J Paleolimnol (2007) 37:65–76
DOI 10.1007/s10933-006-9023-8

ORIGINAL PAPER

# A revised age model for core PG1351 from Lake El'gygytgyn, Chukotka, based on magnetic susceptibility variations tuned to northern hemisphere insolation variations

**Norbert R. Nowaczyk · Martin Melles · Pavel Minyuk**

Received: 9 September 2004 / Accepted: 1 May 2005 / Published online: 25 August 2006

**Abstract** A combined analysis of magnetic susceptibility, total organic carbon (TOC), biogenic silica (opal), and $TiO_2$ content of the 12.6 m long composite core PG1351 recovered from Lake El'gygytgyn, Chukotka Peninsula, indicate a clear response of the lacustrine sedimentary record to climate variations. The impact is not direct, but through variations in oxygenation of the bottom waters. Mixing of the water body is typical for warmer climates, whereas the development of a stratified water body associated with anoxic conditions at the lake floor appears during cold climates. Oxic conditions lead to a good magnetite preservation and thus to high magnetic susceptibilities, but also to a large-scale degradation of organic matter, as reflected by low TOC (total organic carbon) values. During anoxic conditions, magnetite is severely dissolved yielding very low susceptibility values, whereas organic matter is best preserved, reflected by high TOC values. Hence, in general, neither susceptibility reflects the lithogenic fraction, nor does TOC reflect bioproductivity in case of the studied El'gygytgyn sediments. Based on available infrared stimulated luminescence (IRSL) dating, the obtained susceptibility pattern of core PG1351 shows an obvious correlation to northern hemisphere insolation variations, with a dominating impact of the Earth's 18 and 23 kyr precessional cycles for the upper half of PG1351, that is, during the past 150 ka. Therefore, the whole susceptibility record, together with biogenic silica (as a proxy for bioproductivity), TOC (as an indicator for redox conditions), and $TiO_2$ (as a proxy for lithogenic input), was systematically tuned to the northern hemisphere insolation yielding an age of about 250 ka for the base of the composite core.

**Keywords** Solar forcing · Magnetic susceptibility · Lake El'gygytgyn · Siberia · Lake sediments

---

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

N. R. Nowaczyk (✉)
GeoForschungsZentrum Potsdam,
Section 3.3 — "Climate Dynamics and Sediments",
Telegrafenberg Haus C, D-14474 Potsdam, Germany
e-mail: nowa@gfz-potsdam.de

M. Melles
Institute for Geophysics and Geology,
University Leipzig, Talstrasse 35,
D-04103 Leipzig, Germany

P. Minyuk
North-East Interdisciplinary Science Research
Institute (NEISRI), Russian Academy of Sciences,
16 Portovaya St., 685000 Magadan, Russia

## Introduction

In 1998, a joint Russian, American, and German team succeeded in recovering a 12.6 m long composite core (PG1351) from Lake El'gygytgyn (Fig. 1). A comprehensive paleo- and rock-magnetic study was performed on the obtained sediments by Nowaczyk et al. (2002). Splitted cores were scanned for magnetic susceptibility in steps of 1 mm with a Bartington MS2E spot reading sensor. Paleomagnetic samples of 6.2 cm$^3$ were taken about every 2.5 cm. In, addition, about 0.5 cm$^3$ large syringe samples, taken every 2 cm, were used for obtaining hysteresis data, low

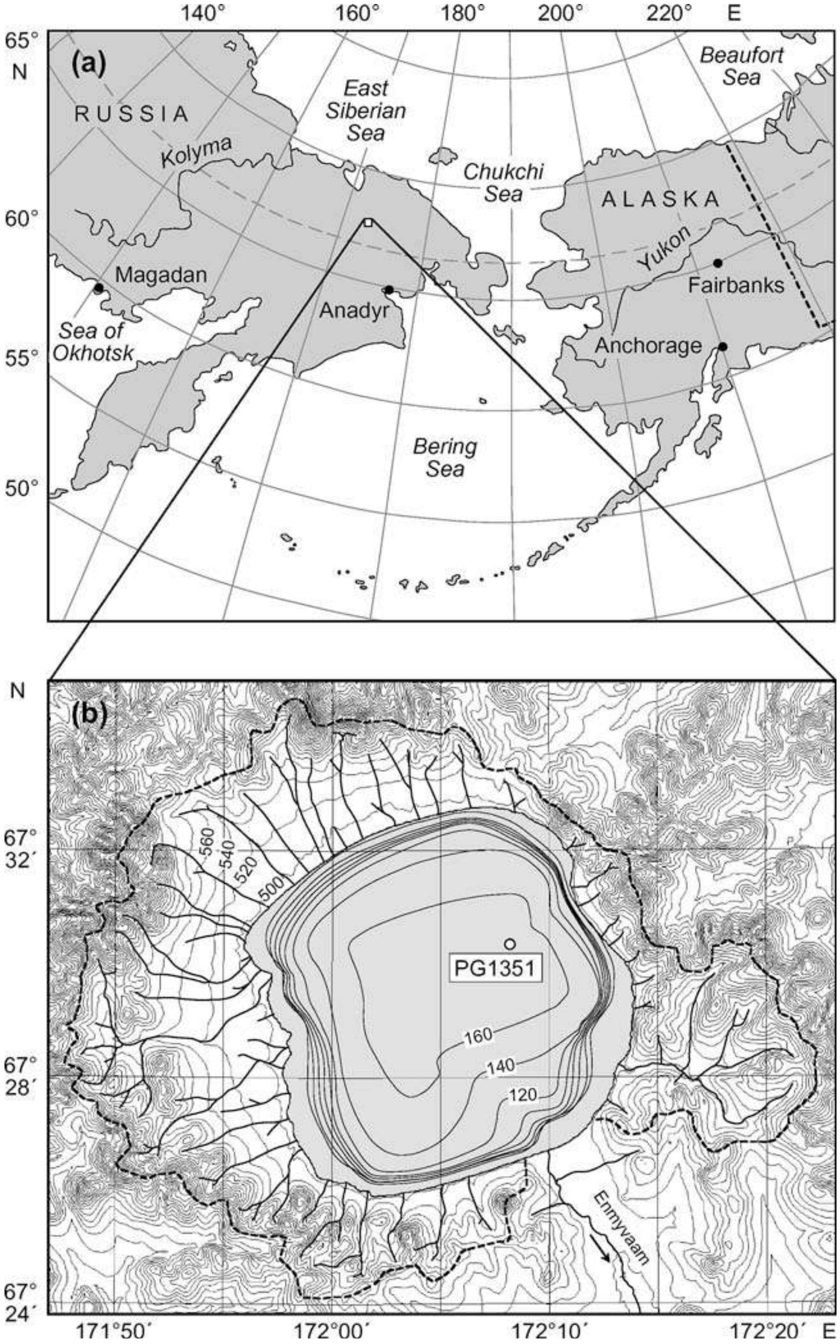

**Fig. 1** Location of Lake El'gygytgyn in Chukotka, NE Siberia (top) and position of site PG1351 within the lake (bottom). The dashed line marks the boundary of the catchment of Lake El'gygytgyn

temperature curves of magnetic susceptibility, and high temperature curves of saturation magnetization. Thus, pure magnetite in the PSD range could be identified as the dominating magnetic mineral. However, also hematite is present in the investigated sediments, mainly controlling the magnetic properties where massive magnetite dissolution occured.

High resolution logging of magnetic susceptibility revealed amplitude variations larger than would have been expected simply from dilution of the lithogenic fraction by biogenic input. Pronounced lows can be attributed to climatically induced reductive dissolution of magnetite in the deposited sediments during glacials. The age model by Nowaczyk et al. (2002), here further referred to as the ‘2002 age model’, was based on infrared-stimulated luminescence (IRSL) ages, a preliminary pollen record, and, for the last about 100 ka (assuming that the magnetic susceptibility record of El’gygytgyn sediments reflects climatic conditions in some systematic way), a correlation to the GRIP oxygen isotope record. The older sections, where Greenland ice cores do not provide reliable data, were tentatively tuned to the oxygen isotope record of ODP 677. This yielded an age of about 300 ka for the core base, that is, about marine isotopic stage boundary 9/8.

With the elaboration of numerous stratigraphic data, organic and inorganic geochemistry, diatoms, and improved pollen data (e.g., Melles et al. 2007; Minyuk et al. 2007), it became obvious that the sediments in the lower half of the core must be significantly younger than proposed by the 2002 age model. Furthermore, these new data confirmed the indication from this age model that variations in the lake sediment composition reflect the 18 and 23 kyr precessional cycles, and, to a lesser extent, the 41 kyr obliquity variations. Therefore, a more reliable age model for core PG1351 can likely be achieved by correlation of variations in sensitive sediment proxies with latitudinal insolation. In this paper, the susceptibility data, which were acquired with the highest resolution of all data sets (1 measurement every mm), together with data obtained with a lower resolution (opal, TOC, and $TiO_2$), are tuned to the insolation at 70°N using data sets provided by Berger and Loutre (1991).

## Main factors controlling the susceptibility of Lake El’gygytgyn sediments

For the elaboration of a proper age model it first has to be understood how climate interacts with sedimentation processes in the environment of Lake El’gygytgyn. Under the present conditions, sediments are mainly carried into Lake El’gygytgyn by about 50 ephemeral creeks (Nolan et al. 2003). The fluvial supply takes place only during summer time, when air temperatures are above 0°C. In summer 2002, positive air temperatures occurred at Lake El’gygytgyn from late May to late September (Nolan and Brigham-Grette 2007). Besides this, there must be some minor aeolian contribution, because tree pollen are found in recent sediments (Nowaczyk et al. 2002; Lozkhin et al. 2007), although the tree boundary nowadays lies 150 km to the west and to the south from Lake El’gygytgyn. Also this material enters the lake in summer time, usually between July and October, when the lake ice cover disintegrates (Nolan and Brigham-Grette 2007). The sedimentation today takes place in well oxygenated bottom water in consequence of complete mixing of the water column in summer times (Cremer and Wagner 2003).

With modern pH values between 6.3 and 7.7 in the water column of Lake El’gygytgyn (Cremer and Wagner 2003), dissolution of biogenic silica (opal) probably is negligible. This makes opal a promising proxy for past bioproductivity. In core PG1351, opal exhibits pronounced alternation of low and high concentrations, ranging between 5 and 20 wt-% (Fig. 2). Low values roughly represent cold phases (glacials) and high values represent major warm phases (interglacials) (Melles et al. 2007). This interpretation is in good agreement with age data available for the last about 150 ka, where the 2002 age model is not in doubt (Nowaczyk et al. 2002; Forman et al. 2007). Taking opal as a proxy for bioproductivity, the biogenic input to the lake sediment varied in the range of about $f \times (5 \text{ to } 20)\%$. The factor $f$ takes into account that diatoms are not only composed of opal but also of organic matter, that is, hydrocarbons. In order to estimate the size of $f$, the total organic carbon (TOC) in core PG1351 is plotted in Fig. 2 in a way that maximum values in

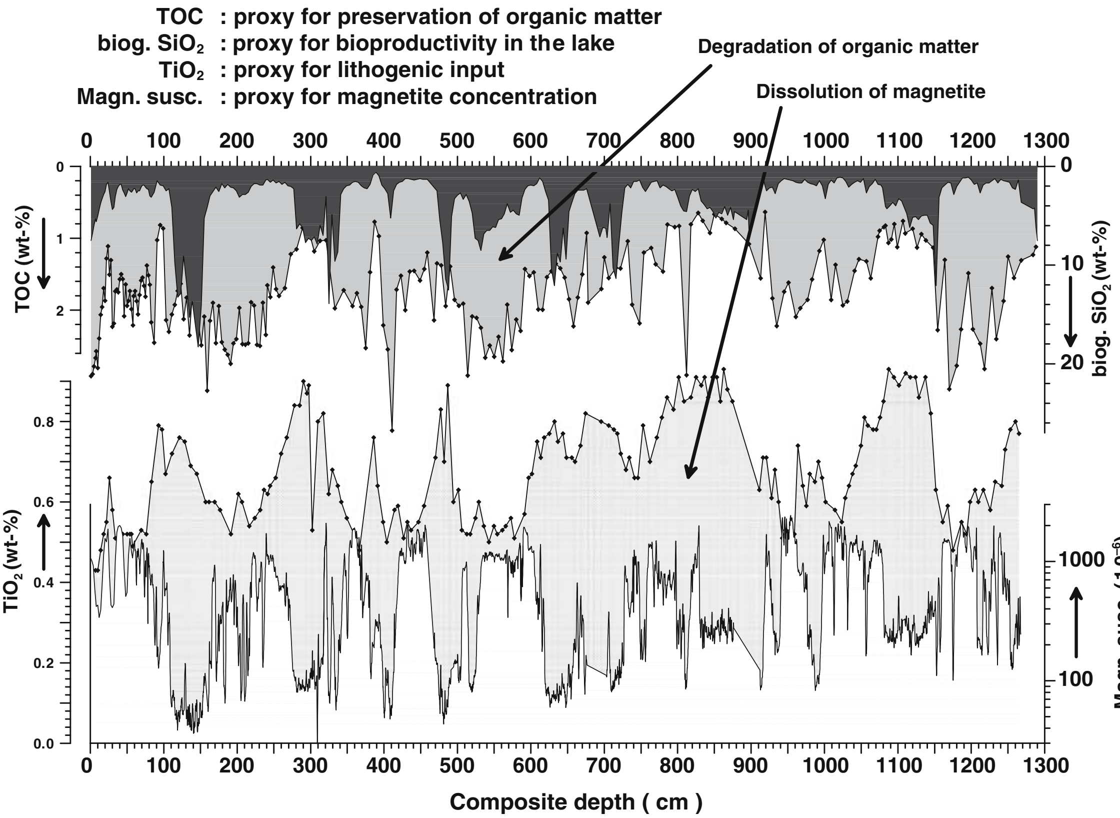

**Fig. 2** Magnetic susceptibility log from core composite PG1351 as derived from 1 mm high-resolution logging (white curve, Nowaczyk et al. 2002), in front of $TiO_2$ variations (dark gray curve, bottom), together with variations in total organic carbon (TOC, dark gray curve, top) and biogenic silica (opal, light gray curve, top), both plotted with inverted axes. The deviations between $TiO_2$ and susceptibility variations mark times of magnetite dissolution during anoxic conditions, whereas deviations between opal and TOC mark times of severe degradation of organic matter during oxic conditions at the lake floor. For further explanation see text

TOC overlap with opal values (both plotted on inverted axes). Overlapping occurs predominantly during peak glacial stages, when preservation of organic matter was best, due to a permanent lake ice cover that lead to a stratified water column and anoxic bottom waters (Melles et al. 2007). In these sections, the ratio of TOC to opal is about 1:6. Assuming a widely complete preservation of TOC, the biogenic contribution to the lake sediments can thus be estimated to vary between about 6 and 25 wt-%. This takes into account that organic hydrocarbons, beside carbon, consist of hydrogen, oxygen, nitrogen, etc.

From the very restricted catchment area, bordered by the crater rim (Fig. 1), it can be assumed that both the general composition and the amount of the lithogenic fraction supplied to the lake are relatively constant. This suggestion is confirmed by the contents of $TiO_2$ in core PG1351 (Fig. 2), a parameter regarded as one of the best proxies for lithogenic supply (Minyuk et al. 2007). Since $TiO_2$ and opal are generally anti-correlated, a significant part of the $TiO_2$ variation between about 0.4 and 0.9 wt-% can be explained by changes in the dilution of the lithogenic fraction with the biogenic fraction in the range of 25–50% maximum.

If magnetic susceptibility would also be a proxy for lithogenic input, just diluted by biogenic remainders (mainly opal and TOC), the variations of the former should follow the variations of the latter in an opposite way than $TiO_2$ does. Thus, when bioproduction is high susceptibility should be lower, but not less than 50%, and vice versa. However, this is absolutely not the case. In contrast, bioproduction highs are associated with susceptibility highs and susceptibility lows are paralleled by bioproduction lows (Fig. 2). Furthermore, magnetic susceptibility is anti-correlated to $TiO_2$, and it shows values spanning not only between 50 and 100 % but nearly two orders of magnitude. Hence, variations in biogenic accumulation do not have a significant impact on the fluctuations of magnetic susceptibility in Lake El'gygytgyn sediments. The susceptibility fluctuations must be caused by another process.

Sediment intervals with low susceptibilities are of dark grey color and mostly laminated. They have a relatively high content of total organic carbon (TOC), reaching about 2.5% (Fig. 2). Minima and maxima in TOC are paralleled by variations in total sulphur (TS), indicating anoxic conditions at the lake bottom (Nowaczyk et al. 2002; Melles et al. 2007). Thus it can be concluded that anoxic phases of the lake lead to massive reductive magnetite dissolution but best preservation of organic matter. The intervening intervals of high susceptibility, in contrast, are generally built up of massive brownish sediments characterized by low TOC and TS values. They in turn represent oxic phases with good preservation of magnetite but severe degradation of organic matter. The alternation of laminated and massive sediment units in core PG1351 leads to the observed susceptibility pattern, being lowered down to 1% (and not 50%) in anoxic units, when compared to the highest values in oxic units. For this process, anoxic conditions must have been severe enough in order to achieve the strong reductive magnetite dissolution observed. The steep flanks of the susceptibility and TOC records imply that there might be a threshold level in energy input for the development or destruction of a permanent stratification in the water body of Lake El'gygytgyn.

Thus, magnetic susceptibility is a proxy neither for the lithogenic input nor for the biogenic dilution, but for oxic (high values) or anoxic conditions (low values) at the bottom of Lake El'gygytgyn, seperated by nearly two orders of magnitude. The amount of dissolved magnetite can be qualitatively estimated by the width of the light grey area in vertical direction between the curves of $TiO_2$ and magnetic susceptibility in Fig. 2. The light grey area between the curves of opal and TOC contents in Fig. 2 thus gives an estimate of how much organic matter has been degraded, when the water at the lake bottom was oxic.

## The insolation-tuned age model

The presence or absence of oxygen at the bottom of Lake El'gygytgyn, most sensitively reflected for the past climatic cycles by the high-resolution susceptibility data from core PG1351, is controlled by the amount of biogenic primary production in the photic zone and by the degree of mixing of the water column (Melles et al. 2007). The primary production affects the flux of organic matter to the lake bottom, where its degradation reduces the oxygen content in the water. It depends, besides nutrient supply and temperature, on the availability of light. Sunlight, due to the proximity of Lake El'gygytgyn to the Arctic Circle, today is supplied nearly 24 h during summer times, but its strength varied in the geological past in dependence on insolation changes due to changes in the astronomical configurations of the Earth on its orbit around the sun. Also the lake mixing, and thus the degree of ventilation of the bottom water via the temperature, depends on the intensity of insolation. Today, complete mixing takes place in summer times, when the lake ice cover disintegrates and surface waters warm to about 4°C (Nolan and Brigham-Grette 2007), but this may not have been the case during times of reduced summer insolation in the past. The dependency of the oxygen content at the lake bottom on the intensity of insolation justifies a correlation of the El'gygytgyn susceptibility record to the insolation record as theoretically calculated for the geological past (Fig. 3), using the available IRSL ages of Forman et al. (2007) as tie points.

Variations in insolation due to quasi-cyclic changes in obliquity (41 kyr) and precession (18 and 23 kyr) of the Earth's rotational axis, and variations in eccentricity (100 and 400 kyr) of the Earth's orbit around the sun were first taken into account as the main reasons for the occurrence of ice ages by Milankovitch (1941). Berger and Loutre (1991) provided, among other data sets, a detailed data base with monthly means of insolation in 10° latitudinal steps every 1 kyr, reaching

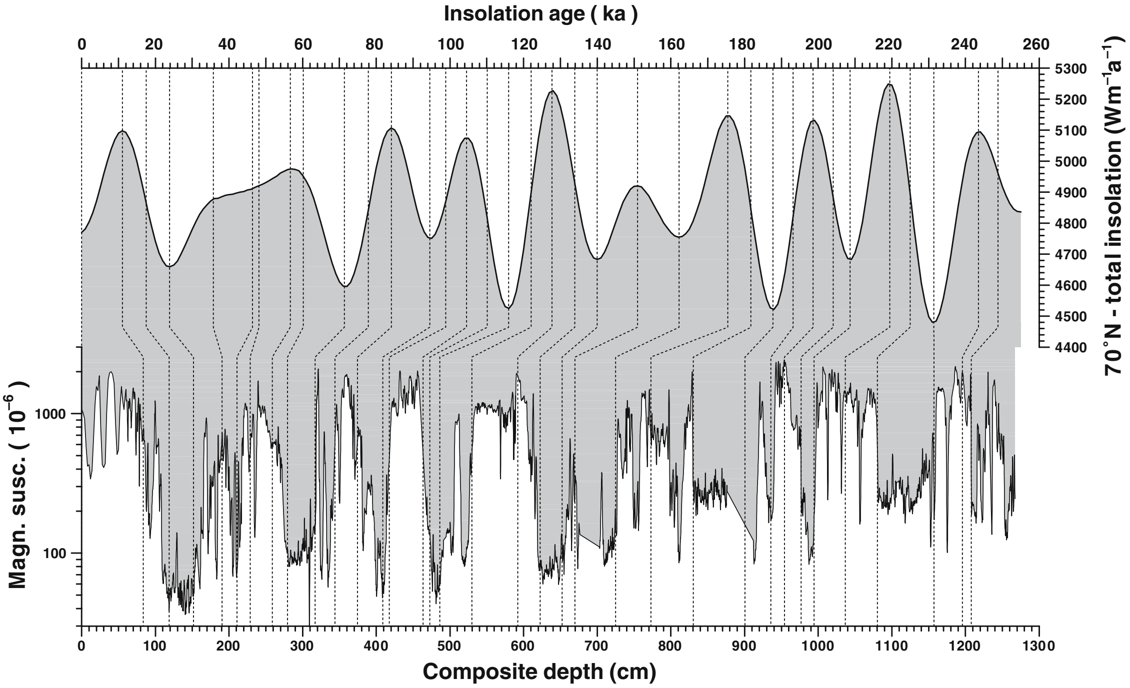

**Fig. 3** High-resolution magnetic susceptibility log from core composite PG1351 correlated to the total insolation per year at 70°N according to Berger and Loutre (1991). For details on the tuning procedure see text

back to 1 Ma. They also provided values for eccentricity, the precession angle Omega, defined as the longitude of perihelion from the moving vernal equinox (degrees), the obliquity (degrees), and 'climatic precession', defined as eccentricity multiplied by the sine of Omega, which is used here for discussion. By this definition, a climatic precession minimum is equivalent to a northern summer during perihelion (Earth closest to the sun) and a northern winter during aphelion (Earth farthest from the sun). This results in colder winters but hotter summers, when compared to the current situation, with the northern winter during perihelion (January, 3rd) and summer during aphelion (July, 3rd). A higher obliquitiy also results in a more intense northern summer insolation because of a steeper insolation angle. For higher latitudes below the arctic circle, this yields longer days during summer.

According to Berger and Loutre (1991), the recent insolation (I) per year at 70°N is 4770 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$ (Fig. 3). This is not the maximum of the Holocene. The highest insolation was seen at 11 ka, during the beginning of the Holocene, with a value of 5098 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, 6.9% more than today. However, during the past 300 ka, there were even higher insolation maxima during the beginning of the Eemian (128 ka), with 5227 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, 9.6% more than today, and the early stage 7 (219 ka), with 5249 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, even 10.0% more than today. Most prominent insolation lows were calculated for 24 ka, the Last Glacial Maximum (4660 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = -2.3\%$), 72 ka (4596 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = -3.7\%$), 116 ka (4525 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = -5.1\%$), 188 ka (4522 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = -5.2\%$), and 231 ka (4480 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = -6.1\%$). Thus, the largest insolation contrast occured at Termination III (stage boundary 8/7), with a total difference of 769 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, or $\Delta I = 16.1\%$, relative to today's insolation level. Termination II (stage boundary 6/5) experienced a difference of 544 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = 11.4\%$, and Termination I (stage boundary 2/1) a difference of 438 $\mathrm{Wm}^{-2}\ \mathrm{a}^{-1}$, $\Delta I = 9.2\%$.

If insolation would be the only climate forcing factor, temperatures would be approaching glacial conditions now (Fig. 3). This is not the case, because changes in the concentration of greenhouse gases ($CO_2$, $CH_4$, water vapor, etc.) and other effects globally keep the balance since the insolation maximum 11 kyr ago. On the other hand, when continental ice sheets start to cover large areas, due to an increased surface albedo, they reflect much more sun light, and thus keep the Earth cold after an insolation minimum. This requires, besides low temperatures, a certain amount of snowfall, because otherwise deeply penetrating permafrost would develop instead of an ice sheet. Another climate factor is the energy redistribution by the global conveyor belt of the ocean current systems. The Gulf Stream as part of the global conveyor belt, for example, currently keeps northern Europe relatively warm and nearly ice-free. Berlin in western Europe (52.5°N, 13.3°E) and Irkutsk in central Asia (52.3°N, 105.3°E) are nearly at the same latitude and, therefore, theoretically receive a similar amount of insolation. However, their annual mean temperatures differ greatly: Berlin +8.0°C and Irkutsk –1.8°C. Or, going to higher latitudes: the mean annual air temperature in Tromsø in northwestern Europe (69.6°N, 18.9°E) is +4.4°C, whereas at Lake El'gygytgyn in northeastern Asia (67.5°N, 172.1°E) it was –10.3°C in the year 2002 (Nolan and Brigham-Grette 2007). So, the effect of insolation on climate regionally can be superimposed by other climate controlling factors, involving the atmospheric and oceanic circulation, the atmospheric composition, and complex feedback mechanisms between atmosphere, cryosphere, hydrosphere, lithosphere, and, via the vegetation on land modulating the albedo, even the biosphere.

In order to correlate the sediment properties from core PG1351 to the insolation data (Fig. 3) it was taken into account that insolation maxima do not occur in the middle but at the beginning of warm stages, being marked by first maximum values within an interval of high susceptibilities. Insolation minima, in contrast, were systematically correlated to the bases of major low-susceptibility layers, which coincide with distinct increases in TOC (Fig. 2) and mark the onset of anoxia. Correspondingly, the steepest gradients in increasing and declining insolation values were correlated to the bases and to the tops of high susceptibility sections, respectively, coinciding with the tops and the bases of major TOC-rich sections (Fig. 3). This tuning yielded the revised age model shown in Fig. 4. It is roughly congruent with the 2002 age model, but yields generally younger ages below about 600 cm composite depth, corresponding with ages of more than 130 ka. According to this age model, the base of the core composite now reaches back to 252 ka.

## Indications for the climatic history

The El'gygytgyn susceptibility, TOC, and $TiO_2$ records plotted versus age are shown in Fig. 5 (lower center), together with the 70°N insolation curve (bottom) and (from top to middle), eccentricity, obliquity, and 'climatic precession' after Berger and Loutre (1991). Obviously, there is a striking similarity of the (logarithmically plotted) low-frequency component of magnetic susceptibility of Lake El'gygytgyn sediments and the 70°N insolation curve, especially to the precessional variations. Each minimum in 'climatic precession' (northern hemisphere summer during perihelion), meaning higher summer insolation, is coincident with a maximum in magnetic susceptibility, representing oxic conditions and mixing of the lake's water body as a consequence of high summer temperatures. In contrast, maxima in 'climatic precession' (northern hemisphere summer during aphelion), with lower summer insolation, coincide with minima in magnetic susceptibility, representing anoxic conditions due to reduced or even absent mixing of the water body as a result of lower summer temperatures and related permanent ice coverage. There is also a similar agreement between the insolation record and the $TiO_2$ record, but with opposite sign, that is, lower $TiO_2$ content (due to higher bioproductivity) in interglacials and higher $TiO_2$ content (due to lower bioproductivity) in glacials. Therefore, it can be concluded that the overall climatic and environmental conditions on the Chukotka Peninsula, which control sediment input, bioproductivity, and preservation of either organic matter (during anoxic phases) or magnetic minerals (during oxic phases) in Lake El'gygytgyn, are strongly controlled by astronomically forced insolation variations, with decreasing importance of precession, obliquity, and eccentricity.

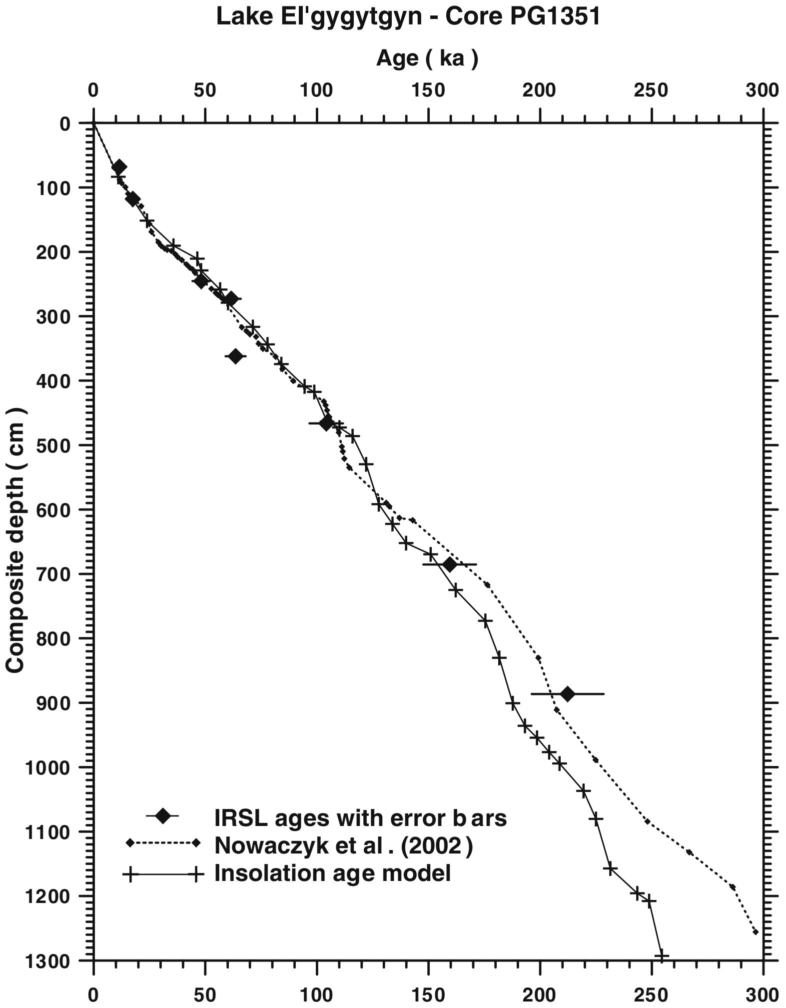

**Fig. 4** New age model (crosses) for core composite PG1351 based on IRSL ages (Nowaczyk et al. 2002; Forman et al. 2007) and tuning of the magnetic susceptibility to the 70°N insolation according to Berger and Loutre (1991) as shown in Fig. 3

On the one hand, susceptibility values during stages 1 (Holocene), 3, 5a, 5c, 5e (Eemian), and early stage 6, for example, are on a comparably high level. On the other hand, susceptibilities during sub-stages 5b, 5d and 7b are characterized by similarly low values as those during the high glacial stages 2, 4, and late 6 (Fig. 5). The lake water mixing controlling the susceptibility mainly depends on positive summer temperatures exceeding a certain level for a sufficient time interval per year. Thus, it becomes obvious that there is a kind of threshold level in insolation for Lake El'gygytgyn that controls whether the water body is mixing during summer, or not. In order to illustrate and also to quantify this, magnetic susceptibility as well as TOC values were plotted versus insolation (Fig. 6, bottom), together with their respective frequency distributions (Fig. 6, top). This way of data display revealed that magnetic susceptibility does not show a bi-modal but a tri-modal distribution: Insolation values lower than about 4900 Wm$^{-2}$ a$^{-1}$ are mostly associated with susceptibilities of either around $90 \times 10^{-6}$ or around $250 \times 10^{-6}$, whereas insolation values higher than about 4900 Wm$^{-2}$ a$^{-1}$ are associated with susceptibilities of around $1000 \times 10^{-6}$. The splitting of the susceptibility distribution in intervals with lower insolation into two maxima is somehow linked with TOC contents. Intermediate susceptibilities of around $250 \times 10^{-6}$, occurring mainly during early stage 6 and stage 7d, are associated with intermediate TOC values of around 0.7%, whereas the highest TOC values of up to 2.6% are associated with the lowest susceptibilities

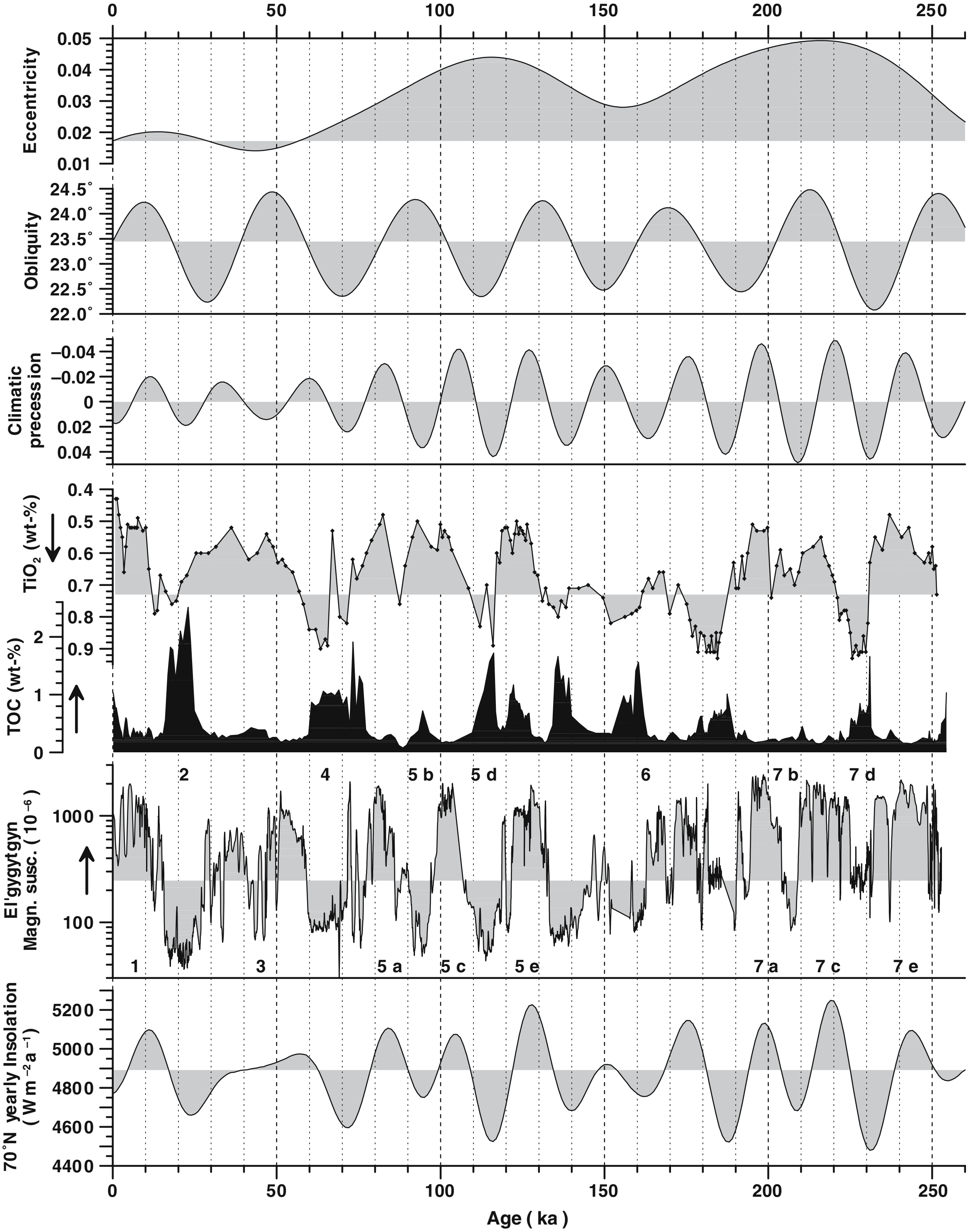

**Fig. 5** El'gygytgyn magnetic susceptibility, TOC, and TiO$_2$ data versus time (lower center), together with variations in eccentricity of the Earth's orbit, obliquity and climatic precession of the Earth's rotational axis (from top to middle), and yearly insolation at 70°N (bottom) according to Berger and Loutre (1991). Numbering from 1 through 7 indicate oxygen isotope stages with letters from a to e indicating their sub-stages

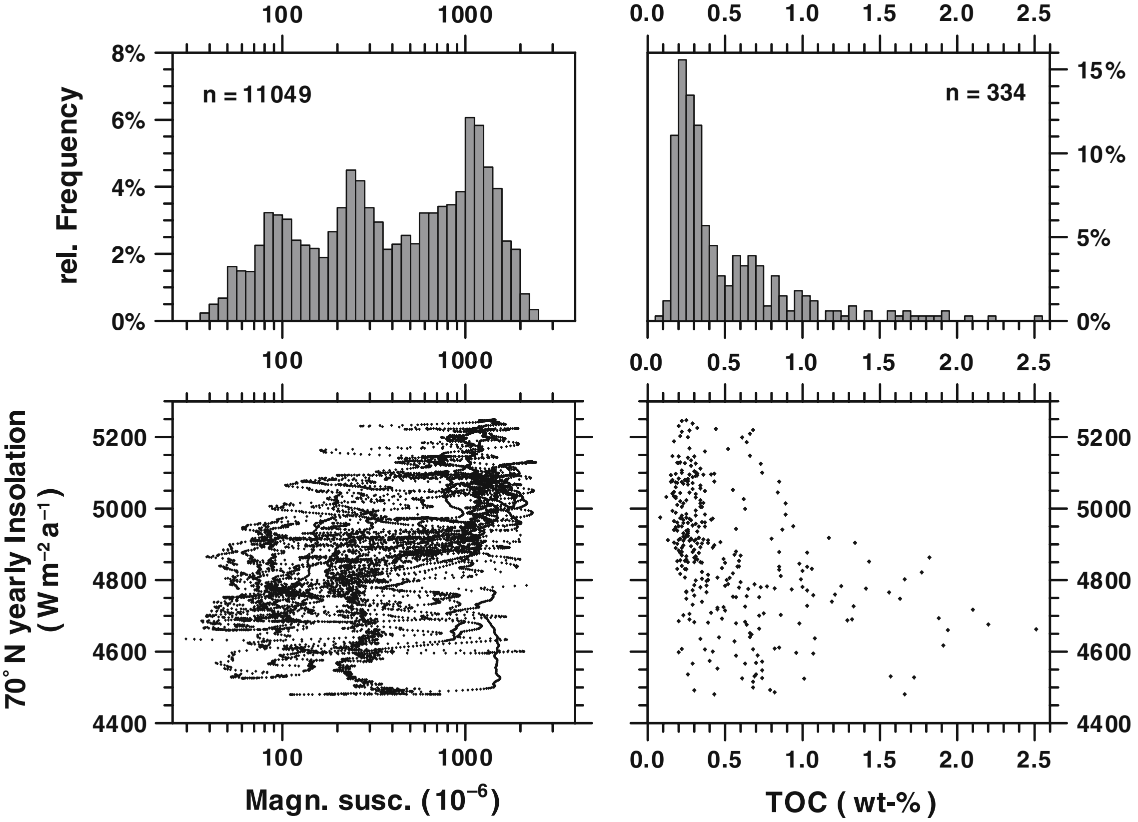

**Fig. 6** Magnetic susceptibility (left) and total organic carbon (TOC, right) in core composite PG1351 plotted versus yearly insolation at 70°N (bottom) together with the respective frequency distributions (top). "*n*" indicates the number of measurements

of around $90 \times 10^{-6}$. Both low susceptibilities (high TOC values) and intermediate susceptibilities (intermediate TOC values) occur during low insolation periods ($< 4900$ Wm$^{-2}$ a$^{-1}$), characterized by anoxic bottom water conditions in Lake El'gygytgyn. Oxic conditions, associated with high insolation periods ($>4900$ Wm$^{-2}$ a$^{-1}$), in contrast, are mainly reflected by high susceptibilities around $1000 \times 10^{-6}$ and low TOC values of up to 0.4% maximum. However, there is one exception, where the oxic conditions are associated with high susceptibilities but also relatively high TOC contents between 0.4 and 1.0% (Fig. 5). This interval represents the Eemian interglacial (stage 5e), when the biogenic accumulation in Lake El'gygytgyn was the highest during the past 250 kyr (Melles et al. 2007).

In summary, this indicates that insolation variations are the dominating controlling factors for magnetite preservation (and TOC degradation) on the one hand, and magnetite dissolution (and preservation of TOC) on the other hand, although there must be at least one additional process leading to the described two different scenarios during low insolation periods. In addition, there are also some high-frequency contributions on a millenial scale, superimposed on the Milankovitch-type (10–400 kyr) of variations. Nevertheless, a high sensitivity to insolation variations and a reduced dependency on changes in the oceanic circulation pattern is what should be expected, given the continental climate of Chukotka. This may be the case for wider areas of eastern Siberia, as indicated by the finding of an insolation dominance during the past 60 kyr also on the sedimentation in Elikchan Lake to the south of Chukotka (60°45′ N, 151°53′ E) (Brigham-Grette et al. 2004). The climatic conditions during warmer time intervals, at least during the short summers, could have been much milder on Chukotka when compared to Europe or North America. This is also indicated by the restricted glaciation on Chuchotka (Glushkova et al. 1994) during times when massive ice sheets of nearly continental size occurred in western Eurasia and North America (e.g., Svendsen et al. 2004).

## Conclusions

By combining the sedimentological key parameters magnetic susceptibility (proxy for magnetite preservation), biogenic silica (opal, proxy for bioproductivity), total organic carbon (TOC, proxy for redox conditions), and $TiO_2$ (proxy for lithogenic input) in composite core PG1351, it was possible to clarify the major (long term) processes that control late Quaternary sedimentation in Lake El'gygytgyn. Sediment transport to the lake is restricted to summer times, when temperatures are above 0°C, so that the lake ice cover disintegrates and precipitation and meltwater from snowfields enters the lake. The lake almost flips between two completely different stages. Oxic bottom water conditions occur during warm climates, leading to good preservation of magnetite but severe degradation of organic matter, whereas anoxic bottom water conditions of different degree occur during cold climates, leading to severe magnetite dissolution but the best preservation of organic matter. The change between oxic and anoxic conditions is obviously mainly a function of insolation variation, since magnetic susceptibility resembles nearly perfectly the pattern of 70°N insolation, with high susceptibilities (low TOC values) during high insolation, and low susceptibilities (high TOC values) during low insolation periods. In general, the contribution of precession is dominating. Starting with available IRSL ages it was thus possible to tune the El'gygytgyn susceptibility record to the 70°N insolation curve in order to obtain a reliable age model for core composite PG1351. The core base is now dated at 252 ka, 45 kyr younger than published by Nowaczyk et al. (2002). According to the revised age model, the long-term pattern of susceptibility variations might reflect a strongly continental type of climatic behaviour deviating to a certain degree from global temperature reconstructions.

**Acknowledgements** We like to thank all the participants on the expedition to Lake El'gygytgyn in spring 1998 for recovering core PG1351. Two anonymous reviewers are acklowledged for their critical as well as constructive comments. Partial financial support was kindly provided by the German Ministry for Education and Research (BMBF), grant no. 03G0586 A.

## References

Berger A, Loutre MF (1991) Insolation values for the climate of the last 10 million of years. Quat Sci Rev 10:297–317

Brigham-Grette J, Lozhkin AV, Anderson PM, Glushkova OY (2004) Paleoenvironmental conditions in western Beringia before and during the Last Glacial Maximum. In: Madsen DB (ed) Entering America: Northeast Asia and Beringia before the last glacial maximum. Univ. of Utah Press, Chapter 2, pp 29–61

Cremer H, Wagner B (2003) The diatom flora in the ultra-oligotrophic Lake El'gygytgyn, Chukotka. Polar Biol 26:105–114

Forman SL, Pierson J, Gomez J, Brigham-Grette J, Nowaczyk NR, Melles M (2007) Luminescence geochronology for sediments from Lake El'gygytgyn, northeast Siberia, Russia: constraining the timing of paleoenvironmental events for the past 200 ka. J Paleolimnol DOI 10.1007/s10933-006-9024-7 (this issue)

Glushkova OYu, Lozhkin AV, Solomatkina TB (1994) Holocene stratigraphy and paleogeography of El'gygytgyn Lake, northwestern Chukotka. Proc. Intern. Conf. Arctic Margins, Magadan, Sept. 6–10, 1994, Magadan, NEISRI FEB Russian Acad. Sci., 75–80

Lozkhin AV, Anderson PM, Matrosova TV, Minyuk P (2007) The pollen record from El'gygytgyn Lake: implications for vegetation and climate histories of northern Chukotka since the late middle Pleistocene. J Paleolimnol DOI 10.1007/s10933-006-9018-5 (this issue)

Melles M, Brigham-Grette J, Glushkova OYu, Minyuk PS, Nowaczyk NR, Hubberten H-W (2007) 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. J Paleolimnol DOI 10.1007/s10933-006-9025-6 (this issue)

Milankovitch M (1941) Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem. Königlich Serbische Akademie, Belgrad, 633 pp

Minyuk PS, Brigham-Grette J, Melles M, Borkhodoev BYa, Glushkova OYu (2007) Inorganic geochemistry of El'gygytgyn Lake sediments (northeastern Russia) as an indicator of paleoclimatic change for the last 250 kyr. J Paleolimnol DOI 10.1007/s10933-006-9027-4 (this issue)

Nolan M, Liston G, Prokein P, Brigham-Grette J, Sharpton V, Huntzinger R (2003) Analysis of Lake Ice Dynamics and Morphology on Lake El'gygytgyn, Siberia, using SAR and Landsat. J Geophys Research 108(D2):8062, doi:10.1029/2001JD000934

Nolan M, Brigham-Grette J (2007) Basic hydrology, limnology, and meterology of modern Lake El'gygytgyn, Siberia. J Paleolimnol DOI 10.1007/s10933-006-9020-y (this issue)

Nowaczyk NR, Minyuk P, Melles M, Brigham-Grette J, Glushkova O, Nolan M, Lozhkin AV, Stetsenko TV, Anderson PM, Forman SL (2002) Magnetostratigraphic results from impact crater Lake El'gygytgyn, northeastern Siberia: a 300 kyr long high-resolution terrestrial palaeoclimatic record from the Arctic. Geoph J Intern 150:109–126

Svendsen JI, Alexanderson H, Astakhov VI, Demidov I, Dowdeswell JA, Funder S, Gataullin V, Henriksen M, Hjort C, Houmark-Nielsen M, Hubberten H-W, Ingólfson Ó, Jakobsson M, Kjær KH, Larsen E, Lokrantz H, Lunkka JP, Lyså A, Mangerud J, Matiouchkov A, Murray A, Möller P, Niessen F, Nikolskaya O, Polyak L, Saarnisto M, Siegert C, Siegert MJ, Spielhagen RF, Stein R (2004) Late Quaternary ice sheet history of northern Eurasia. Quat Sci Rev 23:1229–1272