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ORIGINAL PAPER

# Sedimentary geochemistry of core PG1351 from Lake El'gygytgyn—a sensitive record of climate variability in the East Siberian Arctic during the past three glacial–interglacial cycles

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**Abstract** The ca. 13 m long sediment core PG1351, recovered in 1998 from the central part of Lake El'gygytgyn, NE Siberia, was investigated for lithostratigraphy, water content, dry bulk density (DBD), total organic carbon (TOC), total nitrogen (TN), total sulphur (TS) and biogenic silica (opal) contents, and for TOC stable isotope ratios ($\delta^{13}C_{TOC}$). The event stratigraphy recorded in major differences in sediment composition match variations in regional summer insolation, thus confirming a new age model for this core, which suggests that it spans the last 250 ka BP. Four depositional units of contrasting lithological and biogeochemical composition have been distinguished, reflecting past environmental conditions associated with relatively warm, peak warm, cold and dry, and cold but more moist climate modes. A relatively warm climate, resulting in complete summer melt of the lake ice cover and seasonal mixing of the water column, prevailed during the Holocene and Marine Isotope Stages (MIS) 3, 5.1, 5.3, 6.1, 6.3, 6.5, 7.1–7.3, 7.5, 8.1 and 8.3. MIS 5.5 (Eemian) was characterized by significantly enhanced aquatic primary production and organic matter supply from the catchment, indicating peak warm conditions. During MIS 2, 5.2, 5.4, 6.2 and 6.4 the climate was cold and dry, leading to perennial lake ice cover, little regional snowfall, and a stagnant water body. A cold but more moist climate during MIS 4, 6.6, 7.4, 8.2 and 8.4 is thought to have produced more snow cover on the perennial ice, strongly reducing light penetration and biogenic primary production in the lake. While the cold–warm pattern during the past three glacial–interglacial cycles is probably controlled by changes in regional

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summer insolation, differences in the intensity of the warm phases and in the degree of aridity (changing snowfall) during cold phases likely were due to changes in atmospheric circulation patterns.

**Keywords** Siberian Arctic · Quaternary · Paleolimnology · Paleoclimate · Organic geochemistry · Carbon isotopes

## Introduction

Environmental changes in the Arctic are known to play a major role in the global climate system. For instance, the waxing and waning of ice sheets, changes in sea level, productivity, ice cover, Arctic Ocean circulation, and related variations in permafrost, snow cover and vegetation in the terrestrial Arctic through feedback processes have strong impacts on the global water and carbon cycles, as well as on the global heat balance. This is certainly the case for Quaternary glacial/interglacial cycles driven by variations in solar radiation, but also likely true for abrupt climate changes, such as Dansgaard–Oeschger events triggered by sudden changes in the freshwater supply into the North Atlantic during the last glaciation (e.g., Dansgaard et al. 1993; Labeyrie et al. 2003). Many parts of the Arctic are currently experiencing environmental change at rates unprecedented in historical times (e.g., Chapman and Walsh 1993; Overpeck et al. 1997), making this region a major focus for systemic monitoring and the development of numerical models for predicting future change. Existing climate models, however, partly produce results incompatible with historical data and Holocene reconstructions (e.g., Moore et al. 2001; Polyakov et al. 2002).

In order to validate numerical models, and achieve a better understanding of relevant feedback mechanisms between the high and low latitudes, past climatic and environmental change must be studied in the Arctic on different spatial and temporal scales. Although the Holocene history is reasonably well known, limited knowledge exists of the terrestrial Arctic history over several glacial/interglacial cycles, when climate forcings and boundary conditions were different from today. Records covering this period have recently become available from the marine environment, from the North Atlantic (Thiede et al. 1998) as well as the North Pacific (Keigwin 1998) and the Arctic Ocean (Nowaczyk et al. 2001; Shipboard Scientific Party 2005). The longest ice sheet records, in contrast, only cover the last climatic cycle (Johnsen et al. 1995; Andersen et al. 2004) and are restricted to the Greenland ice cap. Repeated glaciations across most of the Arctic borderlands excluded the formation of long continuous records of sufficiently fine resolution for comparison with the traditional marine archives.

Such a terrestrial record, covering the last three glacial/interglacial cycles in the Arctic, has been recovered from Lake El'gygytgyn, northeastern Siberia (Brigham-Grette et al. 1999). The lake is located in a 3.6 Ma old meteorite crater (Layer 2000), in a region not covered by Quaternary ice sheets (Glushkova et al. 1994). Past work on core PG1351 from Lake El'gygytgyn supplied a preliminary chronology to this sediment record and an early interpretation of the regional environmental history (Shilo et al. 2001; Nowaczyk et al. 2002; Minyuk et al. 2003).

The present paper focuses on the biogeochemical and isotope geochemical data obtained from core PG1351. These data, combined with some lithostratigraphic characteristics, physical properties, and other proxies presented in Nowacyzk et al. (2002) and in this special issue, are used to infer repeating modes of major environmental change thought to have occurred in the catchment and in the water column of Lake El'gygytgyn during the past ca. 250 ka. Moreover we describe changes in regional climate across NE Russia that best explain these environmental changes.

## Site information

Lake El'gygytgyn is located in northeastern Siberia (67°30′ N, 172°05′ E), ca. 100 km north of the Arctic Circle and 150 km northeast of modern tree line (Fig. 1). The lake has a roughly circular shape with a diameter of ca. 12 km, inscribed within the southeastern part of the El'gygytgyn impact crater. The crater itself has a diameter of ca. 18 km, forming a watershed of 293 km$^2$, which

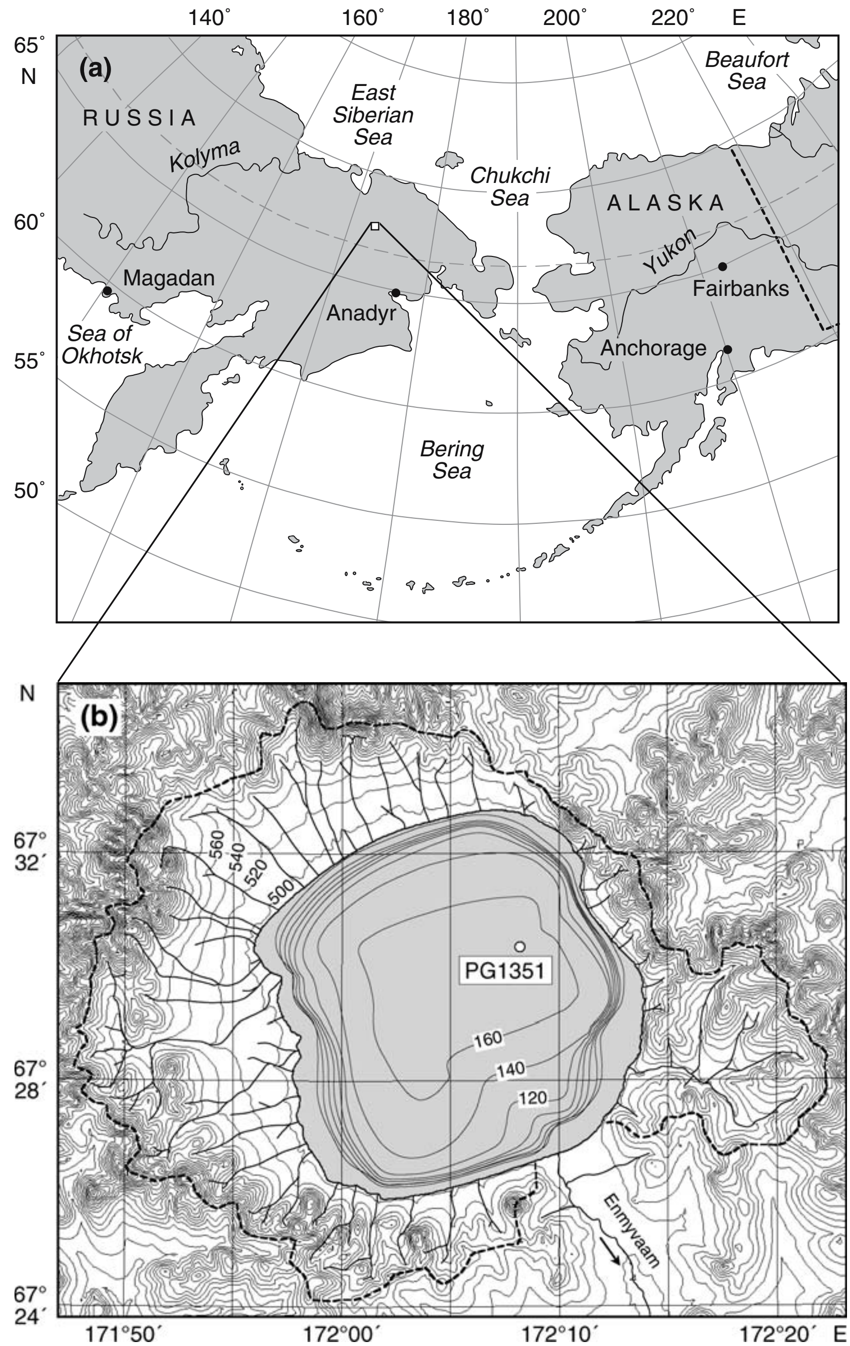


**Fig. 1** Maps showing (**a**) the location of Lake El'gygytgyn in northeastern Siberia and (**b**) the coring site PG1351 in the northeastern part of the lake (contour interval for bathymetry and topography is 20 m; the dashed line indicates the watershed of the El'gygytgyn Crater)

is less than three times the lake's surface area of 110 $km^2$ (Nolan and Brigham-Grette 2007). About 50 streams enter Lake El'gygytgyn at 492 m a.s.l. from a catchment that extends to the crater rim up to 935 m a.s.l. Where these streams enter the lake shallow lagoons are common, being dammed by gravel bars at the lake shore. The lake bathymetry is characterized by shallow shelves to a depth of about 10 m out to varying widths (tens of meters to >1 km), beyond which are very steep slopes, and a broad flat bed with a maximum depth of 175 m. The lake volume amounts to 14.1 $km^3$. Drainage of the lake takes place at the southeastern shore via the Enmyvaam River.

Lake El'gygytgyn today is a cold-monomictic, ultra-oligotrophic lake with slightly acidic pH. A temperature record from summer 2000 to summer 2003 shows that the water column down to 170 m near the center of the lake never exceeds 4°C and is stratified in winter (Nolan and Brigham-Grette 2007). Complete mixing of the water column in summer is confimed by minor variations in vertical profiles of temperature, conductivity, pH, oxygen saturation, and cation and anion concentrations, measured in summer 2000 (Cremer and Wagner 2003). The conductivity values are extremely low ( < 18 $\mu$S cm$^{-1}$), slightly enriched only close to the lake floor. The latter indicates some level of exchange between the lake water and the sediments, as do the pH values, which are slightly higher in the bottom waters compared to values of 6.3–6.6 above. The oxygen saturation decreases to ca. 95% below ca. 140 m water depth, indicating that oxic decomposition takes place close to the lake floor. A low suspension load in Lake El'gyygtgyn is indicated by the remarkably clear surface waters, giving a Secchi transparency depth of 19 m in summer of 2000.

The climate at Lake El'gygytgyn is cold, dry and windy. In 2002, the mean annual air temperature was –10.3°C, with extremes ranging from –40°C in winter to +26°C in summer (Nolan and Brigham-Grette 2007). The annual precipitation amounts to about 200 mm water equivalent. Dominant wind directions are either from the north or from the south. In 2002, the mean hourly wind speed was 5.6 ms$^{-1}$, with strong winds above 13.4 ms$^{-1}$ occurring every month but more frequently in winter. Ice formation on Lake El'gygytgyn usually starts in October (Nolan et al. 2003; Nolan and Brigham-Grette 2007). The blanketing snow cover on the lake ice melts in May/June. The lake ice, measuring 1.5–2 m in thickness, starts disintegration with the formation of moats at the shore in June/July, and ends by July/Aug. This gives a maximum of three months duration to the open-water season. Biogenic primary production is concentrated during this period, however, considerable phytoplankton growth also takes place in winter time beneath the ice cover (Cremer et al. 2005).

The modern vegetation in the catchment of Lake El'gygytgyn is herb-dominated tundra with occasional local patches of low shrubs, particularly willow (*Salix*) (Kohzevnikov 1993; Lozhkin et al. 2007). Erosion, transport and deposition in the catchment is heavily influenced by the continuous permafrost in this region. The weathering products of the source rocks, consisting of rhyodacite tuff and ignimbrite, and minor rhyolite, andesite tuff and basalt (Gurov and Gurova 1979), have constructed wide alluvial fans across the western and northern flanks of the crater, but are not extensive on the eastern and southern crater margins (Fig. 1). Due to the heat capacity of the water it is highly unlikely that permafrost exists beneath the lake (Yershov 1989), even if the meteorite impact took place after formation of permafrost in northeastern Siberia (Layer 2000; Arkhangelov and Sher 1978).

## Material and Methods

Core PG1351 from 175 m water depth in the central part of Lake El'gygytgyn was recovered in spring 1998 through holes drilled in the lake ice cover. A gravity corer (UWITEC Ltd., Austria) was employed for proper sampling of the uppermost sediment decimeters and the sediment–water interface. Deeper sediments were sampled using a 3 m long percussion piston corer (UWITEC Ltd., Austria). This gear makes it possible to core defined depth intervals based upon the controlled release of the piston, which is fixed in the mouth of the core barrel on its way through both the water column and the overlying sediments (Melles et al. 1994). Thus, the piston cores were retrieved so that sections overlapped by about 1 m. The final composite core has a length of 12.91 m; it consists of seven gravity and piston cores, which were correlated on the basis of core descriptions, measurements of magnetic susceptibility, and biogeochemical proxies in overlapping core segments.

The uppermost 58 cm of core PG1351 were subsampled in 2 cm thick slices in the field. Deeper core segments were transported to the laboratory in core liners. There, these PVC tubes of 6 cm diameter were scarred along their axis on two opposing sides by an electrical saw, fully cut by a knife in order to avoid contamination of the sediments by shavings, and finally divided into two halves with a nylon string. Core description and photographic documentation were carried out immediately after core splitting. One core half was then used for continuous subsampling in 2 cm intervals. On the other core half, the magnetic susceptibility was measured, and sample boxes for paleomagnetic measurements were extracted, which subsequently were used for palynological and inorganic geochemical analyses. The remaining sediments from this core half were stored as an archive for future work.

The 2 cm subsamples were freeze-dried, and their water contents calculated (in % of wet bulk sediment) from the mass differences between the wet and dry samples. All other analyses for this study were conducted on aliquots of these subsamples, which were ground to $< 63\ \mu m$ and homogenized using a planetary mill (pulverisette 5, Fritsch Corp.). The dry bulk densities (DBD) were determined with an ACCUPYC 1330 pycnometer (micromeritics Corp.). The contents of total carbon (TC), total nitrogen (TN) and total sulphur (TS) were measured with a CHNS-932 analyzer (LECO Corp.). Total organic carbon (TOC) was analysed with a Metalyt-CS-1000-S (ELTRA Corp.) in corresponding samples, pretreated with HCl (10%) at a temperature of 80°C to remove carbonate. The isotopic ratios of the organic carbon ($\delta^{13}C_{TOC}$) were measured on carbonate-free samples combusted using a CHN-O rapid elemental analyser (Heraeus Corp.), coupled online to a MAT Delta S mass spectrometer (Finnigan Corp.). The results are given in per mil relative to Vienna-Pee Dee Belemnite (V-PDB). Measurements of the biogenic silica (opal) contents were performed according to the wet chemical method described by Müller and Schneider (1993).

## Results and discussion

### Unit classification and interpretation

Core PG1351 consists of clastic muds with variable contents of organic matter. With the exception of single graded layers, which may represent fine-grained turbidites, the sediments are either massive or laminated (Asikainen et al. 2007). Based on the core descriptions and the measured physical properties and chemical characteristics, four units of individual composition can be distinguished in core PG1351, reflecting different environmental conditions we interpret as climate modes (Figs. 2, 3).

#### Unit 1 (warm mode)

Unit 1 contains an association of characteristics that are most common in core PG1351, occurring from 0–113 cm, 154–281 cm, 340–400 cm, 414–477 cm, 493–518 cm, 587–622 cm, 654–683 cm, 727–800 cm, 898–1080 cm, 1156–1203 cm, and 1217–1268 cm sediment depths (Fig. 2). These intervals are characterized by low concentrations in TOC, TN and TS, and by high concentrations in biogenic silica (opal), low TOC/TN ratios, and high TOC isotope ratios ($\delta^{13}C_{TOC}$), compared to the respective values in the other units. The DBD in unit 1 fluctuates around an intermediate level. This is also true for the water content, considering a gradual downcore decrease by ca. 1.5% $m^{-1}$ as a result of natural compaction. Unit 1 is massive to weakly stratified and usually has an olive-grey colour. No proper core description exists for the upper 58 cm in core PG1351, due to subsampling in the field. However, a predominantly massive appearance was found in the surface sediments cored at several other deep water sites in Lake El'gygytgyn in summer 2003. In these cores light olive-brown sediments at the surface are separated from olive-grey sediments below by a brownish redox layer at 10–30 cm depth.

Because unit 1 includes the sediment surface, it likely reflects environmental conditions comparable to modern (Fig. 3a). The common absence of stratification in the sediments is likely due to some minor bioturbation. Infaunal activity is supported by oxygen in the bottom water and requires sufficient food supply. Both conditions are met in the modern, monomictic and semi-permanently ice-covered Lake El'gygytgyn. Mixing in summer follows ice break-up, resulting in good ventilation of the bottom water. This hampers sulfide formation (Müller 2001) and thus leads to low TS contents in unit 1. Another con-

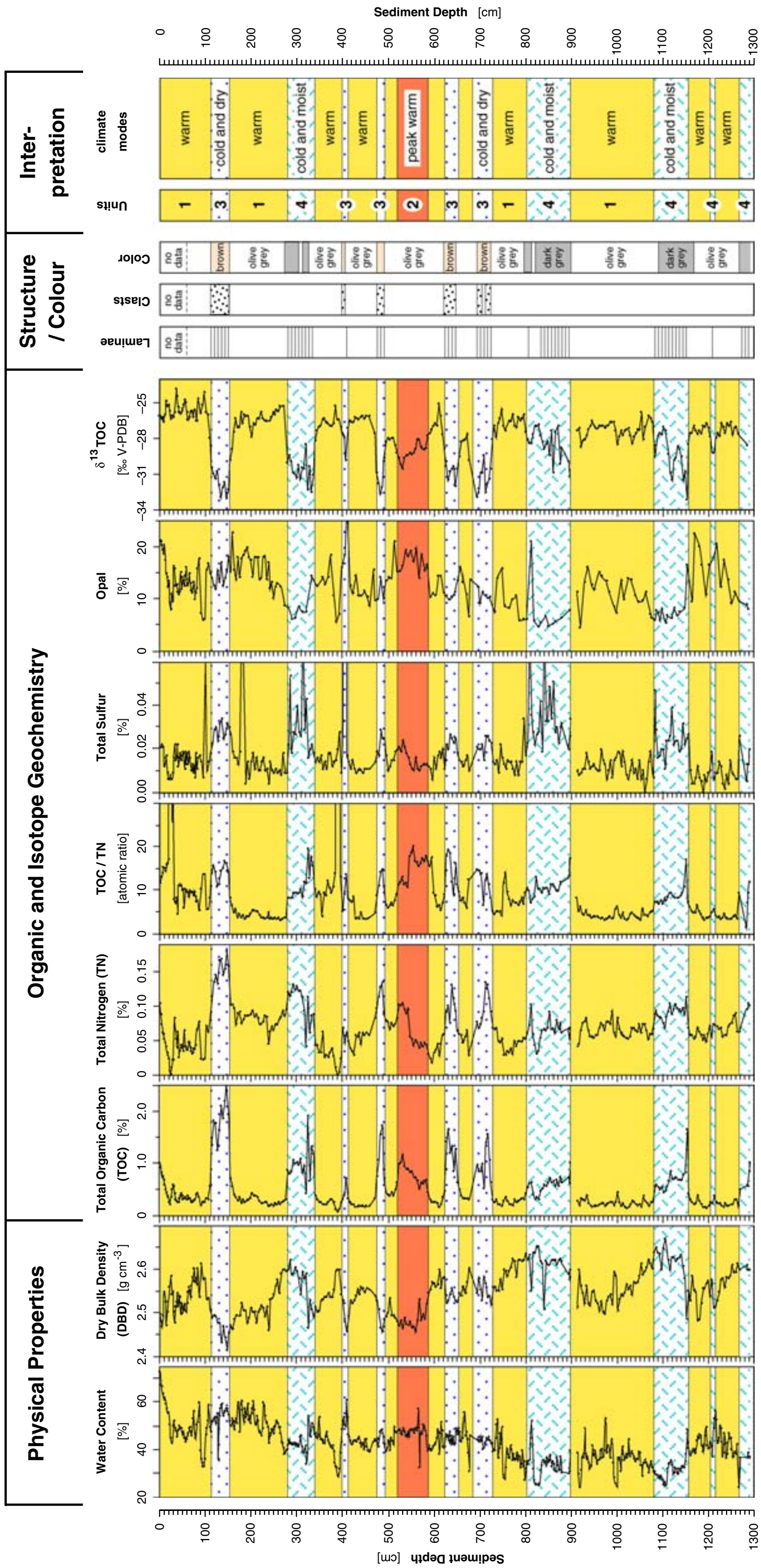


**Fig. 2** Depth plots of physical properties, organic and isotope geochemistry, and major lithological characteristics of core PG1351 indicating warm (unit 1), peak warm (unit 2), cold and dry (unit 3), and cold and more moist (unit 4) climate modes at Lake El'gygytgyn

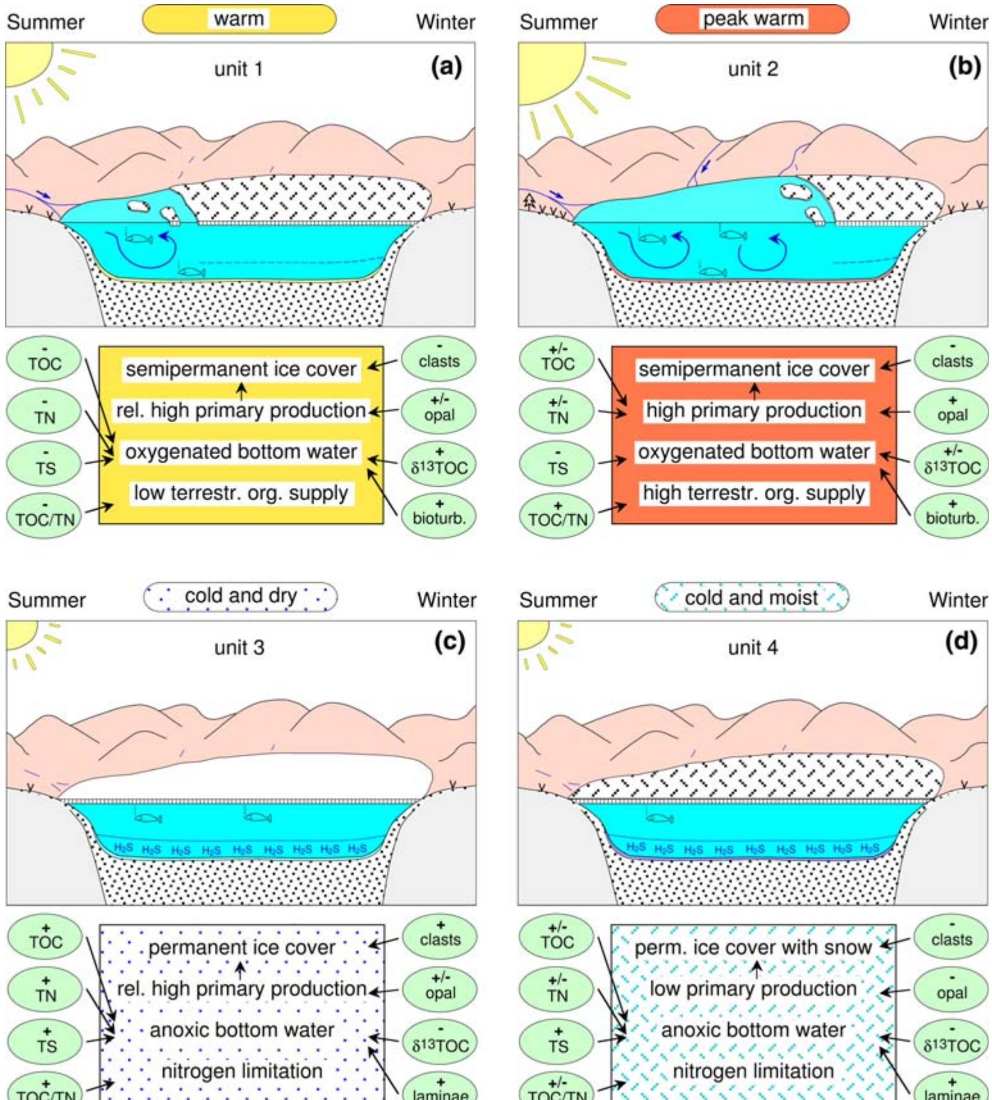


**Fig. 3** Sketches of the environmental conditions from summer (left) to winter (right) at Lake El'gygytgyn during (**a**) warm, (**b**) peak warm, (**c**) cold and dry, and (**d**) cold and more moist climate modes. Arrows mark the geological indicators for the degree of ice and snow coverage, the amount of aquatic primary production, the oxygen content of the bottom water, and the relative portion of terrestrial supply on total organic matter accumulation (in warm periods) or the degree of nitrogen limitation in the surface water (in cold periods). For additional explanations see text

sequence of complete mixing is nutrient enrichment of the surface waters (Doran et al. 2002), resulting in significant primary production in the photic zone, despite the ultra-oligotrophic state of Lake El'gygytgyn. This primary production is further supported by the abundant availability of light in the open water season, especially in July. The flux of organic matter from phytoplankton functions as the necessary food source for deep benthic organisms and complements what is likely provided by density-driven currents from the shallow shelves as they warm to 4°C (Nolan et al. 2003).

Relatively high primary production during the formation of unit 1 is also indicated by fluctuating (6–23%) but in average high (13.2%) opal content in these sediments. This proxy reflects the concentration of diatom valves, which are well preserved in the slightly acidic water of Lake El'gygytgyn. Pronounced fluctuations in opal content indicate that the conditions for phytoplankton blooms were close to a threshold. Most likely, the lake remained largely ice covered during some years, thus preventing sufficient light penetration into the surface waters while hampering mixing and nutrient supply from the bottom waters. During such years, the primary production was mainly restricted to ice cracks and summer-time moats close to the shore. In most years, however, the ice cover fully degraded for a short period allowing for mixing, facilitating plankton blooms and a high primary production.

In contrast to opal, TOC and TN concentrations are at a minimum in the sediments. Both are significantly reduced by the decomposition of organic matter in the oxygenated bottom water. The only exception occurs in the uppermost sediments, where both TOC and TN constantly increase towards the surface. This can best be explained by the ongoing, thus increasingly incomplete oxygenation of the organic matter above the present redox boundary in 10–30 cm sediment depth.

The $\delta^{13}C_{TOC}$ values of ca. –25 to –28 in unit 1 are within the range of values occurring in organic matter derived from phytoplankton, but also in most trees, shrubs and temperate-cold grasses (Cerling and Quade 1993; Meyers and Ishiwatari 1995). The isotope ratios, therefore, cannot be used to estimate the relative portions of autochthonous production and allochthonous supply of the bulk organic matter accumulation. However, TOC/TN ratios are well below 10 in all unit 1 sections, with the exception of the uppermost ca. 30 cm of core PG1351, suggesting that the supply from the catchment normally was rather low (Meyers and Ishiwatari 1995). Lake-internal processes could be an alternative explanation for the low TOC/TN ratios (e.g., Hecky et al. 1993; Talbot and Lærdal 2000), but are regarded as unlikely. First, diagenetic loss of nitrogen from the sediments or nitrogen limitations in the surface water due to high primary production both would have elevated, rather than reduced, the TOC/TN ratio. Secondly, these processes are often associated with lake stratification, which is not the case for Lake El'gygytgyn today or during unit 1 deposition.

The interpretation of a well-ventilated water column is supported by rock magnetic data from core PG1351, which indicates good preservation of magnetite in unit 1 (Nowaczyk et al. 2002, 2007). A variable but altogether relatively high primary production is confirmed by recent diatom flux measurements in the water column (Cremer and Wagner 2003) and by high diatom concentrations and $SiO_2$ content in unit 1 sediments (Cherepanova et al. 2007; Minyuk et al. 2007). Low values for $TiO_2$, $Fe_2O_3$, and MgO suggest that chlorite, indicative of physical weathering, is a minor component in unit 1. This is confirmed for the uppermost 290 cm of core PG1351 by clay mineral analyses (Asikainen et al. 2007). Unit 1 shows relatively low chlorite content, but high smectite and interstratified illite-smectite contents and high illite crystallinities. This composition indicates significant chemical weathering in the lake catchment.

A relatively warm climate but usually limited supply of terrestrial organic matter into the lake sediments during unit 1-style depostion is only partly confirmed by the palynological data obtained on core PG1351 (Lozhkin et al. 2007). In three unit 1 sections (upper 75 cm of 0–113 cm, lower 30 cm of 414–477 cm, and whole 493–518 cm) the sediments have shrub-dominated pollen assemblages and high pollen concentrations. This reflects temperatures and a vegetation cover close to modern. According to the TOC/TN ratios, this kind of vegetation only in the youngest unit 1 section led to significant input of terrestrial organic matter. In all other unit 1 sections, either the autochthonous biogenic production was too high or the allochthonous supply was insufficient to raise the TOC/TN ratio above 10. The latter could have been the case for the unit 1 type portions characterized by mixed herb- and shrub-dominated pollen assemblages with low pollen concentrations. These assemblages suggest somewhat lower summer temperatures than today and a more restricted vegetation cover in the lake catchment. Some unit 1 sections even contain mixed levels of herb-dominated pollen assemblages, indicating temperatures considerably lower than today associated with a restricted vegetation cover of graminoid tundra to polar desert.

Unit 2 (peak warm mode)

Unit 2 occurs only once in core PG1351, between 518 and 587 cm sediment depth (Fig. 2). Like unit 1, unit 2 is weakly stratified to massive and has an olive grey colour and low TS contents. It differs from unit 1 by having slightly higher opal and water content and significantly lower DBD. The TOC and TN content increases within unit 2, reaching intermediate values, whereas the TOC/TN and $\delta^{13}C_{TOC}$ ratios simultaneously decrease.

This unit is interpreted as reflecting the warmest average climate conditions in the record. At this time summer melt of the lake ice cover occurred regularly and the water column was more mixed than modern Lake El'gygytgyn (Fig. 3b). As a consequence, the bottom water was well oxygenated, hampering sulfide formation but enabling endobenthic activity with some bioturbation (Müller 2001).

Biogenic production was significantly higher during the deposition of unit 2 as compared to unit 1. This is indicated by more stable (14–20%) and, on average, significantly higher (17.1%) opal content. The high primary production can best be explained by full degradation of the lake ice cover in all years, which allowed regular mixing, supported light penetration into the surface water, and thus facilitated plankton blooms.

TOC and TN, in contrast, are probably significantly reduced by decomposition of organic matter in the oxygenated bottom water. But unlike unit 1, decomposition was not virtually complete. TOC and TN in unit 2 are significant in concentration, which is also reflected by relatively low DBD and relatively high water content. The conspicuous upward increase in the TOC and TN content most likely reflects progressively enhanced primary production. This probably led not only to the increased flux of organic matter but also to better preservation due to the upward movement of the redox boundary in the sediment column.

Despite the higher aquatic primary production in unit 2 compared to unit 1, the supply of organic matter from the catchment clearly exceeded the accumulation of limnic organic matter. This is determined by TOC/TN ratios well above 10 (Meyers and Ishiwatari 1995), suggesting markedly increased vegetation cover in and around El'gygytgyn Crater. As in unit 1, the TOC/TN ratios in unit 2 can hardly be explained by lake-internal processes. For instance, nitrogen limitation in the surface waters due to the high primary production would not only have led to increased TOC/TN ratios, but also to $^{12}C$ depletion in the surface waters (Talbot and Lærdal 2000). The latter, however, is disproved by lower, rather than higher, $\delta^{13}C_{TOC}$ values in unit 2 sediments. Hence, the trend towards lower TOC/TN ratios within unit 2 suggests that the autochthonous production gradually became more important throughout the period of deposition. This is consistent with the interpretation of increasing primary production derived from increasing TOC and TN contents.

The inferred peak warm climate at Lake El'gygytgyn during the formation of unit 2 is strengthened by palynological analyses on core PG1351 (Lozhkin et al. 2007). A distinct maximum in tree and shrub pollen in these sediments, coincident with the highest pollen concentrations, suggest that deposition took place at a time of exceptionally favourable climatic conditions. It also explains the high proportion of terrestrial plant input to the bulk organic matter deposition. A particularly warm and moist climate may also have led to enhanced chemical weathering in the catchment. This is indicated by high contents of CaO, $Na_2O$ and $K_2O$ and low contents of $TiO_2$, $Fe_2O_3$, and MgO in unit 2, probably reflecting a higher supply of smectite and illite at the expense of chlorite (Minyuk et al. 2007). High $SiO_2$ content in unit 2 coincides with high concentrations of diatoms (Cherepanova et al. 2007). This confirms the interpretation of high aquatic primary production during the formation of unit 2. Support for the suggestion of oxic bottom waters and a redox boundary at some depth within the sediment column comes from rock magnetic measurements, indicating good preservation of magnetite in unit 2 sediments (Nowaczyk et al. 2002, 2007).

Unit 3 (cold and dry mode)

Unit 3 occurs over five intervals in core PG1351, at depths from 113–154 cm, 400–414 cm, 477–493 cm, 622–654 cm, and 683–727 cm (Fig. 2). It is characterized by high TOC, TN and TS concentrations, high TOC/TN ratios, intermediate to high opal content and very negative $\delta^{13}C_{TOC}$ ratios. Moreover, this unit is characterized by distinct lamination, the occurrence of sediment clasts and brownish rather than grey sediment colours. The water content is relatively high and the DBDs are relatively low, compared to neighbouring sediment units.

This composition is interpreted as representing periods when the regional climate was cold and dry. Summer temperatures significantly lower than during the formation of units 1 and 2 probably led to reduced melt-water supply and a permanent ice cover on Lake El'gygytgyn (Fig. 3c). The ice cover, in turn, excluded wind-generated mixing as well as surface water warming to a level that would allow density-driven turnovering. As a consequence, the lake became stratified.

Despite the persistent ice cover on Lake El'gygytgyn, primary production beneath the ice probably remained relatively high during the deposition of unit 3. This is suggested by intermediate to high opal content in the sediments. Algal and bacterial photosynthesis can take place when ice and snow cover permit less than 1% of incident light to penetrate the water column (Hawes et al. 2001). The major limiting factor for light penetration is not the consistency and thickness of the ice cover itself, but the thickness of blanketing snow on the ice (Gore 1997). Hence, the significant primary production during unit 3 formation suggests that the lake ice cover was widely free of snow. This could be due to strong winds sweeping the ice, but it also suggests little precipitation and a rather dry climate. An additional proxy for a largely bare ice cover comes from the sediment clasts, which only occur in unit 3. These clasts usually have a diameter of 1–2 mm and differ from the surrounding sediments by a grey colour and larger mean grain size. They could evolve by agglomeration of wind-blown particles during their transport through the ice along vertical conduits formed in late summer, in a way similar to that observed on a perennially ice-covered lake without blanketing snow in the Dry Valleys, Antarctica (Squyres et al. 1991).

According to the high TOC/TN ratios, the particulate organic matter settling through the water column could originate from vascular land plants with only some admixture of nonvascular aquatic plants (Meyers and Ishiwatari 1995). This, however, is unlikely given the cold climate and significant autochthonous production indicated by the perennial lake ice cover and relatively high opal values, respectively. More likely, therefore, are lake processes, such as limits of nitrogen in the surface waters (Hecky et al. 1993), which can be expected due to the relatively large export production and presumably limited nitrogen supply in the lake as a consequence of lake stratification and ice coverage.

Decomposition of organic matter caused repeated movement of the redox boundary from within the sediments up into the water column. Once anoxic bottom waters became established, endobenthic activity ceased and laminations were preserved without any sign of bioturbation. Due to the absence of oxygen, the organic matter settling through the epilimnion into the hypolimnion remained well preserved. This is suggested by the high TOC and TN content in unit 3, which is also reflected in the relatively high water content and low DBD. High TS content can be traced back to sulfate reduction in the anaerobic sediments (Wilkin and Barnes 1997). In amictic lakes this process leads to hydrogen sulfide ($H_2S$) in the bottom waters (Fig. 3c), which then is transformed to unsoluble FeS or $FeS_2$. In addition, bacterial methanogenesis produces methane ($CH_4$) with particularly light $\delta^{13}C$ values of –60 to −100 (Cohen 2003). Bacterial methane oxidation likely made significant quantities of this light carbon available to the phytoplankton living in the epilimnion (Håkansson 1985), eventually producing $\delta^{13}C_{TOC}$ values of less than −30 in the sediments of unit 3. This process was probably enhanced by the perennial ice cover on Lake El'gygytgyn, which hampered exchange with atmospheric $CO_2$ with much heavier $\delta^{13}C$ ratios.

The interpretation of a cold and dry climate during unit 3 formation is supported by palynological analyses carried out on core PG1351 (Lozhkin et al. 2007). With the exception of the thin unit 3 from 477 cm to 493 cm sediment depth, herb-dominated pollen assemblages in all unit 3 sections indicate graminoid tundra to polar desert with summer temperatures and seasonal precipitation considerably less than modern. This type of climate is also suggested by high concentrations of $TiO_2$, $Fe_2O_3$, and MgO in unit 3, which suggest high concentrations of chlorite originating from physical weathering (Minyuk et al. 2007). For the uppermost unit 3 high chlorite content is confirmed by clay mineral analyses carried out in the upper 290 cm of core PG1351 (Asikainen et al. 2007). Moreover, low smectite and interstratified illite-smectite contents and low illite crystallinities suggest a predominance of physical over chemical wheathering.

Grain-size analyses in the uppermost 290 cm of core PG1351 have shown that unit 3 is more fine-grained than units 1 and 2 (Asikainen et al. 2007). This is consistent with the interpreted absence of internal lake circulation due to a perennial ice cover and lake stratification. Diatom analyses carried out throughout core PG1351 have shown that planktonic diatom assemblages with rather high concentrations occur in unit 3, thus supporting the interpretation of significant primary production beneath the ice (Cherepanova et al. 2007). This is contradictory to low $SiO_2$ content in unit 3 sections (Minyuk et al. 2007), but supported by opal concentrations similar to unit 1 and only slightly lower than in unit 2 (Fig. 2). The assumed anoxic bottom waters are confirmed by rock magnetic data, which indicate reductive magnetite dissolution in unit 3 (Nowaczyk et al. 2002, 2007).

### Unit 4 (cold and moist mode)

The last depositional sequence is unit 4 that occurs over five intervals in core PG1351, at depths of 281–340 cm, 800–898 cm, 1080–1156 cm, 1203–1217 cm and below 1268 cm (Fig. 2). Like unit 3, unit 4 is characterized by distinct laminations, high TOC, TN and TS content, high TOC/TN ratios, and very low $\delta^{13}C_{TOC}$ values. It differs from unit 3 by having dark grey to black instead of brownish sediment colours, the absence of sediment clasts, much lower opal and water content, and significantly higher DBDs. In addition, the TOC and TN content and the TOC/TN ratios in unit 4 are, on average, lower than in unit 3, and TOC content, TOC/TN ratios, and $\delta^{13}C_{TOC}$ values distinctly decrease within individual units 4.

The composition of unit 4 is believed to indicate a cold but rather moist climate in the past. Analogous to unit 3, low temperatures are thought to have led to minor melt-water supply from the catchment and a permanent ice cover on Lake El'gygytgyn (Fig. 3). As a consequence, lake ventilation ceased and anoxic bottom waters became established. This anoxic state is indicated by the absence of bioturbation, which allowed sediments to be deposited as laminations, and by high TS contents as a result of bacterial sulfate reduction (Wilkin and Barnes 1997). Relatively high TOC and TN content suggests good preservation of settling particulate organic matter. Moreover, very light $\delta^{13}C_{TOC}$ values reflect methanogenesis (Håkansson 1985). The trend towards heavy $\delta^{13}C_{TOC}$ values with deposition of unit 4 sections coincides with decreasing TOC contents. This suggests that the degree of methanogenesis depends upon the amount of TOC in the sediments.

In contrast to unit 3, lake ice during the deposition of unit 4 was probably extensively covered by blanketing snow, suggesting a more humid climate. Snow cover may have restricted the formation of vertical conduits in the ice (Squyres et al. 1991), a factor that could have been a precondition for the agglomeration of particles on their way through the ice to form the sediment clasts frequently found in unit 3 but almost absent in unit 4. Moreover, it is likely that blanketing snow strongly reduced light penetration into the surface waters and thus hampered photo-autotrophic organisms (Smol 1988; Gore 1997). Very low primary production is indicated by distinct minima in opal concentrations. Due to the high porosity and low density of diatom valves, the low opal content is also consistent with low water content and high DBD in unit 4. In addition, average TOC and TN content is significantly lower than in unit 3. Despite the lower primary production, the surface waters were also likely depleted in nitrogen during unit 4 formation. This is suggested by high TOC/TN ratios, comparable to those in unit 3. Their decrease within unit 4 sections in turn indicates a successive decline in primary production rather than a decrease in terrestrial organic matter supply. This suggestion is supported by a simultaneous decrease in TOC and, less pronounced, decrease in opal content.

A climate significantly colder than modern during the formation of unit 4 is also indicated by mixed herb and shrub-dominated pollen assemblages in the respective sediments of core PG1351, suggesting summer temperatures 6°C lower than present (Lozhkin et al. 2007). Higher precipitation during this same interval, compared to unit 2, is not confirmed by the palynological data. The cool climate probably led to a predominance of physical versus chemical weathering. This is indicated by high $TiO_2$, $Fe_2O_3$, and MgO content, reflecting high chlorite concentrations in unit 4 sediments (Minyuk et al. 2007). The assumed reduction in primary productivity during unit 4 deposition is confirmed by very low $SiO_2$ content and strongly reduced diatom concentrations over these intervals (Cherepanova et al. 2007). Intense reductive magnetite dissolution in unit 4, as indicated by rock magnetic data, is consistent with the assumed anoxic bottom waters for these time periods (Nowaczyk et al. 2002, 2007).

## Climatic and environmental history

According to the age model presented in this issue by Nowaczyk et al. (2007) core PG1351 spans the past ca. 250 ka. The age model suggests that warm periods, with usual summer melt of the lake ice cover but little organic matter accumulation (unit 1), prevailed at Lake El'gygytgyn during the Holocene and during Marine Isotope Stages (MIS) 3, 5.1, 5.3, 6.1, 6.3, 6.5, 7.1.–7.3, 7.5 and 8.3. These intervals coincide very well with maxima both in the regional insolation and in the stacked marine oxygen isotope record (Fig. 4).

Peak warm conditions, with more regular summer melt of the lake ice cover and enhanced

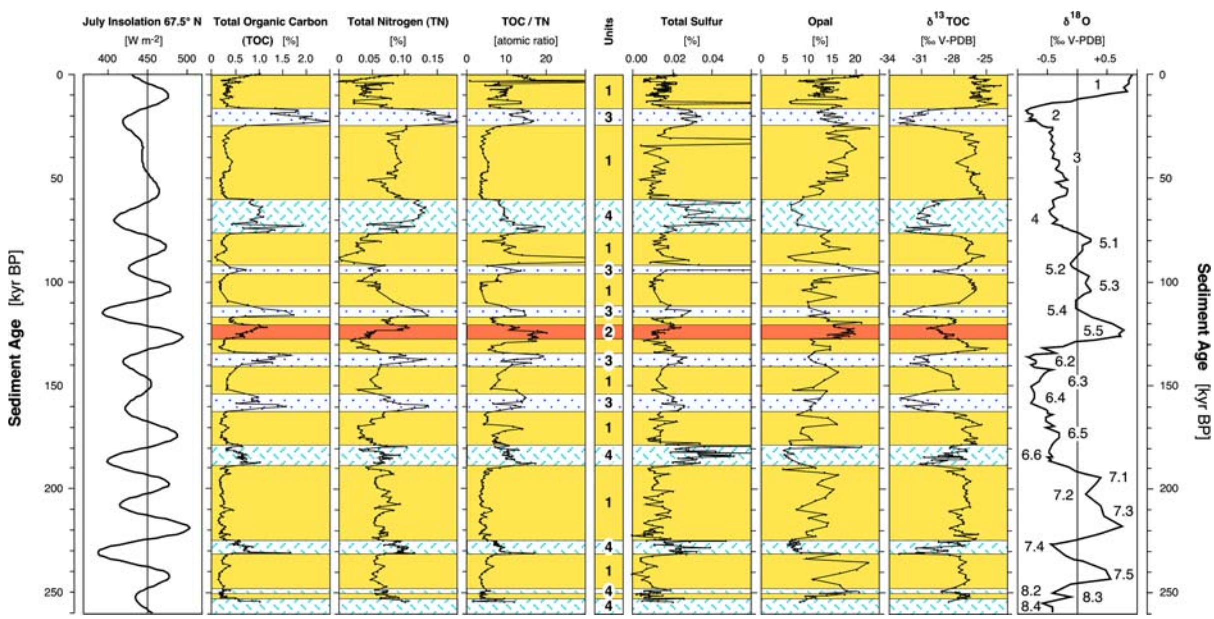


**Fig. 4** July insolation at 67.5° N (Paillard et al. 1996) and stacked marine oxygen isotope record (Martinson et al. 1987) with isotopic stages and substages for the past 260 ka, plotted versus the major biogeochemical proxies in core PG1351 from Lake El'gygytgyn according to the age model presented in this issue by Nowaczyk et al. (2007). The normal warm (unit 1), peak warm (unit 2), cold and dry (unit 3), and cold but more moist (unit 4) climate modes are indicated with the same signatures as in Figs. 2 and 3

organic matter accumulation (unit 2), only occurred at Lake El'gygytgyn during the Eemian (MIS 5.5) (Fig. 4). This suggests that the Eemian was a particularly pronounced interglacial. According to Lozhkin et al. (2007) the Eemian at Lake El'gygytgyn was 2–4°C warmer than modern, consistent with regional warmth for the Bering Strait and most of Beringia (Brigham-Grette and Hopkins 1995; Lozhkin and Anderson 1995). The Holocene thermal maximum in northeastern Siberia, in contrast, was only 1.6+0.8°C warmer than present (Kaufmann et al. 2004). During this warm interval, which occurred during the early Holocene insolation maximum, insolation was less intense than during the Eemian (Fig. 4), and regional temperatures were insufficient to produce sediments with unit 2 characteristics. Unit 1 sedimentation also persisted during MIS 6.5 and 7.3, when insolation maxima were similar or even higher than the Eemian maximum. This suggests that the formation of unit 2 is not only controlled by the degree of insolation but also by the amount of organic matter and nutrients supplied from the catchment, both of which were highest during the Eemian.

During MIS 2, 5.2, 5.4, 6.2 and 6.4 a cold and particularly dry climate at Lake El'gygytgyn led to perennial lake ice coverage and a stratified water column with significant primary production below the ice (unit 3). The low precipitation can best be explained by a predominance of westerly winds. For MIS 2 a strong gradient eastward from the northern Eurasian Ice Sheet towards drier conditions in Beringia has been reconstructed from geological evidence and numerical modelling experiments (Svendsen et al. 1999; Siegert et al. 1999). Such a gradient must have occurred to enable the large expansion of the Eurasian Ice Sheet in central Europe simultaneously with restricted glaciation and an ice sheet margin to the west of the Taymyr Peninsula in central Siberia. In northeastern Siberia, the dry climate led to ice coverage of only 13% of the landscape during MIS 2 (Glushkova et al. 1994).

A cold but more moist climate likely prevailed at Lake El'gygytgyn during MIS 4, 6.6, 7.4, 8.2 and 8.4, characterized by a lake with perennial ice-cover, stable stratification, and a blanketing snow cover which strongly hampered primary production. During these periods, higher regional precipitation led tor glacial ice cover of up to 40% in eastern Siberia, with local ice caps and valley glaciers covering the mountainous regions both to the northeast and to the southwest of the El'gygytgyn Crater (Glushkova et al. 1994). Also in central Siberia the precipitation was higher during MIS 4 than during MIS 2, leading to more pronounced glaciation (Svendsen et al. 1999). However, the eastern margin of the Eurasian Ice Sheet, being controlled by precipitation rather than temperature, remained more than 3000 km to the west of Lake El'gygytgyn. Hence, westerly winds were probably not the moisture source in northeastern Siberia during cold and moist glacial intervals. Rather, we suggest that northerly or easterly winds may have reached the area more frequently due to a westward migration or weakening of the Siberian High.

## Conclusions

Based on the lithostratigraphy, physical properties, and biogeochemical characteristics of sediment core PG1351 from Lake El'gygytgyn four sedimentary units of different composition can be distinguished. These units reflect different environmental settings and climate modes. Their succession during the past three glacial–interglacial cycles is generated by changes in both regional insolation and atmospheric circulation patterns.

Differences in the sediment composition in Lake El'gygytgyn are primarily controlled by the duration of the lake ice cover. During warm periods (units 1 and 2), summer melt of the ice cover leads to high aquatic primary production, ventilation of the entire water column by annual turnover, decomposition of most of the settling particulate organic matter, and bioturbation of the sediments. During past cold periods (units 3 and 4), a persistent ice cover hampered primary production and led to a stratified water column with anoxic bottom waters, good preservation of the settling organic matter, and the preservation of laminated sediments due to the absence of bioturbating organisms. Temporal variations between these two major settings are controlled by regional summer insolation rather than nonlinear feedbacks between the oceans and ice sheets.

Among the warm periods, the Eemian (MIS 5.5) exhibited particularly high aquatic primary production and organic matter accumulation (unit 2). These attributes for a particularly pronounced interglacial were only partly controlled by insolation, which was lower than during MIS 7.3, when merely unit 1-style sedimentation took place. The major driving force of productivity was probably nutrient and organic matter supply from the catchment, the amount of which depended upon the structure of terrestrial vegetation. This is indicated by the more dense vegetation cover at Lake El'gygytgyn during MIS 5.5 compared to most other warm periods (Lozhkin et al. 2007). The density and composition of the regional vegetation, in turn, was not only controlled by insolation, but also by precipitation and/or temperature changes due to changes in atmospheric circulation patterns.

Among the cold periods, two climate modes are reflected in the sediment composition, characterized by differing degrees in aridity. Cold and particularly dry climates led to the widespread absence of blanketing snow on the lake ice cover, enabling the formation of sediment clasts and sufficient light penetration for significant primary production beneath the ice (unit 3). This mode prevailed during MIS 2, 5.2, 5.4, 6.2 and 6.4. The intense aridity can best be explained by a predominance of westerly winds. A cold but more moist climate, in contrast, generated a blanketing snow cover on the ice, which hampered clast formation and significantly reduced aquatic primary production (unit 4). Cold and moist climates prevailed at Lake El'gygytgyn during MIS 4, 6.6, 7.4, 8.2 and 8.4. The higher moisture supply could be due to northerly or easterly winds more frequently reaching the area as a consequence of the westward migration or weakening of the Siberian High.

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