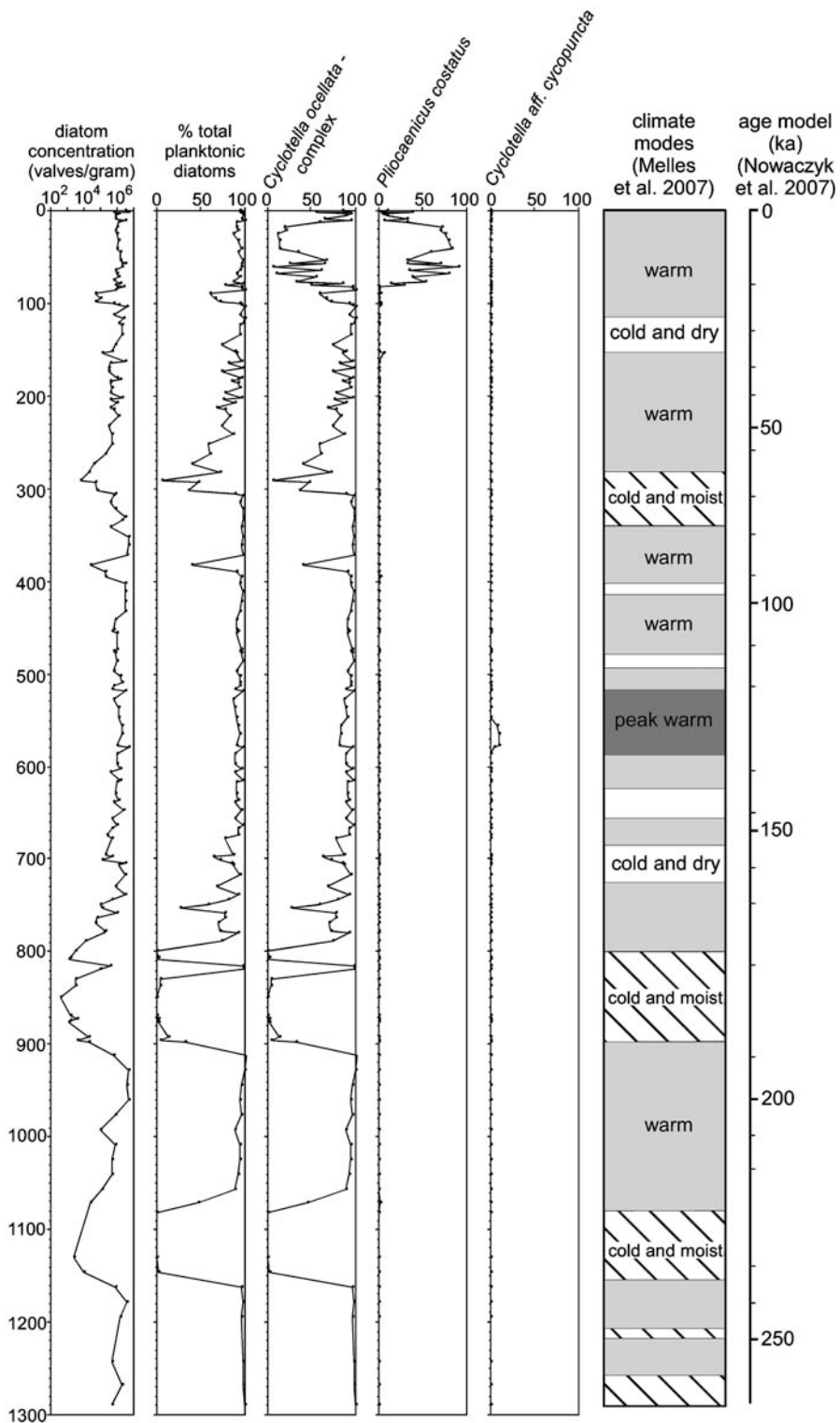


Fig. 2 Core PG1351 total diatom concentration and percent of the most abundant (planktonic) diatom species relative to the whole assemblage (core depth in cm)

Given these limited observations, the autecology of this species must also be considered uncertain.

Periphytic diatoms

Compared to the planktonic diatoms, the generally periphytic taxa are far more diverse (Fig. 3). With the exception of zones of low overall diatom abundance, individual species tend to occur in varying abundance throughout the core record. As a result, these taxa provide a greater potential for reconstructing past environmental changes in the lake.

Down-core changes in periphytic diatom assemblages show a general correlation with climate modes inferred from biogeochemical and isotope geochemical data and other proxies from the cores (Melles et al. 2007). Eight taxa (*Encyonema hilliardii* (Manguin) Krammer, *Psammothidium bioretii* (Germain) Buktiyarova et Round, *Cymbella neocistula* Krammer, *Encyonema silesiaca* (Bleisch) Mann, *Eunotia glacialis* Meister, *Neidium ampliatum* (Ehrenberg) Krammer, *Neidium hercynicum* A. Mayer, and

Surirella spp.) are observed to increase during warm modes and decline during cold modes. In contrast four species (*Amphora copulata* (Kützing) Schoeman et Archibald, *Navicula pupula* var. *baikalensis* Skvortzov, *Diploneis elliptica* (Kützing) Cleve, and *Amphora inariensis* Krammer) show the opposite trend. Other abundant taxa (*Gomphonema clavatum* Ehernberg, *Stauroneis phoenicenteron* (Nitzsch) Ehrenberg, *Pinnularia viridis* (Nitzsch) Ehrenberg, *Caloneis hyalina* var. *robusta* Foged, *Hannaea arcus* (Ehrenberg) Patrick, *Encyonema elginense* (Krammer) Mann, *Gomphonema acutiusculum* (O. Müller) Cleve-Euler, and *Neidium bisulcatum* (Lagerstedt) Cleve) show less clear trends in their down-core variations compared to other proxies (e.g., Melles et al. 2007).

The general habitats of these particular species may provide some insight into what is driving the changes in the periphytic diatom assemblages. The taxa observed favoring cold modes are unattached forms that favor lower energy and/or deeper waters (e.g., *Amphora*, *Diploneis*). The taxa observed to favor warm modes are forms

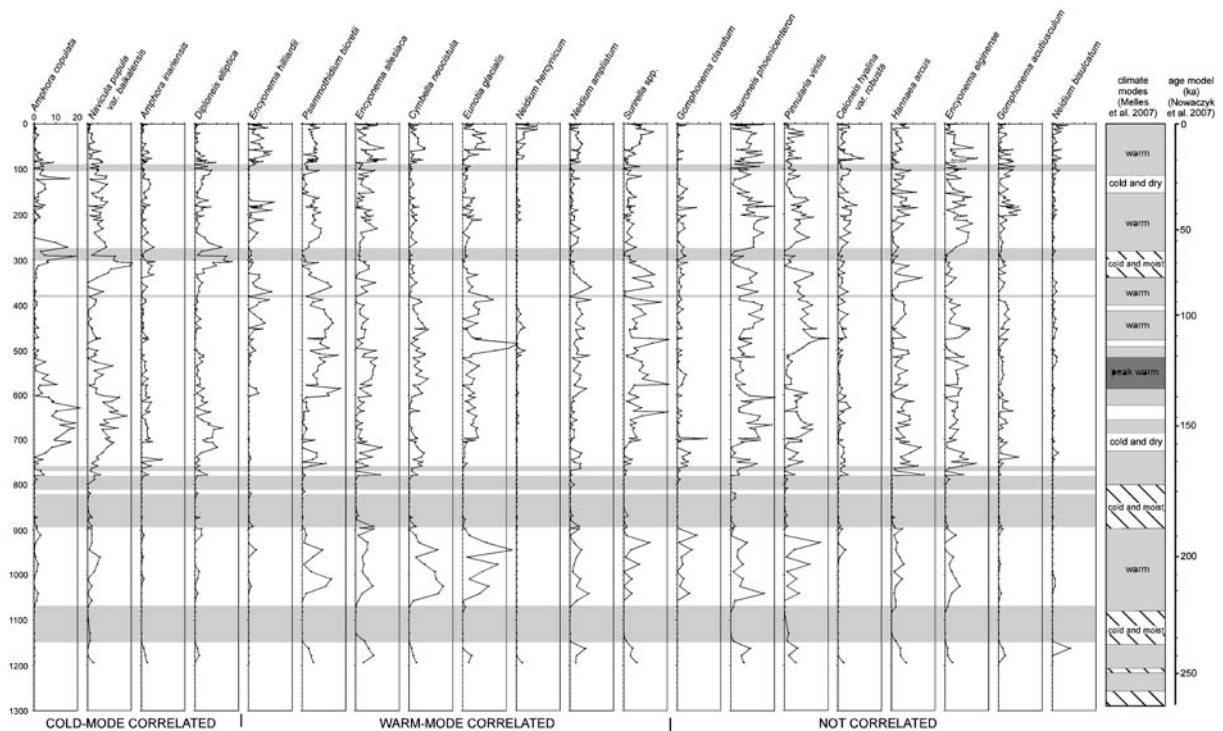


Fig. 3 Periphytic diatom concentrations in core PG1351. Percents are calculated without the abundant planktonic diatoms. Zones of low diatom abundance (generally less than 10⁵ valves/gram) are shown with a grey background (core depth in cm)

that may live attached to substrates and tolerate higher energy environments (e.g., *Encyonema*, *Psammothidium*, *Cymbella*). However, both habitat categories are included in the assemblages without a clear correlation to different proposed climate-modes.

Discussion

According to the sediment geochemistry, magnetic, and pollen records from Lake El'gygytyn, the main links between climate and lake conditions are the extent of lake-ice cover and vegetation differences in the catchment controlling nutrient and organic matter influx (Nowaczyk et al. 2002; Melles et al. 2007; Lozkhin et al. 2007). During relatively cold intervals, lake ice is more persistent in the summer resulting in stratification of the lake. Within these cold intervals, particularly severe conditions and snow accumulation on the lake ice inhibit lake productivity (cold-moist mode). During relatively warm intervals, the lake becomes ice free and fully mixes in summer, resulting in higher productivity. Within these warm intervals, vegetation development in the lake's catchment contributes to peaks in productivity and organic matter accumulation. Variations in diatom assemblages provide another means to assess how the lake responds to climate changes occurring over the last 250 ka.

Planktonic diatoms persist in the sediment record with little variability except for intervals of low overall diatom abundance. Thus, during most of the last 250 ka conditions were suitable to support a planktonic diatom flora. The good preservation of the sparse diatoms present in the zones of low diatom abundance combined with the lack of indications for dilution of the diatom concentration by terrigenous sediment suggests lower productivity in the lake during these intervals. Because considerable diatom productivity is observed under the ice in the modern lake (Cremer et al. 2005) and diatoms are abundant in the cores during past intervals of inferred persistent ice cover (Melles et al. 2007), more extreme lake ice-conditions, coupled with increased snow thickness to decrease light penetration (Melles et al. 2007), may be required to inhibit diatom

growth. The shift in planktonic species toward *P. costatus* between 84 cm (ca. 10 ka) and 20 cm (ca. 3 ka) further indicates significant changes in the lake at these times. Cremer and Wagner (2003) propose the changes at 3 ka may reflect longer open-water conditions or slightly higher pH during the most recent history of the lake. Alternatively, *C. ocellata* may outcompete *P. costatus* at low silica concentrations (Cremer et al. 2005). The occurrence of *C. aff. cyclopunctata* only during the peak warmth inferred during marine isotope stage 5.5 (MIS 5.5) also suggests unique conditions during this interval, although further study of this taxon is required to verify separation of this taxon from the *C. ocellata*-complex. Additional morphological changes in the *C. ocellata*-complex occur abruptly at inferred climate-mode transitions (especially ca. 78, 92, and 176 ka), suggesting climatic control of these forms. However, further quantification of these morphological changes and research on the autecology of these forms are needed to make more specific inferences from these assemblage changes.

Variation in periphytic flora may reflect changes in habitat on the shallow shelves of the lake related to ice conditions. During warm modes, increasing duration of ice-free summers, especially in the shallow areas of the lake, potentially increase the complexity of habitats for periphytic diatoms (Smol 1983, 1988; Douglas and Smol 1999). Furthermore, less ice cover may lead to increased wind-driven currents favoring the diatoms that live attached to substrates. Alternatively, warming of the near-shore areas and the associated density and wind-driven circulation in the lake may lead to enhanced transport of such species into the central basin of the lake where the cores were taken. During at least some cold intervals, it is likely that lake levels may have dropped as much as 10–12 m to the edge of the shallow shelves due to regional aridity (cf., Brigham-Grette et al. 2004). This, combined with the persistent seasonal ice cover, likely decreased the variety of habitats for periphytic flora, limiting opportunities for all but unattached forms that favor lower energy and/or deeper waters at or near the shelf edge.

The transition in the lake at ca. 3 ka inferred from planktonic diatom records and other proxies

is also expressed in changes in the periphytic diatom assemblages. Several of the taxa favoring warm-mode conditions increase in abundance during this interval. The lotic diatom *Hannea arcus* (Ludlam et al. 1996) also increases during this time, further supporting the inference of increased terrigenous input during this interval. In contrast, the peak warmth inferred ca. 120–130 ka (MIS 5.5) is less clearly expressed in the periphytic diatom record. These observations suggest complexity in the diatom response to climate changes within generally warm intervals. More ancient diatom records may become more difficult to interpret as the general environment of the lake becomes less similar to modern (Bradbury 1999).

The interpretations of periphytic diatom assemblage changes are limited by uncertainties in specific diatom habitats within Lake El'gygytyn. Periphytic diatoms preserved in sediment cores from the middle of the lake may actually originate from shallow shelves, warm lagoons at inlets, and streams and bogs draining to the lake. Improved understanding of the distribution of diatoms in microhabitats (e.g., Kingston et al. 1983; Douglas and Smol 1995) and the transport of diatoms to core locations (e.g., Ryves et al. 2003) in the modern Lake El'gygytyn system may provide a better framework for interpreting this and future diatom records.

Conclusions

Diatoms preserved in sediment records from Lake El'gygytyn show variations in abundance and species assemblages in the last 250 ka. Both generally planktonic and periphytic species vary with inferred climate-related conditions in the lake. Zones of low overall diatom abundance provide further support for inferred intervals of low lake productivity during times of extended lake ice and snow cover. The increase in habitat diversity of periphytic diatoms during warm modes is consistent with longer ice-free summer conditions in the shallow margins of the lake. More data on the modern spatial and temporal distribution of periphytic diatom species in the Lake El'gygytyn system are needed to improve inferences in sediment core records.

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